Hydrogeology of Lake Tahoe Basin, California and Nevada, and Results of a Ground-Water Quality Monitoring Network, Water Years 1990-92

By Carl E. Thodal

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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATED UNITS, AND ACRONYMS

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233,000	liter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.02832	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
inch (in.)	25.40	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
ton per year (ton/yr)	0.9072	megagram per year

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

g	gram	mg/kg	milligram per kilogram	ml	milliliter
µg/L	microgram per liter	mg/L	milligram per liter	$\mu mol/m^2/d$	micromole per square meter per day
µm	micrometer	mg/yr	milligram per year		
µS/cm	microsiemens per centimeter	pCi/L	picocuries per liter		

Acronyms:

AA	Atomic Absorption Spectrometry	QA/QC	Quality assurance and quality control
DCNR	Department of Conservation and Natural Resources (Nevada)	SWRCB	State Water Resources Control Board (California)
DWR	Department of Water Resources (California)	TRG	Tahoe Research Group
LTIMP	Lake Tahoe Interagency Monitoring Program	TRPA	Tahoe Regional Planning Agency
MCL	Maximum Contaminant Level	UCD	University of California at Davis
NWIS	National Water Information System	USGS	U.S. Geological Survey
NWQL	National Water Quality Laboratory	VSMOW	Vienna Standard Mean Ocean Water

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ABSTRACT

Decreased clarity in Lake Tahoe has been attributed to accelerated eutrophication due to an increase in nutrients—especially phosphorus, iron, and nitrogen. Water-quality monitoring in the Lake Tahoe Basin initially focused on in-lake measurements of clarity, nutrient concentrations, and algal productivity, and on determining streamflow inputs of water, sediment, and nutrients from selected tributaries. However, to accurately assess water and nutrient budgets and to better understand the processes affecting water quality in Lake Tahoe, all sources, including ground water, that may contribute to these budgets need consideration. The purpose of this study was to design and operate a network to monitor the quality of ground water in the Lake Tahoe Basin and to evaluate available data related to ground-water discharge to the lake.

A hydraulic gradient generally exists between wells in the upland areas and Lake Tahoe, and ground water flows from the upland areas downgradient until it is discharged by evapotranspiration, seepage to streams, springs, and other small lakes prior to reaching the lake, and as seepage directly to Lake Tahoe. Median values of hydraulic variables of Darcy's Law suggest that on the order of 40,000 acre-feet per year of ground water discharges to Lake Tahoe, but variability in relatively sparse measurements and other uncertainties indicate that the discharge could range from less than 800 acre-feet per year to more than 2 million acre-feet per year.

Results of the monitoring program indicate that the quality of ground water in the Lake Tahoe Basin generally meets drinking-water standards. Concentrations of dissolved solids measured in water samples from 32 sites ranged from 59 to 264 mg/L (milligrams per liter; median: 113 mg/L). Mean concentrations of filtered nitrogen ranged from 0.02 to 12 mg/L (median: 0.14 mg/L). Mean concentrations of filtered phosphorus ranged from 0.021 to 0.40 mg/L (median: 0.058 mg/L) and mean concentrations of filtered soluble iron ranged from 1 to 210 micrograms per liter (median: 11 micrograms per liter). Compared to the median concentration of nitrogen, water samples from five ground-water sites had unusually high concentrations; these well waters may have been contaminated by land application of fertilizers, by residual leachate from abandoned septic tank-leach field systems, or by an area that historically (before 1972) has been used for disposal of treated sewage effluent.

Estimates of annual nutrient contributions to Lake Tahoe are subject to considerable uncertainty due to uncertainties associated with estimating the large volume of water that may flow to the lake each year. Assuming that a mean concentration is representative for the entire volume of a hydrologic component results in additional uncertainty. However, this simplistic approach is reasonable as an approximation of the relative significance of ground water to the overall nutrient budget for Lake Tahoe. Order-of-magnitude loading estimates suggest that the atmosphere is the dominant source of nitrogen (300 tons per year) and co-dominant source of phosphorus (20 tons per year).

Streamflow runoff is the dominant source of soluble iron (200 tons per year) and matches estimated atmospheric phosphorus loading (20 tons per year). Estimated ground-water contributions to the lake for nitrogen, phosphorus, and soluble iron are 60, 4, and 2 tons per year, respectively (which in turn represent 86, 20, and 1 percent of the streamflow contributions).

As implemented, this ground-water monitoring program only has begun the processes of data collection and analysis. Baseline conditions of ground-water quality have been documented for ground-water sites distributed throughout the Lake Tahoe Basin. Methods of sample collection and laboratory analyses are documented and consistent, and most of the network sites are expected to be available for repeated sampling in the future for detecting longer term trends in ground-water quality. This program also has identified areas with elevated concentrations of nitrogen that may indicate contamination from historical land-use practices. However, in terms of mass loading, the limitations of this monitoring network are considerable. Only relatively few sites are distributed over 315 square miles of drainage area and 71 miles of lake shore. Information gathered for this program indicates that ground water contains concentrations of nutrients that are larger than those in lake water and that ground water does discharge into Lake Tahoe, but without accurately determined geologic boundaries and hydraulic properties, estimates of ground-water discharge are uncertain.

INTRODUCTION

Background

The Lake Tahoe Basin is an exceptional scenic and recreational resource of national significance, and the lake is noted for its clarity and color (Gilliland and Clark, 1981, p. 397). However, long-term monitoring of the lake indicates that near-surface (~300 ft) lake clarity has declined about 20 percent since 1968. This loss in lake clarity has been attributed to "accelerated cultural eutrophication" (Goldman, 1988, p. 1321), which is indicated by increased phytoplankton productivity, by periphyton biomass accumulation and productivity, and by decreased visibility of Secchi disks at depth. Increased productivity has been attributed to an increase in nutrients—especially, phosphorus, iron, and nitrogen—to the lake and is considered to be a direct result of increased development in the Lake Tahoe Basin (Goldman, 1988, p. 1322-24; Tahoe Regional Planning Agency, 1990, p. 2; Chang and others, 1992, p. 1214). However, algal productivity in Lake Tahoe is complicated by the uncertain role of micronutrients (for example, cobalt, manganese, or molybdenum) that may be colimiting, and by concentrations of all essential nutrients in Lake Tahoe that are so low that small changes in the lake-water chemistry can significantly affect algae productivity (Chang and others, 1992, p. 1213-1214).

California and Nevada adopted the Tahoe Regional Planning Compact (Public Law 91-148; 83 Stat. 360) in 1969 to establish the Tahoe Regional Planning Agency (TRPA)[1] as the land-use and environmental-resources planning agency (Tahoe Regional Planning Agency, 1988, p. 1). The Lake Tahoe Interagency Monitoring Program (LTIMP) was established in October 1979 to acquire and disseminate water-quality information that is necessary to support regulatory, management, and planning activities in the Lake Tahoe Basin. The interagency effort has been maintained by matching support and services from the California State Water Resources Control Board (SWRCB), California Department of Water Resources (DWR), Tahoe Research Group (TRG) of the University of California, Davis (UCD), TRPA, Nevada Department of Conservation and Natural Resources (DNCR) and USGS (U.S. Geological Survey). Monitoring in the Lake Tahoe Basin initially focused on determining surface inputs of flow, sediment, and nutrients from selected tributaries and in-lake measurements of clarity, nutrient concentrations, and algal productivity. However, to accurately access water and nutrient budgets and to better understand the processes affecting water quality in the Lake Tahoe Basin, efforts were expanded to incorporate atmospheric and ground-water monitoring into the LTIMP.

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[1]For readers' quick reference, acronyms are defined on page v in the front of this report.

Purpose and Scope

The purpose of the study described herein was to design and operate a network to monitor the quality of ground water that ultimately discharges to Lake Tahoe. The long-range goal of the study is to provide information to decisionmakers about the relative significance of ground water to the nutrient budget of the lake. Historical data that describe ground-water flow and quality characteristics, including about 600 drillers' logs from the California DWR and the Nevada Department of Conservation and Natural Resources (DCNR), were compiled and reviewed. More than 200 existing wells were canvassed to assess their suitability for use in the monitoring program. Of these 200 wells, a total of 30 initially were selected for the network. One perennial spring was included as representative of a flow system in fractured bedrock. In addition, one well (site 22) was subsequently abandoned by the owner and therefore had to be replaced (site 21). The ground-water monitoring network of 32 sites was thus established in water year 1989; water samples were collected during water years 1990-92. Each site was sampled once for determination of filtered inorganic constituents (major ions, silica, nutrient species, and selected trace constituents), stable isotopes of oxygen and hydrogen, and tritium, of dissolved radon-222 gas, and of total organic carbon. Subsequent site visits were made to collect seasonal samples for nutrient-species determination. Collection of water-quality data for the project ceased in June 1992.

The purpose of this report is to describe and document the design of the network and to present interpretations of the results obtained during its implementation in 1990-92. Historical data are summarized to describe the hydrogeologic and geochemical settings. The network is evaluated in terms of how effectively the results characterize the quality of ground water that may interact with Lake Tahoe, and how effective continued network operation may be at addressing water-quality objectives of the regional planning agency.

Previous Investigations

Several reports were reviewed to establish a foundation for the present study. The general hydrology of the Lake Tahoe Basin was reported by Taylor (1902) in support of early irrigation and water-supply considerations for the Truckee River Basin. McGauhey and others (1963) addressed early environmental and water-quality concerns in the Lake Tahoe Basin, and Crippen and Pavelka (1970) and the Technical Committee on Hydrology (1971) discuss water and other natural resources of the Lake Tahoe Basin. Jorgensen and others (1978) present characteristics of the basins tributary to Lake Tahoe in a map report. Three of the reports (Taylor, 1902; McGauhey and others, 1963; Crippen and Pavelka, 1970) include water-budget estimates, but each considered only the combined contribution of surface water and ground water to Lake Tahoe and not the individual contribution from each of the two pathways.

Several studies report on hydrogeologic characteristics of various areas that are tributary to Lake Tahoe. Harding, Miller, and Lawson & Associates (1971) report on the favorability of developing sedimentary deposits and fractured bedrock on the west side of the basin for ground-water supplies. Hydro-Search, Inc. (1972 and 1974) reports on the public-supply potential of aquifers within the Tahoe City Public Utility District service area, and Harrill (1977) presents a map report of the South Tahoe 7-1/2-minute folio showing relative well yields and contours of estimated depth to ground water. The California Department of Water Resources (1973) lists ground-water levels measured in a network of wells established in the South Tahoe ground-water basin, and Scott and others (1978), Blum (1979), and Woodling (1987) report the results of hydrogeologic investigations in the South Tahoe basin.

Loeb and Goldman (1979) and Loeb (1987) report results of investigations of ground-water nutrient flux from the Ward Creek drainage and in the drainages of the Upper Truckee River and Trout and Ward Creeks, respectively. Thodal (1992 and 1995) reports on ground water and ground-water quality for areas in Douglas County and Carson City, Nev., that are tributary to Lake Tahoe. Feth and others (1964) discuss geochemical processes and list data on the chemistry of water samples from springs in the Lake Tahoe Basin and in similar granitic terrane of the Sierra Nevada. Garrels and Mckenzie (1967) later extended the interpretations from this work and Nathenson (1989) suggests modifications to the divisions of cold springs used by Feth and others (1964).

Other studies related to this ground-water quality investigation include reports and maps of the geology of the Lake Tahoe Basin (Birkeland, 1963; Burnett, 1971; Hyne and others, 1972; Henyey and Palmer, 1974; Bohnam and Burnett, 1976; Grose, 1985 and 1986; Niblack, 1988; and Bureau of Reclamation, 1992); reports on limnology of Lake Tahoe (Goldman, 1974 and 1988; Loeb and others, 1986; Chang and others, 1992); reports on water use in the Lake Tahoe Basin (California State Water Resources Control Board, 1973, and Newman, 1966); and documentation of a geographical information data base developed for the Basin (Cartier and others, 1994).

Acknowledgments

This work was done in cooperation with the Tahoe Regional Planning Agency. Appreciation is extended to the staff of that agency, and to local residents and businesses for allowing use of their wells for collection of the ground-water samples required for this study. Edgewood, Glenbrook, and Incline Village Golf Courses provided access to, and information related to, ground-water monitoring wells that existed on each course. Cedar Water Company, Lake Park Terrace Mutual Water Company, Madden Creek Water Company, McKinney Water Company, Nevada State Parks, U.S. Forest Service, North Tahoe Public Utility District, South Tahoe Public Utility District, Tahoe Keys Property Owners Association, Tahoe City Public Utility District, and Timberland Water Company also provided access to and information concerning construction and ground-water levels for their wells that were included in the network.

GENERAL FEATURES

Location and Physiography

Most of the study area is within the Lake Tahoe Basin Hydrographic Area (hereafter referred to as the Lake Tahoe Basin).[1] The basin is on the California-Nevada State line and is about 20 mi southwest of Reno, Nev. (fig. 1). It is a structural valley of about 315 mi^2, exclusive of the lake itself, that is bounded by the main range of the Sierra Nevada on the west and the Carson Range, which extends from the Sierra Nevada south of the lake northward along the east side of the lake. It is in the Sierra Nevada physiographic province near the boundary with the Basin and Range province to the east. The crest of the Sierra Nevada splits at the southern end of the Lake Tahoe Basin, with the main crest trending to the northwest and the Carson Range trending to the north. The resulting graben slopes downward to the north between these two up-faulted mountain systems and is characteristic of Basin and Range physiography (Burnett, 1971, p. 119).

Lake Tahoe is a 191-mi^2 water body approximately 22 mi long from north to south and 12 mi wide (Crippen and Pavelka, 1970, p. 3). It has about 71 mi of shoreline, a legally defined maximum depth of 1,645 ft, and an average depth of 1,027 ft (Tahoe Regional Planning Agency, 1988, p. 8). The only outlet (other than evaporation) from the lake is the Truckee River, which begins near Tahoe City, Calif., and flows generally to the northeast for about 116 mi to its terminus at Pyramid Lake in Nevada (Nowlin, 1987, p. 12; fig. 1). The dam at Tahoe City controls about 744,600 acre-ft of lake water; regulating the lake-surface elevation between 6,229.1 and 6,223.0 ft above sea level. The drainage area of the Truckee River at Tahoe City is about 506 mi^2, including the lake.

The drainage basin contributing to Lake Tahoe has a perimeter of almost 140 mi, of which more than 100 mi are higher than 8,000 ft. The mountainous topography creates a steeply sloping, bowl-shaped basin. Almost 60 percent of the 315-mi^2 contributing area is above 7,000 ft (Crippen and Pavelka, 1970, p. 8). Fifty-five tributaries discharge directly into Lake Tahoe, draining about 276 mi^2 of contributing area. Fifty-two intervening areas (areas between adjacent drainage basins which, based on topography, would contribute runoff to the lake as both subsurface and overland flow but have no defined stream channel) constitute about 12 percent (38 mi^2) of the total drainage area (fig. 2; Jorgensen and others, 1978, table 1).

Parts of Placer, El Dorado, and Alpine Counties in California, and parts of Douglas and Washoe Counties and Carson City rural area in Nevada are in the Lake Tahoe Basin. South Lake Tahoe, Calif., is the only incorporated city, but more than 20 established communities are within the Lake Tahoe Basin. Population centers include Glenbrook, Incline Village, and Stateline in Nevada and Kings Beach, Tahoe City, Tahoma, Meyers, and South Lake Tahoe in California (fig. 1).

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[1]Formal hydrographic areas in Nevada were delineated systematically by the U.S. Geological Survey and Nevada Division of Water Resources in the late 1960's (Rush, 1968; Cardinalli and others, 1968) for scientific and administrative purposes. The official hydrographic-area names, numbers, and geographic boundaries continue to be used in Geological Survey scientific reports and Division of Water Resources administrative activities. Because this report deals with the entire Lake Tahoe Basin, in California as well as Nevada, the formal hydrographic area name for the Nevada part is used for the California part as well.

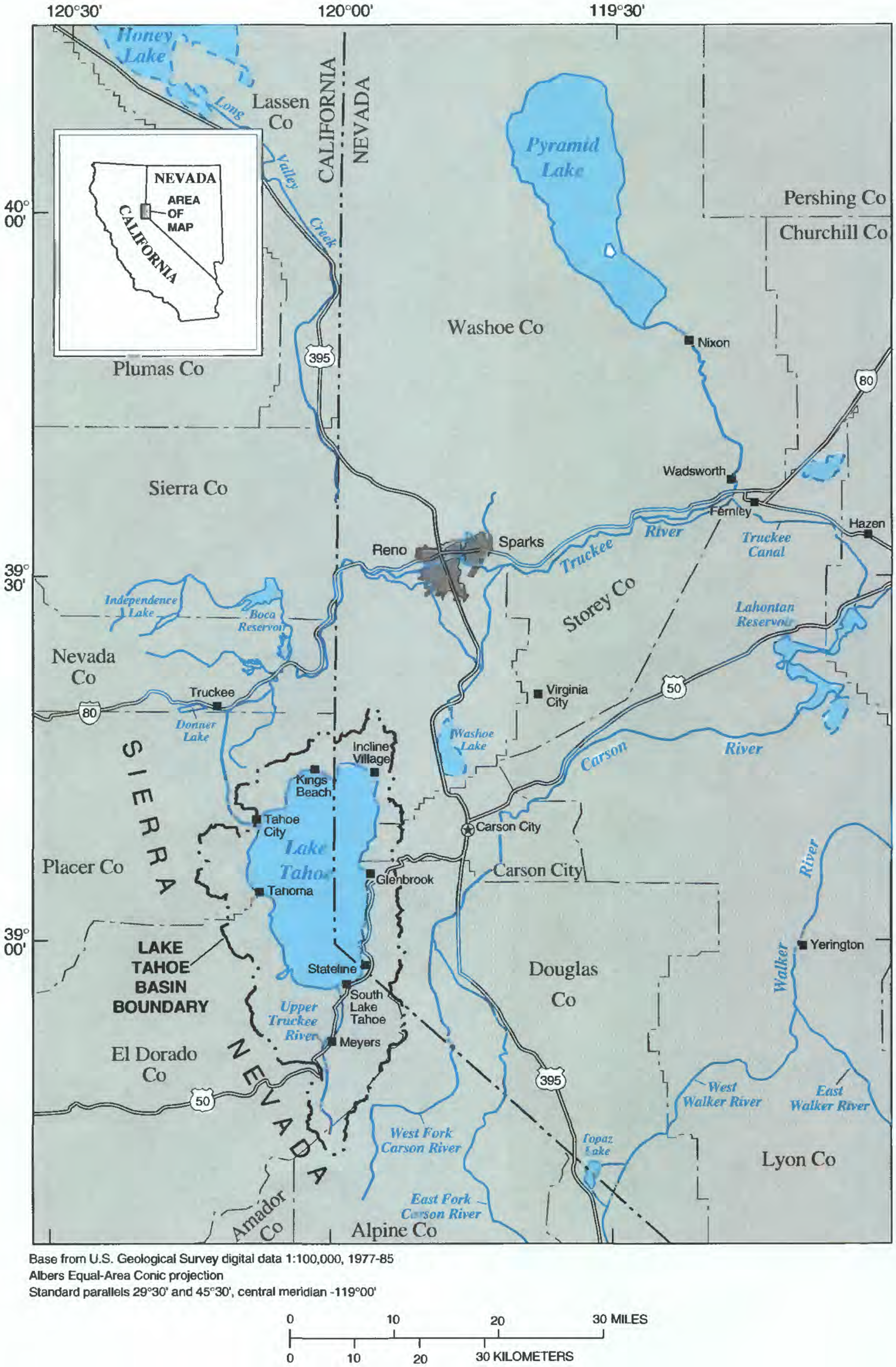

Figure 1. Location of Lake Tahoe Basin, California and Nevada.

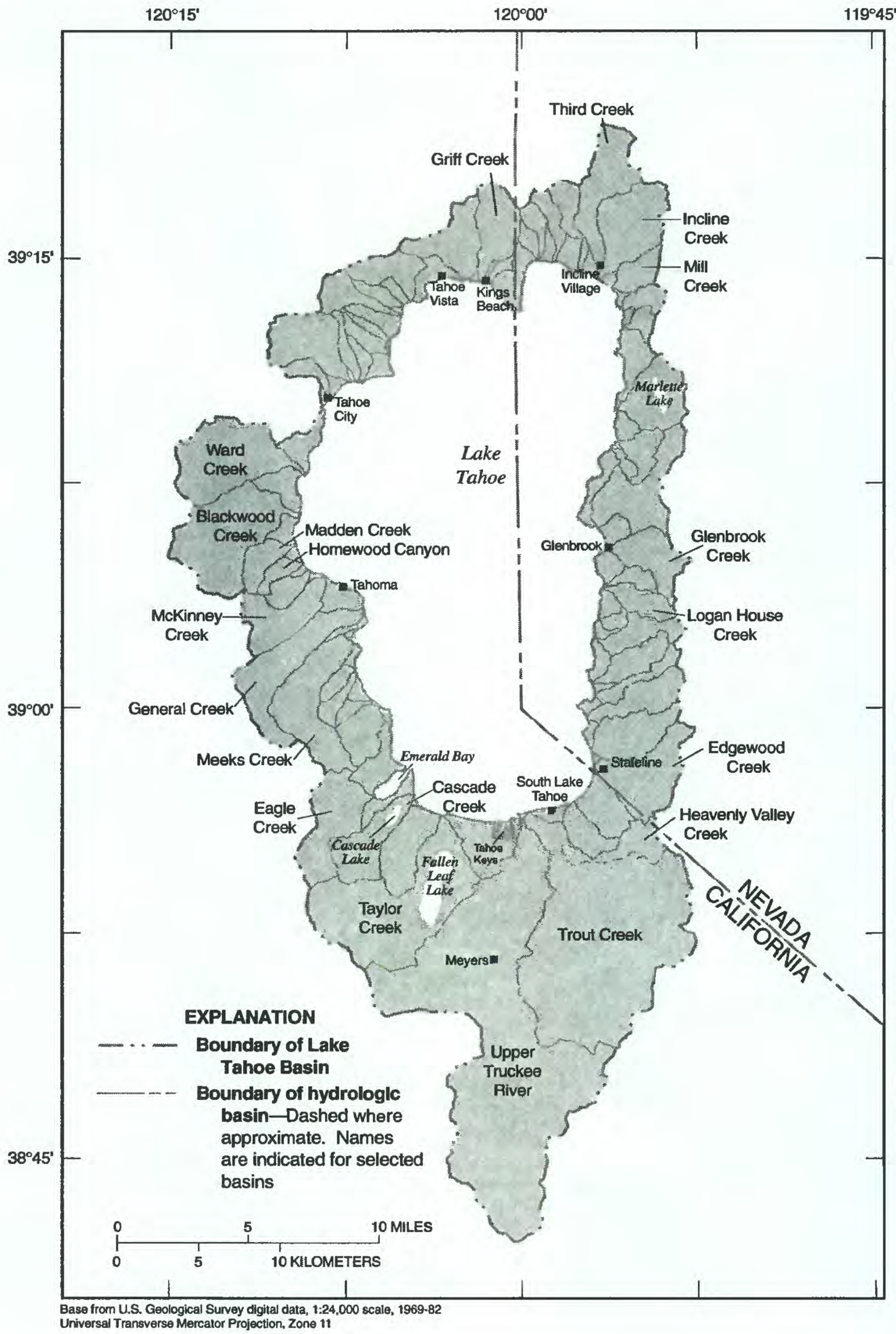

Figure 2. Hydrologic basins contributing inflow to Lake Tahoe, California and Nevada (Jorgensen and others, 1978).

About 50,000 inhabitants resided in the Lake Tahoe Basin in 1991 (E.J. Crompton, U.S. Geological Survey, written commun., 1992); slightly earlier, about 80 percent of the population was in California and about 20 percent was in Nevada (Tahoe Regional Planning Agency, 1988, p. 25).

Climate

The climate of the Lake Tahoe Basin is strongly influenced by the topography of the surrounding mountain ranges. Summers are cool compared to summers in the valleys on either side of the surrounding mountains and winters are cold, but the lake has a moderating effect on the temperature. Mean monthly temperatures recorded by the National Weather Service at Tahoe City, Calif., for October 1932 through September 1992 range from a minimum of -8°C for the month of January to a maximum of 25°C for the month of July. The mean annual temperature is about 6°C and on the average, only 70-120 days per year are frost free, depending on elevation and topography (Crippen and Pavelka, 1970, p. 18-19).

Moist marine air masses from the Pacific Ocean provide average annual precipitation ranging from 15 to as much as 80 in. (fig. 3), most of which falls during winter snowstorms. The lines of equal precipitation in figure 3 are based on data from 26 precipitation stations, 10 snow courses, and 2 weather stations—one at the Coast Guard station near Tahoe City, Calif., and the other at the airport near South Lake Tahoe, Calif.—and adjusted to the 50-year period from 1920 to 1970 (Twiss and others, 1971). Because moisture moves into the Lake Tahoe Basin predominantly from the west, the orographic effect of the Sierra Nevada results in more precipitation falling in the mountains on the west side of the lake and less on the east side. Figure 4 shows annual precipitation for two long-term weather stations: one on the west shore at Tahoe City, Calif. (elevation: 6,230 ft), and the other on the east shore at Glenbrook, Nev. (elevation: 6,360 ft). Variability of annual precipitation and substantial differences in amounts between the two stations are illustrated, indicating potential differences in quantities of ground-water recharge within the Lake Tahoe Basin.

