# APPENDIX B

# SOUTH LAKE TAHOE GROUNDWATER FLOW MODEL

U.S. Army Corps of Engineers, Hydrologic Engineering Center

# Simulation of Lake-Groundwater Interaction, South Lake Tahoe, California

September 2003

**Prepared for:**
**US Army Corps of Engineers, Sacramento District, Environmental Engineering Branch**
**1325 J. St., Sacramento, CA 95814**

**PR-55**

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# 1. INTRODUCTION

The Lake Tahoe Basin lies near the crest of the Sierra Nevada Mountains along the California-Nevada border about 150 miles northeast of San Francisco. Lake Tahoe has a surface area of approx. 191 square miles. The total land area of the Tahoe Basin's watershed is approx. 300 square miles, 70% of which is publicly owned. The volume of inflow and outflow from the lake is very small relative to lake volume. This results in a fragile ecosystem in which the actions of man and nature are tightly linked.

Over the past 40 years, a sharp increase in development has occurred around the lake, especially in the southern basin. During this period, lake water quality decreased dramatically. Increased nutrient and sediment discharge caused increased algae growth in lake water. In Lake Tahoe, algae productivity has been found to accelerate with the addition of phosphorous and nitrogen. Numerous studies have been conducted and remediation measures have been implemented to reduce the discharge of nutrients to the lake. Studies indicate that groundwater may play a significant role in this discharge. Water exchange between the lake and the adjacent groundwater at South Lake Tahoe is not well understood. Groundwater flow provides a mechanism for the transport of nutrients to the lake. The delineation of potential subsurface transport pathways will help aid future remediation efforts.

In July 2002, the U.S. Army Corps of Engineers-Hydrologic Engineering Center (HEC) was contacted by the Sacramento District of the U.S. Army Corps of Engineers to provide technical assistance with an on-going environmental study at the southern Lake Tahoe Basin in California. Specifically, HEC was requested to develop a groundwater flow model to better understand lake-groundwater interaction.

A numerical model was developed to estimate the volume, rate, and distribution of groundwater flux to the lake along its southern shore. Model results will be used to guide future nutrient remediation efforts. The model consisted of 6 layers with cells 200 ft square. Model layers generally varied from 10-50 ft thick. The model was calibrated to water levels and stream flows measured in fall 1996 and spring 2002.

# 2. SITE DESCRIPTION

## 2.1 Overview

The study area encompasses about 6 miles by 6 miles (Figure 1). General site boundaries include: Lake Tahoe to the north, the South Lake Tahoe airport to the south, and the mountain front recharge zones to the east and west. The eastern end of the study area extends to the California-Nevada border. The study area includes the city of South Lake Tahoe, the most populous city (pop. 23,609; 2000 census) in the Tahoe Basin.

## 2.2 Geology

Lake Tahoe is a prime example of a graben lake due to the dominant influence of crustal sinking in its formation. The lake occupies the depression between two up faulted mountain systems: the Carson Range to the east, and the Sierra Nevada to the west. The floor of this depression is 4700 ft MSL, the same as the Carson Valley to the east. There are four main groups of rocks in the Tahoe Basin: Pre-Cretaceous metamorphic rocks, Cretaceous granitic intrusions, Cenozoic volcanic rocks, and Quaternary glacio-fluvial deposits. Glaciation was prevalent along the western, southern, and northern sides of the basin. Huge valley glaciers as much as 1000 ft thick crept down canyons scouring away loose rock and building up great piles of morainal debris. Glaciers extending into the lower Truckee River, the lake's only outlet, formed an ice dam that raised the lake 600 ft above its present level. As the glaciers receded, the melted runoff water washed silt and sand into the lake and built thick deltas, the largest of which underlies the city of South Lake Tahoe.

The geology of the study area can be characterized by glacial, lacustrine, and alluvial deposits at the lower altitudes, flatlands, and low lying hills; and by granitic rocks that make up the steep mountain slopes. The major landforms attributed to glaciation in the study area are deep basin-fill deposits, steep mountain slopes adjacent to the upper reaches of Trout Creek, and large lateral moraines that divide the Upper Truckee River from Trout Creek and the Upper Truckee River watershed from Fallen Leaf Lake (TRPA and USFS, 1971). The unconsolidated deposits are heterogeneous at the project scale and generally consist of sand deposits with layers of clay and silt. The deposition of fine-grained lacustrine strata between coarser grained depositional events resulted in anisotropic conditions that restrict flow in the vertical direction.

## 2.3 Hydrology

The Tahoe Basin is located in what is classified as a humid continental climatic zone. The major characteristics of this type of climate are a cold winter with moderate to heavy precipitation, and a warmer, drier summer. Most of the precipitation in winter months is snow, though heavy winter rains can occur and often cause flooding. Intense summer thunderstorms have also caused localized flooding. The mean monthly temperature at South Lake Tahoe ranges from 28 degrees in January to 59 degrees in July. Average annual precipitation at the South Lake Tahoe airport is 34 inches.

Elevation has a major impact on precipitation. Annual snowfall in the Tahoe Basin can range from 100 in. at lake level to over 500 in. at higher elevations. The snow pack in the Tahoe Basin is usually developed in November and continues to increase through winter and early spring to such a depth that it often persists into June. The maximum water equivalent of snow pack depletion will occur at a rate of about 0.75 inches of water per day as measured in late April (Miller, 1955).

The Upper Truckee River and Trout Creek are the two largest surface inflows into Lake Tahoe. The 1996-2002 average flow of the Upper Truckee River at the I-50 crossing was 90 $ft^3$/sec. The 1996-2002 average flow of Trout Creek at Martin Avenue was 36 $ft^3$/sec.

# 3. PRIOR GROUNDWATER MODELING STUDIES

## 3.1 Woodling (1987) Model

Woodling (1987) developed a two-dimensional, steady-state groundwater flow model of the South Lake Tahoe area. The U.S. Geological Survey (USGS) groundwater flow model MODFLOW (McDonald and Harbaugh, 1988) was used to simulate the net water exchange between groundwater and Lake Tahoe. The model grid consisted of 25 rows (north-south) and 17 columns (east-west). Row spacing varied from 2,000 ft at the southern boundary to 1,000 ft at the lakeshore. Column spacing was a constant 2,000 ft. The model consisted of 1 layer with a total of 193 active cells.

Transmissivity values were derived from analysis of pumping tests. The distribution of transmissivity values correlated with sediment thickness, increasing gradually from the mountain fronts to the Tahoe Keys. Sediment depths ranged from zero at the mountain fronts to greater than 800 ft towards the Tahoe Keys area. Hydraulic conductivity of the sediments was assumed to be 10-15 ft/day. The specification of transmissivity in the model assumed that drawdown at wells was insignificant compared to aquifer thickness. This is a reasonable assumption.

Lake Tahoe was simulated using a constant head boundary specified as 6226 ft MSL. The southern model boundary near the airport was simulated using a constant head boundary. Outcrops on the east and west sides of the site were simulated using a specified flux boundary.

Simulated results indicated a net discharge to the lake of 1.9 $ft^3$/sec (164,000 $ft^3$/day). Over half of this discharge occurred in the Tahoe Keys area. The model simulated total flux to the lake, rather than net flux i.e. outflows – inflows. Significant inflows from the lake likely occurred due to pumping at the Al Tahoe and Paloma wells. The model did not simulate streams. Additionally, the new Valhalla pumping well near the western shoreline of the study area was not in operation at the time of model development.

## 3.2 AGRA (1999) Model

AGRA (1999) developed a three-dimensional groundwater flow (MODFLOW) model of the study area. The focus of the study was groundwater resource evaluation of the Al Tahoe and Paloma well fields. The model grid consisted of 46 rows (north-south) and 39 columns (east-west). Row and column spacing varied from 1,000 ft at the mountain fronts, and 500 ft at the well fields. The model consisted of 4 layers with a total of 4,073 active cells. Layer bottom elevations (MSL) were specified as: 6200 ft, 6100 ft, 5900 ft, and bedrock (5850 ft-5400 ft).

Hydraulic conductivity values were specified as a function of grain size distribution ranging from 2 ft/day for fine-grain sediments to 45 ft/day for coarse-grain sediments. The hydraulic conductivity of weathered granitic rocks was specified as 0.2 ft/day. Specified leakance values allowed for simulation of vertical flow in the model domain. Values of effective vertical hydraulic conductivity incorporated into the leakance term were less than 0.1 times the value of horizontal hydraulic conductivity.

Lake Tahoe was simulated using a constant head boundary specified as 6226 ft MSL. The lake boundary was specified to be a vertical plane. The conductance of lakebed sediments was not addressed. Streams were represented using the MODFLOW River Package. This algorithm requires the specification of stream stage, and allows for specification of riverbed sediment conductance. The algorithm does not simulate stream flow. The Tahoe Keys were also represented using the MODFLOW River Package. The southern model boundary south of the airport was simulated using a constant head boundary. Outcrops on the east and west sides of the site were simulated using specified flux boundaries. Recharge to groundwater from precipitation and snowmelt was assigned to be 25% of surface recharge. The model was calibrated under steady-state and transient conditions. Model results were used to estimate the effects of increased South Tahoe Public Utilities District pumping in the alluvial aquifer near Lake Tahoe.

# 4. DATA ANALYSIS

## 4.1 Surface of Lakebed Sediments

Previous models (Woodling,1987; AGRA,1999) represented the lake as a vertical boundary. However, analysis of the bathymetric surface indicates that the lakebed slopes gently away from the shoreline, especially at shallow depths. The depth of aquifer sediments at the shoreline ranges from 400 to 1,000 ft. The elevation of the lakebed surface decreases as little as 25 ft over a distance of 2,000 ft away from the shoreline. In deeper sediments, the location of the lake-groundwater interface is as great as 8,000 ft beyond the shoreline.

## 4.2 Fluctuations in Lake and Groundwater Elevations

Lake and groundwater elevations do not appear to vary greatly on a seasonal basis. Rather, lake and groundwater elevations show a rising trend during multi-year periods of above average precipitation and a declining trend during drought periods. Loeb et al. (1987) noted that lake and groundwater elevation differences were fairly consistent throughout most years. This “rough correlation between groundwater level and lake level changes made a steady-state model for this basin more credible.” (Loeb et al., 1987) Between 1957 and 2002, lake elevation varied from a high of 6228.1 ft MSL and a low of 6219.1 ft MSL. The average lake elevation during this period was 6225.0 ft MSL.

### 4.3 Stream Flow Data

The U.S. Geological Survey (USGS) maintains six continuous gage stations on the Upper Truckee River and Trout Creek. Three of these stations are in the study area. Stream flows vary greatly seasonally, with high stream flows generally during March and April, and low stream flows generally during September and October. The 1996-2002 average flow of the Upper Truckee River at the I-50 crossing was 90 $ft^3$/sec. The 1996-2002 average flow of Trout Creek at Martin Avenue was 36 $ft^3$/sec. The MSL elevation of these stations has been surveyed.

