Hydrogeologic Setting and Ground-Water Quality of Areas Tributary to Lake Tahoe in Douglas County and Carson City, Nevada, Through 1987

By CARL E. THODAL

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 94-4079

Prepared in cooperation with
DOUGLAS COUNTY and CARSON CITY

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

Carson City, Nevada
1995

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
GORDON P. EATON, Director

For additional information
write to:

District Chief
U.S. Geological Survey
333 West Nye Lane, Room 203
Carson City, NV 89706-0866

Copies of this report can be
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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
cubic foot per day per square foot ($ft^3/d/ft^2$)	304.8	liter per day per square meter
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per second (ft/s)	0.3048	meter per second
inch (in.)	25.40	millimeter
inch per year (in/yr)	25.40	millimeter per year
mile (mi)	1.609	kilometer
square foot (ft^2)	0.0929	square meter
square mile (mi^2)	2.590	square kilometer

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)]+32. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = 0.556(°F-32).

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

Abbreviated water-quality and related concentration units used in report:

kg/yr (kilogram per year)
µg/L (microgram per liter)
µS/cm (microsiemens per centimeter at 25°C)
$mg/d/ft^2$ (milligram per day per square foot)
mg/kg (milligram per kilogram)
mg/L (milligram per liter)
mm (millimeter)
pCi/L (picocurie per liter)

Hydrogeologic Setting and Ground-Water Quality of Areas Tributary to Lake Tahoe in Douglas County and Carson City, Nevada, Through 1987

By Carl E. Thodal

Abstract

Stimulation of phytoplankton productivity by nutrients is the suspected cause of decreasing water clarity in Lake Tahoe, a 190-square-mile body of water that straddles the Nevada-California State line. Studies on the California side of the basin have shown that ground-water inflow can contribute substantial nutrient loads to the lake. This report describes the results of an investigation of a 46-square-mile part of the Lake Tahoe Basin in Nevada during 1985-87 that was made to characterize the hydrogeologic setting and to determine the quality and nutrient content of ground water.

Ground water moves generally westward, through fractures and a thin veneer of decomposed granite on the upland slopes of the Carson Range, into alluvial and lacustrine deposits along the western margin of the study area, and then into Lake Tahoe. Water-level measurements in 53 water-supply wells indicate that the depth to ground water in the study area ranged from land surface to 200 feet below land surface. The wells ranged in depth from 34 to 447 feet below land surface. Hydraulic conductivity, estimated by linear regression of data on slug tests and grain-size distribution variables for 20 samples of saturated aquifer material, ranged from 0.42 to 140 feet per day (median, 4.6 feet per day). Hydraulic gradients for 25 observation wells ranged from 10 to more than 800 feet per mile. Estimates of specific discharge for 16 wells completed in unconsolidated aquifers within one-quarter mile of the lakeshore ranged from 0.0058 to 0.89 foot per day (median, 0.034 foot per day).

Historical data as early as 1963 indicate that nitrate-nitrogen concentrations in supply wells near early residential areas and in areas underlain by organic-rich stream deposits were as high as 5.6 milligrams per liter compared to an average concentration of 0.014 milligram per liter in Lake Tahoe. These water samples generally have calcium as the dominant cation and bicarbonate as the dominant anion.

Twenty-four observation wells, five supply wells, nine streams, and three springs were sampled during 1986-87. Streams were sampled during base-flow conditions, when the discharge was assumed to represent emergent ground-water flow. Water samples were analyzed for physical properties, major dissolved chemical constituents, total and dissolved species of nitrogen and phosphorus, and dissolved iron and manganese. Measured nitrate concentrations generally were highest at golf-course sites, near a resort with an abandoned septic-tank system and horse-riding stables, and near organic-rich alluvial deposits, but the concentrations decreased along the presumed flow path toward Lake Tahoe.

The mass of dissolved nutrients that could be carried by ground water through a square foot of aquifer in one day was estimated for 16 observation wells within one-quarter mile of the lakeshore. These same data also were used to estimate ranges of annual nutrient loads possibly transported to the lake through three aquifers that extend along about 1.3 miles of the 19 miles

of shoreline in the study area. These estimates range from less than 0.005 kilogram per year to about 10,000 kilograms per year of nitrate-nitrogen, less than 0.0005 to about 200 kilograms per year of orthophosphate-phosphorus, and from less than 0.0004 to about 40,000 kilograms per year of dissolved iron. The wide range of load estimates reflects the uncertainty associated with aquifer geometry and hydraulic properties and, in the case of nitrogen and iron, locally elevated concentrations. Nonetheless, the load estimates indicate that ground-water flow can be a pathway for the introduction of nutrients to Lake Tahoe.

INTRODUCTION

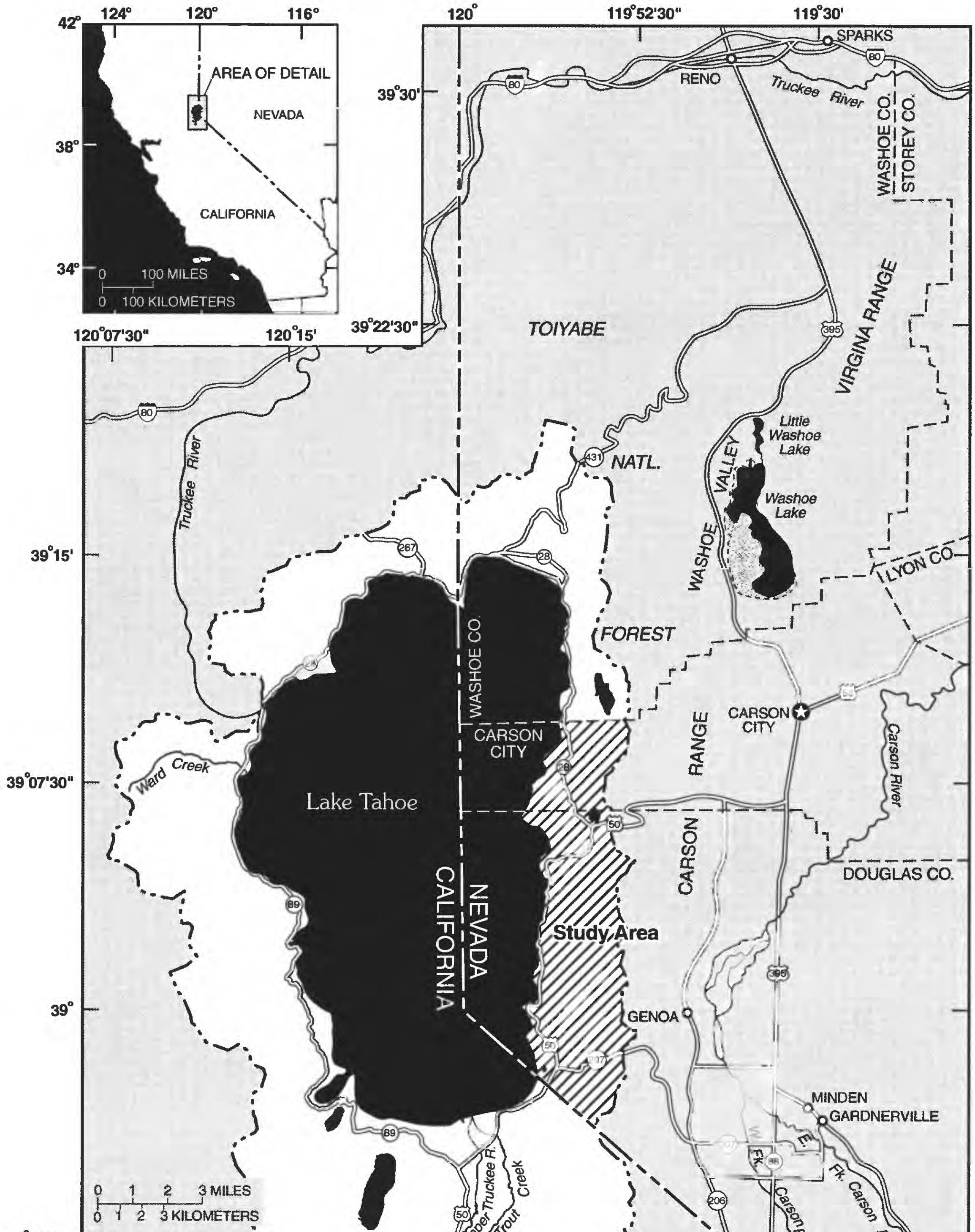
The water of Lake Tahoe, a 190-mi^2 body of water that straddles the Nevada-California State line, is noted for its exceptional clarity. Investigations during the past three decades, however, suggest that water clarity has decreased because of increased phytoplankton productivity. That increase has been attributed to an increase in nutrient loads (nitrogen, iron, and phosphorus) to the lake (Goldman, 1974, p. 1-2; 1981, p. 45-46). Although the total increase in nutrient loads to Lake Tahoe has not been documented or quantified, water-quality investigations on the California side have determined that both surface water and ground water transport nutrients to the lake. Loeb and Goldman (1979, p. 1152-1153) estimated that in 1975 the volume of ground water discharging to the west side of Lake Tahoe from the Ward Creek drainage basin (fig. 1) was equal to 16 percent of the streamflow from Ward Creek and 10 percent of the total precipitation on the drainage basin. They also estimated that ground water transported 49 percent of the nitrate-nitrogen and 44 percent of the soluble phosphorus contributed from this drainage basin to Lake Tahoe. A more recent investigation in the Upper Truckee River, Trout Creek, and Ward Creek drainage basins (fig. 1) estimated that only 5 and 20 percent of the dissolved inorganic nitrogen contributed to Lake Tahoe by the Upper Truckee River and Trout Creek drainage basins, respectively, was transported by ground water, whereas 60 percent of the dissolved inorganic nitrogen contributed by the Ward Creek drainage basin was transported by ground water (Loeb, 1987, p. iv-2). These results demonstrate the water-quality variability of the various ground-water systems that may interact with Lake Tahoe and indicate the potential error associated with extrapolating results from one area to another.

Those previous studies have been logical steps toward assessing the contribution of nutrients to the lake by ground water. They have addressed conditions in three important drainage basins around the lake, identified some of the possible sources of nutrients to the lake, and presented the available data. Furthermore, they have shown that ground water may be a large source of nutrients to the lake. However, the goal of quantifying the role of ground water in determining the quality of lake water has not yet been achieved. The three drainage basins described above represent about 35 percent of the total drainage area of Lake Tahoe and are among the most heavily developed areas in the basin.

The diversity of geologic and physiographic settings and the different degrees of development and types of land use suggest that extrapolation of the results of those studies to other parts of the basin is inappropriate. Rather, characterization of the hydrogeologic setting of the entire basin and identification of features that are related to the distribution of nutrients in ground water is necessary to evaluate the ground-water component of the nutrient budget for Lake Tahoe. In accordance with these long-term goals, the U.S. Geological Survey (USGS), in cooperation with Douglas County and Carson City, investigated a 46-mi^2 part of the Lake Tahoe Basin in Nevada during 1985-87, to determine the quality and nutrient content of ground water and to characterize the hydrogeologic setting. Background information and historical data were compiled in 1985; wells were constructed, water samples were collected (fig. 2), and other field work was done during 1986-87.

Purpose and Scope of this Report

This report describes the hydrogeologic setting and ground-water quality characteristics of the Douglas County and Carson City parts of the Lake Tahoe Basin. Included in the report are descriptions of the lithology and other properties of aquifers; descriptions of nutrient cycles; summaries of selected historical (1960-82) ground-water quality data and of ground-water quality characteristics determined during 1986-87—the sample-collection period of this investigation; and the areal distribution of nitrogen species, phosphorus species, and dissolved iron.



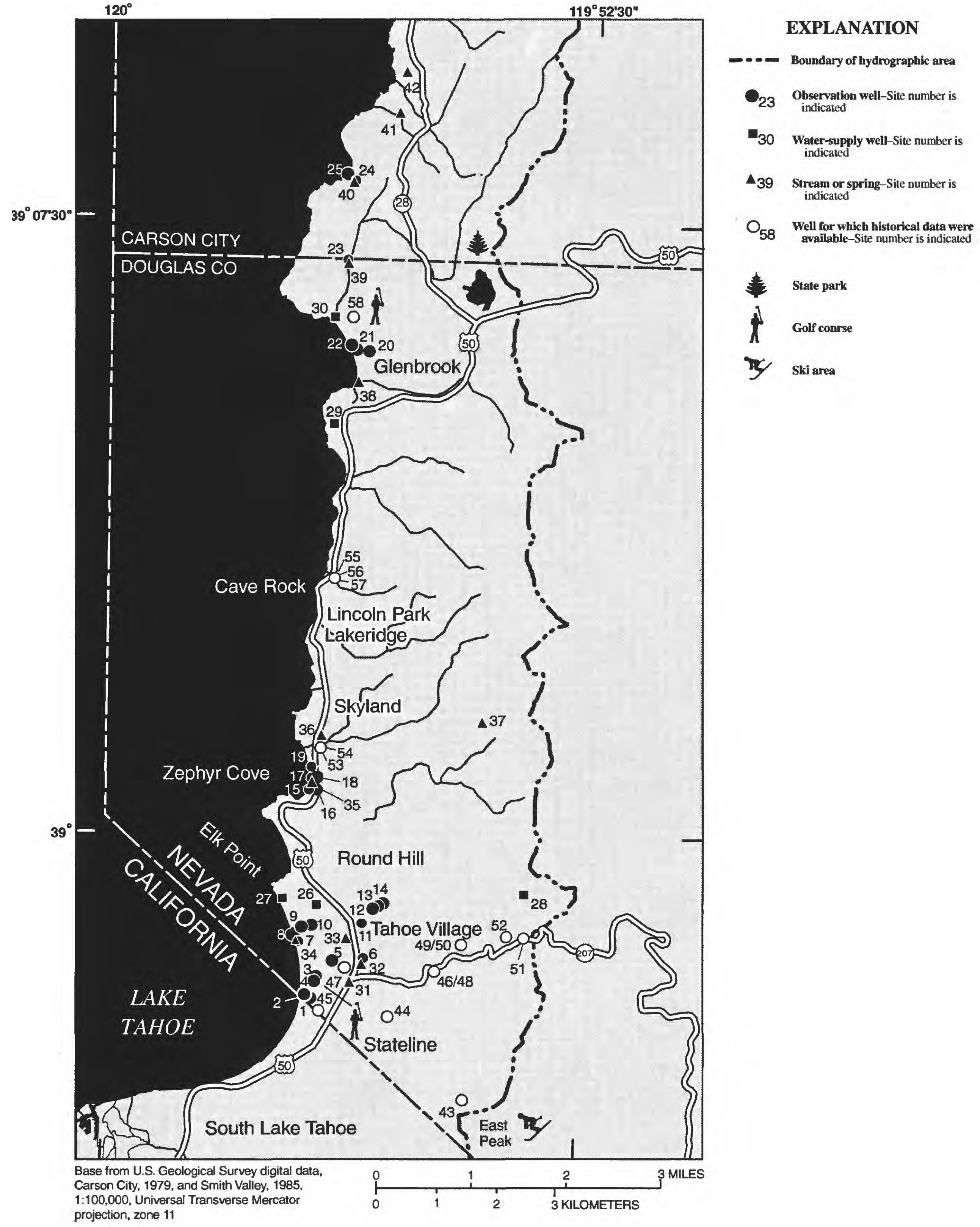
Base from U.S. Geological Survey digital data, 1:100,000, Universal Transverse Mercator projection, zone 11

EXPLANATION

▨ **Study area**

—··— **Boundary of hydrographic area**

Figure 1. Location of study area.



