Ground-Water Modeling and Geothermal Characterization of the New Washoe City Area, Washoe County, Nevada

Washoe County Department of Water Resources

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Department of Water Resources

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By Karlis Kanbergs

Washoe County Department of Water Resources

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Groundwater Flow Modeling and Geothermal Characterization of the New Washoe City Area, Washoe County, Nevada

A thesis submitted in partial fulfillment of the

requirement for the degree of Master of Science

in Hydrogeology

by

Karlis Kanbergs

Stephen W. Wheatcraft, Thesis Advisor

December 1997

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ABSTRACT

New Washoe City has over 1000 homes which utilize domestic wells. Groundwater issues include drought effects, water quality and geothermal waters. Groundwater modeling was conducted to assess system hydrology and predict effects of drought-induced stresses. A twenty-year worst case drought-development scenario model suggests average drawdowns in the western part of NWC of only ten to twelve feet. Drops against the range front are greater, to 30 feet. Geochemical water sampling, including oxygen and hydrogen isotopes and temperature probing of selected domestic wells was completed for temperature perturbations could occur. purposes of geothermal characterization. An approximate one square mile area was identified, best characterized as a thermal plume (to 51 ^{0}C at 100 ft.), that also exceeds primary drinking water standards for fluoride. Fluoride and thermal waters appear linked, with geothermal flow pathways likely from the west, through fractured basement rocks. Severe drought-induced incursion of warm waters into the potable aquifer is unlikely, although local temperature perturbations could occur.

INTRODUCTION

Water availability and quality are important issues in the rapidly growing greater Reno-Sparks community. The metropolitan region's water supply is primarily from municipal sources, but various outlying areas rely on individual domestic wells. Most domestic wells are shallow, less than 200 feet deep, and are often in unconfined aquifers, susceptible to contamination and rapid de-watering. The water table can subside due to a combination of highly variable recharge rates and continued home development. While dropping water tables can be remedied by deepening wells, water quality issues are perhaps a more serious concern.

Water quality is affected by both natural and human-induced events. Western Nevada is tectonically active with scattered occurrences of past or present geothermal activity. These systems can directly affect water quality and often introduce natural toxins into groundwater. Constituents of particular concern are arsenic, boron, and fluorine. Nitrate contamination also poses potentially serious health hazards with the main sources of nitrate contamination being domestic septic systems and farm animals. Rural communities with relatively close-spaced development, on domestic wells and septic systems, and zoned for farm animals, are extremely susceptible to such contamination.

Domestic water systems are not governed by the same water quality criterion as municipal supplies. State water law allows development of one domestic well per home and a draft of up to 1800 gallons per day from that well. No effective mechanism is in place to assure that domestic consumption does not exceed this amount, or that exposure to potential water-borne contaminants does not occur. Therefore existing areas, as described, present a water management problem for governing and planning agencies.

An effective solution to water problems in these communities can be conversion to a central water supply, often through development of municipal wells accompanied by sewer hookup and possible construction of wastewater treatment facilities. These projects are costly and, in the past, communities have objected strongly to such proposals.

For best water management and planning Washoe County requires additional information regarding the hydrology and hydrogeology of these affected communities. Particularly, a better knowledge is required of groundwater flow systems and water budgets, and potentially hazardous groundwater constituents. This can be achieved by data collection, compilation, and groundwater modeling. Such projects can help determine the potential severity of a situation, and also provide planners and water resource managers tools for more informed and cost-effective decisions.

Statement of Problem

New Washoe City (abbreviated as NWC) is an unincorporated community in Washoe Valley that currently includes about 1200 residences on domestic well water and individual septic systems. Most homes are on one acre parcels and many have farm animals. During the latest drought, which ended in 1994, certain portions of the water table dropped rapidly. Other areas exceed the primary standards for fluoride and nitrate. The fluoride may be related to a thermal anomaly in the southwestern portion of NWC. A need exists for greater understanding of the groundwater flow system and groundwater chemistry. While the nitrate contamination has been previously studied, little is known about the thermal anomaly and possibly related geochemistry.

Purpose and Objectives

The primary purpose of this study is to: (a) refine and extend the current conceptual and numeric ground water model of NWC/Washoe Valley , and (b) to test the hypothesis that elevated fluoride levels are caused by the thermal anomaly.

A primary focus of the study is to refine an existing numerical ground water flow model of Washoe Valley, specifically in the NWC area. Through compilation and synthesis of available information, and data collection where appropriate, a revision and refinement of the conceptual model will be made. The conceptual model will then be used to modify the existing numerical model. After proper adjustments, the model will be used to make predictions regarding flow patterns and water table elevations in NWC. The goal is to develop a model for a worst case scenario of a development-drought situation.

A second goal is to characterize the thermal anomaly. Prior to this study the thermal anomaly was described as a one point anomaly. Anomalous ground water fluoride levels had been noted and one hypothesis suggested a genetic relationship with the warm waters. The characterization will be made by compilation of existing data, collection of thermal data and collection of additional water samples. Specifically, the study will outline the extent of the shallow groundwater thermal anomaly and focus on distribution of the fluoride anomaly and its relationship to the thermal anomaly. Data on other analyzed groundwater constituents will also be presented. There is a reason to be concerned about possible accelerated incursion of thermal waters into the domestic water system due to possible future water table drops during drought or overpumping. Quantitative thermal flow modeling was considered but eventually ruled out as being beyond the scope of the study, largely due to lack of sufficient data at depth. However, short of modeling, qualified predictions regarding possible future impacts to the domestic water supply from geothermal influences will be presented.

Project Location and Physiographic Setting

The NWC is located in Washoe Valley which is situated between Reno and Carson City (Figure 1). The focus area of New Washoe City is identified on Figure 2 (1996 conditions). Because flow modeling included the entire east side of Washoe Valley, the whole east side of Washoe Valley is called the project area. Washoe Valley comprises a watershed of approximately 54,000 acres. The valley floor has an area of about 18,000 acres and is flanked on the west by the Carson range, which is considered part of the Sierra Nevada. East of the valley is the topographically lower Virginia range. Due to orographic effects, the west side of the valley is much wetter than the east side. Additionally, the valley floor contains an ephemeral lake, which periodically dries up due to drought. The last dry period was in 1993 and the previous dry event occurred in the mid-1930's. During wetter times the lake can occupy up to 30 percent of the valley floor.

ACKNOWLEDGMENTS

This thesis would not have been possible without the support of my wife Lynn or my two lovely daughters, Mara and Alexa. My deepest appreciation to them for their patience. Gratitude is extended to the Washoe County Department of Water Resources, Utility Services Division, whom funded the thesis effort through a generous internship. I want to especially thank Mike Widmer and Dan Dragan for their encouragement and assistance. Others at Washoe County who helped me out in numerous ways include Ed Evans, Randy Van Hoozer, Jim Hillman, Leonard Crowe, Wynn Ross, and Gail Procknish. A special thanks to Paul Hartley at ADGIS Inc., for help with geophysical data processing. Alan McKay and Todd Mihevic at DRI assisted by supplying various data and loaning equipment. Jim Rumbaugh of Environmental Simulations graciously loaned me a copy of Groundwater Vistas. Of equal importance to funding has been support provided by my thesis committee, Dr. Lisa Shevenell, Dr. Kate Berry and especially my advisor Dr. Steve Wheatcraft, whom I want to personally thank. Dr. Wheatcraft was instrumental in nominating me to the Program of Hydrologic Sciences, and has provided a patient ear and good advice. Students in the program have made the whole experience not only worthwhile but enjoyable. Much appreciation is extended to Maria Dragila whose brilliance and kindness helped me get

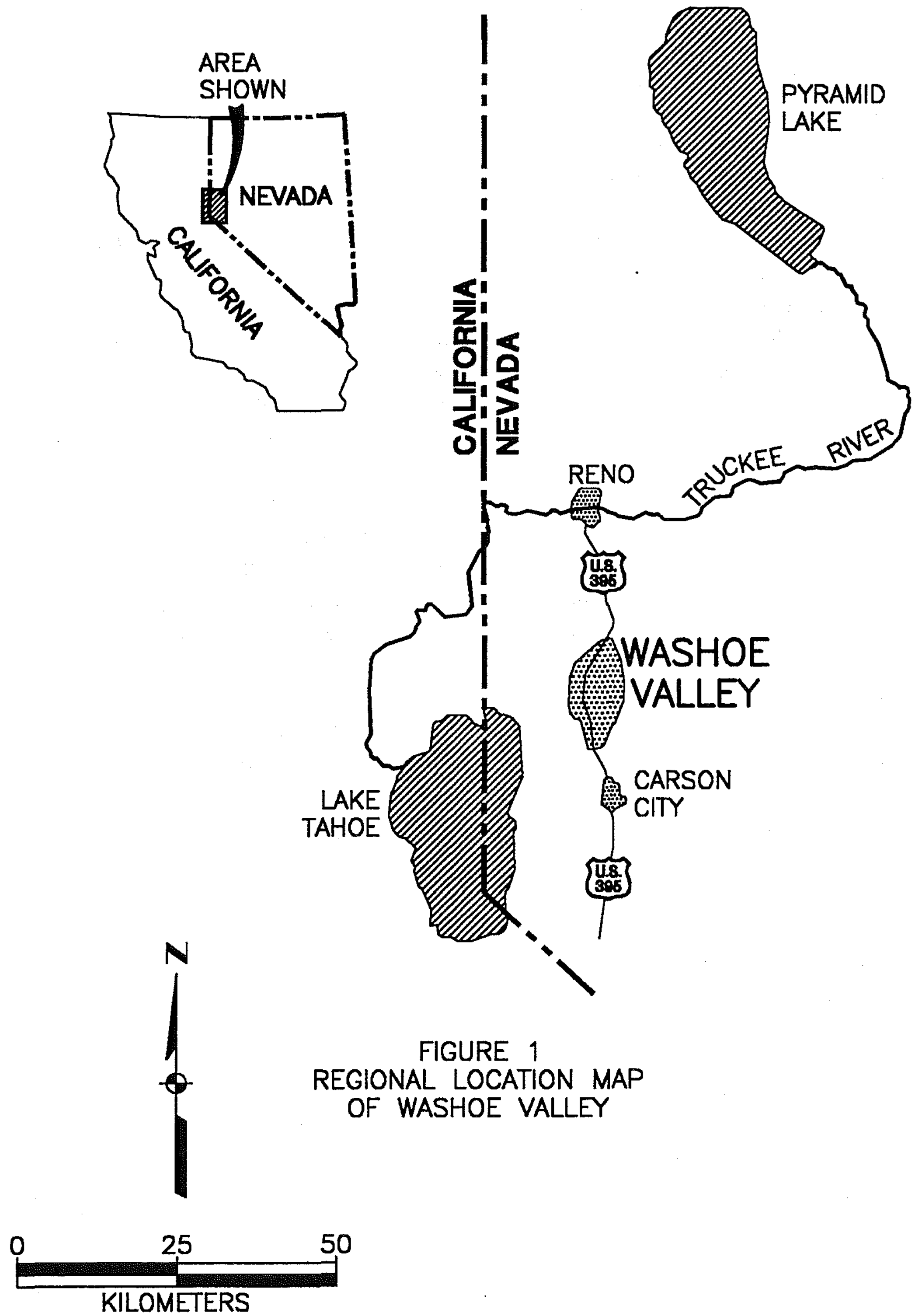


FIGURE 1
REGIONAL LOCATION MAP
OF WASHOE VALLEY

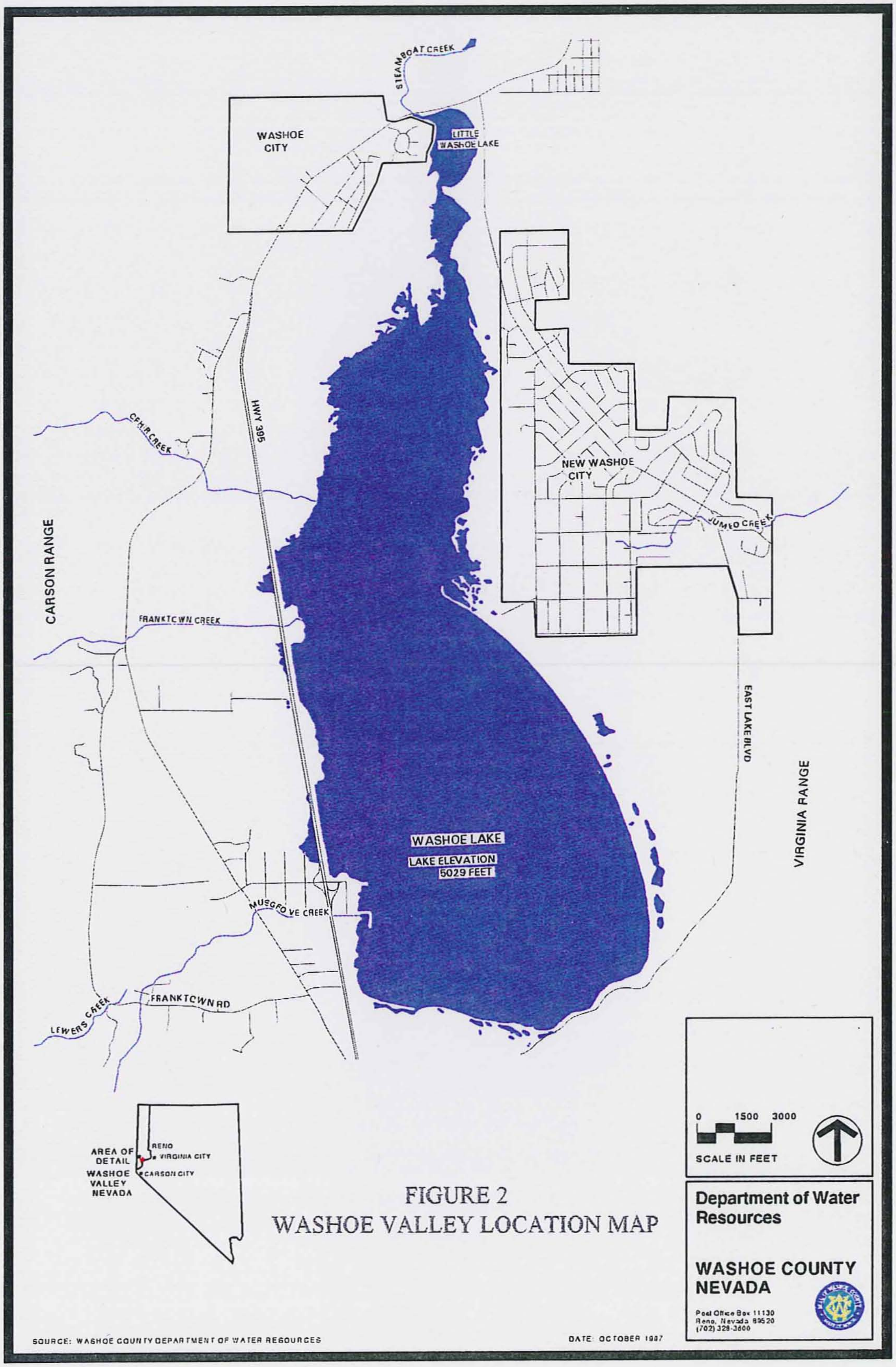


FIGURE 2
WASHOE VALLEY LOCATION MAP

over the rough spots. Also thanks to Bill and Darcy Howecroft, Chris Benedict, Joe Leising, Rina Shumer and Angela Varian. And of course, hats off to Sam Miller.

PREVIOUS INVESTIGATIONS AND METHODOLOGY

This project builds on previous work. Much of the numerical groundwater flow modeling is based on a series of valley-wide models that were either supported by or directly completed by the Washoe County Department of Water Resources, Utility Services Division (references follow). The methodology of the study required collection of additional field data and extensive compilation/synthesis of geologic and hydrogeologic information. Much of the available literature and all of the modeling to date has encompassed the entirety of Washoe Valley. Discussion of NWC hydrogeology is impossible without reference to the hydrogeologic system of the entire Washoe Valley floor.

At the project planning stage, a choice had to be made whether to present the project area as a stand-alone model or whether to treat it as a continuum with the rest of the valley. The latter approach was adopted. Also originally considered was the method of telescopic mesh refinement, or TMR (Ward, et. al., 1987) where a grid with coarse nodal spacing is fitted to the regional boundaries, and boundary conditions for models covering successively smaller geographic area are defined from the regional model. Because Washoe Valley is essentially a closed basin, or applying boundary conditions internal to the basin, without adequate data, can cause serious modeling errors, TMR was not justified, except during sensitivity analysis.

Previous Investigations

General Data

The hydrology and hydrogeology of Washoe Valley were summarized by Rush (1967), published as a USGS Water Resources Reconnaissance Series report. The report establishes a hydrologic framework for Washoe Valley. Rush identifies a valley fill aquifer and notes the disparate recharge between the west (wet) and east (dry) sides of the valley. A water budget is included and figures are provided for precipitation and evapotranspiration. The report does not fully treat ground water recharge, nor quantify aquifer parameters. Arteaga (1982,1984) amplified and refined Rush's work. Main additions are refinement of the hydrologic budget, revision of precipitation and recharge rates, a primary address of groundwater recharge, and also a brief treatment of aquifer parameters.

Geology of the Washoe Lake Area is summarized by Tabor and others (1983) as a text to accompany the Environmental Series Folio maps of the Washoe City Quadrangle. Petersen (1993) contributed useful information regarding subsurface basin geology and hydraulic conductivities. Rush (1975) published the hydrologic map for the folio. To this writers knowledge three previous groundwater level surveys were completed. These are 1965, as measured by Rush, 1982 as measured by Arteaga, and 1994, surveyed by Washoe County. Petersen's thesis (Petersen, 1993) and a summary by Petersen and Karlin (1997) present geophysical data used to characterize the basin geology and provide a hydrogeolgic framework for portions of Washoe Valley. In 1994, Washoe County contracted with Dighem, a Canadian geophysical contractor, who completed an airborne helicopter geophysical survey over the entire Washoe Valley area. The survey consisted of magnetics and multifrequency electromagnetics and provided potentially useful data for interpretation of subsurface lithology, structure and identification of geothermal areas.

Geochemical Data

Groundwater chemistry and quality were documented by Armstrong and Fordham (1977), who noted unsafe or anomalous values of nitrates/nitrites, iron, and fluorine in the New Washoe City area. McKay (1991) continued this work and identified a single point thermal anomaly from a domestic well with temperatures greater than 50^{O}C. Warm water, probably from the same locality, was described as early as 1971 (Garside and Schilling, 1979). Well water geochemical samples were collected by Washoe County in 1994. Miscellaneous public domain water analyses are also available.

Previous Modeling

Modeling of Washoe Valley has been done by several authors. The first attempt at numeric modeling was by Arteaga (1982) who used a code developed by Trescott (1975). Sparse data were available for estimation of aquifer parameters. Petersen (1993) developed a steady state groundwater flow model for the entire Washoe Valley area and used MODFLOW (McDonald and Harbaugh, 1988). Peterson also made significant contributions to development of the hydrogeolgic model through interpretation of ground-based geophysical surveys.

Petersen's steady state model, as presented in his thesis, was further modified, under the direction of the Washoe County Utility Division. The County contracted with the Desert Research Institute, and a draft report (Petersen and others, 1994) was submitted to Washoe County. Additional revisions were made to the model by Widmer (1994) as documented in a Washoe County Technical Memorandum. Major revisions focused on water budgets, boundary condition fluxes and hydraulic properties.

The steady state model has been further adjusted by Washoe County, and transient flow modeling added (Widmer, 1997). The latter report represents the culmination of Washoe County sponsored modeling investigations. As such, it is a pivotal document and a "jumping off point" for the modeling work presented here. Widmer's work also summarizes and refines the groundwater budget, recharge and discharge, including evapotranspiration rates and range front recharge.

Methodology

Discussion of methods is divided into three sections. In all phases of work, available published literature was reviewed.

Groundwater Flow Modeling--Collection and Compilation of Hydrogeologic Data

Prior to numerical modeling a conceptual groundwater model must be conceived. All available geology, hydrogeology, hydrology and climate data were compiled or synthesized. Additionally, more than one hundred domestic well drillers reports with lithologic information were reviewed and a series of lithologic and structural cross sections were prepared for the study area. Very few reliable long term pumping tests are available to determine hydraulic conductivities of the aquifer(s) (K values). Specific capacity data were therefore compiled from the drillers reports and from Washoe County files and K values calculated. A goal of this study was to provide a structural interpretation of the NWC area. This was accomplished by interpretation of the airborne geophysical data, published geologic data and the constructed cross-sections.

This study uses published water budget figures, recharge rates and evapotranspiration (ET) values. However, the values were adjusted during calibration, and the chloride balance method, as used by Thomas, et. al. (1989) and Maurer, et. al. (1996) was applied as a check.

An early important field task was completion of a GPS survey for accurate locations and elevations of the 1994 valley-wide domestic well survey. A list with GPS coordinates and elevations are provided as Appendix A. These were collected during January and February of 1997, during the same quarter as the 1994 survey. A flaw in the earlier surveys was unreliable elevation that caused problems in model calibration. The 1994 and 1997 data set is therefore the most reliable with respect to location. Water table levels were also measured during the 1997 survey, using a stainless steel, chalked tape. The data were used for construction of water level difference (drawdown) maps, study of range front recharge patterns, and were also employed in transient model verification.

Groundwater Flow Modeling and Protocol

A calibrated steady state numerical model was constructed to approximate the conceptual model. With the existing Washoe Valley model, adjustments were made primarily in the project area (east side of the valley). Relatively minor adjustments of hydrologic parameters or boundary conditions were made on the west side.

Anderson and Woessner (1992) suggest a series of steps, or protocol, to achieve modeling goals. These are: 1) Define purposes of the modeling exercise; 2) Prepare conceptual model representative of the physical system; 3) Identify appropriate mathematical (governing) equations; 4) Select a suitable model code; 5) Prepare model design (selection of boundary conditions, etc.); 6)

Calibrate model; 7) Verify model; 8) Use model for prediction; 9) Present results. For this project the selection of appropriate governing equations and a suitable model code that had already been made by previous workers was used. Beginning with Petersen's study (1993) all modeling has used MODFLOW (McDonald and Harbaugh, 1988) which is a finite difference code. Widmer (1997) used a Windows 95 compatible pre and post processor commercial software package called Groundwater Vistas (Rumbaugh and Rumbaugh, 1996), and this study continued with the use of the same software package.

Collection and Compilation of Thermal Data

To delineate the extent of the thermal anomaly, approximately 25 domestic wells were probed using a small diameter YSI tubular stainless steel thermistor probe (#403) attached to a weighted and depth coded depth sounder cable. Temperatures were read with a Fisher Scientific NIST Traceable digital thermometer. The thermistor came equipped and calibrated to an attached short cable. Because the probe had to be spliced to a much longer cable, a new calibration was required. Various controlled temperature water baths were prepared and the temperatures from the modified setup were compared against temperatures obtained from an identical probe with original cable. The temperature shift was linear and a simple correction equation could be applied to the field data, based on a linear regression analysis of the calibration data.

Selection of domestic wells for measurement required cooperation of home owners (many did not respond) and a proper well design. Unfortunately many wells in NWC are of an older design with sealed or difficult to remove caps or inspection ports. Sometimes a minimum down-hole temperature was obtained by running tap water until no further change was noted in temperature. From the collected data several temperature and gradient maps were constructed, along with temperature vs. depth profiles.

Collection and Compilation of Geochemical Data

A large geochemical data base for standard aqueous geochemistry exists for NWC as Nevada State Health Laboratory water chemistry analyses. These samples have been collected at various times at the request of home owners or at time of resale. A standard suite includes total dissolved solids (TDS), hardness, calcium, magnesium, sodium, sulfate, chloride, nitrate (total), alkalinity, bicarbonate, carbonate, fluoride, arsenic, iron, manganese, copper zinc, barium, boron, silica, color, turbidity, pH, and E.C. These data were used to create initial iso-concentration maps of constituents of interest.

During the 1994 water table survey Washoe County collected approximately 50 water samples, valley-wide, and used the same State Health lab with the standard suite and collection procedure. In the present study twenty water samples were collected at sites that were thermally probed. The Nevada State Health Laboratory was selected as the analytical laboratory. The collection procedure was modified. Water was generally run for about ten minutes, enough to purge at least several well bore volumes. The samples were collected in field-rinsed standard polyethylene half-gallon "milk jugs," but the sample was not acidified in the field. The standard laboratory protocol was followed, namely acidification of part of the sample immediately upon receipt by the lab. Prior to lab delivery, samples were filtered. Filtering was through a 0.45 μ nitrate membrane filter, and was completed at the Desert Research Institute using standard laboratory vacuum procedures. Average time from sample collection to laboratory delivery was less than six hours.

To further characterize the thermal anomaly, the twenty sites were also sampled for deuterium (δD) and $\delta^{18}O$. Samples were collected in 40 ml EPA approved amber glass bottles with poly seal caps, and did not require additives or refrigeration. The samples were sent to and analyzed by the Desert Research Institute Water Resources Center isotope lab, in Las Vegas, Nevada.

WASHOE VALLEY HYDROGEOLOGIC FRAMEWORK

The hydrogeologic setting of Washoe Valley has been discussed at some length by a number of authors previously cited. Geologic and hydrologic understanding of the area is general, mostly at the resolution of published 7.5 minute maps (Tabor et.al., 1975 and Trexler, 1977). Tabor et. al. (1983) conducted gravity surveys and seismic surveys that helped establish basin depths. Petersen (1993) and Petersen and Karlin (1997) conducted additional geophysical work, useful for structural interpretation. Washoe County's airborne geophysical survey data sets are also incorporated into the present study and are considered important interpretation tools for the establishment of a hydrogeologic framework.

Valley Wide Geologic Setting

Washoe Valley is a north-south oriented structural depression that resulted from regional Basin and Range extension and uplift of the Sierra Nevada batholith (Fenneman, 1931). Regional effects of tectonic extension can produce high heat flow and attendant geothermal systems (Blackwell, 1983 in Flynn and Buchanan, 1990). Geothermal systems are noted in Washoe Valley and will be treated in a separate chapter.

Petersen and Karlin (1997) conclude, based on joint gravity and magnetic modeling, that Washoe Valley is an asymmetric, fault-bounded half graben, back tilted to the west. The deeper western side of the valley contains up to 2000 feet of sedimentary fill, much of it coarse-grained and alluvial fan derived. The valley aquifer system can generally be viewed as a basin-fill aquifer. The authors further note that the shallower eastern subsurface area, including NWC, is more geologically and hydrologically complex.

Washoe Valley is bounded on the west by the Carson Range, which is composed primarily of Cretaceous-aged granodiorite. The east bounding mountains, the Virginia Range, consist of metasedimentary rocks (possibly pre-Cretaceous), Cretaceous granodiorite, and volcanic rocks primarily of andesitic composition. The two major volcanic units in the Virginia Range are the older Tertiary Alta Formation and the younger Tertiary Kate Peak Formation. The Alta Formation is hydrothermally altered and hosts mineralization in the Virginia Range (Whitebread, 1976).

Basin Fill Aquifer

The valley floor is relatively flat and bordered by several alluvial fans, with upper elevations at 5200 feet, sloping downward on both the west and east valley margins to approximately 5020 feet at the lake. According to Widmer (1997), the valley lithology consists primarily of granodiorite-derived sediments on the west margin and a mixture of volcanic, metasediment and granodiorite-derived clastic units on the east, north and south margins. Of the approximate 1000+ wells in Washoe Valley, most are shallow (less than 200 feet) with lithologic descriptions taken from well drillers' reports.

Petersen's conceptual model (Petersen, 1993) as adopted by Washoe County is illustrated as an interpretive cross-section (Figure 3). Intuitively, coarser sediments would be expected up against the range-front. Volcanic units would tend to produce a greater clay fraction due to rapid chemical weathering. All previous models have incorporated a confining unit at a depth of about 100 feet. An approximately ten foot thick clay unit has been logged at this depth in many wells on both the east and west sides. With noted artesian conditions from wells near the lake (both west and east margins), and the physical presence of the layer, use of an areally continuous confining unit has been a reasonable conceptual tool. A certain amount of discontinuity in this kind of environment should be expected, and some artesian conditions may also be fault related.

Hydraulic Properties

Very few long time pumping tests are available. Two different approaches have been taken by modelers in assigning horizontal hydraulic conductivity values (K_h) to the basin sediments. The early work by Arteaga (1982) relied on specific capacity data and a parameter estimation program. Specific capacity is defined as Q/s, where Q is the pumping rate in ft^3/day and s, is pumping drawdown in feet. Specific capacity is related to transmissivity, T, by an empirical equation, and in turn to hydraulic conductivity K_h, where K_h = T/b. Usually b refers to aquifer thickness, but for estimation of hydraulic parameters it represents the screened well interval. The empirical equation originates from the modified form of the Jacob equation (Driscoll, 1986):

$$Q/s = \frac{T}{264 \log \frac{0.3Tt}{r^2 S}},$$

where Q is water yield in gallons per minute; s is drawdown in feet; T is transmissivity in gallons per day per foot; t is pumping duration in days; r is the well radius in feet; and S is the dimensionless storage coefficient of the aquifer. Taking typical values for a confined aquifer and typical values for the other variables, the empirical equation, giving T in ft^2/day, ranges between:

$$T = 200\ Q/s \text{ and } T = 300\ Q/s.$$

Arteaga (1982) uses the relationship, $T = 275\ Q/s$. He reports transmissivities only, with calibrated values on the west ranging from 400 ft^2/day to 2500 ft^2/day, and values on the east side at 100 to 2500 ft^2/day. This would equate to approximate K_h values in the upper 100 feet of the aquifer, of 4 ft/day to 25 ft/day on the west and 1 ft/day to 25 ft/day on the east. Results of transmissivity tests in the nearby Spanish Springs Valley (Berger, et. al., 1997) over the top 330 feet of saturated basin fill ranged from 0.5 ft/day to 12 ft/day. Higher values are reported for west Washoe Valley presumably due to a higher energy depositional environment (Petersen, 1993).

Petersen (1993 and 1994) attempted to use resistivity data for estimation of K_h, but settled for a similar approach, using specific capacity as the main determinant of hydraulic conductivity. His values (Petersen, 1993) are greater than Arteaga's (1982) and range from about 4 ft/day to 40 ft/day. Widmer (1997) had a different approach in determining initial K_h values, through use of available airborne resistivity survey. The Dighem resistivity techniques in airborne electromagnetic mapping are explained by Fraser (1986). Electromagnetic frequencies are used to induce low voltage current into the ground, with subsequent creation of a secondary electromagnetic field detected by receiver coils on the aircraft. The strength of the signal depends on the resistivity, or conversely electrical conductivity, of the particular earth material. Values of resistivity are measured in ohm meters (ohm-m.). Qualitatively, values of less than 10 ohm-m. usually represent saturated clays and values greater than 200 ohm-m. represent competent bedrock (Widmer, 1997).

The Dighem technique emits three different frequencies allowing successively deeper vertical views. Widmer used the 900 Hz frequency, which has the deepest penetration to set the K_h distribution. His calibrated values range from .25 ft/day to 15 ft/day. An obvious misinterpretation of conductivities can arise if water geochemistry significantly influences the resistivity anomalies. Inspection of TDS values did not suggest that observed levels would affect electrical conductance (Widmer, 1997).

The above approach is considered a valid tool in looking at overall potential distributions of hydraulic conductivity. However, based on literature review, application of resistivity measurements to determine K values requires painstaking correlations of resistivity measurement and pumping test data, or laboratory determined K values based on grain-size analysis. Kelly and Reiter (1984) review the subject. The approach used is to set a formation factor (Kelly, 1977):

$$FF = r/rw,$$

where r is the bulk resistivity and rw is water resistivity. The empirical relationship between the apparent formation factor and hydraulic conductivity is given by (Mazac and Landa, 1979 in Kelly and Reiter, 1984):

$$K = A * Ff^{m}$$

A and *m* are empirically derived constants. Kelly and Reiter (1984) state that the relationship between the formation factor and hydraulic conductivity are strongly shaped by in-situ correlation between porosity and hydraulic conductivity. The authors warn that layer anisotropy may induce additional difficulties in field correlations. Of particular concern are clay-rich environments where inverse correlations between hydraulic conductivity and resistivity have been found. (See for instance, Heigold, et. al., 1979).

Vertical hydraulic conductivity (K_v) of fine-grained, clay-rich, sediments may have values one-hundredth to one-thousandth times smaller than K_h (Harrill, 1986). No data are available in Washoe Valley to estimate K_v precisely. Thomas et. al. (1989) suggests that for mixed deposits, a value of about .8 ft.day may be appropriate. Widmer (1997) used values between .05 ft/day for clay rich lithologies to 3 ft/day in gravel. His calibrated K_v values are approximately 10% of K_h. Ultimately, since the vertical conductivity is generally unknown, appropriate values are determined during model calibration.

Field data on storage factors in Washoe Valley are lacking. Specific yield (S_y) ranges from .01 for fine-grained material to .3 for coarse-grained material. Arteaga (1982) initially estimated storage terms from the literature. His calibrated values for S_y range between less than .1, to .25. An average value of .16 was used for the upper 100 feet of the model. Storativity values were not documented by Arteaga. Widmer's (1997) calibrated storage coefficients in the confined aquifer range between 10^{-6} and 10^{-5}. While these are within the reported range in the literature (Danskin, 1988, p. 26) they are on the low side of "typical" values for confined aquifers.

HYDROGEOLOGIC FRAMEWORK OF NEW WASHOE CITY

Even though this study focuses on the eastern side of Washoe Valley, discussion and occasional reference to the valley-wide system is important because the two systems form a continuum. The current study relies on the hydrogeologic framework that has been established for the greater Washoe Valley area.

Development

A prime goal of this study was to revise the existing conceptual model of the project area by refining knowledge of the hydrogeologic setting, and to apply the gained information to modeling at a finer scale of resolution. There were limitations to the scope of work, in part because of the broad focus of the study, which included aspects of thermal characterization. Review and interpretation of the airborne geophysical data, and a large volume of drillers' reports was initiated. As work progressed, and lithologic information was gathered, it became clear that, near the thermal anomaly, resistivity values were highly unlikely to reflect primarily clay lithology alone. A decision was made to compile specific capacity data in the NWC area and develop a new set of K values from that data.

Existing Hydrogeologic Concepts

The cross section of Washoe Valley, Figure 3, is representative of the existing conceptual model of the project area, prior to the current study; the basin on the east side is shallower, and the basin sediments are overall finer-grained than on the west side. From ground magnetic surveys, Petersen (1993) and Petersen and Karlin (1996) identified a buried magnetic ridge that separates the main part of the Washoe Valley basin from a smaller sub-basin. The causative magnetic body was interpreted to probably represent the Kate Peak Andesite that crops out in the nearby range-front. Figure 4 is a reduced to pole magnetics map of the northern part of Washoe Valley, from the Dighem survey. This survey confirms and essentially mimics the features found by Petersen. The buried ridge is identified as the 51400 to 51500 nanotesla filled contour. It nearly bisects the southern part of Washoe Lake and then takes an easterly turn, trending northeasterly under the extreme southeast part of NWC. The sub-basin is located mainly east and southeast of NWC and is identified by the 51301 to 51400 filled (pink) contour. Petersen estimated depths in the sub-basin to vary between 230 and 360 feet based on respective northern and southern profile interpretations. The crest of the ridge was interpreted to be as shallow as 50 feet below surface in the northern portions. This known feature is clearly one important element of the structural and geologic setting.

Synthesis of Geophysical, Geologic and Stratigraphic Data

<u>Structural Trends</u>

Figure 5 is a total field magnetics map prepared by Washoe County (Widmer, 1997). It is similar to Figure 4 but encompasses a larger area and uses different contouring parameters. Color selection emphasizes the lower magnetic susceptibility units in light blue and dark green. A feature of equal importance to the northeast buried ridge is a parallel magnetic low on the northwest side of the ridge. The magnetic low most likely represents thick basin sediments set in a northeast structurally controlled graben, with the previously discussed ridge possibly representing a horst block counterpart. An important northeast structural grain is therefore established.

The geophysical data sets were re-processed and a lineament analysis of all

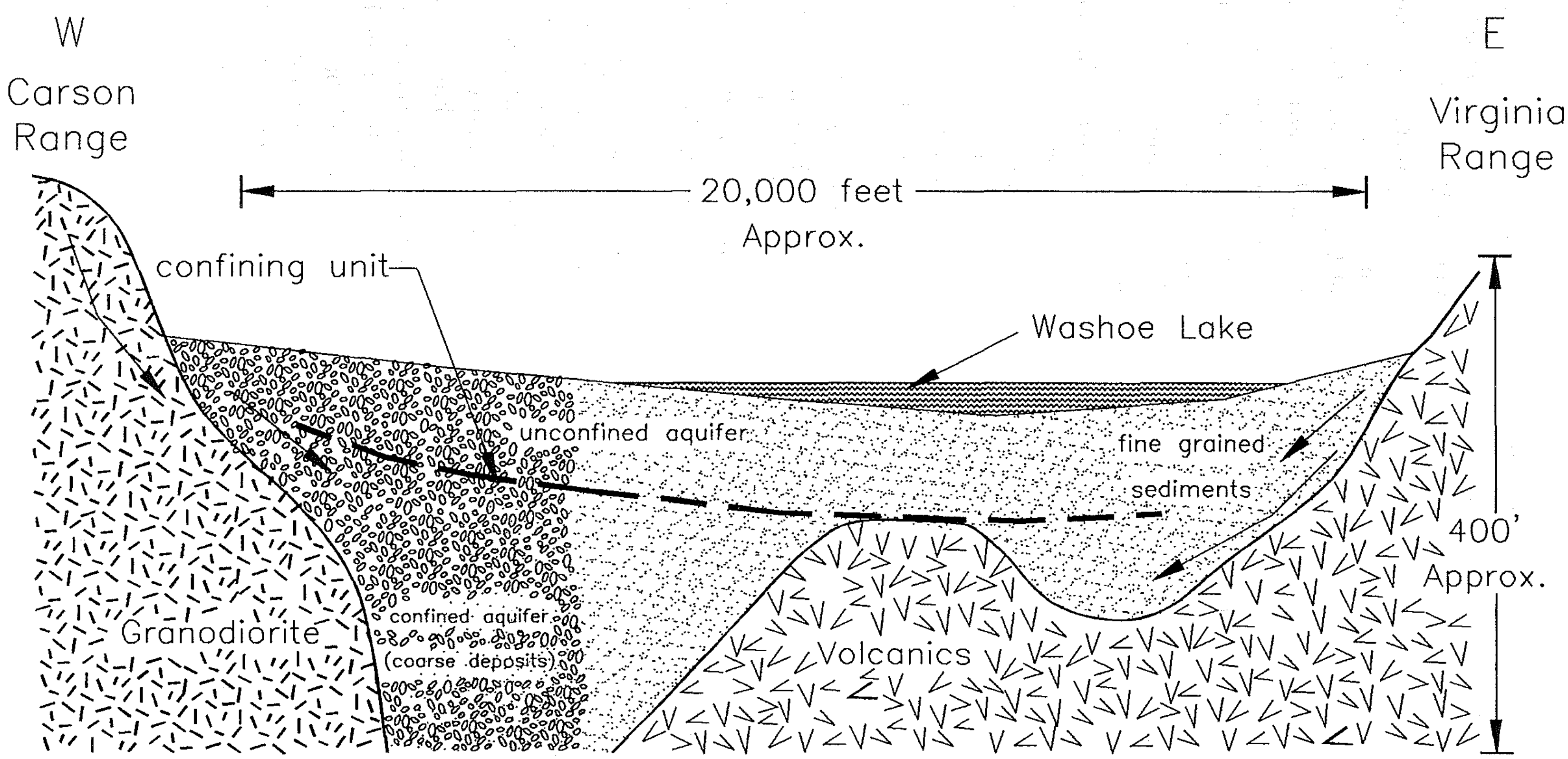


FIGURE 3. GENERALIZED GEOLOGIC CROSS SECTION OF WASHOE VALLEY

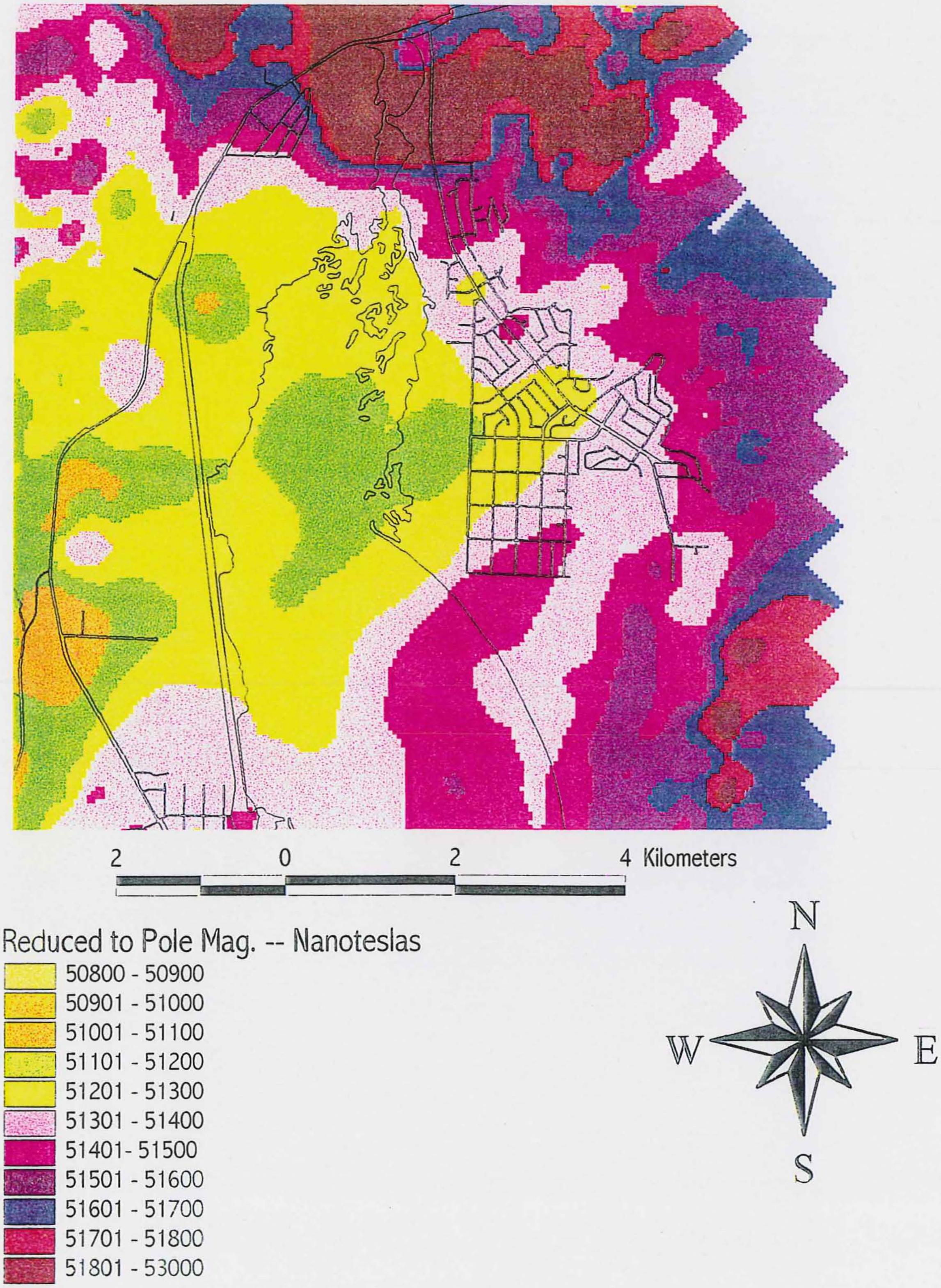
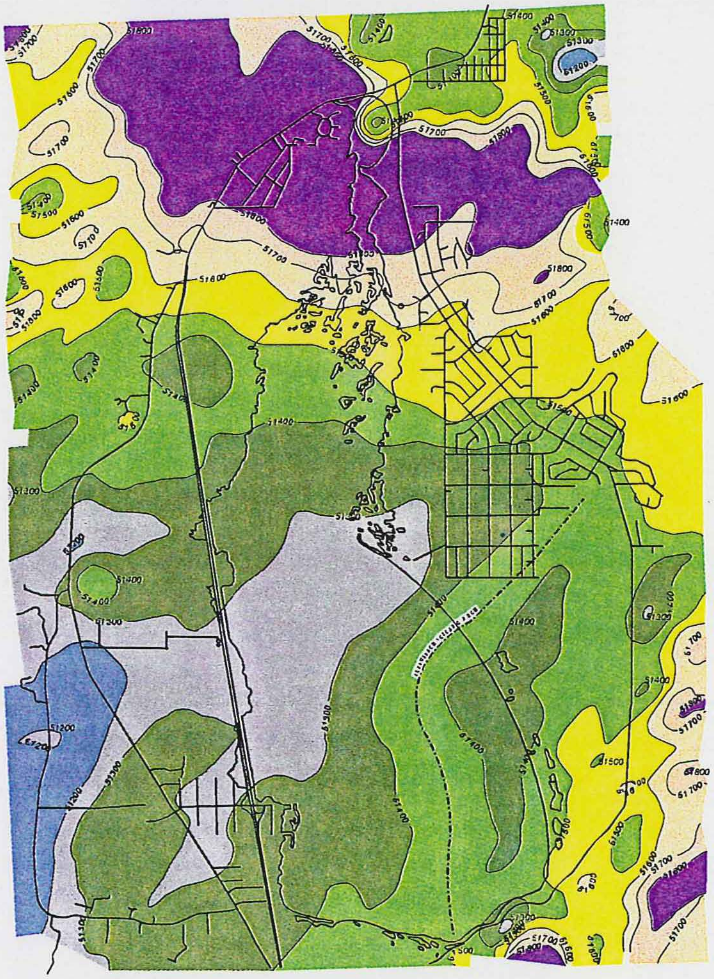


Figure 4. Reduced to Pole Magnetics, Washoe Valley



WASHOE VALLEY

TOTAL FIELD MAGNETICS

CONTOURS IN NANOTESLAS

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

Notes: The scale and configuration of all information shown hereon are approximate only and are not intended as a guide for design or survey work. Reproduction is not permitted without prior written permission from the Washoe County Department of Water Resources.