From 1996 to 2000, the USGS conducted annual stream-flow measurements on the Upper Truckee River and Trout Creek under low-conditions in the fall of each year. These studies provided information on the location and rate of water exchange between the streams and the adjacent aquifer. Rowe and Allandar (1996) provide September 1996 stream flow measurement data and seepage estimates at 63 locations. Results of this study indicate the Upper Truckee River is generally steady or gaining slightly throughout the model domain. Trout Creek loses slightly during low flow periods, except between the Cold Creek and Heavenly Creek confluences, where it gains slightly.

### 4.4 Pumping Well Data

Pumping wells have a direct effect on groundwater flow gradients near Lake Tahoe. A significant amount of pumped water has the lake or adjacent streams as its source. There are nine major pumping wells in the model domain. Total pumping from these wells averaged 844,000 $ft^3$/day (4,380 gpm) between 1996 and 2002. The two most prominent pumping wells in the model domain, the Al Tahoe and Paloma wells, provide the municipal water supply for the city of South Lake Tahoe (Figure 1). The average (1996-2002) groundwater extraction rates by the Al Tahoe and Paloma wells are 360,000 $ft^3$/day (1,870 gpm) and 145,000 $ft^3$/day (750 gpm) respectively. The Al Tahoe well is located about 1,400 ft from the lake shoreline. However, the deep aquifer the well is screened in interfaces with the lakebed a distance of about 5,000 ft from the well. The Paloma well is located about 3,200 ft from the lake shoreline, and about 600 ft from Trout Creek and 1,200 ft from the Upper Truckee River. Another pumping well which effects lake-groundwater interaction is the Valhalla well located at the western end of the model domain, about 1,200 ft from the lake shoreline. The Valhalla well pumps at an average (1999-2002) rate of 49,000 $ft^3$/day (260 gpm).

### 4.5 Selection of Calibration Dates

Model calibration requires data on groundwater levels, stream flows, lake elevation, recharge from precipitation and snowmelt, and groundwater pumping. As a result of data analysis, it was determined that the dates fall 1996 and spring 2002 provide the most complete representation of site conditions.

## 5. DEVELOPMENT OF GROUNDWATER FLOW MODEL

## 5.1 Selection of Computer Code

In saturated groundwater, a combination of continuity (mass conservation) and Darcy's Law leads to the following mathematical description of steady-state groundwater flow:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=0 \qquad (1)$$

In equation (1), the dependent variable is the hydraulic head, *h*, which is defined in the traditional (*x*, *y*, *z*) Cartesian coordinate system. The horizontal and vertical hydraulic conductivities ($K_x$, $K_y$, and $K_z$) are known functions. Boundary conditions must also be specified to solve equation 1. The boundary conditions may be specified head, specified flux, or head-dependent flux. It is assumed that groundwater flow is unchanging in time (steady state).

The United States Geological Survey (USGS) groundwater flow modeling software MODFLOW (McDonald and Harbaugh, 1988) was selected for this study. MODFLOW provides a means to solve equation 1 for *h* in a chosen domain, with specified values for hydraulic conductivity and specified boundary conditions. MODFLOW uses the finite-difference method to approximate the groundwater flow equation as a set of algebraic equations in a discretized three-dimensional grid of rectangular cells.

MODFLOW includes several modules or "Packages" which can be integrated into a model study only when needed. For this study, the MODFLOW General Head Boundary (GHB), Stream (STR), Recharge (RCH), and Well (WEL) Packages were selected.

## 5.2 Model Grid

The model grid consists of 150 rows and 150 columns, encompassing an area of 30,000 ft by 30,000 ft. The model was oriented to the north, parallel to the predominant direction of regional groundwater flow. The horizontal discretization was selected to be: 1) fine enough to represent various hydrogeologic zones with an accuracy commensurate with the ability of the data to represent the system, 2) fine enough to accurately represent lake, stream, and well boundary conditions, and 3) coarse enough to allow for maximum computational efficiency without compromising the above considerations. A cell size of 200 ft square was selected to best meet the grid criteria.

Model layers were defined in accordance with the conceptualization of site hydrogeology developed by the U.S. Army Corps of Engineers, Sacramento District (written communication, Hunter and Crummett, December 2002). The model consists of 6 layers covering a vertical dimension of about 1,000 ft. Layer bottom elevations of the upper 5 layers are specified as constant throughout the model domain. Layer thickness varies from 25 ft in the upper four layers (less in the uppermost layer, depending on water table elevation); to 50 ft in layer 5; to a bottom layer thickness of up to 918 ft (dependent on bedrock elevation). The finer discretization in the upper layers allows for more accurate simulation of interaction between groundwater, and the streams and lake. Specific layer bottom elevations (MSL) are specified as 6243 ft, 6218 ft, 6193 ft, 6168 ft, 6118 ft, and bedrock (6000 ft-5200 ft). The elevation of the bottom layer at the lake-groundwater interface varies from 5800 to 6000 ft. The elevation of the bedrock basement of the model is based upon an isopach map produced by Bergsohn (2002).

Because the bottom of layer 1 is specified to be 6243 ft MSL, large portions of the bottom of layer 1 are located above the water table. In MODFLOW, these areas completely above the water table are flagged as dry and become inactive. Consequently, large portions of the top layer are inactive. The exact location of the water table in the model is determined by MODFLOW, which can automatically dry and re-wet cells as necessary. However, some portions of layer 1 were pre-specified as inactive (dry) to speed the flow solution process.

## 5.3 Boundary Conditions

### 5.3.1 Subsurface Inflow from Mountain Fronts

Along the mountain fronts, groundwater percolates to the unconsolidated sediments at a fairly constant rate throughout the year. Prudic (personal communication, March 2003) indicated that water levels in wells along the mountain fronts in the Cold Creek area did not vary appreciably with change in season. Seasonal fluctuations in wells near the mountain front are generally less than 2 ft. In the numerical model, this was conceptualized as a constant head boundary condition along the edge of the model grid in the upper model layers (Figure 2).

The combined simulated groundwater inflow from the eastern and western mountain fronts is approximately 660,000 ft3/day. Simulated stream outflow averages about 100,000 ft3/day. The recharge from precipitation available along the mountain fronts was estimated external to the model domain. An average precipitation of 40 inches/yr was assumed. By multiplying this value by the estimated area of the contributing watersheds, a total estimated recharge of 3,100,000 ft3/day was derived. Therefore, the simulated groundwater inflow and surface water flows in the model is about 20-25 % of the estimated recharge from contributing areas. This was judged to be reasonable.

### 5.3.2 Bedrock Basement

The bedrock configuration was extrapolated from interpretations of a gravity survey of the study area (Bergsohn, 2002). The model assumed flow through the bedrock basement was negligible. Bedrock was simulated using a specified flux boundary, with the specified flux set equal to zero.

### 5.3.3 Recharge

The average precipitation at the site is approximately 34 inches per year, most of which is snow. Recharge to the aquifer occurs predominantly in spring during snowmelt periods. AGRA (1999) estimated the proportion of snowmelt that infiltrates to the aquifer to be 0.25. Recharge is represented in the model as a specified flux boundary applied to the uppermost active layer. In the model, recharge to groundwater was varied between 0.06 ft/day and 0.015 ft/day to represent climatic extremes.

### 5.3.4 Pumping Wells

The source of the city of South Lake Tahoe's municipal water supply is groundwater. Measured groundwater levels in the vicinity of the Al Tahoe and Paloma wells were 5-10 ft below lake level. Thus, a significant portion of well water appears to have the lake as its source. The Valhalla well, located at the west end of the study area about 1,200 ft from the lake, may also have a significant influence on lake-groundwater interaction. There are nine major wells in the study area, all of which were integrated into the groundwater flow model. Pumping well data included location, screened depth, and rate of withdrawal. Pumping wells were assigned to model layers, as specified flux boundaries, in proportion with the percent screened interval.

### 5.3.5 Streams

Two major streams occur in the study area: the Upper Truckee River, and Trout Creek. The Upper Truckee has a width of approximately 10 ft and a slope of 0.001 throughout the study area. Trout Creek has a width of approximately 10 ft, and a slope that decreases from 0.002 in its upper reaches to 0.001 as it approaches the lake. A Manning coefficient for both streams was estimated to be 0.045. Streambed sediments were estimated to be about 5 ft thick with a hydraulic conductivity of about 4 ft/day. According to stream flow measurement data and seepage estimates made by Rowe and Allandar (1996), flow in the Upper Truckee River is generally steady or increases slightly through the study area. Flow in Trout Creek decreases slightly during low flow periods, except in the area between the Cold Creek and Heavenly Creek confluences, where it is gaining.

The MODFLOW Stream flow-Routing Package (STR Package) was selected to simulate stage and flow in the Upper Truckee River and Trout Creek. Input requirements for the STR Package include: flow into the upper stream reach, initial stage, streambed conductance, streambed elevation, streambed thickness, channel width, bed slope, and Manning's roughness coefficient. Streambed conductance between the stream and an aquifer is computed by:

$$COND_{strmbed} = Klw/m \qquad (2)$$

where:

$COND_{strmbed}$ is streambed conductance ($ft^2$/day);
K is hydraulic conductivity of streambed (ft/day);

l is reach length (ft);
w is reach width (ft);
m is thickness of streambed sediments (ft).

The model reach length is equal to the length of the stream across one model cell. In this study, reach length was set equal to 200 ft. The estimated value of streambed conductance for the Upper Truckee River and Trout Creek was 1600 $ft^2$/day.

The STR Package uses a head-dependent flux boundary condition where flow between the stream and the aquifer ($Q_{str}$) is calculated by:

$$Q_{str} = COND_{strmbed} (h_{str} - h_{gw}) \quad (3)$$

where:
$h_{str}$ is stream stage (ft);
$h_{gw}$ is head in the adjacent aquifer (ft).

Stream stage is computed by the Manning formula. Stream flow is routed using the continuity equation.

### 5.3.6 Lake-Groundwater Interaction

Loeb et al. (1987) performed field measurements of seepage rates from groundwater to the lake. Measured seepage rates were very low in the Upper Truckee River, Trout Creek and Pope Beach discharge areas at the center and western end of the site and slightly higher at the eastern end of the site where the measured groundwater gradient is steeper. Seepage measurements also indicated higher seepage rates near shore than away from the shore.

Measured seepage at the east end of the study area was approximately 0.004 $ft^3$/day per $ft^2$. Measured seepage in the central/west end of the site was approximately 0.002 $ft^3$/day per $ft^2$. It was assumed the large majority of flux occurs across the upper 50 ft of the aquifer. The total area of seepage was estimated to be $2 \times 10^7$ $ft^2$ for the east area, and $5 \times 10^7$ $ft^2$ for the central/west area. This resulted in an estimate of total seepage of 80,000 $ft^3$/day (0.9 $ft^3$/sec) for the east area and 100,000 $ft^3$/day (1.1 $ft^3$/sec) for the central/west area. Thus, a very rough estimate of the total seepage rate from groundwater to the lake in the study area is 2 $ft^3$/sec.