Average monthly precipitation for the weather station at Tahoe City is shown in figure 5. Included in figure 5 are both long-term (1932-92) and recent, short-term (1988-92) records to illustrate conditions that may have affected ground-water conditions during this study. The short-term precipitation record is coincident with a record drought that began in 1987 and lasted through 1994 (Horton, 1997, p. IV-29). However, in both long-term and short-term conditions most of the precipitation occurs between November and March.

Hydrogeologic Framework

Rocks and deposits in the Lake Tahoe Basin include pre-Cretaceous metamorphic rock, Cretaceous granitic rock, Tertiary and Quaternary volcanic rocks, and Tertiary and Quaternary glacio-fluvial and lacustrine sedimentary deposits (Burnett, 1971, p. 120). Cartier and others (1994) document the recompilation of variously scaled geologic maps for the Lake Tahoe Basin (Thompson and White, 1964; Burnett, 1971; Bonham and Burnett, 1976; Loomis, 1981; Armin and John, 1983; Armin and others, 1984; and Grose, 1985 and 1986) into a 1:24,000-scale coverage for a geographic information system. The distribution of geologic units is shown in figure 6. Hydrologic characteristics of these units affect both the volume of water that the sedimentary deposits and fractured bedrock can hold—commonly called storage—and the rate of ground-water movement. In general, bedrock stores and transmits small quantities of water, primarily through fractures. However, exceptions to this general statement include (1) some volcanic rocks that have rubble zones between flows and highly fractured porous zones and (2) decomposed granitic rocks that have weathered to an unconsolidated layer of clay, sand, gravel, and boulders; both types of rocks may store and transmit large quantities of water. Basin-fill deposits have pore spaces between sediment grains that water can fill and move through; thus, these deposits can store and transmit appreciable ground water.

Granitic, volcanic, and metamorphic rocks in the Lake Tahoe Basin are collectively referred to as bedrock, and glacial, fluvial, and lacustrine sediments are referred to as basin-fill deposits. In figure 6, granitic rocks include unconsolidated, decomposed granite that has not been incorporated into basin-fill deposits by glacial or fluvial processes. Bedrock forms the mountain ranges and underlies the structural basins in which the basin-fill deposits have accumulated. About 225 mi^2 (71 percent) of the land area in the Lake Tahoe Basin has exposed bedrock, including decomposed granite, and the remaining 91 mi^2 (29 percent) contains basin-fill deposits (Cartier and others, 1994, table 10).

Basin-fill deposits partly fill most valleys and canyons that drain into Lake Tahoe, and most water wells drilled in the Lake Tahoe Basin are completed

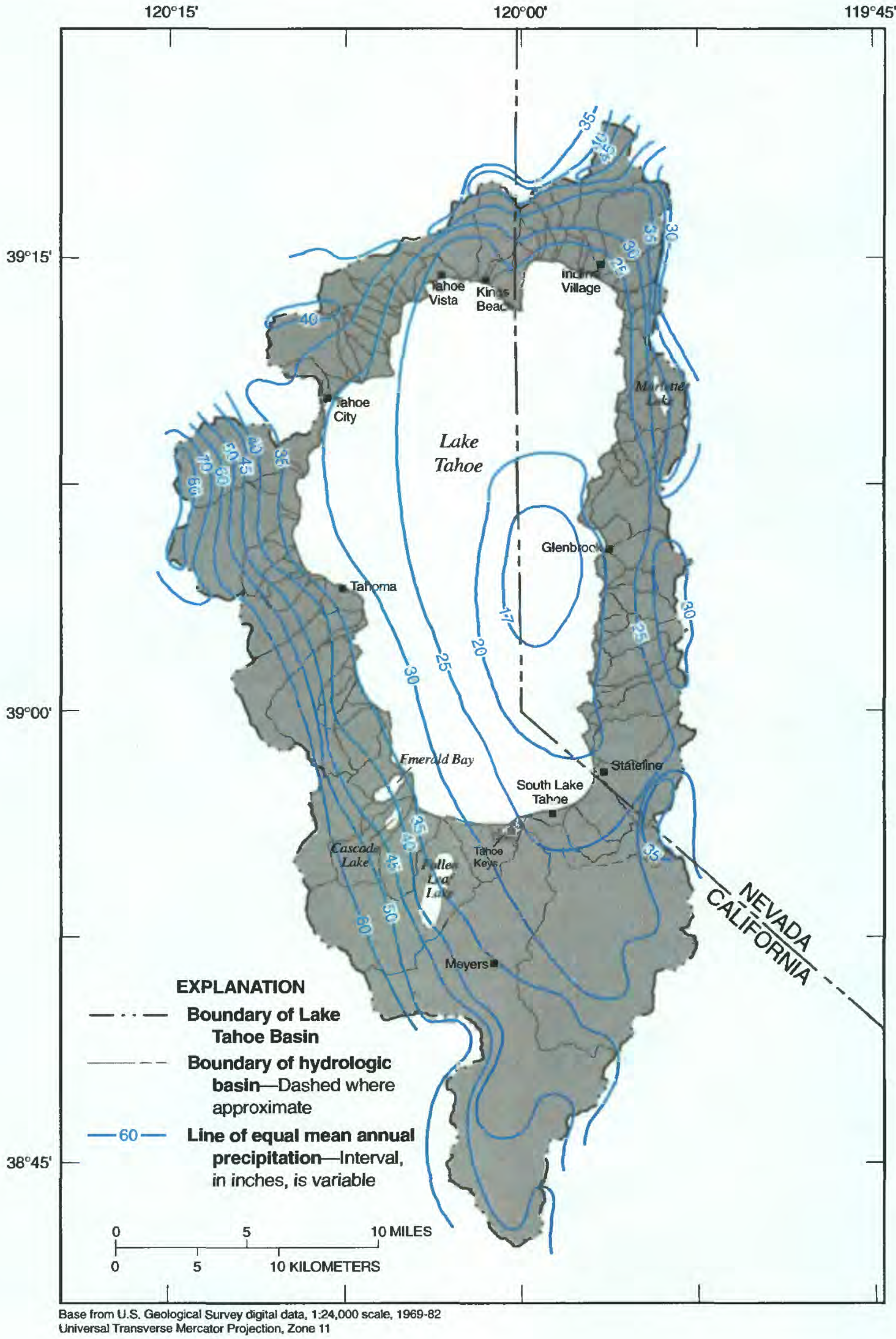

Figure 3. Distribution of mean annual precipitation, Lake Tahoe Basin, California and Nevada (Twiss and others, 1971).

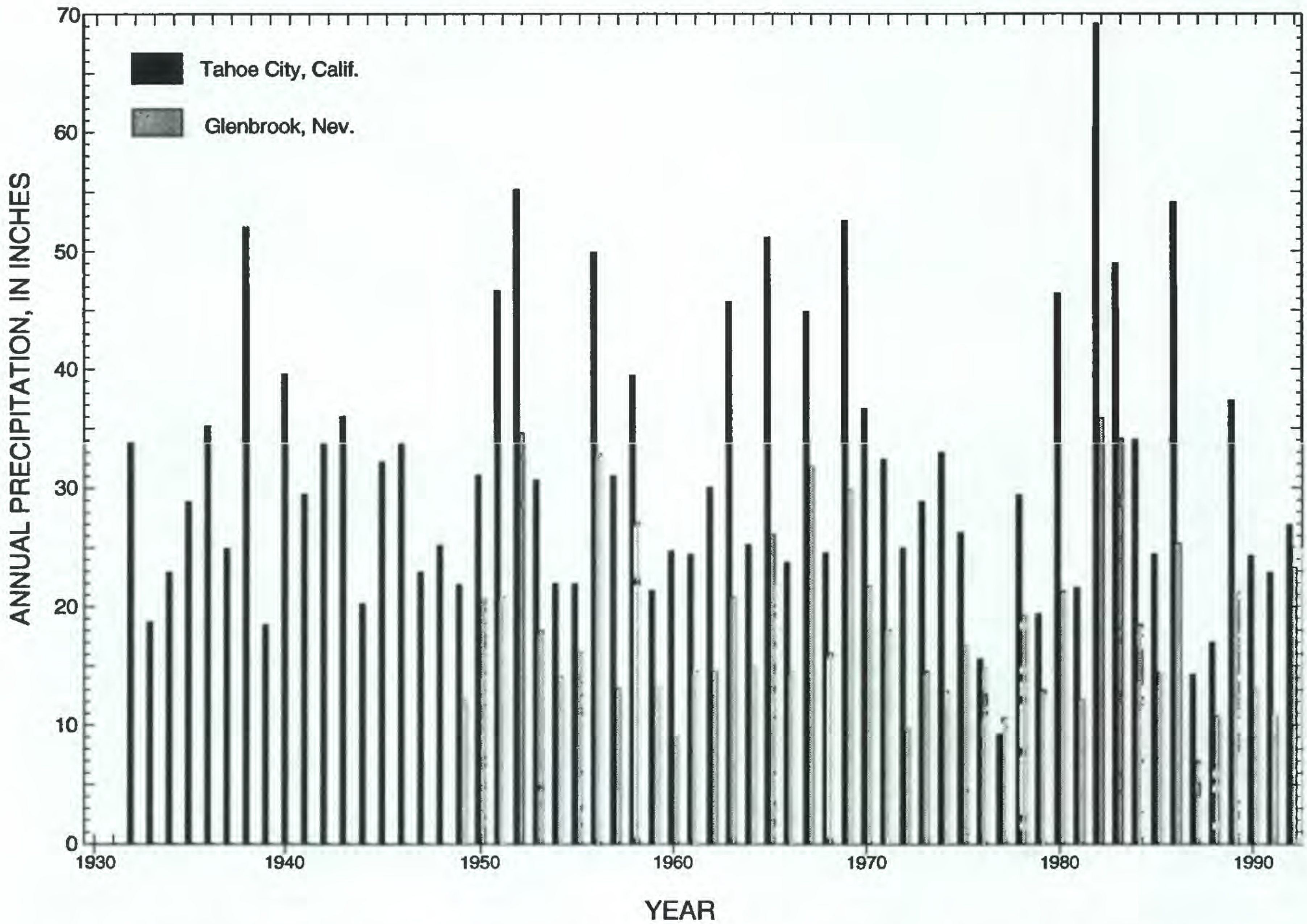

Figure 4. Annual precipitation for the period of record at two long-term weather stations: Tahoe City, California, 1932-92, and Glenbrook, Nevada, 1949-92 (National Climatic Center, 1933-93). Mean annual totals, 31.5 and 18.5 inches, respectively.

in basin-fill deposits. Permeability of these sediments differs considerably, both spatially within each unit and between the different units. Figure 7 shows the distribution of these deposits that are contiguous with Lake Tahoe. Four periods of major glaciation and one minor glacial advance took place during the Pleistocene Epoch (from about 2 million to about 10,000 years before present), greatly modifying much of the landscape in the Lake Tahoe Basin. Large valley glaciers formed in most of the canyons around the lake, except along the eastern shore where glaciation was limited to the northern sides of the highest peaks (Burnett, 1971, p. 121). One effect of glaciation was to move large masses of rock and sediments to form deposits of outwash, till, and moraine, and to discharge considerable quantities of sediment into the lake. It has been estimated that the bottom of Lake Tahoe contains sediment deposits that are at least 1,300 ft thick (Hyne and others, 1972, p. 1438). Much of the glacial rock and sediment was derived from decomposed granite that had been scoured away and reworked from the granitic slopes of the western and southern mountains. However, granitic bedrock on the eastern side of Lake Tahoe escaped extensive glaciation and, therefore, is mantled with decomposed granite that may be as thick as 100 ft, although thicknesses are commonly much less (Harrill, 1977). Runoff from areas that were not glaciated is attenuated compared to runoff from glaciated areas due to greater permeability (Nolan and Hill, 1991, p. 35) and ground-water recharge is therefore greater in areas where soils and decomposed granite have not been scoured away. Decomposed granite covers about 100 mi^2 (32 percent) of land area in the

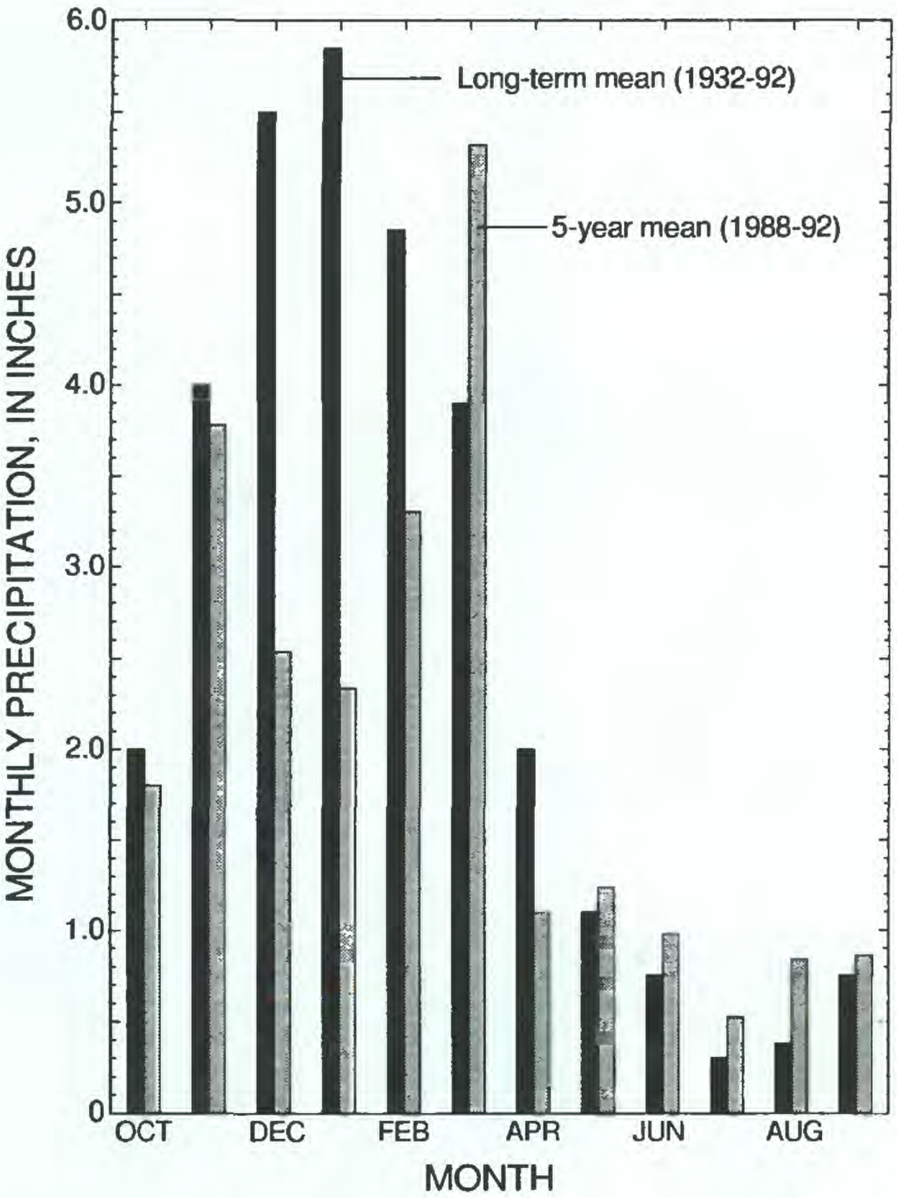

Figure 5. Five-year (1988-92) and long-term (1932-92) mean monthly precipitation for weather station at Tahoe City, California (source of data: National Climatic Center, 1933-93).

Lake Tahoe Basin, accounting for about 67 percent of all granitic rock shown in figure 6 (Cartier and others, 1994, table 10).

Glacial outwash material, shown as basin-fill deposits in figures 6 and 7, typically is composed of rock ranging from fine silt to large boulders that have been sorted and stratified by the action of water flowing from the glacier (Freeze and Cherry, 1979, p. 150). Permeability of these deposits can be moderate to high. Thicknesses of these deposits may be as great as 1,600-1,900 ft in the South Lake Tahoe area (Blum, 1979, p. 57), but typically range from 50 to 150 ft (Hydro-Search, 1974, p. 14). Glacial till has a similar range of rock-fragment sizes but has not been sorted or stratified because it was simply deposited from the underside of a glacier. Terminal and lateral moraine deposits form many of the ridges and other topographic features and are composed of unsorted and unstratified masses of rock ranging from fine silt to large boulders. Because these deposits are unsorted and because the fine-grained sediments produced by the grinding glacial action are retained in the deposit, they typically have only moderate permeability.

Lacustrine deposits containing well-sorted beach sand have relatively high permeability, but those with significant amounts of silts and clays have lower permeability. Changes in the elevation of the surface of Lake Tahoe over the geologic history of the lake have left lacustrine deposits as high as 600 ft above the lake level (about 6,225 ft) reported during the period of the study. Alluvial deposits consisting of decomposed granite and glacial sediments that have been reworked by stream water typically are restricted to stream margins and floodplains. These sediments generally are very permeable.

Human Effects on Ground Water and Ground-Water Quality

Native Americans inhabited the Lake Tahoe area long before the first recorded sighting of Lake Tahoe, by John C. Fremont on February 14, 1844 (Crippen and Pavelka, 1970, p. 24). Little is known of the ways of life of early inhabitants, but the effect they may have had on ground water and ground-water quality probably was minimal.

Few non-natives traveled through the area until gold was discovered in California in 1848. Goldseekers, known as the '49ers, crossed the Sierra Nevada both north and south of Lake Tahoe, but generally avoided the lake, which obstructed passage through the mountainous terrain. However, gold and silver deposits associated with the Comstock Lode were discovered about 15 mi to the east of Lake Tahoe near Virginia City, Nev., in 1858. Large-scale timber harvest in support of mining activities resulted in extensive deforestation of the drainage basins surrounding Lake Tahoe. Glenbrook, Nev., and Tahoe City, Calif., are two communities that were founded about 1860 and 1864, respectively, to support the timber-related activities in the Lake Tahoe Basin (James, 1992, p. 125). Glenbrook had three or four large sawmills operating 24 hours a day and official records of Douglas County report that more than 21 million board-ft of lumber were milled during 1875 (James, 1992, p. 126-127).

The timber harvest required large populations of loggers, rail-construction crews, and laborers to operate sawmills and probably resulted in localized degradation of ground-water quality due to waste-disposal practices. Deforestation also may have

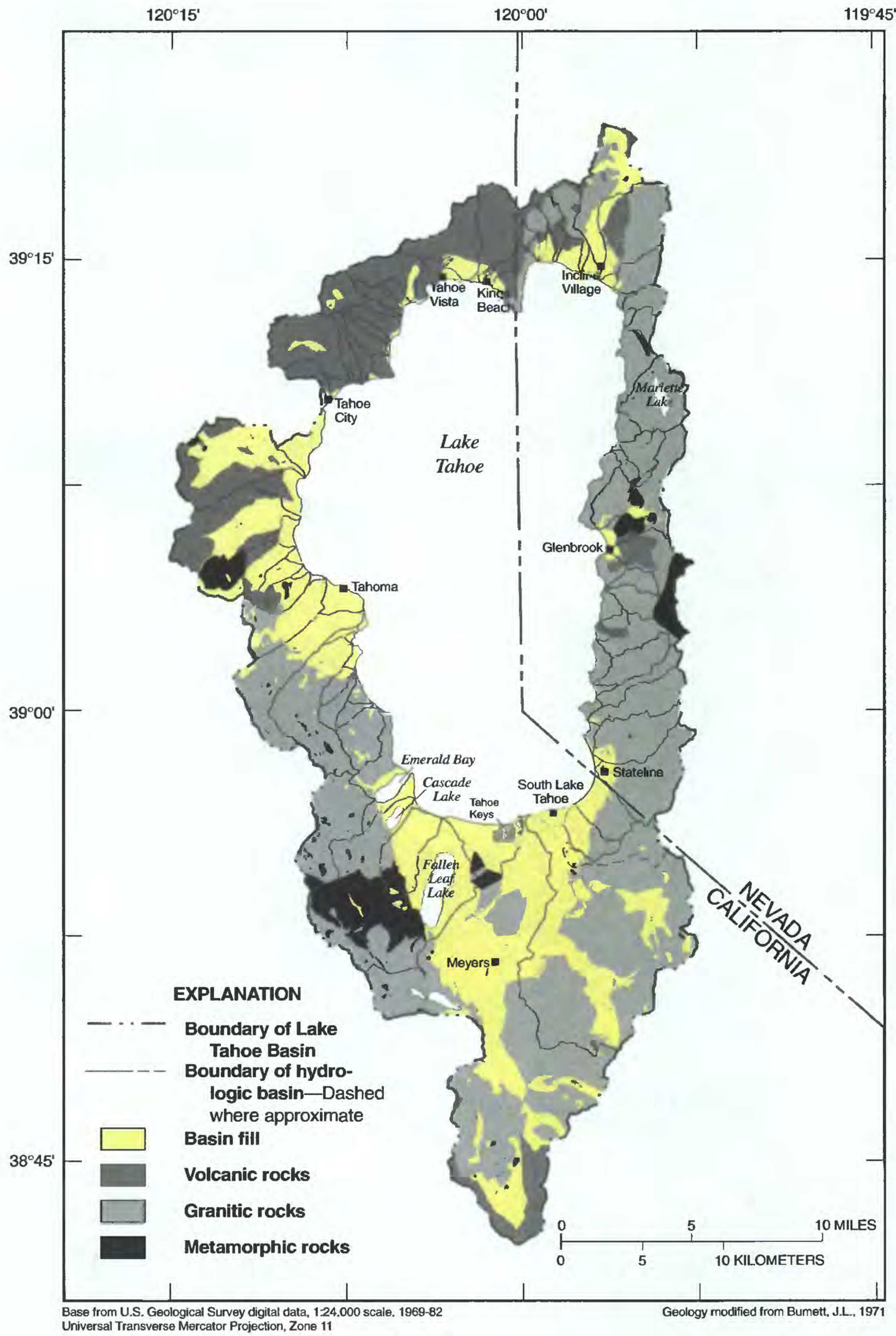

Figure 6. Generalized geology of Lake Tahoe Basin.

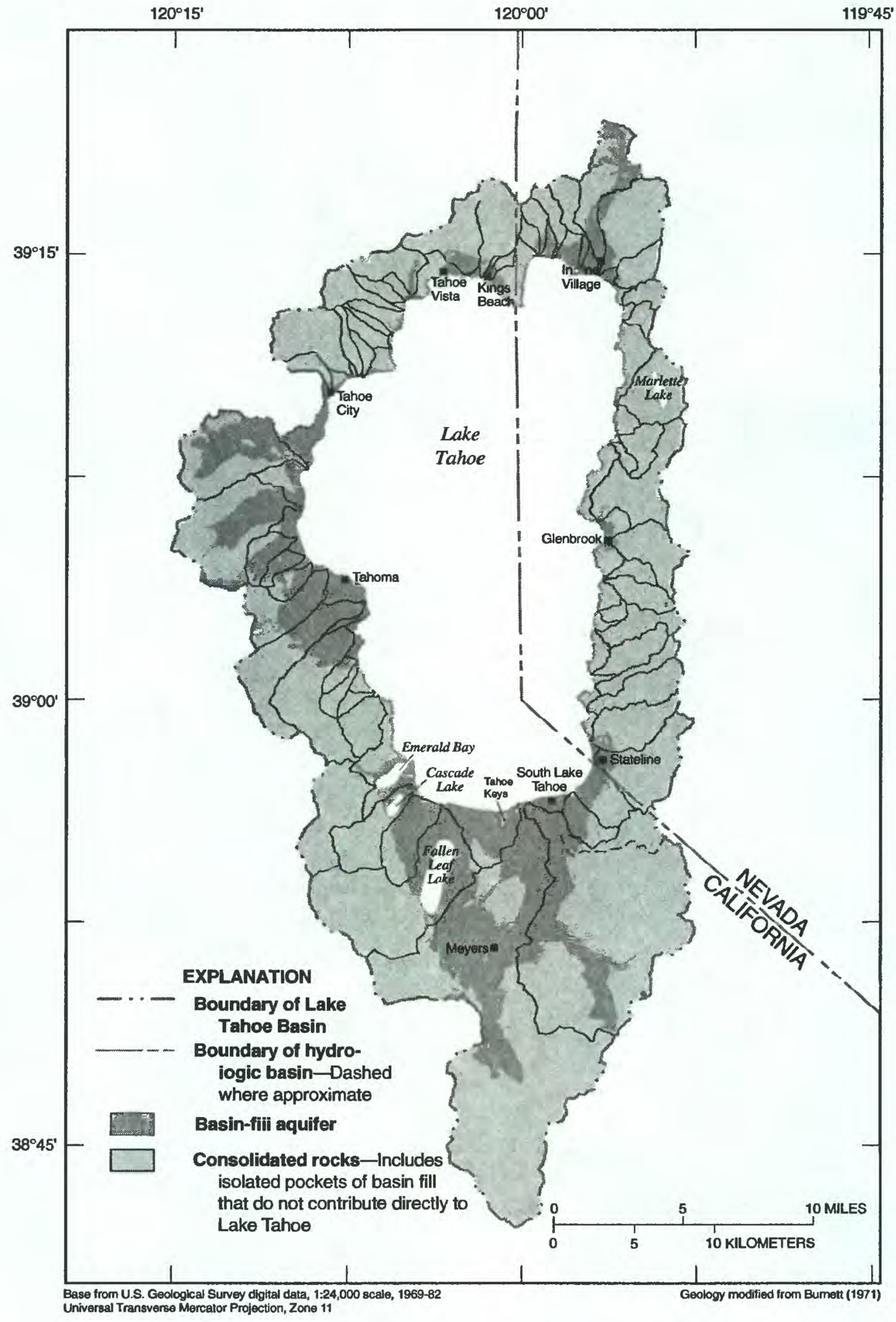

Figure 7. Basin-fill deposits identified as aquifers contiguous with Lake Tahoe.

affected the quality of ground water by eliminating much of the vegetation that normally would assimilate soluble nutrients and by increasing the amount of dead organic material available for decomposition and nutrient leaching. No comparisons to the rate of nutrient assimilation achieved by plant communities revegetating the landscape are available. The water works and reservoirs constructed to flume timber and to convey potable water over the Carson Range to Virginia City may have reduced or re-directed ground-water flow. Lumber activities declined by the late 1800's in response to the decline in the Comstock mining activities and lack of trees remaining for harvest. Timber harvest and deforestation probably increased sediment input to Lake Tahoe.