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SCALE IN FEET

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(702) 328-3600

SOURCE: DIGHEM Figure 5. Total Field Magnetics, Washoe Valley DATE: OCTOBER 1997 data sets, using imaging software provided through Dighem, was completed. A composite lineament map on a generalized geologic base is included as Figure 6. The yellow unit represents the surficial sedimentary deposits and, in a gross sense, the location of basin fill. Granodiorite (in light green) and volcanic rocks in dark purple dominate the outcrops east of the study area and would be the logical candidates for basement rocks underneath the basin fill of NWC. Lineaments in NWC strongly emphasize northeast sets and nearly orthogonal northwest sets. The northeast direction is likely related to faulting, based on the evidence already presented. Furthermore, Tabor and Ellen (1975) map one northeast trending fault in the basement rocks at the northeast end of NWC. To date, the northwest trend is poorly documented but it will be shown that it is an important feature.

A north-south structural component is also identified. This direction is well-represented along the southeast side of Figure 6. Tabor and Ellen (1975) have mapped a north-south trending range front fault at this location. Other north-south lineaments appear further west, in particular just west of NWC, and may represent buried fault traces.

Northwest Trends and Structural Interpretation From Cross Sections

The magnetic data nor existing geologic maps, fail to show any northwest trending faults or lineaments through NWC. The northwest trending lineaments on the lineament analysis map were contributed by the EM data. Figure 7 is a 900 Hz resistivity map for NWC. Here, the northwesterly trend is well represented. Tabor and Ellen (1976) produced a cross-section to accompany their geologic map (Tabor and Ellen, 1975). Several east-west interpretive cross sections portray a series of faults down dropping basin-fill sediments and underlying granodiorite in a step-like manner to the west. Alignment of the inferred structures confirms a series of buried northwesterly trending range-front faults, not shown on the geologic map. The interpretive sections, according to the authors, are based on geologic mapping, water-well data, shallow seismic profiles, and gravity measurements.

From compilation and interpretation of well drillers reports, a set of east-west oriented sections was completed. This was done to take a closer look at the basin fill stratigraphy and lithology and to confirm or amplify the previous structural interpretation. A set of simplified sections is reproduced as Figures 8a through 8d (explanation as Figure 8e), with section locations shown on Figure 6 and a final structural interpretation, also with section locations, included as Figure 9. The sections are based on about 100 drillers logs and involved painstaking construction at a large scale. The shown sections have been reduced and generalized, emphasizing the most important structures, only. Figure 9, is also a generalization of the inferred structural framework. Most domestic wells in the range front or in the northern

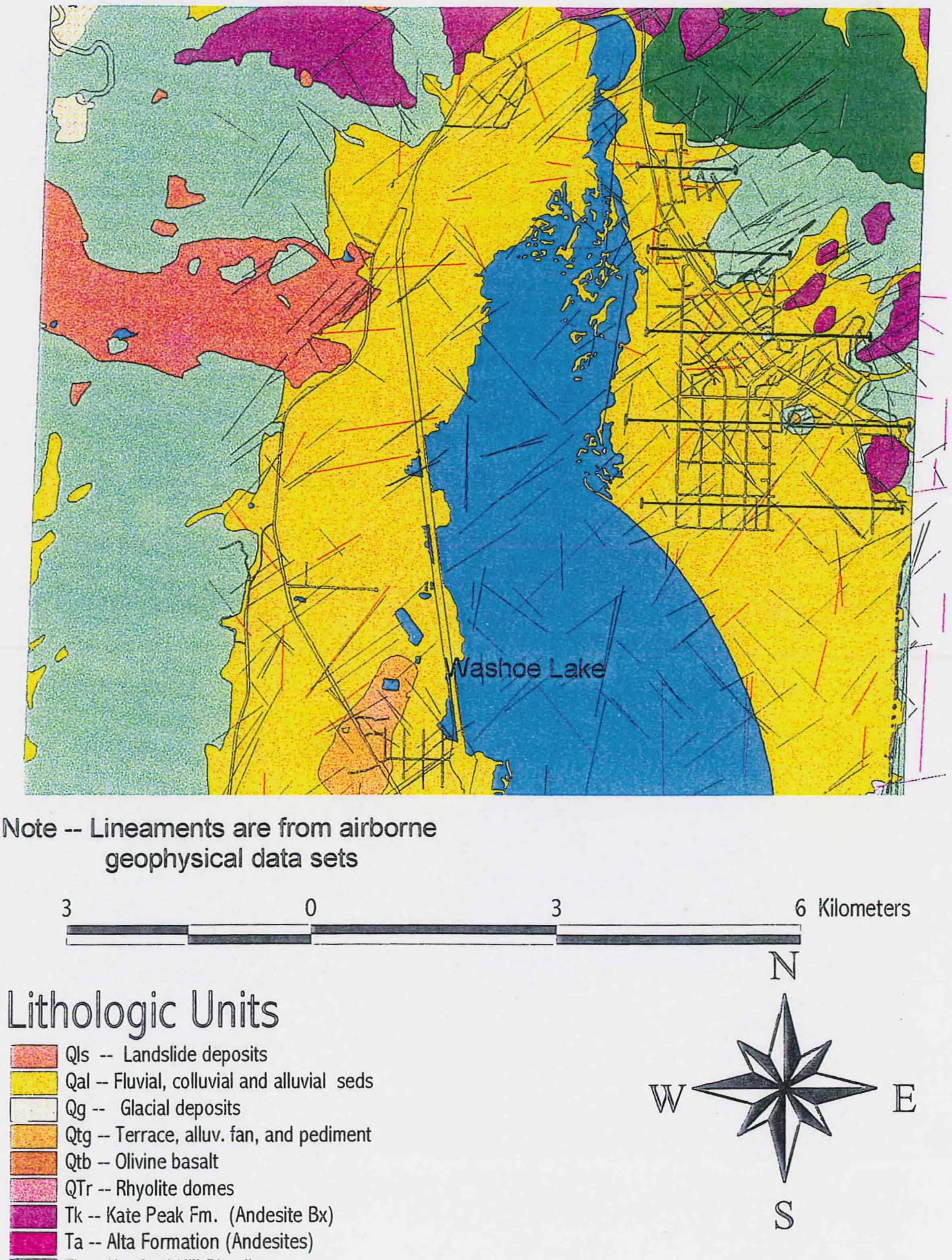


Figure 6. Geologic Lineament Map, Washoe Valley

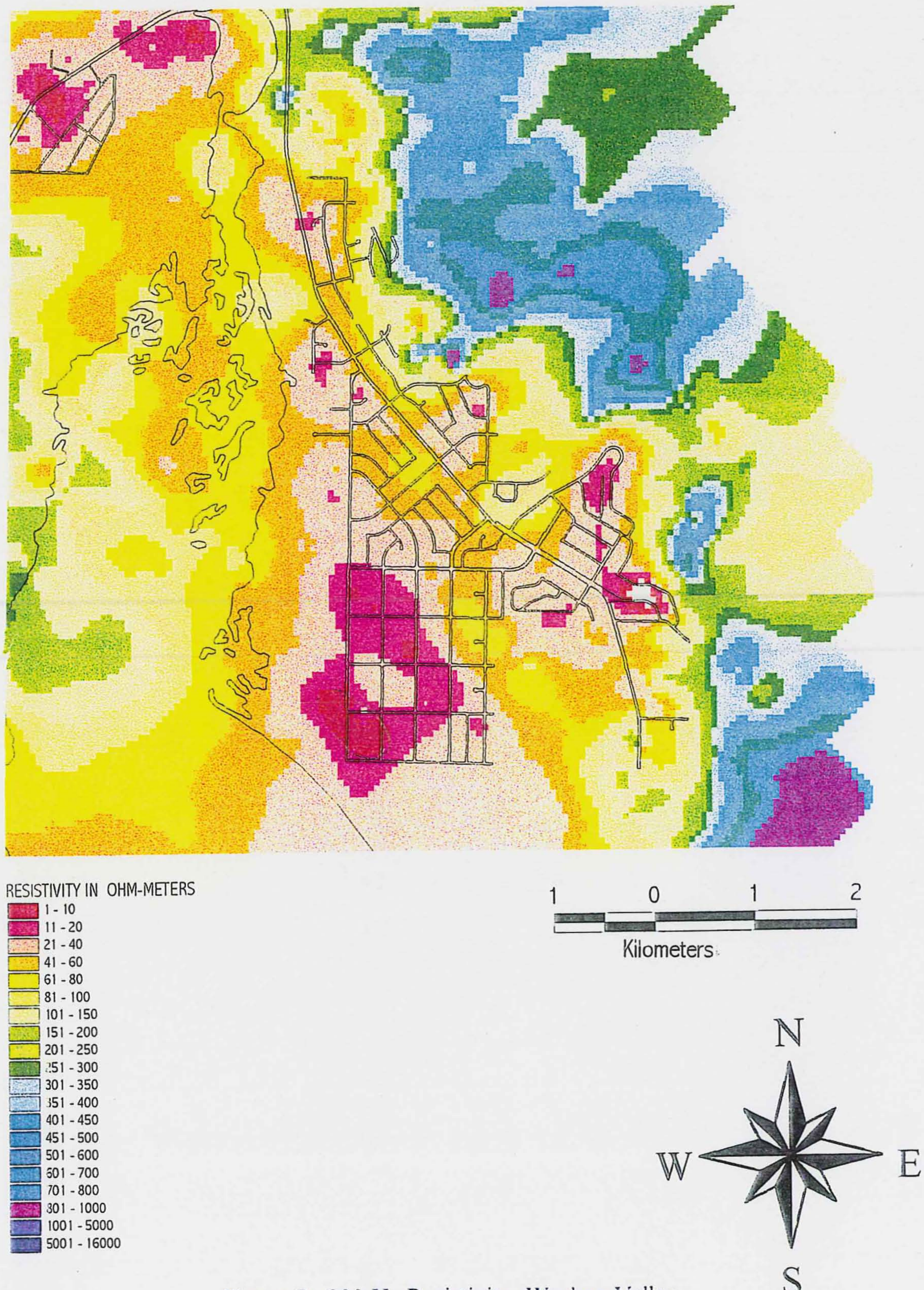


Figure 7. 900 Hz Resistivity, Washoe Valley

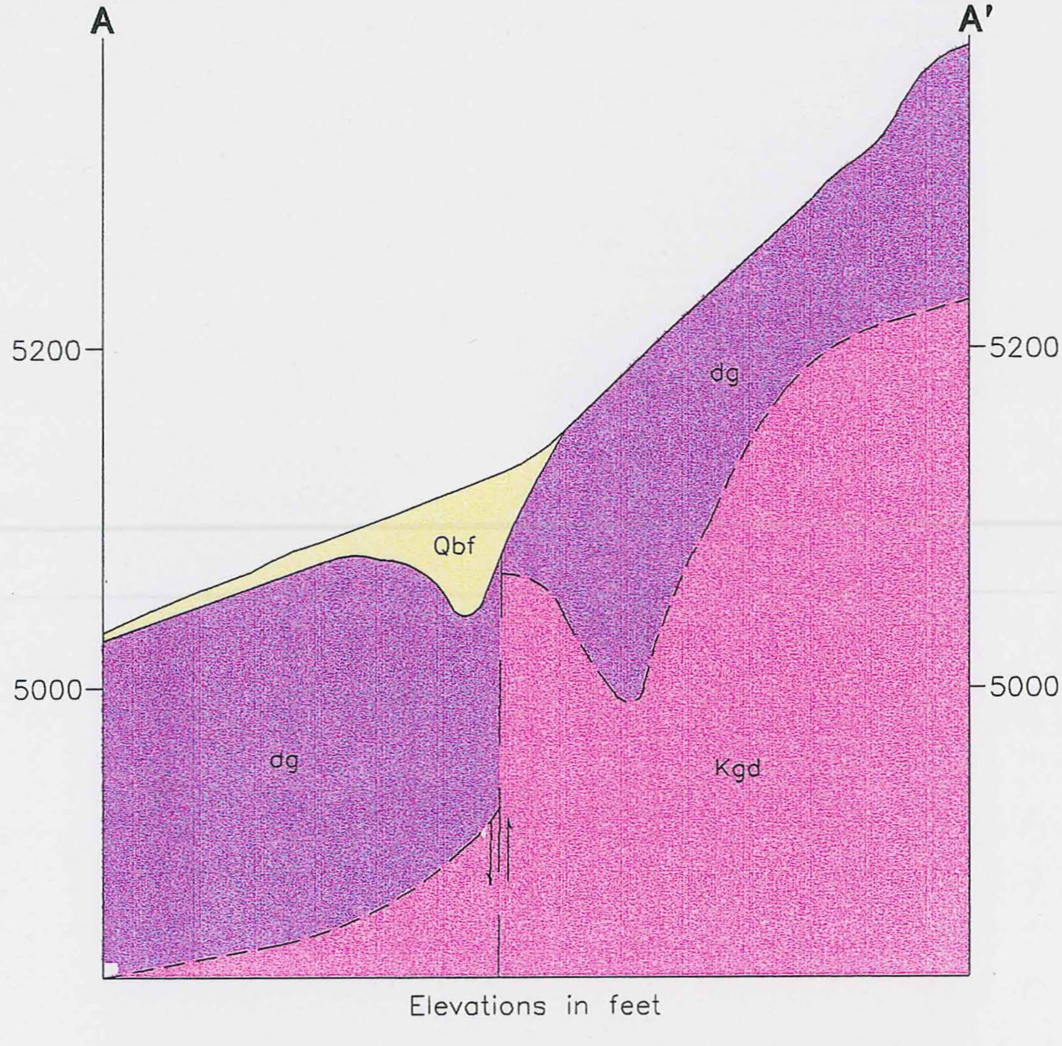


FIGURE 8A
CROSS SECTION A–A'

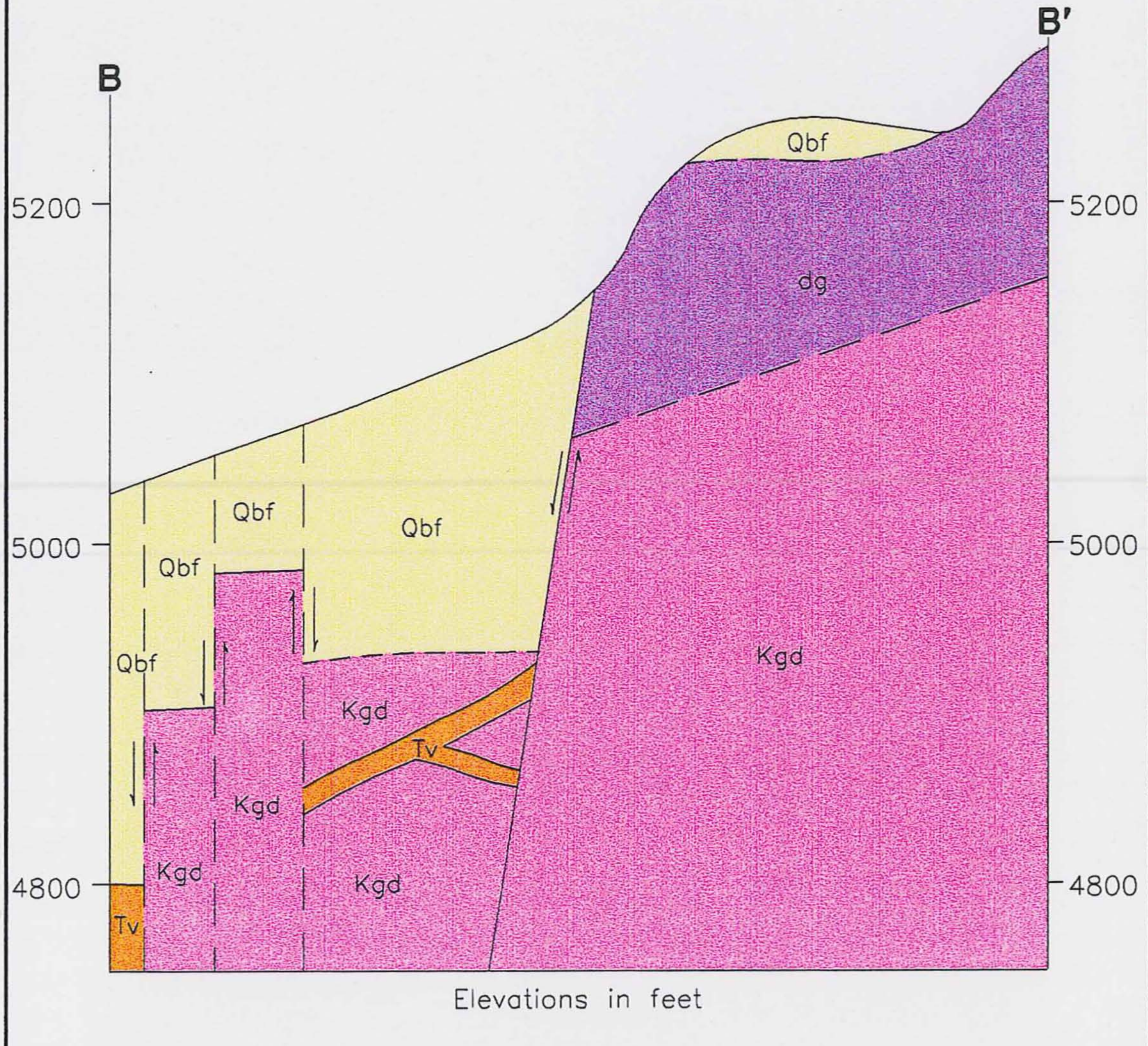


FIGURE 8B
CROSS SECTION B–B'

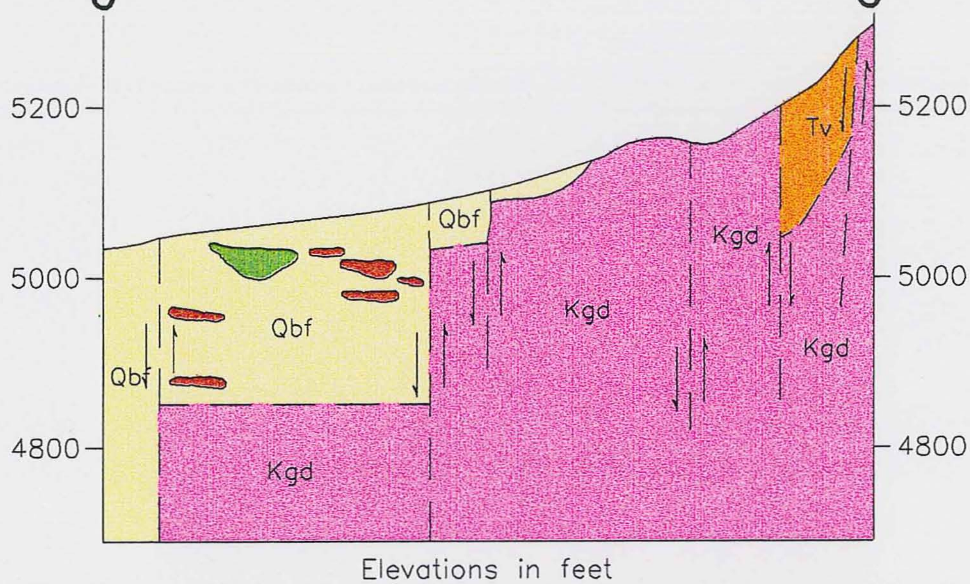
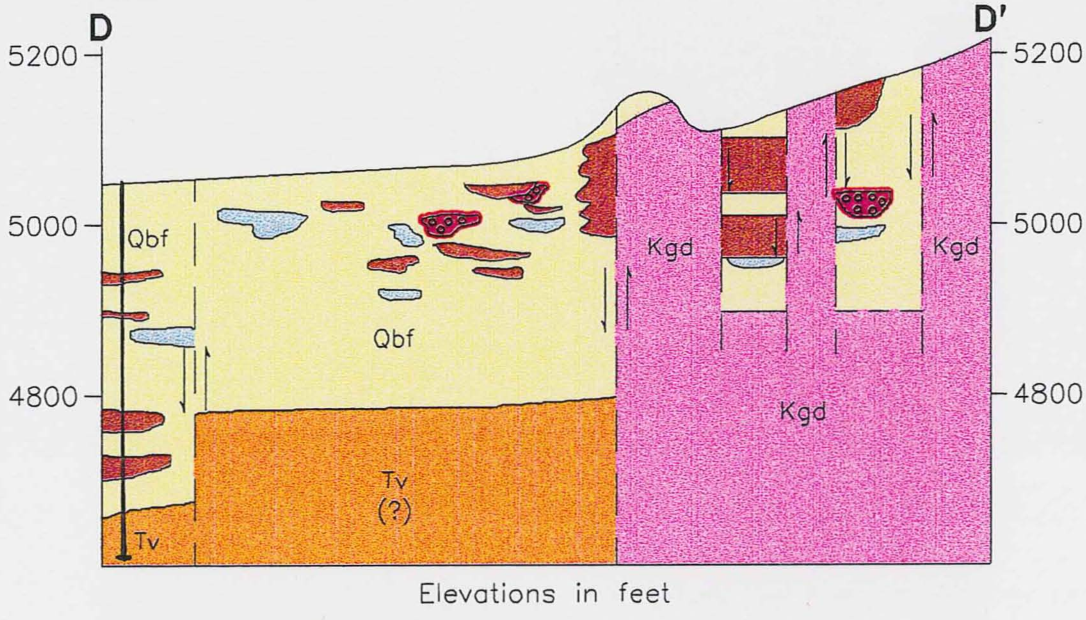


FIGURE 8C
CROSS SECTION C–C', D–D'



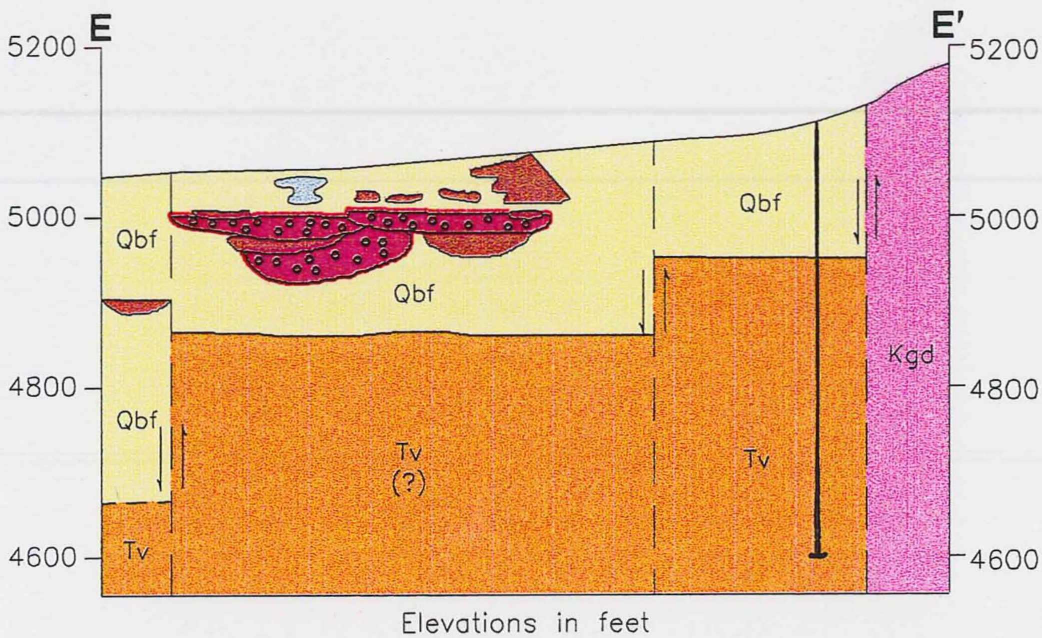


FIGURE 8D
CROSS SECTION E–E'

EXPLANATION

Qbf – UNDIFFERENTIATED BASIN FILL

SILT

CLAY

BLUE CLAY

GRAVEL AND COURSE SAND

Tv – TERTIARY VOLCANIC ROCKS

dg – DECOMPOSED GRANODIORITE

Kgd – GRANODIORITE

FIGURE 8E
EXPLANATION FOR CROSS SECTIONS

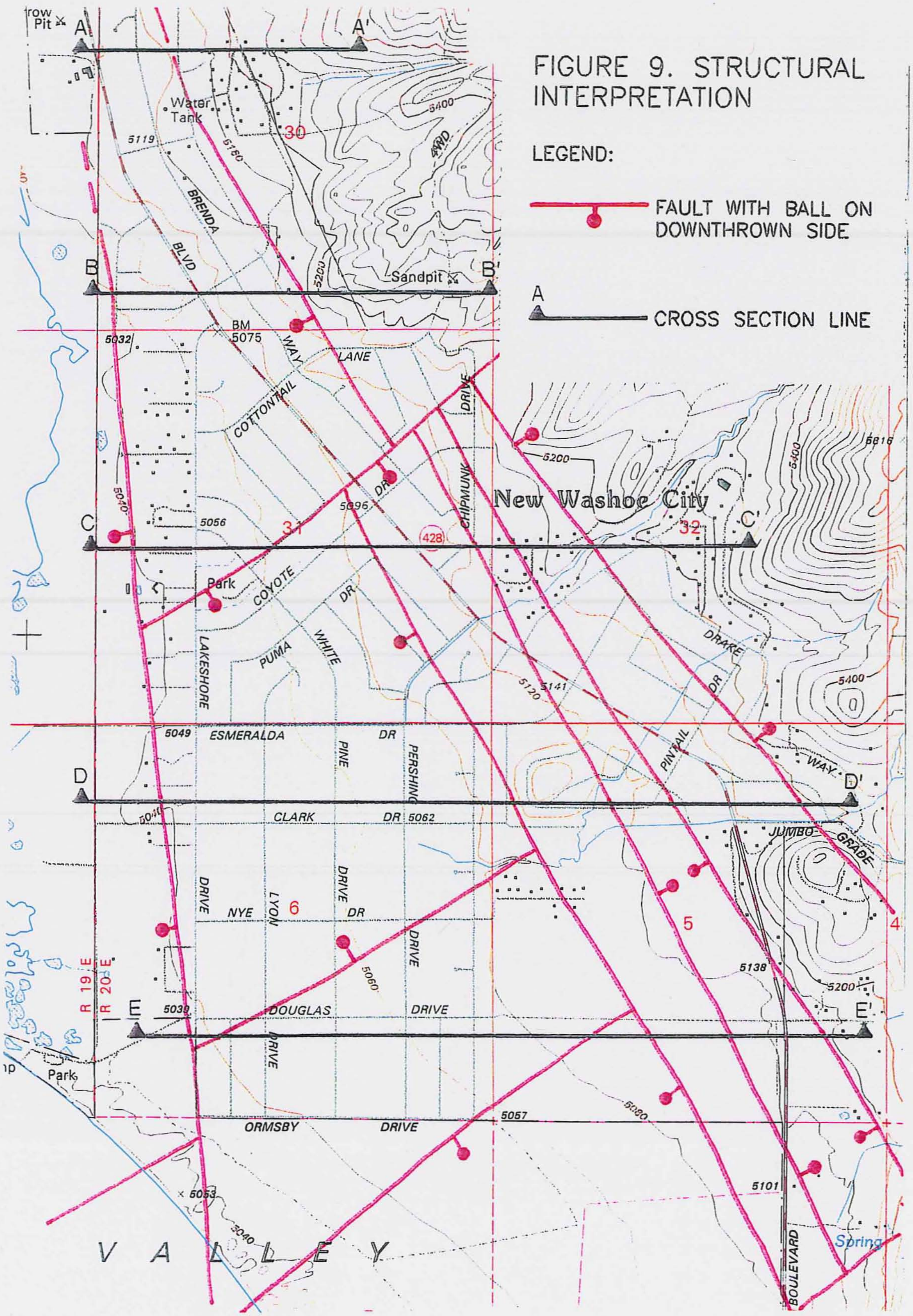


FIGURE 9. STRUCTURAL INTERPRETATION

part of NWC are either collared or bottom in granodiorite. The granodiorite is usually weathered (saprolitic), sometimes to depths greater than 300 feet. The basin fill from the northern sections is dominated by (Figures 8a and 8b), locally-derived granitic (arkosic?) sands. The driller's reports indicate that difficulties were encountered in separating "decomposed granite" from alluvial material of similar composition, however; the average fill thickness appears to be less than 200 feet.

The southern sections, C-C' , D-D' , and E-E' , (Figures 8c and 8d) suggest increasing complexity of basin fill sediments and confirm an overall down-drop of basement and fill to the west. Interpretation suggests that down-drop is not a simple stair-step, but more complex, with a horst and graben style. For instance, a small knob of granodiorite outcrops as an "island" surrounded by basin fill sediment (a small circular outcrop, southeast side of NWC as shown on Figure 6) and is interpreted as an outcropping portion of a northwest trending horst block.

Figure 9 is a final structural interpretation map based on geophysical interpretation, Tabor and Ellen's (1976) cross sections and cross sections produced in this report. Structural interpretation shows a complex orthogonal pattern of northwest and northeast fault-bounded structural blocks. The northeast trending horst block represents the area of Petersen's buried volcanic ridge. An accompanying graben, found to the northwest and containing thicker sediments, is a northeast extension of the main Washoe Valley sedimentary basin. Timing of faulting appears complex with both sets reactivated at various times.

At the extreme west side of NWC a nearly north-south trending, down-drop to the west, fault is interpreted. The structure is based on a combination of Ellen and Tabor's (1976) cross sections, the elevation position of volcanic basement from available well data, and offset of conductive units from resistivity depth sections provided by Dighem (1994). This overall north-south direction may be seen on the 900 Hz resistivity map (Figure 7).

Basin Fill Thicknesses

Depths to basement are variable and controlled by basement faults. Sections D-D' and E-E' provide key constraints on depth to basement, where deeper wells have penetrated to volcanic basement. The key well(s) are respectively shown on the sections. General depths of basin-fill range from about 150 feet to about 300 feet over the southern and south-central portion of NWC. Basin fill is probably thicker than suggested by Petersen (1993) under the buried volcanic ridge based on inspection of the domestic well logs. Presence of volcanic units underlying the sediments, in the southern part of NWC, as shown by the well logs, corroborates the previous magnetics interpretation. It is recognized that the basement depth is estimated from only a few points.

However, decreasing depth to basement

as compared to Tabor and Ellen's (1976) study, by interpretation of drill logs, in conjunction with other lithologic information, is considered a valid approach. In concurrence with the present study, Tabor et. al. (1983) documentation of the geologic map and sections suggests shallower depths to basin fill than shown on their original section J-J'. Their summary of the Bison Seismographic profile 4 (pg. 28) suggests depths to basement of less than 250 feet along Ormsby Lane.

Basin Fill Lithology and Stratigraphy

Tabor et. al. (1975, 1976 and 1983) do not subdivide the basin fill in NWC but simply describe it as old lake deposits (Qold) with a few surficial deposit types consisting of sand or alluvial terrace material. The only description of the lake deposits is from a ditch located northwest of Washoe City where they are described as thin beds of fine sand and silt.

Cursory examination of the constructed cross sections of this study (Figures 8a through 8e) confirm an overall sandy nature to the basin fill sediments underlying NWC. Lenses of clay and silt suggest and confirm a pluvial origin for much of the sedimentary material. The northern two sections, A-A' and B-B' indicate a granodiorite basement with overlying basin sediments comprised mainly of locally derived feldspathic sands and clayey sands. Sections C-C' and D-D' exhibit a finer grained mixed lithology of pluvial origin; mainly medium to fine sand, clayey sand, silt, and thin interbeds of clay.

Many domestic wells around the southern two cross sections, D-D' and E-E', penetrate thin to medium (up to 30 feet thick) lenticular beds of "blue clay." Because no cuttings could be obtained for inspection one can only speculate as to the nature of these clays. McKay (1991) suggests that these clays contain abundant organic material reflecting a reducing lacustrine environment. Alternatively, these blue clays may be locally derived from volcanic units or hydrothermally altered volcanic units. Petersen and Karlin (1996) suggest possibilities of altered andesite at depth. Flynn and Ghusn (1983), in their study of the Moana Geothermal system, discuss the presence of "blue" clay. The blue clay is reportedly associated with that particular thermal system. Lithologic logs indicate that it is found above altered Kate Peak andesite and beneath the alluvial deposits. X-ray diffraction analysis identifies the material as smectite, a clay mineral commonly formed by hydrothermal alteration of volcanic glass. In southern NWC, volcanic glass or blue rock is noted from wells that bottomed in volcanic basement.

The southernmost section, E-E', indicates a coarsening of clast size at the southwest edge of NWC. Lenses or channels of gravel are noted. Some of these sandy to clayey gravels are nearly 50 feet thick. These gravels are probably related to mountain front stream flow and roughly the present day location of the Jumbo Fan. The disruption of lake beds by a coarser sedimentary package modifies the previous interpretation by McKay (1991) that suggested a continual fining of sediments to the southwest.

Hydrostratigraphic and Hydrogeologic Formations

This study defines six separate hydrogeologic units. These are: 1) fractured granodiorite; 2) weathered or saprolitic granodiorite; 3) granodiorite derived sands and clayey sands; 4) lake bed sediments characterized by fine to medium grained sand, and lenses of silt and clay; 5) fluvial deposits of gravel, sandy gravel, clayey gravel and sand; and, 6) fractured volcanic basement, possibly locally altered. No characteristic or continual stratigraphy of the lake beds could be discerned. It is suggested that the entire east side of the valley has had an active tectonic history and stratigraphy is disrupted, reflecting that history. The data do not show a continuous confining clay layer or an upper unconfined aquifer or lower confined aquifer. The presence of a series of clay lenses in the interval between 50 feet and 150 from surface does suggest semi-confining conditions and provides permissive evidence for modeling of the basin fill aquifer as a two-layer system.

Determination of Hydraulic Conductivity

Approximately 90 specific capacity test data points, from domestic wells and a few agricultural wells, were compiled from several sources (public domain well logs and Washoe County files). These measurements represent usually short term pumping or bailer tests and are approximate at best. Nevertheless, this was the best available data. Horizontal hydraulic conductivity values were calculated based on the known screening interval. Calculated values range from .2 ft/day to 40 ft/day. Figure 10 is a contour map of these values. As expected, the highest K_h values are in the southwest section of NWC, where screened intervals were placed in gravels and clean sands. Lowest values are in the granodiorite horst block and clayey sediments of a parallel eastwardly located graben. Some areas of relatively high hydraulic conductivity against the rangefront suggest local concentrations of intense fracturing in the granodiorite.
It was noted, where specific capacity data and lithologic data existed side-by side, that in many cases (but not all), wells were screened in the coarser materials. Therefore, the hydraulic conductivities shown on Figure 10 are considered maximum values. As described under modeling procedures, these values were reduced to account for the described bias.

HYDROLOGIC SETTING AND WATER BUDGETS

A synthesis of the hydrologic setting and water budget of Washoe Valley is presented with special emphasis being placed on aspects of the water budget for the east side of the valley. Discussion of calibrated recharge and discharge groundwater fluxes will be provided under modeling results.

Hydrologic Setting

The Washoe Valley hydrographic basin encompasses approximately 81 mi^2 of

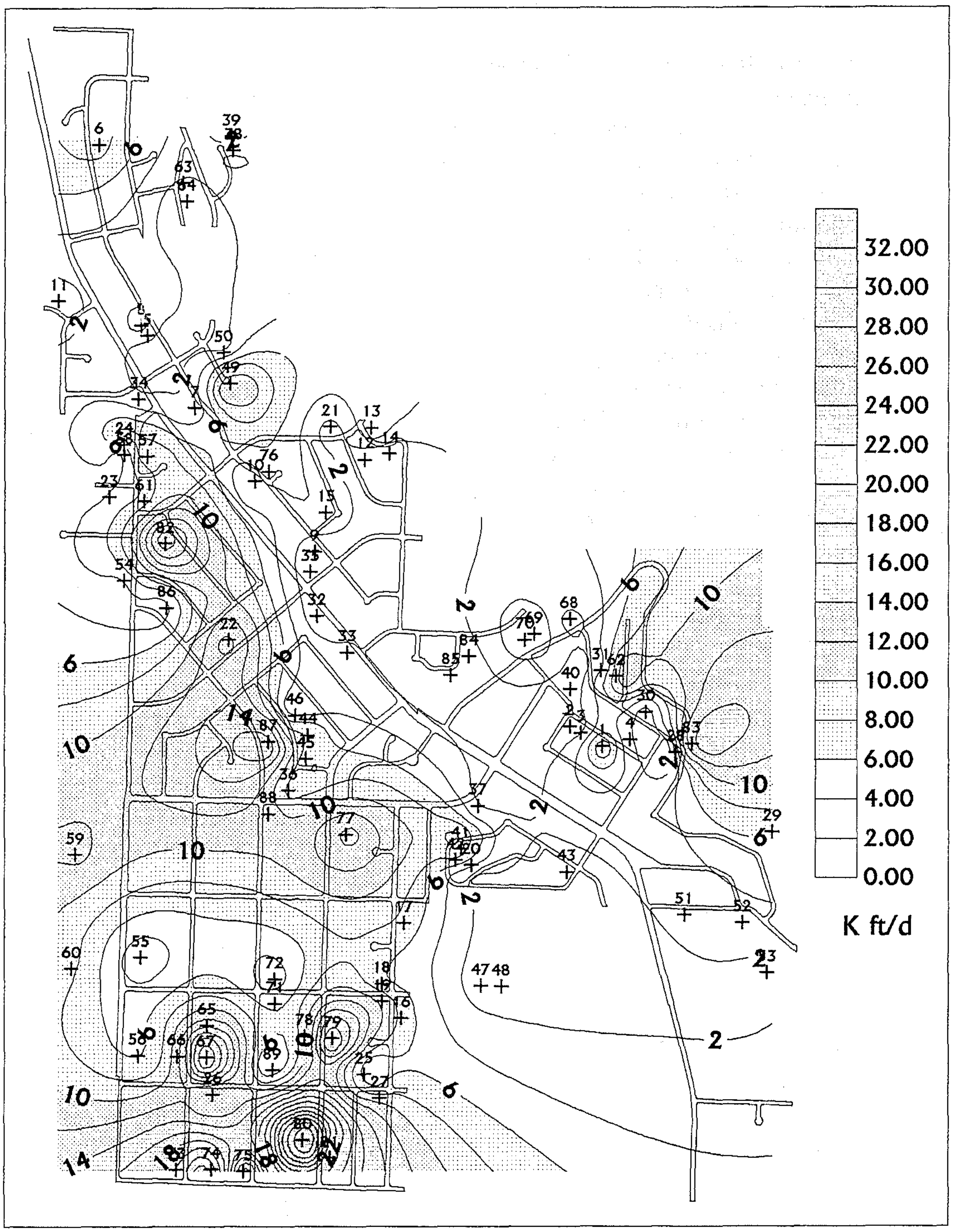


Figure 10. Hydraulic Conductivity From Specific Capacity Data

which about 53 mi^2 is mountainous and the remainder the valley floor. The valley floor hosts Washoe Lake and Little Washoe Lake which, when full, cover nearly 30% of the valley floor. During wet periods the wetlands separating the two lakes are inundated with water. Little Washoe Lake may discharge to Steamboat Creek, a tributary of the Truckee River, via a small dam with flow control-works. Surface water enters the valley floor on the west from a number of perennial creeks, including Franktown, Ophir and Winter's creeks. Only one intermittent creek, Jumbo Creek, discharges water to the valley floor on the drier east side.