Base from U.S. Geological Survey digital data, Carson City, 1979, and Smith Valley, 1985, 1:100,000, Universal Transverse Mercator projection, zone 11

Figure 2. Sampling sites and selected land-use areas.

The information in this report is based on (1) data collected by the USGS during 1986-87, including 48 water-quality analyses from 30 wells, 9 streams, and 3 springs; 83 water-level measurements from 28 wells; 11 discharge measurements at 9 streams and 2 springs; hydraulic-conductivity estimates at 20 observation-well sites; and estimates of specific discharge and the mass of dissolved nutrients possibly carried annually by ground water; (2) historical (1960-82) data on ground-water quality for 16 wells from the Nevada Bureau of Health Protection Services (NBHPS, formerly Nevada Bureau of Consumer Health Protection Services); and (3) construction information for 59 wells from drillers' reports filed at the office of the Nevada State Engineer. Basic data compiled for this investigation have been published in another USGS report (Thodal, 1992).

Description of Study Area

The study area includes a land-surface area of about 46 mi^2 (Matthews and others, 1971, p. 2) in the east-southeastern part of the Lake Tahoe Basin, in Douglas County and Carson City, Nev. (fig. 1). Within this area, which is about 14 percent of the drainage area tributary to Lake Tahoe, the strongly dissected west slopes of the Carson Range reach a maximum altitude of 9,591 ft above sea level at East Peak (fig. 2). The lakeshore lies at an altitude of about 6,225 ft, and much of the lake bottom is at about 4,700 ft.

Climate varies considerably within the study area, primarily in response to seasonal and orographic influences. Most precipitation results from winter storms, usually accumulating as snowpack at altitudes above 7,000 ft. Average annual precipitation near Glenbrook (altitude 6,350 ft) during 1950-80 was 18.5 in. (Garcia, 1988, p. 9). Precipitation increases with altitude and generally averages between 25 and 35 in/yr above 7,200 ft (Matthews and others, 1971, p. 10-11).

The vegetation in the area is dominated by coniferous forests that grew following extensive logging during the late 1800's. Various species of low brush and herbage, collectively referred to as chaparral, dominate exposed slopes and occur within forested areas as an understory community. Revegetation after logging progressed with little disruption until the 1950's, when clearing activities increased due to expansion of residential and recreational facilities.

Most bedrock in the study area consists of intrusive igneous rocks, primarily granodiorite of the Sierra Nevada batholith, which formed about 100 million years ago (Grose, 1985, 1986; Bonham and Burnett, 1976). However, areas east of Glenbrook and Cave Rock (fig. 2) are underlain by extrusive igneous rocks and metamorphosed volcanic tuffs and flows (Grose, 1985). Most unconsolidated materials in the study area are derived from weathering of bedrock. Beach sand, derived from reworked alluvium over the past 10,000 years, has accumulated to estimated thicknesses of less than 80 ft along sheltered stretches of shoreline. Alluvium and colluvium (deposited by slope-erosion processes), estimated to be less than 80 ft thick, have accumulated locally in low-gradient areas throughout much of the study area (Grose, 1985, 1986; Bonham and Burnett, 1976).

The natural physiographic provinces of Lake Tahoe are defined by Hyne and others (1972, p. 1437-1440). The eastern sidewall province (which borders the western boundary of the study area) is described as a steeply dipping slope, characteristic of a fault scarp, with only patches of sediment covering the granitic bedrock. This interpretation supports the widely accepted graben theory for the origin of the Lake Tahoe Basin. The Lake Tahoe graben contains sediment at least 1,200 ft thick, derived from glacial drainages that discharged from the south and west during the past 1-2 million years.

Soils in the study area are described as "gently rolling to very steep, somewhat excessively drained and excessively drained loamy coarse sands and gravelly coarse sands that are shallow to deep over granitic rock" (Rogers, 1974, p. 5). Slopes range from 5 to 70 percent. Other soils are typical of mountainous terrain and are derived from extrusive and metamorphosed parent material (bedrock).

About 65 percent of the study area is privately owned, about 25 percent is managed by the U.S. Forest Service, and almost 10 percent is Nevada State Park land. Much of the land is not developed because of extensive areas with high erosion potential and high-hazard land capability (Bailey, 1974, p. 8, 19). Land capability is defined as "the level of use an area can tolerate without sustaining permanent damage through erosion and other causes" (Bailey, 1974, p. 4). Gambling facilities are present in Stateline, Nev., at the southern end of the study area. Residential and seasonal communities have been built at Stateline, Tahoe Village, Round Hill, Elk Point, Zephyr Cove, Skyland, Lakeridge, Lincoln Park, Glenbrook, and in the vicinity of Nevada State Highway 207 (fig. 2). The average annual population for the Douglas County part of the study area had increased from 7,975 in 1974 (California State Water Resources Control Board, 1979, p. 148) to 10,200 in 1980 (Tahoe Regional Planning Agency, 1982, p. 48-49). The total resident and overnight-visitor population for this part of Douglas County was 11,040 in 1985 and is projected to reach as much as 14,020 by the year 2005. Fewer than 15 homes are located in the Carson City part of the study area (Dan Greenlee, Tahoe Regional Planning Agency, written commun., 1988). Other land uses in the study area include a State Park, two golf courses, a ski area, various resorts and casinos, U.S. Highway 50, Nevada Highways 28 and 207, and U.S. Forest Service land (fig. 2).

Historically, domestic and community wastewater was disposed of either by small community-treatment systems or by individual septic-tank-and-leachfield systems. Nutrients associated with wastewater were thought to have increased algal productivity in the lake during the late 1960's; in response, legislation was passed to mandate the export of sewage from the Lake Tahoe Basin (Committee on Public Works, 1972, p. 607). Sewage exports from the Douglas County part of the study area began in 1973, when 1,020 acre-ft of secondary-treated effluent was exported to Carson Valley, where it was used to create wetlands. Annual effluent exports increased to 1,700 acre-ft by 1977 (California State Water Resources Control Board, 1979, p. 154-163). Although most wastewater is exported from the basin, the potential for wastewater-derived nutrients to enter the lake still exists because of raw sewage overflows, leakage from sewer lines and treatment-facility oxidation ponds, and residual nutrients from abandoned leachfields and land-disposal areas (Tahoe Regional Planning Agency, 1981, p. 21).

Methods Used in the Study

Site Selection, Construction, and Sampling

During 1986-87, water samples for chemical analyses and data necessary to describe the hydrogeologic setting were collected at 42 sites. Locations of these sites, along with 16 wells that had existing (1960-82) water-quality data, are shown in figure 2.

Eleven sites (Nos. 11-14, 26-30, 33, and 37) were inventoried, and water samples were collected from ten sites during April, October, and November 1986 (site 13 was rejected for sampling). Sites 11-14 are ground-water observation wells established prior to this study at a sewage-treatment facility and effluent holding pond; site 13 was used only to measure ground-water levels. Sites 26-30 are water-supply wells that range in depth from 58 to 200 ft below land surface. Sites 33 and 37 are springs that presumably represent ground-water discharge.

During 1987, 21 observation wells (sites 1-10 and 15-25) were installed by Geological Survey personnel, 14 in areas believed to have potential for contributing nutrients (sites 1-5, 8, and 15-22) and 7 in areas where ground-water quality was assumed not to have been affected by land use (sites 6, 7, 9, 10, and 23-25). These wells range in depth from 6.4 to 31.3 ft below land surface. Sites 1-5 and 20-22 are on golf courses; sites 15-19 are in the vicinity of a resort area with a campground, a horse stable, a nearby highway, and an abandoned septic-tank-and-leachfield system; site 8 is downgradient and site 9 is upgradient from a wastewater pumping station; and sites 6, 7, 17, 23, and 24 are adjacent to Lake Tahoe tributaries. Sites 31, 32, 34-36, and 38-42 are nine streams and a spring that were assumed to represent ground water when sampled during late summer.

Observation wells established during this study by the Geological Survey were drilled with a 3.5-in.-diameter, bucket-type hand auger (sites 1-6, 15-18, 24, and 25) or a 3-in.-diameter, solid-stem gasoline-powered auger (sites 7-10, 19-23). Circulation fluid was not used to auger any of the wells. All observation wells installed during this investigation, except wells at sites 3 and 4, were constructed with 2-in.-diameter polyvinyl chloride (PVC) well casings and factory-slotted well screens. Well casings were set in the borehole and the annulus around the screen was back-filled with coarse sand. The annulus around the remainder of the casing was back-filled with a sanitary seal of bentonite clay to land surface, and a waterworks control box was installed flush with land surface to protect each wellhead. Wells at sites 3 and 4 were constructed of 1-in., hand-slotted PVC tubing (wrapped with nylon porch screen) and installed within 5 ft of each other, but were completed at different depths.

Water levels in wells were measured with a steel tape and referenced to the lake surface by running lines of levels between measuring points established at each well and at Lake Tahoe. Well-site altitudes were based on lake-stage altitudes reported for Tahoe City, Calif., on the days the leveling lines were run. All leveling lines were run on calm days to minimize wave-induced errors.

Ground-water samples for water-quality analysis were obtained from wells by using either the existing pump in the well, a portable pump, or a bailer. A water volume equivalent to a minimum of three casing volumes was evacuated from each well before sample collection, to obtain samples that were representative of water in the aquifer. Frequent measurements of water temperature, pH, and specific conductance were made during well evacuation. The stabilization of these properties was assumed to indicate that water was being withdrawn directly from the aquifer, at which time the final samples were collected.

Water samples from springs were collected by extending a length of plastic tubing into the spring orifice and allowing sample water to discharge by gravity for sample collection. Water samples from streams were collected under small waterfalls; this procedure resulted in integrated, representative samples.

Determination of Aquifer Characteristics

Samples of unconsolidated aquifer material were collected from 20 boreholes augered for observation wells. Samples from hand-augered boreholes were collected from the bucket of the auger after discarding at least 1 ft of aquifer material. Aquifer-material samples from power-augered boreholes were collected from auger returns after the drill stem had penetrated 2 ft of aquifer material. Samples were shipped to the Geological Survey sediment laboratory in Vancouver, Wash., for grain-size analysis.

The rate at which ground water is transported through aquifer material can be estimated by using determinations of saturated hydraulic conductivity (K). Hydraulic conductivities were estimated for study-area aquifers by grain-size and sorting analysis and by slug tests. Laboratory tests have demonstrated that the hydraulic conductivity of unconsolidated sand-size particles is best described by a representative measure of grain-size distribution and sorting (Masch and Denny, 1966, p. 677). Grain-size distributions for the unconsolidated aquifer-material samples were determined graphically by plotting the cumulative distribution of grain sizes as a function of the percent of the total sample mass. Grain diameters that corresponded to selected percentiles were then determined from the graph. Percentiles selected to represent grain-size diameters used in previous investigations (Masch and Denny, 1966, p. 666-667) include the median diameter (d_{50}) and the diameter exceeded by 90 percent of the aquifer sample (d_{10}).

Grain sorting is expressed as a measure of the statistical dispersion exhibited by the grain-size distribution. The "inclusive graphic standard deviation" (σ_I) commonly is used to quantify sorting; it can be determined by using the formula given by Folk (1974, p. 46):

$$\sigma_I = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6} , \qquad (1)$$

where ϕ is the grain diameter, expressed in the ϕ (phi) scale, corresponding to the ninety-fifth, eighty-fourth, sixteenth, and fifth percentiles. In the phi-scale system, grain size is expressed as the negative logarithm, to the base 2, of grain diameter. However, to be consistent for this investigation, grain-size diameter, expressed in millimeters, was used in place of ϕ (and σ_I thus became σ_{Id}) when the equation was applied to study-area data.

Saturated hydraulic conductivity also was estimated for selected wells by the slug-test method introduced by Hvorslev (1951) and modified by Bouwer and Rice (1976) for application to wells that partly penetrate unconfined aquifers. The method is based on the instantaneous line-source equation (Theis, 1935). At a well, the procedure consists of quickly raising the water level from the equilibrium level by introducing a measured volume of water, and monitoring the rate at which the water level returns to equilibrium. Water levels were measured with a pressure transducer, connected to a data logger programmed to record as frequently as every second. The observed rate of recovery, along with well-construction geometry, was incorporated into the following equation:

$$K = \frac{r_c^2 \ln\left(\frac{R_e}{r_w}\right)}{2L} \frac{1}{t} \ln\left(\frac{y_o}{y_t}\right) , \qquad (2)$$

where

r_c is the radius of the well casing, in feet;
R_e is the effective radius of aquifer over which the slug of water is dissipated (dimensionless);
r_w is the horizontal distance from the center of the well to the undisturbed aquifer, in feet;
L is the length of the well screen, in feet; and
t is the time, in seconds, required for the water level to fall from the height measured at time zero (water-level height y_o) to a water level recorded at time $t\,(y_t)$.

Because K, r_c, r_w, R_e, and L are constants in equation 2, $1/t$ and $\ln\,(y_o/y_t)$ also must be constant, and $\ln\,y$ plotted against t should yield a straight line. The term "$(1/t)\ \ln\,(y_o/y_t)$" is then determined from the best-fitting straight line obtained by plotting y against t (Bouwer and Rice, 1976, p. 423-424).

