

Prepared in cooperation with the Bureau of Land Management

# Hydrologic and Water-Quality Responses in Shallow Ground Water Receiving Stormwater Runoff and Potential Transport of Contaminants to Lake Tahoe, California and Nevada, 2005–07

Scientific Investigations Report 2008-5162 Version 1.1, December 2008

U.S. Department of the Interior U.S. Geological Survey

**Cover:** Lake Tahoe near Sand Harbor, Nevada. (Photograph taken by Arun Pudipeddi, September 2007.)

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By Jena M. Green, Carl E. Thodal, and Toby L. Welborn

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# **Conversion Factors, Datums, and Water-Quality Abbreviations**

**Conversion Factors** 

Multiply	Ву	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m <sup>2</sup> )
square mile (mi <sup>2</sup> )	2.590	square kilometer (km <sup>2</sup> )
	Volume	
gallon (gal)	3.785	liter (L)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m <sup>3</sup> /yr)
cubic foot per day (ft <sup>3</sup> /d)	0.028	cubic meter per day (m <sup>3</sup> /d)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Hydraulic conductiv	ity
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	t
foot per foot (ft/ft)	1	meter per meter (m/m)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity*	
foot squared per day (ft <sup>2</sup> /d)	0.09290	meter squared per day (m <sup>2</sup> /d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:  $^{\circ}F = (1.8 \times ^{\circ}C) \times 22$ 

$$F = (1.8 \times C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows: °C = (°F-32)/1.8

\*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft<sup>3</sup>/d)/ft<sup>2</sup>]ft. In this report, the mathematically reduced form, foot squared per day (ft2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter ( $\mu$ g/L).

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Altitude, as used in this report, refers to distance above the vertical datum.

Water-Quality Abbreviations

Abbreviations	Definitions	
g	gram	
µg/g	microgram per gram	
µg/kg	microgram per kilogram	
µg/L	microgram per liter	
mg/L	milligram per liter	
mL	milliliter	

# Hydrologic and Water-Quality Responses in Shallow Ground Water Receiving Stormwater Runoff and Potential Transport of Contaminants to Lake Tahoe, California and Nevada, 2005–07

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# Abstract

Clarity of Lake Tahoe, California and Nevada has been decreasing due to inflows of sediment and nutrients associated with stormwater runoff. Detention basins are considered effective best management practices for mitigation of suspended sediment and nutrients associated with runoff, but effects of infiltrated stormwater on shallow ground water are not known. This report documents 2005-07 hydrogeologic conditions in a shallow aquifer and associated interactions between a stormwater-control system with nearby Lake Tahoe. Selected chemical qualities of stormwater, bottom sediment from a stormwater detention basin, ground water, and nearshore lake and interstitial water are characterized and coupled with results of a three-dimensional, finite-difference, mathematical model to evaluate responses of ground-water flow to stormwater-runoff accumulation in the stormwatercontrol system.

The results of the ground-water flow model indicate mean ground-water discharge of 256 acre feet per year, contributing 27 pounds of phosphorus and 765 pounds of nitrogen to Lake Tahoe within the modeled area. Only 0.24 percent of this volume and nutrient load is attributed to stormwater infiltration from the detention basin.

Settling of suspended nutrients and sediment, biological assimilation of dissolved nutrients, and sorption and detention of chemicals of potential concern in bottom sediment are the primary stormwater treatments achieved by the detention basins. Mean concentrations of unfiltered nitrogen and phosphorus in inflow stormwater samples compared to outflow samples show that 55 percent of nitrogen and 47 percent of phosphorus are trapped by the detention basin. Organic carbon, cadmium, copper, lead, mercury, nickel, phosphorus, and zinc in the uppermost 0.2 foot of bottom sediment from the detention basin were all at least twice as concentrated compared to sediment collected from 1.5 feet deeper. Similarly, concentrations of 28 polycyclic aromatic hydrocarbon compounds were all less than laboratory reporting limits in the deeper sediment sample, but 15 compounds were detected in the uppermost 0.2 foot of sediment. Published concentrations determined to affect benthic aquatic life also were exceeded for copper, zinc, benz[a]anthracene, phenanthrene, and pyrene in the shallow sediment sample.

Isotopic composition of water (oxygen 18/16 and hydrogen 2/1 ratios) for samples of shallow ground water, lakewater, and interstitial water from Lake Tahoe indicate the lake was well mixed with a slight ground-water signature in samples collected near the lakebed. One interstitial sample from 0.8 foot beneath the lakebed was nearly all ground water and concentrations of nitrogen and phosphorus were comparable to concentrations in shallow ground-water samples. However, ammonium represented 65 percent of filtered nitrogen in this interstitial sample, but only 10 percent of the average nitrogen in ground-water samples. Nitrate was less than reporting limits in interstitial water, compared with mean nitrate concentration of 750 micrograms per liter in ground-water samples, indicating either active dissimilative nitrate reduction to ammonium by micro-organisms or hydrolysis of organic nitrogen to ammonium with concomitant nitrate reduction. The other interstitial sample falls along a mixing line between ground water and lake water and most of the nitrogen was organic nitrogen.

# Introduction

Lake Tahoe, an approximately 191 mi<sup>2</sup> lake along the state line between western Nevada and eastern California, is a natural resource known for its deep, clear water. Protection of its renowned clarity has become important in the past half century, as clarity has been decreasing by about 1 ft each year (Goldman, 2000). Decreased clarity has been attributed to human activities that increase nutrient and sediment inputs to the lake (Goldman, 1988). In spite of numerous projects implemented to mitigate decreasing clarity, including

exportation of all waste-water effluent and erosion-control regulations, lake clarity has continued to decline (Goldman, 2000). Nutrients enter the lake from streams, atmospheric deposition, erosion of shorelines and intervening areas, and by ground-water inflow (Reuter and others, 1998; Reuter and Miller, 2000). Estimates of nutrient inputs to Lake Tahoe by ground water have been made using regionalized values of hydraulic properties coupled with averaged nutrient concentrations (Thodal, 1997; U.S. Army Corps of Engineers, 2003). Several nearshore areas of Lake Tahoe have been identified as having increased turbidity and algal production that consistently are elevated compared to the midlake. Although atmospheric deposition of nitrogen is estimated to contribute most of the nutrient loading to the lake and may be responsible for overall decline of lake clarity, nearshore clarity losses may be caused by local influences, including nutrientenriched ground-water discharge (Taylor, 2002).

Collection, detention, and infiltration of stormwater runoff in constructed basins is considered an effective best management practice (BMP) for achieving water-quality criteria related to total maximum daily load regulations (Schuster and Grismer, 2004). However, while this type of BMP may mitigate surface-water loads of suspended sediment to the lake, infiltrated stormwater in the detention basin may contaminate shallow ground water and increase ground-water gradients and flow to the lake. In addition, contaminants associated with stormwater runoff often include organic compounds and metals that potentially are toxic when consumed. Processes that affect ground-water contamination from stormwater have only just begun to be considered (Thomas and others, 2004; Prudic and others, 2005; Green, 2006), but understanding these processes is important because growing numbers of environmental improvement program projects are planned to encourage infiltration of stormwater runoff.