Small populations of year-round residents remained at Glenbrook and Tahoe City, supported by commercial fishing and tourism. Several small resort communities, primarily catering to summer visitors who were attracted to the lake for recreation, were established during the decline of the Comstock mining activities. The number of visitors increased when the railroad between Truckee and Tahoe City was completed in 1900. James (1992, p. 168) wrote in 1915: "Last year no less than 80,000 persons visited Lake Tahoe" and further discussed attributes of the Lake Tahoe region as a second-home destination.

Tourism continued to grow steadily through the first half of the 20th century and, after World War II, it expanded dramatically in response to increased affluence and mobility of the Nation's population. Both the large-scale gaming casinos that opened at Stateline, Nev., in 1955 and the winter Olympic competition held at Squaw Valley, Calif., in 1960 established the Lake Tahoe region as a year-round destination for recreation. Increased population brought with it the increased potential for ground-water contamination, primarily from waste-disposal practices.

Early inhabitants and visitors relied on land-based disposal of solid waste and on privies, grey-water sumps, cesspools, or septic-tank and leachfield systems for disposal of sewage. As the population in the Lake Tahoe Basin continued to grow and concentrate in local communities, unsanitary conditions prompted the establishment of local sewer districts to collect and treat sewage. By 1966, sewage from about 25 percent of the estimated summertime peak population (44,500 individuals) for the Lake Tahoe Basin was collected by public sewers and received tertiary treatment prior to land disposal by spray irrigation. Sewage from an additional 11 percent of the summertime peak population (20,800 individuals) received secondary treatment prior to land disposal and sewage from the remaining 64 percent of the summertime peak population (114,700 individuals) was in unsewered areas where untreated sewage was disposed of in privies, cesspools, or septic-tank leachfield systems (West and Mackenthun, 1966, p. 12-13).

Nationally, cesspools and septic-tank systems were the most frequently reported sources of ground-water contamination, according to a 1977 U.S. Environmental Protection Agency report (Canter and Knox, 1985, p. 2). West and Mackenthun (1966, p. 24-27) estimated in 1966 that about 48 percent of all nitrogen and 50 percent of all phosphorus available for transport to Lake Tahoe originated from sewage. They further estimated that unsewered areas in the Lake Tahoe Basin were responsible for 62 percent of all nitrogen and 84 percent of all phosphorus in sewage discharges from the 1966 summertime peak population in the Lake Tahoe Basin (West and Mackenthun, 1966, p. 25). Wastewater-treatment facilities within the Lake Tahoe Basin were capable of removing about 35 percent of the nitrogen and 80 percent of the phosphorus in the sewage and the treated effluent was then disposed of by spray irrigation or trench percolation.

Areas in the Lake Tahoe Basin that were used for land disposal of treated wastewater include an area north of Tahoe Vista, Calif., that was operated by North Tahoe Public Utility District; an area south of the confluence of Heavenly Valley Creek and Trout Creek that was operated by South Tahoe Public Utility District (McGauhey and others, 1963, p. 51-55), and an area in the Mill Creek drainage northeast of Incline Village that was operated by the Incline Village General Improvement District (William Quesnel, Incline Village General Improvement District, oral commun., 1996). Perkins and others (1975, p. 453) report that water samples from Heavenly Valley Creek near South Lake Tahoe, Calif., had unusually high concentrations of nitrate-nitrogen (1.08 mg/L). The nitrate-enriched stream water was attributed to ground-water seepage that had been contaminated by spray-irrigation disposal of treated wastewater, which had been discontinued 5 years prior to sample collection.

Because estimates of nutrients associated with sewage and treated wastewater indicated that the amount of nitrogen discharging to the water of Lake Tahoe in 1968 was more than double the amount estimated for natural conditions, exportation of all sewage from the Lake Tahoe Basin was recommended. The California legislature amended the State Water Code in

1969 to require the export of effluent and prohibit further use or maintenance of other sewage-disposal systems within the Lake Tahoe Basin by January 1, 1972. The Governor of Nevada issued an Executive Order on January 27, 1971, prohibiting the use of septic tanks in the Nevada part of the Lake Tahoe Basin after December 31, 1972 (Technical Committee on Wastewater, 1971, p. 1). However, treated effluent and sewage residuals from past disposal practices may continue to leach into the ground water for an undetermined period of time and may be in ground water that is moving to the lake.

Other potential sources of ground-water contamination in the Lake Tahoe Basin include (1) accidental spills and overflows and leakage from sewage-treatment facilities, conveyance lines, and treated effluent export lines; (2) application of fertilizer to lawns, landscapes, golf courses, and ski slopes; (3) infiltration of street and urban runoff that is collected in detention ponds; (4) road de-icing; and (5) failure of underground storage tanks. Mechanisms that may affect the distribution and concentration of ground-water contaminants include the location and magnitude of the contaminant source, adsorption, biologically and chemically mediated processes, dispersion, and dilution.

MONITORING GOALS AND METHODS USED IN THIS STUDY

TRPA's overall goal for monitoring activities of the LTIMP is "to acquire and disseminate, in a coordinated, cost-effective manner, water-quality information needed to support regulatory, management, planning, and research activities in the Lake Tahoe Basin." To move toward achieving this goal, TRPA has adopted the following objectives (Hill, 1992, p. 5-6).

1. Establish water-quality baseline conditions and identify trends in water quality in Lake Tahoe and its tributaries;
2. Measure and evaluate major pollutant inflows (mass loadings) to Lake Tahoe, including nutrients and sediment;
3. Provide continuity of program direction and funding and minimize overlap and duplication in water-quality monitoring activities;
4. Assist management, planning, research, and regulatory agencies in the implementation and evaluation of their programs;
5. Gain an understanding of the complex Lake Tahoe aquatic ecosystem in order to direct and assist necessary efforts to preserve that ecosystem;
6. Provide monitoring information to potential user agencies and individuals in a timely and understandable manner;
7. Reduce uncertainty of data collected for determining the nutrient budget, water budget, and compliance with regulatory requirements;
8. Ensure and enhance statistical validity of analysis for both regulatory and process-oriented data collection;
9. Monitor, for regulatory purposes, all components of the water-quality program;
10. Assist with research as to the factors that affect water quality and modeling of Lake Tahoe and its watersheds;
11. Ensure cost-effective use of available water-quality mitigation funds;
12. Establish a means of determining effectiveness of remedial programs;
13. Assist with evaluation of water-quality control measures; and
14. Meet quality-assurance/quality-control standards.

With these water-quality monitoring objectives in mind, a ground-water quality monitoring program was designed by USGS and TRPA within the constraints imposed by available funds. The first part of objective 1 requires collecting appropriate data from a network of sample sites that is representative of ground water in the Lake Tahoe Basin. More than 600 well drillers' reports (well logs) were available for the basin from the California Department of Water Resources and the Nevada Department of Conservation and Natural Resources. Most of these wells are clustered in areas of early residential development, many predating community water-distribution systems. About 80 percent of the well logs (about 480) are for wells constructed in the South Lake Tahoe, Calif., area. The advent of community water suppliers has resulted in discontinued use of many of these wells.

About 200 wells were identified as potential monitoring sites on the basis of their areal distribution, relation to land use, and availability of historical water-quality data. Maximum areal distribution was given the highest priority followed by proximity to various land uses thought to be potential contributors of nutrients to ground water. Secondary considerations included access for water-level measurements and for sample acquisition between the well and storage or pressure tank, but these conditions were often unavoidable in areas where ideal wells were not available. Field canvassing was used to verify well location and suitability for sampling, and to assess the well-owner's willingness to participate in the monitoring program. Information concerning the 32 sites used in the monitoring network is found in table 1 and a map showing locations of these sites is shown in figure 8.

Identification of trends (the second part of the TRPA objective 1) requires continued network operation over a period of time that is long enough to quantify variability resulting from analytical and sampling uncertainty and from natural changes. The necessary length of time cannot be defined without some understanding of the ground-water flow system. Within the limited time-frame of this program, baseline conditions and statistical characteristics that may affect trend detection (such as seasonality and variability due to analytical uncertainty and sample contamination) can be evaluated, but trend detection requires long-term, consistently collected and analyzed data.

Objective 2 can be only partly met by results of this program because a water budget or hydraulic analysis that accurately quantifies the ground-water component of the water balance for Lake Tahoe has not been developed and processes affecting the transport of nutrients through aquifers that discharge to Lake Tahoe have not been identified. Information and data about ground-water flow in the Lake Tahoe Basin were reviewed, and water-balance estimates and data from the monitoring program provided information on the distribution of nutrients in ground water. Data on ground-water flow and the distribution of nutrients in ground water are necessary for refining the current understanding of nutrient budgets of the Lake Tahoe Basin.

Objectives 3 through 10 strive to integrate the various monitoring activities of the LTIMP to avoid duplication of effort and to provide consistent data. The ground-water monitoring program addresses these objectives by providing data on a poorly defined component of the Lake Tahoe ecosystem. Nutrient concentrations in samples collected subsequent to the initial samples analyzed by USGS were determined by TRG laboratories to provide data that are comparable to other data on nutrients in the basin; the data are stored in the USGS NWIS and the U.S. Environmental Protection Agency STORET data bases and are published in the USGS Water Resources Data books (Garcia and others, 1992, p. 445-459, and Hess and others, 1993, p. 488-491) to provide timely dissemination for regulatory and scientific purposes.

By establishing baseline conditions, the monitoring program has the potential to meet objectives 11 through 13. Continued or future ground-water monitoring data can be compared to baseline conditions to assess effectiveness of remedial programs and control measures. These data may not be useful for specific control measures due to the limited distribution of ground-water sample sites, but could have application to identifying areas of concern.

Objective 14 refers to all efforts taken to ensure that measurements made in the field and in the laboratory are within accuracy specifications and that data are stored and reported consistently. The USGS provides documentation of standardized methods of water-data acquisition (U.S. Geological Survey, 1977, and Claassen, 1982) to ensure proper data collection. The USGS has a world-wide reputation for collecting accurate and impartial data and many of the methods for data collection developed by the USGS have become standard techniques adopted by other Federal, State, and local agencies (Shampine and others, 1992, p. 1). The USGS also maintains the NWIS as its data base. The computerized system automatically transfers water-quality data to the U.S. Environmental Protection Agency data base (STORET) once the USGS data have been checked.

Because the long-term water-quality data for water samples from Lake Tahoe and its tributaries have been analyzed by the TRG laboratories, TRG was contracted to analyze ground-water samples for nutrient concentrations. TRG laboratories routinely participate in the USGS Standard Reference Water Samples program (Friedman and Fishman, 1989) each year and members of the USGS Branch of Quality Assurance review TRG laboratory facilities onsite about every 3 years. In addition, TRG maintains a QA/QC program, including documentation of laboratory and field procedures and equipment, chain of custody forms, instrument logbooks, quality-control charts, calibration records, and a methods manual for analytical chemistry used by the LTIMP (Janik and others, 1990).

Table 1. Information regarding sites used in ground-water monitoring network, Lake Tahoe Basin, California and Nevada, water years 1990-92

[Symbol: --, information not available]

Site number (fig. 8)	Site designations[a]		Site type	Land-surface altitude (feet above sea level)	Depth of well (feet below land surface)	Depth of open interval (feet below land surface)
	Local identification	Standard identification				
1	90 N16 E18 23CDC 1	391322119555001	Domestic	6,260	163	--
2 [b]	90 N16 E18 19BCA 1	391406119595601	Domestic	6,300	96	70- 90
3	90 N16 E17 14BBCB1	391425120035301	Domestic	6,440	425	335-415
4 [b]	90 N16 E17 15CCAA1	391552120045101	Public supply	6,320	218	75-225
5	90 N15 E17 05ABBC1	391031120075901	Public supply	6,245	160	--
6 [b,c]	N15 E17 06BCC 1	391038120090001	Public supply	6,420	223	--
7	90 N15 E17 07CADB1	390935120084001	Agricultural	6,260	265	255-265
8	90 N15 E17 18BCB 1	390902120090301	Public supply	6,520	450	299-430
9	90 N15 E16 24CBCD1	390748120100701	Public supply	6,460	--	--
10 [b]	90 N14 E16 01CADD1	390510120094101	Public supply	6,270	114	49-109
11 [b]	90 N14 E17 18AADB1	390354120080701	Public supply	6,300	--	--
12 [b]	90 N14 E17 18BBCA1	390352120090201	Public supply	6,380	350	108-323
13	90 N14 E17 29ACB 1	390203120072701	Public supply	6,240	365	200-355
14 [b]	90 N14 E17 29ADC 1	390157120070501	Public supply	6,320	320	190-320
15	90 N13 E17 25CDA 1	385623120030201	Public supply	6,240	40	20- 40
16 [b]	90 N12 E18 29CBD 1	385118120010601	Public supply	6,340	268	218-268
17 [b]	90 N12 E18 05AADD1	385559120001301	Public supply	6,235	318	125-312
18 [b]	90 N12 E18 09ABC 1	385423119593601	Public supply	6,280	380	186-366
19 [b]	90 N12 E18 03ABA 1	385651119581701	Public supply	6,260	125	38-117
20 [b]	90 N12 E18 03BCC 1	385538119585001	Public supply	6,260	--	--
21 [b]	90 N13 E18 33CAD 1	385644119574601	Public supply	6,240	76	36- 76
22	90 N12 E18 33ADB 1	385658119572501	Domestic	6,235	142	122-142
23 [b]	90 N13 E18 27BDA 1	385742119565701	Observation	6,252	23	20- 22
24 [b]	90 N13 E18 22DCA 1	385816119563001	Observation	6,272	24	20- 24
25 [b]	90 N13 E18 23CBB 1	385824119550401	Spring(unused)	6,340	--	--
26 [b]	90 N13 E18 22BAA 1	385857119564201	Public supply	6,280	200	58-200 [d]
27 [b]	90 N13 E18 16CCC 1	385902119571301	Public supply	6,240	58	48- 58
28 [b]	90 N13 E18 10BDBD1	390022119565201	Observation	6,245	31	26- 30
29 [b]	90 N14 E18 34CDD 1	390148119564101	Domestic	6,400	180	114-134
30 [b]	90 N14 E18 10ABD1	390541119562501	Observation	6,243	28	24- 28
31 [b]	90 N14 E18 10ADA 1	390539119561001	Observation	6,277	27	22- 26
32 [b]	90 N15 E18 02BBDA1	391158119555001	Public supply	6,240	110	52- 90

[a] In this table, each site is identified by U.S. Geological Survey site designation that consists of the local (Nevada) site-identification system and a standard identification number. The two designations are usually the most convenient means of identifying and retrieving information for a specific site from computer data bases operated by the U.S. Geological Survey. For convenience, a short site number also is used in this report

The local site-identification system is based on an index of hydrographic areas in Nevada (Rush, 1968) and on the rectangular subdivision of the public lands referenced to the Mount Diablo base line and meridian. Each number consists of four units. The first unit is the hydrographic area number. The second unit is the township, preceded by N to indicate location north of the base line. The third unit is the range, preceded by E to indicate location east of the meridian. The fourth unit consists of the section number and letters designating the quarter section, quarter-quarter section and so on (A, B, C, and D indicate the northeast, northwest, southwest, and southeast quarters, respectively), followed by a number indicating the sequence in which the site was recorded. For example, site 90 N15 E18 02BBDA1 is in the Lake Tahoe Basin (Hydrographic Area 90). It is the first site recorded in the northwest quarter (B) of the northwest quarter (B) of the southeast quarter (D) of the northeast quarter (A) of section 02, Township 15 North, Range 18 East, Mount Diablo base line and meridian. For consistency in this two-state report, the Nevada identification system also is used for sites in California.

The standard site identification is based on the grid system of latitude and longitude. The number consists of 15 digits. The first six digits denote the degrees, minutes, and seconds of latitude; the next seven digits denote the degrees, minutes, and seconds of longitude; and the last two digits (assigned sequentially) identify the sites within a 1-second grid. For example, site 391158119555001 is at 39°11′ 58″ latitude and 119° 55′ 00″ longitude, and it is the first site recorded in that 1-second grid. The assigned number is retained as a permanent identifier even if a more precise latitude and longitude are later determined.

[b] Site had sufficient data for statistical evaluation of seasonal variations.

[c] Site is outside of Lake Tahoe Basin, in California part of Truckee Canyon segment of Truckee River Basin. No Nevada designation exists for hydrographic area.

[d] Uncased interval in granitic bedrock.

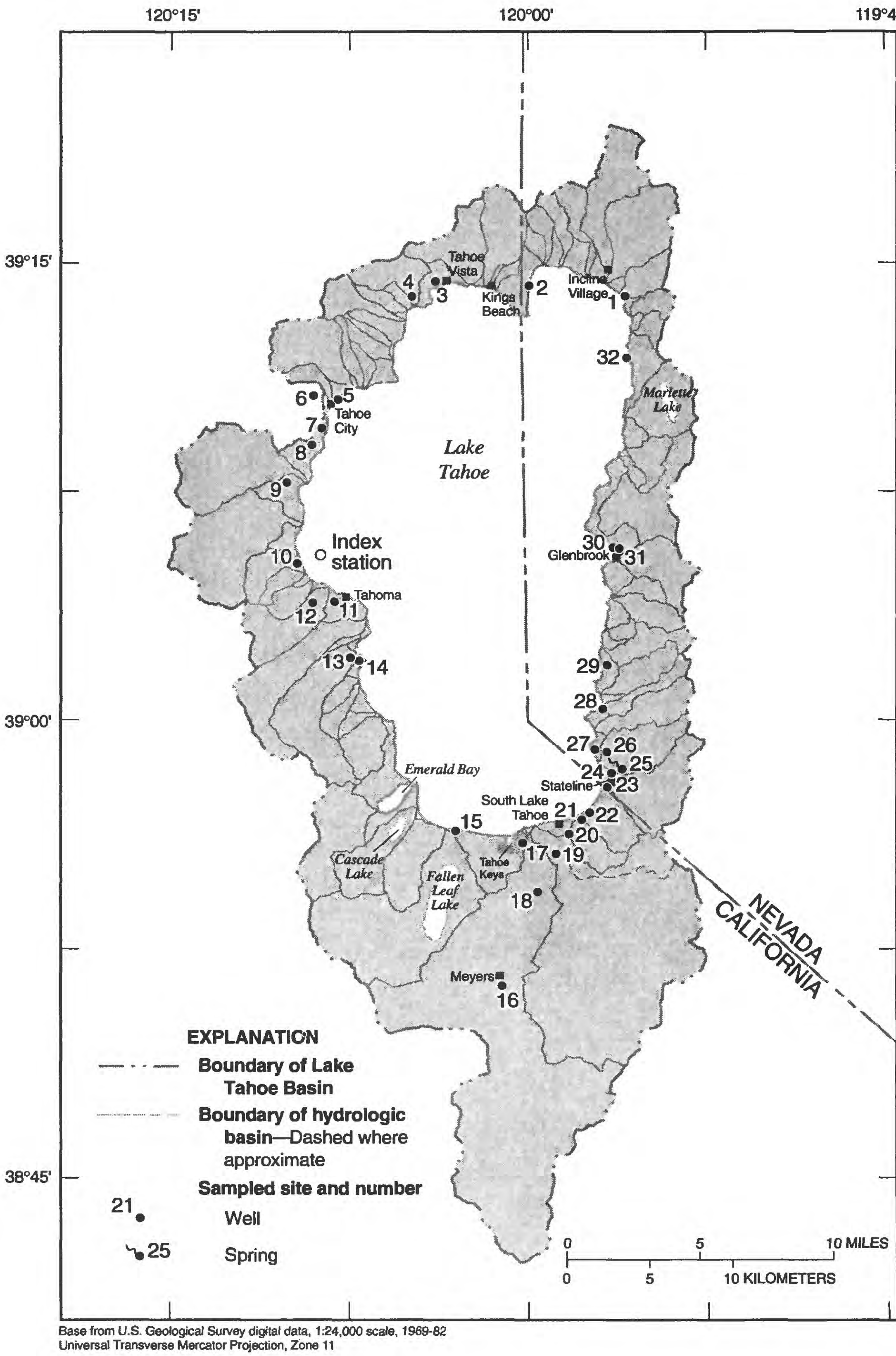

Figure 8. Location of sites used in the ground-water monitoring network, Lake Tahoe Basin, 1989-92.

Characteristics Determined and Monitoring Frequency

Laboratory analyses for nitrogen and phosphorus species and iron were made by the TRG. All other analyses, in addition to initial determination of filtered concentrations of nitrogen and phosphorus species and iron, were made by the USGS NWQL, Arvada, Colo. Field measurements of water temperature, pH, specific conductance, alkalinity, and dissolved oxygen were made every time a site was sampled except for determination of alkalinity and dissolved oxygen, which were measured only during collection of the first and second sets of samples. Major constituents, trace elements, isotopes, and dissolved radon gas also were determined for the first samples collected. Analytical reporting limits are listed in table 2.

Because nutrients are the emphasis of the monitoring program, samples for their determination were collected several times during network operation. Sampling frequency was scheduled to provide four sets of nutrient determinations from as many sampling sites as possible, with each set representing a different season. These data permit evaluation of seasonal variations in nutrient concentrations.

Concentrations of the various species of nutrients were measured to define the distribution of each form of nitrogen and phosphorus dissolved in ground-water samples. Major constituents, trace elements, pH, and water temperature are characteristics primarily determined for geochemical evaluation of the fate and transport of nutrients in ground water but several also have implications to drinking-water standards. Total organic carbon (TOC) was included because it may have a role in biologically mediated transformation of nutrients. TOC also may indicate areas where ground water has been contaminated by manmade organic compounds. The composition of stable isotopes of hydrogen and oxygen were determined to provide a "signature" of water that may differ because of the source or processes that may cause "isotopic fractionation." Tritium was determined because it can be used to estimate how long ground water has been in an aquifer (age dating). The composition of stable isotopes of nitrogen was determined to evaluate the potential for identifying the source of nitrate in ground water. Dissolved radon gas was measured to provide an evaluation of its potential application to quantification of direct ground-water seepage into Lake Tahoe. A maximum contaminant level (MCL) of 300 pCi/L had been

Table 2. Analytical reporting limits for constituents and properties of water sampled from ground-water monitoring sites, Lake Tahoe Basin, California and Nevada, water years 1990-92

[Abbreviations and symbol: NWQL, U.S. Geological Survey National Water Quality Laboratory; TRG, Tahoe Research Group, University of California, Davis; mg/L, milligrams per liter; °C, degrees Celsius; µg/L, micrograms per liter; pCi/L, picocuries per liter; --, not determined.]

Constituent	Analytical reporting limit (mg/L unless noted otherwise)	
	NWQL	TRG
Calcium	0.1	--
Magnesium	.1	--
Sodium	.1	--
Potassium	.1	--
Alkalinity (as $CaCO_3$)	1	--
Sulfate	1	--
Chloride	.1	--
Fluoride	.1	--
Silica	.1	--
Solids, dissolved	1	--
Nitrite (as N)	.001	0.001
Nitrite plus nitrate (as N)	.005	.004
Ammonia (as N)	.002	.004
Nitrogen, ammonia plus organic (as N)	.2	.04
Phosphorus	.01	.01
Orthophosphate (as P)	.001	.001
Phosphorus, hydrolyzable plus orthophosphate (as P)	.01	.01
Cadmium (µg/L)	1	--
Chromium (µg/L)	1	--
Cobalt (µg/L)	1	--
Copper (µg/L)	1	--
Iron (µg/L)	1	--
Iron, soluble (µg/L)	--	5
Lead (µg/L)	1	--
Manganese (µg/L)	1	--
Nickel (µg/L)	1	--
Selenium (µg/L)	1	--
Zinc (µg/L)	3	--
Total radon-222 (pCi/L)	80	--
Total tritium (pCi/L)	2.5	--
δD stable isotope ratio (permil)	(a)	--
$\delta^{18}O$ stable isotope ratio (permil)	(a)	--
Carbon, organic, total (as C)	.1	--

[a] Values are ratios mathematically related to comparable ratios for an international standard.

proposed for public drinking-water supplies (U.S. Environmental Protection Agency, 1991), but has been withdrawn pending additional study.

