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:

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

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 2×10^7 ft^2 for the east area, and 5×10^7 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.