The effective radius R_e is a function of the geometry of the well and the ground-water flow system, and is expressed as the dimensionless variable $\ln\,(R_e/r_w)$. An electrical-resistance network analog was used to evaluate $\ln\,(R_e/r_w)$ in terms of well and aquifer geometry and to develop the following empirical relation (Bouwer and Rice, 1976, p. 424-426):

$$\ln\left(\frac{R_e}{r_w}\right) = \left[\frac{1.1}{\ln\left(\frac{H}{r_w}\right)} + \frac{A + B\ln\left[\frac{(D-H)}{r_w}\right]}{\frac{L}{r_w}}\right]^{-1}, \quad (3)$$

where

A and B are dimensionless coefficients graphically related to L/r_w;
D is the assumed thickness, in feet, of saturated, unconsolidated material, which was estimated for this study from the lithologic thickness reported on geologic maps (Bonham and Burnett, 1976; Grose, 1985, 1986); and
H is the vertical length of the water column in the well under static conditions, in feet.

Other terms are as previously defined. This method is applicable under the assumptions that (1) drawdown of the water table around the well is negligible, (2) flow above the water table can be ignored, (3) head losses as water enters the well are negligible, and (4) the aquifer is homogeneous and isotropic (Bouwer and Rice, 1976, p. 424-426).

The relations between grain-size distribution variables (d_{10}, d_{50}, and σ_{ld}) and hydraulic conductivities estimated by slug test are described by the rank correlation coefficient (Spearman's rho), which measures the amount of linear dependence between the ranks of the two variables. A perfect, increasing (positive) correlation has a coefficient value of +1.00, whereas a perfect decreasing (inverse) correlation has a value of -1.00. Because ranks—rather than the original data values—are compared, the rank correlation coefficient is not influenced by outliers. However, a strong relation between ranks does not necessarily imply that the relation between data values can be described with a linear equation (Iman and Conover, 1983, p. 126-127).

Regression analyses were used to relate characteristics of grain-size distributions determined from aquifer-material samples to hydraulic-conductivity estimates determined from slug tests for the 10 wells that have both types of data. The resulting relation was used to compute hydraulic-conductivity values for wells that have grain-size data, but no slug test. Grain-size variables incorporated in the regression equation were selected on the basis of (1) knowledge regarding the physical properties of aquifer materials that determine hydraulic conductivity and (2) the need to satisfy the underlying assumption of regression analysis that the regression residuals are normally distributed. Regression residuals are determined to be normally distributed when the normal probability plot of the regression residuals is linear (Iman and Conover, 1983, p. 366-370; Ryan and others, 1985, p. 177-179). The coefficient of determination (r^2) also was considered in selection of a regression equation, but strictly to evaluate how much variation is explained by the equation rather than to evaluate the validity of the relation.

Specific discharge is the rate of ground-water discharge per unit area measured at right angles to the direction of flow. It is directly proportional to the hydraulic gradient when the distance to which the hydraulic gradient applies is constant, and is inversely proportional to distance when the hydraulic gradient is constant. The following equation relates specific discharge (q; feet per day) to hydraulic gradient ($\Delta h/\Delta l$; dimensionless), and hydraulic conductivity (K; feet per day):

$$q = -K\frac{\Delta h}{\Delta l} . \qquad (4)$$

Equation 4 (Freeze and Cherry, 1979, p. 16, eq. 2.3) is an empirical law derived from laboratory experiments. Specific discharge has the dimensions of velocity (distance per time), but it is not a measure of the "microscopic" flow velocity of ground water moving between individual grains of aquifer material. Rather, it represents an average flow velocity per unit area, incorporating both the flow velocities between aquifer grains and the zero velocities in areas occupied by solid aquifer grains (Freeze and Cherry, 1979, p. 16-17).

The product of specific discharge and cross-sectional area is the volume of ground water that discharges through the cross section. Volumetric ground-water discharge is estimated by

$$Q = -K\frac{\Delta h}{\Delta l}A , \qquad (5)$$

where

Q is the discharge volume, in cubic feet per day;
A is the cross-sectional area, in square feet; and

the other terms are as previously defined.

Specific load (the mass of a dissolved nutrient carried through a cross-sectional area by ground water during a specified period of time) is estimated as the product of discharge volume and the concentration of the dissolved nutrient species. For this report, hydrodynamic dispersion (mixing and molecular diffusion), biological processes, and geochemical reactions are assumed to have no effect on the concentration of dissolved nutrients. These assumptions are not likely to hold true, particularly as ground water carries nutrients through biologically active lakebed sediments. However, because quantification of reaction rates is beyond the scope of this study, the simplified calculations are appropriate to indicate the general potential for nutrient transport from the study area to Lake Tahoe.

Water-Quality Analysis

Water samples for laboratory analysis were processed onsite using standard U.S. Geological Survey methods (Skougstad and others, 1979) and were shipped within 2 days to the U.S. Geological Survey National Water Quality Laboratory (NWQL) in Arvada, Colo., where they were analyzed for major dissolved chemical constituents, physical properties, dissolved and total species of nitrogen and phosphorus, dissolved and total organic carbon, and dissolved iron, manganese, radium-226, radon-222, and uranium. The methods and precisions of these analyses are described by Feltz and Anthony (1985).

HYDROGEOLOGIC SETTING

Characteristics of Aquifers

Principal aquifers in the study area are of two general types: unconsolidated sedimentary materials that have accumulated by onsite weathering of the granitic parent bedrock, or that have been deposited by alluvial, colluvial, and lacustrine processes; and zones of deeply weathered and fractured granitic bedrock. Depth to bedrock reported in 51 drillers' logs on file with the Nevada Division of Water Resources ranges from land surface to 191 ft below land surface, with a median of 40 ft below land surface. Unweathered granitic bedrock in the study area is relatively impervious to water, acting as a barrier to ground-water flow, and is not considered to be an aquifer.

Grus, material produced by local weathering of granitic rock, is extensive throughout the study area. It is characterized as poorly sorted material, ranging in size from boulders and very coarse sand and gravel to very fine silt and clay. This textural variability causes considerable heterogeneity in aquifer properties over short distances.

Alluvial deposits (gravel, sand, silt, and clay) form narrow bands along margins of stream channels, and accumulate preferentially along stream segments with relatively low gradient. Locally, alluvium is well sorted, but shifting positions of bars and channels during deposition, and variations in depositional velocities, typically result in heterogeneous aquifers. Carbonaceous alluvium has accumulated in marshy areas near the lakeshore that have been inundated frequently with storm water. These deposits, which are clayey to sandy, dark gray to black, contain varying amounts of organic matter (Grose, 1985). Organic-rich alluvium may serve as a natural source of nutrients, both through leaching of reduced and organic forms of nitrogen and phosphorus from decaying plant material, and through chemical interaction of oxidized iron compounds with reduced organic material that mobilizes ferrous iron (Hem, 1985, p. 83).

Lacustrine deposits consist of well sorted beach sand and interbedded, fine-grained lake sediments. The beach sand has accumulated locally along sheltered stretches of shoreline and the lake sediments were deposited over grus because of large fluctuations in lake level (Burnett, 1968, p. 8).

Aquifer-material samples from 20 observation wells had median grain-size diameters (d_{50}) ranging from 0.21 mm at site 23 to 1.7 mm at site 16 and d_{10} values ranging from 0.010 mm at site 20 to 0.60 mm at site 7. The median d_{50} and d_{10} values were 0.41 mm and 0.094 mm, respectively. Values of σ_{Id} (the modified inclusive graphic standard deviation; Folk, 1974, p. 46) range from 0.23 mm at site 5 to 5.2 mm at site 16 and had a median of 0.56 mm. Table 1 presents a statistical summary of grain-size distribution data grouped into four generalized lithologic units. The colluvium group comprises units mapped as fluvial deposits by Bonham and Burnett (1976) and units mapped as sand-and-boulder colluvium by Grose (1985, 1986). The alluvium group comprises the alluvial deposits of Bonham and Burnett (1976) and the sand-and-gravel alluvium and carbonaceous alluvium of Grose (1985, 1986). One sample from an area mapped by Bonham and Burnett (1976) as flood plain and lacustrine deposits is presented separately because both alluvial and lacustrine processes account for these deposits.

Hydraulic conductivity values determined by slug tests at 10 observation wells ranged from 0.18 ft/d at site 23 to 120 ft/d at site 7; the median value was 8.2 ft/d. Relations between hydraulic conductivities estimated by slug tests and the grain-size distribution variables d_{10}, d_{50}, and σ_{Id} were investigated by ranked correlation. The strongest relation was between slug-test hydraulic conductivity and the grain-size diameter d_{10}, which had a ranked-correlation coefficient (Spearman's rho value) of 0.96 (where 1.00 corresponds to a perfect correlation). In contrast, Spearman's rho values for d_{50} and σ_{Id} were, respectively, 0.56 and 0.009.

Distributions of hydraulic-conductivity data from slug tests and corresponding data for grain-size diameter were skewed by results from site 7; therefore, several transformations were attempted to normalize the data distribution, to satisfy assumptions of regression analysis. Normal probability plots of the residuals from regression analysis were compared to identify which transformation had normally distributed residuals. The square root of hydraulic conductivity was selected as the dependent variable transformation for regression with d_{10} as the independent variable. The regression equation is:

$$\hat{K} = (0.459 + 19.1 d_{10})^2 , \tag{6}$$

where

$\hat{K}$ is the estimated hydraulic conductivity, in feet per day.

Table 1. Statistical summary of grain-size distribution for samples of unconsolidated aquifer material, grouped by generalized lithology

[Unit of measure: millimeters. Abbreviations: d_{10}, grain size exceeded by 90 percent of the sample; d_{50}, median grain size; σ_{Id}, modified inclusive graphic standard deviation]

Lithologic unit	Number of samples	d_{10}			d_{50}			σ_{Id}		
		Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum
Beach sand	8	0.044	0.13	0.60	0.31	0.67	1.4	0.37	0.59	1.8
Colluvium	7	.010	.042	.16	.21	.36	.86	.23	.43	1.5
Alluvium	4	.026	.094	.16	.21	.42	1.7	.23	.58	5.2
Flood-plain deposits	1	--	[1].17	--	--	[1].26	--	--	[1].74	--
All samples	20	0.010	0.094	0.60	0.21	0.41	1.7	0.23	0.56	5.2

[1] Only one sample in lithologic category.

Figure 3*A* illustrates the relation between the square root of slug-test hydraulic conductivities and the grain-size diameter; figure 3*B* shows a normal probability plot of residuals from the regression equation. The transformed data from site 7 still exert significant influence on the regression analysis, but the residual plot is fairly linear and the deviation from linearity appears to be random.

Table 2 presents estimates of hydraulic conductivity by slug-test and by grain-size data, and includes the values used to calculate these estimates. Grain-size-method estimates ranged from 0.42 ft/d at site 20 to 140 ft/d at site 7, and the median value was 5.2 ft/d. Figure 4 compares the results of the two methods graphically and shows that conductivities estimated by the regression are larger than those estimated by slug test at wells where slug-test results were less than about 1 ft/d. The equation, however, provides a satisfactory approximation for wells where slug tests were not done.

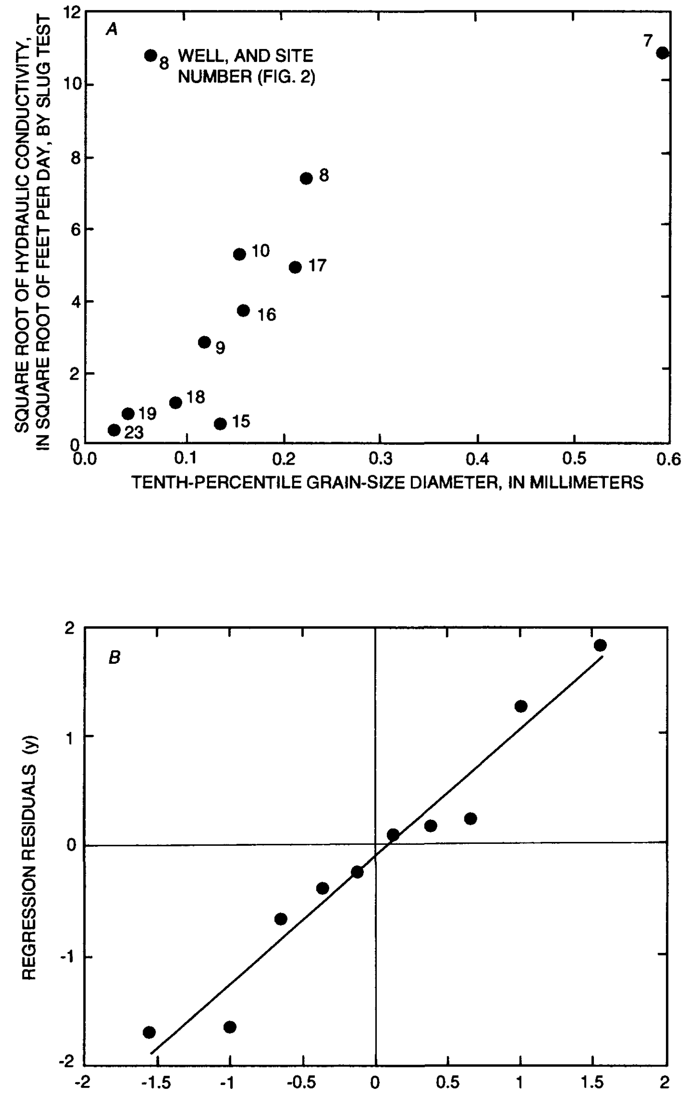


Figure 3. Statistical evaluation of relation between aquifer grain-size distribution and hydraulic conductivities estimated from slug tests. *A*, Square root of hydraulic conductivity versus tenth-percentile grain-size diameter. *B*, Normal probability plot of regression residuals for relation. Statistical regression line ($y = -0.102 + 1.16x$; $r^2 = 0.95$; $n = 10$) is indicated for part *B*.