The lake-groundwater interface is characterized by a gently sloping lakebed surface. In upper model layers, the elevation of the lakebed surface decreases as little as 25 ft over a distance of 2,000 ft from the shoreline. In lower model layers, the location of the lake-groundwater interface is as great as 8,000 ft beyond the shoreline. The gentle slope of the lakebed results in the largest proportion of flow to the lake being discharged vertically. The bathymetric surface and accompanying boundary condition representation are depicted as Figure 3.

Lake-groundwater interaction was simulated using the MODFLOW General Head Boundary (GHB) Package. Horizontal and vertical discharge to the lake was simulated using a 2-cell width boundary condition configuration as illustrated in Figure 4. For each layer, the "horizontal flow GHB cell" was located where the layer center intersects the bathymetric surface. A second "vertical flow GHB cell" was located in the cell directly behind (relative to the shoreline) the horizontal flow cell. Due to the much larger flow area, the specified conductance term in the vertical flow cell was much greater than in the horizontal flow cell. This configuration allowed for a more realistic representation of the flow regime, and a more precise delineation of groundwater discharge with depth.

The GHB Package requires the specification of head (lake elevation), and lakebed conductance.

$$COND_{lakebed} = KA/d \qquad (4)$$

where:

$COND_{lakebed}$ is lakebed conductance ($ft^2$/day);
K is hydraulic conductivity of the lakebed sediments (ft/day);
A is the product of aquifer thickness and cell width ($ft^2$);
d is the thickness of the lakebed sediments (ft).

The GHB Package uses a head-dependent flux boundary condition where flow between the lake and the aquifer ($Q_{lake}$) is calculated by the formula:

$$Q_{lake} = COND_{lakebed} \, (h_{lake} - h_{cell}) \qquad (5)$$

where:

$h_{lake}$ is lake elevation;
$h_{cell}$ is head at the corresponding model cell.

The hydraulic conductivity (K) of lakebed sediments was estimated as 10 ft/day. The thickness (d) of lakebed sediments was estimated as 1 ft. The area (A) of flow in the horizontal direction is equal to the product of layer thickness times the 200 ft cell width. The area (A) of flow in the vertical direction is equal to the product of the 200 ft cell width times the 200 ft cell length. Values of $COND_{lakebed}$ for "horizontal flow GHB cells" ranged from 1,600 $ft^2$/day to 23,000 $ft^2$/day, depending upon layer thickness at the lake groundwater interface. The value of $COND_{lakebed}$ for "vertical flow GHB cells" was specified as 40,000 $ft^2$/day.

An important consideration of vertical discharge to the lake is that it only occurs in the cell containing a GHB boundary condition. The rate of groundwater flow that occurs vertically from an underlying layer is governed by vertical hydraulic conductivity. As will be presented in Table 1, the specified values of vertical hydraulic conductivity were much lower than horizontal hydraulic conductivity values.

### 5.4 Hydraulic Conductivity Distribution

The USACE, Sacramento District was charged with providing a refined interpretation of site hydrogeology: "The goal was to provide relatively high resolution in the upper 100 ft and then lump deeper units to behave as a reservoir in the computations. The rational behind this is that Scott et al. (1978) and Einarson (2003) have demonstrated that thick, continuous fine-grained units exist at depth. These units should impose considerable impedance to vertical flow and therefore restrict flow contaminated by surface processes and anthropogenic inputs to the upper water bearing zones" (Lew Hunter, written communication, March 2003). Layer bottom elevations (MSL) of the conceptual model were specified as: 6243 ft, 6218 ft, 6193 ft, 6168 ft, 6118 ft, and bedrock (6000 ft-5200 ft). This will allow for a more accurate discretization of hydrogeologic units in the upper aquifer, and a more detailed distribution of interaction between the lake and groundwater in the vertical dimension.

According to the USACE, Sacramento District interpretation, variations in hydraulic conductivity were based on relative distribution of grain size. The stratigraphic information used to do this for South Lake Tahoe was extracted from the geologic cross sections in Scott et al. (1978). The hydraulic conductivity units were placed in 7 groups as defined in Table 1 and presented in Figures 5-10.

Table 1. Hydraulic conductivity units

| | | Hydraulic Conductivity (ft/day) | |
|---|---|---|---|
| Unit | Description | Horizontal | Vertical |
| 1 | Clean sand and gravel | 130 | 20 |
| 2 | Sand and gravel with less than 25% fines | 50 | 0.5 |
| 3 | Silty Sand | 50 | 0.5 |
| 4 | 25-50% Fines | 5 | 0.2 |
| 5 | 50 to 75% Fines | 5 | 0.02 |
| 6 | Greater than 75% Fines | 0.1 | 0.01 |

### 5.5 Representation of Tahoe Keys

The Tahoe Keys are a series of shallow, narrow channels located adjacent to the lake in the center of the study area (Figures 1 and 6). The series of channels have one outflow to the lake. Groundwater discharging to the Tahoe Keys is not necessarily assumed to be discharged to the lake. In the numerical model (Figure 6), the Tahoe Keys are simulated as a zone of very high hydraulic conductivity (10,000 ft/day). This allows for the transmission of water towards the lake across a very flat gradient.

# 6. MODEL CALIBRATION

## 6.1 General

As discussed in Section 4.2, Loeb et al. (1987) noted that there were no pronounced seasonal fluctuations in the flow gradient between groundwater and the lake; this "made a steady-state model more credible". Additionally, the availability of transient groundwater elevation data was deemed inadequate for a transient calibration study. Therefore, the groundwater model was calibrated as steady-state. Under steady-state conditions, stresses, flow rates, and water levels are assumed to be constant in time.

The conceptual distribution of hydraulic conductivity zones were provided by USACE Sacramento District, and were not subject to major adjustment during the calibration process. Model calibration focused on adjustment of boundary conditions presented in Section 5. Model calibration requires data on groundwater levels, stream flows, lake level, recharge, and pumping. From data analysis, it was determined that the measurements taken in fall 1996 and spring 2002 provided the most complete representation of site conditions.

## 6.2 Numerical Solution

The MODFLOW Strongly Implicit Procedure (SIP) (McDonald and Harbaugh, 1988), and the Preconditioned Conjugate Gradient (PCG2) (Hill, 1990) numerical solution algorithms were used in concert to attain starting head conditions, and solution convergence. The MODFLOW PCG2 algorithm was used for the final numerical simulations. Head closure criterion was set to 0.001 ft. The final numerical simulation attained a mass balance error of 0.13 % or less for all calibration runs.

## 6.3 Calibration to Fall 1996 Conditions

Specified boundary conditions for the fall 1996 calibration included lake elevation, pumping rates, and recharge to aquifer. The measured lake elevation was specified as 6226.5 ft MSL, the pumping rates at all wells were specified equal to the average pumping rates for 3 months prior to the calibration date. Recharge to the aquifer was assumed to be negligible. Calibration targets included 26 groundwater elevation measurements taken in fall 1996 (Rowe and Allandar, 1996), and stream flow data from fall 1996 seepage measurements along Trout Creek and the Upper Truckee River (Rowe and Allandar, 1996).

Calibration consisted primarily of adjusting the constant head boundaries along the mountain front to match measured groundwater levels at adjacent wells. Constant head boundaries were further adjusted to simulate measured seepage along Trout Creek and the Upper Truckee River. A good match between measured and simulated water levels was attained. The mean difference between measured and simulated water levels was less than 1 ft. The measured flow of Trout Creek at Highway 50 was 1,990,000 $ft^3$/day. The simulated flow was 2,000,000 $ft^3$/day. The measured flow of the Upper Truckee

River at Highway 50 was 968,000 $ft^3$/day. The simulated flow was 972,000 $ft^3$/day. Total simulated discharge to lake was 159,000 $ft^3$/day.

### 6.4 Calibration to Spring 2002 Conditions

Specified boundary conditions for the spring 1996 calibration included lake elevation, pumping rates, and recharge to aquifer. The measured lake elevation was specified as 6223.1 ft MSL, the pumping rates at all wells were specified equal to the average pumping rates for 3 months prior to the calibration date. Recharge to the aquifer was set equal to 0.004 ft/day, the equivalent of 17.5 in/yr.

Calibration targets included 14 groundwater elevation measurements taken in March 2002 by the South Tahoe Public Utilities District, and stream flow data from 2 gages along Trout Creek and 1 gage along Upper Truckee River.

As with the fall 1996 calibration study, the spring 2002 calibration consisted primarily of adjusting the constant head boundaries along the mountain front to match measured groundwater levels at adjacent wells. Constant head boundaries were further adjusted to simulate measured flows in Trout Creek and the Upper Truckee River. Through model calibration, a good match between measured and simulated water levels was attained. The mean difference between measured and simulated water levels was less than 1 ft. The measured flow of Trout Creek at Martin Avenue was 1,395,000 $ft^3$/day. The simulated flow was 1,400,000 $ft^3$/day. The measured flow of the Upper Truckee River at Highway 50 was 5,065,000 $ft^3$/day. The simulated flow was 5,050,000 $ft^3$/day. Total simulated discharge to lake was 318,000 $ft^3$/day.

## 7. MODEL APPLICATION

### 7.1 General

As illustrated by Figure 11, the lakeshore was discretized into 4 regions: Region 1 (the west), Region 2 (Tahoe Keys), Region 3 (South Lake Tahoe), and Region 4 (Stateline). The shoreline length of Region 1 is approximately 9200 ft. The shoreline length of Region 2 is approximately 6000 ft. The shoreline length of Region 3 is approximately 9700 ft. The shoreline length of Region 4 is approximately 8600 ft. The total length of the lakeshore in the model domain is approximately 33,500 ft. The model consists of 5 layers at the shoreline. This allowed for the plan- and side-view discretization of water exchange between the lake and groundwater. The model was applied under varying hydrologic conditions.

### 7.2 Simulation of Lake-Groundwater Interaction

As discussed in Section 6, the model was calibrated to fall 1996 and spring 2002 conditions. The lake level in fall 1996 was 6226.5 ft MSL. The lake level in spring 2002 was 6223.1. Thus, it can be inferred that the increased discharge to the lake during spring

2002 was largely the result of the lower lake level, which is not a function of seasonal fluctuations, but more a function of longer-term trends in lake elevation. Lake elevations varied from a high of 6228.1 ft MSL and a low of 6219.1 ft MSL between 1957 and 2002. The average lake elevation during this period was 6225.0 ft MSL. The fall 1996 and spring 2002 models, extrapolated to represent conditions for a full year, could be considered to represent high and low discharge values. Therefore, a reasonable, though not absolute, range of total flux rates to the lake would be between 145,000 $ft^3$/day and 318,000 $ft^3$/day.