Sampling and Measurement Procedures

Ground-water samples collected during this study were obtained from wells using either existing pumps or a portable pump. A minimum of three well-casing volumes was removed from each well before a sample was collected. At observation wells, a portable pump was required for sample collection. The intake tube was positioned at the screened interval of the well, and water was pumped at a slow rate after three well-casing volumes had been removed. Water samples from the spring (site 25) were collected using a portable pump with the intake tubing positioned at the spring orifice.

Water that was pumped prior to sample collection was passed through a flow-through chamber instrumented to measure temperature, dissolved oxygen, pH, and specific conductance. Chemical stability is indicated when three successive measurements of temperature, pH, and specific conductance, taken at intervals of 5 minutes or more, differ by less than 0.5°C, 0.1 standard pH units, and 5 µS/cm, respectively (Hardy and others, 1989, p. 21). The stabilization of these properties was assumed to indicate that water was being pumped directly from the aquifer. Field meters were calibrated at each site using appropriate pH buffers, conductivity standards, and—for the dissolved-oxygen meter—an air-calibration chamber in water, checked against a zero dissolved-oxygen solution. Alkalinity was determined onsite by incremental, digital titration of 50-mL aliquots of filtered sample water with 0.16N sulfuric acid.

The first set of water samples was processed in the field by standard USGS methods (U.S. Geological Survey, 1977, chap. 1 and 5; Wood, 1976) and shipped within 2 days to the USGS NWQL. Filtered samples were analyzed for major ions, silica, species of nitrogen and phosphorus, selected trace elements, and dissolved solids. Samples collected for determination of filtered nutrient species were immediately packed in ice and chilled until analyzed. Unfiltered samples were analyzed for total tritium activity, ratios of the stable isotopes that compose water molecules, and dissolved radon gas activity. The methods and precision of these analyses are described by Fishman and Friedman (1989), Feltz and Anthony (1985), and Thatcher and others (1977). Subsequent collection of water samples followed identical procedures to obtain water representative of the aquifer, but samples were collected only for determination of filtered nutrient species (nitrogen, phosphorus, and soluble iron) by TRG. These samples were chilled until analyzed within 8 days of collection.

Laboratory analytical methods for iron concentrations were changed during this investigation. Since the LTIMP began in 1979, TRG had been determining concentrations of biologically available iron in unfiltered water samples and soluble iron in filtered samples by colorimetry, using a modification of a ferrozine method described by Stookey (1970). In August 1988, this method was replaced by direct atomic absorption spectrometry (AA) (Fishman and Friedman, 1989, p. 329-332) in response to quality-assurance concerns. However, after 2 years of evaluating the AA method, including a 5-month period when 253 unfiltered samples from Lake Tahoe and selected tributaries were determined by both methods, the TRG laboratory returned to the ferrozine method in order to maintain consistency of the long-term LTIMP data set (October 1979-August 1988).

Regression analysis of the duplicate data indicated that, for the range of concentrations determined (10 - 5,000 µg/L), the AA method produced results averaging 19 percent higher than the ferrozine method because the AA method tends to recover more of the iron that is sorbed to sediment particles (J.E. Reuter and Debbie Hunter, Tahoe Research Group, written commun., 1991). At the same time, duplicate filtered samples of ground water were collected from 22 sites in this network and analyzed by both methods. The results of these analyses, shown in figure 9, indicate that although these samples were filtered through 0.45-µm filters, less than one-half of the concentrations determined by the ferrozine method were within 20 percent of concentrations determined by the AA method. All but two of the concentrations of soluble iron by the ferrozine method are less than concentrations determined by the AA method. Reasons for the differences in these analytical results are not known, but may be due to the presence of either complexed ferric iron or iron sorbed to colloids that pass through the filter and, therefore, were measured only by the AA method.

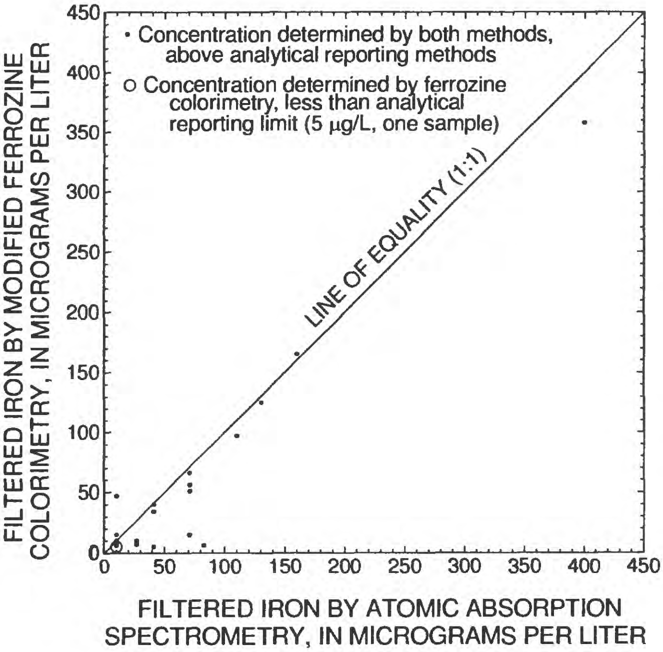

Figure 9. Comparison of Tahoe Research Group laboratory determinations of filtered iron in 22 duplicate samples of ground water from Lake Tahoe Basin, California and Nevada, by atomic absorption spectrometry and by ferrozine colorimetry.

In addition to the documented quality-assurance practices of the TRG laboratory and laboratory review by USGS personnel, three sets of field blanks were processed for nutrient analysis during three sampling rounds. These data can provide insight on the potential and extent of inadvertent contamination that may result from sample handling in the field and in the laboratory. For this investigation, each field blank was an aliquot of deionized water that was treated as a sample. This included exposure of the blank to water-sample containers, filtration apparatus, holding times, sample transport, and laboratory processing. Field-blank data are listed in the following table and show that nearly all determinations were at or below the analytical reporting limit. However, filtered phosphorus, filtered orthophosphate, and soluble iron were detected in at least one of the three field blanks. The source of contamination has not been determined, but the levels at which these constituents were detected in field blanks is only slightly above the analytical limits. Such contamination indicates that confidence in measurements near the analytical reporting limit is reduced.

Concentrations of filtered nitrogen and phosphorus species (expressed in milligrams per liter), and soluble iron (expressed in micrograms per liter), measured in field blanks for quality-assurance purposes. Symbol: <, less than.

Sample date	Kjeldahl nitrogen	Ammonia nitrogen	Nitrite nitrogen
Nov. 6, 1990	<0.04	<0.004	<0.001
Mar. 24, 1992	<.04	<.004	<.001
May 19, 1992	<.04	<.004	<.001
Analytical reporting limit	0.04	0.004	0.001

Sample date	Nitrate nitrogen	Phosphorus	Orthophosphate
Nov. 6, 1990	<0.004	0.005	0.003
Mar. 24, 1992	.004	.002	.001
May 19, 1992	<.004	.002	.002
Analytical reporting limit	0.004	0.001	0.001

Sample date	Hydrolyzable phosphorus	Soluble iron
Nov. 6, 1990	<0.01	<5
Mar. 24, 1992	<.01	<5
May 19, 1992	<.01	8
Analytical reporting limit	0.01	<5

GROUND-WATER FLOW SYSTEM

Knowledge regarding ground-water recharge, movement, and discharge is important to understanding the ground-water flow system that interacts with Lake Tahoe. Evaluation of the relative significance of ground-water discharge to Lake Tahoe and its nutrient budgets is a long-term goal of the LTIMP, and an understanding of ground-water movement is needed to assess migration of contaminants in ground water. This monitoring program emphasizes the quality of ground water that may interact with Lake Tahoe and was designed to collect only existing information about ground-water flow. Limited historical data are available for estimating the volume of ground water that may discharge to Lake Tahoe.

Recharge

Ground-water recharge in the study area is primarily from infiltration of precipitation into faults and fractures in bedrock, into the soil and decomposed granite that overlies much of the bedrock, and into unconsolidated basin-fill deposits. Ground water is recharged over the entire extent of the flow path, except where the land surface is impermeable or where the ground-water table coincides with land surface. Streamflow also recharges ground water when the water-table altitude is lower than the water-surface altitude of the stream.

Areal variation in recharge to aquifers in the Lake Tahoe Basin is related to (1) the areal distribution of precipitation; (2) the amount of precipitation that returns to the atmosphere by sublimation from the snowpack, by direct evaporation of soil moisture and from water surfaces, and by transpiration by vegetation; and (3) the capacity of the overlying soils and ultimately the receiving aquifers to accept and transmit infiltrating water. Secondary sources of recharge include infiltration of irrigation water, leakage from sewer and storm-water conveyance lines, and induced infiltration from retention ponds constructed to control storm-water runoff. While minor compared to recharge over the entire Lake Tahoe Basin, secondary sources may have localized effects on the quality of nearby ground water.

Eakin and others (1976, p. 31) used an empirical relation developed for the Great Basin that relates recharge to precipitation to estimate that about 25 percent of mean annual precipitation falling on drainages tributary to Lake Tahoe is potentially ground-water recharge. The mean volume of annual precipitation falling over the study area, estimated from the distribution shown in figure 3, is about 631,000 acre-ft. Crippen and Pavelka (1970, p. 35) estimated the mean volume to be 672,000 acre-ft, whereas McGauhey and others (1963, p. 9) estimated it to be 626,000 acre-ft. Each of these estimates of the mean volume of annual precipitation is within 5 percent of the average of all three, which is 643,000 acre-ft. On the basis of the empirical relation and estimates of the mean volume of annual precipitation, an average of about 160,000 acre-ft of water is available annually for ground-water recharge. However, because basin-fill aquifers in the Lake Tahoe Basin are nearly full (water levels are near land surface), less precipitation is able to infiltrate the ground compared to basin-fill aquifers in the drier areas where the relation was developed. Consequently, a greater proportion of the annual precipitation becomes streamflow. Within the Lake Tahoe Basin, streamflow from tributaries along the western shore discharges larger proportions of estimated precipitation to the lake compared to the eastern shore because glaciation removed much of the permeable soils and decomposed granite that mantled bedrock in drainage basins on the west side of the lake but not from the east side (Nolan and Hill, 1991, p. 35).

Movement and Storage

Hydraulic conductivity (the capacity of aquifer material to transmit water), specific storage and yield (the amount of water that is stored in and released by aquifers in response to changes in hydraulic head), and the aquifer thickness are properties that define storage and movement of ground water. Hydraulic gradient (the change in static head per unit of distance in a given direction) controls the direction of ground-water flow and provides the potential that drives ground water through the aquifer material. A hydraulic gradient generally exists between the upland peripheral areas and Lake Tahoe, and ground water flows downgradient from the upland areas until it is discharged by evapotranspiration, by pumpage, by seepage to streams, springs, and other small lakes, and by direct seepage to Lake Tahoe.

Hydraulic Conductivity

Hydraulic conductivity is expressed as the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (Lohman and others, 1972, p. 4). Coarse-grained, well-sorted sediments transmit water more readily than fine-grained or poorly sorted sediments, and layers of fine-grained sediments will impede vertical flow from a more transmissive stratum.

Altitude zone (feet)	Area (acres)	Estimated precipitation			Estimated potential recharge	
		Range (inches)	Average			
			Feet	Acre-feet	Percentage of total precipitation	Acre-feet per year
6,229-10,881	201,600	20-60	3.2	640,000	25	160,000

The amount of water that may flow through consolidated rock depends on the distribution, size, interconnection, and orientation of fractures within the rock.

Hydraulic conductivity of basin-fill deposits and fractured rock was estimated using specific-capacity data (Theis and others, 1963) from production tests reported in well-drillers' logs available for the area. This method assumes that the well is 100-percent efficient and that the water removed from storage is discharged instantaneously with decline in head (Lohman, 1979, p. 52). Although idealized conditions seldom prevail, application of this method is a useful means of approximation when aquifer-test data are unavailable. Only 66 of approximately 600 drillers' logs available for the study area included specific-capacity data necessary to estimate hydraulic conductivity. Drillers' reports indicate that 47 of these wells are completed in basin-fill deposits and 19 are in consolidated rock. Estimates of hydraulic conductivity range from 0.04 ft/d to 1,400 ft/d and the median value is 23 ft/d for all 66 wells. The median value for the 47 wells in basin-fill deposits is 39 ft/d, whereas the median value for the 19 wells in consolidated rock is 1.7 ft/d.

Estimates of hydraulic conductivity have been published for selected areas of the Lake Tahoe Basin in several reports. Estimates of average hydraulic conductivity for the South Lake Tahoe ground-water basin range from 1 to 80 ft/d (California State Water Resources Control Board, 1979, p. 192-194). Results of four aquifer tests in the South Tahoe area indicate that hydraulic conductivity ranges from 4 to 130 ft/d (Scott and others, 1978, p. 51-52). Additional aquifer tests reported for the South Tahoe area by Loeb (1987, p.100-102) indicate that hydraulic conductivity estimates also are within this range (9 to 60 ft/d). Hydraulic conductivity of basin fill in the Ward Valley drainage basin averaged about 30 ft/d based on three aquifer tests (Loeb and Goldman 1979, p. 1150). Hydraulic-conductivity values estimated for basin-fill deposits in the Douglas County and Carson City parts of the Lake Tahoe Basin by slug-test and grain-size-distribution methods ranged from 0.18 to 140 ft/d (median, 5.7 ft/d; Thodal, 1995, p.12).

The wide range in estimated hydraulic conductivity is probably due to sorting and packing of basin-fill, varying extent of fracturing in consolidated rock, and variation resulting from the different methods used to estimate hydraulic conductivity. In general, well-sorted sediments, such as alluvium, beach deposits, and glacial outwash, may have hydraulic conductivity values in excess of 100 ft/d, whereas poorly sorted sediments, such as glacial till, may have values of less than 1 ft/d (Freeze and Cherry, 1979, p. 29), and decomposed granite may have values less than 50 ft/d (Thodal, 1995, p. 14).

Aquifers of consolidated rock have estimated hydraulic-conductivity values that vary from less than 10 ft/d for fractured granite to more than 100 ft/d for fractured volcanic rock in the northwestern area of the Lake Tahoe Basin.

Basin-Fill Thickness

The volume of ground water in storage and the distribution of ground water discharged into Lake Tahoe depends, in part, on the thickness of basin fill. In general, glacial and fluvial processes have transported silt, sand, gravel, and boulders from adjacent highland areas and deposited these materials over low-lying areas. Thus, basin-fill deposits have accumulated in low-lying areas—including the bottom of Lake Tahoe—whereas adjacent highlands have relatively small thicknesses of unconsolidated material. However, canyons that have been incised through glacial moraines by streams may have unconsolidated deposits that are topographically higher and thicker than deposits that underlie the stream channel. The thickness of basin fill is most precisely determined by the depth of wells that completely penetrate the aquifer. Because of the limited distribution of such wells, reported thicknesses, geologic maps, and geophysical surveys have been relied on to estimate thicknesses of basin fill. Thicknesses of fractured and otherwise permeable zones of consolidated rock that probably transmit some ground water generally are not known.

Basin-fill deposits in excess of 100 ft partly fill the lower canyons of the Upper Truckee River, and drainage basins of Trout, Cascade, Eagle, Meeks, General, McKinney, Homewood Canyon, Madden, Blackwood, Ward, Griff, and Third Creeks (fig. 2; California State Water Resources Control Board, 1979, p. 176-178). Geophysical surveys indicate that the thickness of basin-fill deposits in the South Tahoe area range from 20 to more than 1,600 ft and average about 350 ft (California State Water Resources Control Board, 1979, p. 191; Blum, 1979, p. 56-57; Bureau of Reclamation, 1992, p. 4-14). Results of a seismic-reflection survey along the northeastern lake shore near Incline Village, Nev., indicate that basin-fill deposits are 1,000 ft thick (Bureau of Reclamation, 1992, p. 18). Geophysical surveys along the northern shore of Lake Tahoe indicate that basin-fill deposits overlying volcanic rock are less than 100 ft thick (Bureau of Reclamation, 1992, p. 21-27), but one driller's log for a well near Tahoe Vista, Calif., reports a clay and gravel contact at 96 ft and basalt at 197 ft below land surface. Estimates of the thickness of basin-fill deposits along the eastern shore of Lake Tahoe are limited, but thicknesses probably range from less than 10 to 200 ft thick (Thodal, 1995, p. 14).

Storage Coefficients and Specific Yield

Storage of water in an aquifer is expressed as a storage coefficient or as a specific yield (Lohman and others, 1972, p. 12-13). The storage coefficient represents the volume of water that a confined aquifer (an aquifer that is confined between two beds of lesser permeability and has water pressure that is greater than atmospheric pressure) releases or takes into storage per unit surface area of the aquifer per unit change in head. Water in a confined aquifer is derived from expansion of the water and compression of the aquifer. The specific yield represents the volume of water which an unconfined aquifer (an aquifer where the water table forms the upper boundary, and water pressure is equal to atmospheric pressure) will yield by gravity drainage per unit volume of aquifer, and commonly is expressed as a percent. Water in an unconfined aquifer is derived from the drainage of pores as the water table declines.

Estimates of specific yield are influenced by several variables that can affect the quantity of water that will drain by gravity. These variables include grain size, sorting, and porosity; the latter typically can range from about 2 percent for clay to more than 30 percent for uniform coarse sand (Johnson, 1967, p. 70). Specific-yield estimates in the South Lake Tahoe ground-water basin range from 6 to 20 percent and average about 10 percent. On the basis of these estimates, the total volume of ground water in storage in the South Lake Tahoe ground-water basin is 828,000 acre-ft with about 341,000 acre-ft in storage above an average lake-surface elevation of 6,225 ft (California State Water Resources Control Board, 1979, p. 191-194). Woodling (1987, p. 29) used estimated mean annual recharge (7 in.) divided by mean annual fluctuation of the water table (67 in.) to compute a mean specific yield of 0.13. Estimates of ground-water storage are not available for other areas of the Lake Tahoe Basin.

Changes in ground-water storage have been minimal. Decreases in ground-water storage have resulted locally in areas of pumping, whereas increases in storage have resulted in areas where storm runoff is temporarily ponded in small basins. In 1991, withdrawal of ground water for domestic, municipal, and agricultural uses in the Lake Tahoe Basin was estimated to be about 13,000 acre-ft/yr (E.J. Crompton, U.S. Geological Survey, written commun., 1994). Much of this water is used in the South Lake Tahoe, Calif., urban area where a cone of depression in the ground-water table had developed in the 1960's and 1970's, but has since begun to recover (Loeb, 1987, p. 88).

Hydraulic Gradient

Hydraulic gradient is the difference between hydraulic heads at two points along a flow path, divided by the distance between the two points. Because ground water will move from areas of high head to areas of lower head, the hydraulic gradient defines the potential for ground-water flow through the aquifer material. Within the Lake Tahoe Basin, the altitudes of ground water reported for wells indicate that ground water flows from the highlands surrounding the lake, through fractured bedrock and overlying weathered material, into thicker accumulations of alluvial deposits along canyon bottoms and lacustrine deposits adjacent to the lake. Loeb (1987, p. 88-89, 111) reports that the average gradient between 26 wells in the South Lake Tahoe ground-water basin and Lake Tahoe was 0.003 (15 ft/mi) for the period 1976-1986, and the hydraulic gradient between 6 wells in the Ward Creek ground-water basin and Lake Tahoe was 0.019 (100 ft/mi).

Hydraulic gradients estimated between network sites and Lake Tahoe are listed in table 3. The mean monthly lake stage for this study period (water years 1989-92) was 6,223 ft. Land-surface altitude and horizontal distance were measured on USGS 1:24,000-scale topographic maps. Accuracy of land-surface elevation is ±20 ft for all sites except site numbers 23, 24, 28, 30, and 31, which had been leveled to lake stage for a previous study (Thodal, 1995, p. 7) and are accurate within 1 ft. Distances are accurate within 100 ft. Depth to water in network wells could be measured at only 14 of the sites because access was not available. Wells without a means to measure depth to water directly were assigned the depth to water reported by the well driller. Hydraulic gradients could not be calculated for five wells where water levels could not be measured and were not reported on the well-drillers' reports. Site 25 is a spring and was therefore assigned a water level that coincided with land surface.

Table 3. Hydraulic gradients between ground-water monitoring network sites and Lake Tahoe, California and Nevada, water years 1990-92. Assumed Lake Tahoe lake-surface altitude, 6,223 feet above sea level

[Symbol: --, not determined.]

Site number (fig. 7)	Water level: Feet below land surface	Water level: Feet above sea level	Distance from Lake Tahoe (feet, rounded)	Hydraulic gradient[a]
1	34	6,226	200	0.015
2	65	6,235	300	.040
3	260	6,180	1,500	-.029
4	72	6,248	2,100	.012
5	--	--	--	--
6	159	6,261	3,600	.011
7	30	6,230	1,200	.006
8	206	6,314	2,400	.038
9	--	--	--	--
10	45	6,225	800	.002
11	--	--	--	--
12	31	6,349	4,200	.030
13	--	--	--	--
14	114	6,206	900	-.019 [a]
15	9	6,231	400	.020
16	66	6,274	30,000	.002
17	8	6,227	200	.020
18	80	6,200	14,000	-.002[a]
19	33	6,227	3,100	.001
20	--	--	--	--
21	10	6,230	800	.009
22	0 [b]	6,235	100	.120
23	13	6,239	1,100	.014
24	16	6,256	2,900	.011
25	0 [b]	6,340	4,300	.027
26	30	6,250	2,600	.010
27	4	6,236	300	.043
28	19	6,226	200	.015
29	83	6,317	1,000	.094
30	20	6,223	200	0
31	12	6,265	1,200	.035
32	9	6,231	400	.020

[a] Negative hydraulic gradient indicates ground-water flow away from Lake Tahoe.

[b] Water level below land surface equal to zero for flowing wells and spring; actual head above land surface was not determined.

Estimated hydraulic gradients ranged from -0.029 ft/ft (-150 ft/mi) at site 3 to 0.12 ft/ft (630 ft/mi) at site 22. The median value is 0.014 ft/ft (75 ft/mi), and the mean for the 27 sites is 0.020 ft/ft (106 ft/mi). Three negative gradients, which indicate the potential for water to move from the lake into the aquifers penetrated by these wells, were calculated (sites 3, 14, and 18). However, uncertainty about the land-surface altitude, whether the water level was measured soon after the well was pumped, and the stage of Lake Tahoe when a particular water level was measured may explain the apparent negative ground-water gradients.

Discharge

Ground water is discharged from aquifers in the Lake Tahoe Basin by evapotranspiration; seepage to springs, streams, and other small lakes; and seepage directly to Lake Tahoe. Ground-water discharge also results from withdrawal from wells for domestic and municipal water supplies and from seepage of ground water into sewer lines (California State Water Resources Control Board, 1979, p. 109). An accurate estimate of the volume of ground water that discharges directly to Lake Tahoe is necessary to evaluate ground-water contributions to nutrient budgets for the lake. A few estimates of ground-water discharge to Lake Tahoe have been made for parts of the drainage area tributary to Lake Tahoe (Loeb and Goldman, 1979; Woodling, 1987; Loeb, 1987; Thodal, 1995), but diverse hydrogeologic characteristics of aquifers in the Lake Tahoe Basin suggest that extrapolation of these estimates to other parts of the basin would result in inaccuracies.

The volume of ground water discharging to a lake is difficult to measure directly (Winter, 1981, p. 105-106), but may be estimated indirectly by (1) using an empirical relation that quantifies the rate of ground-water flow through porous media (Darcy's Law; Freeze and Cherry, 1979, p. 16); (2) assuming that the volume of recharge estimated for the Lake Tahoe Basin (about 160,000 acre-ft; Eakin and others, 1976, p. 31) is equal to ground-water discharge and then subtracting estimates of ground-water seepage to springs and streams and withdrawal from water wells; and (3) accounting for all other components of the hydrologic budget for Lake Tahoe and assuming that ground water is represented by the budget residual. Data required for each of these approaches are limited, but simplifying assumptions may provide estimates of the relative significance of ground water to the water budget of Lake Tahoe.

Hydraulic Approach

The rate at which ground water will move through porous media is estimated by:

$$Q = 0.0084KiA, \qquad (1)$$

where Q is volumetric rate of ground-water discharge, in acre-feet per year;
K is hydraulic conductivity, in feet per day;
i is hydraulic gradient, in feet per foot;
A is cross-sectional area of the aquifer, in square feet; and
0.0084 is the factor to convert cubic feet per day into acre-feet per year.

This relation assumes that water is not added to or removed from the path of ground-water flow being considered and that the aquifer is homogeneous and isotropic. Although these assumptions are known to be violated by conditions in the Lake Tahoe Basin, they are accepted to simplify evaluation of ground-water discharge.

Estimates of hydraulic conductivity in the Lake Tahoe Basin vary considerably, ranging from less than 0.1 ft/d to more than 1,000 ft/d. Representative values for basin-fill aquifers may range from 1 to 50 ft/d. Hydraulic gradients between aquifers and Lake Tahoe also span a considerable range, with estimates from network sites ranging from -0.029 ft /ft (indicating flow away from Lake Tahoe) to 0.12 ft /ft. Representative lakeward values may range from 0.01 to 0.05 ft/ft. The cross-sectional area of basin-fill aquifers that intersect Lake Tahoe probably is the least certain estimate. The length of shoreline intersected by basin-fill deposits is about 54 mi (L.A. Peltz, U.S. Geological Survey, written commun., 1995) and thickness of these deposits ranges from less than 30 ft to more than 1,000 ft. The cross-sectional area of aquifers that intersect Lake Tahoe may range from 9,000,000 to 300,000,000 ft^2. On the basis of these estimates, ground-water discharge to Lake Tahoe could range from about 800 acre-ft/yr to more than 2 million acre-ft/yr.