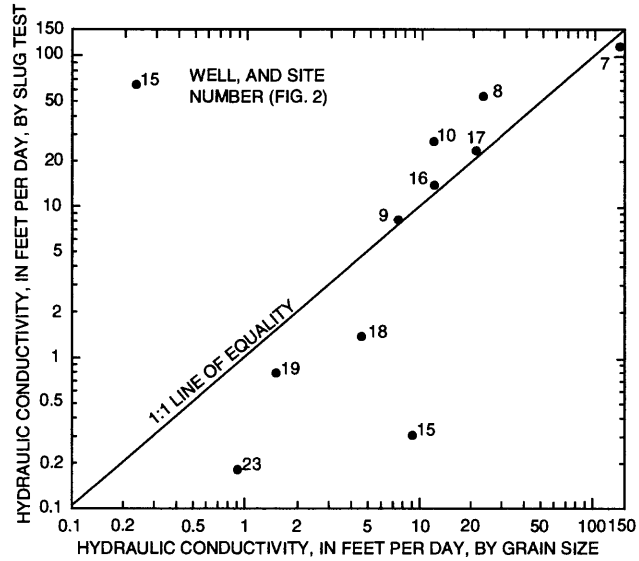


Figure 4. Comparison of hydraulic conductivities estimated by slug tests and by statistical evaluation of aquifer grain-size distribution.

Occurrence and Movement of Ground Water

Ground water originates in the upland slopes of the Carson Range from precipitation and snowmelt recharge, and flows downgradient, generally westward, toward Lake Tahoe. The steep slopes of the upland areas promote drainage from relatively thin, unconsolidated deposits and from the fractured bedrock system. This ground water provides recharge to the thicker, unconsolidated aquifers adjacent to Lake Tahoe. Generally, thicker and more extensive deposits of alluvial and lacustrine sediments that have accumulated along the lakeshore—up to altitudes of about 6,400 ft—receive recharge from upland ground water, from stream water infiltrating through the stream bed, and from direct infiltration of precipitation.

Table 2. Hydraulic conductivities estimated from grain-size and slug-test data for observation wells constructed during this study

[Abbreviations: d_{10}, grain size exceeded by 90 percent of sample; d_{50}, median grain size; σ_{Id}, modified inclusive graphic standard deviation; L, length of screened interval; r_c, well-casing radius; r_w, radial distance from centerline of well to undisturbed aquifer material; D, assumed thickness of saturated, unconsolidated material; H, vertical length of water column in well casing; ln, natural logarithm; R_e, effective radial distance over which hydraulic head above static water level is dissipated; y_o, vertical distance between initial water level inside well casing at time=0 and static ground-water level; y_t, vertical distance between water level in well casing at time=t and static ground-water level; t, time required for y_o to recover to y_t; ft, feet; s, second; ft/s, feet per second; ft/d, feet per day]

Site number (figure 2)[1]	Grain-size statistics (millimeters)			Slug-test statistics										Hydraulic conductivity (ft/d)	
	d_{10}	d_{50}	σ_{Id}	L (ft)	r_c (ft)	r_w (ft)	D (ft)	H (ft)	$\ln(R_e/r_w)$	y_o (ft)	y_t (ft)	t (s)	$\ln(y_o/y_t)/t$ (ft/s)	Grain-size method	Slug-test method
1	0.068	0.407	0.619	--	--	--	--	--	--	--	--	--	--	3.1	--
2	.044	1.11	.512	--	--	--	--	--	--	--	--	--	--	1.7	--
4	.171	.265	.744	--	--	--	--	--	--	--	--	--	--	14	--
5	.042	.207	.226	--	--	--	--	--	--	--	--	--	--	1.6	--
6	.126	.861	1.47	--	--	--	--	--	--	--	--	--	--	8.2	--
7	.600	1.39	.903	2.0	0.083	0.125	80	4.47	1.2	12.96	0.25	6	8.64	140	120
8	.225	.748	.675	2.0	.083	.125	80	6.82	1.9	12.96	4.09	6	.192	23	55
9	.119	.410	.504	2.0	.083	.125	80	4.19	1.9	12.96	6.92	22	.285	7.5	8.2
10	.156	.640	.943	2.0	.083	.125	80	3.65	1.8	6.48	2.87	8	.102	12	28
15	.134	.584	.775	4.0	.083	.146	80	15.27	2.4	12.96	9.90	154	.002	9.1	.31
16	.159	1.69	5.18	2.0	.083	.146	30	7.78	2.0	12.96	3.81	26	.047	12	14
17	.214	.972	1.80	2.0	.083	.146	80	5.97	1.8	6.48	2.72	10	.087	21	24
18	.088	.352	.350	2.0	.083	.146	30	10.97	2.3	9.72	6.65	96	.004	4.6	1.4
19	.040	.362	.433	2.0	.083	.125	80	10.25	1.8	6.48	4.16	153	.003	1.5	.79
20	.010	.231	.296	--	--	--	--	--	--	--	--	--	--	.42	--
21	.016	.241	.321	--	--	--	--	--	--	--	--	--	--	.58	--
22	.062	.312	.372	--	--	--	--	--	--	--	--	--	--	2.7	--
23	.026	.206	.237	2.0	.083	.125	30	15.14	2.4	9.72	3.26	1991	.0005	.91	.18
24	.101	.488	.817	--	--	--	--	--	--	--	--	--	--	5.7	--
25	.063	.416	.484	--	--	--	--	--	--	--	--	--	--	2.8	--
Median														5.2	11
90-percent confidence interval														2.7-9.1	0.79-28

[1] Aquifer material was not collected during construction of site 3 due to proximity to site 4. Sites 11-14 were constructed prior to this study, and analyses of aquifer material were not available.

Flat or gently sloping terrain, small canyons, and depressions with relatively thick surface accumulations of grus also will store and convey ground water (Harrill, 1977). Ground water discharges naturally into streams, from springs, directly into the lake, and by evapotranspiration.

Depths to water reported in 51 drillers' logs range from 1 to 200 ft below land surface; the median depth to water is 28 ft. The 25 observation wells used in this study ranged in land-surface altitude from 6,229.6 to 6,505.7 ft above sea level. The median altitude was 6,243.1 ft. Depths of these wells ranged from 6.4 to 36.0 ft below land surface (median, 18.0 ft). Eighty-four water-level measurements, made at the 25 observation wells and 3 domestic wells during April 1986 through September 1987, ranged from land surface to 32.1 ft below land surface; the median was 9.0 ft.

Figure 5 illustrates the relation of the altitude of ground-water level to distance from lakeshore. Water-table gradients between 25 observation wells and lake level ranged from about 10 ft/mi for sites 7, 8, and 9 to more than 800 ft/mi for site 24, adjacent to an unnamed tributary (site 40). The median gradient was 55 ft/mi.

Estimates of hydraulic properties and specific discharge for observation wells located within one-quarter mile of the lakeshore are listed in table 3. Specific discharge estimates ranged from 0.0025 ft/d for site 21 to 0.91 ft/d for site 24 (median, 0.034 ft/d). Statistically, at a 90-percent level of confidence, the true median value of specific discharge for water-table aquifers near the lakeshore of the study area is between 0.02 and 0.1 ft/d. This order-of-magnitude range is due to the combined variability of hydraulic conductivity and hydraulic gradient estimates.

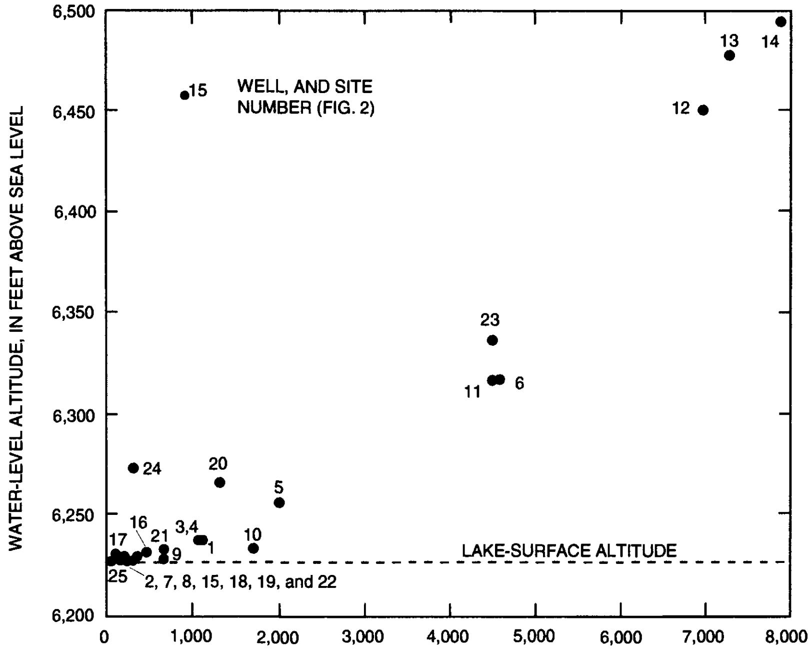


Figure 5. Relation between altitude of ground-water level and distance from shore of Lake Tahoe.

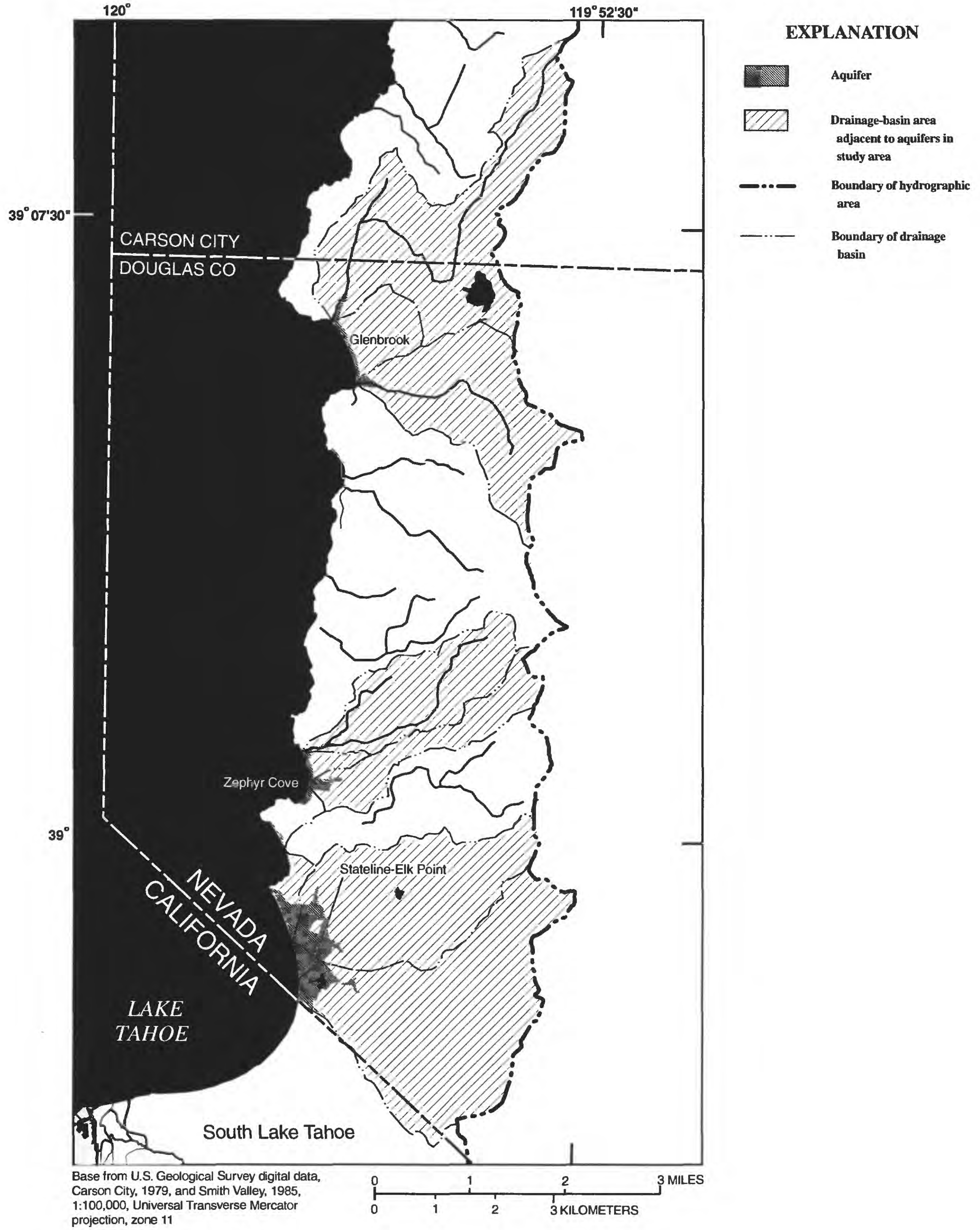
Table 3. Estimated hydraulic conductivity, hydraulic gradient, and specific discharge for observation wells in study area that are within one-quarter mile of Lake Tahoe shoreline

Site number (figure 2)	Hydraulic conductivity (feet per day)	Hydraulic gradient (feet per foot)	Specific discharge (feet per day)
1	3.1	0.010	0.031
2	1.7	.0042	.0071
4	14	.010	.14
7	140	.0023	.32
8	23	.0019	.044
9	7.5	.0025	.019
15	9.1	.016	.14
16	12	.010	.12
17	21	.042	.88
18	4.6	.0083	.038
19	1.5	.0062	.0093
20	.42	.031	.013
21	.58	.0044	.0025
22	2.7	.0095	.026
24	5.7	.16	.91
25	2.8	.0083	.023
Median	5.2	0.0089	0.034
90-percent confidence interval	2.7-11	0.005-0.01	0.02-0.1

Assuming that the estimates of specific discharge are reasonable and representative of aquifers in the study area that interact with Lake Tahoe, the amount of ground water that discharges into the lake can be estimated by multiplying specific discharge by the cross-sectional area of an aquifer of interest. Cross-section geometries have not been precisely delineated, thus ranges of cross-sectional area were estimated to evaluate how warranted the additional effort necessary to delineate aquifer geometry might be.

The specific-discharge estimates can be associated with three discrete shoreline areas considered to be aquifers (fig. 6). Unconsolidated deposits extend along about 1.3 mi (17 percent) of the 19 mi of shoreline in the study area, and about 20 mi^2 of drainage area may contribute recharge to the three aquifers (Jorgensen and others, 1978). Six estimates were made for sites located between the Nevada-California State line and Elk Point (sites 1, 2, 4, 7, 8, and 9). Elk Point extends to the lakeshore from near Round Hill along a bedrock ridge forming the northern boundary of this aquifer. The State line is a political boundary, but for purposes of this investigation the ground-water flow lines are assumed to be perpendicular to the shoreline, permitting such an arbitrary delineation. Beach sand deposits (Grose, 1985) along the lakeshore at Zephyr Cove and at Glenbrook are assumed to delineate the other two aquifers. Five estimates of specific discharge (sites 15-19) were made for Zephyr Cove and three for Glenbrook (sites 20-22).