Precipitation

Arteaga and Nichols (1984) review the basin's climatology and hydrologic processes. From short term precipitation data, as discussed in that report, mean annual precipitation decreases eastward, from almost 60 inches in the highest, westernmost, part of the Carson Range to about 10 inches on the eastern part of the valley floor. Precipitation then increases again further eastward, due to altitude effects, to as much as 24 inches at the crest of the Virginia Range.

Water Yield

Arteaga and Nichols (1984) note that precipitation which falls in the mountain areas is the main source of nearly all runoff reaching the adjacent valley floor and groundwater recharge. Much of the precipitation falling on the valley floor is apparently consumed by vegetation or directly evaporated. They also compute a water yield from the mountain areas, which is defined as the contribution of surface and ground water outflow from the mountains to the valley area. The estimated precipitation from the Virginia Range, 13,700 acre feet, produces an estimated annual yield of only 900 acre feet. The precipitation from the Carson Range was estimated to be 72,000 acre feet and produces an estimated average annual yield of 25,000 acre feet. To arrive at these figures, the Washoe Valley hydrographic basin was subdivided into 29 sub basins. Yield is not even among sub-basins. On the west side, the estimated yield from Franktown Creek, 13,600 acre-ft/yr represents more than half the total estimated yield. Similarly, the estimated yield from Jumbo Creek, 400 acre-ft/yr, is nearly half the total yield from the east side.

Hydrologic Budget of Washoe Valley

Arteaga and Nichols's (1984) hydrologic budget is the most thorough work to date in Washoe Valley. Hydrologic data was collected from the period 1964 to 1980. The budget, for conditions as of 1980, is believed to represent nearly steady state conditions, due to relatively low cumulative impacts by development up to that time. The steady state budget can be simply expressed as Inflow = Outflow. This expression can then be further subdivided into various inflow and outflow components:

$$Yw + Pl + Pv + SWi = El + Etv + SWo + Qe + Qd,$$

where the components are:

Yw = water yield (both surface and groundwater)

P*l* = precipitation on the lake surface
P*v* = precipitation on the valley floor
SWi = imported surface water (from outside of Washoe Hyd. Basin)
E*l* = evaporation from the lake
Et*v* = evapotranspiration
SWo = stream outflow
Q*e* = exported water
Q*d* = domestic consumptive use

The Washoe Valley floor ground water budget for 1980 is presented as Table 1 and was used by Widmer (1997) as the basis for his modeling work.

Table 1

Valley Floor Hydrologic Budget for Conditions as of 1980
(After Arteaga and Nichols, 1984)
Note-- All Values in Acre-Feet/Year

BUDGET ITEM	ESTIMATED QUANTITY
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 Domestic Use	100
Total Outflow (rounded)	53,000

Note - Arteaga's Budget did not directly identify agricultural consumption and one can only assume that the figure is reflected in the evapotranspiration quantity.

Groundwater Budget

Ground water budget estimates are approximate. Rush (1967) estimated potential recharge of 15,000 acre-ft/year from a method described by Eakin et. al. (1951). This figure includes potential recharge from the valley floor. Arteaga (1982) and Arteaga and Nichols (1984) estimated a groundwater recharge figure of 5500 acre-feet/yr. All recharge from the east side of the valley is considered range front recharge with negligible amounts from valley floor precipitation and totals an estimated 900 acre-feet/year. The remainder, 4600 acre-feet/year, is recharge attributed to the Carson Range and valley floor precipitation on the west side.

Knowledge of groundwater recharge to Washoe Lake (or possibly discharge) is poor. This information is important, due to potential influences by the lake to the groundwater system. Arteaga (1982) provides the only estimate. 1977 precipitation was about 33 percent of average. Depletion in lake volume during that year was the result of lake evaporation exceeding inflow. In addition, Arteaga assumes negligible surface flow into the lake. Based on an assumed evapotranspiration rate for the lake and an estimated lake volume, total inflow to the lake in 1977 was entirely from ground water. The estimated inflow of ground water to the lake in 1977 was 5,500 acre feet.

Starting ground water budget figures for modeling presented in this study, including estimates of evapotranspiration (ET) rates, range front recharge volumes, and valley floor recharges are the same as adopted by Widmer (1997). ET rates are best estimates, and no actual physical measurements have been taken. Widmer investigated ET rates further and revised them upwards from previous studies based on observed irrigation practices in the valley, and evaporation pan data from weather stations in the Truckee Meadows. His ground water budget estimate for 1965 conditions are included as Table 2. The budget assumes quasi-steady state conditions and estimates ground water discharge to the lake and wetlands by difference, with calculations based on assuming inflow equals outflow, and the assignment of values to all other budget components. Table 3 provides Widmer's estimates of ET rates.

Table 2
Estimated 1965Ground Water Budget in Acre-feet/year
(From Widmer, 1997)

Component	Rate
Range front Recharge	6500
Valley Precipitation Recharge	2400
Irrigation Recharge	2200
Evapotranspiration	-5100
Discharge to Lake/Wetlands	-5000
Pumpage	-1000
Balance	0

Table 3

Estimated ET from the Ground Water System
(acre-feet/year)

Vegetation Type	**Area** (Acres)	**Precip** (ft)	**ET Rate** (ft/yr)	**ET - Precip** (ft/yr)	**GW ET** (AFA)
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	2.7	0	0
phreatophyte zone west	1000	1.5	4.2	2.7	2700
phreatophyte zone east	500	1.0	4.2	3.2	1600
east Washoe above lake	2800	0.8	1.1	0.3	840
Total	10,100				5,140

Review of Range Front Recharge Using Chloride Balance Method

The chloride balance method is a commonly used method to check range front recharge estimates based on precipitation-yield calculations. The method, as applied to the Smith Creek Valley is described by Thomas et. al., 1989. The technique estimates recharge by comparing chloride input from precipitation in recharge areas against chloride content of ground water recharging the basin-fill aquifer. Where no significant surface streams exist, (east side) recharge is estimated using the following equation:

$$R = P(Cl_P/\mathrm{Cl_R}),$$

where R = recharge, in acre-feet per year; P = total precipitation in the overall recharge area, in acre-feet per year; Cl_P = chloride content of precipitation and dry fallout, in milligrams per liter; and Cl_R = chloride concentration of ground water in the recharge area, in milligrams per liter. A chloride value for precipitation of .4 mg/l based on data from nearby canyons west of Carson City (Maurer et. al., 1996) was adopted for Washoe Valley. For the east side of Washoe Valley, P is equal to 13,700 acre-feet/year and the chloride content of ground water entering the basin averages 4 mg/l using 27 domestic well analyses. As a note of caution, some chloride is anthropogenic, related to septic system recharge and accompanied by high values of total nitrates. Only those wells with negligible values of nitrates were used to obtain the chloride average. A final estimate of range front recharge for the east side is 1,300 acre-feet per year, moderately higher than previous estimates.

Estimation of recharge from the west side of Washoe Valley is more difficult due to presence of surface streams. Insufficient analytical data exists for a definitive estimate, including reliable stream chemistry data. Many domestic wells have chloride contents less than detection levels (1 ppm) from the State

Health Lab analysis. The only stream chemistry (Armstrong and Fordham, 1977) shows chloride values that average about 2 ppm. Surface waters should not be higher in chloride than ground waters, and it is suggested that input from farm animals has elevated the surface water values. A ballpark range front estimate was attempted and assumes 1mg/l Cl in ground water and 1 mg/l in surface streams. Using a modified chloride balance method as explained by Mauer, et. al, 1996, and precipitation and surface runoff data from Arteaga (1982) and Arteaga and Nichols (1984), a figure of 7,900 acre-feet was reached.

Potentiometric Surface and 1997-1994 Water Level Surveys

The potentiometric surface map for the unconfined, upper, aquifer of Washoe Valley for 1965 conditions is shown as Figure 11, adapted from the head contour map of the calibrated 1965 steady state model. Figures 12 and 13 respectively show water table contours measured in the 1994 and 1997 Washoe County surveys. The shape of some contours is an artifact of the gridding/contouring program and therefore may deviate from actual conditions. All three maps indicate steep hydraulic gradients against the range front. These are probably a function of low crystalline rock transmissivities and relatively high recharge rates (Rush, 1967). The main portion of NWC is characterized by gentle gradients and overall low horizontal ground water velocities.

Drought conditions were in force from the winter of 1987 through the winter of 1994. The situation reversed itself and the period summer 1994 through winter 1997 was unusually wet. Figure 14 is a water level difference contour map, using the program Surfer™, showing gains in water table elevation from 1994 to 1997. Note that the increase is not uniform. The regions with large gains near the range front probably represent recharge areas and suggest that recharge is not evenly distributed.

Numerical Simulation of Ground Water Flow and Steady State Modeling

Previous chapters have described the various components of the conceptual hydrogeologic model. This chapter begins by describing the process of turning the conceptual model into a mathematical/numerical model. The steady state model is then presented and a discussion of initial conditions and boundary conditions, and hydraulic parameters is given. Calibration results and sensitivity analysis results are reviewed. The subsequent chapter takes up the verification process, namely transient modeling and concludes with several predictive scenario models.

Reference to, and inclusion of illustrations for the valley-wide model is provided where deemed necessary for the reader's comprehension of project area hydrogeologic concepts. For an amplified treatment of previously completed models, the reader is referred to those authors, in particular, Widmer (1997).

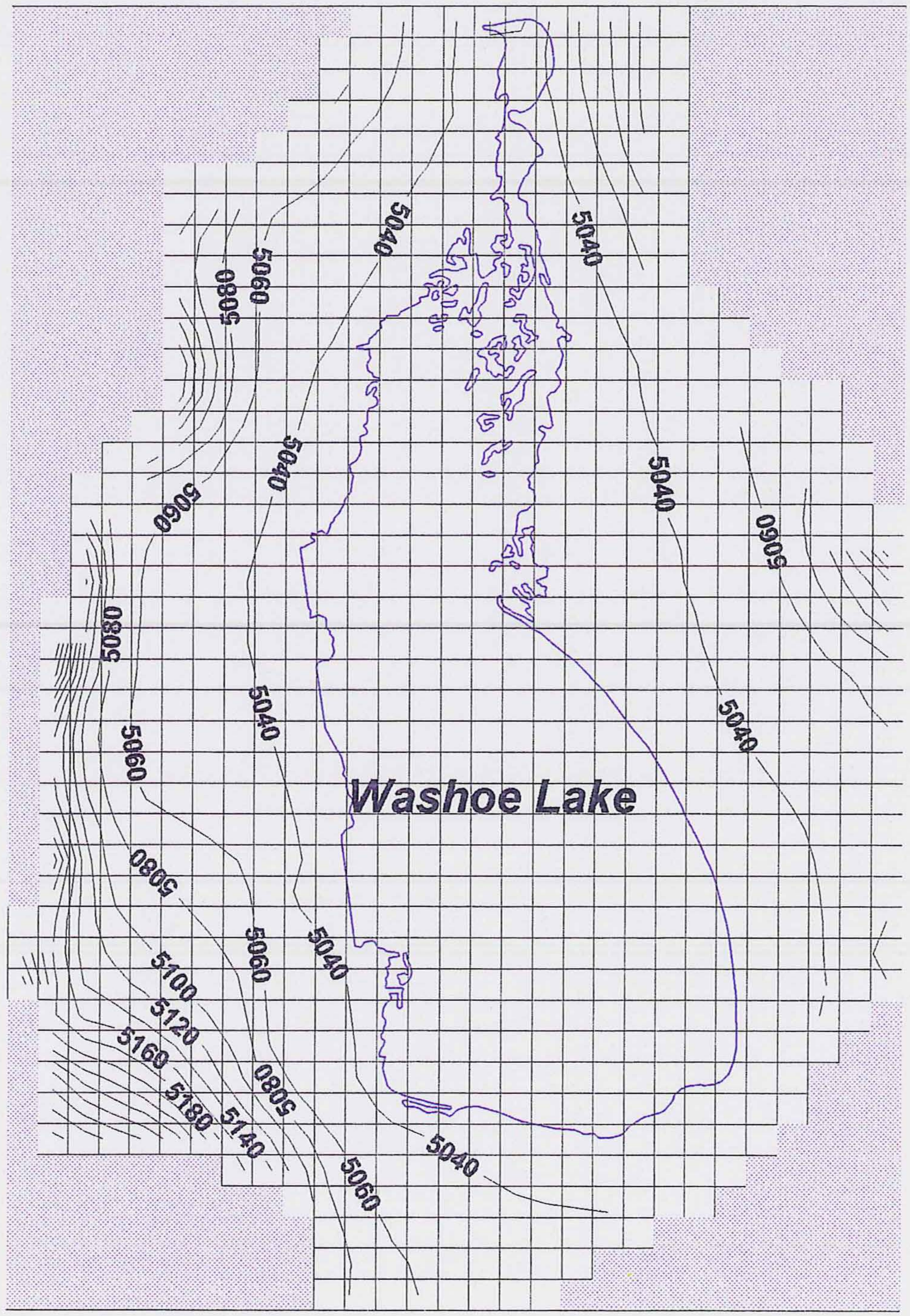


Figure 11. Potentiometric Surface, 1965
Washoe County Model

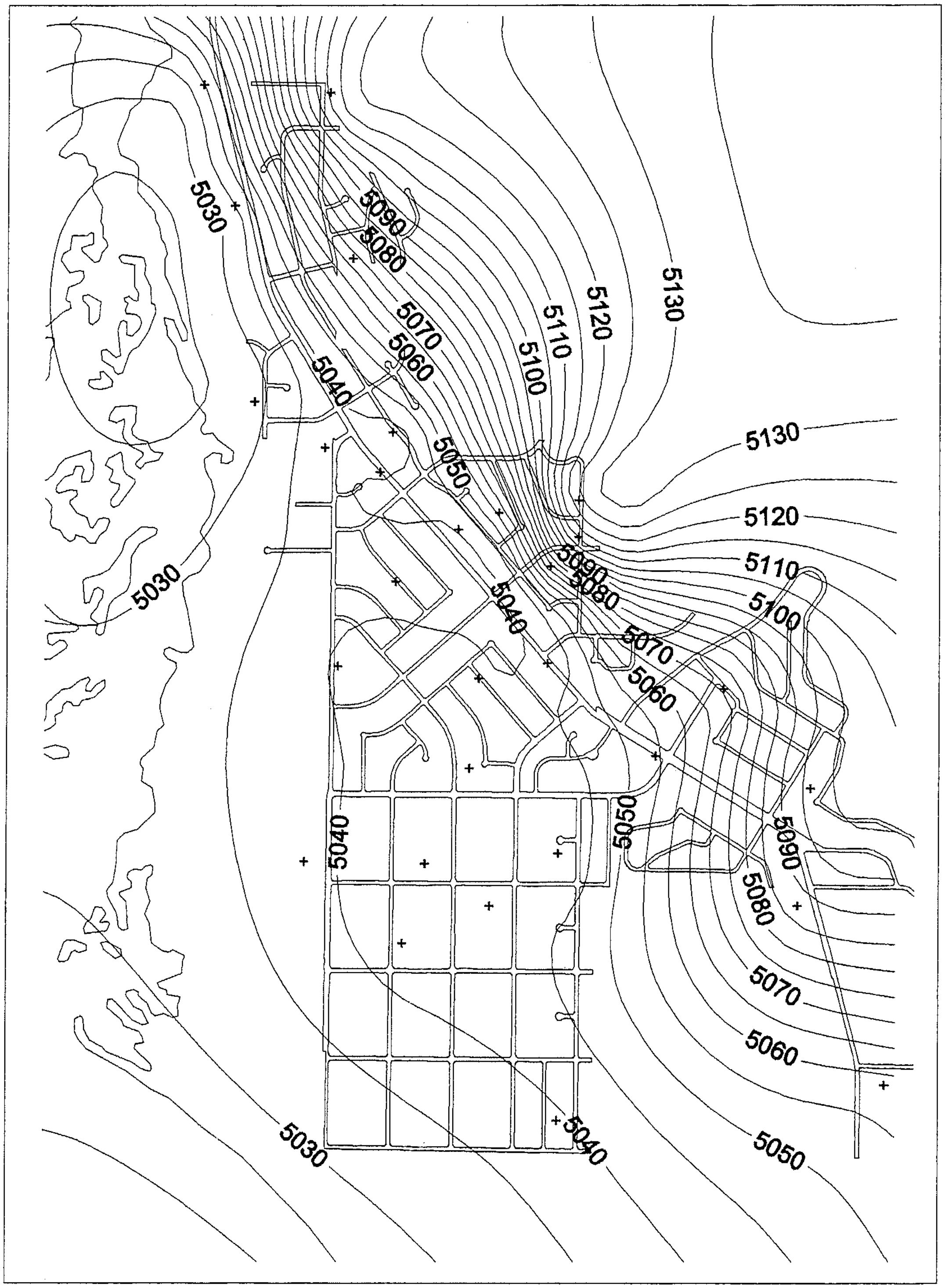


Figure 12. Water Table Contours, NWC 1994

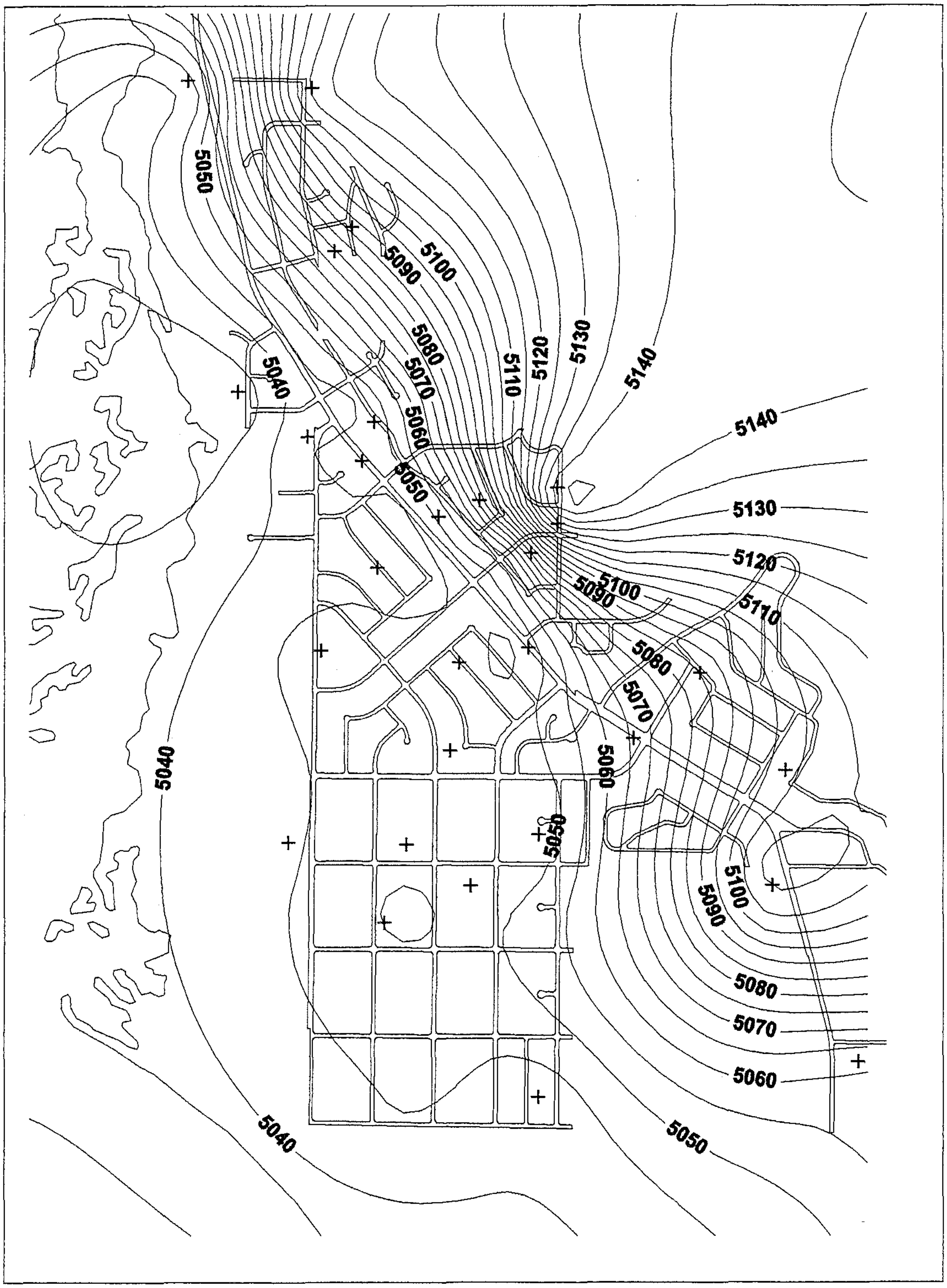


Figure 13. Water Table Contours, NWC 1997

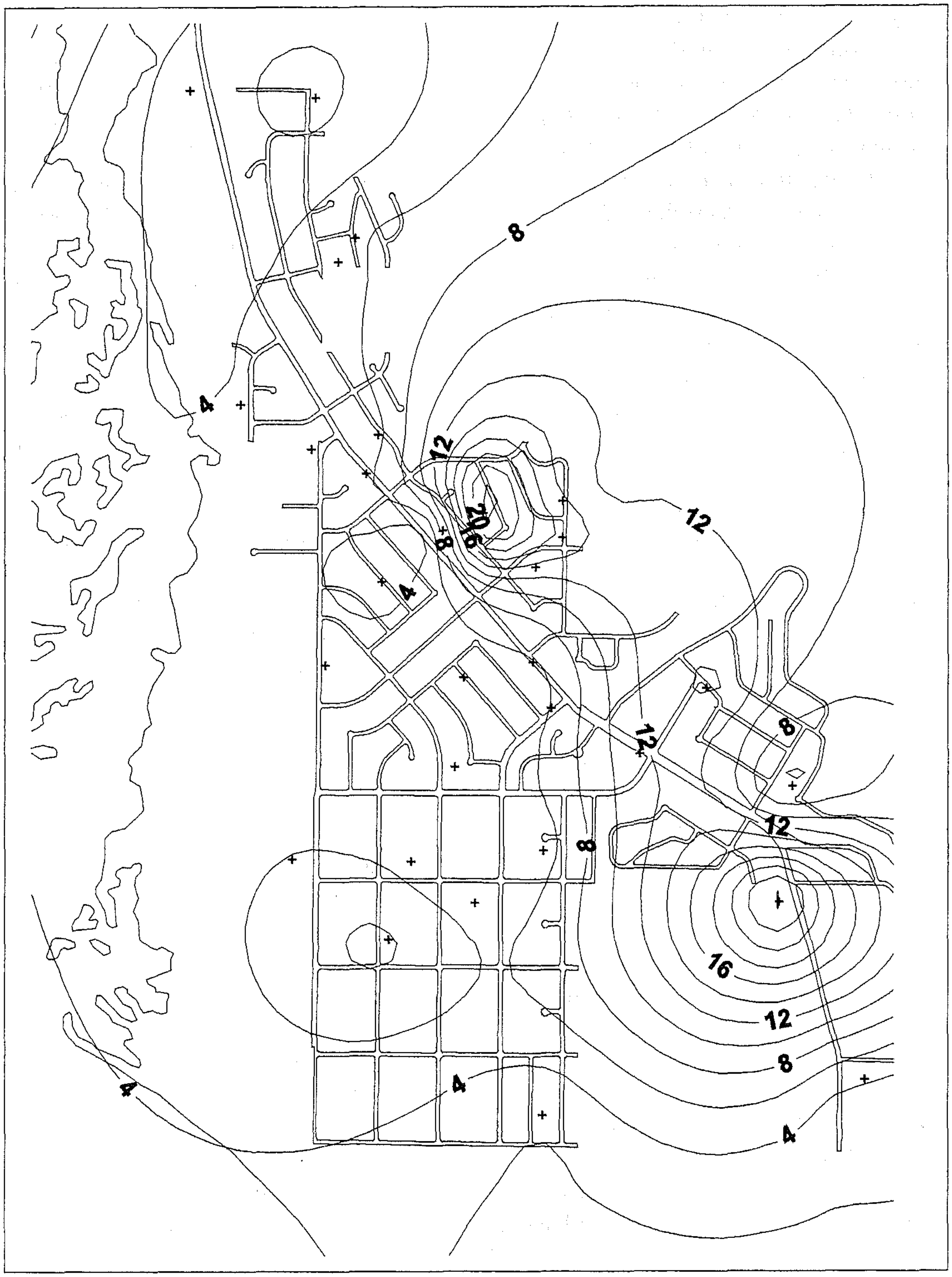


Figure 14. Water Table Difference Map, 1994 - 1997, NWC

Transition--Conceptual Model to Numerical Model

Existing Conceptual Model

A conceptual model is essentially comprised of four components. These are (1) the water budget, (2) basin structure and lithology, (3) boundary conditions and (4) constraints on ground water flow as determined from existing data. A nearly closed basin model is implied by previous work. Recharge is primarily generated from the range front mountain blocks and moves toward the lake (or dry lake bed during drought). Valley floor precipitation and secondary recharge from irrigation and domestic development adds to recharge. Discharge of all ground water varies with evaporation and transpiration rates. Evapotranspiration is particularly strong at the lake periphery and the wetlands and is a significant component from crop lands on the west side. Direct discharge of ground water to the lake and wetlands is also an important component of the discharge equation. Modest amounts of ground water pumping completes the discharge equation. Subsurface outflow is considered minor (Rush, 1967, pg. 22).

Basin structure and lithology have been reviewed. A graben-like setting with a deeper west side has been suggested by gravity data. Portions of the west side are conceptualized as an alluvial fan model, with sediments fining eastward toward lower energy environments, and interfingering with lake sediments. To date, the east side sedimentary basin has been treated as a relatively uniform lake bed environment with low transmissivities. Division of the aquifer into an upper unconfined aquifer and a lower confined aquifer is a good initial approximation, considering lack of data at depth. The conceptual model assumes that lithologies and hydraulic properties are similar in the deeper parts of the basin. No deep drill holes are available to confirm or deny this hypothesis. The conceptual model includes fractured crystalline rock and volcanic rock as part of the ground water flow system along the basin edges, and for NWC, at depth.

Boundary conditions at the valley margin are prescribed flux where recharge enters from the range front. Lateral and horizontal contacts between the granodiorite and basin fill, where no recharge occurs are no flow boundaries (prescribed flux equals zero). The lake itself would be a prescribed head boundary, but the lake bottom is a mixed boundary condition depending on both the lake head and hydraulic conductivity of the lake substrate. The ET surfaces are considered a mixed boundary condition because they depend on flux rates and head levels.

As Rush (1967) notes, ground water flow in the valley-fill reservoir is from areas of recharge toward areas of discharge. Based on water level contours, water flows from the foot of both mountain ranges toward the central axis of the valley, or the lake. All measured well heads are higher than the average 1965 lake stage of 5027 feet. Furthermore, many wells are under artesian conditions near the lake. Under the described scenario, ground water is expected to move laterally toward the lake, from the sides, and vertically toward the lake, from the aquifer below.

<u>Conceptual Model, New Washoe City</u>

The predominant change of the conceptual model in NWC is associated with refinement of basin structure and lithology. Basin fill thickness has been reduced. Volcanic units are no longer directly considered part of the flow domain, however; certain portions of the basin fill and volcanic unit contact are modeled as prescribed flux boundaries. Revisions of the hydrogeologic setting have resulted in a conceptual model that has more variable lithology, and is structurally more complex than previous conceptual models. The variable lithology allows a greater range of hydraulic parameter values. The structural interpretation is permissive of increased amounts of infiltration into the fractured rock aquifers, via greater fracture permeability. Some "range front" waters could flow through fractured basement rocks and then ascend up permeable fault zones or in front of fault permeability barriers into the shallow valley fill cover. Other water budget concepts or boundary conditions, including the lake, remain unchanged.

Mathematical Flow Model

The U. S. Geologic Survey modular finite difference model, commonly called MODFLOW (McDonald and Harbaugh, 1988) was used in this study, in conjunction with pre and post processor software (Groundwater Vistas). A numerical solution, using the finite difference method, solves for head values at discrete points. A numerical method is used to approximate a solution to a three-dimensional flow equation for ground water movement in porous media as described by McDonald and Harbaugh (1988):

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

where K is the hydraulic conductivity in the horizontal (x and y) and vertical (z) directions; h is the potentiometric head; W is the volumetric flux per unit volume, which represents a source or sink of water; S_s represents the specific storage of the porous material; and t is time.

The finite difference method is reviewed, among others, by Wang and Anderson (1982). Numeric ground water modeling is a useful tool to model systems with complex boundary conditions and large areal extent. For this project, as with most ground water flow modeling, the accuracy of the model is constrained by available subsurface data or accurate boundary and/or initial conditions and the non-uniqueness of ground-water modeling. The selection of an appropriate conceptual model is also very important for creation of a valid numeric model.

The strongly implicit procedure (McDonald and Harbaugh, 1988, p. 12 - 1) was used to solve the system of differential equations for each time step by iteration. The iteration head change convergence criterion was set at 0.001 feet for solutions at individual model grid nodes, centered in model grid cells, with dimensions of x, y and z.

Model Construction

The model is constructed with orthogonal grid cells. Petersen's and Widmer's valley wide model uses grid cell dimensions of 1000 feet per side and is the starting point for the present study. Their model has two layers, with the vertical (z) dimension a function of layer thickness, variations in surface topography and variations in bottom layer topography. The model peripheral boundaries were generally established as the range-front /mountain block contact. The model has inactive cells (about 25% of the model area) that represent no-flow condition mountain blocks. Portions of the valley periphery with crystalline rock are modeled, however, and it is assumed that the fractured crystalline rock in those area acts as an equivalent porous media. Homes in parts of NWC are reliant on fractured and weathered granodiorite as the principal aquifer.

The model grid was refined along the eastern side of the valley to a 500 feet by 500 foot spacing in NWC and to the southeast. The new model grid contains 2788 cells, of which the same portion as previously is active. Figure 15 shows the project model grid, inactive cell distribution and location of the lake area.

The current model retains the two layer concept. The first layer simulates unconfined conditions and models lake-related ground water phenomena, most recharge and discharge and domestic pumping. The base of layer 1 is at a consistent elevation of 4920 feet above mean sea level (amsl). From previous work, the idealized confining layer, which is estimated to be ten feet thick, is found about 100 feet below land surface. The top surface of the entire confined aquifer has been assigned an elevation of 4910 feet amsl. Groundwater Vistas calculates a vertical leakance term called Vcont, for the semi-confining layer, using the gap thickness between layers 1 and 2 and an estimated vertical hydraulic conductivity for the semi-confining layer. Surface topography is from U.S.G.S digital elevation model data (DEM), and for the active model area ranges from 5010 feet amsl to an average elevation of about 5300 feet amsl. The actual thickness of layer 1 varies between about 90 feet underneath the lake to about 300 feet at the model margins. Layer 2 extends to a maximum depth of 4030 feet aml. Thus, the maximum thickness of the modeled basin is about 1000 feet.

A modification of layer 2 bottom elevations was made in this study for the NWC area, in conformance with the horst and graben structural setting. However, the base elevations for layer 2 were left unchanged from the eastern lake boundary, westward. The significance of this adjustment is presented in discussions of the steady state model hydraulic parameters. Figure 16 is a plan view map of the project area showing the modified layer 2 bottom elevations which reflect, but generalize, the conceptualized structures as depicted in Figure 9. Final bottom elevations were obtained through calibration. Figure 17 is a typical model cross section

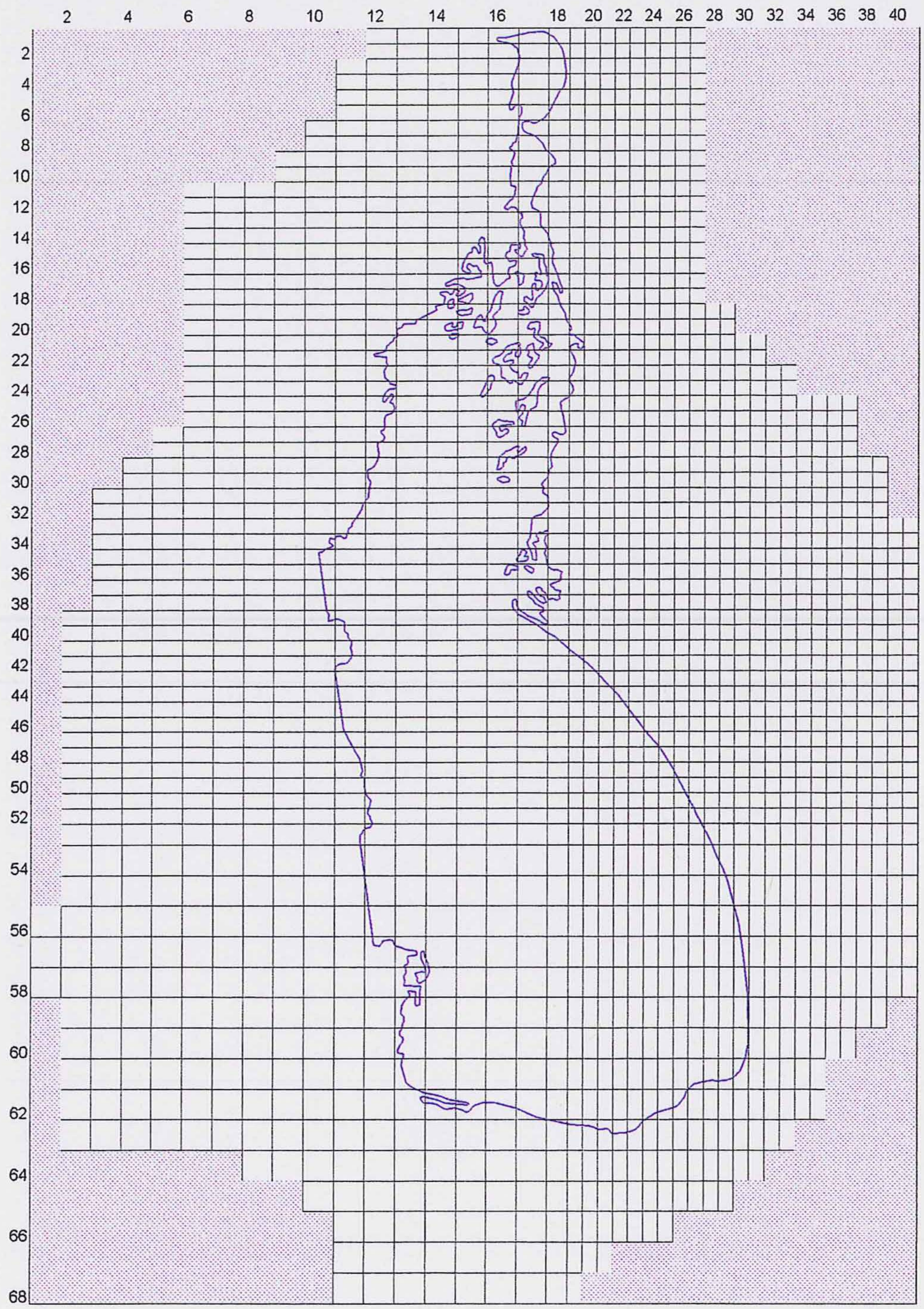


Figure 15. Model Grid Cells and Boundaries

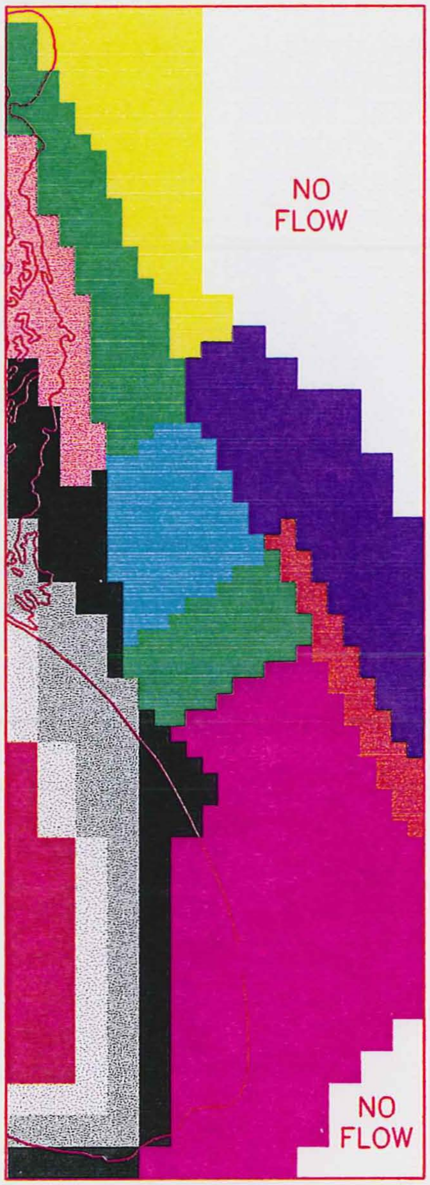


FIGURE 16
CALIBRATED LAYER 2
BOTTOM ELEVATIONS

LEGEND:

4030
4280
4530
4650
4700
4750
4775
4850
4875
4900
4909

Values in Feet above sea level

through NWC.

Treatment of the Lake

A unique problem with Washoe Valley ground water modeling has been how to treat the lake system. Previous workers have adopted the General Head Boundary (GHB) package (McDonald and Harbaugh, 1988, p. 11-1). The present study continues with this package to simulate the lake, for the steady state model and transient verification phases of the investigation. For transient predictive modeling the GHB package was not used; instead an ET boundary was used to simulate surface conditions on a dry lake bed.

The GHB package is a prescribed head boundary condition that allows water to move into or out of a "reservoir," or source of water, and is meant to represent a simple physical boundary model. The head value in the GHB reservoir is set at the desired lake stage elevation. Flow into or out of the reservoir and into the aquifer depends on two parameters as expressed in the following equation:

$$Q_b = C_b(h_b - h),$$

where Q_b is the ground water flow through the boundary between the reservoir and the aquifer; C_b is the conductance of the boundary; and the term $(h_b - h)$ is the difference between the head at or beyond the boundary (h_b) and in the aquifer. In turn, the conductance term has semi-physical basis and is defined as:

$$C_b = K_v LW/T,$$

where K_v is the vertical hydraulic conductivity of sediments underlying the lake bed; with L and W respectively representing the length and width of one grid cell. T is the thickness of the lake bed sediments. The term C_b is a parameter that must be adjusted during calibration to allow the GHB to remain at the required lake stage, but does not always represent a realistic value for a calibrated steady state model. For the present model the K_v value is estimated at .1 ft/day, and is consistent with other calibrated values representing silt and clay. The approximate average assigned conductance value is 10,000 ft^2/day with L and W equal to 1000 feet and T estimated at 10 feet.