Assuming that available data are representative of basin-fill aquifers, median values of hydraulic conductivity (23 ft/d) and gradient (0.014) result in 40,000 acre-ft/yr (rounded; about 6 percent of mean annual precipitation) of ground-water discharge from the top 50 ft of saturated basin fill. However, because numerous streams incise many of the basin-fill deposits, the principal direction of ground-water flow may not be directly toward Lake Tahoe except in areas near the lake shore. The wide range of estimated ground-water discharge is important to show as a measure of uncertainty associated with data available. Determinations of geologic boundaries, hydraulic gradients, and hydraulic conductivities have uncertainties and variabilities that are inherent (Winter, 1981, p. 106) but can be estimated with reasonable confidence with enough measurements. However, extending sparse data over the entire Lake Tahoe Basin results in potentially serious errors.

Empirical Precipitation-Recharge Relation

Under steady-state conditions, long-term average ground-water recharge and discharge can be assumed to be equal. If the empirical relation reported by Eakin and others (1976, p. 31) is reasonable, then 160,000 acre-ft/yr of water recharges to and discharges from aquifers in the Lake Tahoe Basin. However, because the Lake Tahoe Basin is much wetter than areas in the Great Basin where the relation was developed, part of the ground-water recharge becomes streamflow. Ground-water runoff sustains streamflow when direct runoff does not contribute to streamflow, and the ground-water runoff may increase in response to a rise in water levels caused by recharge.

The area-weighted mean monthly percentage of mean annual precipitation in runoff from 10 Lake Tahoe tributaries with USGS stream-gaging stations is shown in figure 10. Drainage area, period of record, estimates of mean annual precipitation, streamflow discharge, and percentages of mean annual precipitation that is streamflow for these 10 stations are listed in table 4. Mean annual precipitation was adjusted to account for variation during the period of record for each station. Because most precipitation in the Lake Tahoe Basin falls November through March (fig. 5) and accumulates as a winter snowpack, mean monthly discharge during the drier months after the snowpack has melted (August through October) may provide an estimate of minimum ground-water runoff to streams. This accounts for about 110,000 acre-ft/yr (69 percent) of the 160,000 acre-ft/yr of ground-water recharge estimated for the Lake Tahoe Basin (Eakin and others, 1976, p. 31) when distributed over 12 months. An additional 13,000 acre-ft/yr of ground water was withdrawn for domestic supplies in 1991 (E.J. Crompton, U.S. Geological Survey, written commun., 1994), leaving 37,000 acre-ft/yr for direct seepage to Lake Tahoe. The part of this remaining 37,000 acre-ft of ground-water recharge that contributes to streamflow, in response to water-level rise, or to evapotranspiration losses is unknown.

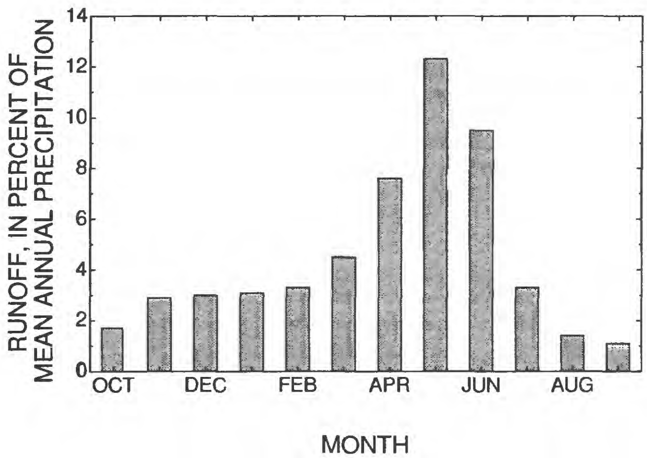

Figure 10. Mean monthly runoff as percent of annual precipitation for 10 gaged tributaries of Lake Tahoe, California and Nevada. (See table 4 for sources of data.)

Hydrologic Budget Approach

The hydrologic budget for Lake Tahoe can be quantified in terms of ground water by accounting for the various components of the hydrologic mass-balance equation and by assuming that any imbalance (residual) represents the ground-water component of the budget. The hydrologic mass-balance equation, in acre-feet per year, is expressed as:

$$RES = P + SWI - SWO - E - D + \Delta S, \qquad (2)$$

where *RES* is residual (a positive value indicates ground-water discharge into Lake Tahoe and a negative value indicates ground-water discharge out of Lake Tahoe);
P is precipitation directly on the surface of Lake Tahoe;
SWI is streamflow into Lake Tahoe;
SWO is streamflow out of Lake Tahoe;
E is evaporation from the surface of Lake Tahoe;
D is water diverted from Lake Tahoe; and
ΔS is change in storage in Lake Tahoe.

Hydrologic budgets have been computed previously for Lake Tahoe (McGauhey and others, 1963, p. 17; Crippen and Pavelka, 1970, p. 34-37; Dugan and McGauhey, 1974, p. 2270-2274; and Myrup and others, 1979, p. 1506-1507) and are summarized in table 5. None of these investigations consider ground-water flow as an independent component, and at least two estimated other components as the residual. Crippen and Pavelka (1970, p. 35) included ground-water seepage with streamflow into the lake, and the other budgets assume that ground-water seepage is negligible. Minimum and maximum values of estimates for each major budget component (precipitation, evaporation, streamflow in and streamflow out) range more than 100,000 acre-ft/yr beyond the means of the four budgets, primarily due to the method of estimation and to hydrologic conditions during the period considered. The large range also provides a measure of uncertainty in each estimate.

Precipitation estimates (table 5) by McGauhey and others (1963), Crippen and Pavelka (1970), and Dugan and McGauhey (1974) are based on isohyetal lines over the 192-mi^2 lake surface. Myrup and others (1979) averaged mean annual precipitation reported for long-term weather stations at Glenbrook, Nev., and Tahoe City, Calif., and distributed that over the area of the lake. The mean volume of precipitation on Lake Tahoe is 250,000 acre-ft/yr (table 5). Factors that may contribute to errors in estimating precipitation are associated with design and operation of the precipitation gages, their areal distribution, and how precipitation measured at discrete points is regionalized over the lake surface. These factors may result in uncertainties that range from ±15,000 to ±180,000 acre-ft/yr (Winter, 1981, p. 85-86). Due to complications of measuring precipitation over Lake Tahoe—particularly during winter storms—and effects of the surrounding mountainous terrain, the true accuracy of these estimates is unknown.

Streamflow into Lake Tahoe from most of the 55 tributaries has not been measured continuously. Stream-gaging stations operated on 10 tributaries are listed in table 4. Because streamflow from much of the drainage basin is not gaged, this component of the hydrologic budget was estimated by various methods. McGauhey and others (1963, p.16) used a precipitation-runoff relation that was developed for the Truckee River Basin. Crippen and Pavelka (1970, p. 34-35) assumed that the amount of estimated precipitation on contributing drainage areas that remained after subtracting diversions and evapotranspiration was equal to combined streamflow and ground-water seepage to Lake Tahoe. Evapotranspiration was estimated from a standard Class-A pan located near Tahoe City, Calif., and operated by the U.S. Weather Bureau. Dugan and McGauhey, (1974, p. 2269-2270) used data from six stream-gaging stations in the Lake Tahoe Basin (Blackwood, Incline, Taylor, Third, and Trout Creeks, and the Upper Truckee River; fig. 2) to develop a precipitation-runoff relation that was then applied to each of the ungaged tributaries. Myrup and others (1979, p. 1501) used data from three stream-gaging stations

Table 4. Estimates of mean annual precipitation and mean annual discharge for tributaries that have U.S. Geological Survey stream-gaging stations in Lake Tahoe Basin, California and Nevada

U.S. Geological Survey stream-gaging station (fig. 2)		Drainage area (square miles)	Period of record (water years)	Mean annual (acre-feet per year)		Discharge, as percent of precipitation
Number[a]	Name			Precipitation	Discharge	
10336610	Upper Truckee River at South Lake Tahoe, Calif.	54.9	1972-74, 1981-91 (14)	118,000	72,000	61
10336626	Taylor Creek near Camp Richardson, Calif.	16.7	1969-91 (23)	45,000	32,000	71
10336645	General Creek near Meeks Bay, Calif.	7.44	1981-91 (11)	21,000	12,000	57
10336660	Blackwood Creek near Tahoe City, Calif.	11.2	1961-91 (31)	34,000	26,000	76
10336676	Ward Creek at Highway 89, near Tahoe Pines, Calif.	9.70	1973-91 (19)	29,000	19,000	66
10336698	Third Creek near Crystal Bay, Nev.	6.05	1970-73, 1978-91 (18)	12,000	6,000	50
10336700	Incline Creek near Crystal Bay, Nev.	7.00	1970-73, 1989-91 (7)	12,000	4,000	33
10336730	Glenbrook Creek near Glenbrook, Nev.	4.07	1972-75, 1989-91 (7)	6,000	900	15
10336740	Logan House Creek near Glenbrook, Nev.	2.08	1984-91 (8)	3,000	300	10
10336780	Trout Creek near Tahoe Valley, Calif.	36.7	1961-91 (31)	60,000	26,000	43

[a] An eight-digit number is used to identify each stream- and spring-gaging station. For example, station number 10336610 consists of a two-digit part number (10) followed by a six-digit downstream-order number (336610). The part number refers to the drainage area or group of areas that is generally regional in extent. Records in this report are for sites in Part 10 (the Great Basin). The downstream-order number is assigned according to the geographic location of the station in the drainage network; larger number stations are downstream from smaller number stations

Table 5. Hydrologic budget estimates for Lake Tahoe, California and Nevada

[Budget components are in acre-feet per year]

Reference	Period considered (water year)	Precipitation directly on Lake Tahoe	Streamflow into Lake Tahoe	Streamflow out of Lake Tahoe	Evaporation from surface of Lake Tahoe	Diversions from the Lake Tahoe Basin	Changes in Lake Tahoe storage	Residual
McGauhey and others, 1963	1901-62	205,000	308,000	176,000	332,000	5,000	-4,000	+4,000
Crippen and Pavelka, 1970	1901-66	212,000	312,000	172,000	352,000	0 [a]	1,000	-1,000
Dugan and McGauhey, 1974	1960-69	272,000	372,000	168,000	438,000 [b]	6,000 [c]	32,000	0
Myrup and others, 1979	1967-70	315,000	413,000	298,000	447,000 [b]	0 [d]	-17,000	0
Mean (rounded)		250,000	350,000	200,000	390,000	3,000	3,000	<1,000
Uncertainty		±15,000 to ±180,000 [e]	±45,000 to ±105,000 [e]	±30,000 [e]	±78,000 to ±120,000 [e]	±2,000	±5,000	

[a] Estimate assumed 5,000 acre-feet per year diverted from streamflow prior to discharge to Lake Tahoe.

[b] Estimated as residual of hydrologic budget.

[c] Estimate includes mean wastewater export begun in 1968.

[d] Hydrologic budget component not addressed.

[e] Estimated by multiplying decimal percent error (Winter, 1981; Hess and others, 1993) by mean value of corresponding hydrologic budget component.

(Blackwood and Trout Creeks and the Upper Truckee River) and assumed that these tributaries contributed 40 percent of all runoff to Lake Tahoe. Estimates of streamflow into Lake Tahoe by these methods are listed in table 5, and the mean is 350,000 acre-ft/yr.

Streamflow out of Lake Tahoe by way of the Truckee River has been measured continuously since March 1900 at Tahoe City, Calif. Except for three diversions, exportation of sewage effluent, and evapotranspiration, the Truckee River is the only outlet for surface water leaving the Lake Tahoe Basin. The wide range of estimates of this component listed in table 5 (168,000-298,000 acre-ft/yr) is due primarily to hydrologic conditions (for example, variation in annual precipitation shown in fig. 4 and in lake storage) that dominated the period for which this budget component was estimated. The mean volume of streamflow out of Lake Tahoe is 200,000 acre-ft/yr.

Factors contributing to errors in estimates of streamflow are related to instrumentation, measurements, and the method used to distribute streamflow data over time and to ungaged tributaries. Accuracies for gaged tributary streamflow into and out of Lake Tahoe is estimated to range from about 95 percent of the daily discharges within 5 percent of the actual values (good) to 95 percent of the daily discharges within 15 percent or more of the actual values (poor; Hess and others, 1993, p. 20 and 228-308). Therefore, the uncertainty associated with gaged streamflow (1) into Lake Tahoe may be about ±35,000 acre-ft/yr and (2) leaving Lake Tahoe may be ±30,000 acre-ft/yr. Uncertainty associated with regionalizing stream discharge from gaged drainages to those that are not gaged may range from 10 to 70 percent or more (Winter, 1981, p. 98). Because about half of the area tributary to Lake Tahoe is not gaged, an additional ±10,000 to ±70,000 acre-ft/yr of uncertainty may be associated with estimated streamflow into Lake Tahoe.

Evaporation from the surface of Lake Tahoe was either estimated on the basis of data from a standard Class-A pan (McGauhey and others, 1963, p. 9-16; Crippen and Pavelka, 1970, p. 34) or assumed to equal the residual of hydrologic budgets that assume ground-water seepage is negligible (Dugan and McGauhey, 1974, p. 2270; Myrup and others, 1979, p. 1501). These estimates are listed in table 5, and the mean volume of evaporation is 390,000 acre-ft/yr. Uncertainties associated with estimates based on pan evaporation are related to design and placement of the pan, selection of an appropriate pan-to-lake coefficient, and regionalizing data (Winter, 1981, p. 88-89). Several studies have shown that estimates of annual pan evaporation differ between 20 and 30 percent from annual estimates calculated by the energy-budget method (Winter, 1981, p. 93). If the energy-budget method is an accurate method of estimating evaporation from lakes, then uncertainty associated with the estimates for Lake Tahoe that are based on pan evaporation may range from about ±78,000 to ±120,000 acre-ft/yr. Uncertainty associated with estimates calculated as the residual is not known because this approach incorporates errors associated with estimates for each of the other budget components (Winter, 1981, p. 108-109).

Diversions from the Lake Tahoe Basin have been limited to three water rights that total 5,000 acre-ft/yr (McGauhey and others, 1963, p. 11). However, in 1969, legislation was enacted that required exportation of wastewater from the California part of the basin by 1972, and Nevada passed similar legislation in 1971. Wastewater exports are in addition to the 5,000 acre ft/yr water rights for export from the Lake Tahoe Basin. About 1,250 acre-ft of wastewater was exported in 1968, wastewater exports increased to about 8,000 acre-ft in 1974 (California State Water Resources Control Board, 1984), and about 9,000 acre-ft of wastewater was exported in 1991 (E.J. Crompton, U.S. Geological Survey, written commun., 1992). Only one budget estimate includes wastewater export (Dugan and McGauhey, 1974, p. 2271). The estimates that do not consider diversions specifically may have assumed that the diversions were removed from streamflow into Lake Tahoe (Crippen and Pavelka, 1970, p. 35-36). Uncertainty associated with this budget component is related primarily to measurement and reporting error. Because the total volume of water diverted from the Lake Tahoe Basin is small, associated uncertainty probably represents less than 2,000 acre-ft/yr.

Changes in storage are estimated on the basis of lake stage that has been measured since April 1900. Water in Lake Tahoe that is represented by lake-stage altitudes between 6,223 and 6,229.1 ft is treated as a storage reservoir with a usable capacity of about 744,600 acre-ft. The volume of water represented by the change in stage may be estimated from a capacity table that is based on the area of the lake surface. Lake-surface area for stage altitude between 6,223 and 6,224 ft is 121,400 acres and increases to 123,000 acres for a stage altitude of 6,229.1 ft (Hess and others, 1993, p. 306). Estimates of change in storage used for hydrologic budgets generally assume that lake-surface area is a constant 123,000 acres and that storage changes 768,600 acre-ft over the 6.1-ft range of usable storage (McGauhey and others, 1963, p. 11; Myrup and others, 1979, p. 1501). The difference between the two methods of estimation is about 5,700 acre-ft (less than 1 percent of usable capacity) for the entire range in stage. Uncertainty associated with measuring stage is believed to be small, but a measurement error of only 0.01 ft of stage represents more than 1,000 acre-ft of storage.

Summary of Discharge Estimates

Ground-water discharge into Lake Tahoe was not specifically considered in any of the hydrologic budgets and each budget estimate has minimal to no residual. However, estimates of uncertainty for any one of the primary budget components (precipitation, streamflow in, evaporation, and streamflow out) could account for the volume of ground water that was estimated by the first two methods used. Although uncertainty associated with the estimates of ground-water discharge to Lake Tahoe made by the first two methods is at least as much as with the other budget components when expressed as a percentage, 40,000 acre ft/yr (rounded) may be a reasonable first approximation for considering the relative significance of mass loading from each budget component.

Estimated ground-water discharge represents about 11 percent of the mean annual precipitation estimated to fall on the drainage areas tributary to Lake Tahoe. Area-weighted mean runoff estimated from 10 stream-gaging stations represents about 55 percent of precipitation, leaving about 34 percent of mean annual precipitation to be returned to the atmosphere by sublimation from snowpacks, evaporation of precipitation that was intercepted prior to ground-water recharge, and ground-water discharge by phreatophytes. Evapotranspiration in the Lake Tahoe Basin has not been quantified, but Kattelmann and Elder (1991, p. 1553) investigated a small alpine basin in the southern Sierra Nevada and estimated that 19-32 percent of the total annual precipitation was returned to the atmosphere. Crippen and Pavelka (1970, p. 35) estimated, on the basis of the class-A evaporation pan at Tahoe City, Calif., that 53 percent of annual precipitation in the Lake Tahoe Basin is lost to the atmosphere. However, this estimate was made before most of the streamflow data were available and the residual estimate made for this study (34 percent) is within the uncertainty associated with estimating evaporation by class-A pan.

Each of the three approaches used to estimate ground-water discharge to Lake Tahoe has errors and uncertainties. The hydrologic budget approach is least certain due to the large volumes of water in each of the budget components. Inherent errors due to measurement and extrapolations are large enough to account for a ground-water component of more than 100,000 acre-ft/yr. The empirical precipitation-recharge relation (Eakin and others, 1976) has not been evaluated for areas with climate and geology typical of the Lake Tahoe Basin. The hydraulic approach was limited by relatively few data about aquifer geometry and about ground-water levels and their relation to streamflow and to lake stage. The data necessary to accurately estimate ground-water discharge to Lake Tahoe cannot be gathered from the present ground-water network. However, construction of additional wells to help define hydraulic properties and geometries of aquifers intersected by Lake Tahoe would provide a more accurate estimate using the hydraulic approach.

RESULTS OF THE MONITORING PROGRAM—1990 THROUGH 1992

Results of physical and chemical analyses of ground-water samples collected from the network during this investigation are stored in the USGS NWIS data base and the U.S. Environmental Protection Agency STORET data base, and have been published in USGS Water Resources Annual Data Reports for Nevada (Garcia and others, 1992, p. 445-459, and Hess and others, 1993, p. 488-491). The data are statistically summarized in table 6. These data have been obtained from a relatively few samples collected over a brief period and are not sufficient to allow detailed assessment of trends or of the geochemical processes that affect observed ground-water chemistry. In addition, all the information necessary to determine ground-water flow to Lake Tahoe and to make accurate estimates of nutrient loads contributed to Lake Tahoe by ground water has not been collected. However, the available data do indicate the type of information that a continuing monitoring program could provide and suggest potential problem areas within the Lake Tahoe Basin. To better understand nutrient loading by ground

Table 6. Statistical summary of water-quality data collected from ground-water monitoring network, Lake Tahoe Basin, California and Nevada, 1989-92

[Concentrations are in milligrams per liter unless otherwise noted. Abbreviations: µS/cm, microsiemens per centimeter at 25°C; °C, degrees Celsius; <, less than; N, nitrogen; P, phosphorus; µg/L, microgram per liter; pCi/L, picocurie per liter; C, carbon; NA, not applicable.]

Constituent or property	Number of determinations	Number of determinations less than analytical reporting limit	Mean	Minimum	25th percentile	50th percentile (median)	75th percentile	Maximum
pH (standard units)	175	0	6.9	5.7	6.5	6.8	7.1	9.0
Specific conductance (µS/cm)	175	0	179	82	114	162	228	440
Dissolved oxygen	47	0	4.8	0.3	3.0	5.2	6.9	9.2
Water temperature (°C)	174	0	9.5	6.0	8.0	9.5	10.5	14
Calcium	32	0	17	4.1	11	14	17	52
Magnesium	32	0	5.1	.27	2.3	4.4	7.9	14
Sodium	32	0	9.8	3.9	5.6	8.3	11	24
Potassium	32	0	2.0	.4	1.1	1.7	2.6	5.2
Bicarbonate	59	0	88	46	56	76	117	220
Carbonate	2	2	<1	<1	NA	NA	NA	<1
Sulfate	32	11	3.1	<1	0.78	1.6	4.8	14
Chloride	32	0	7.3	.2	0.72	3.0	12	47
Fluoride	32	20	0.08	<.1	0.03	0.05	0.1	.4
Silica	32	0	32	15	26	32	37	53
Dissolved solids	32	0	120	59	86	110	140	260
Nitrogen	31	0	1.0	0.02	0.065	0.14	0.38	12
Organic nitrogen (as N)	31	25	NA	<.04	<.04	<.04	.05	.11
Ammonia (as N)	31	23	NA	<.004	<.004	<.004	.004	.10
Nitrate (as N)	31	1	.98	<.004	.034	.14	.38	12
Phosphorus	31	0	.074	.021	.033	.058	.082	.4
Organic phosphorus (as P)	31	0	.023	.005	.019	.023	.030	.038
Hydrolyzable phosphorus (as P)	31	13	NA	<.01	<.01	<.01	<.01	.014
Orthophosphate (as P)	31	0	.050	.005	.015	.028	.062	.36
Soluble iron(µg/L)	31	10	35	<5	<5	11	72	210
Chromium (µg/L)	32	20	NA	<1	<1	<1	1	4
Copper (Cu; µg/L)	32	6	NA	<1	1	1	2	9
Lead (µg/L)	32	24	NA	<1	<1	<1	1	1
Manganese (µg/L)	32	14	NA	<1	<1	1	3	55
Nickel (µg/L)	32	19	NA	<1	<1	<1	1	2
Selenium (µg/L)	32	32	NA	<1	<1	<1	<1	<1
Zinc (µg/L)	32	6	NA	<3	4	8	32	130
Total organic carbon (as C)	31	6	NA	<1	0.2	0.3	0.4	2.7
Deuterium/Hydrogen (ratio)	32	NA	-104	-114.5	-112	-106	-100	-62.9
^{18}Oxygen/^{16}Oxygen (ratio)	32	NA	-14	-15.5	-15.1	-14.5	-13.8	-6.65
Tritium (pCi/L)	32	4	NA	<2.5	8.5	22	38	56
Dissolved Rn^{222} (pCi/L)	30	1	2,900	<80	620	1,100	4,200	10,000

water to Lake Tahoe, additional information about ground-water levels and hydraulic properties of the aquifers that discharge to Lake Tahoe is necessary.

While the project objectives emphasize nutrient monitoring, other physical and chemical properties were determined to characterize ground water, to identify processes that may influence the fate or mobility of nutrients, and to evaluate the distribution and mobility of trace elements that may stimulate algal productivity in Lake Tahoe (Chang and others, 1992).

Ground-Water Quality and Geochemistry

The results of the monitoring program indicate that the inorganic quality of ground water in the Lake Tahoe Basin generally is excellent. Concentrations of dissolved solids determined from samples at 32 sites (fig. 8, table 1) ranged from 59 mg/L at site 18 to 260 mg/L at site 23. The median is 110 mg/L. Ground-water quality of the Lake Tahoe Basin is similar to that of the spring water of the Sierra Nevada, which has been studied in detail by Feth and others (1964), Garrels and Mackenzie (1967), and Nathenson (1989). Most of the dissolved constituents found in ground water are the result of weathering by infiltrating water having a high concentration of dissolved CO_2 (carbon dioxide; Feth and others, 1964, p. 66). Microbial respiration in the soil zone is responsible for increasing the partial pressure of CO_2 in the infiltrating water from about $10^{-3.3}$ atmosphere in the open air to about $10^{-1.8}$ atmosphere in the soil water. The infiltrating soil water reacts with silicate minerals in soil and rock (primarily plagioclase plus biotite and potassium-feldspar) and dissolves silica and other ions into solution, leaving a rubble of quartz and potassium-feldspar while producing residual clay minerals similar to kaolinite at shallow depths and montmorillonite at greater depths (Garrels and Mackenzie, 1967, p. 223-229).

Water can be classified into general chemical types based on major cations (calcium, magnesium, sodium, and potassium) and major anions (bicarbonate, sulfate, chloride, fluoride, and nitrite plus nitrate), in milliequivalents per liter (equivalent units account for different atomic weights and different electrical charges of ion species), expressed as a percentage of their respective totals. For example, a water is classified as a calcium bicarbonate type when at least 60 percent of the cations are calcium and at least 60 percent of the anions are bicarbonate. If no single cation or anion accounts for at least 60 percent of the respective total, the water is classified as mixed (Piper and others, 1953, p. 26).