Beach sand deposits and sand-and-boulder colluvium deposits are estimated to be less than 80 ft thick (Grose, 1985), and the average depth to bedrock reported for sec. 27, T. 13, R. 18 in California (in the vicinity of the State line) is 100 ft (California State Water Resources Control Board, 1979, p. 193). Well drillers' reports filed for the areas of interest indicate that the bedrock surface was encountered from land surface to more than 200 ft below land surface. Because of the uncertainty in estimation of aquifer thickness, a conservative minimum thickness and a maximum thickness based on limited well drillers' reports for each area were used as a range of aquifer thickness. The maximum and minimum values of specific discharge for each aquifer were then used to compute an estimated range of annual flux of ground water to Lake Tahoe. These values are listed in table 4.



Base from U.S. Geological Survey digital data, Carson City, 1979, and Smith Valley, 1985, 1:100,000, Universal Transverse Mercator projection, zone 11

Figure 6. Selected aquifers and associated drainage areas used for this study.

Table 4. Estimated ground-water flux for selected aquifers in study area

Aquifer location	Cross-section geometry			Specific discharge (feet per day)	Ground-water flux (acre-feet per year)
	Width (feet)	Thickness (feet)	Area (square feet)		
Stateline-Elk Point	7,500	20	150,000	0.0071-0.32	9-400
		200	1,500,000		90-4,000
Zephyr Cove	450	10	4,500	.0093-.88	.4-30
		100	45,000		4-300
Glenbrook	600	10	6,000	.0025-.026	.1-1
		100	60,000		1-10

Estimates of ground-water flux range from 0.1 acre-ft/yr from the Glenbrook aquifer to as much as 4,000 acre-ft/yr from the Stateline-Elk Point aquifer. This range of values brackets estimates for the Upper Truckee River-Trout Creek aquifer system (1,395 acre-ft/yr; Loeb, 1987, p. 130) and the Ward Creek aquifer (3,324 acre-ft/yr; Loeb, 1987, p. 139). However, the Upper Truckee River-Trout Creek aquifer system also provides more than 100,000 acre-ft of ground water per year for public water supplies (Loeb, 1987, p. 130).

GROUND-WATER QUALITY

Background Regarding Nutrients in Relation to Lake Tahoe

Nitrogen and phosphorus are essential nutrients for productivity of algae. Results of bioassay experiments to determine the response of Lake Tahoe algal communities to concentrations of nitrogen, phosphorus, and iron indicate that nitrogen is the nutrient that controls primary productivity in the lake, and that dissolved iron stimulates algal productivity to a greater degree than phosphorus (Goldman, 1974, p. 6-7). However, studies during the last decade indicate that the growth rate of algae in Lake Tahoe may be becoming limited by the availability of phosphorus (Goldman, 1988, p. 1322).

Knowledge of the processes controlling the availability and mobility of nutrients is essential to determining their sources and the effect they may have on the water quality of Lake Tahoe. Nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), ammonia (NH_3), organic nitrogen (amides, amines, amino acids, proteins and urea), and nitrogen gas (N_2) are species of nitrogen in ground water. Biologically mediated processes can hydrolyze organic nitrogen to ammonium (ammonification), oxidize ammonium to nitrite and nitrite to nitrate (nitrification), chemically reduce nitrate to nitrite and nitrite to nitrogen gas (denitrification), and reduce atmospheric nitrogen gas to organic nitrogen (nitrogen fixation). Reaction rates for nitrogen cycling are controlled by the biological community and by environmental factors such as temperature, pH, light intensity, energy source (carbon), and dissolved-oxygen concentration (Behnke, 1975, p. 156-161).

Nitrogen in ground water typically originates from land-surface sources, with only minor contributions from the water-bearing formation. The average nitrogen content of granitic rock is only 18 mg/kg, of which less than 8 mg/kg is water soluble (Feth and others, 1964, p. 44). Land-surface sources include atmospheric precipitation, plant and animal wastes, nitrogen-fixing leguminous plants, nitrifying bacteria, fertilizers, septic-system leachate, and sewage spills.

Nitrate is the nitrogen species most readily transported by ground water. Nitrite and organic nitrogen are not stable in aerated systems (that is, they are readily oxidized to nitrate) and ammonium is strongly sorbed to the mineral surfaces of the soil and rocks. The mobility of organic nitrogen is also limited due to its complex molecular structure. In anaerobic (nonaerated) conditions, nitrite can move freely with ground-water flow.

The orthophosphate ion is the predominant form of phosphorus in ground water, but organic phosphorus species—synthesized by plants and animals—also can contribute phosphorus to ground water. Orthophosphate, the most biologically reactive form of phosphorus, is derived primarily from dissolution of soils and rock, hydrolysis of organic phosphorus, and from fertilizers. Adsorption, coprecipitation with metals, and biological assimilation are the major controls on phosphorus availability and mobility in ground-water systems (Hem, 1985, p. 126-129).

Iron is essential to virtually all organisms because it serves as an electron carrier in metabolic oxidation-reduction reactions (Brock, 1974, p. 182). The aqueous chemistry of iron is strongly controlled by the oxidation potential and pH of the aqueous system. High concentrations of ferrous iron (Fe^{2+}), the most abundant form of iron in solution, result from either reduction of ferric oxyhydroxides or oxidation of ferrous sulfides (Hem, 1985, p. 77). Aerobic aqueous systems with pH in the range of about 6.5 to 8.5 rarely have dissolved-iron concentrations greater than 10 mg/L. Higher concentrations of iron in ground water within this pH range may indicate a reducing environment or interaction between oxidized iron compounds and reduced organic matter (Hem, 1985, p. 83).

These biological and geochemical processes affect speciation of nutrients that are important to algae productivity in Lake Tahoe. Because of these factors, nutrients are nonconservative (reactive) solutes in ground-water systems; that is, a concentration measured in a sample of ground water collected some distance from the lakeshore may change by the time that ground water discharges into Lake Tahoe. Depending upon the particular nutrient, its oxidation state, and specific sources and sinks along the ground-water flow path, concentrations in wells could increase or decrease in magnitude between the sampled well and the point of ultimate ground water discharge to Lake Tahoe. Therefore, areas with elevated nutrient concentrations in ground water represent only potential nutrient sources, and the actual effect on the lake depends on the concentration and biological availability of the nutrients that ultimately discharge into the lake.

Historical (1960-82) Ground-Water Quality

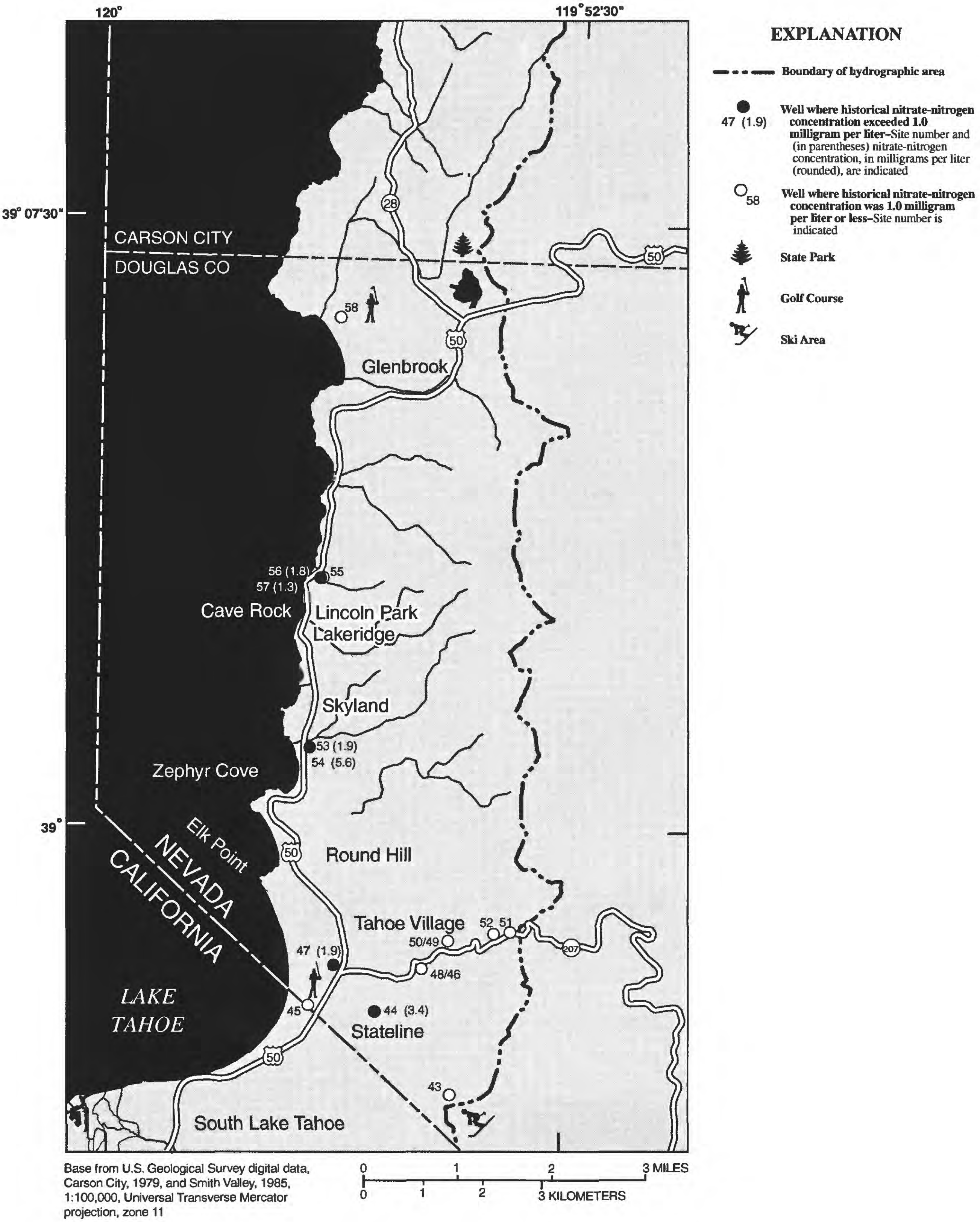
Historical data on ground-water quality for the study area were obtained from records of the NBHPS (Nevada Bureau of Health Protection Services). The data are for 22 water samples collected from 16 wells during 1960-82. The locations of these sites are shown in figure 2. The data have been published in a previous U.S. Geological Survey report (Thodal, 1992, table 8, p. 25). The NBHPS data are for whole-water (unfiltered) samples that were collected at the consumer's tap and may not be representative of water quality in the aquifer. A statistical summary of these data is presented in table 5. An average value was calculated for wells that had more than one analysis, to avoid biasing the statistical summary toward such wells.

The maximum reported concentration of nitrate, expressed as nitrogen (hereafter referred to as "nitrate-nitrogen"), was 5.6 mg/L for a 1963 water sample from a public-supply well (site 54, fig. 2). This water sample also had the highest concentration of dissolved solids (210 mg/L) and the third highest concentrations of sodium (37 mg/L) and chloride (13 mg/L). This well has since been abandoned and sealed with concrete, reportedly because of low water yield. Analysis of limited available data indicates that septic-field leachate may have affected the quality of this well water. Historical nitrate-nitrogen concentrations exceeding 1 mg/L are shown in figure 7. Although these concentrations do not seem high, the monthly average nitrate-nitrogen concentrations in Lake Tahoe for water year 1987 were far lower, ranging from 0.003 to 0.026 mg/L (Byron and others, 1988, table 5, p. 54).

Table 5. Statistical summary of historical (1960-82) ground-water quality data used in this study, as reported by Nevada Bureau of Health Protection Services

[Units of measure: milligrams per liter, except as indicated. Abbreviations: ROE, residue on evaporation at 105 degrees Celsius; µg/L, micrograms per liter]

Property or constituent	Number of determinations	Minimum	Median	Maximum
Calcium	21	6.0	16	33.6
Magnesium	21	1.0	4.4	11.7
Sodium	6	3	11	31
Potassium	6	1	2.2	4
Sodium plus potassium (expressed as sodium)	16	6	26.8	76.3
Bicarbonate	22	22	83	137
Sulfate	22	0	5	149
Chloride	22	1.0	5.5	27
Fluoride	11	.00	.06	1.06
Dissolved solids (ROE)	22	17	116	210
Nitrate (as nitrogen)	19	.0	.9	5.6
Iron (µg/L)	18	.00	120	4,000



Base from U.S. Geological Survey digital data, Carson City, 1979, and Smith Valley, 1985, 1:100,000, Universal Transverse Mercator projection, zone 11

Figure 7. Nitrate-nitrogen concentrations at historical (1960-82) sampling sites used for this study.

Water is classified into general chemical types on the basis of major cations (calcium, magnesium, sodium, and potassium) and major anions (bicarbonate, sulfate, and chloride), in milliequivalents per liter (units of measure that account for differing atomic weights and electrical charges among the ions), expressed as a percentage of their respective totals. A water is classified as a calcium bicarbonate type when at least 50 percent of the cation total (in milliequivalents per liter) is calcium and at least 50 percent of the anion total (in milliequivalents per liter) is bicarbonate. If no single cation or anion accounts for 50 percent of the respective total, the water is classified as "mixed" and the two dominant ions are used to designate the chemical type (Piper and others, 1953, p. 26). According to this classification scheme, ten of the historical samples were mixed-cation (calcium and sodium dominate) bicarbonate waters, six were calcium bicarbonate waters, four were sodium bicarbonate waters, and one was a sodium sulfate water.

Ground-Water Quality for Sites Sampled in this Study (1986-87)

Water-quality data for 48 water samples collected from 30 wells, 9 streams, and 3 springs (fig. 2) are documented in another USGS report (Thodal, 1992, table 9, p. 26-27). A statistical summary of water-quality data collected during this study (1986-87) is presented in table 6.