For Washoe Valley, the GHB package is a relatively simple algorithm that must represent potentially complex interactions between the ground water system and the lake. The model is not a surface water model. Water will flow from the aquifer to the GHB when the aquifer head is higher than the prescribed GHB head and vice versa. Since the model has only two layers one has to use all of layer 1 in the area of the physical lake as the GHB domain. A thin, say 10 to 20-foot thick top layer, representing the GHB was not attempted because this would have required creating a completely new model as constrained by the preprocessing software and would probably be numerically unstable due to

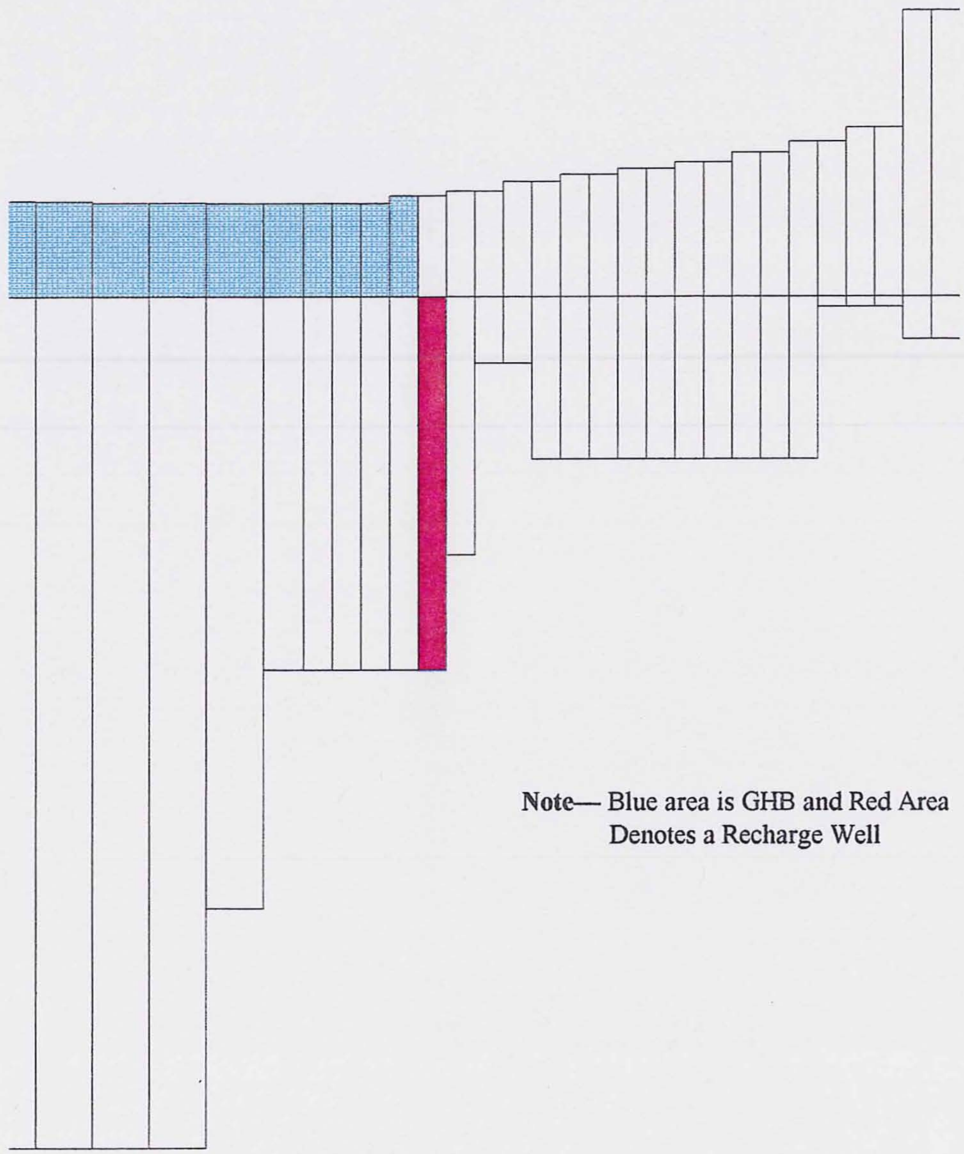


Figure 17. Model Cross-Section Through Project Area

relatively high projected flux rates. True to the conceptual model of ground water flow toward the lake, modeling results were considered satisfactory when net inflow from the aquifer to the GHB was about 5000 acre-feet per year. The model cross section, Figure 17, illustrates the position of the GHB cells along a typical east-west section. Flow will be toward the GHB cells if the head is higher in the adjacent cells of layer 1 or the underlying layer 2 grid cells.

The limitations of the GHB package are that potentially it can supply an unlimited amount of water to the aquifer. Therefore careful attention must be paid so that unrealistic flows into or out of the aquifer, according to the conceptual model, do not occur. Alternatives to the package were considered. These include a lake package for MODFLOW developed by Cheng and Anderson (1993). The lake package works somewhat similarly to the GHB package but relies on precise surface water budgets and accurate lake bed conductance values. This package was not used, primarily because the data to support its use is non-existent, and secondarily because the package was not available with the preprocessing software.

Two additional alternatives were considered and experimented with. The first, was to calibrate the model using only evapotranspiration to govern lake heads. In this case the lake is numerically modeled as part of the aquifer and is therefore not treated correctly. Furthermore, it was found that calibration to achieve a "flat" uniform head distribution was virtually impossible. The second alternative was to treat the lake as a thin third layer with a very high conductance value (two orders of magnitude greater than the underlying layer) and a specific yield and porosity of 1. Some simple experimental grids were created in MODFLOW. Under certain conditions this model will converge, despite contrasts in parameters between adjacent layers. Chances of achieving a successful transient calibration were considered low, based on the unpredictable results of the experimental trial models, and therefore beyond the scope of the study.

Steady State Model

Initial Conditions and Recharge/Discharge

The steady state model was calibrated to 1965 ground water and lake levels based on data by Rush (1967) and the pre-calibration ground water budget given in Table 2. The 1965 data set is considered the most representative of what can best be described as "quasi steady state conditions." These conditions represent a time before most residential development, but even more important, an average precipitation year (Widmer, 1997). Because the lake is a major part of the hydraulic system and lake stage varies annually, this type of system also requires transient modeling. Major modifications of boundary conditions or hydraulic parameters were done only for the project area; with an attempt to make realistic transitions from the modified areas to the unmodified areas, for the parameter changes involving basin depth and hydraulic conductivity. The following text refers to the project area, except where noted.

Range front recharge is simulated as a series of wells, with positive flow rates, using the Well Package from MODFLOW. Wells on the east side are located primarily in layer 1 because it represents most of the modeled aquifer thickness at the model boundary. Recharge is unevenly distributed due to different flow inputs from the various sub basins.

For NWC a significant portion of recharge is derived from the Jumbo sub-basin and a second source about one mile to the northwest. The uneven recharge is confirmed by water level difference data from the 1994 and 1997 surveys. Some range front cells are considered to have minimal recharge and are represented as no flow (zero flux) cells. Ground water flow from basement rocks (assumed to be fractured volcanic units) is simulated by a series of recharge wells located under the western portion of NWC, in layer 2, and in an area east of the southeast edge of the lake. Location of the basement recharge wells under NWC was governed by the structural interpretation. Discharge or pumping wells include a series of wells designed to simulate domestic consumption in NWC, and several agricultural wells. Figures 18 and 19 show the recharge/discharge wells and location of the General Head Boundary for layers 1 and 2, respectively. The average lake level was assumed to be 5027 feet (Widmer, 1997) under conditions of the 1965 water budget.

Recharge is also governed by valley floor precipitation. Recharge rates, using MODFLOW's Recharge Package were not changed and use the same assumptions for precipitation/infiltration ratios as described by Widmer (1997). Most of the east side receives little precipitation induced ground water recharge. However, in the calibration process, particularly transient calibration, a better calibration was achieved by increasing the extent of recharge further eastward underneath NWC. This may be a function of vadose zone saturation from septic effluent and domestic irrigation, allowing more precipitation recharge to reach the water table than previously recognized. The areal extent and rates of calibrated recharge, in feet/day are shown on Figure 20.

Ground water discharge is also governed by ET, using the ET Package. Evapotranspiration is handled by MODFLOW using a recharge rate in feet per day, and an extinction depth, to simulate root penetration. The maximum ET rate occurs at the surface, and decreases linearly to zero at the extinction depth specified. Areas with a shallow water table are expected to have less root penetration and therefore shallower extinction depths. Figure 21 shows the areal distribution and rates/extinction depths for ET, after calibration.

Hydraulic Properties

The pre-calibration configuration of the horizontal hydraulic conductivities was

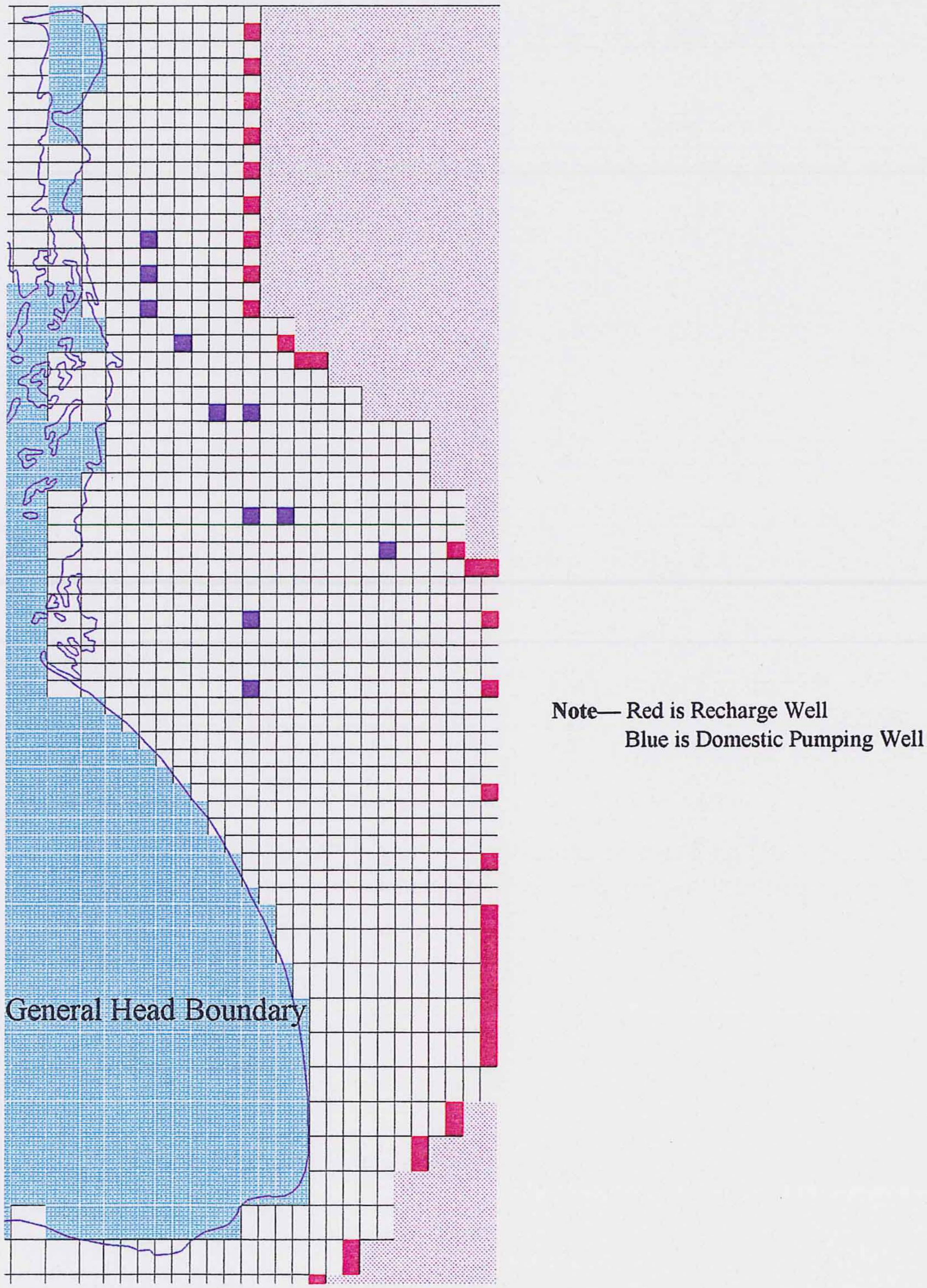


Figure 18. Well Distribution and General Head Boundary, Layer 1

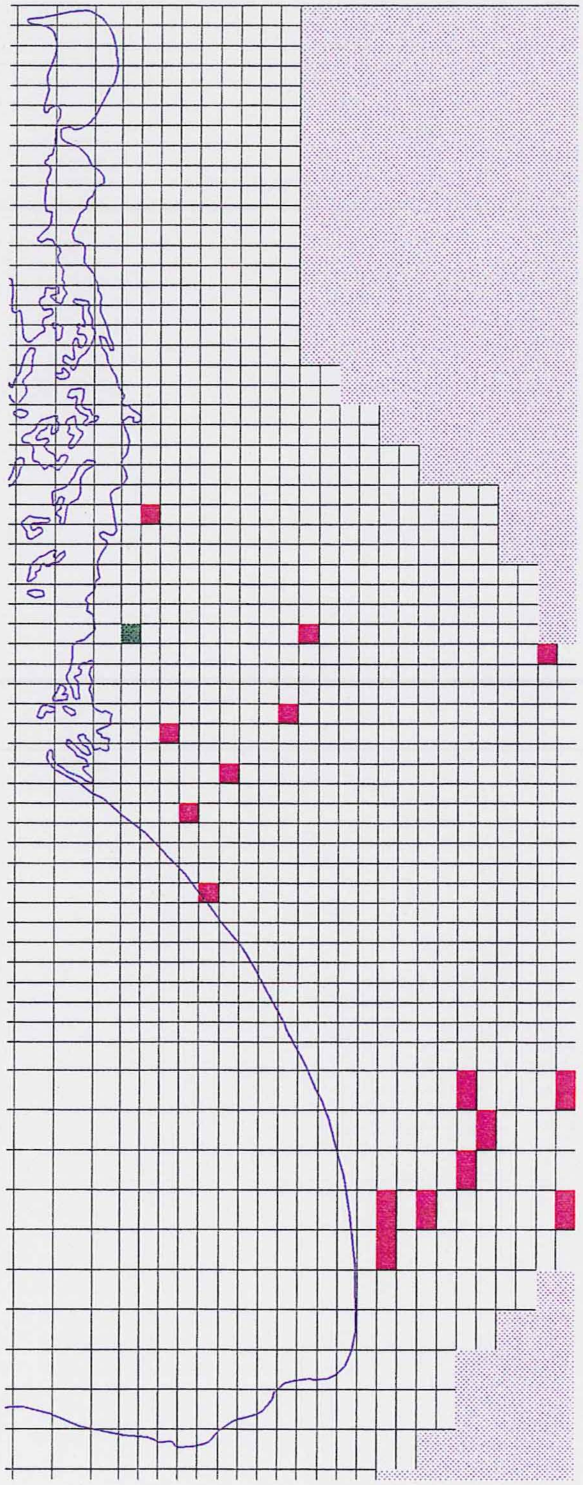


Figure 19. Well Distribution, Layer 2

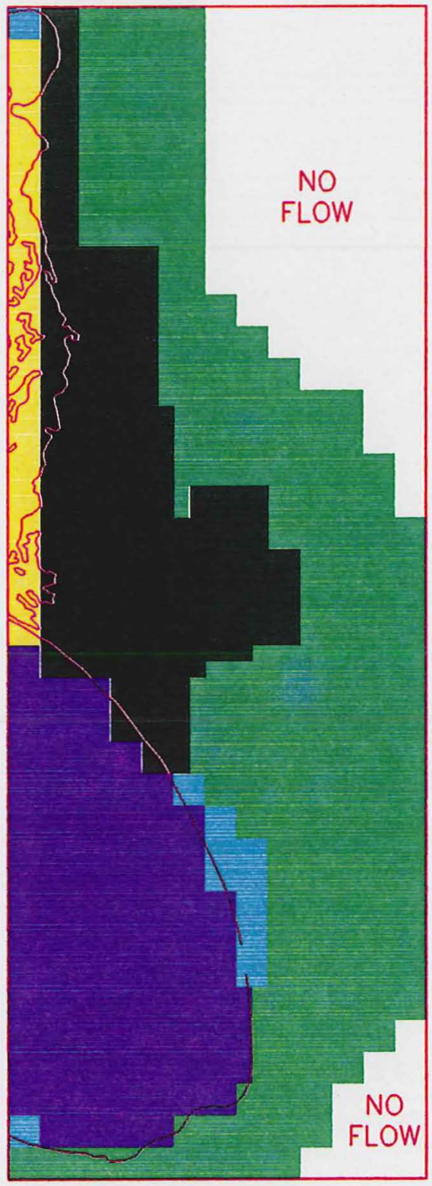


FIGURE 20
VALLEY FLOOR RECHARGE

LEGEND:

- *Ø (purple)
- *Ø (green)
- *Ø (yellow)
- ** 1.1×10^{-3} (light blue)
- ** 5.0×10^{-4} (black)

* Denotes ET not on, equals "0", when GHB on.
** Values in Ft./Day

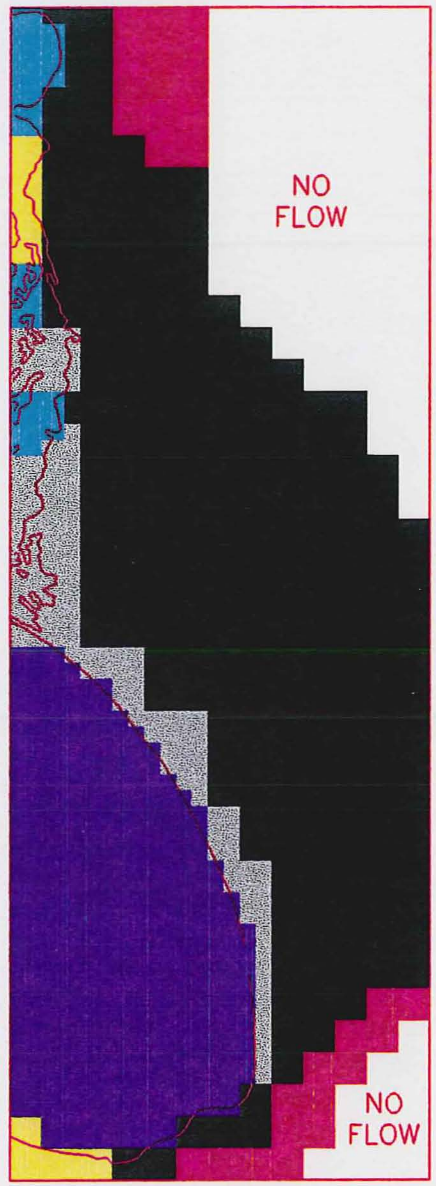


FIGURE 21
EVAPOTRANSPIRATION

LEGEND:

Blue	*Ø	Yellow	** $1.01 \times 10^{-2/7'}$
Red	*Ø	Black	** $3.1 \times 10^{-3/25'}$
Purple	*Ø	Stippled gray	** $8.22 \times 10^{-3/7'}$

* Denotes ET not on, equals "0", when GHB on.
** Values in Ft./Day with extinction depth.

based on the specific capacity data. The K values, shown on Figure 10, were approximately halved before computer model data base entry. This was done because wells are often screened in the coarser sediments and the calculated K values were thought to be too high, or unrepresentative, of the overall mixed package of gravel, sand, silt and clay.
Distribution and values of K_h were further adjusted during calibration and are shown as Figure 22 for layer 1. Values and distribution are similar for layer 2. The K_h values range from 1 to 10 feet/day. For comparison, the previous model (Widmer, 1997) has calibrated values that range from .25 feet/day to 3 feet per day.
Adjustment of layer 2 bottom elevations and hydraulic conductivities effects transmissivity, defined as K times aquifer thickness, of layer 2. Decreasing aquifer thickness and conversely increasing K values has moderated changes in the transmissivity of the confined, second, layer. Conversely, lesser K values and greater thicknesses have had a similar effect in previous modeling. Thus, the two models do not have significantly different transmissivites in layer 2.

MODFLOW does not use the K_v term directly, but rather calculates V_{cont}, a leakance term. V_{cont}, in its simplest form, is calculated as K_v divided by the vertical distance between any two coinciding cell-centered nodes of layer 1 and layer 2. Since there is not a layer beneath the bottom layer, V_{cont} cannot be specified for the bottom layer.
Transmissivity represents the aquifer flow parameter for the bottom layer.

Calibration Results
Target calibration was done by adjusting various model parameters to achieve best fit to 1965 water levels. Water levels from only 9 domestic wells were available to calibrate the model in the project area. These were taken from Rush's (1967) report. It should be noted that surface elevations were taken form topographic contour maps and, at best, are believed to be within 5 feet of accurate elevation. Accuracies in actual water level measurement are affected by human error and by possible drawdowns due to recent pumping of the well. A greater confidence for model calibration was achieved during the transient verification, where for the 1994 survey, 26 wells were used for calibration in NWC.

<u>Calibration Results and Statistics</u>
Calibration was achieved by adjusting hydraulic conductivity, layer 2 bottom elevations, range front recharge wells, discharge wells in layer 2, and V_{cont} for the semi-confining layer. Additionally, Groundwater Vistas supports the Slurry Wall Package of MODFLOW. This package allows placement of a vertical permeability barrier, with user specified width and hydraulic conductivity. It can be used to simulate structures. A slurry wall was added on the west side of NWC during calibration and is discussed later.
Calibration results were evaluated using four different statistical relationships that compare measured heads, h_m, against simulated heads, h_s, as discussed by Anderson and Woessner (1992). The relationships are the mean error (ME),

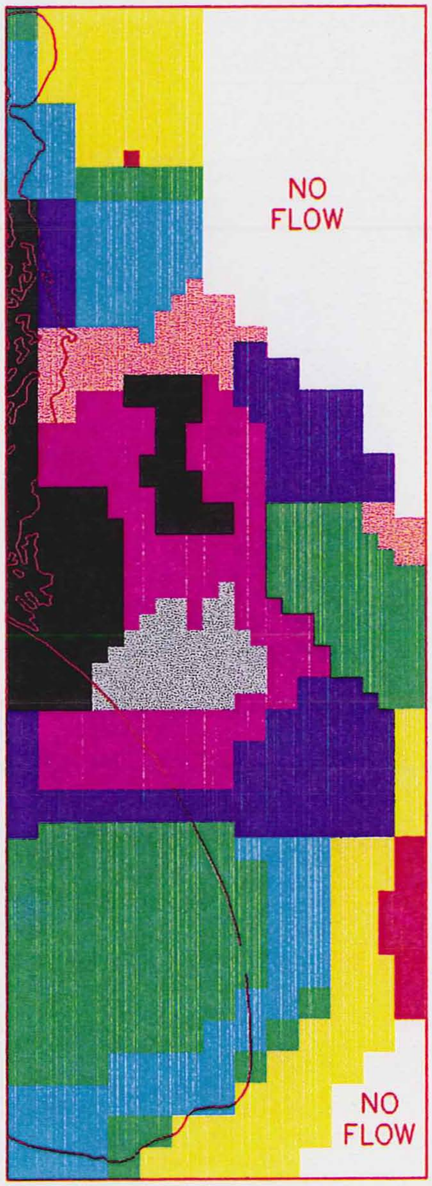


FIGURE 22
CALIBRATED HYDRAULIC
CONDUCTIVITIES FOR LAYER 1

LEGEND:

0.25
0.5
1.0
2.0
3.0
4.0
5.0
7.0
10.0

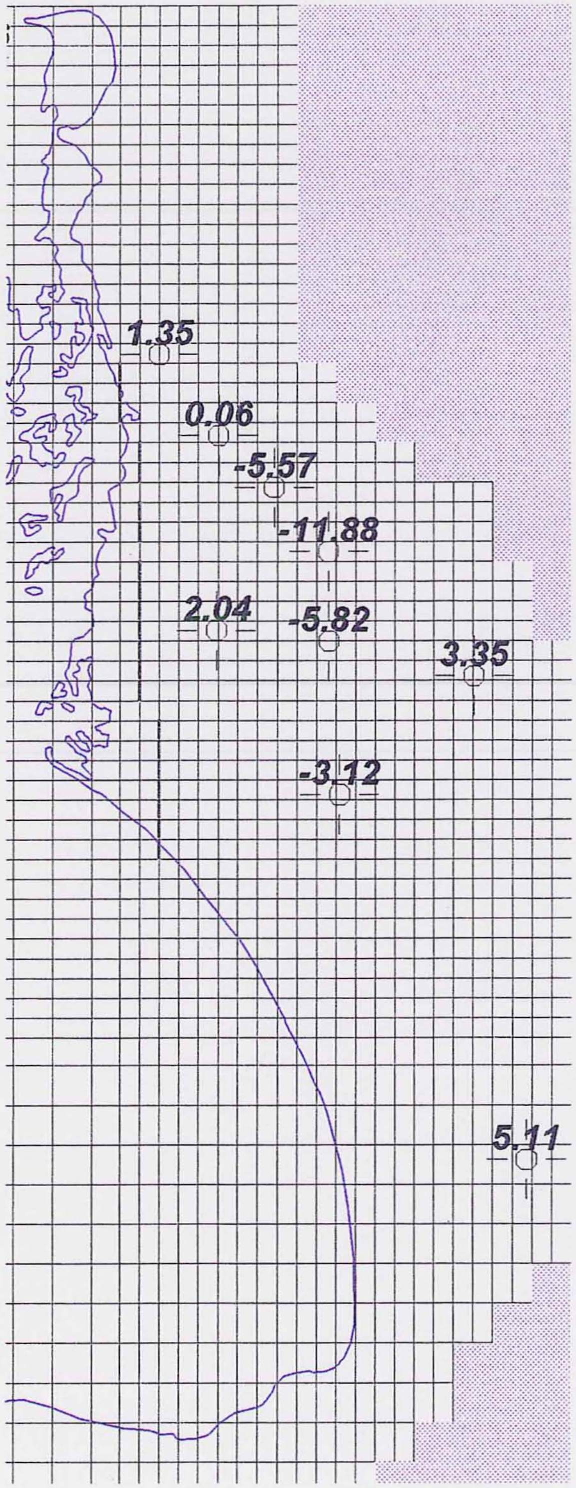
Values in Ft./Day

mean absolute error (MAE), the root mean squared error (RMS), or standard deviation, and the ratio of RMS to range of observed head values. The last term often gives the best indication of error, because if the ratio of RMS to range of observed head values is small, the errors are only a small part of the overall model response (Anderson and Woessner, 1992). For the calibrated steady state model, east side of the valley only, the ME is -1.61 ft., the MAE is 4.26 ft., and the RMS is 5.12 ft. The ratio of RMS to observed head range is 7 %, for the whole area.

The criterion for calibration should generally be established before the modeling effort. The calibration goals for the project were initially set according to previous modeling by Washoe County. The goals set were: 1) simulated heads generally within 10 feet of measured heads; 2) hydraulic gradients consistent with the conceptual model; 3) mass balance has an error of less than 1%; 4) the mass balance is reasonable compared with the derived ground water budget; and 5) the ratio of RMS to head range is less than 5 %. It is the normal goal of calibration to have hydraulic parameters and boundary conditions be within the range of values reported in the literature and consistent with the conceptual model. Boundary conditions as initially conceptualized were maintained throughout the calibration process.

For the valley wide model the ratio of RMS to head range was kept at less than 5%, primarily because the head range is 163 feet, verses 72 feet for the study area.

Figure 23 is a map of calibration targets for the steady state model. Also shown is location of the slurry wall. The adjacent number represents the residual, or measured head minus calculated head. A negative number represents areas of "too much water," where calculated heads are higher than measured heads. A positive number means there is "not enough water," or calculated heads are lower than measured heads. Both the current modeling effort and previous modeling have had difficulty with too much water near the range front and not enough water toward the lake. Namely, the model has a higher than measured hydraulic gradient. The target well with the high residual value (-11.88 feet) is found within the granodiorite aquifer and could represent an atypical well, or measured water table elevation error. Decreasing range front recharge or increasing the K value around this well, tended to further lower the calculated heads to the west. Conversely, decreasing K values and increasing layer 2 recharge in the western area aggravated the problem near the range front. Use of the slurry wall allowed better calibration in the western part of NWC. The wall thickness was set at 300 feet and the K_h value at 0.5 feet/day, which is an order of magnitude lower than surrounding values. The wall is applied to both layers. It is also consistent with geologic interpretations that indicate a north to northwest trending lineament, and a possible fault structure.



Note- Black Line is Slurry Wall

Figure 23. Calibrated Targets and Residual Head Values, Steady State Model

Sensitivity Analysis

A sensitivity analysis was done to determine which input variables have the greatest influence on model results. A stand-alone model was created using the telescopic mesh refinement (TMR) option in Groundwater Vistas, so only parameters of the study area would effect the statistical output. The program requires selection of boundary condition types and then calculates flux or head at the boundaries. In both layer 1 and 2, the north, south and east sides are constant flux boundaries. For layer 1, the west edge is all part of the lake domain and is therefore a general head boundary. For layer 2, the west edge was selected as a constant head boundary. Results of the sensitivity analysis are presented in Table 4. Target residuals for the calibrated model are nearly identical to the valley wide model.

Input variables selected are K_h, V_{cont}, Valley Recharge, Range Front (RF) Recharge, Layer 2 Recharge (recharge from the volcanic basement, sw NWC), ET, and ET extinction depth. Parameters were doubled and halved.

The sensitivity analysis shows that the model is most sensitive to adjustments of horizontal hydraulic conductivity and range front recharge. Table 4 shows that the RMS to head range indicator is not always the most sensitive statistical parameter and that statistics should be used together for effective evaluation. Changing ET, Valley recharge, or ET extinction depth did not affect the overall statistics significantly. As seen on Table 4, occasionally the RMS and RMS to head range ratio (RMS/h) were slightly improved. The selection of the final calibration parameters was based on fine tuning the head gradient relationship and avoiding getting too low of a calculated head in the western part of NWC. This was based not only on the steady state calibration, but the transient calibration process, also.

Table 4

Sensitivity Analysis, Steady State Model
Project Area — East Side of Washoe Valley

Simulation	ME	RMS	MAE	Min. Residual	Max. Residual	RMS/h ratio
Calibration	-1.42	5.10	4.29	-11.73	4.97	7.1%
K x 2	9.03	10.79	9.15	-.54	36.61	15.0%
K x 0.5	-13.93	11.04	13.93	-37.08	-2.18	15.3%
V_{cont} x 2	-1.10	5.26	4.45	-11.51	6.20	7.3%
V_{cont} x 0.5	-1.80	4.97	4.15	-12.05	3.85	6.9%
Valley Rech. x 2	-4.22	5.77	5.49	-15.18	4.62	8.0%
Valley Rech x 0.5	0.07	4.77	4.21	-9.88	5.15	6.6%
R. F. Rech x 2	-14.21	9.99	14.21	-34.81	-3.02	13.9%
R. F. Rech x 0.5	6.76	9.30	7.46	-3.16	29.47	12.9%
Lay. 2 Rech x 2	-3.74	6.00	5.37	-15.06	4.86	8.3%
Lay. 2 Rech x 0.5	-0.17	4.67	4.00	-9.93	5.03	6.5%
ET x 2	0.60	5.18	4.48	-9.80	8.01	7.2%
ET x 0.5	-3.46	4.88	4.19	-13.48	1.93	6.8%
Ext. Depth x 2	5.54	5.76	6.64	-4.95	16.78	8.0%
Ext. Depth x 0.5	-4.48	4.96	4.91	-14.75	0.83	6.9%

Calibrated Ground Water Mass Balance and Fluxes

A ground water budget was calculated for the valley-wide model to compare against previous models. In addition, a groundwater mass balance is presented for the lake area, and range front/layer 2 recharge. Also, domestic consumption is investigated. Table 5 presents the valley-wide ground water mass balance in acre-feet/year. Mass balance error is less than 0.1%. The Washoe County model had total inflow/outflow of 11,290 acre-feet/year.

Table 5
Valley Wide Steady State Ground Water Mass Balance
(Acre-feet/year)

FLUX	INFLOW	OUTFLOW
Wells	7149	1080
Recharge	4586	
ET		5812
Head Dep. Bound.	93	4935
TOTAL	**11828**	**11827**

For the study area, range front recharge is approximately 740 acre-feet/year, with another 545 acre-feet /year coming from recharge wells in layer 2. Total recharge from both sources is 1285 acre-feet/year.

The well outflow figure largely represents estimated agricultural well pumpage on the west side of the valley. Calibrated domestic pumpage in NWC is 61 acre-feet per year. It is estimated that there existed only 200 homes in NWC in 1965. The consumption per household, based on the model, is therefore only .31 acre-feet per year in NWC. Estimated rates of water pumpage for the nearby Spanish Springs Valley (Kennedy/Jenks/Chilton in Berger et. al., 1997) range from .6 to .8 acre-feet/year per residence. Rush (1967) uses the figure of 50% of pumped water for actual consumptive use, with the remainder going back to the aquifer as secondary recharge. Therefore, the figure of .31 acre-feet per year is within the estimated consumptive use range. Part of the process in determining the domestic consumption rate included running sensitivity analysis on the TMR model by doubling the rate. The sensitivity analysis suggests that a double rate of consumption does not significantly perturb the system (non-sensitive). The statistics actually show a slightly improved RMS/head range ratio (6.7% verses 7%), but heads over much of the western part of NWC were considered too low to justify increased pumping rates. The same effect was noted in transient modeling.

A ground water budget was investigated for the lake area. Approximately 4894 acre-feet enter the unconfined aquifer that underlies the lake from the surrounding layer 1 and from the top of layer 2. Simulation of ground water flow to the physical lake from the aquifer is modeled by how much water enters the GHB reservoir. The model is further constrained by all of layer 1 within the lake boundary having the same head value. Physically this is not completely accurate because the lacustrine sediments are probably heterogenous and small head variations might be expected.

Conversely, with lack of field data, a uniform head value for this domain is a reasonable first approach. Net lateral inflow from all sides (layer 1) is positive, and conforms with the conceptual model. Most of the ground water under the lake enters nearly vertically from layer 2. Discharge from layer 1 is mostly via the general head boundary with minor amounts by evapotranspiration from wetlands. Water enters the general head boundary reservoir as a function of a positive horizontal and lateral head gradient. Unless the conductance term is set to a very low value, a water balance is usually achieved between recharge and discharge of the lake-aquifer system.

Table 6 provides a water balance summary for the aquifer under and lateral to the lake. Most inflow, 72%, is from layer 2 to layer 1. Very little water enters layer 1 from the east, only 5%.

The 2% of inflow from the GHB simulates flow from the lake to the aquifer. As Widmer (1997) points out, flow from the lake to the aquifer might be expected, due to varying lake depths and lake bottom hydraulic conductivities. In the simulation, this occurs primarily around the southeast side of the lake where heads in layer 1 are lower than the GHB. Whether this flow realistically simulates the system is difficult to conclude, due to lack of field data. An effort was made to reduce flow from the GHB to the aquifer. This included adjustment of K_h values near the lake and lowering of GHB conductance values near the lake-aquifer boundary. The 92 acre-feet per year of flow, or 2% of total inflow to the system, is a reasonable "fit" of flow from the lake to the aquifer, according to the conceptual mode.

Table 6
Water Balance Summary — Layer 1 Aquifer Underlying Washoe Lake
(In Acre-Feet/year) Error = -1.8%

Flux	Inflo	Outflow	% of Total Inflow
From East Side	251		5%
From West Side	1070		21%
Layer 2 to Layer 1	3573		72%
ET		234	
Head Dependent Boundaries	93	4842	2%
Total	4987	5076	

Use of the GHB appears to work reasonably well for the steady state model, however; if the aquifer is stressed by pumping, the GHB will provide essentially an unlimited supply of water. This can not be stressed enough. An experiment was conducted wherein a large volume pumping well(s) was placed under the middle of the lake in layer 2. The discharge was simulated at -5000 acre-feet/year, -10,000 acre-feet/year, and -26,400 acre-feet/year (the entire basin yield). As expected, flow from the GHB to the aquifer predominates, and increases commensurately with greater pumping volumes. A water balance is always achieved, but the lake head, as prescribed by the GHB, does not drop significantly. Instead, flow from the GHB to layer 1 and layer 2 is caused by head drop in those respective layers, as compared with the higher head in the GHB. Instead of draining or drying up the unconfined aquifer in layer 1, a large cone of depression forms in layer 2 and in layer 1 along the west side of NWC. This causes unrealistic flows from the lake to the west side of NWC and from the lake to the underlying layer 2 aquifer.

Transient Simulation of Ground Water Flow and Predictive Scenario Modeling

This chapter presents transient and predictive ground water flow modeling results. Transient simulations serve to verify the model, and present the model's strengths and weaknesses. The model was calibrated to 1981 and 1994 water level data. The 1994 data has superior quality because all wells were measured during the same winter quarter (December through March) and were later GPS surveyed. In contrast, the 1981 data includes measurements collected over one year with elevations picked from the topographic map. Once satisfactory transient simulations were achieved, a model verification for the period 1994 to 1997 was done. The final modeling task involved running several predictive transient situations that simulated hypothetical drought and worst case drought-plus-development scenarios. The last section of this chapter discusses and summarizes ground water flow regimes.

Transient Simulations

Transient Modeling 1965-1981-1994

Transient modeling relies on starting conditions from the 1965 steady state model. The process of calibrating both the steady state and transient models was iterative. Any changes made in model parameters during the transient simulations had to be incorporated into the steady state model, with the exceptions of storage values, which only apply to transient conditions.

Temporally variable parameters, valley-wide, were boundary conditions representing range front recharge, domestic/agricultural consumption, and the level of the lake, using the GHB package. For NWC the valley-floor recharge was also varied, in direct proportion to estimated precipitation. In previous modeling studies (Widmer, 1997) valley-floor recharge was held constant because it was assumed that the combination of precipitation and irrigation remained constant, i.e. there was an inverse relationship between the two. While the above may be true for the more heavily irrigated west side of the valley, the east side probably does not exhibit this relationship due to lesser, primarily non-agricultural, irrigation practices.

Recharge was varied using the same formula as incorporated by Widmer (1997). Precipitation data from Carson City, and two locations on the west side of Washoe Valley was averaged because precipitation data are not available from the east side. Yearly percentages of normal were calculated based on the year 1965, which was considered a normal year.

Transient modeling with MODFLOW requires the selection of a stress period and time step. A stress period is simply the length of time between changes in the boundary conditions. From 1965 to winter, 1994, there are 29 stress periods. Each stress period is 365 days long except period 29 which is 182.5 days. The last stress period was shortened to a half year, so that the model could be calibrated to the 1994 data set. Numerical modeling also requires a series of time steps to converge during each stress period as specified by the head change convergence criterion. The model uses ten time steps. Each time step is longer than the previous one, according to the following formula:

DELT (1) = PERLEN (1-TSMULT) / (1-TSMULT**NSTP),

where DELT (1) is the initial time step, PERLEN is stress period duration, TSMULT is the time step multiplier, and NSTP is the number of time steps. The time step multiplier was chosen to be square root of 2 according to recommendations by Anderson and Woessner (1992).

Drought conditions occurred in northern Nevada from 1987 through 1994. Consequently, lake levels began declining, and the lake was completely dry in 1991. The drying up process was simulated in modeling by taking domains, selected by surface elevations, and converting them from the GHB to an ET surface, at the appropriate stress period, as those areas became dry land. From stress period 26 through 29 the entire lake area was modeled as an ET surface. Physically, during portions of the winter months there where minor amounts of water in the deepest part of the valley. However, the ET approximation was considered a good choice for simulation of general drought conditions. Calibrated ET rates and extinction depths varied from .8 ft/year on the dry playa surface, with an extinction depth of 2 feet, to 4.5 feet/year in the wetlands area, with an extinction depth of 7 feet.

Transient model calibration was primarily limited to adjusting the specific yield of layer one and the discharge well flux that represents agricultural and domestic consumption. Only minor adjustments were required for discharge amount and distribution. The estimate of times normal recharge (1965 as the base year) is an integral part of the model verification, as is the lake level. These estimates are assumed to be reasonably accurate, based on calibration results. Times normal recharge and lake stage elevations are shown on Table 7. Specific yield was adjusted upward from previous model values. Its distribution is shown on Figure 24.

It is estimated that there were approximately 200 homes in 1965 and about 1000 homes in 1993 (the last full-year stress period modeled). Furthermore, an assumption was made that growth and corresponding consumptive use exhibit a direct linear relationship. Therefore, at the consumption rate of .31 acre-feet/year, per home, the net consumption values for NWC are 60 acre-feet/year in 1965 and 314 acre-feet/year in 1994.