Figure 11 is a trilinear diagram showing the general character of ground water sampled from the monitoring network. Plotting positions of points on the diagram are based on milliequivalents per liter expressed as percentages of cations or anions. The figure illustrates that the sampled waters are generally of the mixed-cation bicarbonate type (mean cation composition, 46 percent calcium, 27 percent sodium, 23 percent magnesium, and 4 percent potassium; mean anion composition, 81 percent bicarbonate, 11 percent chloride, 4 percent sulfate, 3 percent nitrite plus nitrate, and 1 percent fluoride). The left triangle shows, in addition to mostly mixed cation samples, that sites 16 and 18 have sodium as the dominant cation (68 and 79 percent, respectively) and site 22 is dominated by calcium (62 percent). The right triangle shows three samples (sites 20, 24, and 26) that do not have bicarbonate as the dominant anion. These are from site 20 (31 percent chloride and 10 percent nitrate), site 24 (almost 25 percent nitrate and 15 percent chloride), and site 26 (just less than 50 percent chloride). Bicarbonate still represents at least 50 percent of the anions in all samples except one from site 26.

Water samples from 56 perennial springs and 15 ephemeral springs were analyzed for an earlier investigation by Feth and others (1964). Ephemeral springs typically have a sodium bicarbonate or a mixed-cation bicarbonate character, whereas the cations in samples from perennial springs are more commonly dominated by calcium and magnesium. All but one perennial spring has bicarbonate as the dominant anion (Feth and others, 1964, p. 35). Concentrations of dissolved solids ranged from 11 to 162 mg/L for all samples; the perennial springs had a median concentration of 72 mg/L and the ephemeral springs had a median concentration of 29 mg/L (Feth and others, 1964, p. 16).

Granitic rock of the Sierra Nevada batholith probably underlies the entire Lake Tahoe Basin, and concentrations of major ions in ground-water samples appear to reflect having been in contact with that mineralogy. However, volcanic rocks cover much of the northwestern part of the basin and smaller exposures exist throughout the basin. Scattered exposures of metamorphic rock and alluvial, colluvial, and glacial deposits also are composed of various proportions of these parent rocks. Feth and others (1964, p. 52) found that, except for generally higher concentrations of

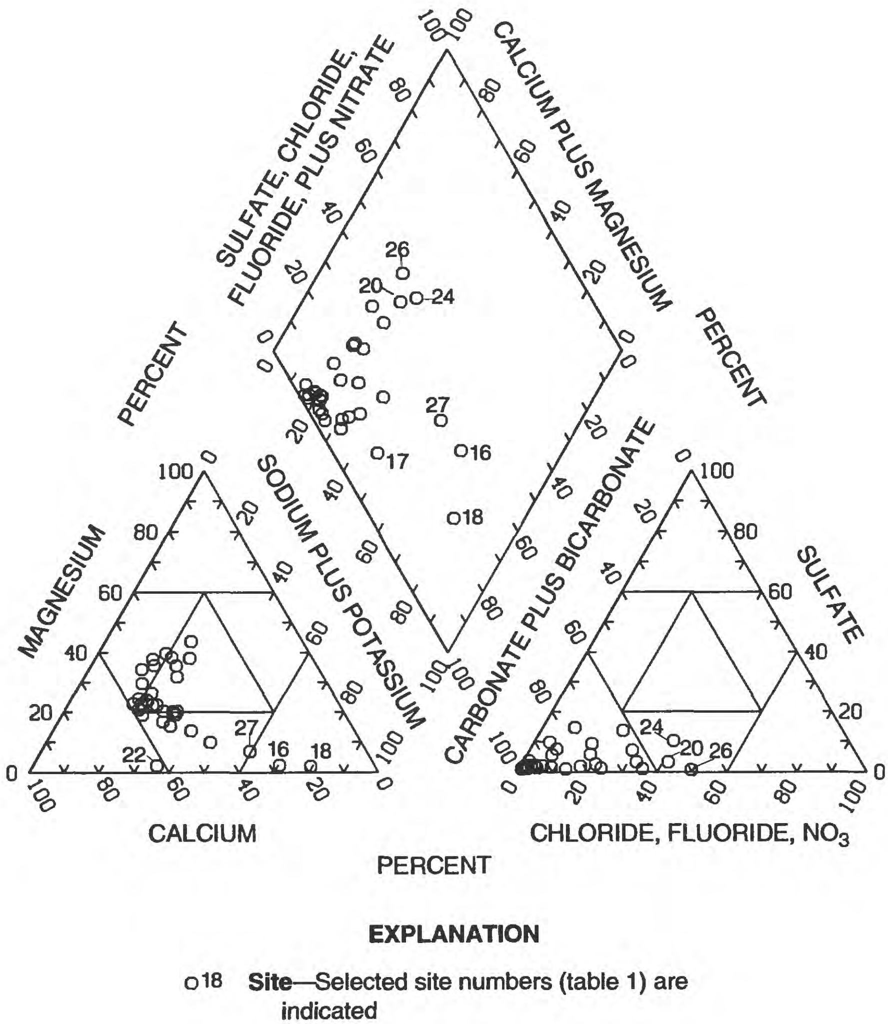

Figure 11. General chemical character of water sampled from ground-water monitoring sites, Lake Tahoe Basin, California and Nevada, 1989-90.

major ions and an increased percentage of magnesium among cations, perennial springs in volcanic rocks of the Sierra Nevada and the southern Cascade mountains have major-ion characteristics similar to those of springs from granitic rock.

Nutrient Chemistry

Nitrogen, phosphorus, and iron are essential nutrients for algal productivity. The availability of other required elements also will influence algal growth. Results of early bioassays to determine the response of Lake Tahoe algal communities to nitrogen, phosphorus, and selected micronutrients indicated that nitrogen controlled primary productivity in the lake and that iron would stimulate algal productivity to a greater degree than phosphorus (Goldman, 1974, p. 6-7). However, during the 1980's, similar bioassays have demonstrated an increasing response to phosphorus additions (Goldman, 1988, p. 1322) and 25 years of bioassay record (1967-92) indicate that long-term colimitation by both nitrogen and phosphorus prior to 1982 shifted to phosphorus being the dominant limiting nutrient (Goldman and others, 1993, p. 1490-1491). Chang and others (1992, p. 1214) also report bioassay results indicating that algal productivity in Lake Tahoe is limited by phosphorus, and they found no indication of nitrogen limitation. Because concentrations of all essential nutrients are low in Lake Tahoe, those authors emphasize that primary productivity is sensitive to small changes in lake-nutrient chemistry.

Discussion of Results

Summary statistics for nutrients measured for this study are listed in table 6 and are based on mean values for each site. Only analyses made by TRG were included in these computations to provide results that are comparable with other LTIMP monitoring efforts. The areal distribution of mean concentrations of filtered nitrogen, phosphorus, and soluble iron are shown in figures 12-14, respectively.

Knowledge of the processes controlling the availability and mobility of nutrients is essential to determining their sources and the impact they may have on the water quality and algal productivity of Lake Tahoe. Nitrogen in ground water occurs primarily as organic nitrogen (amides, amines, amino acids, and proteins), ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), and nitrogen gas (N_2).[1] Biologically mediated processes can hydrolyze organic nitrogen to ammonium (ammonification), oxidize ammonium to nitrite and nitrite to nitrate (nitrification), chemically reduce nitrate to nitrous oxide and 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, and dissolved-oxygen concentration (Behnke, 1975, p. 156-161).

Nitrogen in ground water most commonly originates from land-surface sources with only minor contributions from the aquifer. For example, the average nitrogen content of granitic rock is 18 mg/kg (milligrams of nitrogen per kilogram of granitic rock), of which only 7.2 mg/kg is water soluble (Feth and others, 1964, p. 44). Land-surface sources of nitrogen to ground water include atmospheric precipitation, plant and animal wastes, leguminous plants, soil organisms, fertilizers, septic-system leachate, and sewage spills. Nitrate is the nitrogen species most readily transported in oxidized ground water. Nitrite is quickly oxidized to nitrate in aerated water but, in anaerobic conditions, nitrite will move freely with ground water. Ammonium is strongly sorbed to the mineral surfaces of the soils and rocks and is not readily transported in ground water. The mobility of organic nitrogen may be limited due to its complex molecular structure.

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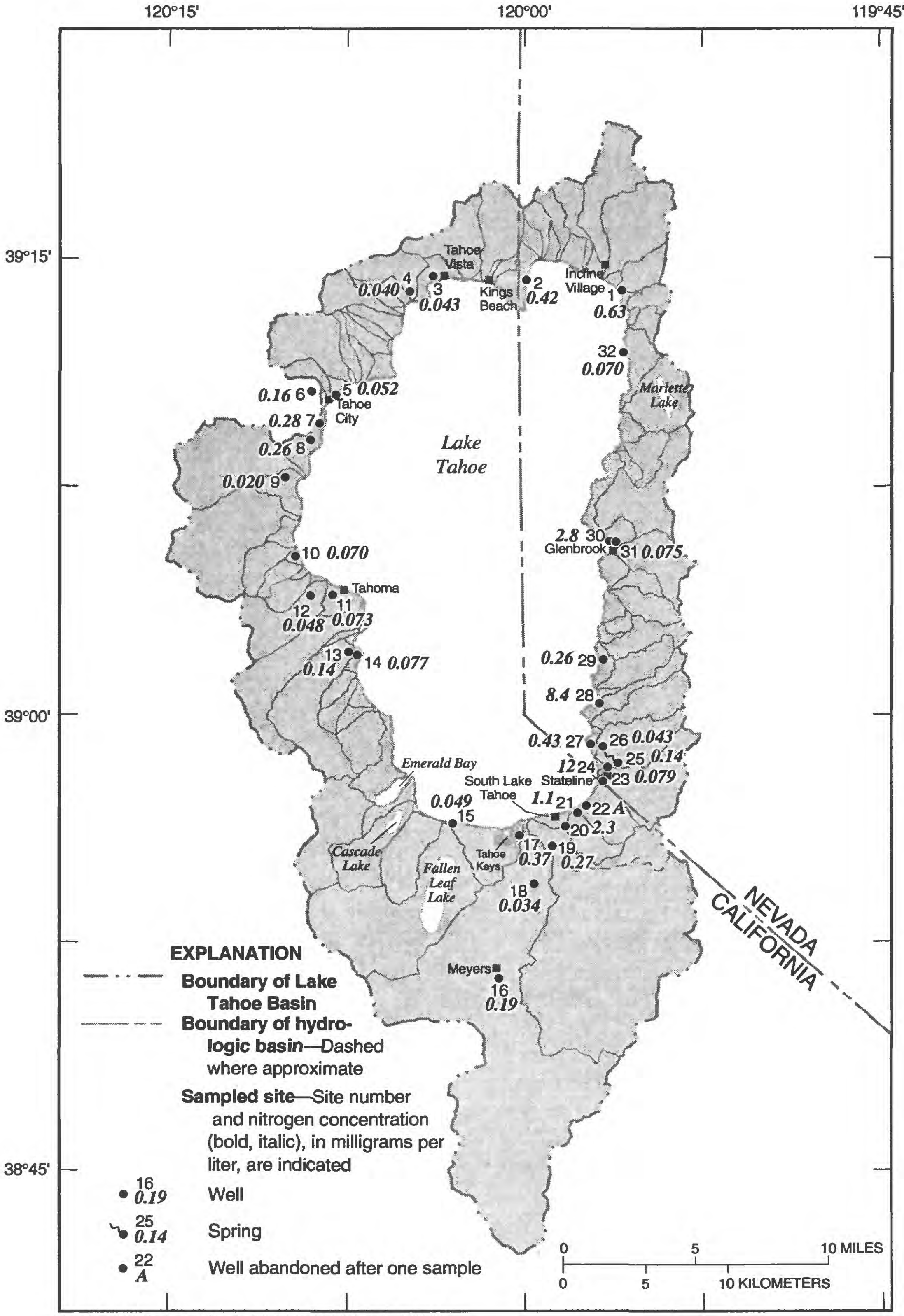
[1]In most unpolluted natural waters having a pH less than about 8.5, ammonium ions (NH_4^+) predominate over dissolved ammonia gas (NH_3). Nonetheless, the combined concentration of ammonium and ammonia is, by convention, reported as "ammonia" for USGS laboratory results.

Mean concentrations of filtered nitrogen (sum of species) ranged from 0.02 mg/L at site 9 to 12 mg/L at site 24 (median: 0.14 mg/L), and concentrations of filtered nitrate-nitrogen ranged from <0.004 mg/L at site 23 to 12 mg/L at site 24 (median: 0.14 mg/L). Only nitrate-nitrogen is reported for Lake Tahoe, with monthly mean concentrations in samples collected during water year 1987 from the Index station (fig. 8; sample depths: 0-340 ft) averaging 0.014 mg/L, as N (Byron and others, 1988, p. 54). Thus, the average nitrate concentration for Lake Tahoe is an order of magnitude less than the median nitrate-nitrogen concentration for sampled ground water. For comparison, concentrations of filtered nitrogen (sum of all species) measured in 111 stream samples collected during October 1989 through September 1992, from 7 LTIMP tributary monitoring sites (General, Blackwood, Ward, Third, Incline, Glenbrook, and Logan House Creeks; fig. 2) ranged from 0.04 mg/L at Ward and Blackwood Creeks to 0.43 mg/L at Incline Creek (Pupacko and others, 1990; Bostic and others, 1991; Garcia and others, 1992; Hess and others, 1993).

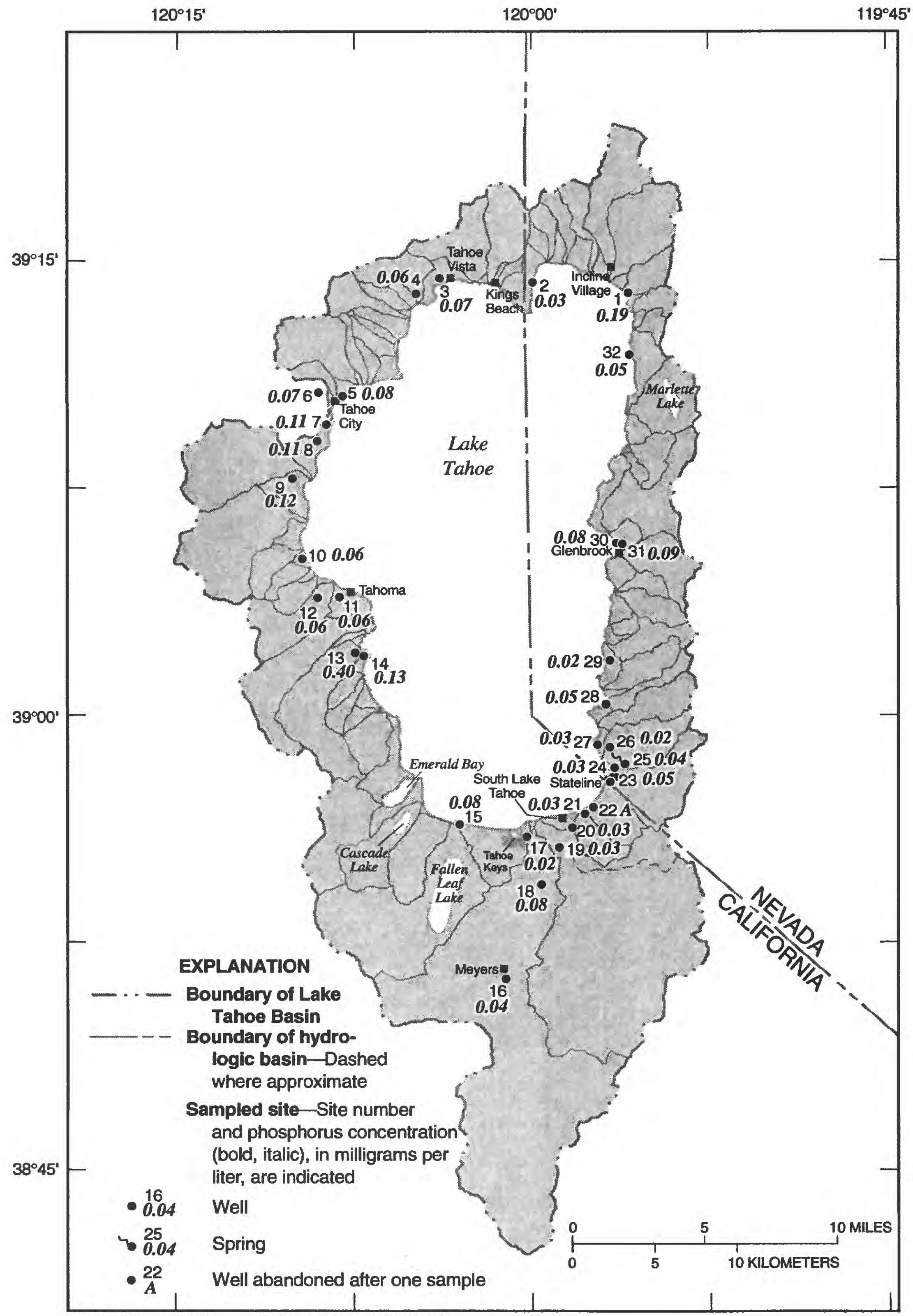
Figure 15 shows cumulative frequency distributions for concentrations of nitrogen and of chloride in samples from ground-water monitoring sites. Five sites (sites 20, 22, 24, 28, and 30) have mean concentrations of filtered nitrogen greater than 1 mg/L and the remaining 26 sites have mean concentrations ranging from 0.02 mg/L to 0.63 mg/L. Nitrate concentrations at site 24 exceeded the maximum contaminant level for drinking water in Nevada (10 mg/L NO_3, as N; Nevada Bureau of Consumer Health Protection Services, 1980) with a mean concentration of 12 mg/L. Sites 20 and 22 are in the South Lake Tahoe urban area and down-gradient from an area historically used for spray-disposal of treated sewage effluent. Sites 24 and 30 are observation wells on golf courses, and site 28 is an observation well near a resort that historically relied on a septic-tank leach-field system for disposal of domestic waste. A horse stable associated with this resort is another possible source of the nitrogen in samples from this site.

The cumulative frequency distribution of filtered chloride concentrations suggests contamination at 10 sites, with a range from 11 mg/L (site 21) to 47 mg/L (site 26). A statistically significant correlation was found between concentrations of chloride and nitrate in well-water samples from the Upper Truckee River and Trout Creek drainage basins collected for another study (Loeb, 1987, p. 35-36); no statistically significant correlation was found for similar analyses for the present study.



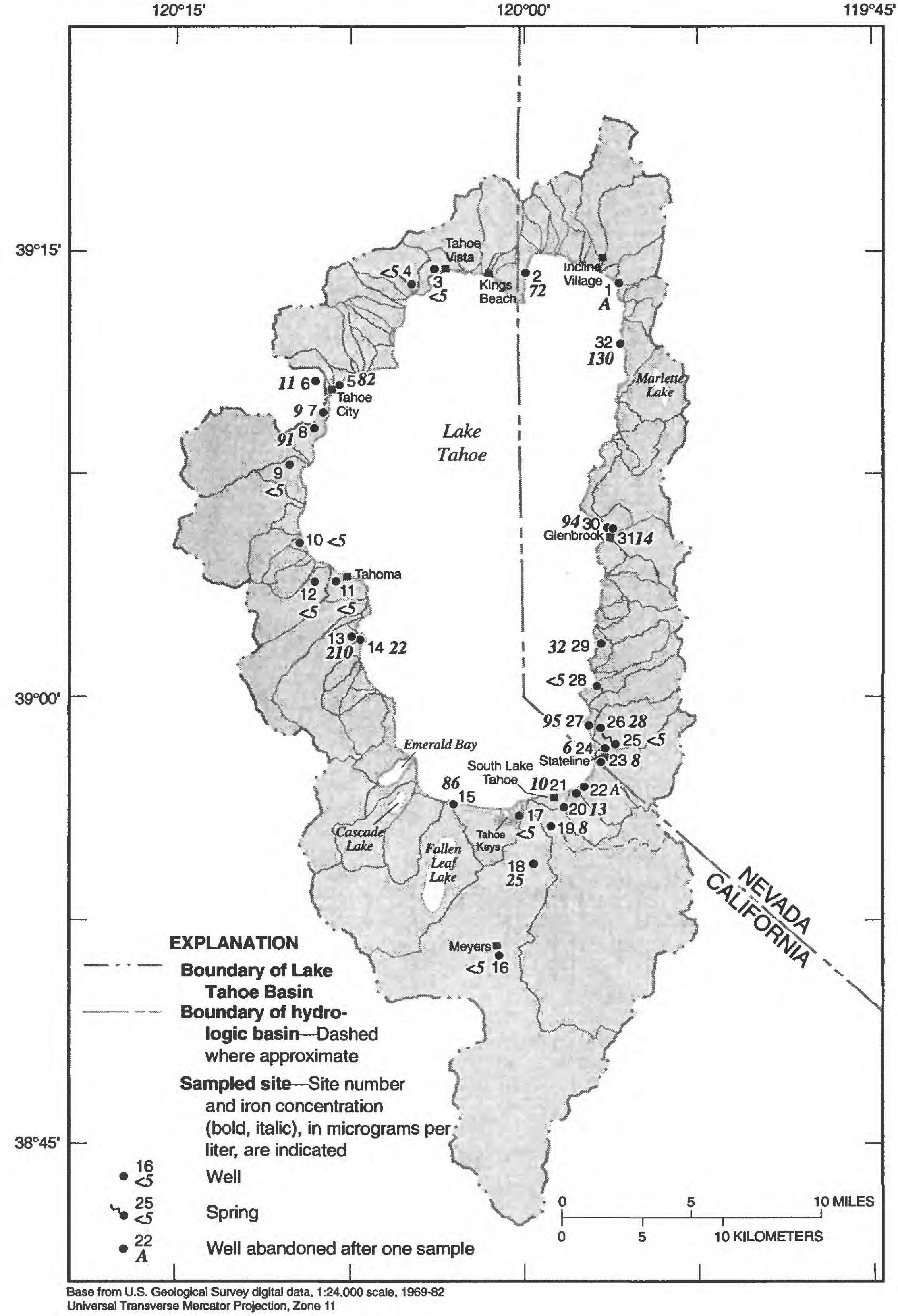
Base from U.S. Geological Survey digital data, 1:24,000 scale, 1969-82
Universal Transverse Mercator Projection, Zone 11

Figure 12. Distribution of mean concentrations of nitrogen in filtered water samples from ground-water monitoring sites, Lake Tahoe Basin, 1990-92.



Base from U.S. Geological Survey digital data, 1:24,000 scale, 1969-82
Universal Transverse Mercator Projection, Zone 11

Figure 13. Distribution of mean concentrations of phosphorus in filtered water samples from ground-water monitoring sites, Lake Tahoe Basin, 1990-92.



Base from U.S. Geological Survey digital data, 1:24,000 scale, 1969-82
Universal Transverse Mercator Projection, Zone 11

Figure 14. Distribution of mean concentrations of soluble iron in filtered water samples from ground-water monitoring sites, Lake Tahoe Basin, 1990-92.

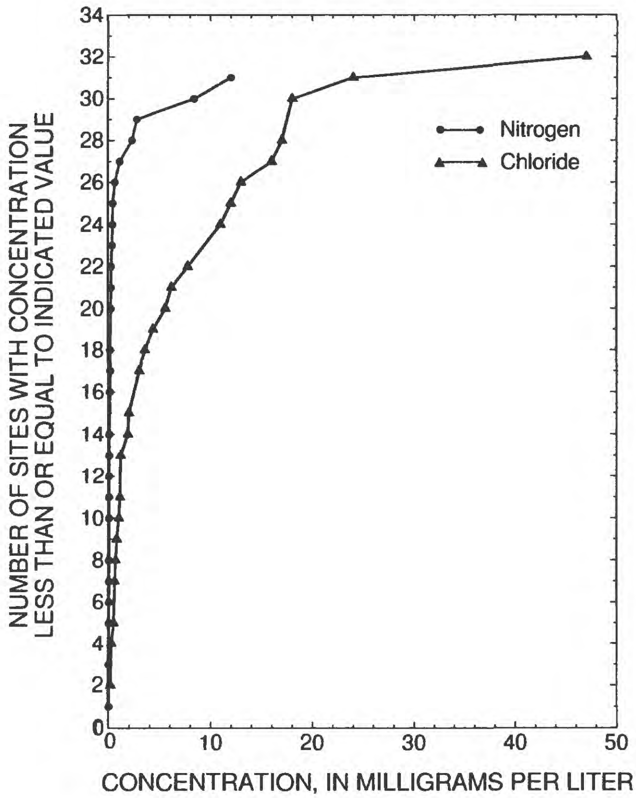


Figure 15. Cumulative frequency distribution of concentrations of nitrogen and chloride in filtered water samples from ground-water-monitoring sites, Lake Tahoe Basin, California and Nevada, 1989-92.

Salt used for de-icing can be a source of chloride contamination but not of nitrate, which probably explains the poor correlation between chloride and nitrate in samples collected for this study.

Phosphorus in ground water is derived predominantly from land-surface sources and from chemical weathering of aquifer material. The phosphorus content of igneous rocks is about 1,100 mg/kg (Hem, 1985, p. 5). Phosphorus in ground water generally is found as the orthophosphate ion (as $H_2PO_4^-$ in ground water with pH between about 2.5 and 7, and as HPO_4^{2-} for pH between 7 and 12), but organic phosphorus, synthesized by plants and animals, also can represent a measurable fraction of the phosphorus in ground water. Hydrolyzable phosphorus is composed of polyphosphates (for example, $P_2O_7^{4-}$, $P_3O_{10}^{5-}$) and a few simple organic phosphorus compounds. Orthophosphate is the most biologically reactive form of phosphorus, and 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 concentration and mobility in ground water (Hem, 1985, p. 126-129).