General Chemical Characteristics

Calcium, magnesium, sodium, and potassium are derived from weathering of feldspar, hornblende, and biotite minerals common in the study area (Feth and others, 1964, p. 37-42). Bicarbonate is derived primarily from dissolved carbon dioxide (CO_2). The atmosphere is one source of dissolved CO_2, but plant respiration and oxidation of organic matter in soils substantially increase the concentration of dissolved CO_2 and, consequently, the concentration of bicarbonate (Hem, 1985, p. 106-107). Natural sources of chloride and sulfate include atmospheric precipitation and ground water rising along fault zones (Feth and others, 1964, p. 43-44). Concentrations of chloride and sulfate typically are low in ground water of the Sierra Nevada. The unusually high chloride concentrations (greater than 100 mg/L and as high as 500 mg/L) at sites 16, 18, and 19, near U.S. Highway 50 (Thodal, 1992, table 9) are believed to result from road salt, septic-tank leachate, or both. The dissolved-solids concentration includes all dissolved ions. Relatively large concentrations of dissolved solids (greater than 300 mg/L) are characteristic of the calcium chloride type water at sites 16 and 18 and the mixed-cation chloride type water at site 19 (Thodal, 1992, table 9). The distribution of the chemical characteristics of sampled water and dissolved-solids concentrations among sites sampled for this study is shown in figure 8.

Water from 11 of 12 surface-water sites and from 15 of the 29 ground-water-sample sites is classified as calcium bicarbonate type. Other water types in the study area include sodium bicarbonate; mixed-cation bicarbonate (cations dominated by calcium and sodium and by calcium and magnesium); mixed-cation chloride; calcium chloride; calcium mixed-anion (bicarbonate and chloride as dominant anions); and mixed-cation, mixed-anion (calcium and sodium as dominant cations and bicarbonate and chloride as dominant anions). The distribution of water types among sites sampled for this study is shown in figure 8. The high chloride concentrations indicate that ground water is affected by leachate from road salt or abandoned septic-tank systems.

Nutrients

Distribution of Concentrations

Maximum and median dissolved-nutrient concentrations measured in the water samples collected during this study were, respectively: nitrogen (sum of measured nitrogen species), 9.3 and 0.54 mg/L; nitrate-nitrogen, 8.2 and 0.028 mg/L; nitrite-nitrogen, 0.58 and 0.003 mg/L; ammonia-nitrogen, 0.89 and 0.03 mg/L; organic nitrogen, 1.5 and 0.36 mg/L; phosphorus (sum of all species), 0.065 and 0.014 mg/L; orthophosphate-phosphorus, 0.049 and 0.007 mg/L; and iron, 22,000 and 98 µg/L. Nutrient data are statistically summarized in table 6. The distribution of dissolved-nitrogen concentrations (the sum of measured nitrogen species) among sites sampled for this study is shown in figure 8.

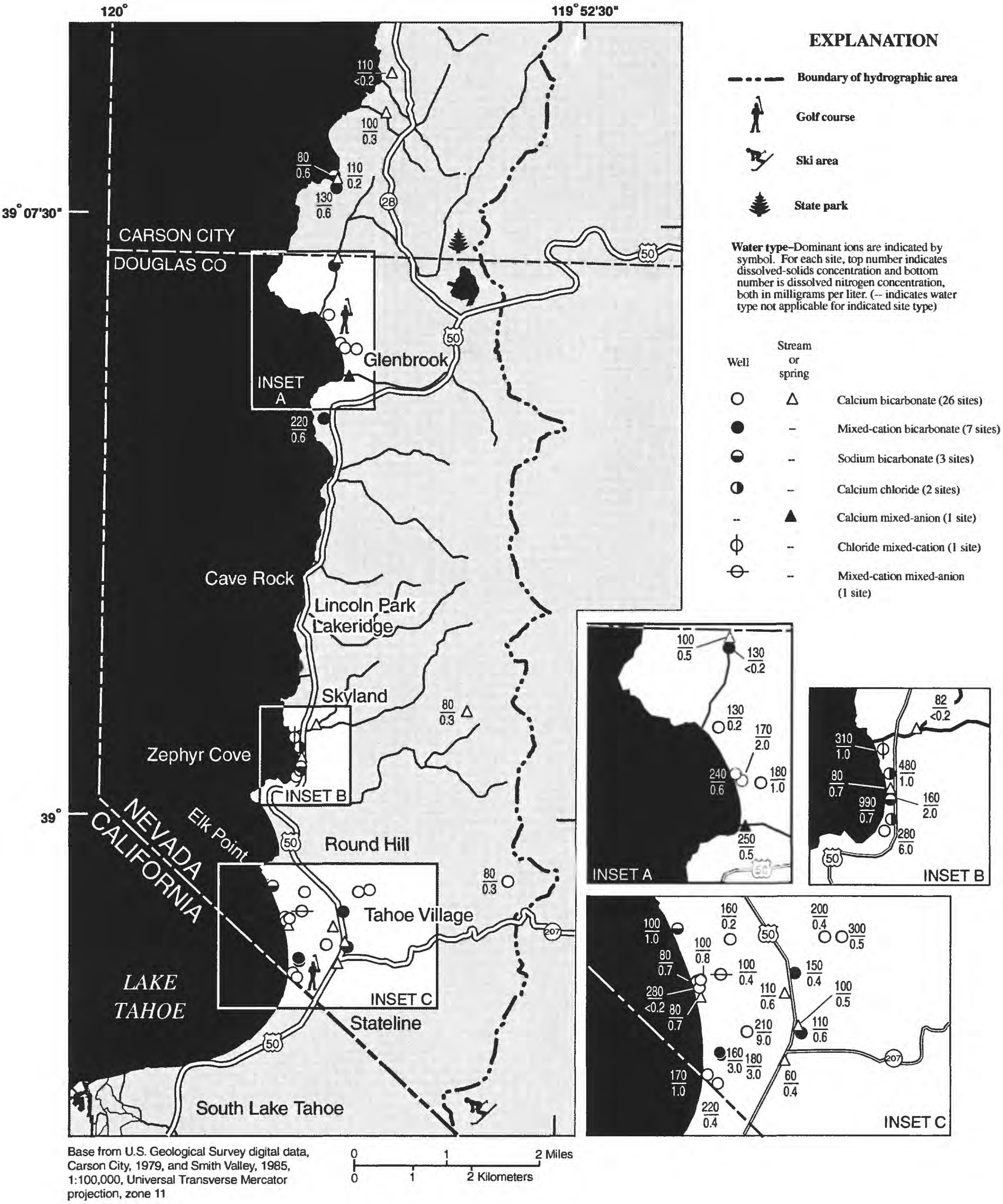
Table 6. Statistical summary of water-quality data collected during this study (1986-87)

[Units of measure: milligrams per liter, except as indicated. Abbreviations: µS/cm, microsiemens per centimeter at 25°C; °C, degrees Celsius; ROE, residue on evaporation at 180°C; µg/L, micrograms per liter; pCi/L, picocuries per liter; N, nitrogen; P, phosphorus; NA, not applicable; <, less than; data rounded to two significant figures]

Constituent or property	Number of determinations	Number of determinations less than analytical reporting limit	Mean[1]	Standard deviation[1]	10th percentile[1]	25th percentile[1]	50th percentile (median)[1]	75th percentile[1]	90th percentile[1]	Minimum	Maximum
Specific conductance (µS/cm)	48	0	270	230	120	140	220	350	430	100	1,600
pH (standard units)	48	0	NA	NA	6.5	6.6	7.0	7.4	7.7	6.2	8.4
Temperature (°C)	48	0	11.0	2.7	8.5	9.5	10	12	15	7.0	22
Calcium, dissolved	48	0	28	24	12	14	18	38	48	6.0	150
Magnesium, dissolved	48	0	6.8	7.0	2.3	2.7	3.7	9.8	13	1.2	43
Sodium, dissolved	48	0	16	10	6.8	8.9	13	20	32	5.5	55
Potassium, dissolved	48	0	3.0	1.6	1.9	2.1	2.6	3.4	5	.9	10
Bicarbonate	45	0	110	60	64	77	89	120	200	57	370
Alkalinity	45	0	91	49	52	63	73	100	160	43	300
Sulfate, dissolved	48	0	7.9	8.9	1.5	2.2	4.0	11	19	1.1	50
Chloride, dissolved	48	0	27	75	.79	2.8	6.8	20	65	.40	500
Fluoride, dissolved	48	17	.10	.08	.06	.07	.10	.10	.11	<.10	.50
Silica, dissolved	48	0	26	6.7	18	21	25	29	36	13	41
Solids, dissolved (ROE)	48	0	180	150	82	100	140	210	280	55	940
Nitrogen, dissolved	46	4	1.0	1.6	.17	.35	.54	.85	2.4	<.2	9.3
Nitrate, dissolved (as N)	47	21	.50	1.5	.0001	.005	.028	.15	1.6	<.010	8.2
Nitrite, dissolved (as N)	48	18	.018	.084	.0005	.001	.003	.008	.015	<.001	.58
Ammonia, dissolved (as N)	45	6	.07	.15	.005	.01	.03	.06	.18	<.002	.89
Organic nitrogen, total (as N)	14	1	.70	.40	.24	.36	.72	.89	1.4	<.2	1.7
Organic nitrogen, dissolved (as N)	48	6	.42	.27	.15	.22	.36	.54	.76	<.2	1.5
Orthophosphate, dissolved (as P)	48	13	.011	.011	.002	.003	.007	.015	.032	<.005	.037
Phosphorus, total (as P)	30	1	.042	.036	.006	.015	.028	.064	.10	<.005	.13
Phosphorus, dissolved (as P)	48	8	.017	.014	.004	.007	.014	.020	.040	<.001	.065
Iron, dissolved (µg/L)	48	3	1,600	4,500	4	16	66	350	7,400	<3	22,000
Manganese, dissolved (µg/L)	48	8	150	230	.9	5.2	31	160	600	<1	830
Organic carbon, total	34	1	3.2	2.4	.8	1.3	3	4.3	7.0	<.1	10
Organic carbon, dissolved[2]	6	0	.9	.3	--	--	--	--	--	.4	2.9
Radium-226, dissolved (µg/L)[2]	4	0	.009	.073	--	--	--	--	--	.04	.20
Radon-222 gas, dissolved (pCi/L)	31	6	3,700	4,400	73	180	1,400	7,700	10,000	<100	16,000
Uranium, dissolved (µg/L)[2]	11	0	19	25	--	--	--	--	--	.50	83

[1] Mean and standard deviation were estimated using log-probability regression; percentiles (10th, 25th, 50th, 75th, and 90th) were estimated using log-normal maximum likelihood (Helsel and Cohn, 1988, p. 1997-2004).

[2] Number of determinations insufficient for meaningful calculation of summary statistics.



Base from U.S. Geological Survey digital data, Carson City, 1979, and Smith Valley, 1985, 1:100,000, Universal Transverse Mercator projection, zone 11

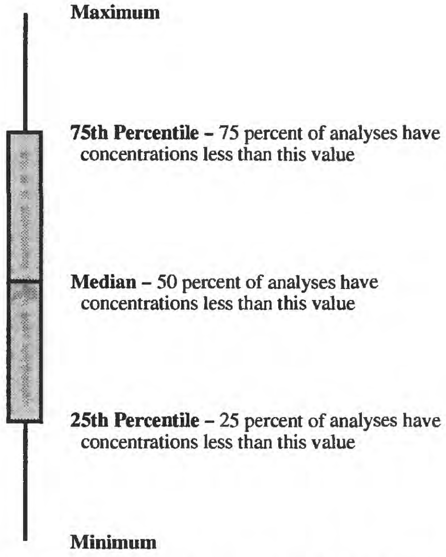
Figure 8. Chemical character of water for sites sampled during this study (1986-87).

Graphical “boxplots” of the nutrient data are shown in figures 10 through 15, and an explanation of boxplot components is shown in figure 9. A boxplot is a means of displaying statistics regarding the distribution of reported concentrations of a constituent. The “box” defines the distribution of the central 50 percent of the concentrations (that is, the concentrations between the 25th and 75th percentiles). The line dividing the box represents the median value, or 50th percentile. Lines drawn beyond the box, which are referred to as “whiskers,” span all values that are greater than the 75th percentile and less than the 25th percentile (that is, the whiskers extend, respectively, to the maximum value and the minimum value, or detection level).

Water-quality sites are grouped into six categories for boxplot presentation in figures 10-15. The group “golf-course wells” consists of sites 1-5 and 20-22 (8 samples); “effluent-pond wells” are sites 12 and 14 (5 samples); “resort wells” are sites 15-19 (5 samples); “background wells” are sites 6-11 and 23-25 (10 samples); “domestic wells” are sites 26-30 (6 samples); and “springs and streams” are sites 31-42 (14 samples).

Groupings were made on the basis of the land use immediately surrounding each site. "Golf course wells" include all wells located on golf courses in the study area. Three of these wells (sites 1, 5, and 20) were intentionally installed near the edge of golf courses and are assumed to be located at the upgradient end of the ground-water flow path under the golf course. "Effluent-pond wells" were installed prior to this investigation for the Douglas County Sewer Improvement District in response to regulations concerning wastewater treatment and storage. This group consists of two wells (sites 12 and 14) located along the assumed ground-water flow path downgradient from a treated-effluent-holding pond. "Resort wells" include five wells installed for this investigation in the vicinity of a resort that was established during the 1930's, more than 30 years prior to an Executive Order issued by the Governor of Nevada that prohibited the use of septic-tank systems in the Nevada part of the Lake Tahoe Basin after December 31, 1972. Prior to the Executive Order, this resort relied on a septic-tank system for wastewater disposal. A riding stable and a campground also are associated with the resort. The five wells in this group are in the general vicinity of the resort, but a leachate plume from a septic-tank system had not been delineated. "Background wells" include nine wells installed on U.S. Forest Service land for this study: four wells (sites 6, 11, 23, and 24) are in stands of mature trees, four wells (sites 7, 8, 9, and 25) are along beaches that are downgradient from an open meadow and mature forest land, and one well (site 10) is in an open meadow. "Domestic wells" that were sampled for this study are considered as a single group because they are deeper than the observation wells that make up the other groups. "Springs and streams" are grouped because discrete land-use areas that contribute ground water to flow could not be identified.