Reasonable calibration was achieved for the 1965 to 1994 transient simulation. Figure 25 displays the residual head values, showing the difference between measured head values in 1994, against the calculated heads. The statistics support a good calibration-- better than

Table 7
Stress Period, Lake Stage, and Times Normal Range Front Recharge

Stress Period	Year	X Normal Recharge	Lake Stage (Ft.)
1	1966	0.74	5028
2	1967	1.22	5028
3	1968	0.74	5028
4	1969	1.67	5029
5	1970	1.13	5029
6	1971	1.22	5028
7	1972	0.55	5027
8	1973	1.06	5027
9	1974	1.22	5027
10	1975	1.13	5027
11	1976	0.58	5026
12	1977	0.61	5024
13	1978	1.03	5023
14	1979	0.71	5024
15	1980	1.03	5026
16	1981	0.55	5025
17	1982	1.84	5030
18	1983	2.00	5030
19	1984	1.42	5029
20	1985	0.87	5028
21	1986	1.90	5029
22	1987	0.67	5028
23	1988	0.55	5025
24	1989	1.03	5024
25	1990	0.74	5021
26	1991	0.68	5018
27	1992	0.71	5018
28	1993	0.74	5020
29	1994	0.57	5021

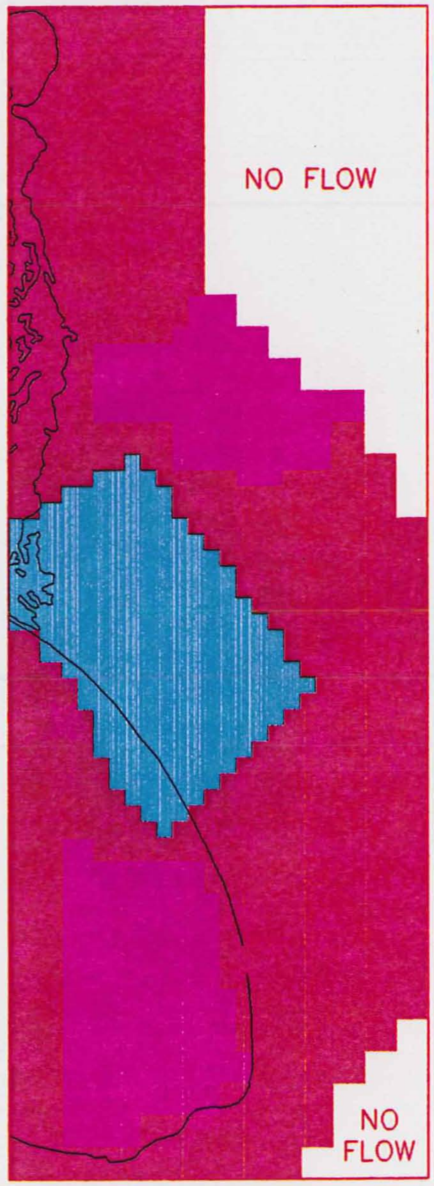


FIGURE 24
SPECIFIC YIELD, LAYER 1

LEGEND:

- 0.10
- 0.20
- 0.25

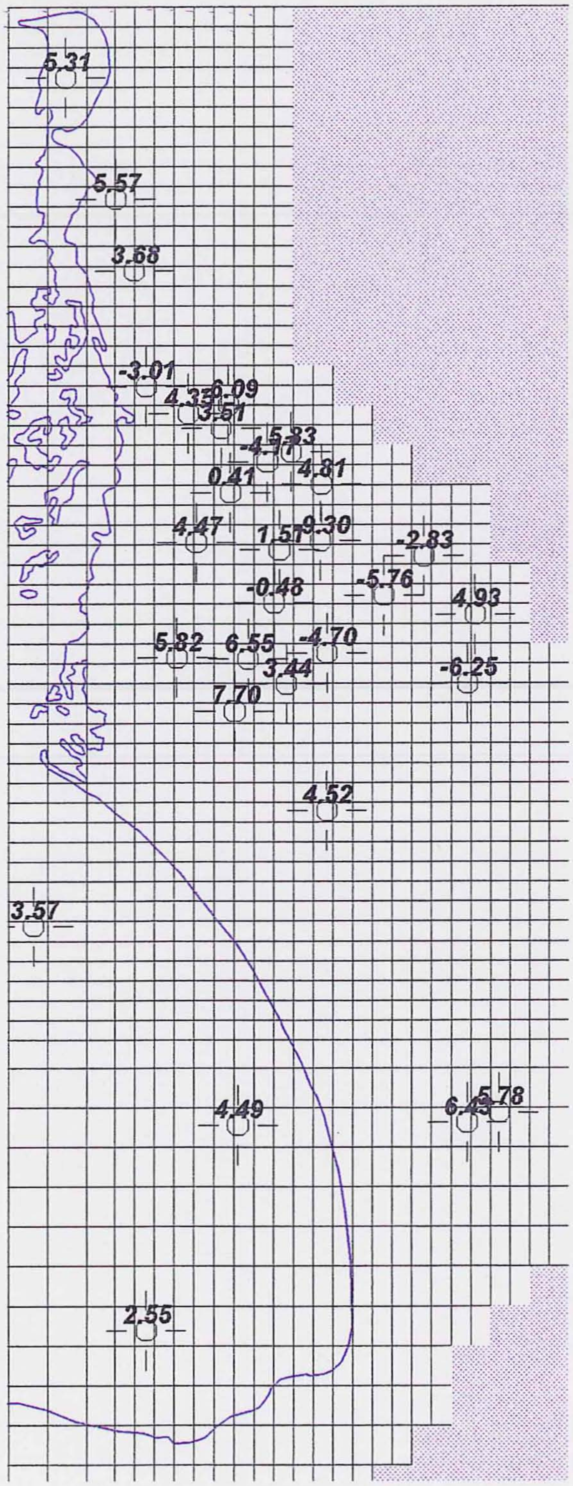


Figure 25. 1994 Transient Calibration Residual Values

the steady state simulation. For the 1994 simulation, the ME is 1.41 feet, RMS is 4.90 feet, MAE is 4.69 feet and the RMS/head range value is 6.7%. A calibration was also completed for the 1981 data set. Hydraulic parameters cannot be different for the two calibrations and must also be consistent with the final selected parameters of the steady state model. If they were different, this would violate the consistency of the modeling process, and be physically unrealistic as well. Only boundary conditions, as mandated by recharge/precipitation amounts, differentiate the two modeling runs. The 1981 data set was more difficult to calibrate. Final calibration achieved an ME of -1.54, an RMS of 8.06, an MAE of 6.39 and an RMS/head range value of 9.0%. Figure 26 shows the calculated head residuals for the 1965 to 1981 simulation. Both 1994 and 1981 residual maps display simulated heads consistently lower than measured heads in the western part of NWC. The 1981 calibration is further flawed because simulated heads are significantly higher than the measured heads in the eastern part of NWC. A similar effect is seen in the 1994 simulation but not of the same magnitude. Differences in the statistics are most likely caused by the generally lower data quality of the 1981 survey.

Dynamics of the General Head Boundary for the Transient Simulation

The dynamics of the GHB lake simulation were also investigated. Recall that the steady state simulation had a net influx of ground water from the aquifer to the GHB. A small amount of water (93 acre feet) flowed from the GHB to the aquifer. A concern during transient simulation was that possibly an excessive, unrealistic, amount of water would flow from the GHB to the aquifer, as the lake went dry. Model runs were completed from 1965 starting conditions to consecutive terminations at model years 1986 through 1993 (stress periods 21 through 28). The average lake stage dropped from 5029 feet in 1986, to a low of 5018 feet in 1992 and then recovered slightly to 5020 feet in 1993. The lake area of the model was changed from a combined ET-GHB surface to ET only beginning with stress period 26 (1991).

The Mass Balance package of Groundwater Vistas allows view of flows into or out of any prescribed polygonal area. Table 8 shows selected flux data for the portion of the aquifer underlying the lake (lake area). Ground water flux from the west side is not listed, but it is always greater than from other sides of the lake and always positive. The completed simulations indicate that flow from the GHB to the aquifer is not excessive and is similar to the flow in steady state modeling. As the lake level drops, ground water flux increases from the east, possibly due to a steeper hydraulic gradient. Ground water discharge from the lake area is at maximum in stress period 24 (lake stage 5024). At this stage only a portion of Washoe Lake proper still exists, and the entire wetland area has ground water essentially at the surface. This scenario is conducive to maximum ET rates due to maximum model extinction depth.

Ground water flow simulations and corresponding physical surface water processes require comment. Arteaga

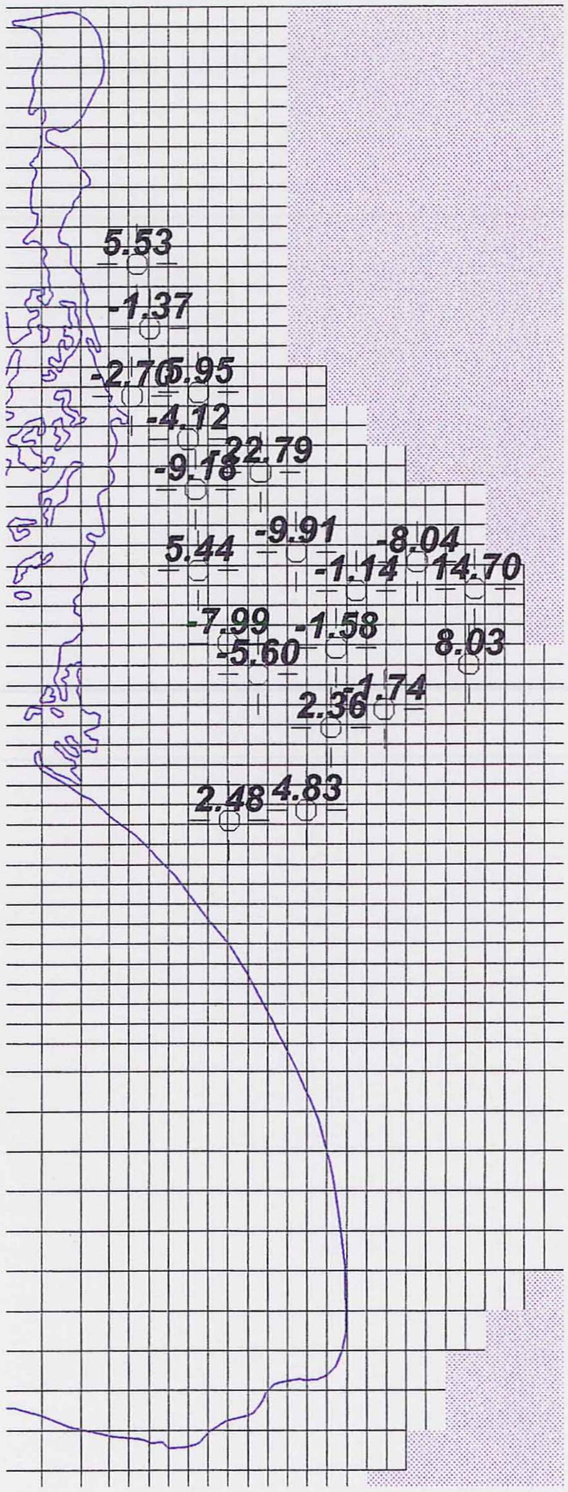


Figure 26. 1981 Transient Calibration Residual Values

(1984) estimates an open water body evaporation rate of 4.6 feet/year for Washoe Lake. With an area of 5600 acres, at lake stage 5029 (Rush, 1967), the lake would be discharging (evaporating) about 25,000 acre feet per year. Lake water and overland flow are simply not part of the model domain. The approximate 5000 acre feet of ground water that enters the GHB is not a simulation of lake evaporation, but rather simulates ground water discharge to the lake. Discharge rate is governed by head differences between layer 2 and layer 1. Physically, lake surface evaporation will, to some extent, indirectly affect ground water flux to the lake, but the GHB does not model this process. The GHB is a convenient tool to simulate observed lake stages. It indirectly takes care of evaporation from the lake and discharge from the aquifer to the lake. However, the GHB does not "intelligently" model surface water processes, rather the modeler must input appropriate lake stage values.

Table 8

Selected Flux Data for Lake Area, Transient Modeling

YR.	Stress Per.	Lake Stage (ft)	GHB into Aquifer	Aquifer to GHB	Net Aquif. to GHB	ET	Total Flux Out	In from lay 2	In from E. Side lay 1
1986	21	5029	100	4715	4615	644	5259	3682	152
1987	22	5028	67	4843	4776	780	5556	3690	170
1988	23	5025	61	4854	4793	1425	6218	4023	255
1989	24	5024	37	5000	4963	4786	9749	4631	276
1990	25	5021	0	2180	2180	4558	6738	4570	276
1991	26	5018	0	0	0	6772	6772	4514	250
1992	27	5018	0	0	0	6352	6352	4478	250
1993	28	5020	0	0	0	5914	5914	4323	235

Head Difference Maps and Model Verification

The water table in NWC experienced overall moderate declines between 1965 and 1994. Figure 27 is a drawdown map representing the difference between the calibrated 1994 potentiometric surface and the 1965 steady state calibrated surface (used for starting heads in the transient simulation). Head drops are about five to six feet in southwest NWC. Greater declines are observed from pumping of agricultural wells southeast of the developed area. Most significant declines in NWC occur against the range front where domestic wells tap the low transmissivity granodiorite aquifer. A number of homeowners in this area had to deepen their wells (Widmer, 1997). For a look at head drops in the western portion of NWC refer to Figure 28. This figure shows the 1994 potentiometric surface accompanied by posting of the original measured 1965 head values from Rush (1967). The 5040 and 5050 contours from the 1965 data define an area of five-foot head decline, corroborating the model simulated declines.

A final step prior to predictive simulation was model verification using the time period 1994 to 1997. The simulation uses starting heads from winter 1994, created in previous model runs. Confidence in model verification was hampered by lack of precipitation records. Boundary conditions varied in this transient simulation were seasonal range-front recharge, valley precipitation-induced recharge and lake stage. Hydraulic parameters were left unchanged. Precipitation data were obtained from the Carson City fire station (Ashby, 1997). Carson City receives more precipitation than NWC, but an assumption was made that relative percentages of normal are equivalent for Carson City and the study area. Data for average Washoe Lake stage were obtained for the same period, 1994-1997 (Bostic, 1997).

Weather conditions completely reversed themselves in 1994. A dry summer was followed by three consecutive wet years. The 1997 survey was conducted during January and February. January was an unusually wet month, with more than four inches of estimated precipitation. Therefore, it is likely that some unusual fluxes and variations in the water table existed at the time of survey. Table 9 lists the stress period, lake stage and calibrated estimated "times normal" range front and valley recharge.

Table 9
Key Data, 1994 - 1997 Model Verification

Year	Stress Period	Lake Stage (ft)	Calib. x Normal Rech.	Pre-calib. x Normal Rech.
Summer '94	1	5020	0.57	0.57
Winter '95	2	5020	1.53	1.53
Summer '96	3	5026	2.0	1.53
Winter '96	4	5028	1.53	1.39
Summer '96	5	5030	1.53	1.39
Winter '97	6	5030	2.0	1.50

Each stress period is six months long. The model has a GHB boundary during every stress period, expanding from the southeast side of Washoe Lake, in stress period 1 to cover the entire lake and wetlands in stress period 6. Recharge percentages were adjusted upward during various simulation runs, as shown on Table 9.

Based on head residuals and statistics, the verification results are considered fair. Simulated head values were lower than measured heads. This suggests that either actual recharge was greater than simulated recharge or some other model parameter is incorrect. The former hypothesis is more likely because good verification was achieved in the transient simulation, 1965 to 1994. Target residual head values are shown on Figure 29 for the 1994 to 1997 transient simulation. Modeled verses measured head values have an ME of 4.61 feet, an RMS of 5.17 feet, an MAE of 6.09 feet and an RMS/head range ratio of 7.2%.
Water table changes between 1994 and 1997 are shown on figures 30 and 31.

Figure 30 is a head drawdown map based on model simulation. The values are negative, and represent the 1994 starting heads subtracted from the 1997 simulated head values. Figure 31 is a comparable map generated using the grid and contouring packages of Surfer. Values here are positive and represent 1997 actual measured heads subtracted from 1994 measured heads. The tick marks represent well locations for both the 1997 and 1994 surveys. The gridding and contouring packages always pose difficulties where irregular areas of sparse or no data occur. Therefore, contours in the northeast part of the map are considered questionable. Generally, good agreement exists between the model simulation and the difference map created from actual measured data sets, except in southeast NWC. Note from Figure 31 that the closed contours representing up to 20 feet of water table rise are based mostly on one data point. During the field survey it was observed

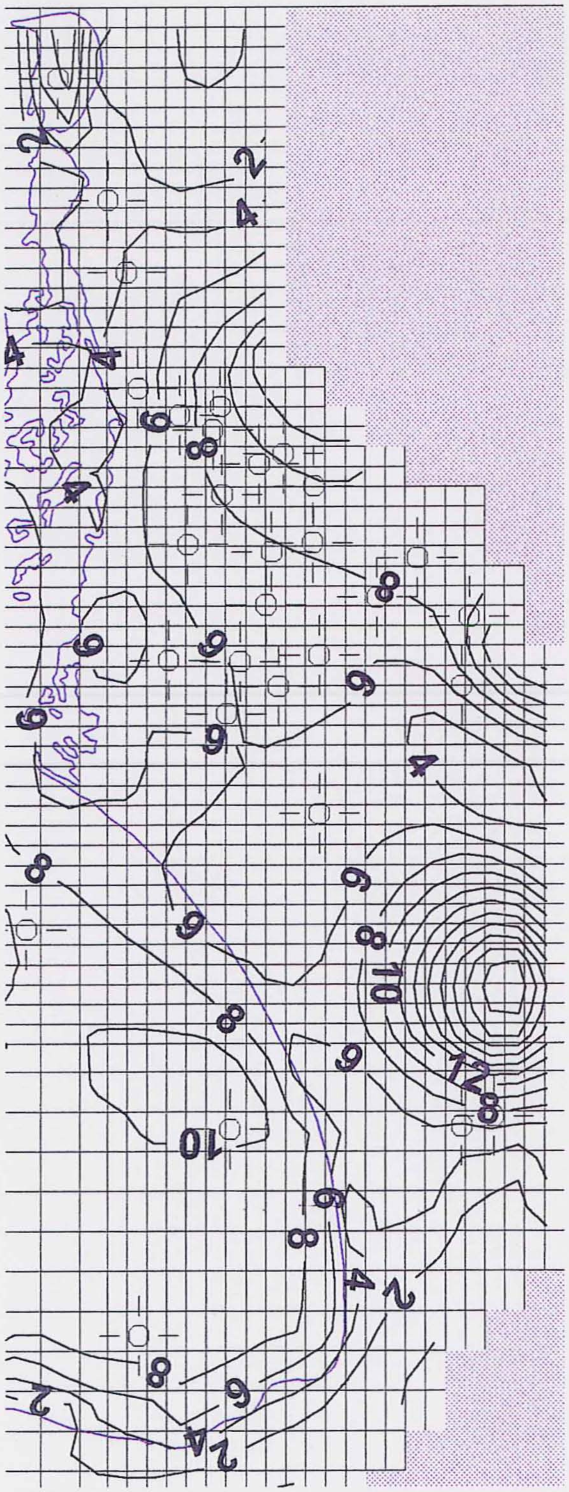
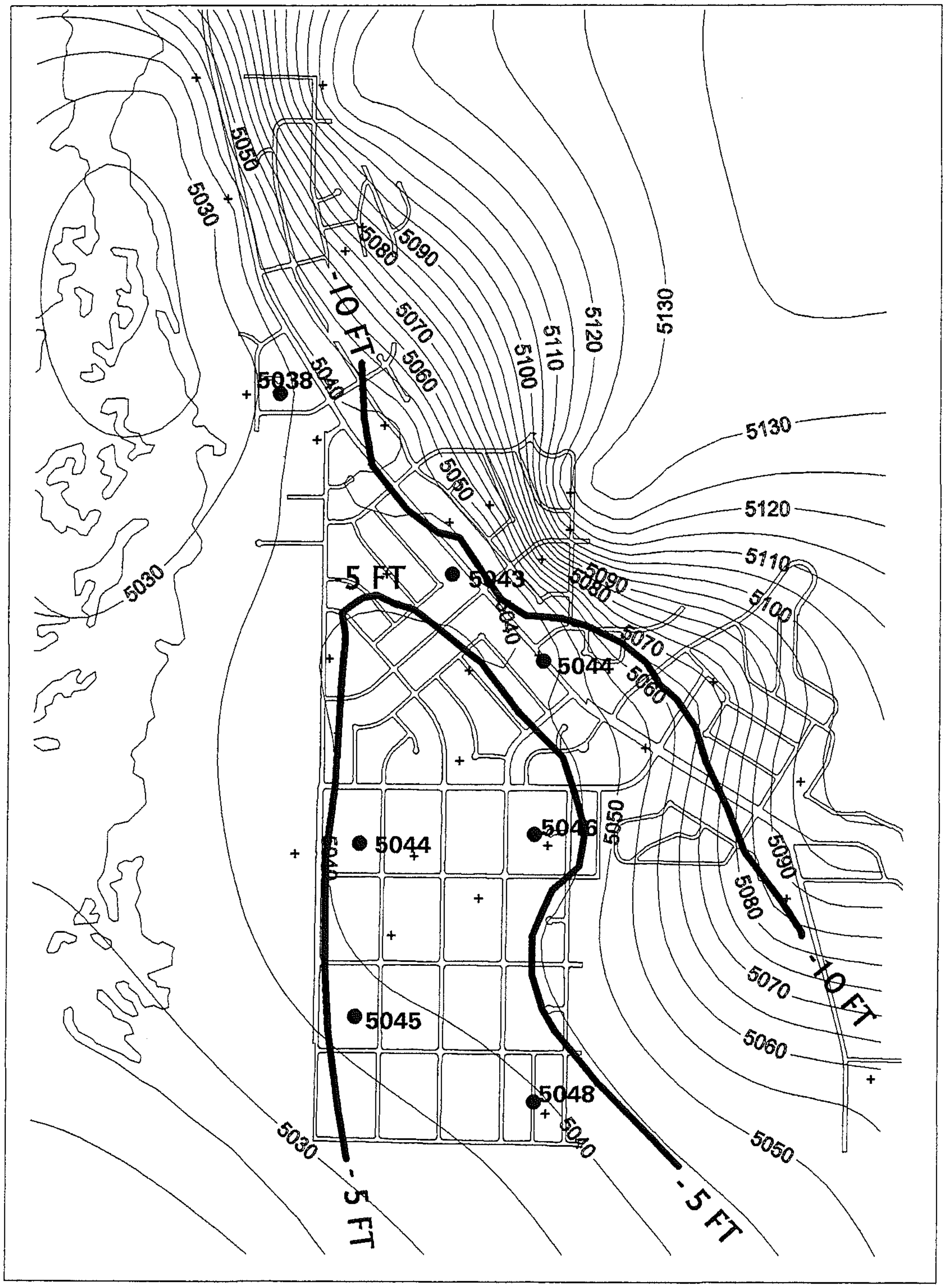


Figure 27. Head Difference Contours, 1994 - 1965



Note— Solid symbols with values are measured 1965 heads
Heavy contour lines represent average drawdown--see text

Figure 28. 1994 Static Water Level with Posted 1965 Measured Heads

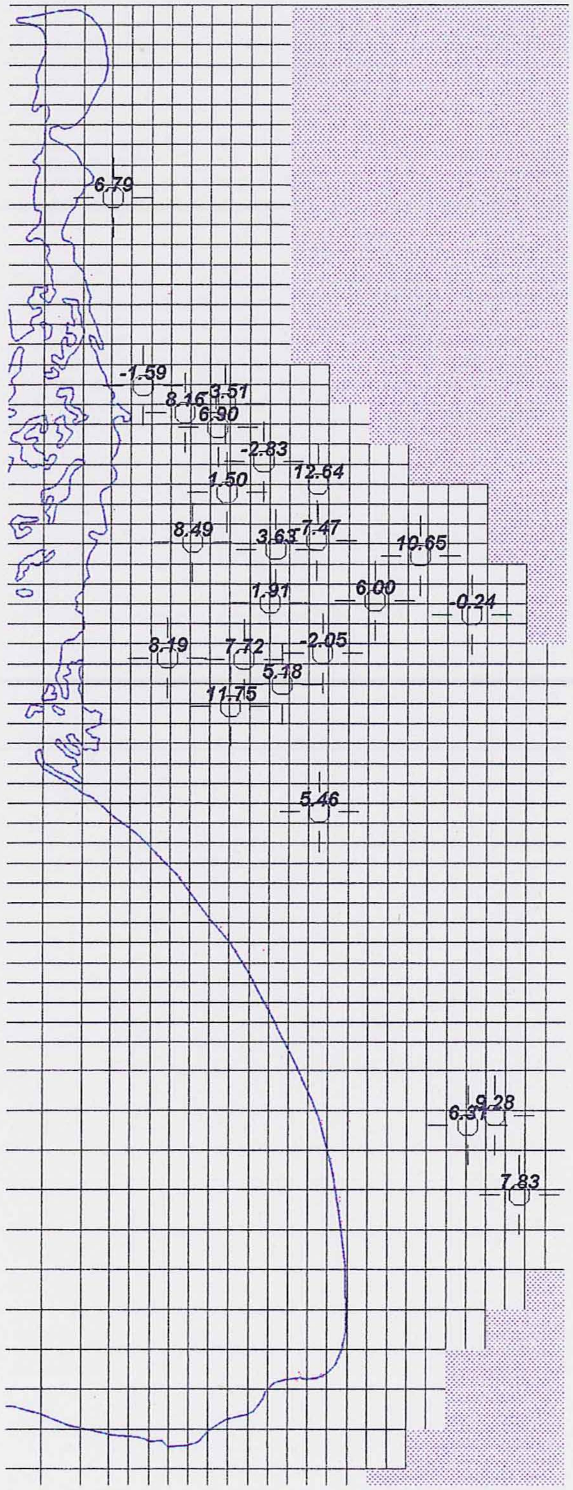


Figure 29. 1994-1997 Verification Residual Values

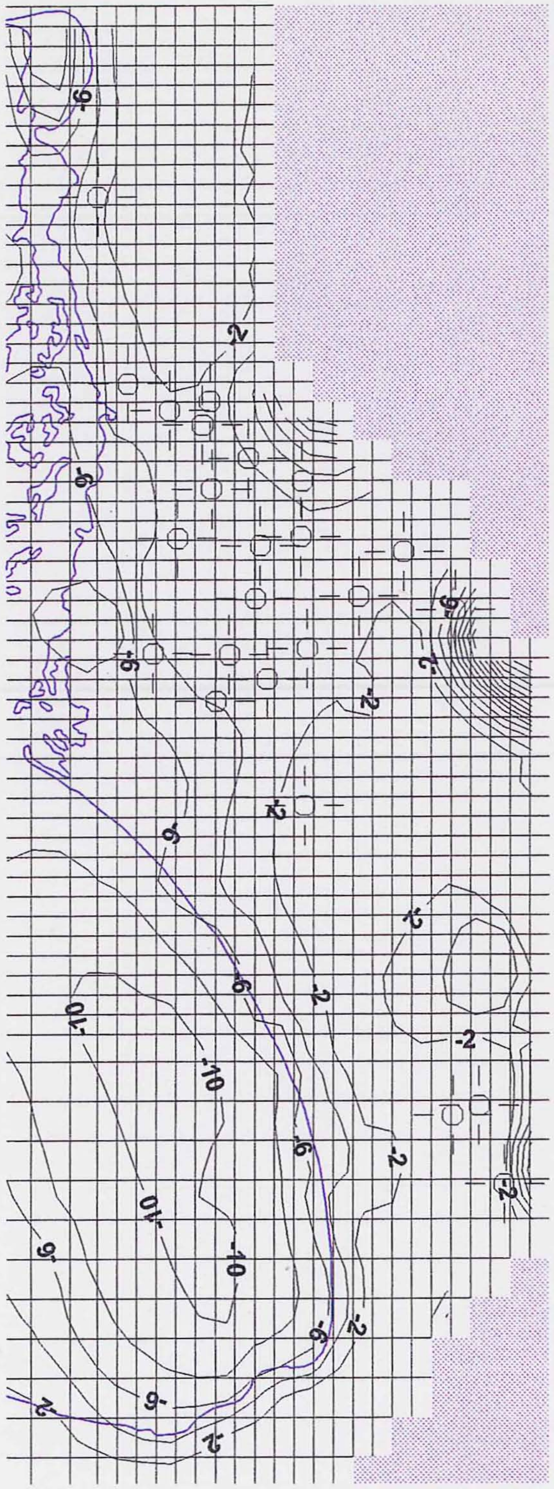


Figure 30. Head Difference Contours, 1994-1997

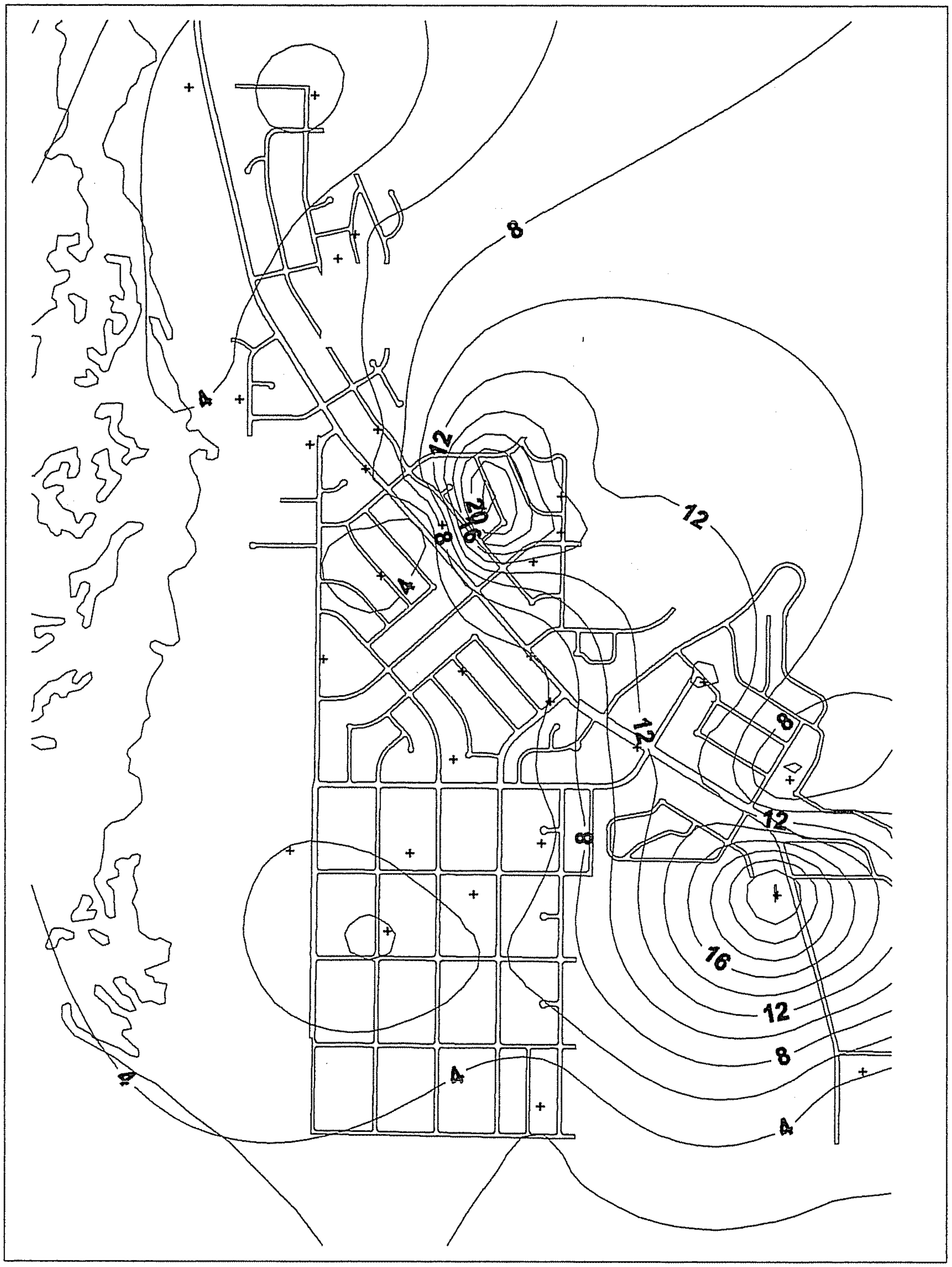


Figure 31. 1994-1997 Static Water Level Difference Map From Survey

that this well had an unusually high water table rise as compared with increases from other wells. The data is therefore suspect.

Predictive Modeling

The goal of predictive modeling is to simulate drought scenarios and increased consumption scenarios for a period of twenty years. Previous transient modeling in this study has shown moderate head change responses to recharge and development. Head changes against the range front can be severe, whereas the western portions of the study area experience milder temporal head variations. The aim of the predictive modeling is not to synthesize data nor attempt "real-time" predictions of the potentiometric surface elevation twenty years from now. Instead, worse and worst case drought scenarios were selected. Starting heads are from 1994. The starting conditions therefore already represent effects from seven years of drought. Recharge values used for the twenty-year simulation were based on actual estimates of runoff from the Truckee River basin for the period 1917 to 1936 (Hardman and Venstrom, 1941). The runoff percentages were estimated from reliable gage data. Surface runoff figures are probably better indicators of relative ground water recharge percentages than precipitation values alone because they reflect evaporative losses due to temperature and wind variations. Table 10 lists the year, corresponding model stress period, and percentage of average runoff.

Table 10
Key Data, Predictive Scenario Modeling

Year	Stress Per.	% Avg. Runoff	Year	Stress Per.	% Avg. Runoff
1917	1	56	1927	11	80
1918	2	85	1928	12	31
1919	3	38	1929	13	50
1920	4	93	1930	14	21
1921	5	107	1931	15	63
1922	6	84	1932	16	33
1923	7	37	1933	17	20
1924	8	62	1934	18	59
1925	9	45	1935	19	90
1926	10	110	1936	20	68

Both model scenarios begin with the entire lake bed as an ET surface, and continue with the ET surface throughout the simulation. Any applied stresses should not induce unrealistic flows from the lake area, as could happen with the GHB application. The first scenario, scenario 1, assumes no additional development or increased non-domestic/agricultural pumping. The full drought conditions, specified in Table 10, are in force. Recharge from the volcanic basement, layer 2, varies according to the same percentages as the range front recharge. This is an assumption and simplification. There simply is no data to indicate how the basement flow (underflow) varies temporally. The second scenario, scenario 2, takes the prediction to a worst case level. Additional development is assumed and increased agricultural pumping takes place.

Results of the scenario 1 modeling are presented as a head drawdown map in Figure 32. Decline in the water table follows the same pattern as previously observed, with greater declines against the range front. In the flat, west and west-central portions of NWC, head drops vary from 4 to 12 feet and average approximately 8 feet.

Scenario 2 models the same drought conditions, but also accommodates an additional 20% development in the existing portion of NWC, based on maximum lot buildout. Furthermore, a new development is placed at the southeast end of NWC in section 5, T20N, R16E. The development assumes a municipal well water supply with individual septic systems. This scenario is plausible because such a proposal has been previously presented to Washoe County planners. The actual development proposed construction of 206 homes and this was simulated in the model. Each home is estimated to use about .75 acre-feet of water per year (Widmer, 1997), or 153 acre feet, total. In this scenario, a pumping well was located at the east end of the development. The developers have placed a test well in this area, but reliable pumping tests are unavailable. It is likely that actual water supply will come from conversion of agricultural rights from existing wells in the southeast part of the study area. This scenario assumed one new dedicated well, as described above, pumping 9130 ft^3/day, and the remaining equal amount of water piped from the existing agricultural wells. Because the new community would be on septic systems, some water would infiltrate back into the aquifer. Secondary recharge of .28 acre-feet/year, per home, was applied, based on estimates from Spanish Springs Valley (Berger et. al., 1997).

Scenario 2 has one further source of water consumption. A moderately high yielding well is located at the extreme west side of NWC on the Scripps Wildlife Management Area, just west of the termination of Esmeralda Drive. The Wildlife Management Area is administered and managed by the State of Nevada Division of Wildlife. Currently, the state owns 1800 acre feet of water rights. During normal years, water is leased for irrigation purposes of pasture land, and about 175 acre-feet per year is pumped. In 1994 the State pumped its full allotment, which then was

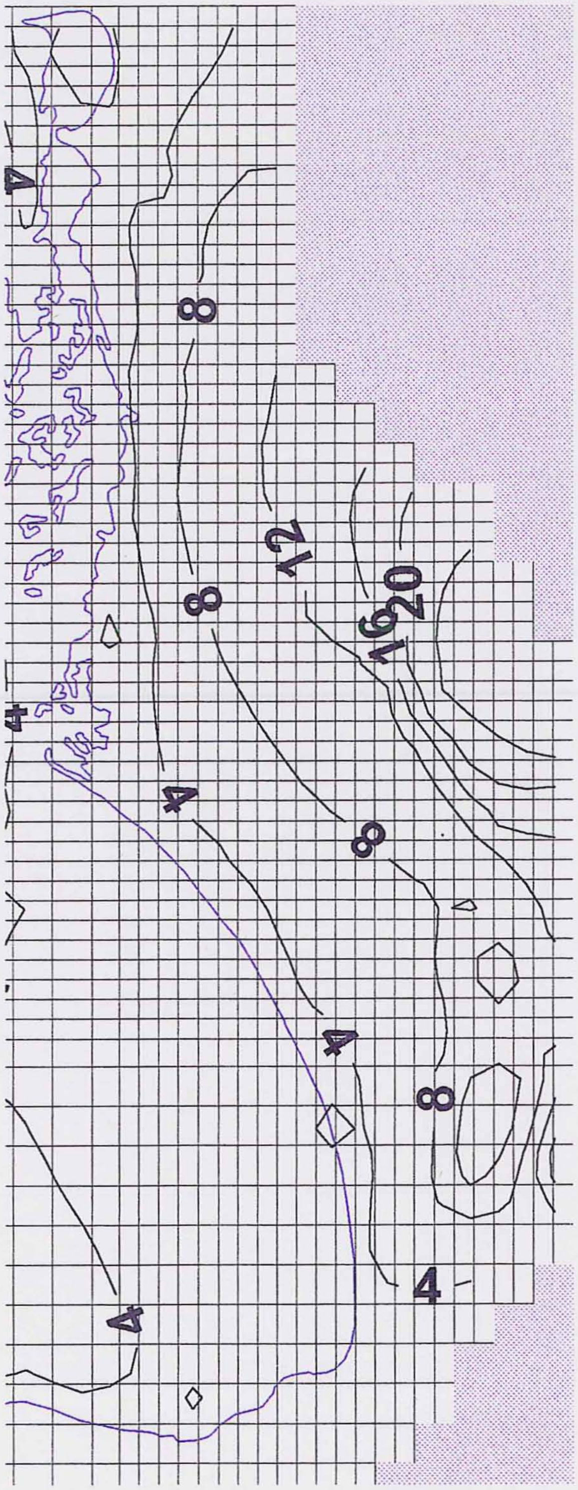


Figure 32. Head Drawdown Map, Predictive Scenario 1

2500 acre feet (700 acre-feet were recently sold). Pumping was solely for wetland and wildlife habitat preservation. According to Nevada Division of Wildlife (Huffy, 1997) continued pumping is an extreme measure in response to serious drought conditions only. Modeling scenario 2 incorporated pumping of this well at the full 1800 acres per year during extreme low water years. Stress periods 3, 7, 13, 16, and 17 were selected for pumping years. No allowance for infiltration was provided, instead the whole amount was assumed to be evaporated or transpired.
Figure 33 shows the resulting drawdown for scenario 2. Locations of the two pumping wells (Scripps and Section 6 development) are shown. Average water table decline in central NWC has increased from about 8 feet to 12 feet. Drawdown due to the new municipal well is evident, with up to 30 feet of decline, as a distinctive cone of depression. The pumping from the Scripps Well does not show an obvious cone of depression at the end of the twenty-year simulation, probably due to higher transmissivities at this location. The last active wetland irrigation occurred during stress period 17 (three years of recovery). Nevertheless, cumulative drawdown in the western part of NWC is probably largely attributable to periodic pumping from this well.

Analysis of Flow Patterns and Flux

This section presents information on flow directions and flux variations. First, the specific discharge vectors are shown for the steady state model. This is followed by discussion and examples from transient and predictive transient simulations.

Flow Patterns, 1965 Steady State Conditions

Figure 34 displays the specific discharge vectors for the steady state model, valley-wide, for layer 1. The vector pattern is nearly identical for layer 2. Usually, the flow direction is toward the lake, which is the ultimate discharge area. As Table 5 shows, more than half the ground water is discharged as evapotranspiration, with the remainder discharged to the lake system via the GHB simulation. Valley-wide, the most striking feature of note is the west to east flow direction, which extends across most of Washoe Lake. Figure 35 is an east-west cross section along row 45. This section displays a strong vertical component to ground water flow. The vectors do not represent flow volume, rather, they represent specific discharge magnitude. As such, this section illustrates that portions of the study area, in contrast to the west side, have a strong vertical flow component. Placement of recharge wells in layer 2 (Figure 35) is compatible with the conceptual model and further facilitates upwelling conditions.

In the southeast portion of the study area a ground water divide is noted. Calibration techniques failed to force water to flow uniformly westward. Physically this area is low lying, with several ponds. It is unclear whether the model realistically portrays the physical conditions or whether this feature is related to the GHB lake stage constraints.