Mean concentrations of filtered phosphorus (all species) in samples from network sites ranged from 0.021 mg/L at site 26 to 0.40 mg/L at site 13 (median: 0.058 mg/L). Similar to data on nitrogen, phosphorus concentrations may be considered low except when compared to concentrations reported for water samples from Lake Tahoe. The monthly mean concentrations of total (unfiltered) phosphorus in samples collected during water year 1987 from the Lake Tahoe Index station (fig. 8) averaged 0.003 mg/L as P (Byron and others, 1988, p. 54). Ground-water concentrations of filtered phosphorus are greater than 0.1 mg/L at six sites (nos. 1, 7, 8, 9, 13, and 14), but there is nothing to indicate that higher concentrations are associated with human activity. For comparison, concentrations of filtered phosphorus measured in 116 stream samples collected during October 1989 through September 1992, from 8 LTIMP tributary monitoring sites (General, Blackwood, Ward, Third, Incline, Glenbrook, Logan House and Edgewood Creeks; fig. 2), ranged from 0.003 mg/L at Logan House and Edgewood Creeks to 0.078 mg/L at Incline Creek (Pupacko and others, 1990; Bostic and others, 1991; Garcia and others, 1992; Hess and others, 1993).

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

Mean concentrations of filtered soluble iron in samples of ground water range from less than 5 µg/L at 10 sites (fig. 14) to 210 µg/L at site 13 (median: 11 µg/L). Monthly mean concentrations of soluble iron are not reported for Lake Tahoe after water year 1984 when concentrations at the Index station averaged 3 µg/L (Byron and Goldman, 1985, p. 45). Concentrations of filtered soluble iron measured in 84 samples collected during October 1989 through September 1992, from 7 LTIMP tributary monitoring sites (General, Blackwood, Ward, Third, Incline, Glenbrook, and Logan House Creeks; fig. 2), ranged from <1 µg/L at Third, Incline, Glenbrook, and Logan House Creeks to 430 µg/L at Third Creek (Pupacko and others, 1990; Bostic and others, 1991; Garcia and others, 1992; Hess and others, 1993).

Figure 16 shows the relative contribution of the various species of nitrogen (nitrite, nitrate, ammonia, and organic nitrogen) and of phosphorus (orthophosphate, hydrolyzable phosphorus, and organic phosphorus) expressed as percentages of the mean concentration. Nitrite contributions were insignificant with concentrations generally below the analytical reporting limit (0.001 mg/L), but low level concentrations (0.001-0.002 mg/L) were measured in samples from sites 7, 8, and 30. Nitrate is the dominant form of nitrogen, representing 100 percent of measurable nitrogen at 17 of the 31 sites considered and averaging 85 percent for all sites. Anomalous nitrogen speciation is noted at sites 13 and 18, where ammonia represented about 78 percent (0.10 mg/L) and 57 percent (0.013 mg/L) of measurable nitrogen, respectively. Although these concentrations are low, ammonia concentrations were below the level of detection (0.004 mg/L) at 23 of the 31 sites. Organic nitrogen accounted for 84 percent (0.08 mg/L) of measurable nitrogen at site 31 and 68 percent (0.05 mg/L) at site 32.

Speciation of mean phosphorus concentrations shown in figure 16 is only weighted slightly toward the orthophosphate form (55 percent) compared with the organic form (42 percent). Hydrolyzable phosphorus represents only 3 percent of the mean distribution. Sites with higher concentrations of filtered phosphorus generally have larger contributions from orthophosphate: for mean filtered-phosphorus concentrations at the 75th percentile and higher (0.082-0.40 mg/L), orthophosphate accounts for 69 percent (site 7; 0.076 mg/L) to 90 percent (site 13; 0.36 mg/L) of the phosphorus.

Seasonal changes in ground-water quality may result in different probability distributions for samples collected at different times of the year. Such changes may result in greater statistical variance among samples that can invalidate most statistical hypothesis tests, including statistical tests for trends (Smith and others, 1982, p. 5). Seasonal changes in ground-water quality may be caused by natural or anthropogenic factors (Hipel, 1985, p. 616). For example, natural changes in surface-water quality are common because of seasonal variation in the volume of streamflow, ambient

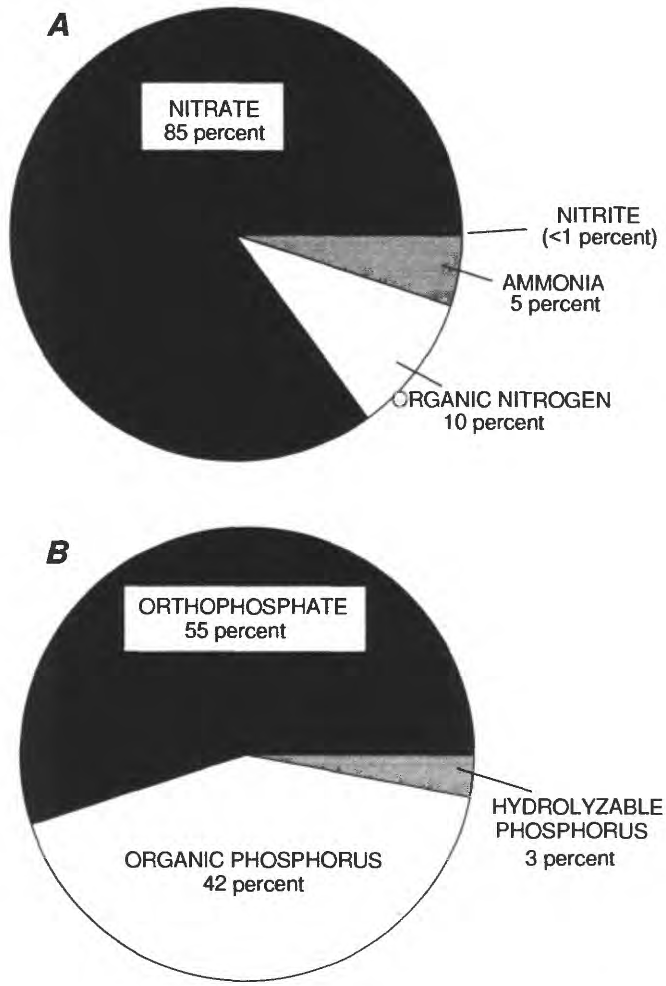


Figure 16. Relative contributions of nutrient species that constitute mean concentrations of *A*, nitrogen and *B*, phosphorus in filtered water samples from ground-water monitoring sites, Lake Tahoe Basin, California and Nevada, 1990-92.

temperature, or biological activity. Natural changes in ground-water quality have been related to seasonal fluctuations in natural recharge and water levels. Seasonal changes in ground-water quality caused by human activities have been attributed to seasonal patterns of water use, irrigation, and land application of agricultural fertilizers (Montgomery and others, 1987, p. 180).

Seasonal changes in water quality can be evaluated graphically by displaying the distribution of selected constituents for each season using boxplots. The "box" of the plot defines the distribution of the central 50 percent of the data (that is the data between the 25th and 75th percentiles). The line dividing the box represents the median value, or the 50th percentile.

Lines drawn beyond the box, referred to as "whiskers," extend to the extreme (maximum and minimum) values (Montgomery and others, 1987, p. 180-182). Graphical presentation also illustrates the range of concentrations demonstrated by each nutrient species. Statistical significance of seasonal changes can be evaluated quantitatively using tests for variance. Because water-quality data do not meet the assumption of normal distribution, the Kruskal-Wallis test (Helsel and Hirsch, 1992, p. 159-169) was used to measure the degree to which the sums of ranks of concentrations (nitrogen, phosphorus, and soluble iron) for each season differ at the 0.005 probability level.

Nutrient concentrations analyzed seasonally (quarterly) for samples collected at 24 sites (sites indicated in table 1) are summarized in figure 17. The results of Kruskal-Wallis tests for statistically significant seasonality are presented in table 7. These tests indicate that concentrations of nitrogen and soluble iron do not change significantly from one season to the next, but concentrations of phosphorus vary enough to be statistically significant at the 0.005 probability level. Seasonal median values of nitrogen concentrations vary by about 0.1 mg/L, phosphorus medians vary by about 0.04 mg/L, and median values of soluble iron are within 6 µg/L for each seasonal data set (table 7). However, the mean rank of phosphorus concentrations for samples collected in the winter season (38th) is statistically different than the mean rank for fall concentrations (63d). Although the overall seasonal changes of nutrient concentrations in ground water are small, the seasonal variation in phosphorus concentrations may invalidate most statistical tests for trends because assumptions of normal distribution and serial independence are violated. Tests for seasonal change made for this study do not confirm that seasonal processes are controlling phosphorus concentrations. However, the data do have statistically significant variability coincident with the seasons investigated.

Estimated Nutrient Loads to Lake Tahoe

To evaluate the contributions from ground water in terms relative to the nutrient budget of Lake Tahoe, all sources must be considered. Estimates of nutrient income to Lake Tahoe from the atmosphere, tributaries, and ground water are listed in table 8.

Nutrient contributions from ground water are estimated by multiplying mean concentrations of nitrogen (1.0 mg/L), phosphorus (0.074 mg/L), or soluble iron (35 µg/L), times the volume of ground water estimated to discharge to Lake Tahoe annually (40,000 acre-ft). This approach results in the following rounded estimates of annual loads to Lake Tahoe from ground-water inflow: 60 tons/yr of nitrogen, 4 tons/yr of phosphorus, and 2 tons/yr of soluble iron.

Atmospheric contributions to the nutrient budget of Lake Tahoe are estimated from deposition rates measured for precipitation and airborne fallout (dry deposition) collected near the mouth of Ward Creek (110 µmol/m^2/d nitrogen and 2.9 µmol/m^2/d phosphorus; Jassby and others, 1994, p. 2211). On the basis of these rates, about 300 tons of nitrogen and about 20 tons of phosphorus are deposited yearly on the surface of Lake Tahoe. Data collected at lesser frequency along an east-west transect of three collectors floating on the lake surface indicate that rates decrease away from the western shore. Nitrogen deposition on the shore was about twice the rate, and phosphorus on the shore was about nine times the rate estimated for the middle of Lake Tahoe (Jassby and others, 1994, p. 2213). These limited results were not used in the preliminary estimates of atmospheric nutrient contribution to the lake. No data were found for atmospheric deposition of iron on Lake Tahoe.

Annual nutrient loads associated with streamflow can be estimated by multiplying the mean annual volume of surface-water runoff (350,000 acre-ft; table 5) by the mean of annual mean concentrations reported for LTIMP streams. Mean concentrations of nitrogen, phosphorus, and biologically available iron measured in unfiltered samples from the five California LTIMP streams are 0.15 mg/L, 0.035 mg/L, and 302 µg/L, respectively (Tahoe Regional Planning Agency, 1993, p. 43). Concentrations in water samples collected from LTIMP streams in Nevada during October 1989 through September 1992 (Pupacko and others, 1990; Bostic and others, 1991; Garcia and others, 1992; Hess and others, 1993) had the following ranges: unfiltered nitrogen, 0.06 mg/L (Logan House Creek) to 24 mg/L (Third Creek); unfiltered phosphorus, 0.008 mg/L (Logan House Creek) to 9.4 mg/L (Third Creek); and (unfiltered) biologically available iron, 18 µg/L (Logan House Creek) to 33,000 µg/L (Third Creek). Drainage-area weighted mean concentrations, based on mean concentrations reported for LTIMP streams in California (Tahoe Regional Planning Agency, 1993, p. 43) and on median concentrations from each of the four LTIMP streams in Nevada, resulted in the following concentrations of total nitrogen, total phosphorus, and biologically available iron, respectively: 0.16 mg/L, 0.037 mg/L, and 390 µg/L. Annual mass loads estimated by

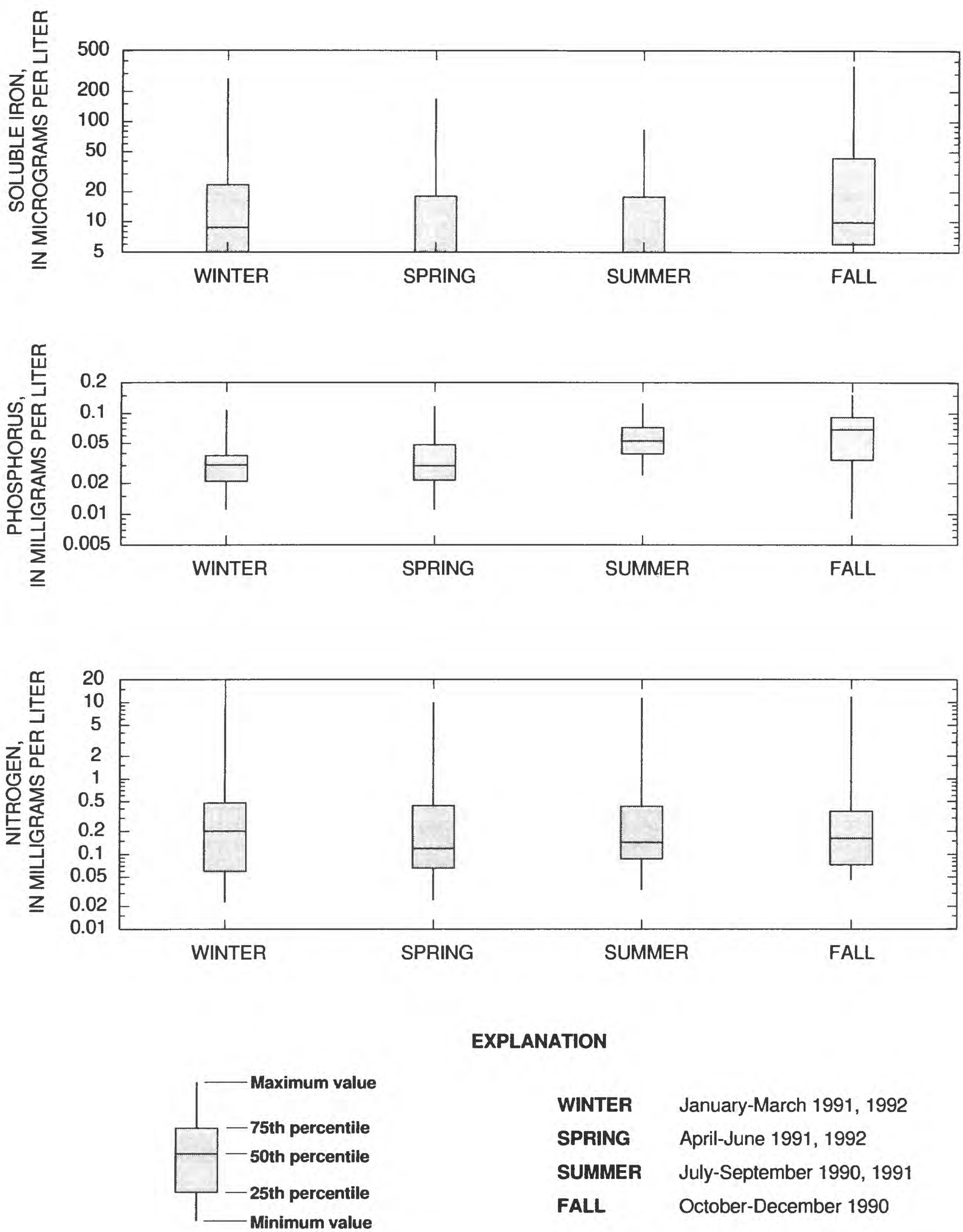


Figure 17. Boxplots of seasonal variation in nutrient concentrations in filtered water samples from 24 ground-water monitoring sites, Lake Tahoe Basin, California and Nevada, 1990-92.

Table 7. Results of Kruskal-Wallis tests for statistical significance of seasonal variation in concentrations of nitrogen, phosphorus, and soluble iron in filtered water samples from ground-water monitoring sites, Lake Tahoe Basin, California and Nevada, water years 1990-92

[Symbol: --, not computed]

Season	Nitrogen			Phosphorus			Soluble iron		
	Median concentration (milligrams per liter)	Mean rank	p-value	Median concentration (milligrams per liter)	Mean rank	p-value	Median concentration (micrograms per liter)	Mean rank	p-value
Winter (January-March, 1991 or 1992)	0.19	48	--	0.030	38	--	8.8	46	--
Spring (April-June, 1991 or 1992)	.10	46	--	.030	39	--	5.1	44	--
Summer (July-September, 1991)	.10	50	--	.045	54	--	4.5	44	--
Fall (October-December, 1990)	.15	50	--	.069	63	--	9.8	60	--
Overall	.16	48	0.975	.040	48	0.005	7.6	48	0.150

this simplistic approach are about 70 tons/yr of total nitrogen, 20 tons/yr of total phosphorus, and 200 tons/yr of biologically available iron.

Another estimate of nutrient mass-loadings to Lake Tahoe from its tributaries (Dugan and McGauhey, 1974, p. 2273) used an inflow volume that is about 6 percent greater than the estimate used herein, and 0.273 mg/L and 0.022 mg/L were used as representative concentrations of total nitrogen and phosphorus. Annual mass loads estimated on the basis of these values are about 58 percent more nitrogen (120 tons/yr of total nitrogen) and 46 percent less phosphorus (9.2 tons/yr of total phosphorus) than those used in this study. These relatively large differences in mass loadings result primarily from comparatively small differences in concentrations (+0.11 mg/L, nitrogen and -0.015 mg/L, phosphorus).

Poorly defined processes that may affect the estimated load contributions in table 8 have been assumed to be negligible. For example, estimates of the volume of water from each source were made on a mean annual basis. Thus, episodic events that contribute large volumes of streamflow with elevated concentrations of nutrients associated with suspended sediment were not

Table 8. Estimated nutrient contributions to Lake Tahoe, California and Nevada

[Estimated loads are rounded to one significant figure. Symbol: --, not estimated.]

Budget component	Nitrogen	Phosphorus	Soluble iron	Source of information
	Tons per year	Tons per year	Tons per year	
Atmospheric deposition	300	20	--	Jassby and others, 1994
Runoff	70	20	200	Tahoe Regional Planning Agency, 1993; Pupacko and others, 1990; Bostic and others, 1991; Garcia and others, 1992; Hess and others, 1993
Ground water	60	4	2	Current study
Total	400	40	200 [a]	

[a] Total does not include atmospheric contribution of iron, for which no estimate is available.

considered. Similarly, estimates of mass loading by atmospheric deposition did not consider the limited data indicating that deposition rates decrease substantially away from the western lake shore, and relatively high concentrations of nitrogen in ground water that is affected by anthropogenic activities also were not considered. Nevertheless, the estimates in table 8 provide (1) a perspective of the overall system that contributes to the nutrient budget of Lake Tahoe and (2) a background for effective allocation of the limited funds available for managing the water quality of Lake Tahoe.

Isotope Chemistry

Ratios of Oxygen and Hydrogen Stable Isotopes

The isotopic composition of water is often measured to make inferences about factors that may have affected a hydrologic system. The stable isotopes evaluated herein are oxygen-18 relative to oxygen-16 ($^{18}O/^{16}O$) and deuterium (^2H) relative to hydrogen-1 ($D/^1H$). Each ratio is determined for a water sample and is then related mathematically to the comparable ratio for an international reference standard known as VSMOW. By convention, the computed results are expressed as "delta oxygen-18" ($\delta^{18}O$) and "delta deuterium" (δD); the units of measure are parts per thousand (abbreviated permil). A negative delta value indicates that the sample water is isotopically lighter than the standard (that is, the sample has a smaller proportion of ^{18}O or D, relative to ^{16}O or ^1H, than the standard). Because "isotopic fractionation" results from physical, chemical, or biological processes, the delta value of the stable isotopes of water will change. For example, during the physical process of evaporation, $\delta^{18}O$ increases because ^{16}O is lighter and evaporates from liquid water at a greater rate than the heavier ^{18}O. The terms isotopically heavier and isotopically lighter are relative and are used for comparing the composition of water samples (Fritz and Fontes, 1980, p. 4-5).

The isotopic composition of precipitation typically varies between storms and from place to place due to isotopic fractionation. Phase changes (for example, from liquid water to ice or vapor) cause fractionation and the temperature at which phase changes occur largely will control the extent of fractionation (Friedman and Smith, 1970, p. 467). Although the variation due to fractionation can be substantial, the average isotopic composition of precipitation at a site will lie close to the "meteoric-water line" (Craig, 1961), a regression line defined by the equation:

$$\delta D=8(\delta^{18}O)+10. \quad (3)$$

Figure 18 shows the relation of stable-isotope values for ground-water samples collected from the monitoring network, 1 sample collected from Lake Tahoe (Nehring, 1980, p. 18), the range of 30 samples collected from the Truckee River at Tahoe City, Calif. (Welch and others, in press), and the Global meteoric water line (Craig, 1961). Most of the ground-water samples fall within a fairly tight grouping along the meteoric line. However, five ground-water samples fall outside this group and probably represent a mixing of ground water with lake water.

The symbol labeled "1" represents a sample from site 1, a 163-ft deep domestic well close to the lake shore that is reportedly screened in fractured granite. The proximity of this well to the lake and the similarity of the isotopic composition to that of lake water suggests that lake water is the primary source of water to this well. However, the reported water level in this well is greater than the lake level, and other chemical data for this site suggest that the sampled water is not directly from Lake Tahoe. Concentrations of filtered silica (29 mg/L), and mean concentrations of nitrate-nitrogen (0.66 mg/L), and phosphorus (0.27 mg/L) in water sampled from site 1 are higher than concentrations reported for Lake Tahoe [silica, 12 mg/L (Imboden and others, 1977, p. 1040), and nitrate-nitrogen and phosphorus, 0.014 and 0.003 mg/L (Byron and others, 1988, p 54)]. An alternate explanation for the isotopic composition of the sample from site 1 is secondary recharge of Lake Tahoe water from the following sources: (1) snow making at the nearby ski area that uses water from Lake Tahoe, (2) treated wastewater effluent that was disposed of historically by spray land-application or that leaked from nearby holding ponds, or (3) irrigation of lawns and landscaping with lake water. The symbols labeled 23, 24, 30, and 31 represent samples from four shallow observation wells (less than 30 ft deep) at two golf courses.The ratio of δD to $\delta^{18}O$ for water samples from these wells deviates from the meteoric water line toward the ratio of δD to $\delta^{18}O$ reported for Lake Tahoe (Nehring, 1980, p. 18). Because both golf courses are irrigated with lake water, the isotopic composition of samples from these wells may reflect infiltration of water applied to the courses.

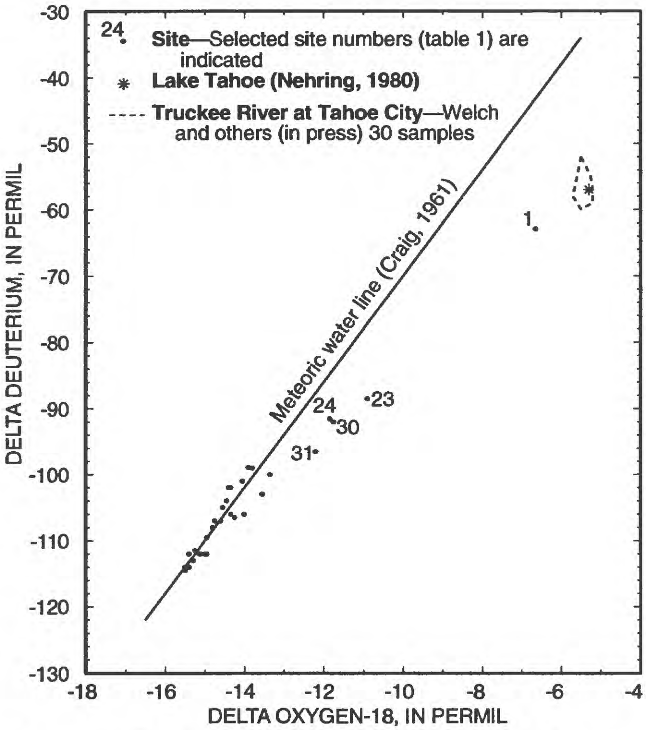


Figure 18. Relation between stable isotopes of hydrogen and oxygen in water samples from ground-water monitoring sites, Lake Tahoe Basin, California and Nevada, 1989-90, and in samples collected earlier from Lake Tahoe and the Truckee River.

Tritium

Tritium (^3H) is a radioisotope of hydrogen with an atomic mass of 3 and half-life of 12.3 years (Hem, 1985, p. 150). It is produced naturally at very low concentrations in the atmosphere by interaction of cosmic rays with nitrogen and oxygen. However, thermonuclear weapons testing between 1952 and 1969 introduced large quantities of tritium into the atmosphere, providing a useful indicator of the "age" (the time since the ground water was isolated from the atmosphere). Tritium is incorporated into water molecules in the atmosphere, resulting in concentrations in precipitation near Lake Tahoe similar to values shown in figure 19. Values for 1953-87 are interpolated from a data base of tritium deposition in the continental United States (Michel, 1989) and have been weighted to monthly precipitation recorded at Tahoe City, Calif. Values for 1988-92 are interpolations of concentrations measured in precipitation at Portland, Oreg., and Albuquerque, N. Mex., (R.L. Michel, U.S. Geological Survey, written commun., 1995), and values for 1950-52 are assumed to be the same concentration as those for 1953. All concentrations are adjusted to account for radioactive decay to 1990. On the basis of these rates of tritium deposition and of radioactive decay, and assuming "piston flow" for ground-water movement, ground water with tritium levels less than 10 pCi/L presumably recharged prior to 1952. Ground water with tritium concentrations greater than 10 pCi/L recharged since 1952 (Welch, 1994, p. 16). However, some samples could be mixtures of ground water that recharged before 1952 and more recently. Thus, a "tritium age" would be skewed depending on the ratio of the mixture.