### Background

Past detention-basin studies have focused more on suspended-sediment reductions than nutrient reductions. Martin (1988) experimented with routing flow through a detention basin and wetlands in series and found that while suspended-sediment loads were reduced, nutrient-load reductions were variable. The efficiency rates were between 0 and 72 percent (Martin, 1988), depending on the type of nutrient, the detention basin, and wetlands. Similarly, Reuter and others (1992) routed flow through a wet meadow and found a reduction in suspended solids but little change in nutrient concentrations. Ground water underlying detention basins near Lake Tahoe may have increased water-quality degradation because much of the stormwater runoff occurs during snowmelt, when vegetation is dormant and not assimilating nutrients (Prudic and others, 2005).

#### **Purpose and Scope**

This report documents 2005–07 hydrogeologic conditions in a shallow ground-water flow system adjacent to Lake Tahoe and the effects of an engineered stormwater-control system. Descriptions of the basin-fill aquifer and a stormwater collection and control system; quantification of components of the ground-water budget; and characteristics of the quality of stormwater, bottom sediment from a stormwater detention basin, ground water, and nearshore lake and interstitial water are included. Results of a three-dimensional, finite-difference, ground-water flow model also are presented as a tool to evaluate responses of ground-water flow to stormwater runoff accumulation in the stormwater-control system.

The city of South Lake Tahoe hired 2NDNATURE, LLC, in June 2005, to "design and implement a two year datacollection program to promote a quantitative understanding of the impacts of urban surface water infiltration via stormwatertreatment systems on the quality of shallow groundwater resources" (Maggie Mathias, 2NDNATURE, LLC, written commun., September 2006), which provided the opportunity for collaboration and data sharing. Ground-water flow and seepage across the lake interface was simulated by the U.S. Geological Survey (USGS).

# Location and General Features

The study area is in the Lake Tahoe basin, along the California–Nevada state line. It coincides with a 2.91 mi<sup>2</sup> intervening area, delineated topographically as an area that is tributary to Lake Tahoe without a perennial stream draining into the lake (site 69; Jorgensen and others, 1978). The area is bounded by the drainage basins of Bijou and Heavenly Valley creeks in California, by Edgewood Creek Basin in Nevada, and by about 8,000 ft of Lake Tahoe shoreline (fig. 1). The area's land surface slopes steeply (0.46 ft/ft)from the ridge northwest of Heavenly Valley Creek to the consolidated rock-alluvium contact at 6,350 ft. Land surfaces slope more gradually (about 0.03 ft/ft) from that contact to the legally defined minimum lake stage altitude of 6,223 ft above sea level. The nearshore lakebed slopes more gradually (0.015 ft/ft) to about 0.75 mi offshore, before plunging steeply (0.11 ft/ft) to the 600 ft depth contour about 1.5 mi offshore.

Consolidated rocks in the study area are light-gray, fine- to medium-grained, well foliated granitic type rocks of Cretaceous age (about 90 million years ago; Armin and John 1983; Bonham and Burnett, 1976; Saucedo, 2005). These consolidated rocks have little porosity and generally are impermeable to ground-water flow, except where fractured or weathered. Unconsolidated basin-fill deposits are weathered mostly from consolidated granitic rocks and sorted to varying degrees by fluvial processes. During the Pleistocene Epoch,



Figure 1. Location of study area, South Lake Tahoe, California and Nevada.

#### 4 Hydraulic and Water-Quality Responses in Shallow Ground Water, Lake Tahoe, California and Nevada, 2005–07

glaciers dammed outflow from Lake Tahoe resulting in formation of lacustrine deposits of moderately to poorly sorted silt, sand, and gravel that accumulated as broad terraces 15–30 ft above current lake levels. Pleistocene beach deposits are gravelly, coarse arkosic sand that have been moderately sorted by wave action during higher lake levels. Younger (Recent Holocene) beach deposits are moderately sorted fineto very coarse-grained sand to gravelly arkosic sand coincident with modern lake levels. A small, manmade deposit of varying composition was imported for construction of the casinos and associated development along the state line. Two narrow bands of alluvium have been poorly to moderately sorted by intermittent streamflow from the area's upland areas. The distribution of these deposits is shown in <u>figure 2</u>.

The area between the lake and the consolidated-rock alluvium is urbanized (fig. 2). Development prior to about 1940 was limited to logging, agricultural, and fishing communities, and several roadhouses catering to trans-Sierra travelers and those attracted to the health and pleasure attributes of Lake Tahoe. Tourism and recreation became increasingly important to the economy of the area, especially following World War II, and most of the area's manmade impervious surfaces were originally constructed between 1940 and 1969 (C.G. Raumann, U.S. Geological Survey, written commun., 2007). Along the Highway 50 corridor within the study area are several casinos in Nevada and numerous side streets with motels, shopping complexes, and residential developments that result in increased impervious land cover and stormwater runoff. The mountainous uplands of the area are forested with residential developments, motels, and shops catering primarily to Heavenly Valley Ski Resort. The city of South Lake Tahoe incorporated in November 1965, with a population of about 14,000 (Crippen and Pavelka, 1970, p. 26). According to the 2000 U.S. Census, the population of the city of South Lake Tahoe, California, was 23,609 and Stateline, Nevada, was 1,215.

Prior to a 1970 mandate to treat and export all domestic wastewater from the Lake Tahoe Basin, disposal practices had evolved from privies and wastewater cesspools and lagoons to septic tank-leachfield systems to land application of treated municipal effluent. These practices resulted in nitrogen contamination of the regional ground-water flow system that was reported in low-flow stream samples (Perkins and others, 1975) and in ground-water monitoring results (Thodal, 1997).

#### Park Avenue Stormwater Control System

Stormwater-drainage networks in South Lake Tahoe have developed in a piecemeal fashion since rain and snowmelt were diverted from unpaved wagon trails in the early 1900s. By May 2008, an estimated 1,500 drainage inlets collect stormwater from street and parking lot gutters in the city with 15 stormwater treatment vaults and 100 outfalls to surface waters that are tributary to Lake Tahoe (City of South Lake Tahoe, 2008, p. 6-29). The Federal Water Pollution Control Act (also referred to as the Clean Water Act) was amended in 1987 to include controlling pollutants in stormwater runoff under the National Pollutant Discharge Elimination System. The U.S. Environmental Protection Agency promulgated regulation in 1990 to require separate municipal stormsewer systems serving a population of 100,000 or more to obtain stormwater permits. These regulations were amended in 1999 to require permits for stormwater discharges from small conveyance systems and from construction sites disturbing between 1 and 5 acres of land. The Lahontan Regional Water Quality Control Board adopted Order 6-92-02 in 1992 that requires stormwater permits for all municipal separate stormsewer systems (MS4s) on the California side of the Lake Tahoe basin. This permitting system provides a mechanism to work with the local municipalities to improve stormwatermanagement and maintenance practices, and requires permittees to develop comprehensive stormwater-management programs in the Lake Tahoe area (California Regional Water Quality Control Board, Lahontan Region, 2005).

Application for a stormwater permit typically requires one or more BMPs (methods that have been determined to be the most effective, practical means of preventing or reducing pollution from stormwater runoff). These practices may include behavioral BMPs such as education, structural BMPs such as source and treatment controls to treat runoff before it discharges to the storm drain or local waterways, and other practices that prevent or reduce pollutants from reaching the stormdrain or other waters (California Regional Water Quality Control Board, Lahontan Region, 2005, attachment A).