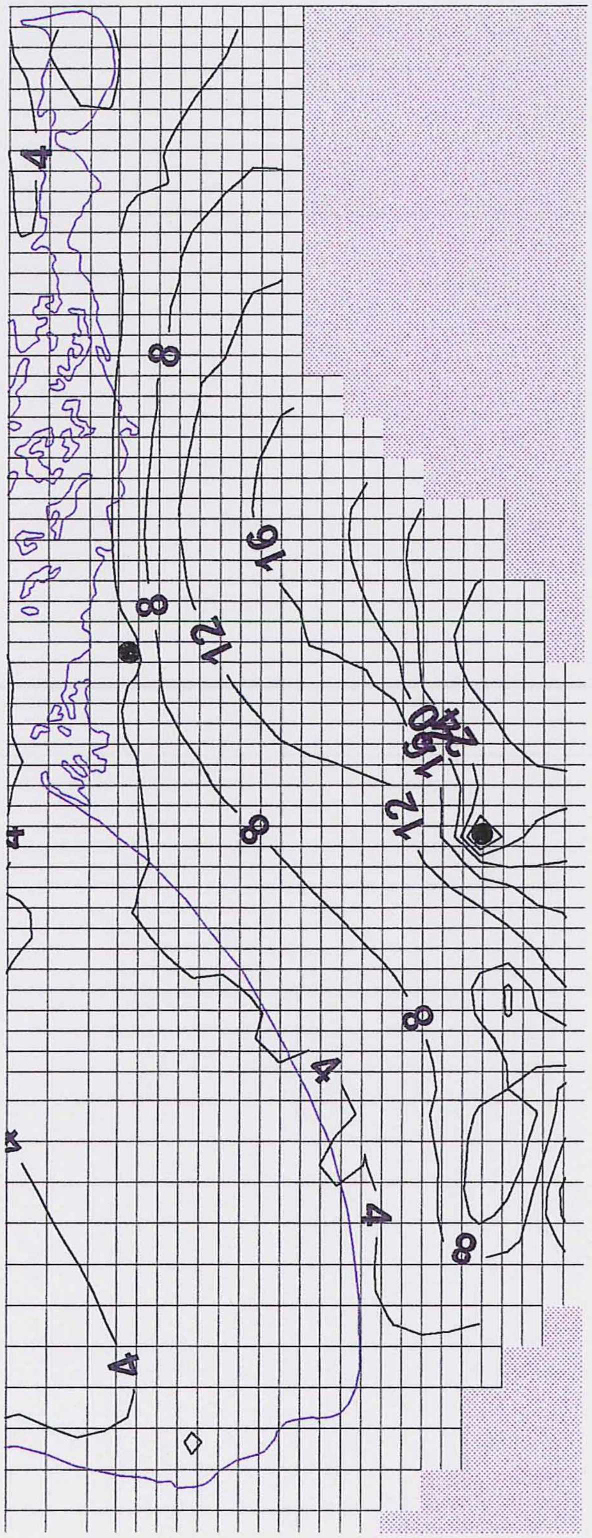


Figure 33. Head Drawdown Map, Predictive Scenario 2

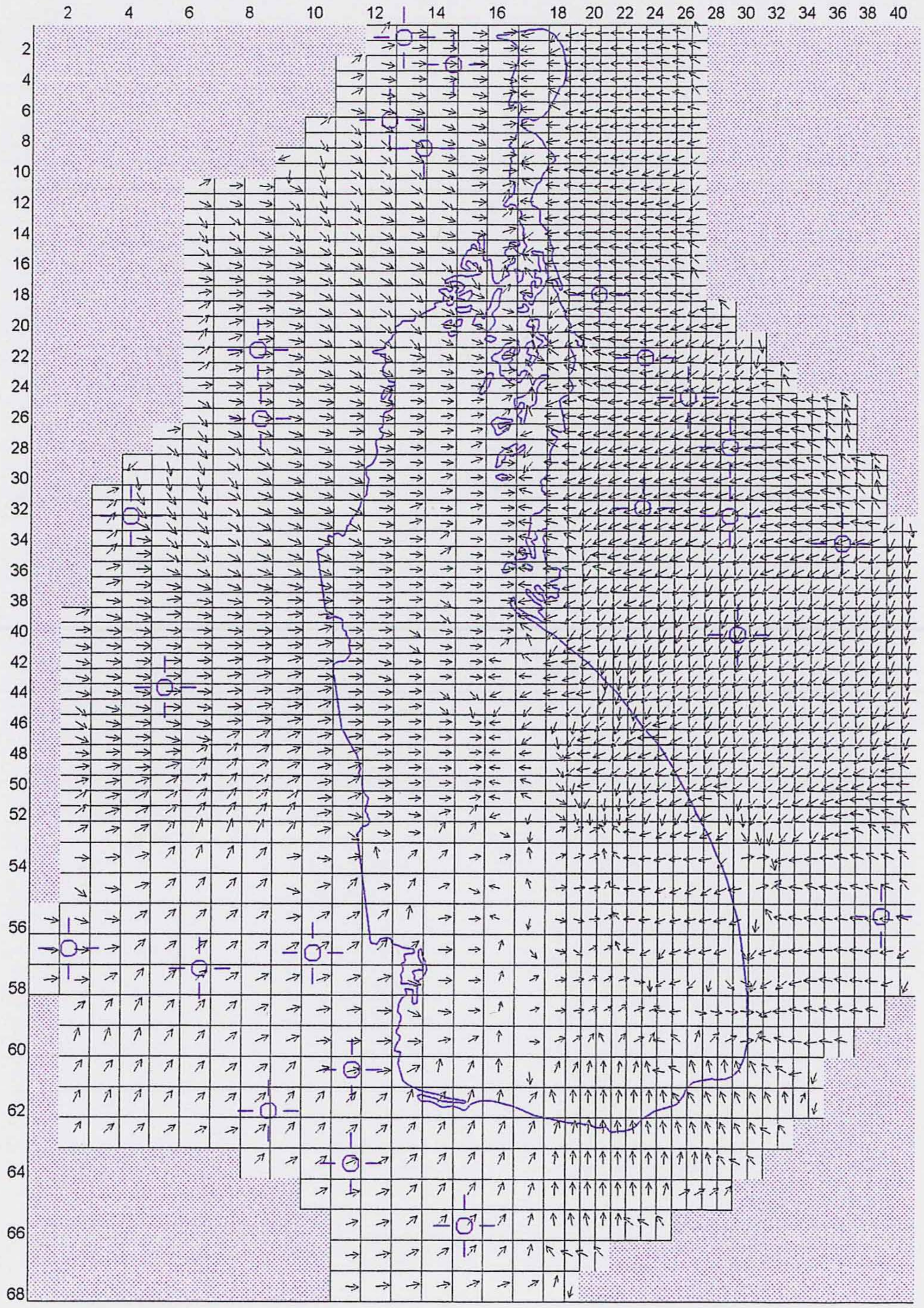


Figure 34. Specific Discharge Vectors
Steady State Model

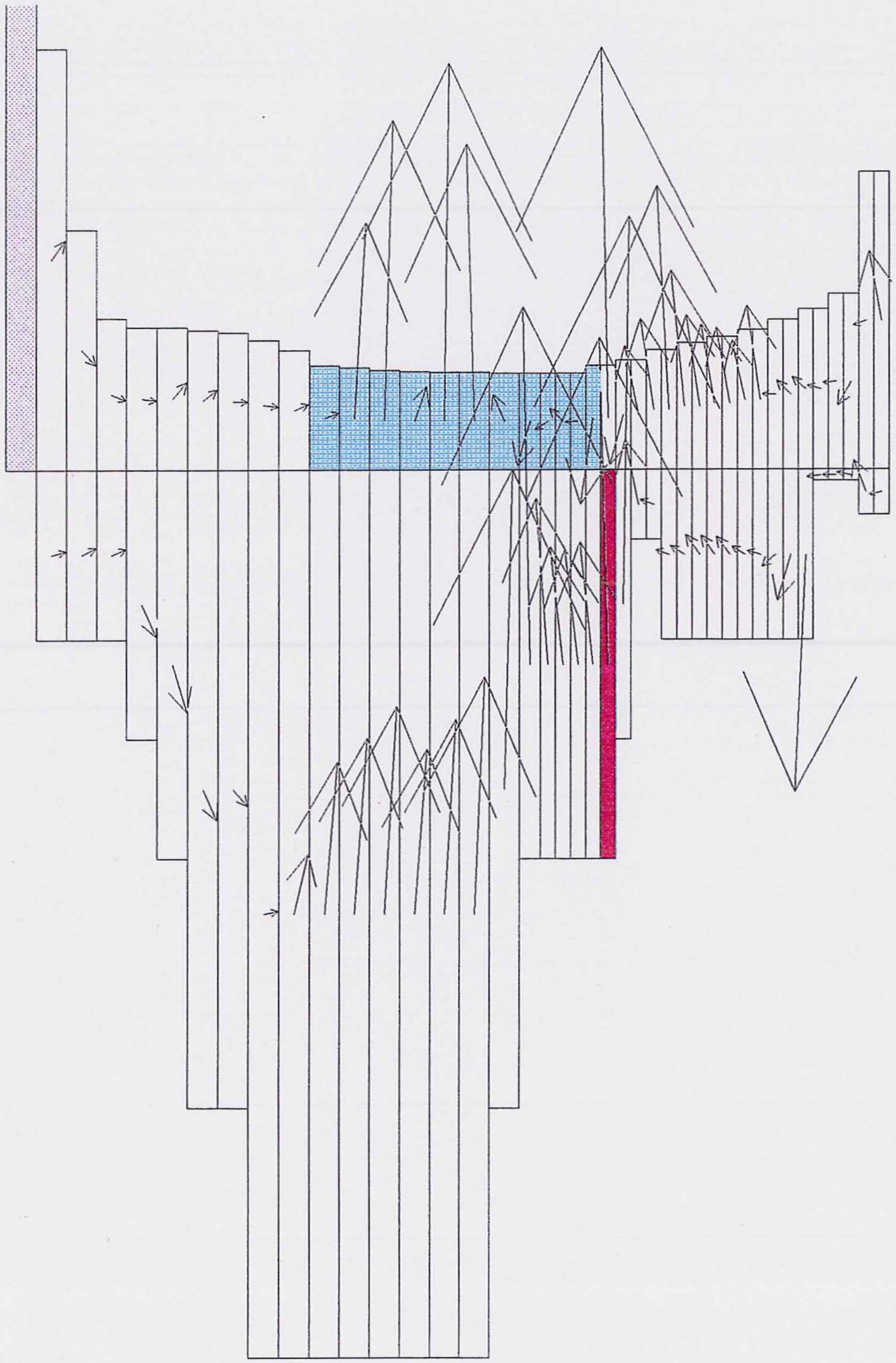


Figure 35. Steady State Model, Row 45, Showing Specific Discharge Vectors

Flow Patterns, 1994 Transient Simulation

A plan map was plotted showing the specific discharge vectors for layer 1 at the end of stress period 29. The entire lake area has been reduced to a dry lake bed modeled by an ET surface. As can be seen in the plot (Figure 36) the flow pattern is not significantly different from the steady state simulation. However, in layer 1, westwardly directed flow extends slightly further west than in 1965. This change is probably caused by a slightly steeper head gradient under drought conditions, as heads are lowered in the lake area. An accompanying cross section of row 45, Figure 37, indicates that flow patterns and specific discharge magnitudes are generally similar between 1994 conditions and 1965 conditions. Both cross sections (Figures 35 and 37) suggest that in layer 2, flow extends from west to east underneath most of the lake area. It then discharges into layer 1 just west of NWC.

Flow Patterns and Fluxes, Predictive Scenarios

Flow patterns and ground water fluxes were investigated for scenario 2. The areal flow distribution is nearly identical to that of the 1994 starting conditions. The "divide" between flow from the west and east has not changed significantly, as can be seen in Figure 38.

A method was devised to investigate fluxes affecting NWC. Because the lake area appears to effect the NWC groundwater system and is a unique, trackable, physical feature, a study was completed to look at flows entering and leaving the dry Washoe Lake bed, by stress period. The post-processor package allows mass balance calculations for any polygonal area within layer 1 or 2. Flux into or out of the lake area, on the east side, was tabulated both for layer 1 and 2. Flux from layer 2 to layer 1 was also recorded, as was the total amount of evapotranspiration during each stress period. Additionally, total pumping from discharge wells located within the project area was determined, and compared against the other measured parameters.

Figure 39 shows the four measured components of flux, in acre-feet/year, plotted against stress period. Times normal recharge is plotted on the second Y axis. Flux from the east side represents added layer 1 and 2 values. A positive number means ground water flow from the east toward the west, whereas a negative number represents reversal of flow direction, and therefore flow from the lake area to the east. Reversals only occur during accelerated rates of pumping. The observed spikes on Figure 39 are produced by high volume pumping from the Scripps well during certain years. Scripps well pumping does not produce significant drawdowns. This is probably a function of the moderately high hydraulic conductivities and available water in storage within the aquifer underlying the lake area. As an experiment, pumping was increased by 50% for this well for the full 20 year period. Drawdown increased by less than two feet over the that period, as compared against the previous simulation.

Groundwater pumping clearly influences groundwater flow patterns by temporarily reversing flow directions near the lake, and creating drawdowns

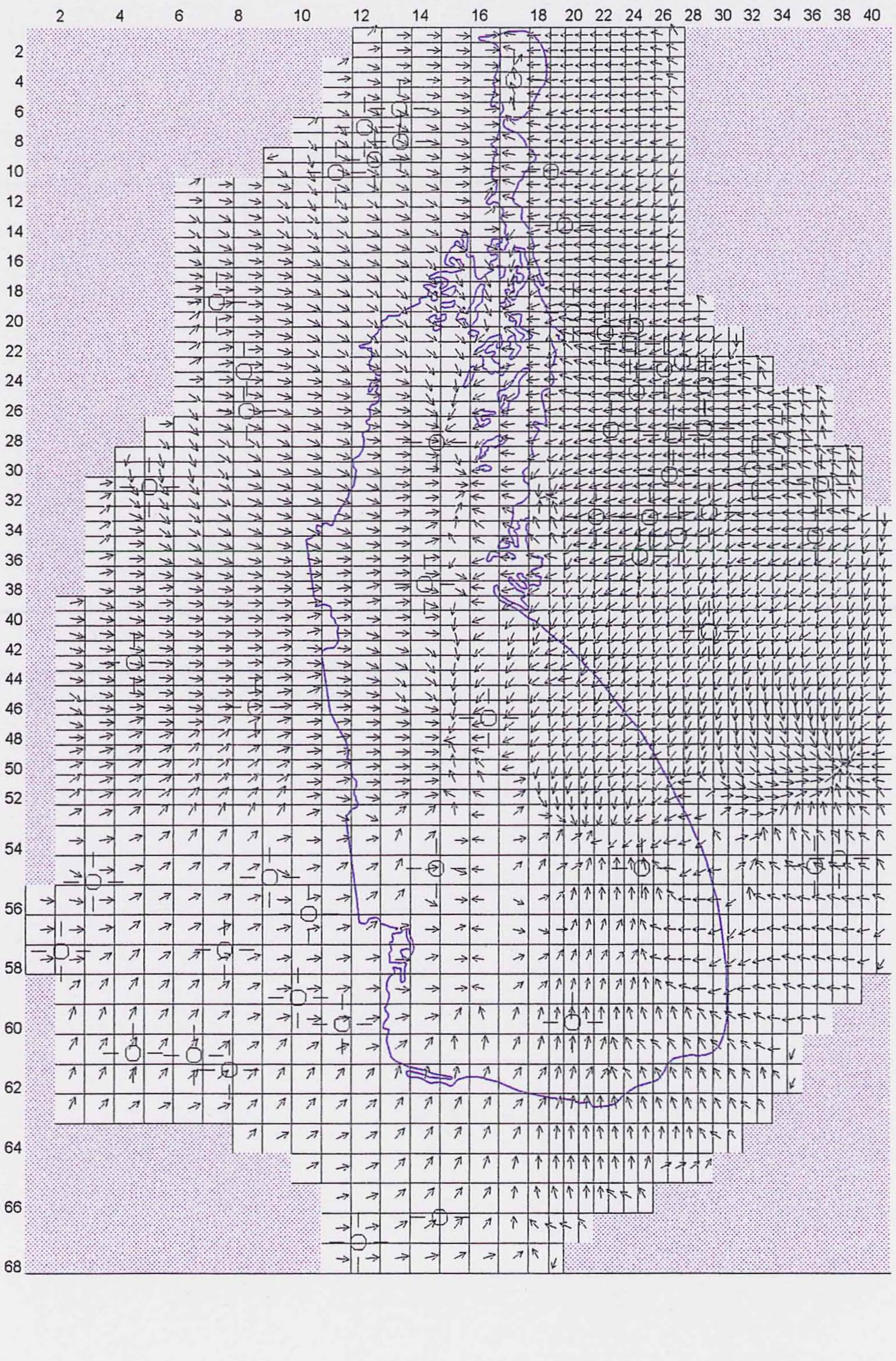


Figure 36. Specific Discharge Vectors, 1994 Transient Simulation

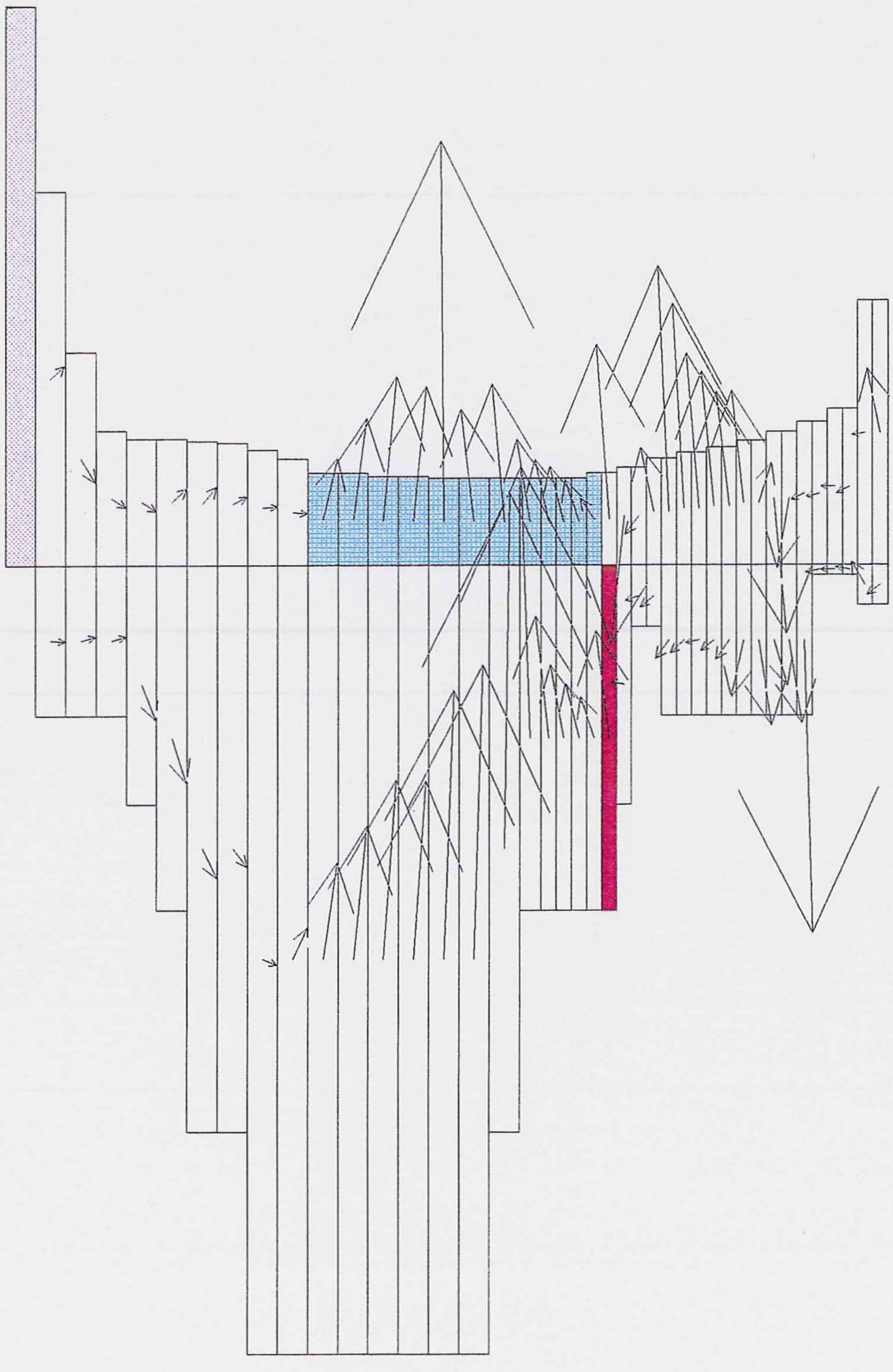


Figure 37. 1994 Transient Simulation, Row 45, Showing Specific Discharge Vectors

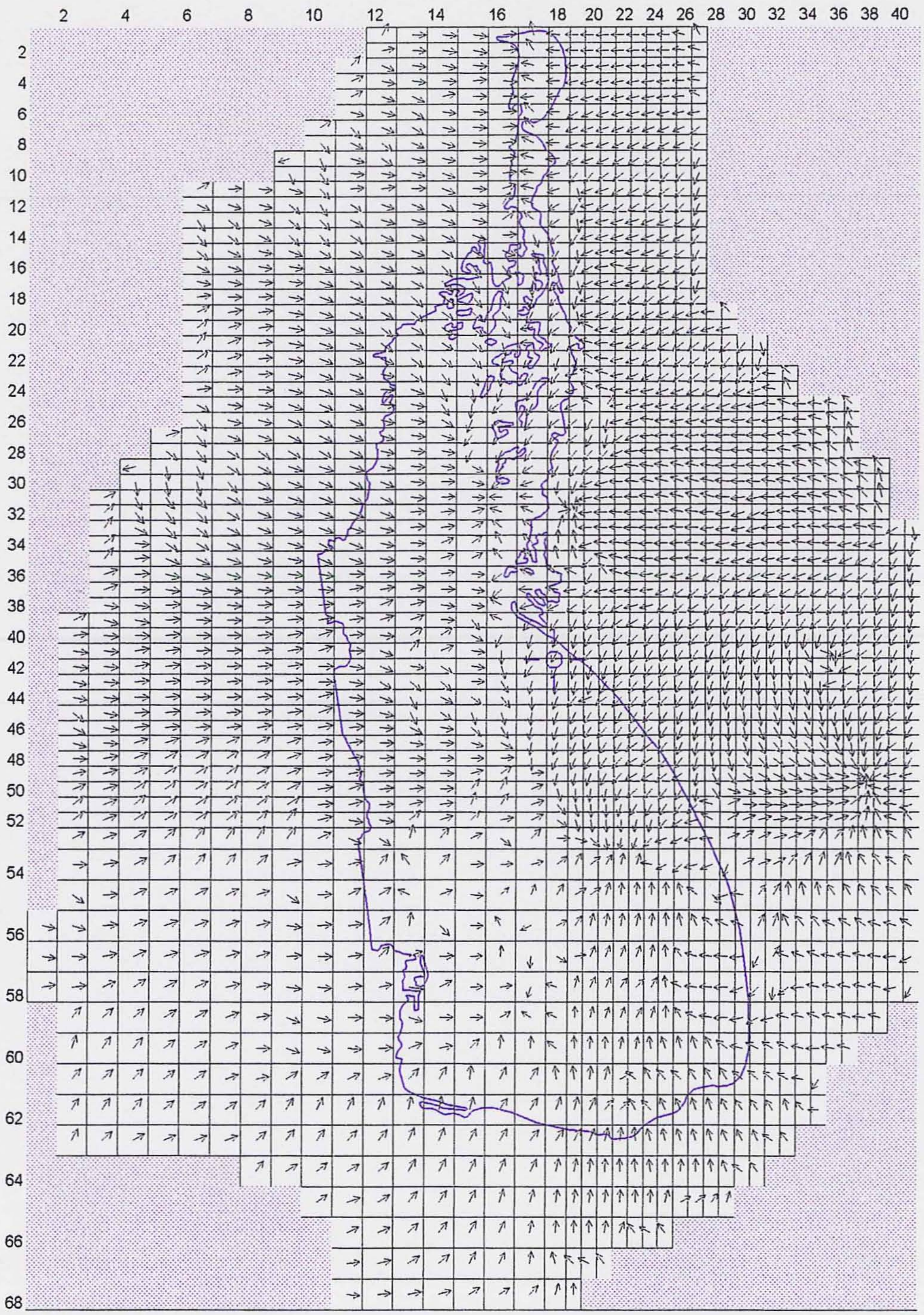


Figure 38. Specific Discharge Vectors, Predictive Scenario 2

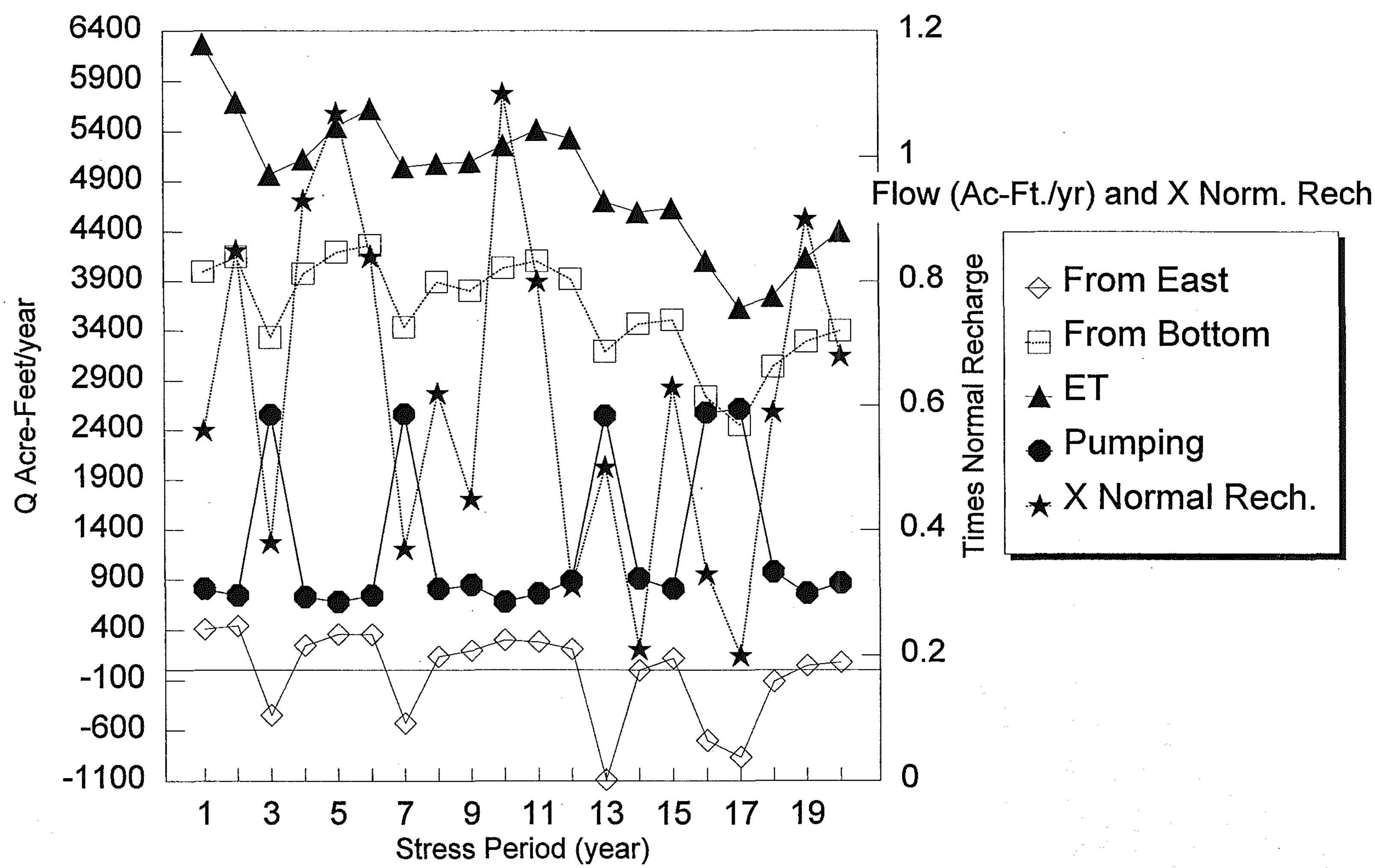


Figure 39. Temporal Flux Variations and Recharge Variations, Predictive Scenario 2

whose magnitude is influenced by hydraulic parameters and proximity to the lake area. However, pumping constitutes only a moderate percentage of total flux, which is dominated by ET discharge, and flows from layer 2 to layer 1 and through layer 1 from the west (not shown). As can be seen from Figure 39, trends in flux volume over the twenty year period are definitely more sensitive to the recharge factor than to pumping. A similar conclusion was reached from groundwater level studies on the Mt. Rose and Galena Fans, southwest of Reno (Kanbergs, 1996).

The aquifer underlying the lake region exerts a strong influence over the hydrogeologic system by establishing a base-level head and therefore controlling the overall system's horizontal hydraulic head gradient. Generally, flux rates are reduced near the lake boundary due to gentle horizontal gradients. Furthermore, the lake region represents most of the storage capacity of the valley-fill reservoir, and even during drought is nearly saturated to the surface. Therefore, the lake area essentially buffers flows from the east, and to a lesser extent from the west, and represents a large groundwater reservoir.

Geothermal Characterization

Three main sections are included in this chapter. These are: 1) presentation of the thermal data and introduction to geothermal concepts; 2) presentation and discussion of ground water geochemistry and its relationship to the thermal anomaly; and 3) a discussion of the anomaly in the context of groundwater flow and interaction with the shallow aquifer system. Appendix B documents the 1997 geochemical and thermal surveys.

The terms thermal and geothermal are used interchangeably. The definition of geothermal has often been used in an economic sense, to determine if a system has potential for commercial production. Here, geothermal and thermal simply refer to waters that are above normal in their heat content and consequently represent areas of anomalous heat flow.

Thermal Data

Background

McKay (1991) reported an elevated domestic well temperature, located in the extreme southwest part of NWC. The temperature was in excess of 50^{0}C (1991?). This particular well has a total depth of 130 feet, and penetrates the upper part of the confined aquifer. Seasonally, the well is artesian, but no natural warm springs are noted.

The nearest documented thermal anomaly is located at Bowers Mansion on the west side of the valley, where several warm water springs and wells occur. Garside and Schilling (1979) have compiled geochemical and thermal data in this area. The highest measured temperature is 128^{0}F (53.3^{0}C) from a spring discharging at 76 gpm. The same authors document warm water wells and workings in the Comstock Lode, Virginia range.

Temperature Measurements at NWC

The temperature data were collected from selected domestic wells using a thermistor probe, as described in the section on methods. Depth verses temperature profiles are included as

Appendix B. Figure 40 is a groundwater temperature iso-contour map at a depth of 30.5 meters (100 feet). For some of the shallower wells, a linear extrapolation was made to obtain an estimated temperature at 100 feet. Figure 40 defines a coherent thermal anomaly with sample point 5 as the high value at 51.4 ^{0}C.

Limitations exist for the type of data collected from these shallow domestic wells. Temperature measurement taken among wells will be influenced by well design, screening interval and depth. Many measurements were done at depths less than 100 feet, with the deepest data point being 180 feet. Lovering and Morris (1964), in their study of thermal characteristics in the East Tintic District, Utah, completed temperature probes of numerous wells. They state that direct well measurements at depth less than 100 feet are unreliable unless seasonal ground temperature variation corrections are added. The wells probed in the current study were all measured during the winter quarter, under similar temperature conditions. The relative temperature and geothermal gradient relationships among wells is assumed to be valid. However, care should be taken when comparing this data against future data sets.

Spatial Characteristics

The data clearly indicate a hot spot or plume anomaly. The anomaly is open to the southwest and its character in that direction is unknown due to lack of data. Conductors from the airborne geophysical data, south of NWC, are noted (Widmer, 1997). The relationship between these conductors and any extensions of the identified thermal anomaly remains speculative.

The thermal anomaly forms a local north-northeast trend, across the southern part of NWC, but the overall trend is north-northwest, as illustrated in Figure 40. The pattern and spatial location of the thermal anomaly may be compared against the resistivity data shown on Figure 7. A very good spatial correlation exists between the conductor anomaly and the thermal anomaly. The physical causes for the conductor are speculative.

The laboratory analyses indicate no unusually high TDS or conductance values from water samples within this area. The conductor is therefore most likely caused by aquifer clay content, despite areas with coarse gravels and some clean sands. Other factors that may enhance the anomaly would be the elevated water temperature, possible low temperature alteration of aquifer material to clay, or even presence of H_2S as noted at most warm well locations.

Thermal Gradients

The temperature of the earth increases with depth at an average rate of 2.5°C per 100 m of depth (Fetter, 1994). White (1968) suggests a background geothermal gradient of about 3.3^{0}C per 100 meters as typical for western Nevada. Individual depth verses temperature profiles (Appendix B) show most wells to have a near linear increase of temperature with depth. Others, such as sample point 5, show a convex upward profile. According to Jacobson and Johnston (1991) convex upward profiles with elevated temperatures represent discharging parts of hydrothermal systems, whereas the linear

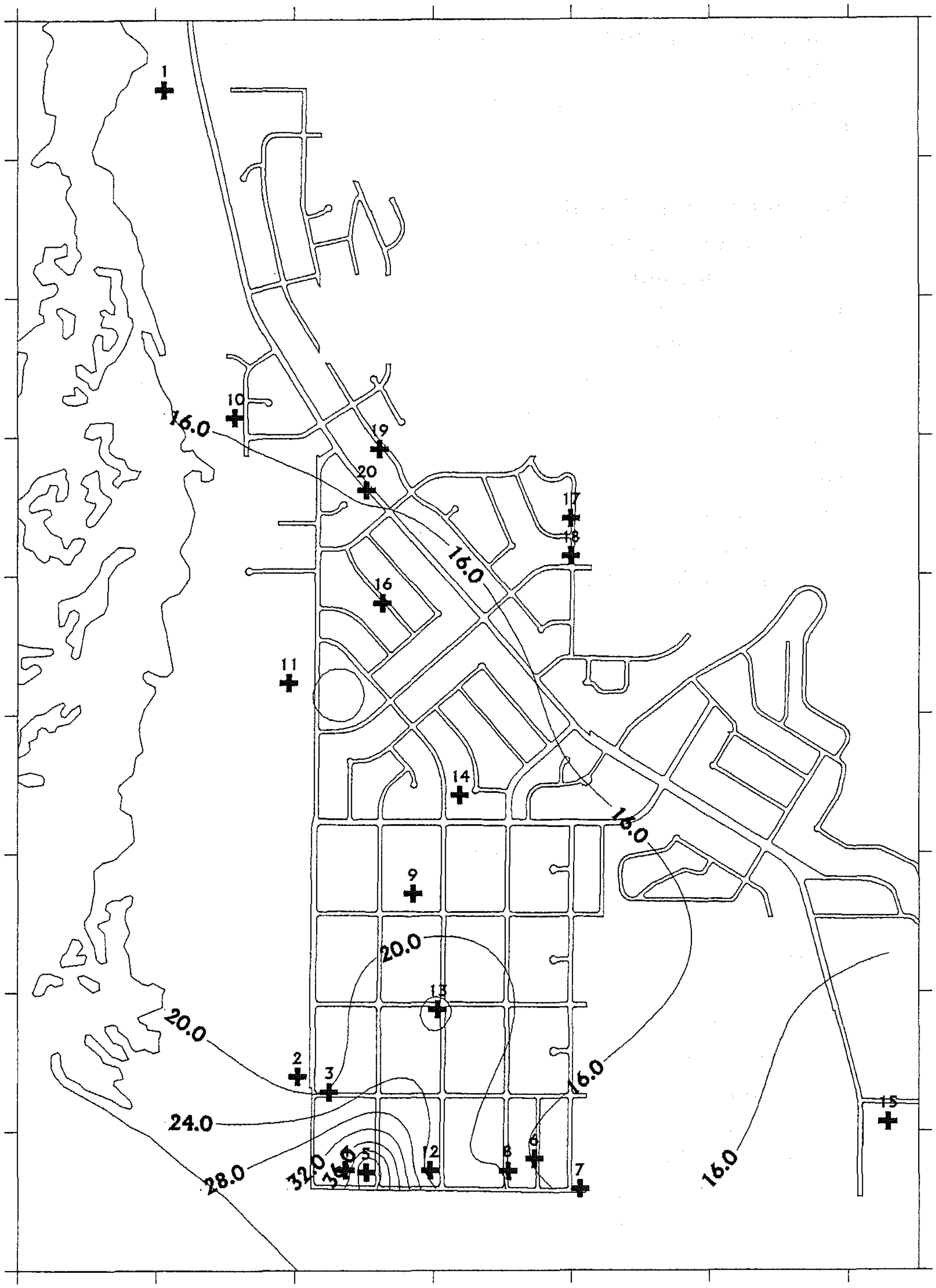


Figure 40. Groundwater Temperature Iso-Contour Map, ^{0}C At 100 Foot Depth (30.5 m), NWC

profiles represent "quasi-conductive" situations.

A thermal gradient was estimated for each sample location, by taking the difference between the top and bottom temperature value divided by depth interval. Values were converted to degrees Centigrade per meter, and a shallow thermal gradient map was created (Figure 41). The shallow nature of the data cautions against extrapolation of the measured gradient deeper than maximum sample depths. Figure 41 shows a pattern similar to Figure 40 and is believed to be representative of shallow conditions. Gradients in the study area are well above normal. In terms of degrees Centigrade per 100 meters, gradients range between no detectable change over 100 meters to 78^0C per 100 meters at sample station 5. The sample mean is 14^0C per 100 meters, however; this high value is skewed by the thermal plume area and is not statistically representative of the gradient in NWC. Values at several locations near the range front are at or below normal (sample points 13 and 17). The thermal plume is further defined by a low temperature gradient in the southwestern most sample station (sample point 2). The character of the thermal anomaly and temperature gradients are less clear to the northwest, due to lack of sufficient data.

Geochemistry

Introduction

The degree of mineralization in groundwater is a function of both initial chemistry, character and solubility of the aquifer material, and length of exposure time to the aquifer (Back and Hanshw, 1970 in Fetter, 1994). An increase in water temperature usually increases the solubility of most minerals, with notable exceptions, e.g. $CaCO_3$ (Driscoll, 1986). Documented geothermal systems may have very high mineral contents, measured as total dissolved solids (TDS), and concentrations of certain constituents that are unique to elevated temperature conditions.

Geochemical Classification of Thermal and Non-thermal Waters

Ellis and Mahon (1977) and Nicholson (1993) provide an overview of the geochemistry of geothermal, systems. These systems may be classified according to temperature and/or chemistry. Most geochemical classifications of thermal waters describe high temperature systems. Low temperature systems are more difficult to classify. They have a varied origin (Nicholson, 1993) and their composition will depend on relative contributions of formation waters and meteoric waters to the discharge features. Low temperature systems often do not have a characteristic geochemistry. Nicholson (1993) summarizes a general opinion held by most workers that thermal waters, usually regardless of temperature, are predominantly heated meteoric waters. Isotope data allow perhaps 5 to 10 percent of the fluids to be of possible magmatic origin. These magmatic brines may significantly influence the fluid geochemistry and account for elevated constituent concentrations, such as chloride or CO_2.

Ellis and Mahon's (1977) classification of high temperature systems may aid the study of more dilute or lower

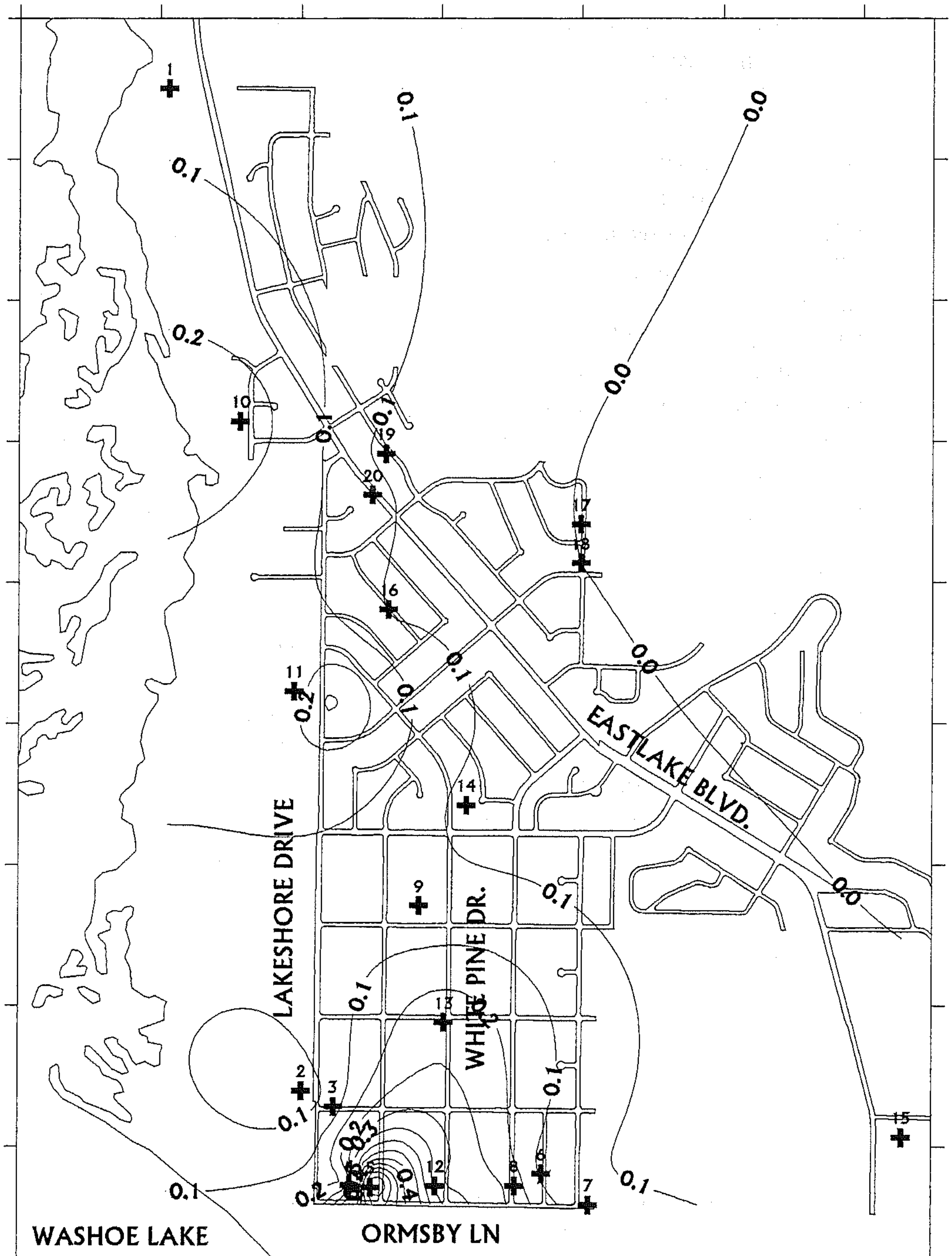


Figure 41. Shallow Vertical Temperature Gradient Map, °C/Meter, NWC

temperature waters. Their four end-member classification consists of Alkali Chloride Waters (type A), Acid Sulfate Waters (type B), Acid Sulfate-Chloride Waters (type C), and Bicarbonate Waters (type D). Type A waters represent common geochemistry seen in many systems in the western United States. These are characterized by high chloride contents, often high dissolved silica values, high TDS, and classic trace minerals such as arsenic, boron, and lithium.

In their study of the moderate temperature Moana geothermal area, located in west Reno, Flynn and Ghusn (1983) describe the geochemistry as marked by high sulfate levels, with sodium as the dominant cation. Chloride is present but below levels of the sulfate. Total dissolved solids (TDS) are in the 500 to 1200 ppm range. The geochemistry resembles most closely type C waters, described previously. In contrast, the Steamboat Springs geothermal system, located about 5 miles north of the project area, exhibits TDS in the 2000+ ppm range and very high chloride concentrations and other constituents, which would group it with Ellis and Mahon's type A fluids. Flynn and Ghusn (1983) identify nearby non-thermal waters as calcium bicarbonate type, typically dilute and of near neutral pH. The above authors and Jacobson and Johnston (1991) present evidence that indicates mixing of nonthermal and geothermal fluids in and around the Moana area. The result of mixing can create fluids with intermediate compositions. Most identified geothermal occurrences in Nevada are low temperature (Garside and Schilling, 1979).

The thermal anomalies in Washoe Valley are low temperature and are almost certainly dominated by meteoric water. The study area offers an opportunity to study characteristics of a low temperature anomaly. Nicholson (1993) suggests a classification of geothermal waters according to a Ternary plot with end member compositions dominated by a Chloride Type, Sulphate Type, and a dilute Chloride (Bicarbonate) type. The Ternary plot classification for geothermal systems is similar to the use of Piper diagrams, a well known method for characterizing all ground waters (Drever, 1997). The relationship between the site thermal characteristics and ground water geochemistry is further explored and developed below with the aid of Piper diagrams and various plots of individual constituents.