The fall 1996 and spring 2002 models were rerun using 1996-2002 averaged pumping rates. This included the new Valhalla well at the western end of the site. Applying current average pumping rates to both models allows for an analysis of current flow conditions. Using this new pumping scenario, total simulated discharges from groundwater to the lake were 165,000 $ft^3$/day and 306,000 $ft^3$/day for "low discharge conditions" and "high discharge conditions" respectively. Normal annual discharge was estimated to be 226,000 $ft^3$/day (2.6 $ft^3$/sec), the average of these low and high discharge conditions. Figure 11 presents the distribution of water exchange between groundwater and the lake in plan view. Figures 12 and 13 present the vertical delineation of simulated "high discharge conditions" and "low discharge conditions" representations of water exchange between groundwater and the lake. The normal average year is based upon taking the average of annually extrapolated spring 2002 (high discharge) conditions and fall 1996 (low discharge) conditions.

### 7.3 Analysis of Hydrologic Effects of Groundwater Pumping

A precursory analysis was performed to quantify the effects of pumping on lake-groundwater interaction and stream flows. The "low discharge conditions" model was used for this analysis. Pumping rates were adjusted to the average withdrawal rates for the period 1996 to 2002.

An initial simulation was run where all pumping wells were removed from the model, and a comparison was made between the model results with pumping and without pumping. Total discharge from groundwater to the lake increased from 145,000 $ft^3$/day (with pumping) to 403,000 $ft^3$/day (without pumping). Discharge from groundwater to streams increased from 359,000 $ft^3$/day (with pumping) to 529,000 $ft^3$/day (without pumping). Discharge from streams to groundwater decreased from 64,000 $ft^3$/day to 600 $ft^3$/day. Outflow from Trout Creek increased from 2,000,000 $ft^3$/day to 2,113,000 $ft^3$/day. Outflow from the Upper Truckee River increased from 1,020,000 $ft^3$/day to 1,141,000 $ft^3$/day. The total discharge increase to the lake via surface water (234,000 $ft^3$/day) or groundwater (258,000 $ft^3$/day) was 492,000 $ft^3$/day (5.7 cfs). The total simulated pumping in the study area was 844,000 $ft^3$/day (9.8 cfs). Thus, approximately 60% of groundwater withdrawn from wells directly impacts surface waters by reducing stream flow or reducing lake volume.

The simulated effect of pumping from the Al Tahoe and Paloma wells was also investigated. Average 1996-2002 pumping rates at these two wells were

362,000 ft$^3$/day and 145,000 ft$^3$/day respectively. A simulation was run where these two wells were removed from the model, while all other pumping wells remained. A comparison of model results with and without the Al Tahoe and Paloma wells was made. Simulated flows from groundwater to the lake increased from 145,000 ft$^3$/day to 314,000 ft$^3$/day, an increase of 169,000 ft$^3$/day. Simulated flows from the lake to groundwater decreased from 195,000 ft$^3$/day to 8,000 ft$^3$/day, a decrease of 187,000 ft$^3$/day. Thus, simulated results indicate about 37% of pumped water from the Al Tahoe and Paloma wells has the lake as its source. The simulated effect of the Al Tahoe and Paloma pumping wells on stream flows was less pronounced. With the Al Tahoe and Paloma wells turned off, simulated outflows at the lake from Trout Creek increased by 60,000 ft$^3$/day to 2,060,000 ft$^3$/day; simulated outflows at the lake from the Upper Truckee River increased by 40,000 ft$^3$/day to 1,060,000 ft$^3$/day.

# 8. SENSITIVITY ANALYSIS

## 8.1 General

An "average conditions" model was developed by employing averaged boundary condition values to the current calibrated model. Pumping rates at all wells were averaged for the period of 1996-2002 and input into the model. The average lake elevation for the period of 1957-2002 (6225 ft MSL) was input into the model. Averaged 1996-2002 stream flows (Section 2.3) were simulated by the model. Constant head values used in the spring 2002 calibration study were used. Recharge was set to an estimated average annual value of 0.003 ft/day (13.1 in/yr). Simulated discharge to the lake was 240,000 ft$^3$/day. The "average conditions" model was used for the analysis of the influence of model parameters and conceptualizations on simulated results.

Sensitivity analysis is used to measure the uncertainty in the calibrated model caused by uncertainty in estimates of aquifer parameters and boundary conditions. During sensitivity analysis, parameters are systematically changed, one at a time, within a predefined plausible range factor. The accompanying change in model results are then analyzed as a measure of the sensitivity of the model to that particular parameter. Factors of 0.5 and 2.0 were selected as a plausible range of aquifer parameters and boundary conditions.

## 8.2 Analysis of Hydrologic Parameters

The "average conditions" model (Section 8.1) was used to estimate the influence of various model parameters on groundwater discharge to the lake. Hydrologic parameters were varied by factors of 2.0 and 0.5. These parameters include horizontal hydraulic conductivity (Kh), vertical hydraulic conductivity (Kv), recharge to the water table, and lakebed conductance (COND). Results of this study are presented as Table 2.

Table 2. Sensitivity of simulated groundwater discharge to hydrologic parameters

| Parameter | Initial Discharge ($ft^3$/day) | (x 2) ($ft^3$/day) | (x 0.5) ($ft^3$/day) |
|---|---|---|---|
| Kh | 240,000 | 542,000 | 99,000 |
| Kv | 240,000 | 251,000 | 230,000 |
| Recharge | 240,000 | 274,000 | 224,000 |
| Lakebed COND | 240,000 | 242,000 | 182,000 |

### 8.3 Analysis of Variations in Lake Elevation

A study was performed to estimate the effects of lake elevation on groundwater discharge to the lake. Lake elevation simulated by the "average conditions" model (Section 8.1) was varied over the range of measured values between 1957 and 2002. Results of this study are presented as Table 3.

Table 3. Sensitivity of simulated groundwater discharge to lake elevation

| Lake Elevation (ft MSL) | Discharge ($ft^3$/day) |
|---|---|
| 6219 | 451,000 |
| 6222 | 353,000 |
| 6225 | 240,000 |
| 6228 | 139,000 |

### 8.4 Analysis of Effect of Lakebed Boundary Condition

Previous modeling efforts (Section 3) employed a vertical constant head boundary to represent the shoreline of the site. The current model used a GHB boundary condition that addressed the bathymetric surface, the vertical discharge component, and the conductance of the lakebed sediments. A study was performed to assess the effect of this new boundary condition on model results.

An "old boundary condition" model was constructed using the same hydrologic parameters as the "average conditions" model (Section 8.1), except the boundary condition representing the shoreline was specified as a vertical plane with a constant head of 6225 ft. This resulted in an increase in discharge to the lake from 240,000 $ft^3$/day to 503,000 $ft^3$/day. Figure 14 presents a graphical depiction on the effect of the new lakebed boundary representation.

# 9. CONCLUSIONS AND RECOMMENDATIONS

A numerical model was constructed to estimate the volume and distribution of water exchange between groundwater and Lake Tahoe at South Lake Tahoe. The model utilized a 2-cell width boundary condition configuration to simulate lake-groundwater interaction over the gently sloping lakebed surfaced. An array of hydraulic conductivity distributions was provided by the U.S. Army Corps of Engineers, Sacramento District. The model was calibrated to groundwater levels and stream flows measured in fall 1996 and spring 2002. From the model study, an average groundwater discharge to the lake was estimated as 226,000 $ft^3$/day (2.6 $ft^3$/sec). A likely range of total discharge rates to the lake in the study area would be 100,000 $ft^3$/day to 350,000 $ft^3$/day. According to model results, the total simulated flux to the lake is relatively negligible below 100 ft. This is due to the gently sloping lakebed surface, and the impedance to vertical flow created by confining units. A study was performed to estimate groundwater discharge to the lake using seepage measurements taken by Loeb et al. (1987). Study results produced a rough estimate of 2 $ft^3$/sec, which correlates well with model results.

Sensitivity analysis indicates that changes in hydraulic conductivity and lake elevation parameters have the greatest influence on simulated groundwater discharge to the lake. Future studies should focus on creating an accurate conceptualization of the distribution of hydraulic conductivity values. Additionally, a regularly scheduled groundwater-level measurement program would help provide a more clear understanding of the effect of seasonal fluctuations on surface water-groundwater interaction in the study area. A key calibration target was stream flows. The model was not calibrated to stream stage because gage stations were thought to be unsurveyed. This was later found to be untrue. The stream gage stations have been surveyed.

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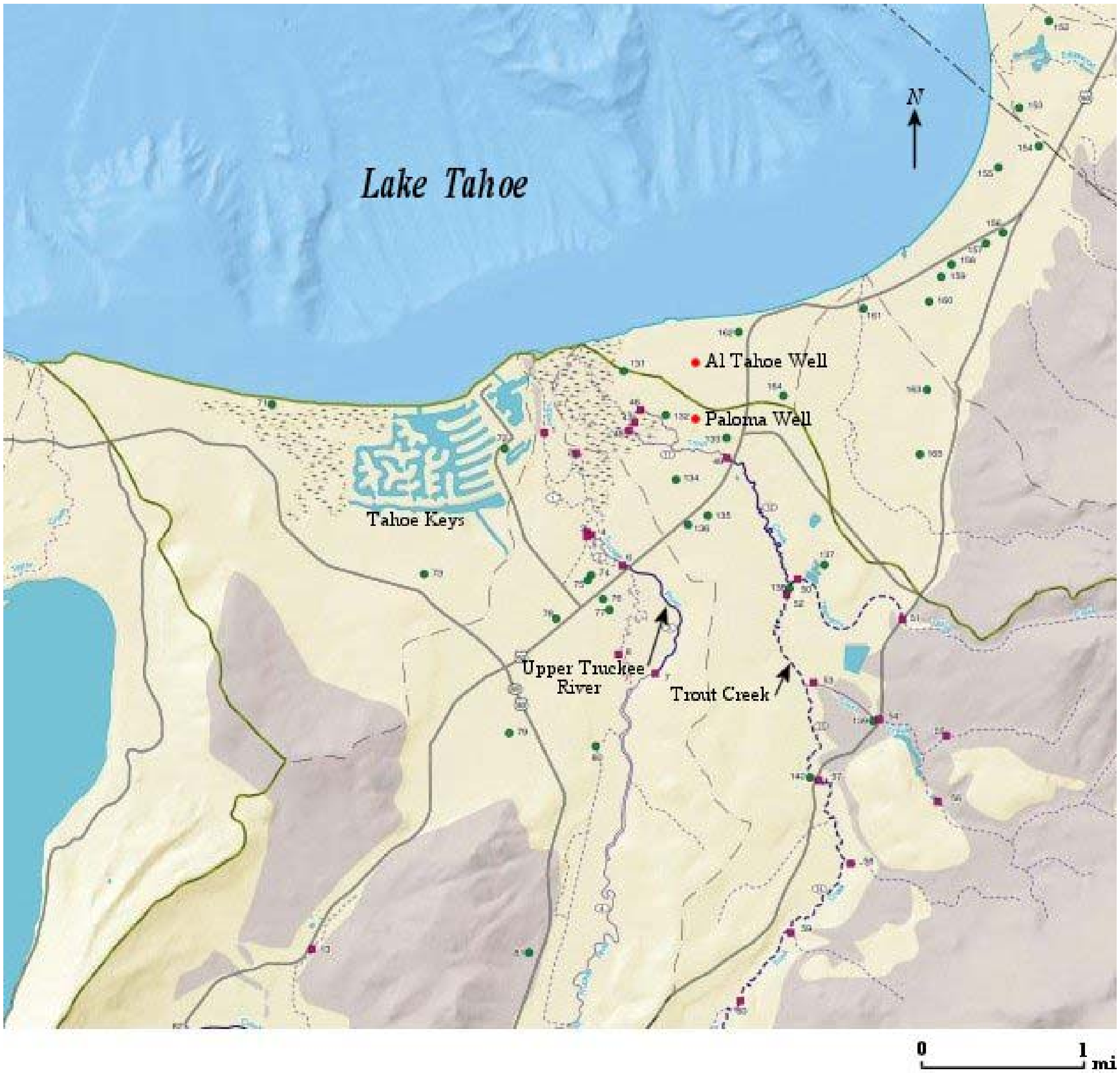