The grouping scheme used in this analysis is not ideal due to limited historical records to confirm that one particular land use did not replace a previous land-use activity that actually affected ground-water quality. In addition, each group has a relatively small number of samples, and other activities upgradient from some sample sites may affect the quality of water from those sites. Thus, the data for these groupings should be interpreted with caution. However, the results could be used to guide more detailed investigations of land-use activities that may be potential sources of ground-water contamination.



Note: Where the distribution of data is limited, the minimum, 25th percentile, median, and 75th percentile can have same value.

Figure 9. Components of boxplots shown in figures 10-15.

Figure 10 indicates that dissolved nitrate-nitrogen concentrations—both the maximum (8.2 mg/L) and median (0.83 mg/L)—were highest at the golf-course sites. The highest concentration was at site 5, which was in the vicinity of sites where high nitrate-nitrogen concentrations were reported by the NBHPS (1.9 mg/L in 1961 and 3.4 mg/L in 1963). However, the golf course, which is downgradient from these sites, did not open until 1968. Also, nitrate-nitrogen concentrations decreased in a downgradient direction, along the apparent ground-water flow paths from site 5 to site 2 and from site 21 to site 23, near the lakeshore. These decreases could be attributed to dilution, biological removal (assimilation, denitrification, or both), or to local point-source inputs that have not migrated far. Relatively high nitrate (5.8 mg/L) was measured at site 15, which is near an abandoned septic system. High nitrate-nitrogen concentrations (5.6 mg/L and 1.9 mg/L) in the vicinity of site 15 for ground-water samples collected in 1963 and in 1973 also were reported by NBHPS.

It is important to note that almost 90 percent (43 samples) of the 48 samples analyzed for nitrate had concentrations less than 1 mg/L (median, 0.011 mg/L) and that the 10 samples believed to represent background conditions had a maximum concentration of 0.16 mg/L (median, <0.10 mg/L). Nevertheless, the monthly average concentration of nitrate reported for samples from Lake Tahoe during water year 1987 ranged from 0.003 to 0.026 mg/L (annual average: 0.014 mg/L; Byron and others, 1988, table 5, p. 54). A slight nitrate-concentration gradient apparently exists even between uncontaminated ground water and the lake. Sewage-disposal practices that are no longer allowed within the study area, and possibly golf-course fertilization practices, may be responsible locally for relatively high nitrate concentrations.

The boxplot graphs of dissolved organic nitrogen (fig. 11) and of ammonia-nitrogen (fig. 12) indicate that septic-system sites and golf-course sites had some higher concentrations of these reduced-nitrogen species than the other four groups.

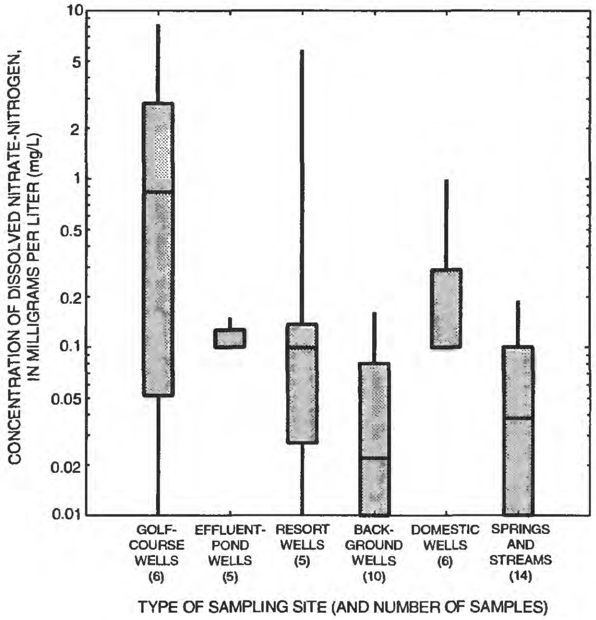


Figure 10. Distribution of dissolved nitrate-nitrogen concentrations among site groups sampled during this study. Analytical reporting limits: water from observation wells near treated effluent holding ponds and from domestic wells, 0.1 mg/L; water from other wells, springs, and streams, 0.01 mg/L.

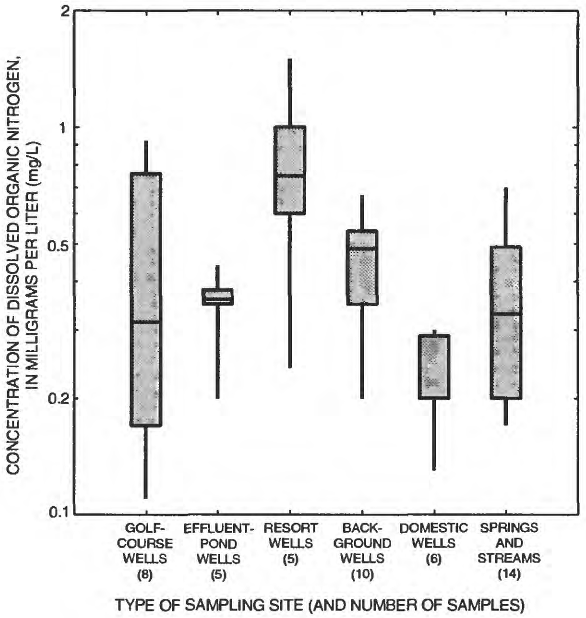


Figure 11. Distribution of dissolved organic nitrogen concentrations among site groups sampled during this study. Analytical reporting limit: 0.1 mg/L.

Although the analyses report ammonia, in the normal pH range of most natural water, the ammonia in solution is present as ammonium (Hem, 1985, p. 126). No historical data are available for these nitrogen species, but both may be considered to indicate septic-system leachate (Canter and Knox, 1985, p. 46-48). Reduced-nitrogen species also can be derived from decomposition and oxidation of nitrogen-rich organic matter, which could be associated with the organic-rich alluvium mapped in this area by Grose (1985). Average chemical characteristics typical of septic-tank influent in the United States include total Kjeldahl nitrogen (organic nitrogen plus ammonia-nitrogen) in concentrations of about 38 mg/L, ammonia-nitrogen concentrations of about 12 mg/L, and nitrate-nitrogen concentrations of less than 1 mg/L (Canter and Knox, 1985, p. 46). These concentrations are affected by geochemical conditions in the receiving ground-water system, where the leachate generally is diluted and oxidized.

Concentrations of dissolved phosphorus (maximum, 0.065 mg/L at site 9; median, 0.014 mg/L) and orthophosphate-phosphorus (maximum, 0.049 mg/L at site 6; median, 0.007 mg/L) in ground water were low, but were higher than monthly average concentrations of total phosphorus in Lake Tahoe, which were reported to range from 0.0014 to 0.0042 mg/L (annual average, 0.0026 mg/L; Byron and others, 1988, table 5). The potential for soils to sorb phosphorus species from solution is probably the controlling mechanism limiting ground-water transport of these nutrients. Figures 13 and 14 illustrate the narrow range of measured phosphorus concentrations, with values of 0.01 mg/L or less in each group and maximums less than 0.07 mg/L. Available data do not indicate that elevated concentrations of dissolved phosphorus species are associated with any particular site group in this study.

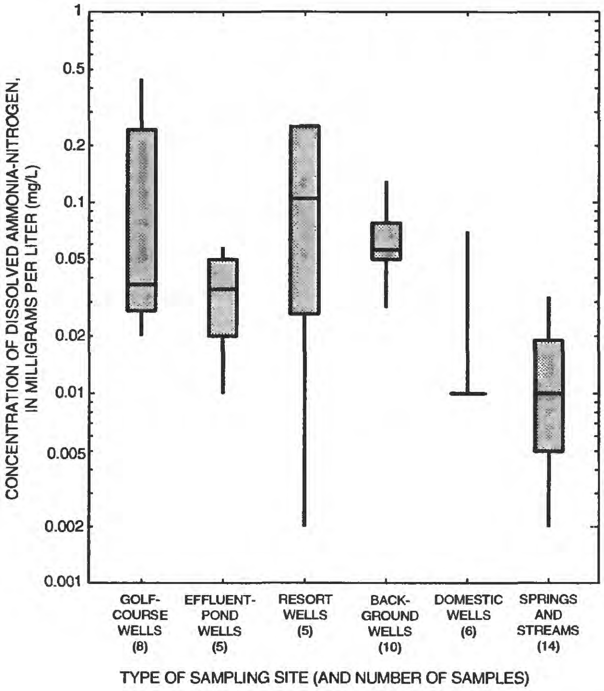


Figure 12. Distribution of dissolved ammonia-nitrogen concentrations among site groups sampled during this study. Analytical reporting limits: water from observation wells near treated-effluent holding ponds and from domestic wells, 0.01 mg/L; water from other wells, springs, and streams, 0.002 mg/L.

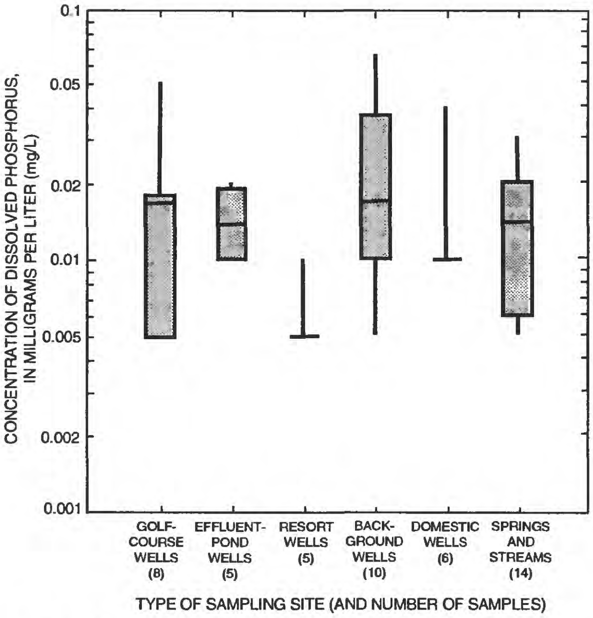


Figure 13. Distribution of dissolved phosphorus concentrations among site groups sampled during this study. Analytical reporting limits: water from observation wells near treated-effluent holding ponds and from domestic wells, 0.05 mg/L; water from other wells, springs, and streams, 0.001 mg/L.

Figure 15 presents boxplots of dissolved iron concentrations. The surface-water sites had low concentrations, as expected in aerated water. Ground-water samples generally had iron concentrations less than 10,000 µg/L; the median concentration was 66 µg/L. In Lake Tahoe, concentrations of total iron generally are less than 7 µg/L (Goldman, 1974, p. 80). The high iron concentrations illustrated by figure 15 for the resort well group may be an indication of metallic contamination from septic-tank effluent (Canter and Knox, 1985, p. 79). However, interaction between reduced organic matter associated with the organic-rich alluvium in the vicinity of the resort well group and immobile oxidized iron minerals also may have mobilized ferrous iron (Hem, 1985, p. 83).

Rates of Nutrient Transport

The mass of a substance transported by ground water through a one-square-foot cross-sectional area of aquifer in one day may be estimated for purposes of this report as "specific load," expressed as milligrams per day per square foot. Specific loads were estimated for 16 observation wells within one-quarter mile of the lakeshore (table 7) by using the nutrient concentration measured at each site (Thodal, 1992, p. 28-29) and estimates of specific discharge (table 3) in the equation

$$\text{specific load} = q \times A \times c \times n\,, \qquad (7)$$

where

q is specific discharge, in feet per day;

A is one-square-foot cross-sectional area;

c is 28.316, a constant to convert cubic feet to liters; and

n is concentration, in milligrams per liter.

These site-specific estimates (table 7) exhibit a wide range of solute mass that may pass through a unit cross-sectional area of aquifer, primarily the result of the wide range of specific-discharge estimates. For example, sites 4, 7, 15, 17, and 24 have the largest estimates of specific discharge and, consequently, they generally have the largest estimates of specific load. Exceptions result from concentrations that were (1) below the level of detection at those sites, or (2) much larger than the median concentration at other sites.

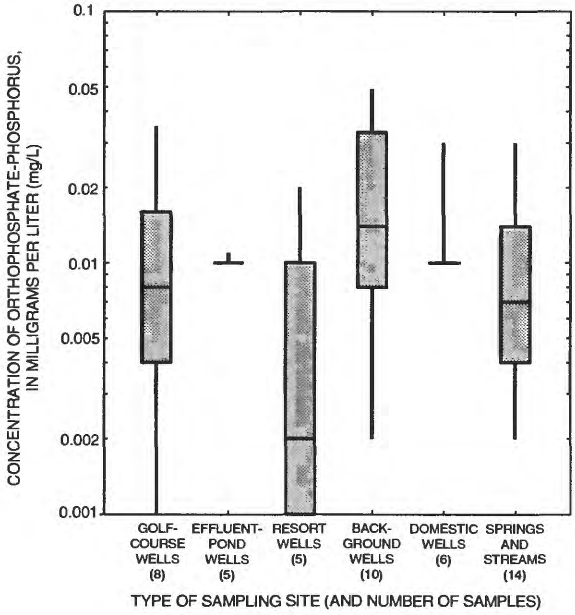


Figure 14. Distribution of dissolved orthophosphate-phosphorus concentrations among site groups sampled during this study. Analytical reporting limits: water from observation wells near treated-effluent holding ponds and from domestic wells, 0.01 mg/L; water from other wells, springs, and streams, 0.001 mg/L.

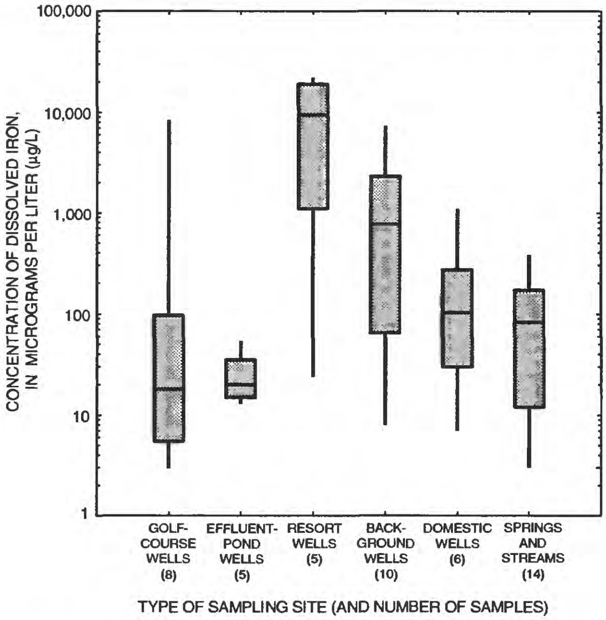


Figure 15. Distribution of dissolved iron concentrations among site groups sampled during this study. Analytical reporting limit: 3 µg/L.