The Park Avenue stormwater control system is a BMP selected for investigation of ground water responses to infiltration of stormwater runoff. It is a structural treatment control that includes two detention basins near Park Avenue, in South Lake Tahoe, north of Highway 50 (fig. 3). The system is designed to collect runoff from a pre-existing urban stormwater-drainage network into detention basins that allow suspended sediment and associated nutrients to settle or be assimilated by vegetation, or infiltrate through soil to the shallow ground water. One detention basin (site PA1; fig. 4A) was constructed in 2000 and a second detention basin (site PA2; fig. 4B) was constructed in 2002. PA1 normally is a perennial wetland/shallow detention basin, with cattails, rushes, sedges, and duckweed (genera Typha, Juncus, Carex, and Scirpus, respectively) and a benthic periphyton community capable of assimilating biologically available nutrients. PA2 is a dry basin that receives stormwater only when inflow to PA1 exceeds the basin's capacity. Runoff from upgradient areas serviced by the stormdrain network flows into PA1 via two culverts (sites PA1 inletA and PA1 inletB; fig. 4A) and when PA1 reaches its capacity, overflows into a culvert (PA1 out) that conveys water to PA2 and into an open unlined ditch. A dam in the ditch can be operated manually to divert flow to a wet meadow in an adjacent neighborhood during excessive stormwater runoff.



Figure 2. Generalized geology of study area, South Lake Tahoe, California and Nevada.

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Figure 3. Location of data collection sites, South Lake Tahoe, California and Nevada.







**B** 

# **Methods**

Data-collection sites used for this investigation are listed and described in <u>table 1</u> and locations are shown in <u>figure 3</u>. 2NDNATURE, LLC, purchased, installed, and maintained instrumentation used to monitor water-level changes in the detention basins and selected wells, and to monitor stormwater inflow. These data are presented courtesy of 2NDNATURE, LLC.

### **Surface Water and Park Avenue Basins**

2NDNATURE, LLC, installed and maintained two recording pressure transducers and staff plates to monitor water stage in basins PA1 and PA2 and two flow-velocity meters and automated samplers (Sigma®) in two culverts (sites PA1 inletA and PA1 inletB) that convey stormwater into PA1. A third pressure transducer was installed to correct nonvented transducers for changes in barometric pressure. The transducers recorded average pressure every 30 minutes that was converted to depth of water below the measuring point; the staff plates provided a visual check of the altitude of the water surface in each detention basin. USGS used a real-time kinematic Global Positioning System to survey locations and altitudes of each transducer to convert all data to a common datum and also surveyed the bathymetry of each detention basin (fig. 4). Elevation of the surface of Lake Tahoe was obtained from the water-stage recording gage that is operated by USGS (station number 10337000) on the U.S. Coast Guard pier on the north shore of Lake Tahoe. The datum of the gage is 6,220.00 ft above Bureau of Reclamation datum, which is 6.218.86 ft above the National Geodetic Vertical Datum of 1929. Lake elevations referred to Bureau of Reclamation datum because that datum is used as the official reference point by all Federal, State, and local agencies (available at http://waterdata.usgs.gov/nwisweb/local/state/ca/ text/10337000-manu.html).

## **Ground Water**

## Well Construction

Seven observation wells were installed during October and November 2005 to characterize local aquifer hydraulic properties, monitor ground-water levels, and to sample ground water (fig. 4). The wells also were used to evaluate responses of local ground water to infiltration of stormwater that accumulated in detention basins (PA1 and PA2). Boreholes used for well installation were drilled using a trailer-mounted hollow-stem auger that produced a borehole diameter of about 6.6 in. Wells were installed in boreholes drilled to depths of 14–30 ft below land surface and constructed of flushthread, 2-in. nominal diameter ASTM 480-88A, schedule 40 polyvinyl chloride well casing, screens, and end points. Well screens (5 ft long with 0.020 in. factory slots) were positioned below the water table and surrounded with clean, coarse (#6) aquarium gravel. Clean, fine (#12) sand was used to fill the borehole to about 1 ft above the water table and high-swelling 100 percent pure sodium bentonite (certified by the National Sanitation Foundation, International, to meet ANSI/NSF Standard 60; Drinking Water Treatment Chemicals–Health Effects) was emplaced from the top of the fine sand to 2 ft beneath land surface to provide a sanitary seal. The top of well casings extend about 3 ft above land surface to avoid inflow of surface water and a 0.3 ft by 0.3 ft locking well protector was cemented into the remaining 2 ft of annulus and the finish hand-troweled so that surface water drains away.

In addition to the seven wells constructed in 2005, 2NDNATURE had contracted construction of four observation wells in August 2003 for an earlier project. These wells were used to monitor water levels and ground-water quality for this investigation. Domestic wells and wells not included in the real-time-kinematic survey were located with a hand-held Global Positioning System and altitudes were determined with a laser level (table 1).

# **Aquifer Characteristics**

Hydraulic conductivity near the Park Avenue detention basins ranged from 0.3 to 20 ft/d for sandy clay and medium sand (<u>table 2</u>). Hydraulic conductivity was estimated from the results of slug tests in eight wells that were analyzed with the method described by Bouwer and Rice (1976). Results from these slug tests constrained ground-water velocity estimates utilized in the ground-water flow model, which control transport and travel times of nutrients.

# Sub-Littoral Ground-Water Discharge to Lake Tahoe

Water exchange between Lake Tahoe and the adjacent aquifer system is controlled by the hydraulic gradient and permeability of the lakebed and aquifer material. Lakebed permeability is variable due to fluvial processing of deltaic sediments and texture of basin-fill deposits, wave sorting of beach deposits, and the mineralogy of parent rock (which controls the size and uniformity of sediment grains resulting from weathering). The hydraulic gradient controls the direction of ground-water exchange between lake and aquifer, and the energy available to move water through variably permeable deposits. Lake Tahoe receives most of its inflow as snowmelt runoff and is managed as a storage reservoir, such that the hydraulic gradient may be subject to artificial variability and possible gradient reversals (Winter and others, 1998, p. 18).

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**Table 1.** Information regarding data-collection sites used to investigate responses of shallow ground water receiving stormwater runoff from Park Avenue stormwater control system, South Lake Tahoe, California, 2005–07.

[Site locations are shown in figure 3 and 4. Site designations: The local identification is based on the rectangular subdivision of the public lands referenced to the Mount Diablo base line and meridian. Each number consists of three units. The first is the township, preceded by N to indicate location north of the base line. The second unit is the range, preceded by E to indicated location east of the meridian. The third unit consists of the section number and letter designating which is a unique number based on grid system of latitude and longitude of the site. For wells MW194-MW202, which are located in California, wells are numbered according to their location in the rectangular system for subdivision of public lands. Identification consists of the township number, north or south (N or S); the range number, east or west (E or W); and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O) beginning with "A" in the northeast corner of the section and progressing in a sinusoidal manner to "R" in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The standard identification consists of 15 digits: First six denote degrees, minutes, and seconds of longitude; and last two digits (assigned sequentially) identify sites within 1-second grid. If more precise latitude and longitude subsequently are determined, initial site-identification number is retained. The eight-digit numbers are station numbers that follow the "downstream-order system": The first two digits, or part number, refer to the regional drainage basin (Part 10 is Great Basin). The following six digits are the downstream-order number, which is assigned according to the geographic location of the site in the drainage basin; larger numbers stations are downstream from the smaller number stations. Land-surface altitude: Vertical accuracy ±1.97 inches. Site type: SWI, stormwater inflow; DBG, detention basin gage; SWO, stormwater outflow; OBS