Figure 1  Study area

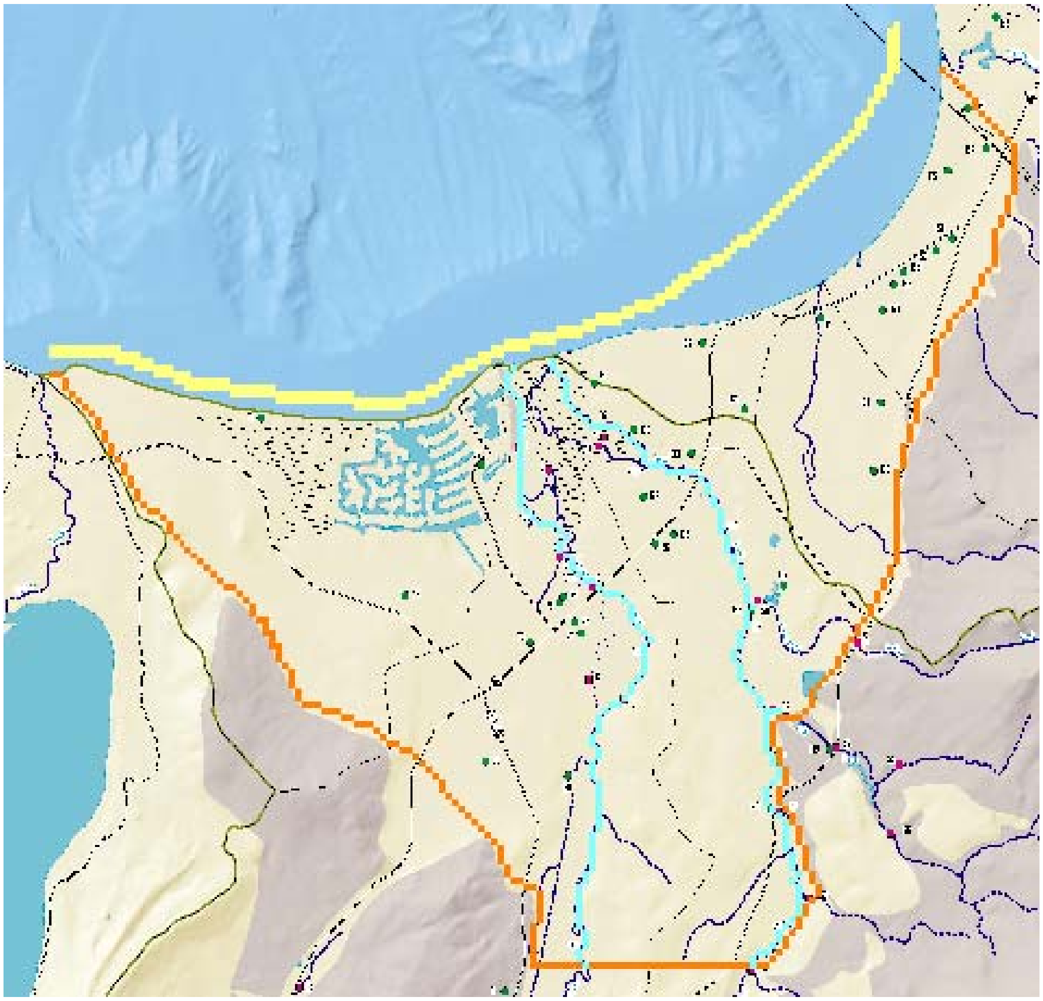
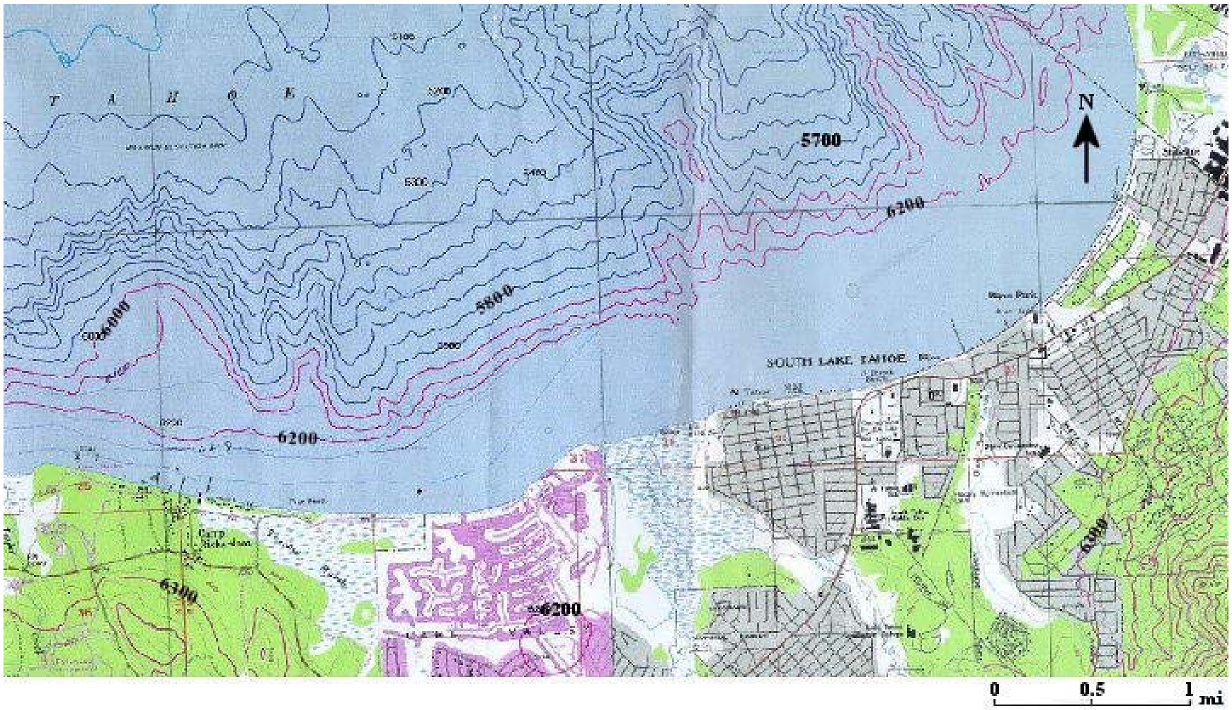
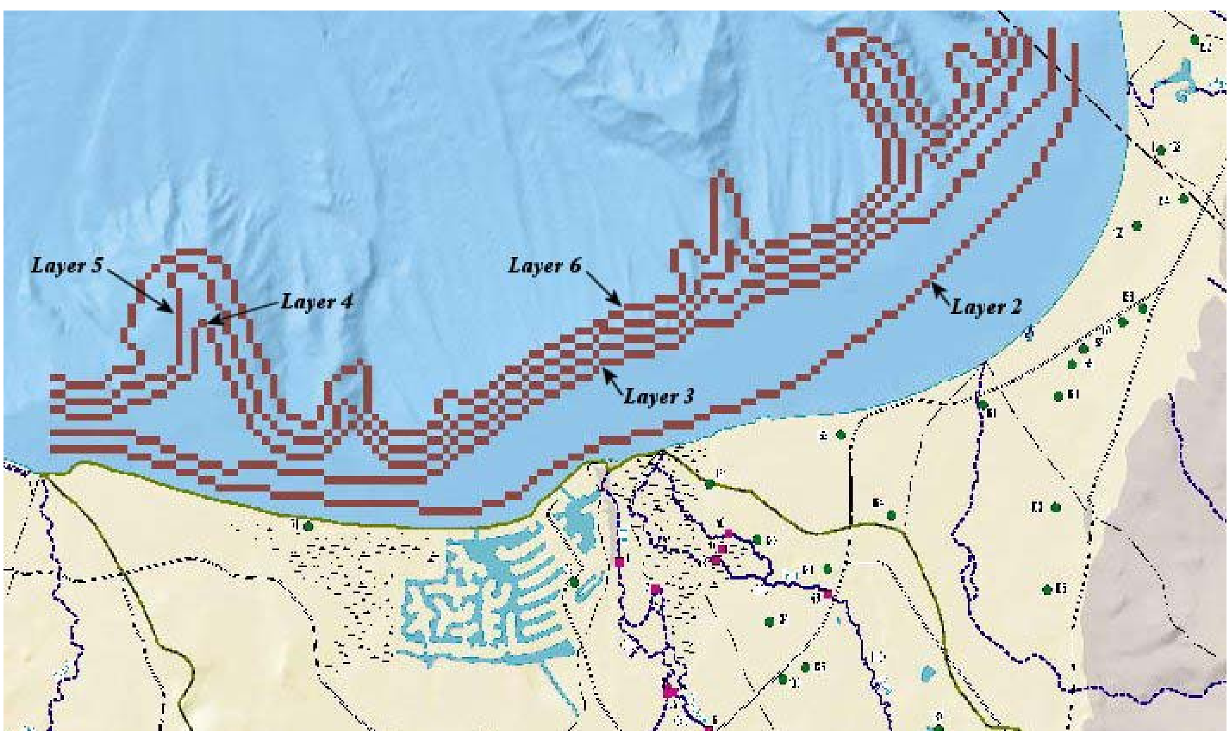


Figure 2 Representation of model boundary conditions. Orange represents a constant-head boundary. Yellow represents a head-dependent flux boundary. Blue represents the MODFLOW Stream Package.




(a)




(b)

Figure 3 (a) Lakebed elevation at south Lake Tahoe and (b) lakebed elevation simulated by model.