Table 7. Estimates of specific load for observation-well sites within one-quarter mile of Lake Tahoe

[Symbol: <, concentration was less than the analytical reporting limit]

Site number (figure 2)	Milligrams per day per square foot of cross-sectional area						
	Nitrate-nitrogen, dissolved	Ammonia-nitrogen, dissolved	Organic nitrogen, dissolved	Nitrogen, dissolved	Ortho-phosphate phosphorus, dissolved	Phos-phorus, dissolved	Iron, dissolved
1	0.01	0.03	0.3	0.4	0.008	0.01	0.02
2	<.0002	.008	.01	.02	.0005	.0006	.2
4	10	.1	1	12	.02	<.02	.1
7	<.08	.6	<2	<2	.05	.08	.4
8	.1	.07	.7	.9	.02	.02	.2
9	<.004	.05	.3	.3	.02	.03	.003
15	20	1	1	30	<.008	.04	.1
16	.07	.3	2	2	.03	<.02	70
17	2	.7	40	40	.5	<.1	30
18	.1	.2	.7	1	<.001	<.005	20
19	<.002	.0005	.2	.2	<.0002	.001	2
20	.03	.02	.3	.4	.003	.007	.003
21	.2	.004	.1	.4	.005	.008	<.0005
22	.1	.01	.05	.2	.002	.005	.001
24	4	2	8	10	.4	.8	60
25	.02	.04	.3	.4	.02	.02	.04
Median	0.08	0.06	0.3	0.4	0.01	0.008	0.2
90-percent confidence interval	0.06-2.4	0.02-0.3	0.3-1	0.4-3	0.005-0.03	0.007-0.03	0.04-4

The estimates of specific load are important because they present ranges of possible nutrient load and they also may serve as an index to types of local settings where nutrient flux could be higher than at other locations. However, to evaluate the significance of the role of ground water in the nutrient budget of Lake Tahoe, nutrient loads in ground water must be estimated in units that may be compared to estimates of nutrient loads from other sources. Although available data are insufficient to make such estimates for the entire study area, the three aquifers for which estimates of ground-water flux have been made (table 4) provide an opportunity to consider a range of estimates in terms that can be compared to load estimates made for surface-water sources and other aquifers that interact with Lake Tahoe.

Table 8 lists ranges of annual nutrient load estimates computed by the equation:

$$L = (Q \times n) \times 1.23344 \ , \qquad (8)$$

where

L is the estimated annual load, in kilograms per year;
Q is the estimated ground-water flux, in acre-feet per year (table 4);
n is concentration, in milligrams per liter; and
1.23344 is a constant to make the dimensional units compatible.

Of the three aquifers considered, the Stateline-Elk Point aquifer has the largest load estimates except when concentrations were below the level of detection. This is due primarily to the larger cross-sectional area of the Stateline-Elk Point aquifer relative to the other two. The wide range of load estimates listed for each aquifer (for example, 0.4 to 2,000 kg/yr of nitrogen for the Zephyr Cove aquifer) is the result of aquifer heterogeneity (variation in hydraulic conductivity), uncertainty of aquifer geometry, and, in the case of nitrogen and iron concentrations, the relatively wide ranges of concentrations that were measured. Neither the maximum nor the minimum concentrations are

Table 8. *Estimated annual nutrient load for selected aquifers in study area*

[Symbol: <. concentration was less than the analytical reporting limit]

Aquifer location	Nutrient load (kilograms per year)							
	Nitrogen		Organic nitrogen		Ammonia-nitrogen		Nitrate-nitrogen	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Stateline-Elk Point	<2	20,000	<2	3,000	0.1	2,000	<0.1	10,000
Zephyr Cove	.4	2,000	0.1	600	.001	100	<.005	2,000
Glenbrook	.02	30	.02	10	.003	.8	<.01	20

Aquifer location	Nutrient load (kilograms per year)					
	Phosphorus		Orthophosphate-phosphorus		Iron	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Stateline-Elk Point	<0.05	300	0.03	200	0.09	40,000
Zephyr Cove	<.002	4	<.0005	7	.01	8,000
Glenbrook	.002	.6	.0009	.4	<.0004	10

likely to be representative of the ground-water quality of the entire aquifer, and the limited data are insufficient to estimate what a representative concentration might be. It was beyond the scope of this report to delineate the size and distribution of solute plumes with higher concentrations.

Loeb (1987, p. 132-141) reported that 153-799 kg/yr of nitrate-nitrogen and 26.56 kg/yr of soluble reactive phosphorus were discharged to Lake Tahoe by ground water from the Upper Truckee River and Trout Creek drainage basins, and that 525 kg/yr of nitrate-nitrogen and 185 kg/yr of soluble reactive phosphorus were discharged by ground water from the Ward Creek drainage. Loeb and Goldman (1979, p. 1152) estimated that ground water from the Ward Creek drainage contributed 660 kg/yr of nitrate-nitrogen and 300 kg/yr of soluble reactive phosphorus.

Annual nutrient loads are estimated for tributaries of Lake Tahoe by the Tahoe Research Group of the University of California at Davis. In water year 1987, four tributaries to Lake Tahoe each contributed between 48 and 610 kg/yr of nitrate-nitrogen, between 45 and 190 kg/yr of soluble reactive phosphorus, and between 220 and 13,400 kg/yr of biologically available iron (Byron and others, 1988, p. 68-70). These load esti-mates are probably lower than normal because annual streamflows reported for these four tributaries during water year 1987 were less than 50 percent of the mean annual discharge for each stream. However, these values still provide ranges of reference for comparison.

The ground-water load estimates made herein are based on limited data, and the wide range of each estimate reflects the uncertainty resulting from the limitations of these data. While nutrient concentrations can be determined with relative confidence to levels of a tenth of a milligram and less, the limited distribution of wells and springs and spatial variability make identification of "representative concentrations" problematic. Nutrients also are subject to biological processes and geochemical reactions that can change the concentration as ground water moves through the aquifer and particularly as ground water discharges through the lake bed into the lake.

Estimates of the hydraulic properties of each aquifer are made with even less confidence because of the limitations of the slug-test technique of aquifer testing. Slug tests will test only that part of the aquifer that is immediately surrounding the screened interval of the well, providing an estimate of the hydraulic conductivity of perhaps 100 ft^3 of aquifer. Additional uncertainty is due to the fact that wells used in this investigation penetrate only the top 3-22 ft of the aquifer. With emphasis on these limitations, the results of this investigation still indicate that the ground-water system is a pathway for nutrients to enter Lake Tahoe.

SUMMARY AND CONCLUSIONS

Stimulation of phytoplankton productivity by nutrients (nitrogen, phosphorus, and iron) is the suspected cause of decreasing water clarity in Lake Tahoe, a 190-mi^2 water body that straddles the Nevada-California State line. Studies on the California side of the basin have shown that ground-water inflow can contribute substantial nutrient loads to the lake. This report describes the results of an investigation of a 46-mi^2 part of the Lake Tahoe Basin in Nevada during 1985-87 to characterize the hydrogeologic setting and to determine the quality and nutrient content of ground water.

During this study, water-quality and hydrogeologic data were collected from 5 domestic wells, 25 observation wells, 9 streams, and 3 springs. Stream and spring data were collected during summer low flow, which was assumed to represent ground-water. The data include water-level measurements and aquifer tests for wells, discharge measurements for streams and springs, grain-size distributions for unconsolidated aquifer-material samples, and physical and chemical analyses (major dissolved chemical constituents, total and dissolved species of nitrogen and phosphorus, dissolved and total organic carbon, and dissolved iron, manganese, radium-226, radon-222, and uranium) for water samples from the wells, streams, and springs. Additionally, historical (1960-82) data on ground-water quality and information from 59 well-drillers' logs were compiled. All data collected during this study were published separately (Thodal, 1992).

The 59 well-drillers' reports filed with the Nevada Division of Water Resources indicate that well depths ranged from 34 to 447 ft below land surface (median, 124 ft). Water levels reported for 53 of these wells ranged from land surface to 200 ft below land surface (median, 28 ft).

Ground-water altitudes measured during this study in 25 observation wells ranged from 6,226.4 to 6,506 ft above sea level. The median altitude was 6,237 ft. In comparison, the lake-surface altitude for August 28, 1987, was 6,226 ft. Ground water flows west from recharge areas on upland slopes of the Carson Range, by way of fractured granitic bedrock and unconsolidated deposits of alluvium and decomposed granite, into lowland alluvial and lacustrine deposits adjacent to Lake Tahoe. Ground water discharges naturally into streams, from springs, directly into the lake, and by evapotranspiration.

Ten hydraulic-conductivity estimates made from aquifer slug-test data ranged from 0.18 to 120 ft/d (median, 11 ft/d). Regression analysis of grain-size distribution variables and hydraulic-conductivity values was used to estimate hydraulic conductivity for 10 additional well sites where slug tests were not done. Regression-equation estimates for the 20 wells ranged from 0.42 to 140 ft/d (median, 5.2 ft/d). The regression equation overestimated slug-test results that were less than about 1 ft/d, but the equation does provide a satisfactory approximation for wells where slug tests were not done.

Measured hydraulic gradients between 25 wells and Lake Tahoe ranged from about 10 ft/mi to more than 800 ft/mi. The median gradient was about 55 ft/mi. Specific discharge (the rate of discharge of ground water per unit area measured at right angles to the direction of flow) was estimated for 16 observation-well sites within one-quarter mile of the lakeshore on the basis of hydraulic-conductivity estimates and hydraulic gradients between each well and the lake surface. Specific-discharge estimates ranged from 0.0058 to 0.89 ft/d (median, 0.034 ft/d).

Maximum and median dissolved-nutrient concentrations in water samples collected during this study were, respectively: nitrogen, 9.3 and 0.54 mg/L; nitrate-nitrogen, 8.2 and 0.028 mg/L; nitrite-nitrogen, 0.58 and 0.003 mg/L; ammonia-nitrogen, 0.89 and 0.03 mg/L; organic nitrogen, 1.5 and 0.36 mg/L; phosphorus, 0.065 and 0.014 mg/L; orthophosphate-phosphorous, 0.049 and 0.007 mg/L; and iron, 22,000 and 66 µg/L. Although nutrient concentrations in ground-water samples generally appear to be low, median dissolved nitrate and phosphorus values are higher than monthly average concentrations of dissolved nitrate and total phosphorus reported for water samples from the lake itself (Byron and others, 1988, table 5, p. 54). This indicates that a concentration gradient exists from the ground water that was sampled within the study area to the lake. Dissolved nitrate concentrations at least two-orders of magnitude greater than concentrations reported for Lake Tahoe were measured in samples from wells on golf courses and near an abandoned septic-tank system. However, historical data indicate that comparable nitrate-nitrogen concentrations existed in these areas as early as 1961, predating the golf courses. The concentrations of nitrate-nitrogen apparently are diluted or removed from solution biochemically as the ground water moves downgradient along presumed ground-water flow paths from the observation wells to wells adjacent to Lake Tahoe.

Concentrations of reduced nitrogen species (organic nitrogen and ammonia-nitrogen) greater than 1 mg/L were measured in ground water in the vicinity of a resort that relied on a septic-tank system for disposal of wastewater and that also has a riding stable. This area also is underlain by carbonaceous alluvial deposits that could contribute these species of nitrogen to the ground-water system.

Concentrations of dissolved phosphorus and orthophosphate-phosphorus were less than 0.07 mg/L and 0.05 mg/L as P, respectively. These concentrations were greater than the total phosphorus reported for water samples from Lake Tahoe in 1987 (less than 0.005 mg/L as P; Byron and others, 1988, table 5), suggesting that ground water does contribute phosphorus to the lake. Available data do not indicate that phosphorus species are directly associated with the land uses identified in this study.

Dissolved-iron concentrations were higher in ground-water samples than those reported for Lake Tahoe, but generally were less than a few thousand micrograms per liter. The highest measured concentration (22,000 µg/L) was in a ground-water sample from carbonaceous alluvium near Zephyr Cove (site 16), and could have resulted from the interaction of reduced organic material with oxidized iron minerals.

Water from all of the surface-water sites and most of the wells is classified as either a calcium bicarbonate or a mixed-cation bicarbonate type, dominated by calcium and sodium. Chloride was a predominant anion in water samples from three wells near U.S. Highway 50. Chloride concentrations as high as 500 mg/L indicate that ground-water quality may be locally affected by leachate from road salt.

Specific-load estimates (the mass of a dissolved nutrient carried by ground water through a one-square-foot cross-sectional area of aquifer during a specific period) was estimated for 16 observation-well sites within one-quarter mile of the lakeshore. Values were calculated as the product of specific discharge and the concentration of the dissolved nutrient. Hydrodynamic dispersion, biological processes, and geochemical reactions were assumed to be negligible; quantification of these influences was beyond the scope of this study.

The range of specific-load estimates is shown in the following table:

Constituent	Milligrams per day per square foot (<, less than)	
	Range	Median
Dissolved nitrogen	<2-40	0.4
Dissolved phosphorus	<0.005-0.8	0.008
Dissolved iron	<0.0005-70	0.2

Ranges of annual nutrient loads possibly transported to the lake by three aquifers that extend along 1.3 mi of the 19 mi of shoreline in the study area are listed in the following table:

Aquifer location	Kilograms per year (<, less than)					
	Nitrogen		Phosphorus		Iron	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Stateline-Elk Point	<2	20,000	<0.05	300	0.09	40,000
Zephyr Cove	.4	2,000	<.002	4	.01	8,000
Glenbrook	.02	30	.002	.6	<.0004	10

The wide range of load estimates reflects the uncertainty associated with aquifer geometry and hydraulic properties, and, in the case of nitrogen and iron, locally elevated concentrations.

These estimates of potential nutrient load are inappropriate as a means of estimating the quantity of nutrients to Lake Tahoe by ground water because the processes that control the mobility and speciation of nutrients are poorly defined and, therefore, are not included in the transport calculations. For an estimation of nutrient loading, the rates of reactions that affect nutrient mobility and speciation must be quantified. Nonetheless, the nutrient-load estimates made herein do indicate that the ground-water system is a pathway for solutes to enter Lake Tahoe.

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