Site No.	Site designations		Land-surface altitude	Cite town	Depth of well
Sile No.	Local identification	Standard identification	(feet above sea level)	Site type	land surface)
		Detention basin sites			
PA1_inletA	NA	385720119565301	6,239.0	SWI	NA
PA1_inletB	NA	385719119565401	6,233.4	SWI	NA
PA1_stage	NA	385721119565401	6,232.2	DBG	NA
PA1_out	NA	385721119565501	6,237.1	SWO	NA
PA2_stage	NA	385725119565401	6,229.2	DBG	NA
		Well sites			
MW194	13N18E34B-01	385715119562901	6,306.4	OBS	30.4
MW196	13N18E27P-04	385719119565302	6,242.1	OBS	19.5
MW197	13N18E27P-05	385719119565301	6,243.7	OBS	28.4
MW198A	13N18E34P-07	385719119565601	6,240.6	OBS	14.4
MW198B	13N18E27P-09	385720119565602	6,240.4	OBS	23.9
MW199A	13N18E27P-06	385720119565501	6,240.7	OBS	15.2
MW199B	13N18E27P-08	385720119565603	6,240.9	OBS	24.6
MW200	13N18E27P-10	385720119565502	6,238.1	OBS	18.0
MW201A	13N18E27P-11	385725119565401	6,242.2	OBS	13.0
MW201B	13N18E27P-12	385725119565402	6,242.0	OBS	23.0
MW202	13N18E27P-13	385726119565401	6,241.9	OBS	13.0
MWB1	NA	385709119571801	6,233.2	OBS	24.0
MWB3	NA	385703119571901	6,233.6	OBS	24.5
MWB4	NA	385703119571902	6,233.5	OBS	9.8
MEADOW	NA	385733119565401	6,230.6	DOM	26.3
AZURE	NA	385704119571901	6,232.5	DOM	18.1
BEACH	NA	385717119571501	6,230.4	DOM	95.0
MT JOY	NA	385703119572201	6,230.4	DOM	NA
NWIS5001	NA	385756119565001	6,230	OBS	6
NWIS5701	N13 E18 27BDA 1	385742119565701	6,245	OBS	23
NWIS3401	NA	385736119563401	6,276.7	DOM	116
NWIS5601	NA	385705119565601	6,250	DOM	58
NWIS1001	NA	385658119571001	6,235	OBS	8
NWIS1401	NA	385654119571401	6,240	DOM	77
		Lake Tahoe sites			
L1	NA	10337000	NA	LAKE	NA
L2	NA	10337000	NA	LAKE	NA
L3	NA	10337000	NA	LAKE	NA
L4	NA	10337000	NA	LAKE	NA
L5	NA	10337000	NA	LAKE	NA

 Table 2.
 Estimated results of monitoring well slug tests near Park Avenue stormwater control system, South Lake Tahoe,

 California.
 California.

Site No.	Date of test	Initial water-level altitude	Aquifer material at	Mean displacement	Number of	Hydraulic (	conductivity ft/d)
		(ft)		(ft)	10313	Mean	Range
MW-194	06-07-06	6,292.2	Sandy clay	1.82	2	0.9	0.9–0.9
MW-196	06-06-06	6,231.7	Medium sand	1.67	2	0.3	0.3-0.4
MW-197	06-06-06	6,239.0	Medium sand	1.74	3	4	2-5
MW-198A	06-07-06	6,231.1	Medium sand	1.80	2	0.8	0.6-1
MW-198B	06-07-06	6,230.9	Medium sand	1.55	2	7	2-20
MW-199A	06-07-06	6,230.9	Medium sand	0.90	3	20	20
MW-199B	06-07-06	6,230.9	Medium sand	1.99	2	3	2–3
MW-201B	06-06-06	6,230.2	Medium sand	1.05	4	8	6–10

Sites are shown in	figure 3.	Abbreviations:	ft, foot;	ft/d,	foot per	day]
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Estimates of ground-water discharge to Lake Tahoe have been made using regionalized values of onshore aquifer hydraulic properties. The mass of nutrients transported to the lake with ground water was estimated by coupling groundwater volume with averaged nutrient concentrations (U.S. Army Corps of Engineers, 2003; Thodal, 1997). Growing acceptance that ground water is a significant variable to consider in water and nutrient budgets of surface water (Winter and others, 1998; Brock and others, 1982) has led to the development of a variety of novel hydrological tools used to quantify and corroborate the connection between lakes and ground-water systems (Schuster and others, 2003).

## Water-Quality Sampling Procedures and Analytical Methods

A total of 95 ground-water and 37 stormwater samples were collected following procedures described in USGS National Field Manual for the Collection of Water-Quality Data (variously dated). The collection of samples were made prior to and during snowmelt runoff (November 2005-May 2006 and December 2006-April 2007) and sent to High Sierra Water Laboratory in Truckee, California, for determination of nutrients (Kjeldahl nitrogen; ammonium; nitrate plus nitrite, phosphorus and soluble reactive phosphate; American Public Health Association, 1998; Solorzano, 1969; Liddicoat and others, 1975; Woodworth and Conner, 2003). Ground-water samples were collected after well purging by using a bailer dedicated to each observation well or a portable submersible pump. Subsamples were filtered through a 0.45-µm mixed cellulose ester membrane for laboratory analyses. Unfiltered stormwater samples were collected by the open-mouth bottle method with subsamples filtered through a 0.45-µm mixed cellulose ester membrane for determination of ammonium, nitrate plus nitrite, and orthophosphate-phosphorus. Concentrations of organic nitrogen and hydrolysable

phosphorus were estimated by subtracting laboratory values of ammonium-nitrogen from Kjeldahl-nitrogen, and orthophosphate-phosphorus from phosphorus, respectively. In addition, ground-water samples were collected in February 2006 for field determination of filtered concentrations of bicarbonate and alkalinity (Rounds, 2006) and laboratory determination of stable isotope ratios of oxygen and hydrogen (Epstein and Mayeda, 1953; Coplen and others, 1991; Coplen, 1994) and filtered concentrations of organic carbon (Brenton and Arnett, 1993), major ions, silica, chromium, copper, iron, lead, nickel, and zinc (Fishman and Friedman, 1989; Fishman, 1993). Isotope samples were shipped to the USGS Reston Stable Isotope Laboratory in Reston, Virginia and other samples were shipped to the USGS National Water Quality Laboratory in Lakewood, Colorado.

Ten samples of lake and interstitial water also were collected from five locations along the shoreline of Lake Tahoe (fig. 3). A multiparameter meter was used to measure temperature, pH, specific conductance, and dissolved oxygen of the lakewater prior to sample collection. Lakewater samples were collected from 1 ft beneath the water surface and from the water-lakebed interface using 0.25-in. diameter polyethylene tubing and a 60 mL syringe at a rate of 30 mL/ min. Interstitial water was collected by pushing a 0.5-in. diameter minipeizometer 0.8 ft beneath the lakebed and withdrawing water through 0.25-in. diameter tubing and a 60 mL syringe at 30 mL/min. Unfiltered water was collected for stable isotope analysis (Epstein and Mayeda, 1953; Coplen and others, 1991; Coplen, 1994). Subsamples were passed through 0.45-µm Supor® syringe filters into 125-mL opaque polyethylene bottles and chilled on ice for overnight shipment for nutrient analyses by the USGS National Water Quality Laboratory (Fishman, 1993; Patton and Kryskalla, 2003). Laboratory reporting levels of each analyte are listed in table 3. All water-quality data are listed in appendix A (at back of report).