<u>Washoe Valley and Study Area Groundwater Geochemical Characterization</u>

Piper diagrams plot proportions (in milli-equivalents) of three major cations (Ca, Mg, Na+K), and three major anions (alkalinity, chloride, sulfate) on two separate triangular plots. The plot vertices represent pure end-member compositions of the respective triad of cations or anions. A third diamond-shaped figure combines information from the triangular plots and displays composition with respect to end members of, Na+K, Ca+Mg, $Cl+SO_4$, and alkalinity. Together, the information can by used to characterize the water, in effect determine a "geochemical facies". It can also be used to determine possible mixing and geochemical evolution along flowpaths.

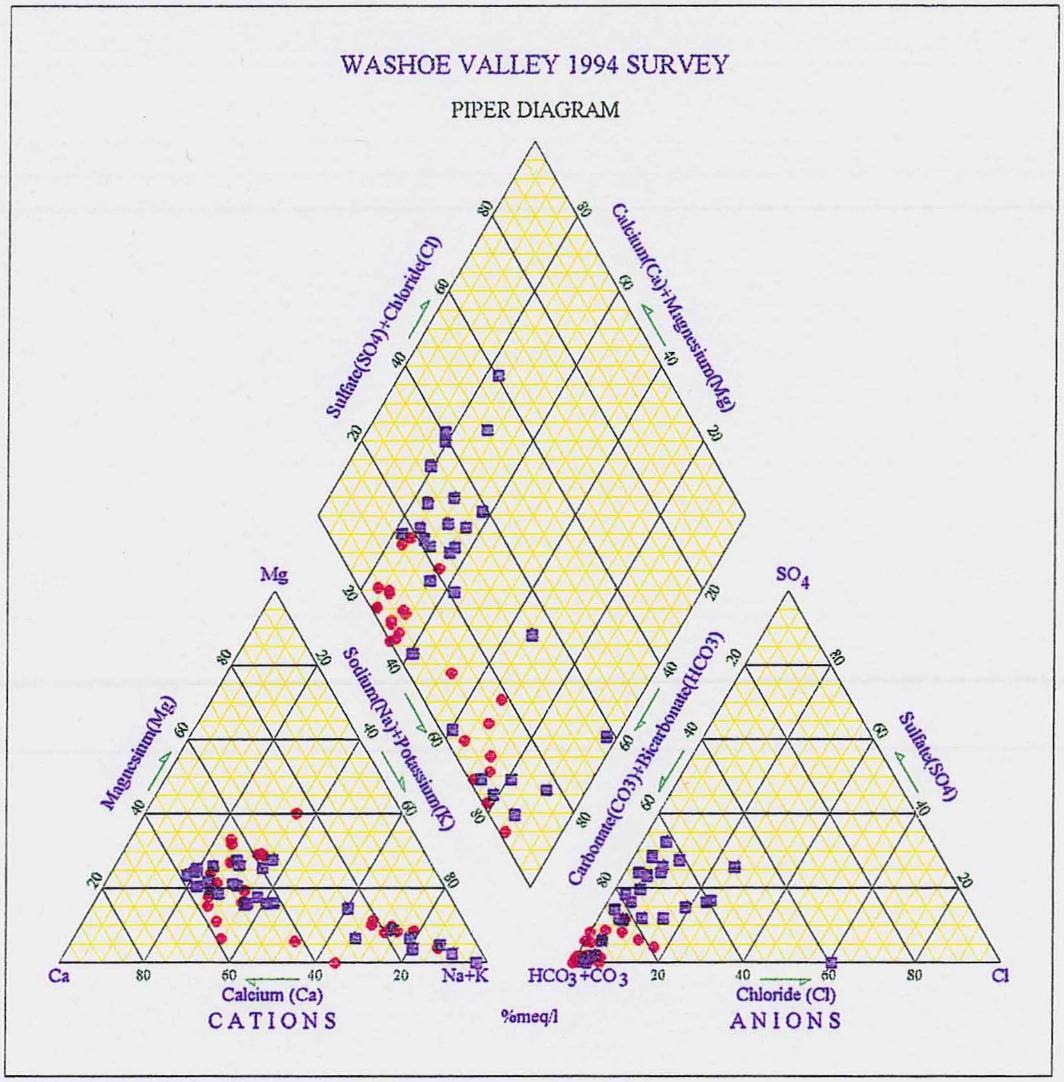
Figure 42 is a Piper diagram of the 1994 Washoe County survey data. Red symbols are samples from the west side of Washoe Valley and blue symbols are from the east side. The dominant anion chemistry indicates that the water is alkaline. Analysis show that the bicarbonate anion dominates over carbonate, as expected in the measured pH range. The pH averages 7.8 and has a range between 7.1 and 8.8. The cation triangle indicates that neither calcium nor Na+K dominate. Locally, the waters could be classified as either sodium bicarbonate type or calcium bicarbonate type. Neither sodium or calcium dominate on any particular side of the valley. Generally, sulfate contents are higher in east Washoe Valley. Higher values could be expected in a basin with more restrictive conditions, that contains lake beds (possible gypsum) rather than only alluvial material. Conversely, some of the sulfate could originate from sulfide oxidation or oxidation of H_2S gas related to the geothermal system. In general total dissolved solids (TDS) are slightly higher in NWC, possibly due to slower fluid flow paths allowing greater fluid-rock interaction and anthropogenic additions of nitrates and possible chloride.

Water type at the Bowers Mansion system was compared against NWC waters. Figure 43 is a Piper Diagram from the Bowers Mansion area (data from Garside and Schilling, 1979). Based on the diagram, the chemistry at Bowers Mansion matches sodium-bicarbonate classification found in most ground water at NWC. With one exception, the Bowers waters are generally lower in chloride. They tend to be slightly more basic than the NWC waters (pH up to 9.6). Trace element geochemistry is incomplete, but the samples are anomalous in fluorine, as are thermally related samples in NWC.

<u>Relationship of Ground Water Geochemistry to the Thermal System, NWC</u>

NWC waters, including the warmer waters, do not have an unusually high contents of chloride, sulfate or TDS that would signal a clear geothermal signature. McKay (1991) indicated that the fluorine could be related to the warmer waters but preferred other hypotheses to explain the anomaly (see section on "Constraints on Fluorine Anomaly"). Various contour plots of the analyzed constituents were systematically generated and respectively compared to the distribution of the warm water anomaly. After careful analysis, three constituents or properties are shown to have a good spatial correlation with the thermal anomaly. These are fluorine, arsenic and pH, respectively shown on Figures 44, 45 and 46. Plotted data are from the current 1997 survey.

A coincident fluorine and arsenic anomaly lends permissive, but not conclusive, evidence that this geochemistry is related to the thermal system. The correlation of high pH and elevated temperatures could be explained by CO_2 related phenomenon. CO_2 and H_2S are commonly found in geothermal systems (Nicholson, 1993). During the study, H_2S odor was noted in the western part of NWC, but was not quantified. Certain well waters in the



Note— Blue symbols are from east side
Red symbols are from west side

Figure 42. Piper Diagram, 1994 Washoe Valley Survey

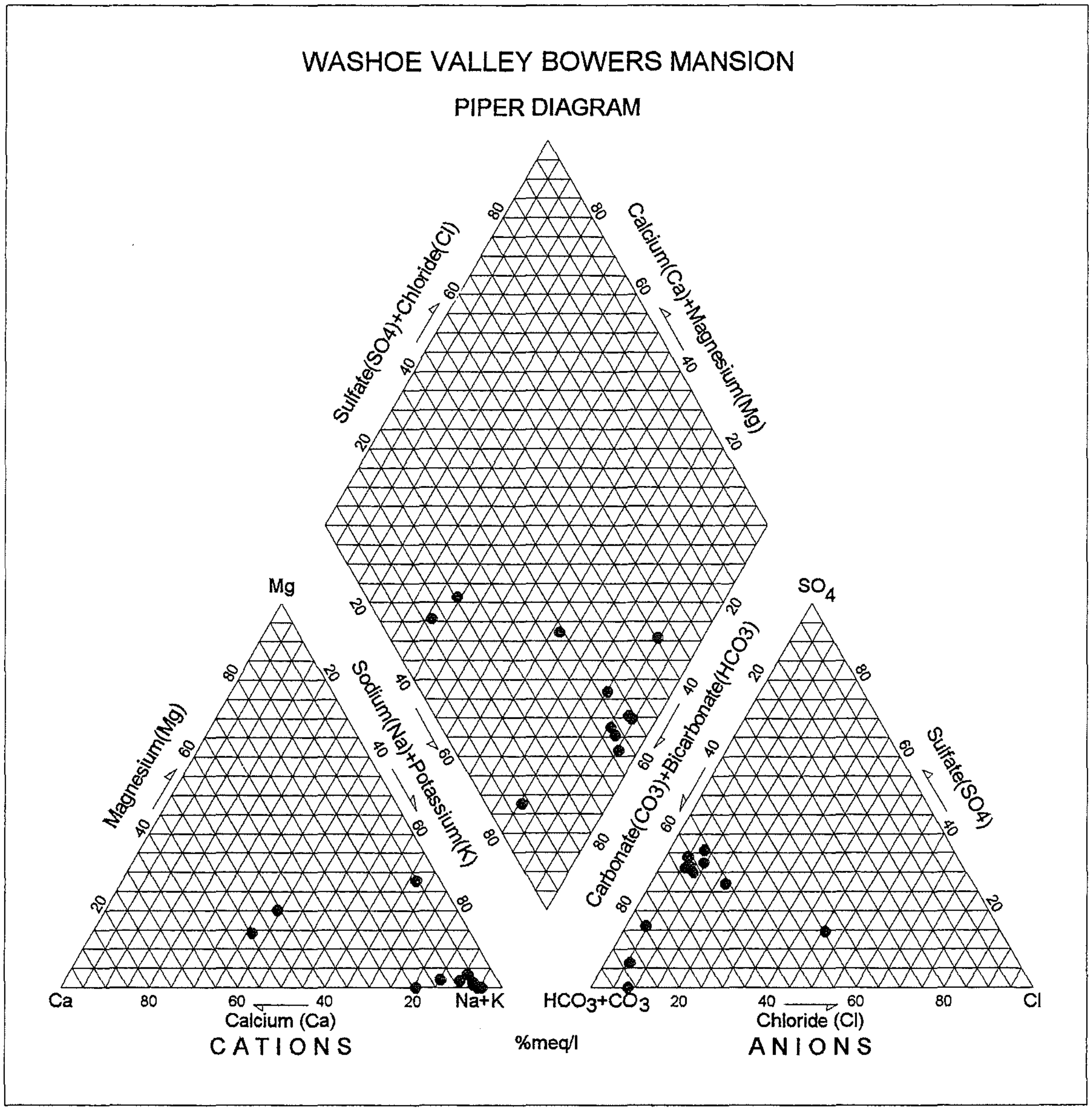


Figure 43. Piper Diagram, Bowers Mansion Area

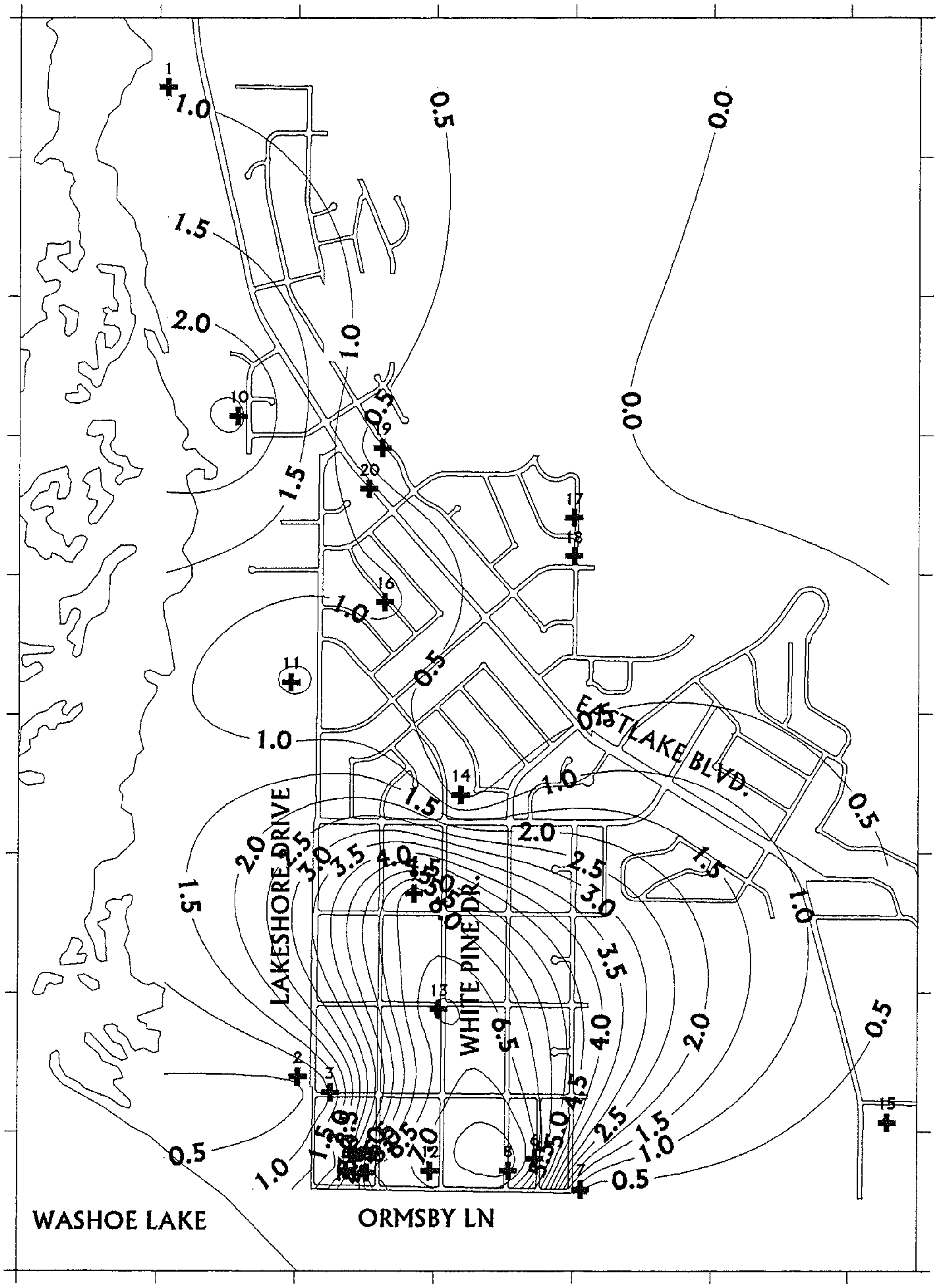


Figure 44. Fluoride (ppm) in Groundwater, New Washoe City

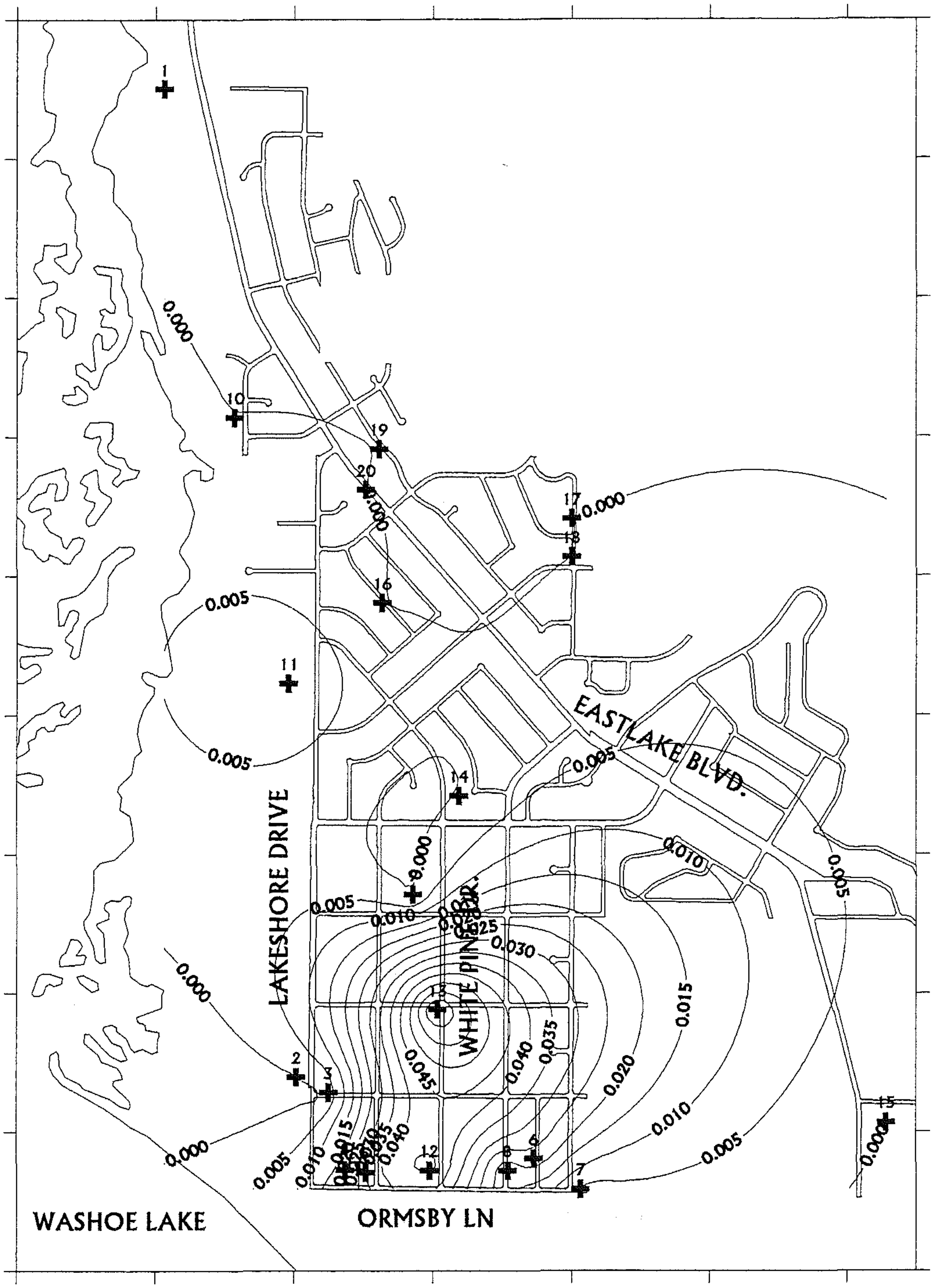


Figure 45. Arsenic (ppm) in Groundwater, New Washoe City

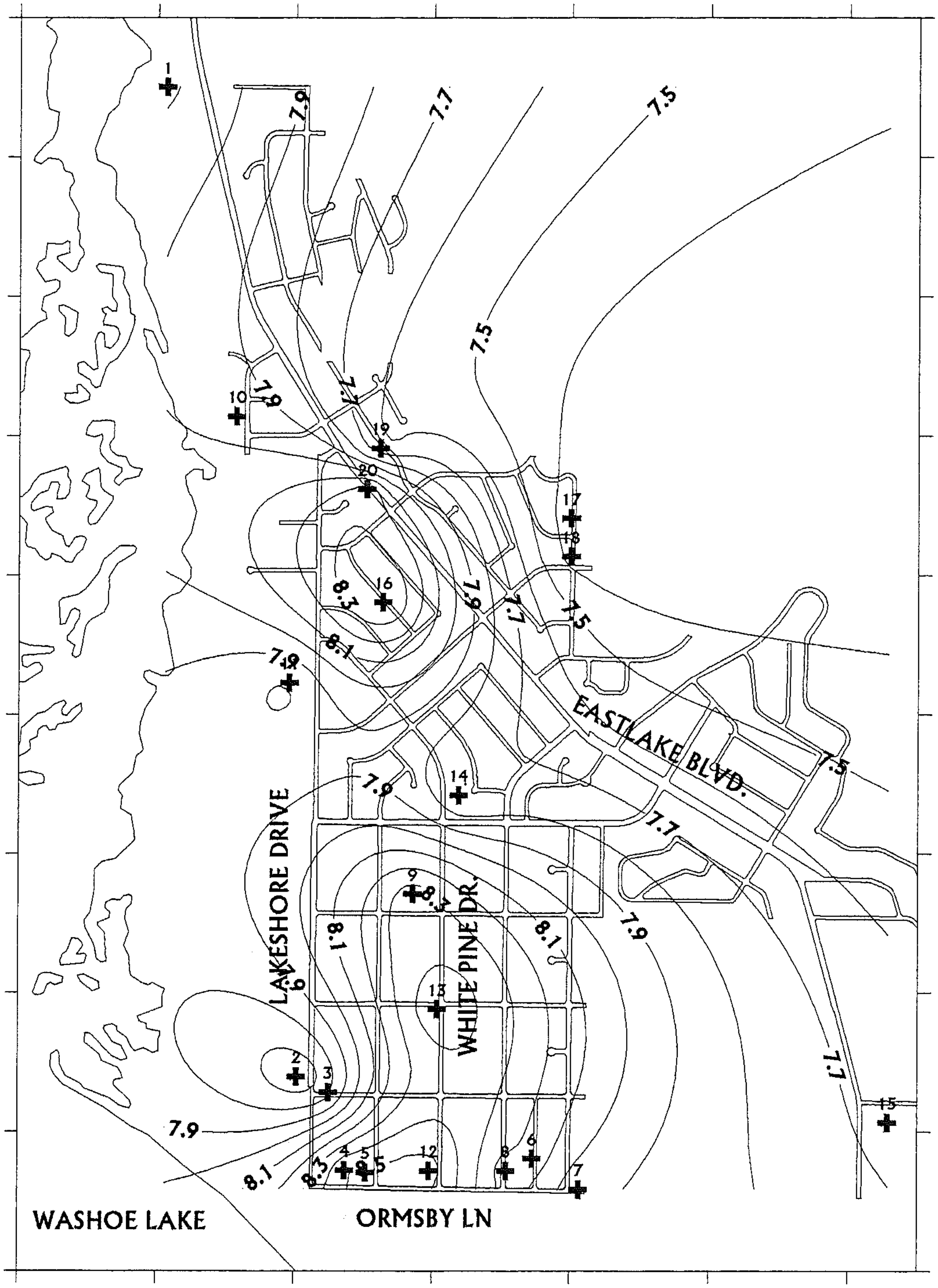


Figure 46. pH of Groundwater, New Washoe City

heart of the thermal anomaly exhibit an unusual amount of exsolving gasses from the tap. Presence of other gasses, perhaps CO_2, is suspected. Nicholson notes that CO_2 degassing will raise pH and decrease calcite solubility. A decrease in dissolved calcium can increase fluorine concentrations, which are partially governed by carbonate solubility reactions.

Fluorine Geochemistry

In order to accurately evaluate the significance of the fluorine anomaly a sound basic understanding is required of fluorine aqueous geochemistry. Of the halides, only iodine possesses more than one oxidation state in the limits of the stability field (Eh-pH) of water (Brookins, 1988). Higher oxidation states of the halides all plot well above the upper stability field of water. Therefore, fluoride (F^-) is the stable oxidation state found in ground water and surface water. Fluoride will however readily form various metal cation complexes which can be important transport agents, particularly in lower pH environments.

The abundance of fluorine in natural waters largely depends on its content in the source rock environment (Shawe, 1976). Fluorite (or fluorspar) is the most common fluorine mineral and often occurs as hydrothermal veins and replacement deposits (Shawe, 1976). A significant feature of fluoride is its similar ionic radius to the hydroxyl ion, $(OH)^-$, which allows substitution between the two species. As a consequence, rock forming and accessory hydroxyl bearing silicate minerals (micas and amphiboles) often contain high concentrations of fluorine (Koritnig and Allman ,1974). Clays may also hold a significant amount of fluorine (Thomas et.al, 1977). While the exchange of fluoride for the hydroxyl ion of various minerals, including clays, is documented by these authors, the reverse reaction, fluoride released from the hydroxyl site, and entering solution, is not well documented. Suspected presence of clays within the thermally anomalous area poses an interesting question as to the relationship between these clays and their direct influence on aqueous geochemistry.

According to Hem (1985), the average concentration of fluoride in natural waters with TDS of less than 1000 mg/L is less than 1mg/L. Shawe (1976) notes that the fluorine content of waters collected from specific rock types generally reflects the relative abundance of fluorine in those types of rocks. Among common rock types, waters from granite provenances have the highest values, approaching about 1 ppm (Koritnig and Allman, 1974). Thermal waters have some of the highest reported values of fluorine. Generally, thermal waters contain values below 20 ppm (Nordstrom and Jenne, 1976) but concentrations over 1000 ppm have been reported from acid hot springs (Ellis, 1973 quoted in Nordstrom and Jenne, 1976). Hem (1985) describes high values in some thermal water characterized by high pH and low Ca^{2+}. Ellis and Mahon (1964 and 1967) conclude that fluoride concentrations in geothermal fluids are largely limited by solubility of fluorite in silica bearing solutions.

Most studies have emphasized that

fluorite equilibria strongly controls fluoride concentration. The solubility of fluorite (Hem, 1985) can be expressed as:

$$CaF_2 (s) = Ca^{2+} + 2 F^-$$

$$[Ca^{2+}] * [F^-]^2 = 10^{-10.58}$$

Addition of calcium to the solution will depress the amount of dissolved fluoride. High fluoride concentrations will be more likely in water that has a low calcium concentration (Hem 1985). Ellis and Mahon (1964) conclude that fluorite solubility provides an equilibrium control on dissolved fluoride activity in selected geothermal waters. Their work, and that of Strubel, 1965 (as quoted in Koritnig, 1974) indicate that fluorite solubility is prograde, i. e. fluorite increases in solubility with temperature.

Fluorine concentrations can be enhanced by formation of various fluorine-metal complexes, generally at low pH (Cadek and Malkovsky, 1966). Fluorine solubility may also be enhanced in high pH environments. The work by Hubner, 1969 (as quoted in Koritnig and Allmann, 1974) suggest that fluoride may be exchanged with hydroxyl groups on mineral surfaces under high pH conditions. Kraynov et. al. (1978) discuss fluorine occurrences in neutral and alkaline ground water. They note that fluorine-bearing ground waters with pH > 7.7-8 are widely distributed in the earth's crust, with fluorine contents of 10 to 20 mg/l and more. Waters of low salinity and Na-HCO_3 composition are reported to statistically predominate among all types of fluorine-bearing ground waters. The aqueous geochemistry of the thermal plume area fits the above water category. Work by Handa (1975) and Gaciri and Davies (1993) suggest that fluorine content can increase along aquifer flowpaths. Increases are suggested to be a function of exposure time between groundwater and the aquifer.

Fluorine and General NWC Water Quality

State of Nevada Drinking Water Standards set primary standards for fluoride at 4 mg/l and secondary standards at 2 mg/l. (Division of Water Planning, 1995). Primary standards limit contaminants which may affect consumer health and secondary standards were developed to deal with aesthetic qualities of drinking water. Referring back to Figure 44, a significant area of southern NWC is above the 4 mg/l level.

Constraints on Fluorine Anomaly

McKay (1991) concluded that the fluorine anomaly was most likely caused by increase of fluorine concentration along the ground water flowpath (east to west) and the occurrence of a "fluorine sink" in the western part of NWC. The concentration of fluorine was suggested to be related to the presence of clays which would exchange the fluoride ion for hydroxide ions. While the components of the explanation are technically correct, the exchange of fluoride for hydroxide would decrease the concentration of groundwater fluorine, while acting as a fluorine sink in the aquifer itself.

The fluorine anomaly is fully consistent with the hydrogeologic setting and associated ground water geochemistry of

NWC. Components include source rock with potentially high concentrations of fluorine (e. g. granodiorite or altered volcanic/ intrusive units), an alkaline aqueous environment, low calcium ground water and elevated temperatures. Data from the current study, together with review of aqueous fluorine chemistry, strongly suggest a unique relationship between the thermal anomaly and the fluorine anomaly. Presentation of oxygen and hydrogen isotope data will provide further detail on the thermal system and related geochemistry.

Isotope Analysis

Oxygen and deuterium (D) isotope samples were collected at the twenty samples sites described previously. The theory of stable light isotopes is presented by several authors including Drever (1997) and Buchanan (1990). An isotope is a variation of a single element defined as possessing the same number of protons but varying numbers of neutrons. The term "stable" refers to the non-decaying or non radioactive nature of certain isotopes. Subtle differences in atomic weight allow isotopes of a particular element to partition or fractionate, causing different isotopic ratios in different regions or phases. Fractionation occurs during chemical reactions or physical changes, such as evaporation. The fractionation process is more readily measurable or trackable in lighter elements as compared to heavier elements where the ratio of mass difference between isotopes is of lower magnitude.

The ratios $^{18}O/^{16}O$ and $^{2}H/^{1}H$, commonly written as D/H, are particularly useful in various water studies. To compare ratios, and their significance, the δ(delta) notation is used. As an example, as explained by Drever (1997), $\delta^{18}O$ is written as:

$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{standard}}{(^{18}O/^{16}O)_{standard}} \times 1000$$

$\delta^{18}O$ represents the relative difference in parts permil ($^{0}/_{00}$) between the ratio in the sample and the ratio of a universally recognized sample, generally V-SMOW, or Vienna Standard Mean Ocean Water. δD is also expressed in parts per mill, using a similar formula and the same standard. A more positive (or less negative) per mill sample would contain relatively more of the heavy isotope (e. g. deuterium or ^{18}O) and is considered to be enriched while a more negative value would contain relatively more of the lighter isotope (e. g. hydrogen or ^{16}O) and is said to be depleted. Classic δD and $\delta^{18}O$ fractionation effects include depletion of these isotopes in rainwater, as opposed to ocean water, due to the lighter fraction preferably partitioning into the atmosphere. Similarly, precipitation occurring at higher altitudes would be depleted, as compared to that at lower elevations due to loss of the heavier isotopes and subsequent enrichment of the remaining vapor phase as it continues its ascent.

Buchanan's excellent 1990 work studied the isotopic character of thermal and non-thermal fluids within the Great Basin. He found that nearly everywhere thermal fluids are more isotopically depleted than the non-thermal fluids. His paleoclimate work also shows a definite depletion in stable light isotopes during the Pleistocene from 35,000 to 10,000 BP. Buchanan challenged a widely held position that the depletion of thermal waters is caused by a local meteoric recharge source water falling at high elevations. Instead, he favors recharge of geothermal reservoirs in the Great Basin during late Pleistocene during a climactically-induced period of isotope depletion.

δD and $\delta^{18}O$ (permil) are respectively shown in Figures 47 and 48 for the project area. Both elements show a distinct depletion which mimics the thermal anomaly and related constituents, including fluoride. Similar depletion patterns for both oxygen and hydrogen were seen by Flynn and Ghusn (1983) in isotope analysis of Moana Geothermal waters.

The permil values of δD and $\delta^{18}O$ are often plotted against each other and compared against local water lines or Craig's (1961) global meteoric water line. Classic interpretations suggest that values located further to the left and lower on the graph would have sources from higher elevations. An additional phenomenon known as the "oxygen shift" occurs in water rock interactions at high temperatures. At high temperatures (greater than 140 ^{0}C according to Nehring, 1980 in Flynn and Ghusn, 1983), oxygen-18 is preferentially fractionated into the fluid phase in hot water- rock reactions while deuterium fractionation is inhibited due to low quantities of hydrogen in most rocks. Figure 49 is a δD verses $\delta^{18}O$ plot of the project data. The data do not plot along a straight line, and upon initial inspection a possible oxygen shift may be present. Closer inspection indicates that the values with the apparent ^{18}O enrichment are almost exclusively those not associated with the thermal anomaly. Therefore no shift occurs, implying no detectable water-rock interaction.

Figure 49 also includes Craig's meteoric waterline and a local meteoric water line from the Honey Lake Basin (Varian, 1997), located northwest of Reno. The plot is characterized by clustering of the data as thermally related or range front related. Of great interest is the apparent concordance of the two clusters to the two water lines; with the thermal waters plotting along the global line and the nonthermal waters plotting along the local line.

The isotope data set is unfortunately somewhat limited in scope. Additional basin-wide samples, including the isotope signatures from recharge-producing snowmelt of the Carson and Virginia Ranges would be helpful.

Significance of Geochemical and Thermal Signature

Excellent spatial correlation has been demonstrated between elevated ground water temperatures, isotope depletion, pH, arsenic and fluorine. The coincidence of these parameters and constituents defines a unique ground water fluid chemistry for portions of NWC. Isotope data suggest the presence of two different groundwater types in NWC: 1) cool groundwater derived from recharge areas within the Virginia Range, and 2) "warm" water, typified by isotope depletion and other unique chemistry, with a less defined source.

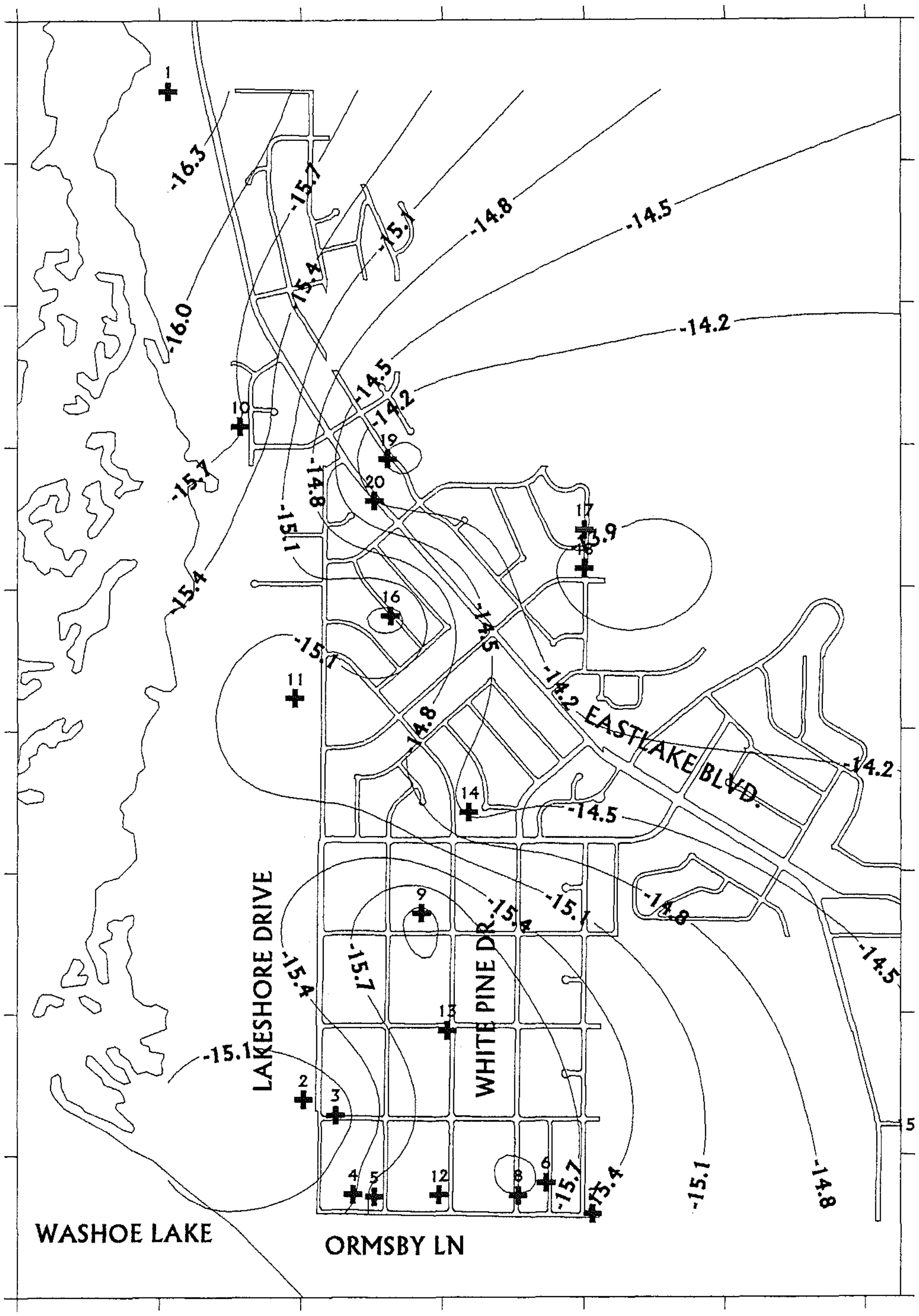


Figure 47. δ ^{18}O in Groundwater, New Washoe City

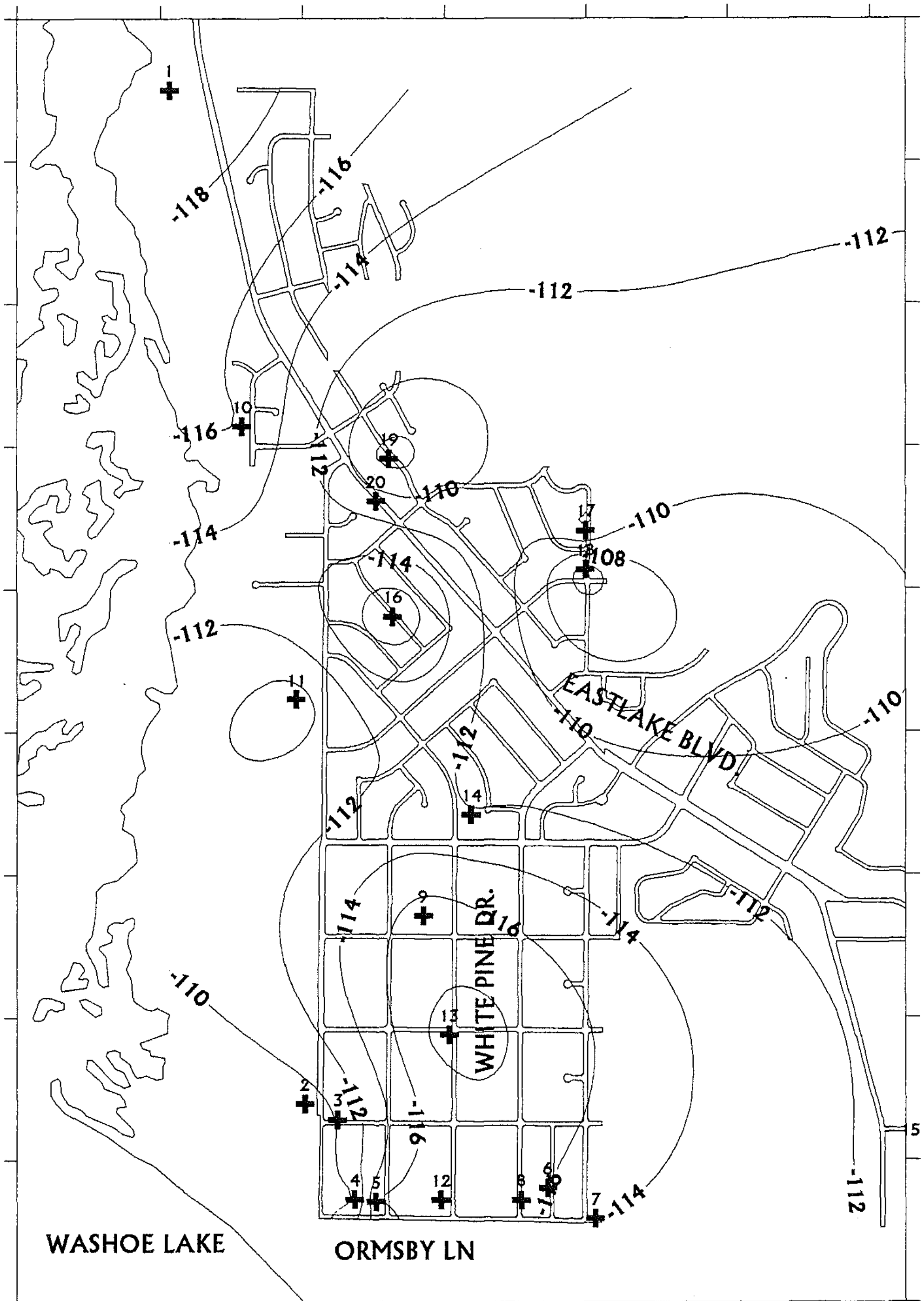


Figure 48. δ D in Groundwater, New Washoe City

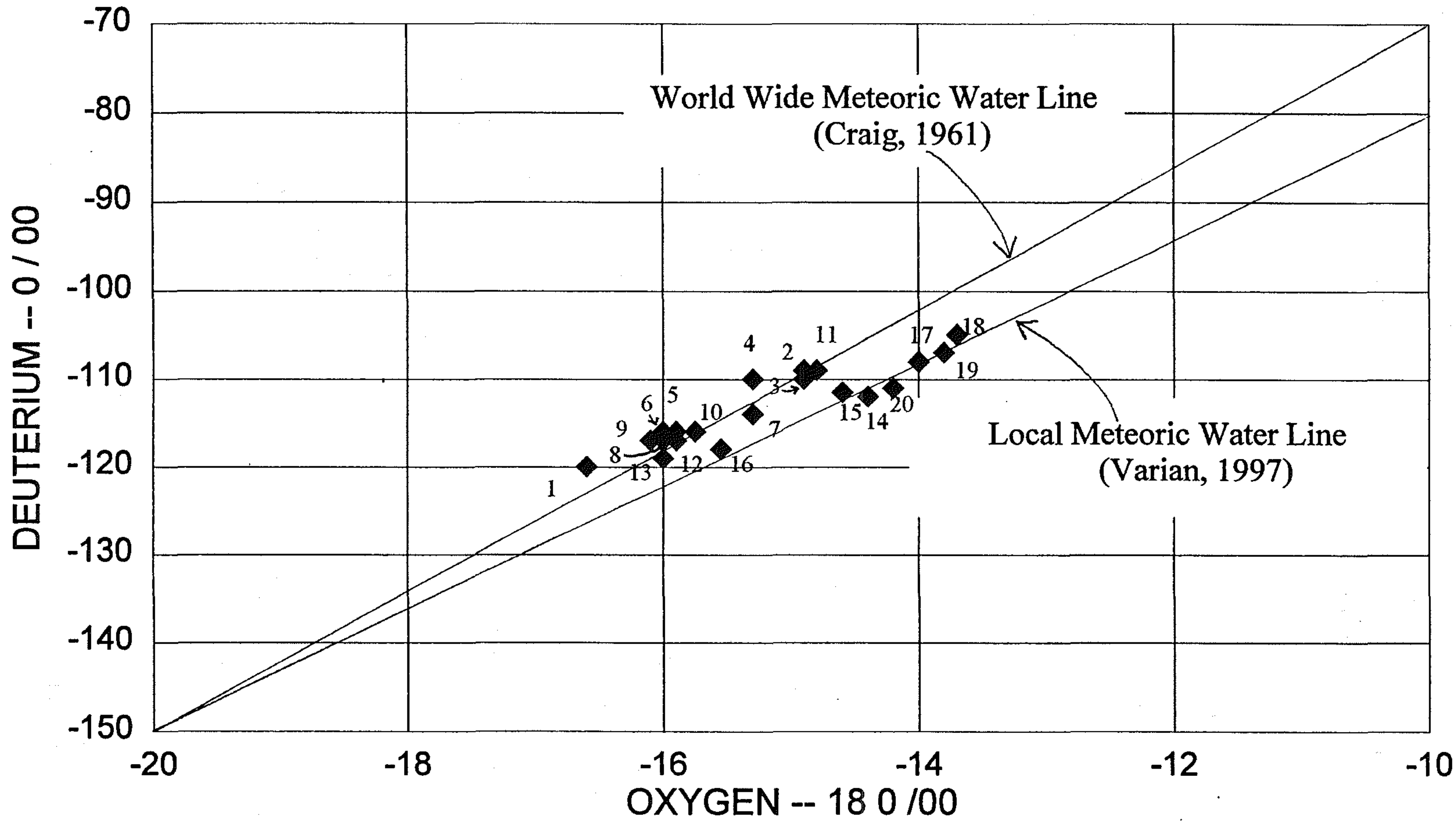


Figure 49. Deuterium Vs Oxygen — 18, New Washoe City

Previous discussions have indicated that the entire Washoe Valley, from Bowers Mansion on the west up into the Comstock Lode area of the Virginia Range, contain geothermally anomalous areas. Based on studies of the Steamboat Springs system DeRocher (1997) suggests that thermal discharge areas are often laterally removed from the actual heat source. Therefore it is not necessary to have a magmatic heat source directly under a geothermal plume.