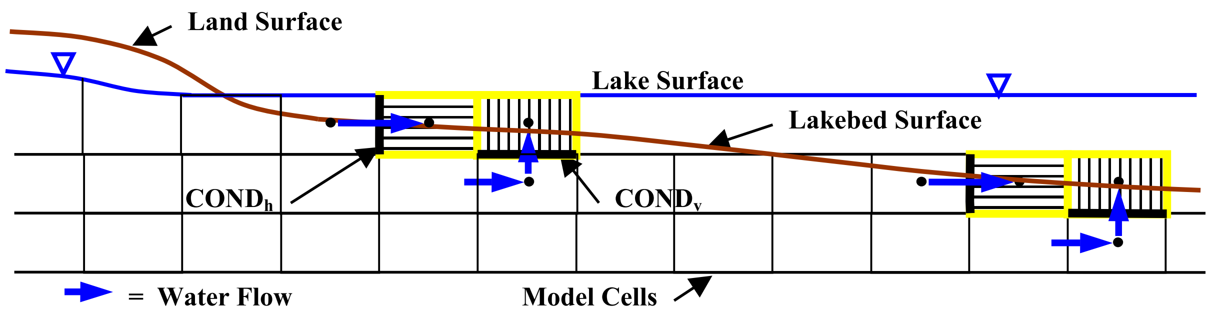



Figure 4  Representative profile of General Head Boundary (GHB) configuration used to simulate lake-groundwater interaction.

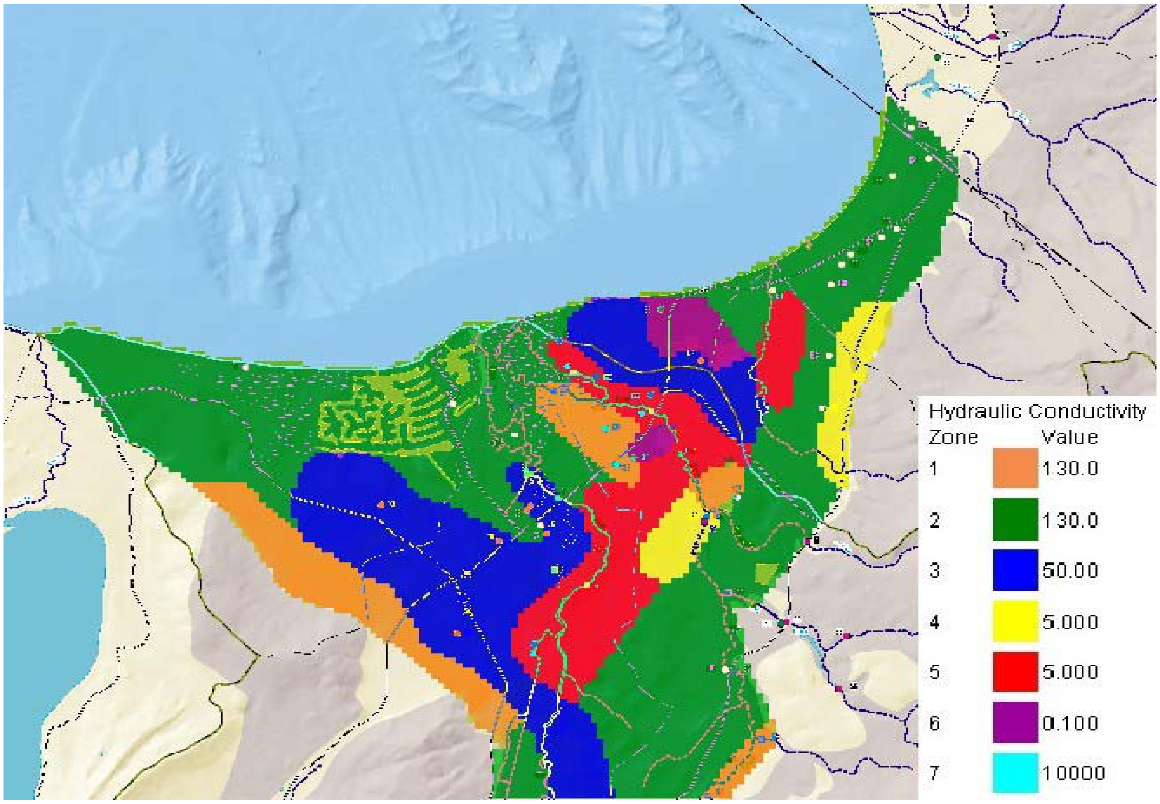


Figure 5 Representation of layer 1 hydraulic conductivity ($K_h$) used in model.

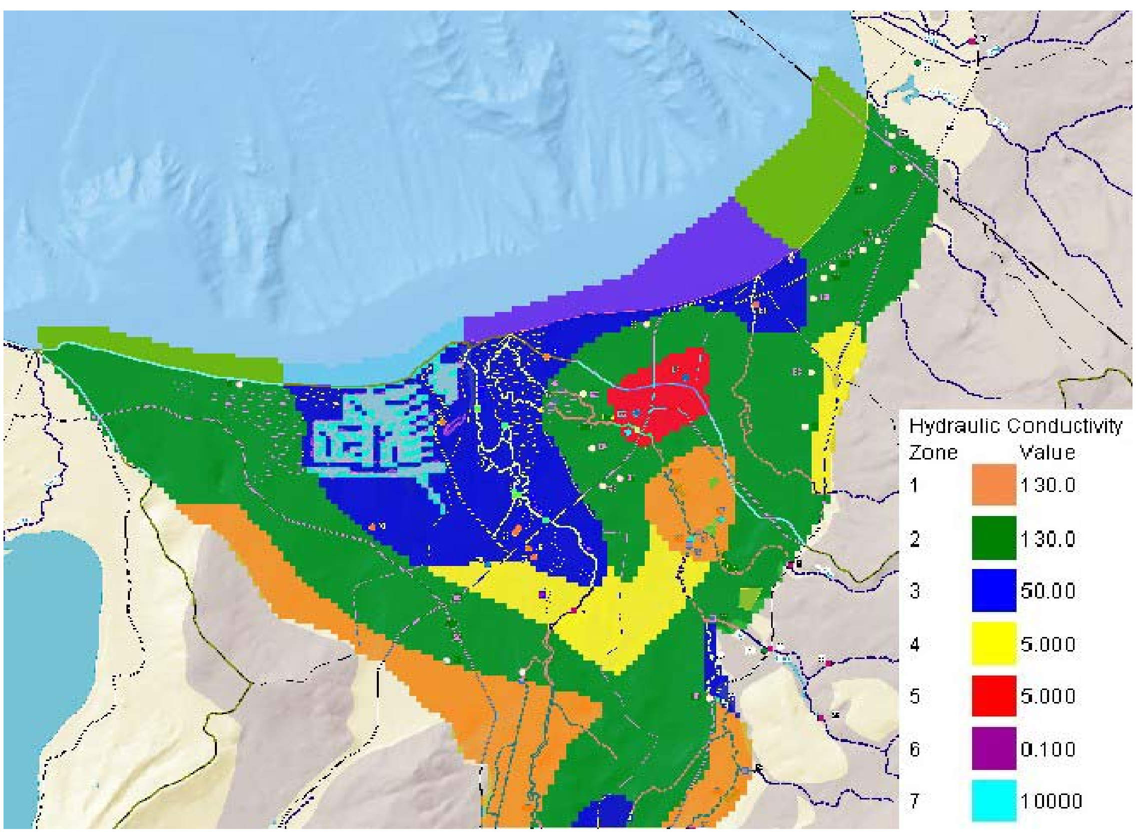


Figure 6 Representation of layer 2 hydraulic conductivity ($K_h$) used in model.

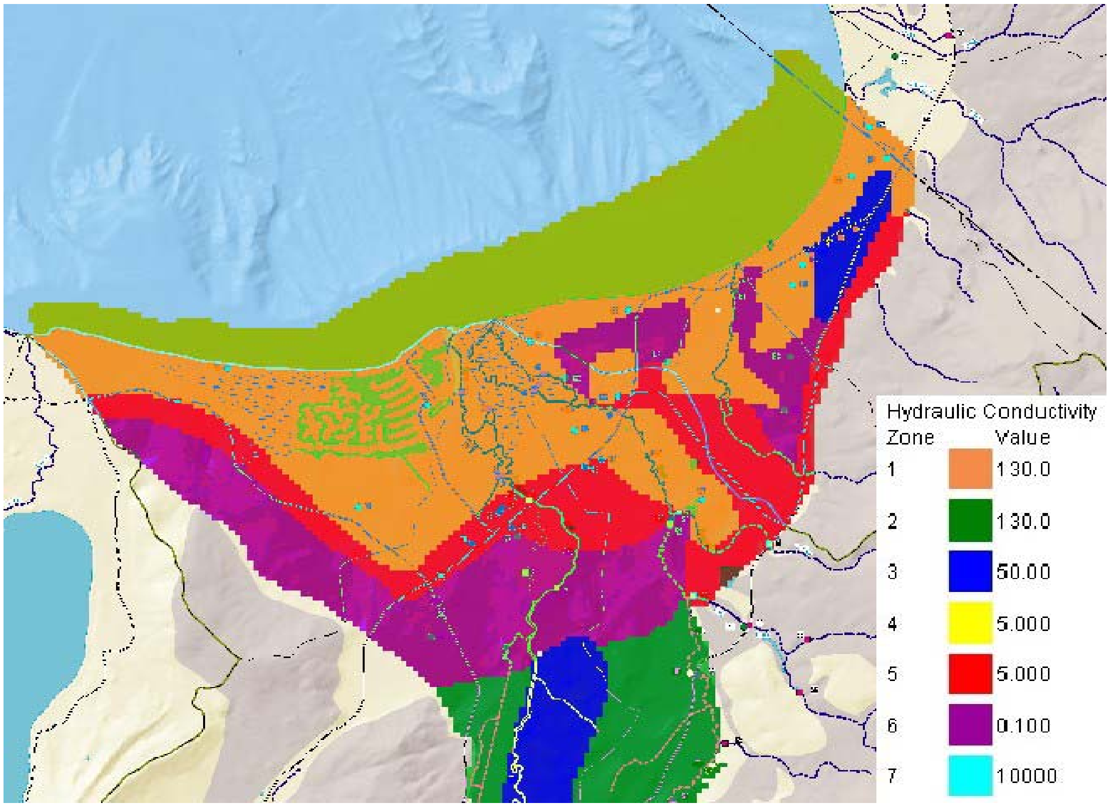


Figure 7  Representation of layer 3 hydraulic conductivity ($K_h$) used in model.