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#### Table 3. Constituents determined in water and sediment samples and laboratory reporting levels.

[Values are ratios mathematically related to comparable ratios for an international standard. Abbreviations:  $\delta$ , delta; NA, not applicable]

Laboratory Constituent reporting level		Constituent	Laboratory reporting level	
Calcium <sup>1, 2</sup>	<sup>3</sup> 0.02; <sup>4</sup> 0.005	Nitrate+nitrite <sup>1</sup>	51	
Chloride <sup>1</sup>	<sup>3</sup> 0.2	Arsenic <sup>2</sup>	60.1	
Fluoride <sup>1</sup>	<sup>3</sup> 0.1	Bismuth <sup>2</sup>	61	
Magnesium <sup>1, 2</sup>	<sup>3</sup> 0.008; <sup>4</sup> 0.005	Cerium <sup>2</sup>	61	
Potassium <sup>1, 2</sup>	<sup>3</sup> 0.16; <sup>4</sup> 0.005	Europium <sup>2</sup>	61	
Dissolved solids <sup>1</sup>	<sup>3</sup> 10	Gallium <sup>2</sup>	61	
Sodium <sup>1, 2</sup>	<sup>3</sup> 0.2; <sup>4</sup> 0.005	Gold <sup>2</sup>	<sup>6</sup> 1	
Sulfate <sup>1</sup>	<sup>3</sup> 0.18	Iron <sup>2</sup>	<sup>6</sup> 1	
Aluminum <sup>2</sup>	40.005	Lanthanum <sup>2</sup>	61	
Antimony <sup>2</sup>	<sup>6</sup> 0.1	Lithium <sup>2</sup>	61	
Barium <sup>2</sup>	<sup>6</sup> 1	Mercury <sup>2</sup>	60.02	
Beryllium <sup>2</sup>	<sup>6</sup> 0.1	Neodymium <sup>2</sup>	61	
Cadmium <sup>2</sup>	<sup>6</sup> 1	Niobium <sup>2</sup>	<sup>6</sup> 4	
Chromium <sup>2</sup>	<sup>6</sup> 1	Scandium <sup>2</sup>	<sup>6</sup> 2	
Cobalt <sup>2</sup>	<sup>6</sup> 1	Selenium <sup>2</sup>	60.1	
Copper <sup>2</sup>	<sup>6</sup> 1	Strontium <sup>2</sup>	<sup>6</sup> 22	
Lead <sup>2</sup>	<sup>6</sup> 1	Sulfur <sup>2</sup>	60.05	
Manganese <sup>1, 2</sup>	<sup>6</sup> 4	Tantalum <sup>2</sup>	<sup>6</sup> 1	
Molybdenum <sup>2</sup>	<sup>6</sup> 0.5	Thallium <sup>2</sup>	<sup>6</sup> 1	
Nickel <sup>2</sup>	<sup>6</sup> 2	Thorium <sup>2</sup>	<sup>6</sup> 1	
Silver <sup>2</sup>	<sup>6</sup> 0.1	Tin <sup>2</sup>	<sup>6</sup> 1	
Uranium <sup>2</sup>	0.1	Titanium <sup>2</sup>	60.005	
Zinc <sup>2</sup>	<sup>6</sup> 2	Vanadium <sup>2</sup>	<sup>6</sup> 2	
Organic carbon <sup>1, 2</sup>	<sup>3</sup> 0.33; <sup>4</sup> 0.01	Ytterbium <sup>2</sup>	<sup>6</sup> 1	
Inorganic carbon <sup>2</sup>	40.01	Yttrium <sup>2</sup>	<sup>6</sup> 2	
Phosphorus <sup>1, 2</sup>	<sup>5</sup> 2; <sup>4</sup> 0.005	$\delta$ deuterium <sup>1</sup>	NA	
Orthophosphate <sup>1</sup>	<sup>5</sup> 1	$\delta$ oxygen-18 <sup>1</sup>	NA	
Kjeldahl nitrogen <sup>1</sup>	<sup>5</sup> 35			
Ammonium <sup>1</sup>	51			

<sup>1</sup>Constituent determined in water samples.

<sup>2</sup>Determined in sediment samples.

<sup>3</sup>Reporting level in milligrams per liter.

<sup>4</sup>Reporting level in percent.

<sup>5</sup>Reporting level in micrograms per liter.

6Reporting level in micrograms per gram.

### **Collection of Bottom-Sediment Samples**

Two bottom-sediment samples were collected from site PA1 (fig. 4*A*) on August 31, 2005, using a 2-ft split-spoon sampler with polyethylene core liner and soft-fingered core catcher. The sampler was driven 2 ft into the sediment about 20 ft from the PA1\_inletA. The resulting core was extruded into two glass bowls for processing. One bowl included the uppermost 0.2 ft (0–0.2 ft) of dark grey sediment and the other bowl contained 0.2 ft of brown-orange sediment from

1.5–1.7 ft beneath the sediment surface. Each sample was homogenized thoroughly with a Teflon policeman and about 100 g was transferred into 1-L widemouth glass jars that had been baked to 450°C. These samples were placed in an ice chest and shipped overnight to the USGS National Water Quality Laboratory for determination of selected polycyclic aromatic hydrocarbon compounds (table 4) following analytical procedures described by Arbogast (1996), Hageman (2007), Taggart (2002), and Briggs and Meier (1999). **Table 4.** Polycyclic aromatic hydrocarbon compoundsdetermined in bottom-sediment samples collected fromstormwater control basin, site PA1, South Lake Tahoe, California,and laboratory reporting levels.

[Laboratory reporting level in micrograms per kilogram]

Compound	Laboratory reporting level	
Acenaphthene	10	
Acenaphthylene	10	
Anthracene	10	
Benz[a]anthracene	10	
Benz[a]pyrene	10	
Benzo[b]fluoranthene	10	
Benzo[e]pyrene	10	
Benzo[g,h,i]perylene	10	
Benzo[k]fluoranthene	10	
Chrysene	10	
Dibenz[a,h]anthracene	10	
1,2-Dimethylnaphthalene	10	
1,6-Dimethylnaphthalene	10	
2,6-Dimethylnaphthalene	10	
2-Ethylnaphthalene	10	
Fluoranthene	10	
Fluorene	10	
Indeno[1,2,3-cd]pyrene	10	
2-Methylanthracene	10	
1-Methyl-9H-fluorene	10	
1-Methylphenanthrene	10	
1-Methylpyrene	10	
Naphthalene	10	
Perylene	10	
Phenanthrene	10	
Pyrene	10	
2,3,6-Trimethylnaphthalene	10	

The sediment remaining in each bowl was sieved through precleaned 62.5- $\mu$ m nylon mesh using a Teflon policeman and native water. About 10 g of the resulting fine-grained fraction was placed in 500-mL polypropylene widemouth jars and shipped to the USGS Branch of Geochemistry Laboratory in Lakewood, Colorado, for determination of selected metals, and inorganic and organic carbon (table 4), following analytical methods describe by Olson and others (2004). Laboratory reporting levels of each analyte are listed in tables 3 and 4. All bottom-sediment quality data are listed in appendix B (at back of report).