Concentrations of tritium measured in ground water range from below the detection level (less than 2.5 pCi/L) at four sites (sites 3, 7, 13, and 18) to 56 pCi/L at site 8. The median concentration was 22.5 pCi/L. Eight sites had concentrations less than 10 pCi/L, indicating that sampled water had been isolated from the atmosphere for at least 38 years prior to August 1990. Three of these sites (3, 5, and 7) are wells completed in or adjacent to volcanic flows near the northwest shore of the lake; three sites (16, 18, and 22) are wells completed in glacial outwash, moraine, and till deposits near South Lake Tahoe; site 13 is a well completed in glacial outwash deposits on the

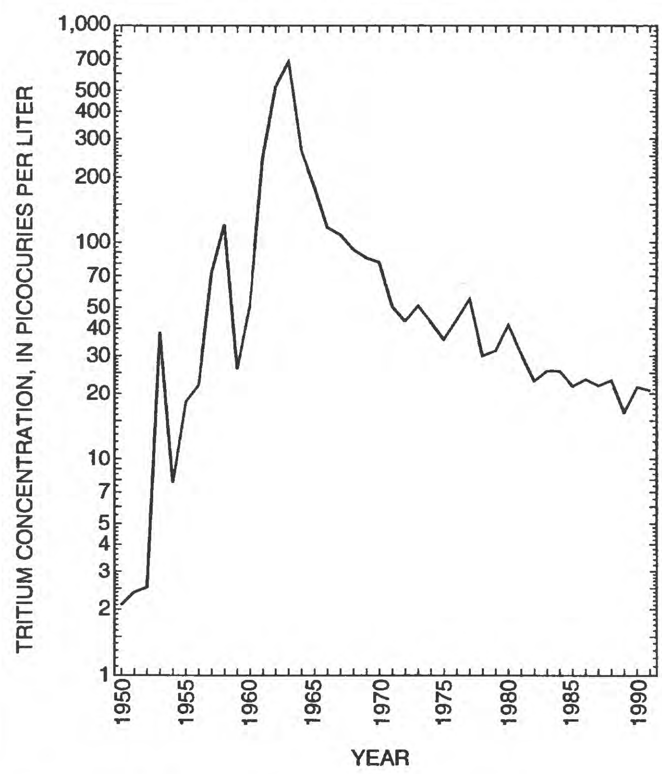


Figure 19. Estimated tritium activity in precipitation, adjusted for precipitation rate (precipitation-weighted mean) and radioactive decay to 1990, Lake Tahoe Basin, California and Nevada, 1950-92 (Michel, 1989).

western shore; and site 25 is a perennial spring near the southeastern lake shore that discharges from decomposed granite. Only samples from sites 9 (18 pCi/L), 29 (16 pCi/L), 30 (23 pCi/L), and 31 (16 pCi/L) had concentrations of tritium in the range estimated for precipitation in the Lake Tahoe Basin during this study (1989-92; 16-23 pCi/L). The areal distribution of tritium values is shown in figure 20.

Ratios of Nitrogen Isotopes

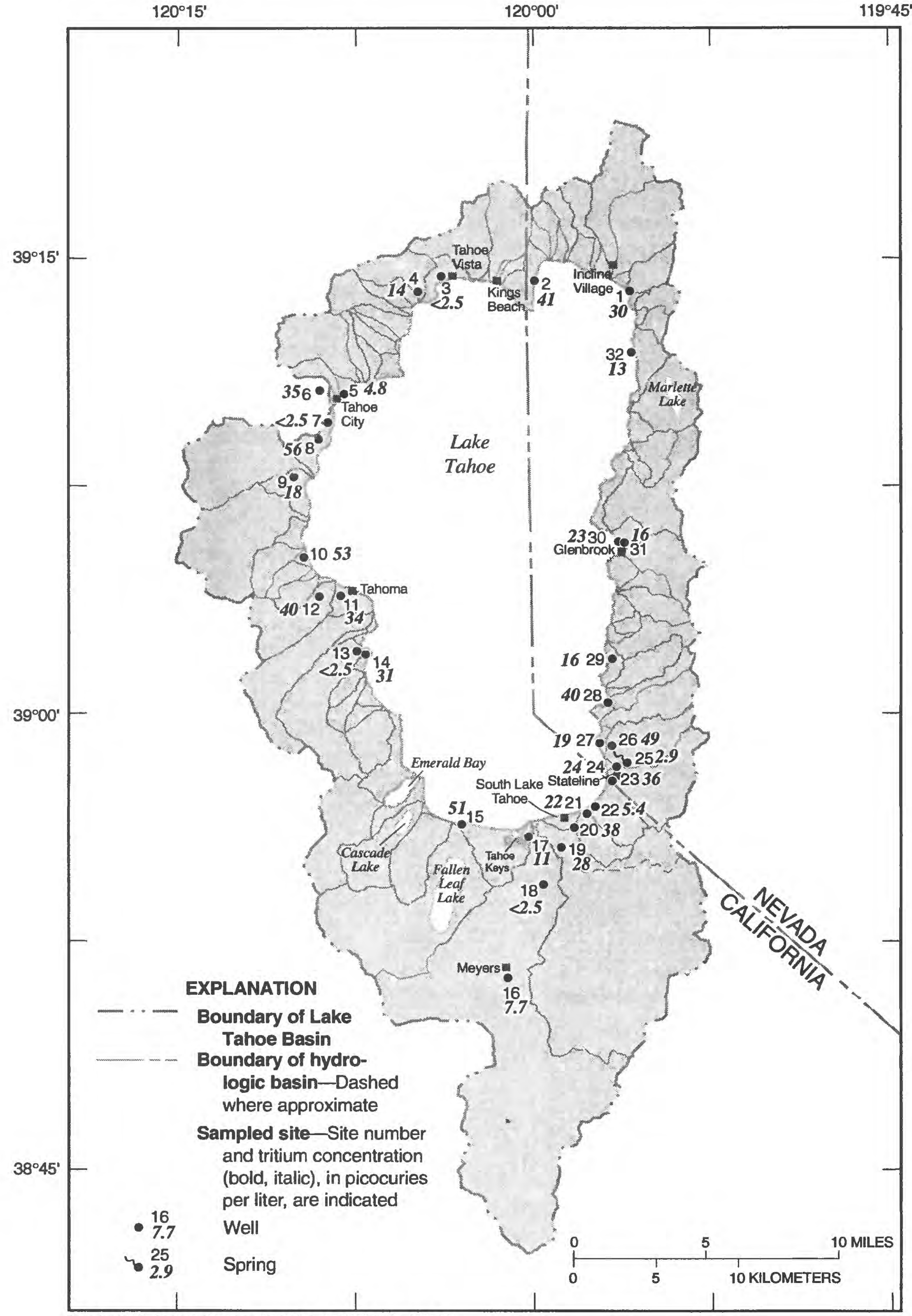
Variation in the abundance of the two stable isotopes of nitrogen has been used in many hydrologic investigations to identify sources of nitrogen in the hydrologic cycle (Heaton, 1986). Atmospheric nitrogen represents the largest pool of nitrogen in the environment and is comprised of one atom of the stable isotope ^{15}N per 273 atoms of ^{14}N (Drever, 1982, p. 347). Analytical determinations of nitrogen isotopes are expressed as a ratio of $^{15}N/^{14}N$ that is related to a similar ratio determined for a standard. Atmospheric nitrogen is the accepted standard because it is considered to have a globally uniform isotopic composition (Heaton, 1986, p. 88). Thus, isotopic ratios of nitrogen are reported as differences from the standard and expressed as "delta nitrogen-15" ($\delta^{15}N$), in permil.

Chemical and biological processes involving nitrogen species result in varying isotopic fractionation. Although the fractionation processes are not well understood, the resulting variations have been successfully used to distinguish ground water contaminated with fertilizer nitrogen from ground water contaminated with nitrogen from human or animal wastes (Exner and Spaulding, 1994, p. 73). Values of $\delta^{15}N$ for nitrogen compounds typically range from -15 permil to +20 permil (Heaton, 1986, p. 88). Typical $\delta^{15}N$ values for nitrate from synthetic fertilizer (ammonium nitrate) range from -2 permil to +4 permil; values for nitrate oxidized from soil organic nitrogen range from +3 to +8; and values for nitrate associated with human or animal waste range from +10 permil to +20 permil (Aravena and others, 1993, p. 180). Potential sources of nitrogen in ground water of the Lake Tahoe Basin are (1) mineralization of soil nitrogen; (2) wet and dry atmospheric deposition; (3) urban runoff; (4) synthetic fertilizers; (5) domestic sewage, residuals from abandoned septic-tank systems and cesspools, and land disposal of treated sewage effluent; and (6) domestic livestock wastes.

Four sites (20, 24, 28, and 30) found to have concentrations of filtered nitrogen in excess of the minimum concentration required by the laboratory were sampled for determination of $\delta^{15}N$. Values of $\delta^{15}N$ measured in samples from these sites are 6.6, 3.5, 6.7, and 6.0 permil, respectively. All of these $\delta^{15}N$ values are within the range reported for oxidized soil nitrogen (+3 to +8), but the sample from site 24 (3.5 permil) is also within the range for synthetic fertilizers. Elevated concentrations of filtered nitrogen suggest that mechanisms capable of accumulating soil nitrogen may exist near these sites. Possible natural mechanisms include nitrogen fixation and evaporative concentration. Nitrogen fixation has been indicated by concentrations of nitrate-nitrogen as high as 18 mg/L in soil-water samples collected from an alder (*Alnus tenuifolia*) meadow near Ward Creek (Robert Coats and Robert Leonard, Tahoe Research Group, written commun., 1973). An alternative explanation is that the $\delta^{15}N$ values are for nitrate that was derived from a mixture of sources such as synthetic fertilizer and sewage effluent (Carol Kendall, U.S. Geological Survey, written commun., 1995).

Program Evaluation

The effectiveness of this ground-water quality monitoring program can be best evaluated in terms of the LTIMP goals and objectives that were listed previously in the Methods section. Summarized, LTIMP objectives related to ground-water monitoring directed this program to (1) establish baseline conditions of ground-water quality, (2) establish continuity with other LTIMP monitoring efforts, (3) meet quality-assurance standards, (4) identify trends, (5) evaluate mass loading of nutrients to Lake Tahoe, and (6) assist with research to enhance the understanding of water-quality dynamics and the aquatic ecosystem of Lake Tahoe. As initially implemented, this monitoring program only has begun the process of data collection and analysis necessary to meet these objectives. Baseline conditions of ground-water quality have been documented for 31 sites distributed throughout the generally lowland parts of the Lake Tahoe Basin. Samples were collected for determination of nutrient concentrations using consistent methods and analyzed by the same laboratory that has analyzed water samples from Lake Tahoe and its tributaries since the inception of the LTIMP (October 1979) and has a documented quality-assurance plan. Most of the network sites are expected



Base from U.S. Geological Survey digital data, 1:24,000 scale, 1969-82
Universal Transverse Mercator Projection, Zone 11

Figure 20. Distribution of tritium concentrations in water samples from ground-water monitoring sites, Lake Tahoe Basin, California and Nevada, 1989-90.

to be available for repeated sampling in the future and continued monitoring will eventually result in a data set that is suitable for statistical analysis to detect trends in ground-water quality.

However, with regard to providing sufficient data to make credible estimates of mass loading to Lake Tahoe, the limitations of this monitoring network are considerable. Only relatively few sites (31) are distributed over 315 mi^2 of drainage area and about 71 mi of shore line. Aquifers are three dimensional and, in the Lake Tahoe Basin, some basin-fill deposits are more than 1,000 ft thick with complex hydrogeologic characteristics. Few of the sites used in this network have access for measuring the depth to ground water, and most measuring-point altitudes are only accurate within ±20 ft. Without accurately determined geologic boundaries, hydraulic gradients, and hydraulic conductivities, estimates of ground-water discharge are subject to considerable error (Winter, 1981, p. 106). The range in tritium ages of water samples collected from network sites provides a qualitative indication of variability of ground-water movement through aquifers in the Lake Tahoe Basin. Information gathered for this program indicates that ground water does discharge into Lake Tahoe, but estimates of ground-water contributions to the water budget of the lake have a large degree of uncertainty.

Computation of nutrient loads carried by ground-water discharge combines the errors associated with estimating ground-water discharge and with estimating a representative concentration of each nutrient. Concentrations of filtered nitrogen ranged from 0.02 to 12 mg/L, filtered phosphorus ranged from 0.021 to 0.4 mg/L, and soluble iron ranged from <5 to 210 μg/L. Nevertheless, data provided by this program do allow decisionmakers to consider each component of the nutrient budget in relative terms. Uncertainty for each component may be the largest factor to consider but, based on available information, the relative significance of each component can be evaluated.

Selection of the sites used in this network was restricted to existing wells and springs. The information gained from this limited network can be used to conceptualize an ideal network which would provide data to more accurately evaluate ground-water discharge and the nutrient loads it carries to Lake Tahoe. An ideal network would consist of wells constructed and distributed to provide data on hydraulic characteristics of aquifers (including water levels) that have potential to contribute ground water and nutrients to Lake Tahoe. Several aquifers have been identified in the Lake Tahoe Basin, and specific land-use activities have been identified to have the potential for adding nitrate to ground water. Five network sites with higher concentrations of nitrogen appear to be contaminated from abandoned septic-tank systems, treated-effluent disposal areas, or from fertilizer applied on golf courses. Wells constructed to provide data about the areal extent of contaminated ground water would help to clarify how it moves to Lake Tahoe. Additional wells drilled in areas known to have relied on septic systems historically (pre-1972) for wastewater disposal and in areas used for land-disposal of treated wastewater would help determine how extensive this type of ground-water contamination is and provide information necessary to evaluate whether remedial action is warranted. Concentrations of phosphorus and iron did not range as high as nitrogen concentrations, and no relation to land use was apparent from available data.

Ground-water samples collected from the monitoring network were analyzed for constituents in addition to nutrients. Determination of major ions provided general characterization of ground-water quality and an indication of areas where road salt may have resulted in elevated chloride concentrations. Determination of stable-isotope ratios indicated that similar processes affect recharge water throughout the Lake Tahoe Basin and that the isotopic composition of ground water is different than the composition of Lake Tahoe (fig. 18). Because the isotopic compositions of ground water and lake water are measurably different, it was possible to infer that ground-water samples collected from wells on golf courses irrigated with lake water may be a mix of local ground water and infiltrated irrigation water. The isotope mass-balance method (Krabbenhoft and others, 1990) may provide a means to estimate ground-water exchange with Lake Tahoe. Concentrations of dissolved radon gas also were determined in water samples from network sites because this constituent has been used as a tracer of ground-water transport through lake sediments (for example, by Demas and others, 1989). Additional data, including analyses of samples from sites representative of the aquifer-lake seepage face, would be required for either of these tracer methods.

Data from four samples analyzed for $\delta^{15}N$ did not clearly indicate the source of nitrate in the sample water. Two of these sites are on golf courses, but only one had a $\delta^{15}N$ value in the range published for synthetic fertilizers. The other three samples had values that indicate mineralization of soil nitrogen, but these values may also represent a mixture of fertilizer and animal or human waste. These data are too limited to draw conclusions about nitrate sources, but refinements in sampling methods and $\delta^{15}N$ and $\delta^{18}O$ analysis of low concentrations of nitrate are being evaluated (Kendall and others, 1996). Other chemical indicators of sources of nitrate in ground water also are being evaluated in northwest Nevada (Seiler, 1996).

SUMMARY AND CONCLUSIONS

Lake Tahoe is noted for its clarity and color, but long-term limnological data indicate that this clarity has declined about 20 percent since 1968. Accelerated algal productivity in the lake, attributed to an increase in nutrient loads from increased development in the basin, is widely accepted as the cause of the loss in clarity. The U.S. Geological Survey, in cooperation with the Tahoe Regional Planning Agency (the land-use and environmental-resources planning agency for the basin), initiated a monitoring program to evaluate the role of ground water in processes of nutrient loading to Lake Tahoe. Historical data describing ground-water flow and quality were reviewed and a quality-monitoring network was designed and operated to provide information about the relative significance of ground water to the nutrient budget of Lake Tahoe was implemented. Water from 30 wells and 1 spring was sampled once for filtered concentrations of major ions, silica, nutrient species, selected trace constituents, and radon gas. Because one well was abandoned after initial sample collection, it was replaced with a nearby well. Consequently, data for water samples from a network of 32 sites were collected. Concentrations of total organic carbon, tritium, stable isotopes of oxygen, hydrogen, and for a few selected wells, nitrogen also were determined. Additionally, samples were collected quarterly and analyzed for nutrient concentrations to assess seasonal variability. Evaluations of (1) historical data on ground-water flow and (2) the effectiveness of data collected from the monitoring network to characterize the quality and nutrient content of local ground water were made.

The Lake Tahoe Basin is on the California-Nevada State line about 20 mi southwest of Reno, Nev. It is a structural valley of about 315 mi^2 that is bounded by the main range of the Sierra Nevada on the west and the Carson Range to the east. Lake Tahoe is a 191-mi^2 water body with about 71 mi of shoreline and an average depth of 1,027 ft. The only outlet from the lake is to the Truckee River, and the dam at Tahoe City regulates releases from storage of up to about 744,600 acre-ft of lake water; maintaining the lake-surface altitude between 6,229.1 ft and the base of the dam at 6,223.0 ft. Fifty-five tributaries discharge directly into Lake Tahoe. Parts of Placer, El Dorado, and Alpine Counties in California, and parts of Douglas and Washoe Counties and Carson City rural area in Nevada are in the Lake Tahoe Basin. About 80 percent of the population lives in California and 20 percent lives in Nevada.

Geologic units in the Lake Tahoe Basin are pre-Cretaceous metamorphic rock, Cretaceous granitic rock, Tertiary and Quaternary volcanic rock, and Tertiary and Quaternary glacio-fluvial and lacustrine sedimentary deposits. Unconsolidated and semiconsolidated sediments partly fill the valleys and canyons that drain into Lake Tahoe as well as the bottom of the lake itself. These sediments were deposited by glacial, alluvial, and lacustrine processes and, where they are saturated, generally are considered to be aquifers. Consolidated geologic units are much less permeable except where interconnected fractures and porous zones permit secondary permeability.

Recharge to ground-water flow systems is primarily from infiltration of precipitation into faults and fractures in consolidated rock, into the soil and decomposed granite that overlies much of the bedrock, and into unconsolidated basin-fill deposits. Under steady-state conditions, ground-water recharge is assumed to equal ground-water discharge. According to an empirical relation developed for the Great Basin that relates recharge to precipitation, about 25 percent of total precipitation in the Lake Tahoe Basin is potential ground water recharge. On the basis of the empirical relation and estimates of the mean volume of annual precipitation, an average of about 160,000 acre-ft of water is available annually for ground-water recharge. However, because basin-fill aquifers in the Lake Tahoe Basin are nearly full (water levels are near land surface), less precipitation is able to infiltrate into the ground compared to basin-fill aquifers in the drier areas where the empirical relation was developed. Consequently, a greater proportion of the annual precipitation becomes streamflow. Estimates of ground-water discharge to streams indicate that 69 percent (110,000 acre-ft) of ground-water recharge estimated by this method discharges as streamflow before reaching Lake Tahoe. About 13,000 acre ft/yr of water is pumped from wells, leaving 37,000 acre-ft to discharge to Lake Tahoe each year.

Representative estimates of hydraulic conductivity for valley-fill aquifers and gradients between network sites and Lake Tahoe may range from 1 to 50 ft /d and from 0.01 to 0.1 ft/ft, respectively. The length of shore line intersected by unconsolidated deposits is about 54 mi, and thickness of these deposits ranges from less than 30 ft to more than 1,000 ft. On the basis of these estimates, the cross-sectional area of aquifers that intersects Lake Tahoe ranges from 9,000,000 to 300,000,000 ft^2, and estimated ground-water discharge to Lake Tahoe ranges from less than 800 acre-ft/yr to more than 2 million acre-ft/yr. Median values of hydraulic conductivity and gradient suggest that about 40,000 acre-ft of ground water may discharge to Lake Tahoe each year through the top 50 ft of saturated basin-fill deposits.

Mean concentrations of filtered nitrogen ranged from 0.02 mg/L to 12 mg/L (median: 0.14 mg/L), which indicates that concentrations were greater in ground water than in Lake Tahoe. Nitrate-nitrogen concentrations at one site averaged 12 mg/L, which exceeds the maximum contaminant level for drinking water (10 mg/L). Nitrate concentrations at three other sites averaged 2.2 to 8.3 mg/L, which is more than an order of magnitude greater than the median concentration. These data suggest that contamination has affected the four sites. Possible contaminant sources include an area in the South Lake Tahoe area historically used for spray-disposal of treated sewage effluent, areas where fertilizer is applied to lawns or landscape, and abandoned septic-tank/leach-field systems. Mean concentrations of filtered phosphorus ranged from 0.021 mg/L to 0.40 mg/L (median: 0.058 mg/L), which are higher than concentrations of total phosphorus in samples collected from Lake Tahoe (mean: 0.003 mg/L as P). Mean concentrations of filtered soluble iron range from <5 μg/L to 210 μg/L (median: 11 μg/L).

Nitrate is the dominant form of nitrogen measured in samples from the network, representing 100 percent of measurable nitrogen at 17 of the 31 sites sampled and averaging 85 percent for all sites. Ammonia represents about 5 percent of the mean nitrogen concentration, and organic nitrogen represents about 10 percent. Nitrite contributions are insignificant. The distribution of mean phosphorus concentration is about 55 percent orthophosphate and 42 percent organic phosphorus. Hydrolyzable phosphorus represents only 3 percent of the mean distribution.

Seasonally, median values of nitrogen concentrations varied between fall (October-December) 1990 and spring (April-June) 1992 by about 0.1 mg/L, phosphorus medians varied by about 0.04 mg/L, and median values of soluble iron were within 6 μg/L for each seasonal data set. Only the seasonal phosphorus variations were statistically significant at the 0.005 probability level.

Concentrations of dissolved solids analyzed from samples collected at 32 ground-water sites range from 59 to 264 mg/L, and the median is 113 mg/L. Most of the ground water sampled is a mixed cation bicarbonate type water. Stable-isotope ratios indicate that similar processes affect recharge water throughout the Lake Tahoe Basin and that the isotopic composition of ground water is distinctly different from that of Lake Tahoe. Ground-water samples collected from wells on golf courses irrigated with lake water probably are a mix of local ground water and infiltrated irrigation water based on isotopic composition. The isotope mass-balance method may provide a means to estimate ground-water exchange with Lake Tahoe. Concentrations of dissolved radon gas also were determined in water samples from network sites because this constituent has been used as a tracer of ground-water transport through lake sediments. Effective use of either of these tracer methods would need additional data, including analyses of samples from sites representative of the aquifer-lake seepage face. Tritium activity in network samples indicates that most of the sampled ground water was recharged after 1952, although samples from the South Lake Tahoe ground-water basin, glacial outwash aquifers on the western side of the lake, and an interbedded volcanic rock aquifer at the north end of the lake were probably recharged prior to 1952.

Estimates of annual mass loading of nutrients to Lake Tahoe are subject to considerable uncertainty, due to uncertainties associated with estimating large volumes of water that flow to the lake each year and the relatively small percentage of inflow actually sampled. Additional uncertainty results from assuming that a mean concentration is representative for the entire volume of a hydrologic component. However, this simplistic approach is reasonable as an approximation of relative significance of ground water to the overall nutrient budget for Lake Tahoe. By the approach applied to estimate loads for this investigation, ground water may contribute 15 percent of the 400 tons per year of nitrogen and 10 percent of the 40 tons of phosphorus estimated to be discharged annually to Lake Tahoe. Ground-water discharge may contribute only 2 tons of soluble iron compared to 200 tons estimated for runoff.

As implemented, this ground-water monitoring program only has begun the processes of data gathering and analysis necessary to meet objectives of the Lake Tahoe Interagency Monitoring Program. Baseline conditions of ground-water quality have been documented for ground-water sites distributed throughout the Lake Tahoe Basin. Methods of sample collection and laboratory analyses are documented and consistent, and most of the network sites are expected to be available for repeated sampling in the future and are representative for detecting longer term trends in ground-water quality. Analysis of data from this network also has identified areas with elevated concentrations of nitrogen that may indicate contamination from historical land-use practices. However, in terms of mass loading, the limitations of this monitoring network are considerable. Only a relatively few sites are distributed over the 315 mi^2 of drainage area and 71 mi of shoreline. Without accurately determined geologic boundaries, hydraulic gradients, and hydraulic conductivities, estimates of ground-water discharge are subject to considerable error. Information gathered for this program indicates that ground water has concentrations of dissolved nutrients that are greater than those of Lake Tahoe. Ground water does discharge into Lake Tahoe, but estimates of ground-water contributions to the water budget of the lake have a large range of uncertainty.

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