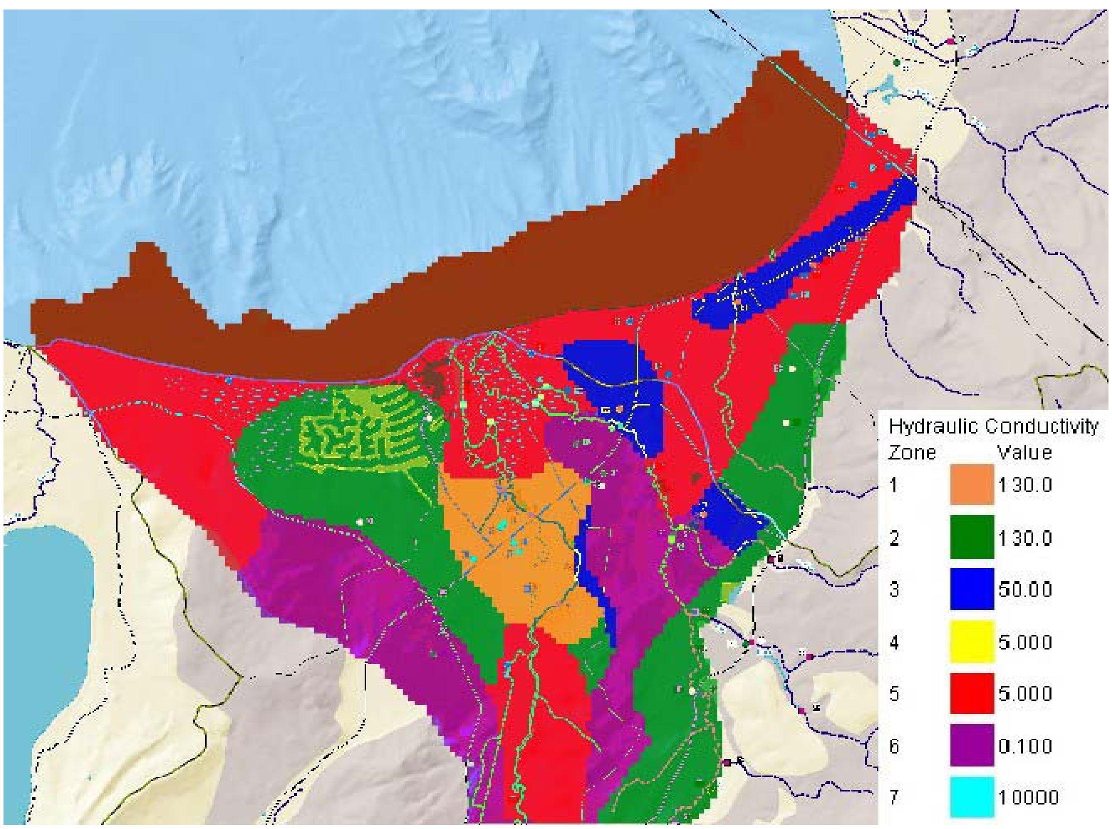


Figure 8  Representation of layer 4 hydraulic conductivity ($K_h$) used in model.

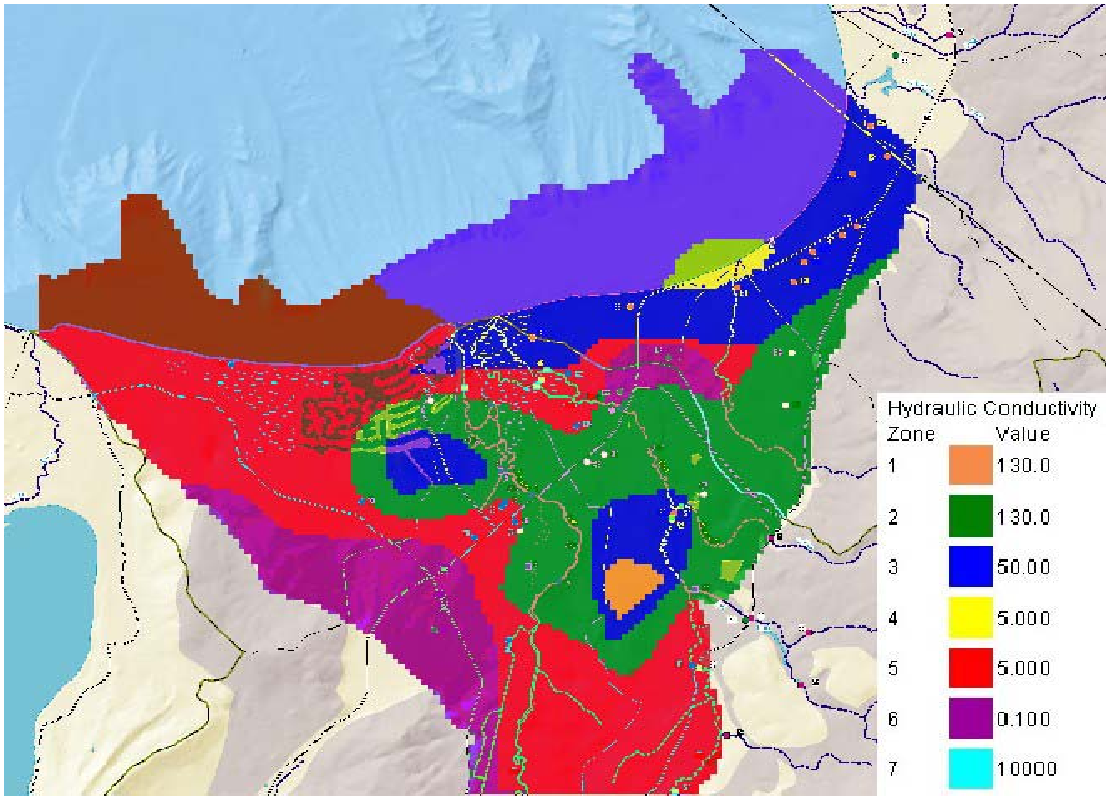


Figure 9 Representation of layer 5 hydraulic conductivity ($K_h$) used in model.

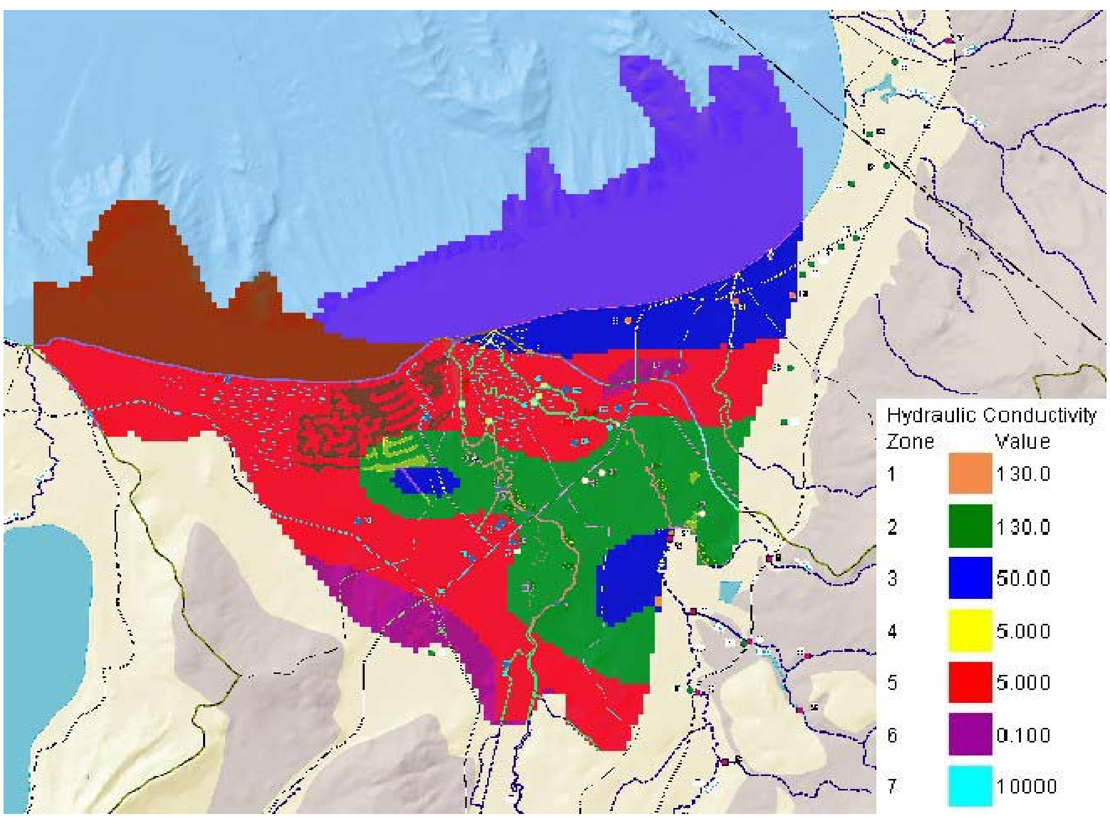
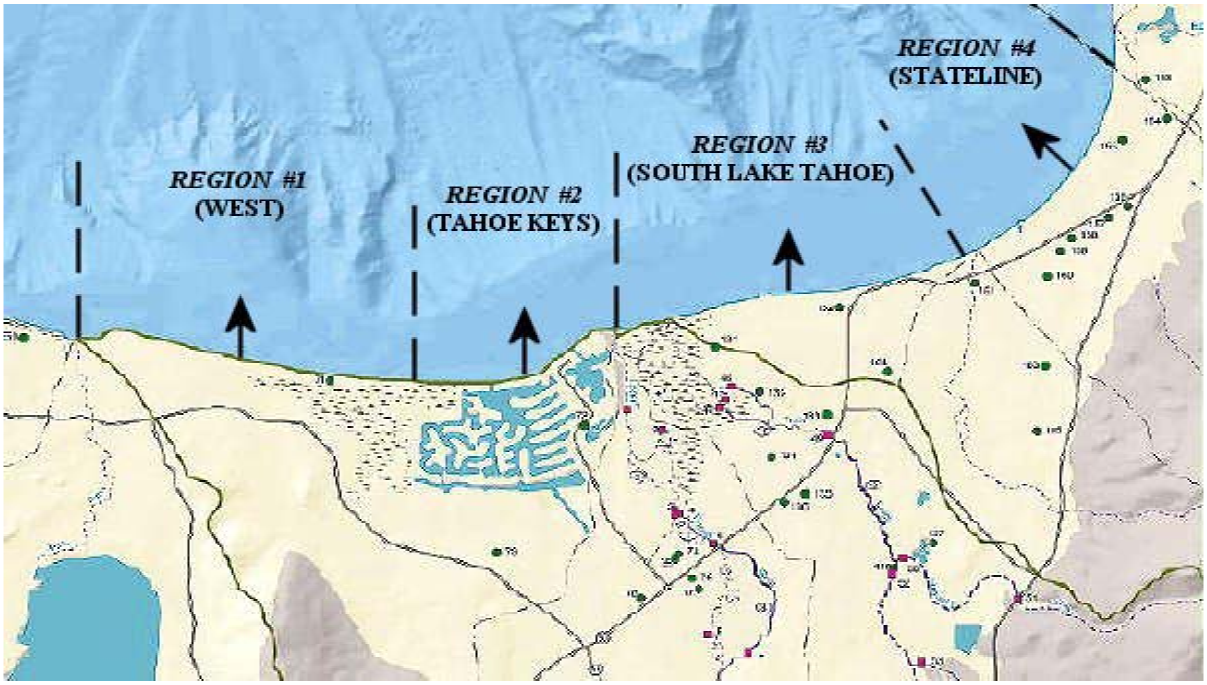