# **Simulation of Ground-Water Flow**

The effects of an engineered stormwater-control system on shallow ground-water flow adjacent to Lake Tahoe were simulated using a three-dimensional, finite-difference, ground-water flow model (hereafter referred to as the model). Included are descriptions of the basin-fill aquifer and quantification of components of the ground-water budget. Model results are presented as a tool to evaluate responses of ground-water flow to stormwater-runoff accumulation in the stormwater-control system. The model simulated groundwater flow and seepage across the lake interface.

### Flow Model Description

Ground-water flow through the basin-fill aquifer beneath the study area was simulated using MODFLOW, a threedimensional, numerical (finite-difference) ground-water flow model (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). The model area was discretized into a grid of 23,925 rectangular model cells in 165 rows and 145 columns areally and 6 layers vertically. Each model cell was about 66 ft wide in the row and column dimensions and had variable thickness. The model grid was rotated 25 degrees clockwise about row 83 and column 73 (UTM NAD 1983, zone 10N 763,855.52, 4,316,204.58 meters) so that the major axes were parallel to the general direction of ground-water flow, which generally is toward the lake in the model domain. Rotation of the grid caused 43 percent of the cells to fall outside the area of interest; therefore these cells were inactive. The top of layer 1 represented land surface and covered about 2.1 mi<sup>2</sup>. The southeast boundary extended upgradient to where bedrock is quite shallow, generally along the 6,350-ft topographic line. A sharp dropoff of the lake bottom served as the submerged northwest boundary (fig. 5).

Aquifer thickness generally is very thin near the upgradient southeast boundary and thickens toward and under the lake (fig. 6). Total aquifer thickness along the upgradient boundary mostly is less than 50 ft, while along the northwest boundary beneath Lake Tahoe, it is nearly 1,500 ft thick (Eric LaBolle, University of California, Davis, written commun., 2006).



Figure 5. Layer 1 boundary conditions in steady-state ground-water flow model, South Lake Tahoe, California and Nevada.



**Figure 6.** Cross section of the modeled area along row 71, South Lake Tahoe, California and Nevada. Location of cross section is shown in <u>figure 5</u>.

The model objective was to understand movement of shallow ground water; therefore a finer discretization was used in the upper 50 ft of the model domain (fig. 6). Model layer thicknesses in layers 1–5 were designed to keep uniform thickness throughout each individual layer. Layer 1 was a constant 5 ft thick, while layer 2 was a constant 10 ft thick. Layers 3–5 were each a constant 15, 10, and 10 ft thick, respectively. Layer 6 varies in thickness from the bottom of layer 5 to bedrock. The large and varying thickness of layer 6 is assumed to have no effect on the simulation of shallow ground-water movement, although it likely stores a large quantity of ground water. Discontinuous lacustrine units typically are less than 20 ft in thickness and likely are reworked by meandering streams; therefore a continuous confining unit was not simulated in this model.

### **Boundary Conditions**

Shallow ground-water flow was simulated as a steadystate flow system. Annual Lake Tahoe stage fluctuations will have a time-varying effect on nutrient loads discharged by ground water, although in evaluating the suitability of a detention basin as a BMP, long term loading is more of a concern. Therefore, modeling the transient ground-water system as a steady-state flow system is considered sufficient for the model objectives.

Various boundary conditions were used across the model (fig. 5). All interior model cells exposed to Lake Tahoe in the northwest were simulated using a constant-head boundary of 6,225 ft, which is the average stage of Lake Tahoe over the study period. The southern Park Avenue detention basin (PA1),

which contained standing water throughout the study, also was simulated using a constant-head boundary in six contiguous cells. A network of stormwater drainage ditches and sewers scattered across South Lake Tahoe were simulated using drains (Jim Marino, city of South Lake Tahoe, written commun., 2006). These drains were placed 5 ft below land surface. In this way, if the simulated ground-water surface came within 5 ft of land surface, ground water would discharge to the stormwater ditches and flow directly to Lake Tahoe.

Recharge was applied to the onshore modeled area by areal recharge and mountain-front recharge from watersheds upgradient of the study area. Areal recharge, for the purposes of this model, was defined as precipitation that passes beneath the root zone and crosses the water table. All layer 1 onshore pervious model cells or those cells simulated as not being impervious due to urbanization (about 62 percent of all active layer 1 cells; Raumann, 2007) received areal recharge. The volume of areal recharge was estimated during model calibration and constrained by local precipitation and evapotranspiration estimates.

Mountain-front recharge was defined as surface runoff from contributing watersheds that flows over bedrock and infiltrates at the bedrock-alluvium contact. Mountain-front recharge was applied to all cells along the southeast domain boundary, as well as to two adjacent zones that extend northwest from the mountain front (fig. 5). The two larger zones represent small drainages where coarser grained material is present (Rogers, 1974); therefore, mountain-front recharge naturally is greater in these locations (fig. 7). The volume of annual precipitation averaged 4,400 acre-ft in the watersheds upgradient of the model area between 1971 and 2000 (Flint and Flint, 2007). Results from Flint and Flint indicated that of the total precipitation about 2 percent becomes in-place recharge, 54 percent is consumed by evapotranspiration, and the remaining 44 percent is attributed to potential runoff. The percentage of the potential runoff that actually becomes mountain-front recharge was estimated during model calibration.

No-flow boundary conditions were used in several locations in the model (fig. 5). Bedrock underlies all of layer 6 and represents a no-flow boundary. Model boundaries to the northeast and southwest were aligned along hydrologic basin boundaries (Cartier and others, 1995) and therefore were represented as no-flow boundaries.

### **Model Calibration**

Calibration is the attempt to reduce the difference between model results and measured data by adjusting model parameters. The improvement of the calibration is based on minimizing the differences between simulated and measured ground-water levels. The discrepancy between model results and measurements (known as the residual) commonly is, in part, the cumulative result of simplification of the natural system by the conceptual model, the model grid, and the scarcity of sufficient data to account for the spatial variation in hydraulic properties and recharge throughout the study area.

Uniform hydraulic conductivity distributions were assigned throughout all model layers because of limited hydraulic information. Calibration was constrained by assuming the transmissivity of the alluvial aquifer was known from a pump test completed in wells near the Park Avenue detention basins. Transmissivity is equal to the hydraulic conductivity of aquifer materials, multiplied by the aquifer thickness. The pump test completed by the South Tahoe Public Utility District yielded transmissivity estimates of 1,800 ft<sup>2</sup>/d (fig. 5; Bergsohn, 2000). Horizontal hydraulic conductivity was 2 ft/d and was not estimated during model calibration. This resulted in a transmissivity estimate of 2,000 ft<sup>2</sup>/d near the Lake Tahoe shoreline, where the aquifer has a thickness of about 1,000 ft (fig. 6). This is reasonable as it falls into the 0.3-20 ft/d range of values (median value of 3 ft/d) estimated from slug tests (table 2). Discontinuous lacustrine units were assumed to be distributed uniformly throughout the aquifer and were simulated in the average vertical hydraulic conductivity. Vertical hydraulic conductivity was assumed to be lower in the six cells between layers 1 and 2 beneath PA1 because of sediment compaction during basin construction. Vertical hydraulic conductivities were estimated during model calibration.