The inferred structural setting in NWC argues for structural controls as the dominant mechanism for focusing or shaping the noted geochemical ground water anomaly. Ratanasthein and Ramingwong (1982) found a good spatial correlation of fluorine in groundwater and structural basement fault patterns from their studies in northern Thailand. The plume portion of the NWC anomaly is suggested to be controlled by structural intersection between a northeast trending fault, bounding the volcanic high, and a north-northwest trending cross-structure. The isolation of the hot spot at shallow depth is likely aided by selective migration of fluids up a permeable coarse sedimentary section as they ascend out of fractured basement rocks.

Modeling from this study supports strong vertical flow components, based on plots of specific discharge vectors (see Figure 35). Proper calibration required simulation of discharge through fractured basement rocks on the valley floor. Underflow is therefore suggested and the thermal/geochemical anomaly is likely a discharge area. Certain depth verses temperature profiles in wells also indicate discharge. This interpretation is consistent with the use of recharge wells in layer 2 of the ground water flow model. Fluid flux through this mechanism, as per the groundwater flow model, would be on the order of 35,000 ft^3/day or about 300 acre feet per year.

The isotopic signature of the thermal waters is permissive for source water from snowmelt in the Carson Range, due to the greater expected depletion from that range, verses the Virginia Range. The longer flow path from the Carson Range would be compatible with the observed chemistry and elevated temperatures. As Fetter (1994) suggests, water from regional flow systems is likely to have an elevated temperature due to deeper circulation influenced by the geothermal gradient. Modeling of the sediment-hosted groundwater system has clearly demonstrated dominance of flow from the west, probably at considerable depths, and therefore lends support to a western source for the geothermal fluid.

Washoe County government is concerned about possible interactions between the potable water system and warm waters, and the related threat to water quality. The final section of this chapter examines these concerns and provides some further interpretation and constraints regarding this complex ground water system.

Geothermal Influences on the Shallow Water System

A key question for water resource managers, and also a matter of public health and safety, is whether this system has the potential to further affect the drinking water supplies of the community, especially if the water table is lowered due to development. A number of qualified conclusions can be reached from the information available to date. First, a discussion of fundamental modes of heat transfer in porous media is pertinent to understanding the flow characteristics and stability of the system in question.

According to Bear (1972), heat can be transported via conduction, convection or radiation. Bear states that convection is the primary mechanism of thermal energy transport in fluids associated with actual mass transport, as is the case for the general project area. Convection can be further classified as forced convection and free convection. In this study, heat transfer via forced convection is defined as heat transfer by external means, or simply by hydraulically driven flow. Convection imposed by density differences, generally due to temperature but at times also influenced by total dissolved solid content of the thermal waters, is defined as free convection. Thermal and density variations will induce rotational tendencies to otherwise laminar flow. This tendency is defined as vorticity by Phillips, 1991.

It is suggested that flow in the study area is probably governed by hydraulics, essentially by hydraulic head difference, or as potential energy per unit mass of water, between recharge area and discharge area. This inference is based on the low magnitude of thermal effects observed, shallow position of the flow system with respect to any possible heat source, and a significant elevation head capable of driving flows in the given study area. Several empirical measures of the tendency for fluid to freely convect have been developed. These can be applied at NWC to help gauge stability of the groundwater flow system. If free convection is present or easily induced by water table lowering, subsequent upwelling could rapidly increase groundwater temperatures.

Phillips (1991) uses a "rule of thumb" relationship to gage the influence of geothermal effects on flow fields. The empirical gage is:

$$\zeta \gg \alpha h l \, \partial T / \partial X, \quad (1)$$

where ζ is the hydraulic head differential, α is the thermal expansion coefficient of water, h is the aquifer thickness, l is the longitudinal flow transport distance, and $\partial T / \partial X$ is the thermal gradient along the direction of flow. The flow field is hydraulically dominated if the left hand term is significantly greater than the free convection term on the right. Essentially, flow is hydraulically dominated if vorticity induced variations in transport velocity are small compared to the advective transport velocity. The calculation simply assumes an aquifer of constant thickness, a prescribed flowpath distance, and average ground water tempertures at some specified starting and ending measuring points (distance l), which define a horizontal thermal gradient, $\partial T / \partial X$.

Applying equation (1) to the study area requires simplifications and assumptions because the actual flow path of the fluids that discharge in NWC is unknown. Assuming a source from the west, one can look at flow from the west side of

Washoe Valley beginning at the point of range front recharge, with an estimated average temperature of 15^0C, to the discharging plume at NWC with an average temperature of 51^0C. The entire flowpath distance, *l*, is approximately 5600 meters, and the thickness, *h*, is taken as 300 meters (here the thickness of the modeled valley fill). A major simplification assumes flow mostly within the sedimentary package. The calculated thermal gradient is approximately .006 ^0C. Incorporating Phillip's value for α of $3 \times 10^{-4}\ ^0C^{-1}$, the right hand side of the equation is approximately 3.0m and the hydraulic head is about 80m. The thermal effect components comprise about 4 % of the system. Therefore, forced convection via hydraulically-induced flow dominates. Applying equation 1 to a situation involving the basement is problematic because the head gradient nor the actual thickness of the basement aquifer are known.

A second mathematical expression, here a dimensionless ratio, can be applied to test for the tendency toward free convection. The ratio is called the Rayleigh number and its application is discussed by Bear (1972). Empirical and numerical studies indicate a critical value for the Raleigh number of approximately 40 to initiate free convection. The physical assumptions are somewhat restrictive and assume two horizontal layers, each with a constant, but differing, thermally caused density. The ratio tests for stability or "turnover" tendency of this configuration and may be written as (Bear, pg. 656):

$$Y = \frac{K\eta(T_1 - T_0)H}{D_h} \qquad (2)$$

where Y is the Raleigh Number, K is hydraulic conductivity, η the coefficient of linear thermal volume expansion, T_1-T_0 a vertical temperature difference measured along a distance H, and D_h is thermal diffusivity of water at T_0. Equation (2) is applied to the center of the thermal plume at NWC with T_1-T_0 equal to 23.7 ^0C and H set at 100 feet (30.47 m). GSA Memoir 36 provides a value for D_h of $3.0 \times 10^{--7} m^2/sec$ (at 20 ^0C), and the η value at 20 ^0C is $2.06 \times 10^{-4}\ ^{\circ}C^{-1}$ (CRC Handbook, 77th ed.). The K value is set at 10ft/day, or 3.53×10^{-5} m/sec . With the above values, Y equals 17.5, which suggests that free convection would most likely not occur in an ideal two layer model.

From the previous chapter, it was predicted that a worst case drought/consumption scenario would approximately lower the water table by about ten feet. Near the center of the plume, one well survey indicates that the geothermal gradient decreases with depth and levels out at about 100 feet below surface. Therefore, a drop of ten feet should not change the Raleigh number and therefore would not significantly perturb the system. The qualitative calculations serve as a basis to suggest that flow would continue to be dominated by hydraulically induced, forced convection, even if the water table were to be lowered according to predictive model scenarios.

The above conclusions should be considered guarded. The calculations do suggest that large scale overturning or free convection causing massive incursion of warm waters into the potable aquifer is unlikely, especially since projected water table fluctuations are moderate. However, an upwelling condition has been documented, and the ability of such relationships as the Raleigh Number to accurately predict local flow stability should be questioned. Additionally, McKay (personal communication) noted rapidly varying temperature fluctuations at sample point 5 during the period between 1989 and 1991, but without detailed long-term data, causes of such fluctuations remain speculative.

Several further questions can be raised regarding the effects of drought conditions on the thermal/freshwater system. Unlike the simplifications in the flow model, annual flow variations from the fractured basement may not mimic flow variations in the overlying alluvial aquifer. Assuming a westwardly located flow source, and an implied long and deep flowpath, the warm ground water could lag years behind quicker flux responses associated with the shallow system. When a drought occurs, the thermal system may still receive input volumes reflective of wetter periods. However, pressure response to reduced discharge would have to be considered, in addition. A change in the ratio of thermal and shallow waters could create a tendency for waters to warm during drought conditions, due to a greater proportion of warm water relative to cool water. Based on the only available temporal study (single measurements in 1991 and 1997), water temperatures at sample point 5 have remained nearly constant. The maximum temperatures in 1991, during the drought (McKay, 1991) and in 1997 are approximately the same.

Possible negative thermal or water quality effects to the fresh water system could also be induced by catastrophic geologic events. Rapid changes in fluid pressure caused by seismicity could occur, and trigger relatively quick changes in local groundwater temperatures. Prediction of such events, or even their likelihood, is difficult.

Conclusions and Recommendations

Conclusions

1. New information has been presented on the lithologic character of the basin fill aquifer and the structural setting. Basin fill is lithologically more variable than previously characterized. Coarse sand with gravel channels occurs within the southwest part of NWC, which was described as containing fine lacustrine sediments in an earlier study. With regard to structure, the New Washoe City area is underlain by a series of northwest elongate horst and graben blocks, traversed by northeast trending cross-structures. Geophysical evidence and flow modeling also support the presence of an important nearly north-south trending structure located west of NWC near the east edge of Washoe Lake.

2. The study has shown the combined use of well drillers reports, existing geologic data, and the airborne geophysical survey to be an effective tool for establishing the structural and hydrogeolgic setting of the study area. Additionally, use of specific capacity data, in combination with the synthesized lithologic information, can be an effective method for determination of initial hydraulic conductivities, which can be further adjusted during model calibration.

3. The inferred structural setting, in combination with flow implications based on the identified thermal anomaly, supports structurally-controlled basement underflow and upwelling (discharge) through fractured basement volcanic units, into overlying coarse valley fill. This inferred feature has been incorporated into the conceptual hydrogeologic model and applied in the numeric model, as a series of layer 2 recharge wells. Recharge to the valley fill aquifer does not merely occur at the range front, but also through basement structures away from the range front.

4. Modeling suggests that drawdowns in the west, south and west-central portion of NWC would be moderate, generally less than ten feet, in response to a worst case drought/development scenario. Greater drawdowns against portions of the range-front are predicted where the water table is shown to drop twenty feet or more. Lowering is accentuated by lack of storage capacity in the low-permeability granodiorite fracture-controlled aquifer, in combination with range front recharge reductions during drought.

5. Fluctuations in the water table along the west side of NWC are moderated by hydraulic conditions from the lake area. Modeled pumping at this location does not produce a significant cone of depression. A combination of relatively high hydraulic conductivities and water supply from the aquifer underlying the lake area moderates potential drawdowns. The aquifer underlying Washoe Lake represents a significant body of groundwater storage, and buffers water table drops during droughts. Furthermore, the model has verified that groundwater from the wetter west side of the valley flows eastward, underneath the valley floor, nearly to NWC. Therefore, if water of poor quality can be avoided, potential municipal water supply may be available from the extreme west side and southwest side of NWC, adjacent to the Washoe Lake shoreline.

6. The geothermal system is suggested to be relatively stable. Drought-related water table declines would probably not induce an irreversible thermal incursion, because the system is unlikely to undergo free convection, even if perturbed, and is dominated by hydraulic head-controlled, forced convection through fractures. Local temperature variations during drought may occur, possibly caused by volume reduction of cool water relative to warm water, but their severity and duration would be difficult to predict without additional data.

7. Fluoride in domestic drinking water exceeds primary drinking water standards. The fluoride is almost certainly related to the geothermal feature, and will impair water quality into the foreseeable future. However, the restricted nature of the geothermal plume and related fluoride anomaly suggest that alternative potable sources may be available west of the thermal plume. While not addressed in this study, nitrate and nitrite contamination continue to pose problems in the eastern to east-central portion of NWC. Therefore, the resolution of water quality issues should remain a primary focus for water

planners and health authorities.

8. The geochemical ground water sampling program, including isotope analysis, has fingerprinted the geothermal waters. Isotope analysis and simple water balance considerations suggest, but do not prove, that the thermal water source is from the west side of the valley.

Recommendations

The following recommendations propose future work that would further understanding of the project area's and Washoe Valley's hydrology and hydrogeology.

1. The continued study of the extreme western and southwest portion of NWC is recommended. Specifically, additional modeling of lake-groundwater interaction would help quantify feasibility of this area as a groundwater source and refine drawdown predictions under various pumping and drought conditions. Collection of additional hydraulic data is recommended, including pumping tests (e.g. Scripps well) or slug tests on selected domestic wells. If the lake bed were to go dry, further examination of the underlying aquifer system via drilling or ground-based geophysical surveys would be warranted.

2. Modeling has indicated rapid drawdowns around simulated agricultural wells in the southern part of the study area, based on low assigned K_h values as inferred from limited data. This area should be further examined for its municipal water supply potential because the water quality here may be better than to the north. Obtaining additional information on the hydraulic conductivities storativities and yields of these wells and collection of water analysis is recommended.

3. Although major changes in water temperature or quality are not expected to threaten NWC water supply in the foreseeable future, a thermal/chemical monitoring program is recommended. Such a program would provide additional baseline and long term scientific data, document short term thermal fluctuations, and also provide an "alert" capability if an unexpected change were to occur in the system. This would involve drilling of one or two monitoring wells and the preferable use of down-hole dedicated temperature and water level sensors. The information could also be applied to the study of geothermal-freshwater interaction at Steamboat Springs and Moana Hot Springs.

4. The geochemical study shows a good correlation between isotope anomalies and the thermal anomaly, and offers an opportunity for continued scientific studies of low temperature geothermal features. An expanded isotope survey of the entire basin would probably confirm the source of the thermal waters. The current study suggests that H_2S and other gasses such as $C0_2$ may be related to the thermal event. Additional follow-up in the form of water-contained gas analysis or use of soil gas sniffing techniques may be warranted. The study could delineate areas to avoid in future well drilling, and would further characterize the geothermal feature.

5. The available quality airborne resistivity and magnetics data invites

geophysical modeling for better definition of basement structures, and confirmation of the inferred lithologic and structural setting presented in this thesis. Additional field gravity surveys should be conducted to help determine basement depths. The drilling of future wells would provide opportunity to conduct down-hole resistivity testing and collection of aquifer parameters that could be compared against the airborne data.

6. Continuing field investigation of various water budget components is recommended. The study area is influenced by the wetter west side of the valley. Therefore, studies within Washoe Valley that help refine estimates of discharge and/or recharge will provide useful water planning information.

REFERENCES

Anderson, Mary P. and William W. Woessner, 1992. Applied Groundwater Modeling. Academic Press, San Diego.

Armstrong, Thomas A. and Fordham, John, W., 1977. Investigation of groundwater quality and its effect on suburban development in Washoe Valley, Nevada. Water Resources Center, Desert Research Institute Project Report No. 48.

Arteaga, Freddy, and Nichols, William D., 1984. Hydrology of Washoe Valley, Washoe County, Nevada. U.S. Geological Survey Open File Report 84-465.

Arteaga, Freddy, 1982. Hydrogeology of Washoe Valley, Washoe County, Nevada. Unpublished Report, assembled by Washoe County.

Ashby, Jim, 1997. Person Communication. Regional Climatic Center, Desert Research Institute, Reno, Nevada.

Back, W. and B. B. Hanshaw, 1970. Comparison of the Chemical Hydrogeology of the Carbonate Peninsulas of Florida and Yucatan. Journal of Hydrology 10:330 - 68.

Berger, David L., Wyn C. Ross, Carl E. Thodal, and Armando R. Robledo, 1997. Hydrogeology and Simulated Effects of Urban Development on Water Resources of Spanish Springs Valley, Washoe County, West - Central Nevada. U. S. Geological Survey Water - Resources Investigations Report 96 - 4297.

Blackwell, D. D., 1983. Heat Flow in the Northern Basin and Range Province. Geothermal Resources Council Special Report 13, p. 81 - 91. Bostic, Bob, 1997. Personal Communication. U.S. Geological Survey, Water Resources Division, Carson City, Nevada.

Brookins, D. G., 1988. Eh-pH Diagrams for Geochemistry. Springer-Verlag, Inc., New York.

Buchanan, Paul K., 1990. Determination of Timing of Recharge for Geothermal Fluids in the Great Basin Using Environmental Isotopes and Paleoclimate Indicators. Masters Thesis, University of Nevada, Reno.

Cadek, Josef and Malkovsky M., 1966. Transport of fluorine in natural waters and precipitation of fluorite at low temperatures. Acta Universitatis Carolinae - Geologica 4, 251-270.

Cheng, Xiangxue, and Mary P. Anderson, 1993. Numerical Simulation of Ground - Water Interaction with Lakes Allowing for Fluctuation of Lake Levels. Ground Water, Vol. 31, No. 6, p. 929 - 933.

Craig, H., 1961. Isotopic Variations in Meteoric Waters. Science, 133, 1702 - 1703.

Danskin, Wesley, 1988. Preliminary Evaluation of the Hydrogeologic System in Owens Valley, California. U. S. Geological Survey Water Resources Investigations Report 88 - 4003.

De Rocher, Ted, 1997. Personal Communication. PhD candidate, University of Nevada, Reno.

Dighem, 1994. DIGHEM Survey for Utility Division, Washoe County Public Works, Washoe County Nevada. REF: NJ11-1. Division of Water Planning, 1995. Nevada Water Words Dictionary. Nevada Department of Conservation and Natural Resources, Carson City, Nevada.

Drever, James I. 1997. The Geochemistry of Natural Waters, 3rd ed. Prentice Hall, Upper Saddle River, NJ.

Driscoll, Fletcher G. 1986. Groundwater and Wells, 2nd Edition. Johnson Screens, St. Paul, Minnesota.

Eakin, T. E. and others, 1951. Contributions to the Hydrology of Eastern Nevada. Nevada State Engineer, Water Resources Bull. 12, 171 p.

Ellis A. J., 1973. Chemical Processes in Hydrothermal Systems — a Review. In Proceedings of Symposium on Hydrogeochemistry, (editor E. Ingerson), Vol. I, Chapter 1, pp. 1 - 26. Clarke.

Ellis, A. J. and Mahon W. A. J., 1964. Natural Hydrothermal Systems and Experimental Hot Water/rock Interactions. Geochim. Cosmochim. Acta 28, 1323-1357.

Ellis, A. J. and W. A. J. Mahon, 1977. Chemistry and Geothermal Systems. Academic Press, New York.

Ellis, A. J. and Mahon W. A. J., 1967. Natural hydrothermal systems and experimental hot water/rock interactions (Part II). Geochim. Cosmochim. Acta **31,** 519-538.

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

Fetter, C. W., 1994. Applied Hydrogeology, *3rd Ed.* Prentice Hall, Englewood Cliffs, NJ.

Flynn, Thomas and Paul K. Buchanan, 1990. Geothermal Fluid Genesis in the Great Basin. Division of Earth Sciences Report 90R1, University of Nevada, Las Vegas.

Flynn, Thomas and George Ghusn, Jr., 1983. Geologic and Hydrologic Research on the Moana Geothermal System, Washoe County, Nevada. Division of Earth Sciences, Environmental Research Center, University of Nevada, Las Vegas.

Fraser, Douglas C, 1986. Dighem Resistivity Techniques in Airborne Electromagnetic Mapping, in, Airborne Resistivity Mapping, ed. G. J. Palacky. Geological survey of Canada, Paper 86 - 22, p. 49 - 54.

Freeze, R. Allen, and John A. Cherry, 1979. Groundwater. Prentice-Hall Incorporated.

Gaciri, S. J. and Davies T. C., 1993. The Occurrence and Geochemistry of Fluoride in some Natural Waters of Kenya. Journal of Hydrology 143, 395-412.

Garside, Larry J. and John H. Schilling, 1979. Thermal Water of Nevada. Nevada Bureau of Mines and Geology Bull. 91.

Handa, B. K., 1975. Geochemistry and Genesis of Fluoride - Containing Ground Waters in India. Ground Water 13, 275 - 281.

Hardman, George and Cruz Venstrom, 1941. A 100-Year Record of Truckee River Runoff Estimated From Changes in Levels and Volumes of Pyramid and Winnemucca Lakes. Transactions of 1941 of the American Geophysical Union.

Harrill, James R., 1986. Groundwater Storage Depletion in Pahrump Valley, Nevada - California, 1962 - 75. U. S. Geological Survey Water Supply Paper 2279.

Heigold, Paul C., Robert H. Gilkeson, Keros Cartwright, and Philip C. Reed, 1979. Aquifer Transmissivity from Surficial Electrical Methods. Ground Water, Vol. 17, No. 4, pp. 338 - 345.

Hem J. D., 1985. Study and Interpretation of the Chemical Characteristics of Natural Waters, 3d ed. U.S. Geol. Survey Water-Supply Paper 2254.

Hubner M., 1969. Geochemische Interpretation von Fluorid/hydroxed - Austauschversuchen an Tonmeralen. Ber. Deutsch. Ges. geol. Wiss. B. Miner. LagerstattenforscH, 14, 5.

Huffy, Bob, 1967. Personal Communication. Nevada Division of Wildlife, Yrington, Nevada.

Jacobsen, Elizabeth and Jeffrey W. Johnston, 1991. The Moana Geothermal System in Reno, Nevada: A Hydrologic, Geochemical, and Thermal Analysis. DRI Public. No. 41131.

Kanbergs, Karl, 1996. Groundwater Level Charcterization Study: Mt. Rose and Galena Fan Areas, Washoe County, Nevada. Internal, unpublished, Washoe County report.

Kelly, William F., 1977. Geoelectric Sounding for Estimating Aquifer Hydraulic Conductivity. Ground Water, Vol. 15, No. 6, pp. 420 - 425.

Kelly, W. E. and P. F. Reiter, 1984. Influence of Anisotropy on Relations Between Electrical and Hydraulic Properties of Aquifers. Journal of Hydrology, Vol. 74, pp. 311 - 321.

Koriting S. and Allmann R., 1974. Fluorine; in Handbook of Geochemistry (K. H. Wedepohl, ed.), Berlin, Springer-Verlag.

Kraynov, V. K et. al., 1978. Fluorine Compounds in Ground Water with Nearly Neutral and Alkaline Reactions. Geochemistry International 15, 66-73.

Lohman, S. W., 1972. Ground-water Hydraulics. U. S. Geological Survey Professional Paper 708.

Lovering, T. S. and H. T. Morris, 1964. Underground Temperatures and Heat Flow in the East Tintic District, Utah. U. S. Geologicial Survey Professional Paper 504-F.

Maurer, Douglas K., David L. Berger, and David E. Prudic, 1996. Subsurface Flow to Eagle Valley from Vicee, Ash, and Kings Canyons, Carson City, Nevada, Estimated from Darcy's law and the Chloride - Balance Method. U. S. Geological Survey Water Resources Investigations Report 96-4088.

Mazac, O. and I. Landa, 1979. On Determination of Hydraulic Conductivity and Transmssivity of Granular Aquifers by Vertical Electric Sounding. J. Geol. Sci. (Czech), Vol. 16, pp. 123 - 139.

McDonald, M. G., and A. W. Harbaugh, 1988. A Modular Three-Demensional Finite Difference Ground-Water Flow Model. Book 6, Chapter A1. Techniques of Water Resources Investigations of the United States Geological Survey.

McKay, Alan, 1991. Analysis of Groundwater Quality in New Washoe City, Nevada. Unpublished Master's Thesis, University of Nevada, Reno.

McKay, Alan, 1997. Personal Communication.

Nehring, N. L., 1980. Geochemistry of Steamboat Springs, Nevada. U.S. Geological Survey Open File Report 80 887, 61 p.

Nordstrom, Darrell K. and Jenne E., 1977. Fluorite Solubility Equilibria in Selected Geothermal Waters. Geochim. Cosmochim. Acta 41, 175-188.

Petersen, Ronald, 1994. Final Documentation, Washoe Valley Groundwater Model. Water Resources Center, Desert Research Institute Publication, Draft Copy.

Petersen, Ronald and Robert Karlin, 1997. A Hydrogeologic Framework of Washoe Valley, Nevada From Joint Gravity and Magnetic Modeling and Terrain Conductivity Data. In, Proceedings on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP '97, V. 1). Environmental and Engineering Geophysical Society, Reno, Nevada.

Petersen, Ronald Clayton, 1993. Geophysical applications to the development of a groundwater model of Washoe Valley, Nevada. Masters Thesis, University of Nevada, Reno.

Phillips, O.M., 1991. Flow and Reactions in Permeable Rocks. Cambridge University Press, New York.

Ratanasthein, Benjavun and Tavisakdi Ramingwong, 1982. The Intrusion of Thermal Water into Domestic Groundwater System in the Areas of San Kampaeng and Lamphun. Department of of Geological Sciences, Chang Mai University, Special Publication Number 3, 1982.

Rumbaugh, James O., and Douglas B. Rumbaugh, 1996. Guide to Using Groundwater Vistas. Environmental Simulations Inc., Herndon Virginia.

Rush, F. Eugene, 1967. Water-Resources appraisal of Washoe Valley, Nevada. Nevada Dept. Conser. and Nat. Resources Water Resources Reconn. Ser. Rept. 41., 39 p.

Rush, F. Eugene, 1975. Washoe City Folio Hydrologic Map. Nevada Bureau of Mines and Geology.

Shawe, Daniel, R. editor, 1976. Geology and Resources of Fluorine in the United States. U.S. Geol Survey Professional Paper 933.

Strubel G., 1965. Quantitative Untersuchungen uber die Hydrothermale Loslichkeit von Fluorspat (CaF_2). Nues Jahrb. Mineral. Monatsh, 83.

Tabor, R. W., et. al., 1983. Geology, Geophysics, Geologic Hazards, and Engineering and Geologic Character of Earth Materials in the Washoe Lake Area. Text to accompany the maps of the environmental series, Washoe City Quadrangle, Nevada. Nevada Bureau of Mines and Geolgogy Open File Report 83-7.

Tabor, R. W., S. E. Ellen, 1976. Washoe City Folio Geologic Cross Sections. Nevada Bureau of Mines and Geology, Environmental Series.

Tabor, R. W., S. E. Ellen, 1975. Washoe City Folio Geologic Map. Nevada Bureau of Mines and Geology, Environmental Series.

Thomas, James M., Stephen M. Carlton, and Lawrence B. Hines, 1989. Ground-Water Hydrology and Simulated Effects of Development in Smith Creek Valley, a Hydrologically Closed Basin in Lander County Nevada. U. S. Geological Survey Professional Paper 1409 - E.

Thomas, Josephus Jr. et. al., 1977. Fluoride Content of Clay Minerals and Argillaceous Earth Materials. Clays and Clay Minerals 25, 278 - 284.

Trescott, P. D., 1975. Documentation of Finite-Difference Model for Simulation of Three-Dimensional Ground-Water Flow. U.S. Geological Survey Open File Report 75-438, 32 pp.

Trexler, Dennis, 1977. Carson City Folio Geologic Map. Nevada Bureau of Mines and Geology, Environmental Series Map no. 1Ag.

Varian, Angela R., 1997. Use of Environmental Isotopes to Investigate Hydrologic Processes at Honey Lake Basin, Lassen County, California, and Washoe County, Nevada. Unpulblished Master's Thesis, University of Nevada, Reno.

Wang H. F. and Mary P. Anderson, 1982. Introduction to Ground-water Modeling — Finite Difference and Finite Element Modeling. New York, Freeman, 237 p.

Ward, D. S., et. al., 1987. Evaluation of a Groundwater Corrective Action at the Chem-Dyne Hazardous Waste Site Using a Telescopic Mesh Refinement Modeling Approach. Water Resources Research 23(4), pp 603-617.

Washoe County, 1997. 1995 - 2015 Washoe County Comprehensive Regional Water Management Plan. Washoe County Department of Water Resources, Reno, Nevada.

White, Donald E., 1968. Hydrology, Activity, and Heat Flow of the Steamboat Springs Thermal System, Washoe County, Nevada. U. S. Geological Survey Professional Paper 458 - C.

Whitebread, D. H., 1976. Alteration and geochemistry of volcanic rocks in parts of the Virginia City Quadrangle, Nevada. U. S. Geological Survey Professional Paper 936.

Widmer, Mike, 1994. Technical Memorandum: Washoe Valley Steady State Ground-Water Model. Washoe County Department of Public Works, Utility Division.

Widmer, Mike, 1996. Personal Communication. Senior Hydrogeologist, Washoe County Utilities Division, Reno Nevada.

Widmer, Michael C., 1997. Washoe Valley Steady State and Transient Modeling. Washoe County Department of Water Resources.

Widmer, Mike, 1997. Personal Communication. Senior Hydrogeologist, Washoe County Utilities Division, Reno Nevada.

APPENDIX A

Well GPS Survey and Water Level Data

Note — Northings and Eastings are NAD 27 in feet (State Plane Coordinates). All head measurements and elevations are in feet.

Well97.xls showing 1997 and 1994 static water level meas.							
Date	Northing	Easting	MP Elev	Static '97	Static '94	'97 stat. ele	'94 stat. elev
1/28/97	1652248	161375	5059	7.63	16.5	5051	5043
1/28/97	1653459	159913	5045	1.43	6.95	5044	5038
1/24/97	1654844	162370	5085	38.53	43.57	5046	5041
2/7/97	1647627	143540	5119	4.14	23.59	5115	5095
2/5/97	1631584	151322	5157	17.07	42.9	5140	5114
2/5/97	1654453	144822	5112	22.06	24.85	5090	5087
1/6/97	1656405	163537	5127	84.19	88.83	5043	5038
2/4/97	1647740	145181	5074	1.99	3.48	5072	5071
2/5/97	1665401	152405	5066	1.02	11.58	5065	5054
2/5/97	1640140	150210	5034	flowing	3.79		5030
1/6/97	1658385	162196	5099	54.62	60.09	5044	5039
2/4/97	1660651	147081	5148	56.44	71.28	5092	5077
2/5/97	1664973	151103	5076	7.67	18.73	5068	5057
2/6/97	1641223	142937	5154	9.27	17.4	5145	5137
2/6/97	1642181	142879	5198	6.71	6.28	5191	5192
2/5/97	1666489	152055	5086	16.18	25.77	5070	5060
1/8/97	1664879	160265	5158	42.93	43.84	5115	5114
1/8/97	1662774	160876	5173	83.02	88.68	5090	5084
1/28/97	1653579	163700	5087	42.13	47.12	5045	5040
2/7/97	1647032	143577	5098	flowing	flowing		
1/21/97	1659237	161036	5082	33.26	39.42	5049	5043
2/7/97	1634500	150154	5095	1.32	5.5	5094	5090
2/7/97	1656018	166157	5190	107.48	122.58	5083	5067
2/4/97	1658329	148004	5091	7.32	13.26	5084	5078
1/21/97	1659604	160206	5067	20.66	26.62	5046	5040
2/6/97	1636448	151352	5044	flowing	0		5044
1/21/97	1657833	163579	5131	65.31	77.57	5066	5053
1/8/97	1629977	154650	5057	flowing	1.87		5055
1/8/97	1652806	167269	5159	43.15	69	5116	5090
1/30/97	1656179	162502	5097	47.83	53.08	5049	5044
1/24/97	1653424	161708	5063	13.53	18.3	5049	5045
1/21/97	1658275	163995	5160	15.92	33.3	5144	5127
2/5/97	1667093	153233	5075	5.83	18.88	5069	5056
2/6/97	1635613	144282	5210	22.1	17.82	5188	5192
2/7/97	1658637	162797	5123	42.44	70.94	5081	5052
12/19/97	1663195	158846	5069		35.78		5033
1/21/97	1660284	159141	5035	3.57	7.98	5031	5027
2/4/97	1639069	147374	5092	14.17	20.96	5078	5071
1/8/97	1659826	161220	5094	53.62	58.6	5040	5035
2/5/97	1666342	150925	5132	25.65	45.82	5106	5086
1/8/97	1662412	160617	5155	82.53	87.95	5072	5067
1/30/97	1650136	168565	5147	87.14	90.44	5060	5057
2/7/97	1667894	154345	5056	flowing	1.68		5054
2/5/97	1665999	153287	5071	2.7	16.64	5068	5054
1/29/97	1629150	151913	5089	17.24	17.3	5072	5072

1/29/97	1630442	151663	5112	flowing	flowing		
1/30/97	1654542	167463	5206	102.56	106.06	5103	5100
2/4/97	1647078	148404	5043	flowing	0		5043
1/21/97	1658822	163996	5166	24.96	35.85	5141	5130
2/7/97	1634183	150349	5097	3.53	7.55	5093	5089
1/24/97	1652799	162674	5070	21.13	25.98	5049	5044
1/30/97	1655030	165147	5139	74.5	86.36	5065	5053
1/28/97	1649602	163696	5062	20.69	22.85	5041	5039
1/30/97	1657615	161266	5071	27.5	30.89	5044	5040
1/30/97	1656361	160406	5056	8.16	14.64	5048	5041
1/8/97	1641736	167398	5051	12.26	13.78	5039	5037
2/4/97	1641504	148895	5060	9.9	15.46	5050	5045
2/6/97	1657015	148101	5086	14.5	21.35	5072	5065
12/19/97				7.1	10.42		
12/19/97	1664996	158375	5056	18.22	21.55	5038	5034
1/8/97	1640126	168708	5109	53.5	65.71	5056	5043
1/6/97	1641983	168071	5075	31.67	32.88	5043	5042
2/6/97	1663048	149905	5110	23.87	34.09	5086	5076
2/6/97	1635404	146336	5195		56.03		5139
2/6/97	1635295	146636	5181	38.17		5143	5181
2/6/97	1634920	147531	5147	10.23	24.02	5137	5123
2/6/97	1635912	149829	5072	4.46	9.13	5068	5063
2/7/97	1636142	142707	5194	flowing	flowing		
1/29/97	1628056	152037	5107	flowing	3.66		5103
2/4/97	1648582	144314	5065	5.6	10.2	5059	5055
2/6/97	1638907	146153	5104	2.49	3.13	5102	5101
2/6/97	1637332	149856	5056	3.8	10.28	5052	5046
2/6/97	1638888	141849	5205	flowing	0.8		5204

Name and Location
ASHWORTH 3390 LYON LN
BARCOMB 3095 LAKESHORE DR
BATCHELDER 3010 WHITE PINE DR.
BAUER 4799 FRANKTOWN RD
BEAM 7570 OLD US 395 HY
BOWERS PARK 400 US 395 N CC HY
BRITT 3045 EASTLAKE BLVD.
CARR 4955 SUSAN LEE CR
CHAPMAN 885 OLD OPHIR RD
COX 5655 MEACHAM ST
CRYER 2270 EASTLAKE BV
DAVIS 6190 FRANKTOWN RD
DYER 960 WASHOE DR
ESTUM 5590 FRANKTOWN RD
EVANS 5555 FRANKTOWN RD
FLOYD 315 VIOLA WY
FRIBERG 1005 DUNBAR DR
FRY 1440 LORD ST
GALLO 3155 CHURCHILL DR
GOLDMAN(Flowing) 4920 FRANKTOWN RD.
HARGER 1955 EASTLAKE BV
HENDRICKSON 7425 FRANKTOWN RD
HENKLE 230 FINCH WY
HOOD 3000 OLD US 395 HY
IMUS 1915 LAKESHORE DR
KAPLAN 7480 PALOMA LINDA WY
LENSING 170 COYOTE DR
LIST 0 US 395
MALOFF 3500 EASTLAKE BV
MANOUKIAN 2935 FALCON ST
MCGUIRE 3625 CLARK DR
MILTON 2485 CHIPMUNK DR
MOORE 600 WASHOE DR
MURPHY 7115 SAN ANTONIO RCH RD
MYERS 2405 CHUKAR DR
NDF REGIONAL OFFICE 855 EAST LAKE
NELLEMANN 1745 SLIDE VIEW WY
NELSON 42 BELLEVUE RD
PASLEY 1905 BRENDA WY
RILEY 715 US 395 N CC HWY
ROLLINS 1485 LORD ST
RUSHTON 4680 CAVATAIO RD
SANDERS 40 MIDDLEFIELD PL
SCHULER 195 WAYNE RD
SIMPSON 70 LONESOME POLECAT LN

25 LONESOME POLECAT			
SPANIER 200 DRAKE WY			
TAYLOR 305 NIKKI LN			
TELKA 2345 CHIPMUNK DR			
TOUYAROT 7445 FRANKTOWN RD			
TURNER 3285 PERSHING LN			
VACANT 105 ESMERALDA DR			
VHAY 3355 ORMSBY PL			
WALLS 2265 RABBIT DR			
WASHOE COUNTY PARK (Ed Kruse)			
WASHOE Lake STATE PARK			
WASSON 70 LEWERS CREEK RD			
WEATHERWAX 3190 OPHIR HILL RD			
NDF NURSERY 6"			
NDF NURSERY 8"			
VHAY 5440 EASTLAKE			
VHAY AG WELL			
WINTERS RANCH HWY 395			
AG WELL NEAR WEIR RES. (LIGHT. W)			
SEVENTEENTH TEE WELL (LIGHT. W)			
CORRAL WELL			
SHELDON WELL			
HEIDENRICH STOCK WELL			
LIST RANCH STOCK WELL			
USGS WELL (NEAR BM)			
DAVIS WINDMILL			
AG WELL 395			
MC CLARY 6185 FRANKTOWN			

APPENDIX B

1997 Geochemical Data and Thermal Survey Data

WVTHERM.XLS								
		Table provides coordinates, water temps in degrees F@ 100 feet, based on linear regression analysis, and gradient in degrees C/ 100 feet, and deg. F/100 feet						
X	Y	T @ 100' (F)	Grad (F)	T @ 100' (C)	Grad(C)	C/meter	Location	
159141	1660284	60.7	10.0	15.94	5.5	0.180	1745 Slideview	
161220	1659827	60.4	1.8	15.78	1.0	0.033	1905 Brenda	
161266	1657615	63.7	2.4	17.61	1.3	0.043	2265 Rabbit	
163995	1658275	58.1	0.0	14.5	0.0	0.000	2485 Chipmunk	
162370	1654844	61.7	1.9	16.5	1.1	0.036	3010 White Pine	
160735	1649450	97.8	9.7	36.56	5.4	0.177	3585 Ormsby	
159913	1656459	61.1	6.2	16.17	3.5	0.115	3095 Lakeshore	
162063	1651762	76.8	10.8	24.89	6.0	0.197	3580 White Pine	
161949	1649445	69.3	14.7	20.72	8.1	0.266	3605 Ormsby	
161708	1653424	64	3.4	17.77	1.9	0.062	3625 Clark	
161035	1649418	124.6	42.7	51.44	23.7	0.778	3685 Ormsby	
160496	1650571	67	3.7	19.44	2.0	0.066	3790 Lakeshore	
163996	1658822	57.6		14.22			2345 Chipmunk	
161036	1659237	60.5	3.9	15.83	2.1	0.069	1955 Eastlake	
163076	1649441	68	10.2	20	5.7	0.187	3940 Pershing	
163459	1649613	58.7	4.4	14.83	2.4	0.079	3955 Ormsby Pl	
164126	1649176	58.6	3.5	14.78	2.0	0.066	3990 Churchill	
168565	1650136	63.3	1.0	17.39	0.6	0.020	4680 Cavatio	
160406	1656361	70.6	12.0	21.44	6.6	0.216	Washoe Co. Park (Ed Kruse)	
158122	1665006	58.7	4.4	14.83	2.5	0.082	NDF 6" on Eastlake	
166661	1653818	60.2		15.67			40 Pintail	
		65.2	0.2	18.44	0.1	0.033	3865 Lakeshore	