Figure 10 Representation of layer 6 hydraulic conductivity ($K_h$) used in model.




| TOTAL (INFLOW) FLUX TO LAKE BY REGION | | | | | |
|---|---|---|---|---|---|
| | REGIONS | | | | |
| | 1 | 2 | 3 | 4 | Total |
| **High Discharge** | 64,146 | 151,986 | 7,260 | 82,860 | 306,252 |
| **Low Discharge** | 22,697 | 68,947 | 124 | 53,314 | 145,082 |
| **Average Discharge** | 43,422 | 110,466 | 3,692 | 68,087 | 225,667 |

* Values in $ft^3$/day (cfd)

| NET (INFLOW-OUTFLOW) FLUX TO LAKE BY REGION | | | | | |
|---|---|---|---|---|---|
| | REGIONS | | | | |
| | 1 | 2 | 3 | 4 | Total |
| **High Discharge** | 60,253 | 114,310 | -92,014 | 82,860 | 165,409 |
| **Low Discharge** | 14,279 | 12,703 | -108,825 | 53,059 | -28,784 |
| **Average Discharge** | 37,266 | 63,507 | -100,420 | 67,959 | 68,312 |

* Values in $ft^3$/day (cfd): (-) flow out of lake, (+) flow into lake

Figure 11 Delineation of south Lake Tahoe shoreline and tables of total and net fluxes per region for various scenarios. The shoreline length of Region 1 is approximately 9200 ft. The shoreline length of Region 2 is approximately 6000 ft. The shoreline length of Region 3 is approximately 9700 ft. The shoreline length of Region 4 is approximately 8600 ft.

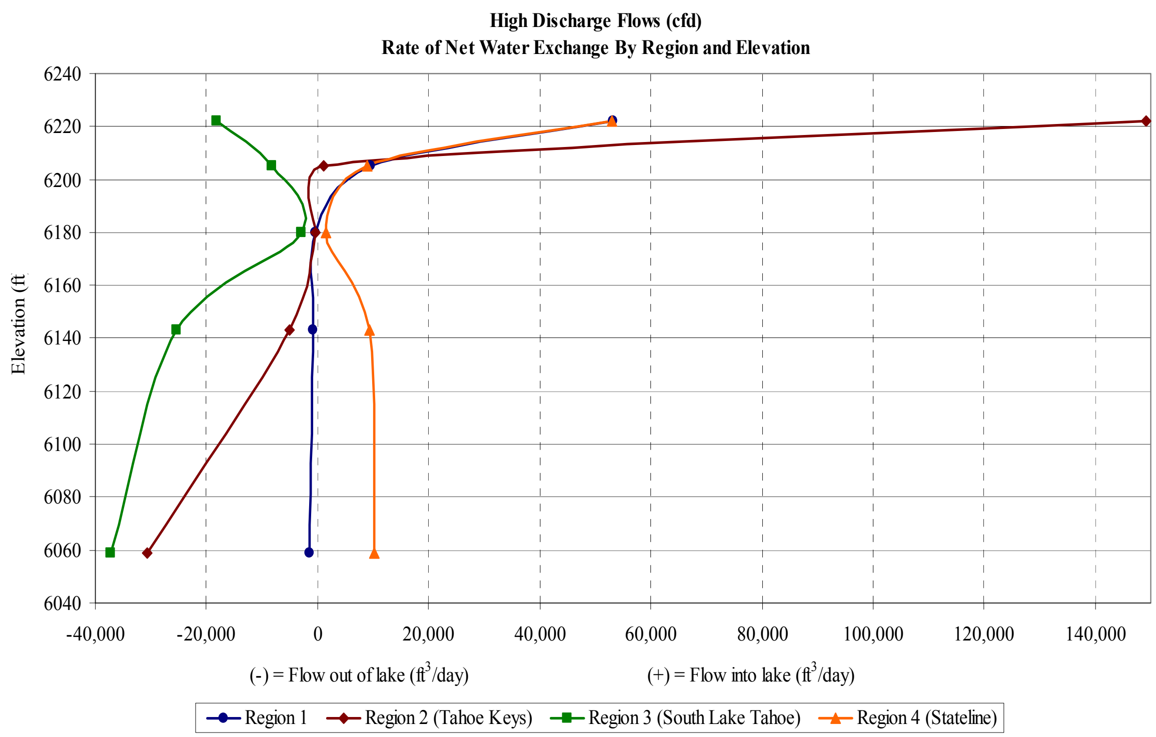



Figure 12 Side-view representation of "high discharge conditions" water exchange between groundwater and south Lake Tahoe.

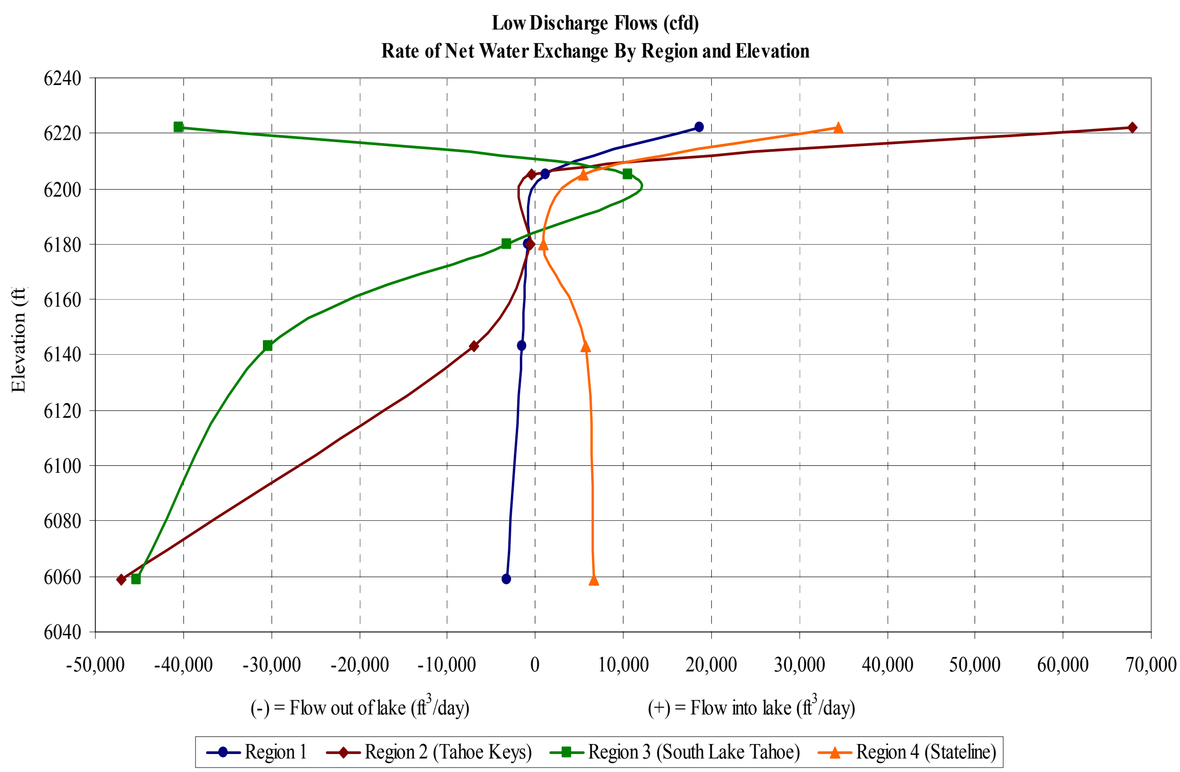



Figure 13 Side-view representation of "low discharge conditions" water exchange between groundwater and south Lake Tahoe.

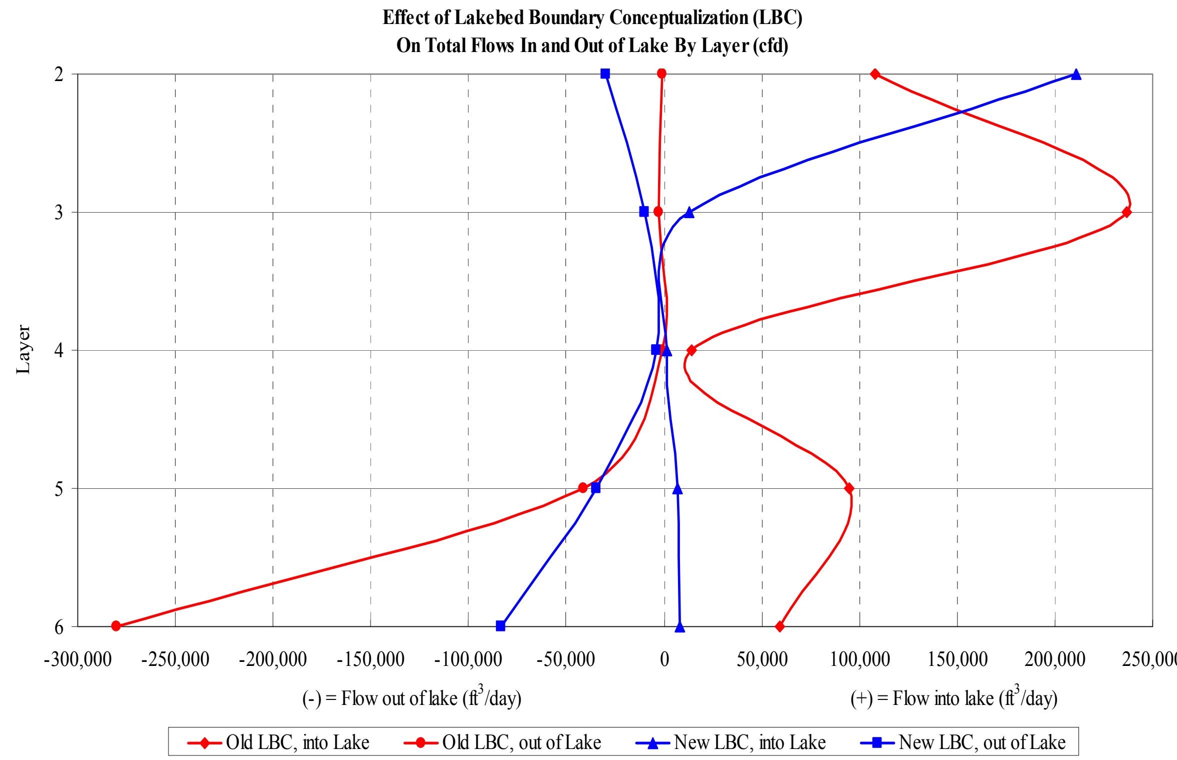



Figure 14 Side-view representation of effect of GHB boundary conceptualization on water exchange between groundwater and south Lake Tahoe.