The ground-water flow model was calibrated to average water-level measurements in 18 wells. The following weighted (w)i, sum-of-squares (SS) objective function was minimized during calibration,

$$SS = \sum_{i=1}^{nwl} (\hat{h}_i - h_i)^2 w_i , \qquad (1)$$

where

h is simulated water levels, in feet;  $h_i$  is measured water levels, in feet; and nwl is the number of water level measurement:

Note: The root-mean-square (RMS) error is reported instead because RMS error is more directly comparable to actual values and serves as a composite of the average and the standard deviation of a set. RMS error is related to SS error by

$$RMS = \sqrt{\frac{SS}{\sum_{i=1}^{nwl} w_i}} \quad . \tag{2}$$



Figure 7. Upgradient watersheds used to calculate mountain-front recharge, South Lake Tahoe, California and Nevada.

Model calibration was further facilitated by parameter estimation. Estimated parameters included (1) the volume of potential runoff generated in the watersheds adjacent to the modeled area that becomes mountain-front recharge along the southeast boundary, (2) the volume of areal recharge distributed homogeneously to pervious model cells, (3) the vertical hydraulic conductivity in the area surrounding the Park Avenue detention basins, (4) the vertical hydraulic conductivity of the remaining aquifer, and (5) stormdrain conductance.

Each parameter was changed a small amount and MODFLOW was used to compute new water levels for each perturbed parameter. As a secondary calibration procedure, recharge rates were bracketed within 200 and 450 acre-ft/yr (Flint and Flint, 2007). Vertical hydraulic conductivity near Park Avenue detention basins, also was given an upper limit lower than that of estimates at Cattlemans detention basin of 0.027 ft/d because PA1 remains wet year round, whereas Cattlemans is dry for many months per year (Green, 2006). An iterative process was followed by estimating parameters, running revised models using the estimated parameters, and calculating new water levels until the objective function change was minimize and could not be improved.

#### **Model Results**

The final calibrated model was the best fit possible of the observed water levels given the parameter constraints described above. Simulated water levels representative of conditions from 2005 to 2007 approximated the 18 measured water levels in the modeled area (fig. 8). Fourteen shallow wells were screened within layers 1 and 2 (within 15 ft below the water table) and 4 deep wells were screened within layer 3 (between 15 and 30 ft below the water table). However, simulated water levels did not exactly reproduce all measured water levels in all wells. Figure 9 shows the simulated waterlevel contours and monitoring well residuals. Measured water levels in a cluster of wells within about 300 ft of each other in the south-central part of the model (wells B-3, B-4, Beach, and Azure) ranged about 1.5 ft. The flow model assumes homogeneous aquifer properties and therefore was not able to simulate such a span of water levels in close proximity to each other. Simulated water levels near model boundaries may be less reliable than simulated water levels that are distant from boundaries. Boundary effects are most notable when there are nearby stresses. For instance, detention basin PA1 was simulated with a constant-head boundary of 6,234 ft.



**Figure 8.** Measured water levels compared with model-simulated water levels, South Lake Tahoe, California and Nevada.



**Figure 9.** Calibrated model simulated water-level contours, monitoring well residuals (simulated-average observed values), and simulated annual ground-water discharge to South Lake Tahoe, California and Nevada.

Observed water levels in wells upgradient and downgradient of PA1, however, were 4–5 ft lower than this level. Therefore, the model was not able to simulate accurately such a localized field condition. During the construction of PA1, sediment possibly was compacted in the basin, resulting in stormwater inflow being semiperched above the regional water table. Small drains discharging water in the south-central part of the model near wells B-1 and NWIS5601 also affected the accurate calibration of water-level contours. Average measured water levels in these wells differed by 10.5 ft, and therefore had rather large simulated residuals. The final calibrated model produced a RMS error of 2.55 ft.

The final calibrated values for model parameters are listed in table 5, and components of the water budget are shown in figure 10. Total mountain-front recharge was estimated as 306 acre-ft/yr. This value is comprised of 2 percent of precipitation as in-place recharge as computed by the Basin Characterization Model of Flint and Flint (2007) and a calibrated value of 16 percent of runoff becoming recharge. These values are within the bounds present by Flint and Flint (2007). Areal recharge was estimated quite low at about 5 acre-ft/yr and recharge from detention basin PA1 was about 1 acre-ft/yr. Drains used to simulate storm ditches were estimated to discharge about 56 acre-ft/yr, allowing ground water to exit the subsurface and discharge to the lake. Direct ground water discharge from the study area to Lake Tahoe was 256 acre-ft/yr. About 75 percent of ground-water discharge to Lake Tahoe occurs from layer 1. The distribution is shown in figure 10.

### **Model Sensitivity**

To determine how model parameters affected simulation results, all estimated parameters were varied independently from 0.2 to 5 times their calibrated value. This range was greater than the uncertainties associated with the parameters, but provided a more complete perspective on model sensitivity. Model sensitivity was described in terms of the RMS error. The sensitivity of model results to changing one parameter while all others are held at their calibrated values is shown in <u>figure 11</u>. Residuals were determined to be more sensitive to changes in mountain-front recharge, especially through the course-grained channel to the northeast than to any other model parameters. Model results were rather insensitive to storm-drain conductance and vertical hydraulic conductivity of the detention basin and the rest of the model.

Model sensitivity to specified boundary conditions and hydraulic properties was further investigated with four alternative models. Alternative models included increasing the stage of Lake Tahoe within the constant-head boundary to 6,229 ft (historical high watermark), lowering it to 6,223 ft (altitude of lake outlet at Tahoe City Dam), incorporating a clay layer into the hydrogeology, and increasing the model horizontal hydraulic conductivity from 2 to 4 ft/d. The continuous clay layer was simulated in the model by reducing the horizontal hydraulic conductivity of only layer 3 to 0.001 ft/d. Each alternative model was calibrated after changing the selected boundary conditions and hydraulic properties. Results of these alternative models are listed in <u>table 5</u>.

 Table 5.
 Model parameters and their calibrated values, in order of sensitivity for original model, South Lake Tahoe, California and Nevada.

[Abbreviations: acre-ft/yr, acre-foot per year; ft/d, foot per day; ft, foot]

	Model run parameter estimates					
Parameter name	Original	Lower stage	Raised stage	Clay layer present	Horizontal hydraulic conductivity (4 ft/d)	
Mountain-front recharge (acre-ft/yr)	306	322	205	278	495	
Channel recharge (acre-ft/yr)	160	163	177	137	338	
Mountain-length recharge (acre-ft/yr)	146	159	28	141	157	
Basin vertical hydraulic conductivity (ft/d)	0.0024	0.0024	0.0024	0.0024	0.0024	
Areal recharge (acre-ft/yr)	5	5	5	5	5	
Aquifer vertical hydraulic conductivity (ft/d)	0.33	0.32	0.98	0.33	0.36	
Storm-drain discharge (acre-ft/yr)	56	39	94	48	80	
Discharge to Lake Tahoe (acre-ft/yr)	256	289	116	236	421	
Model root mean square error (RMS) (ft)	2.55	2.67	1.31	2.64	2.54	



Figure 10. Estimated ground-water budget for model area, South Lake Tahoe, California and Nevada.

Computed RMS error of the four alternative models varied by about 1.4 ft. Raising the stage of Lake Tahoe had the greatest effect on the model error by reducing it by about 1.2 ft. As expected, discharge to Lake Tahoe was reduced when the stage of Lake Tahoe was increased because it has a direct effect on the hydraulic gradient within the model. In response to a shallower gradient, the mountain-front recharge was decreased within the calibration process to allow ground-water levels in the aquifer to approach their observed elevations. Model error was insensitive to simulations of (1) lowering the stage of Lake Tahoe, (2) layer 3 representing a continuous clay layer, and (3) increasing the horizontal hydraulic conductivity to 4 ft/d.

### **Model and Data Limitations**

The flow model reasonably describes local ground-water flow near the Park Avenue detention basins, but it cannot mimic exactly the true ground-water flow system. Simulated values often are similar to, but do not match precisely with the measured values. The ground-water flow model is a numerical approximation of the flow system, and is limited by simplifications in the conceptual model, discretization effects, and the scarcity of measurements to account for the spatial variation in hydraulic properties throughout the study area.

Inherent in the conceptual model is the assumption that all sources of flow and stresses on the natural system are represented in the numerical model. Because measurements of water levels used to constrain the model calibration were made over a short time period, it is not known how completely or how accurately the numerical model simulates the natural system, especially under steady-state conditions.

Areal discretization of the study area into a rectangular grid of cells and vertical discretization into layers required averaging of hydraulic properties. Each model cell represents an averaged block of the aquifer system. Due to this averaging, the model cannot simulate the local effects on flow caused by aquifer heterogeneity. Further simplification of the heterogeneous aquifer system occurred in the methods used to describe the distribution of the hydraulic conductivity. The lack of sufficient measurements to account for the spatial variations in hydraulic properties necessitated the uniform



Figure 11. Relative sensitivity of model parameters.

assignment of horizontal hydraulic conductivity across the study area. Simplifying the model to this degree does not invalidate the model results, but should be considered when interpreting the results.

The reliability of ground-water flow models is affected by the choice and accurate representation of the aquifer and related boundary conditions. For purposes of simplification, the upper model boundary (land surface) was simulated as a confined system. The variations in transmissivity with respect to water-level change were trivial and limited error was introduced as a result of this simplification. A one-toone correlation does exist between uncertainties of assigning transmissivity and estimating recharge. For example, a lower hydraulic conductivity, which yields a lower transmissivity, does not require as much water for simulated heads to approach measured heads. In turn, a lower recharge is estimated. Measured water levels in a well cluster in the southern part of the model varied about 2.9 ft; therefore the model, assuming homogeneous aquifer properties, was not able to accommodate such a span of water levels in close proximity to each other. Simulated water levels near model boundaries may be less reliable than simulated water levels that are distant from boundaries. Boundary effects are most notable when there are nearby stresses. For instance, PA1 was simulated with a constant-head boundary of 6,234 ft and observed water levels, upgradient and downgradient, were 4–5 ft below that of PA1. Therefore, the model was not able to simulate such a localized field condition. During the construction of PA1, sediments possibly were compacted and resulted in stormwater inflow being semiperched on a less conductive area of aquifer.

# Water Quality in and Near Park Avenue Stormwater Control System

Median values of pH, specific conductance, dissolved oxygen, and temperature in ground water were 6.4 standard pH units, 450 µS/cm, 3.2 mg/L (34 percent saturation), and 9°C, respectively. Concentrations of dissolved solids in water samples collected from seven observation wells ranged from 150 mg/L for site MW194 to 390 mg/L for site MW197 and the average concentration was 300 mg/L (figs. 3 and 4A). Concentrations of major ions indicate that upgradient ground water tapped by MW194 is mixed cation (dominated by calcium) bicarbonate type water. Downgradient samples from wells near detention basin PA1 (wells MW196-MW200) have evolved to mixed cation (sodium and calcium)/mixed anion (mostly dominated by chloride) type water (Piper and others, 1953). This evolution is most likely due to the chemistry of recharged stormwater runoff that may be contaminated by deicing road and sidewalk treatments and residual leachate from abandoned septic-tank systems mixing with regional ground water. Decreased concentrations of dissolved oxygen and sulfate in ground-water samples collected downgradient of PA1 may be the result of activity of sulfate-reducing bacteria.

## **Nutrient Chemistry**

Concentrations of filtered nitrogen were generally largest in ground-water samples collected upgradient of the stormwater control system compared to unfiltered samples of stormwater and filtered ground-water samples collected downgradient of the stormwater control system (fig. 12*A*). In contrast, concentrations of filtered phosphorus were generally smallest in ground-water samples collected upgradient of the stormwater control system and largest in stormwater (fig. 12*B*). The maximum concentration of filtered phosphorus was measured in ground water collected downgradient of the stormwater control system (site MW199A; 420 µg/L).

Maximum concentrations of unfiltered nitrogen and phosphorus (table 6, fig. 13) are highest among the 22 samples of stormwater inflow to PA1. Maximum values for nitrogen (7,400 µg/L) and phosphorus (1,500 µg/L) were measured in a stormwater sample collected on March 2, 2007, after several inches of snow had accumulated. Air temperature was less than 0°C during the week prior to March 2, 2007, and only intermittent snowmelt runoff entered PA1 during this time (fig. 13*A*). Minimum values of unfiltered nitrogen (390 µg/L) and phosphorus (79 µg/L) were measured in a stormwater sample collected on April 18, 2006, after several inches of snow had melted for 6 days prior to sample collection (fig. 13B) and meltwater had flushed the stormwater-collection system. Although the study area typically receives less precipitation than Fallen Leaf Lake (fig. 1), data for the snow pillow at Fallen Leaf Lake, operated by the U.S. Department of Agriculture Natural Resources Conservation Service offered the closest representation of daily snowmelt near the shore of Lake Tahoe (Natural Resources Conservation Service, 2008 [http://www.wcc.nrcs.usda.gov/snow]). Median values of unfiltered nitrogen (2007: 1,300 µg/L; 2006: 870 µg/L) and phosphorus (2007: 470 µg/L; 2006: 240 µg/L) in stormwater samples were 1.5 and 2.0 times as large in 2007 as median values for 2006. Precipitation in 2006 was about 2.4 times the precipitation in 2007 (fig. 13C). The correlation between lower precipitation and higher nutrient concentrations indicates that increased runoff may dilute nutrient concentrations entering the detention basins. However, the total mass of nutrients delivered by stormwater to the Park Avenue detention basins may be similar from year to year.

Unfiltered concentrations in eight samples of stormwater outflow (seven from site PA1-out and one from PA2; table 6) had the smallest statistical-distribution variables (mean, median, maximum, and minimum) of nitrogen and phosphorus. Comparison of inflow and outflow concentrations indicates that about 55 percent of total nitrogen and 47 percent of total phosphorus may be retained in detention basins due to settling of suspended nutrients. However, filtered concentrations of nitrogen and phosphorus are larger in outflow samples than in detention-basin samples because outflow was sampled during stormwater-runoff events during water years 2006 and 2007 and samples of standing detention basin water were collected only during water year 2007 when precipitation was much less (fig. 13C). The term "water year" means a 12-month period beginning on October 1 and ending on September 30.

The largest mean concentrations of unfiltered nitrogen (table 6; 1,500  $\mu$ g/L) and phosphorus (570  $\mu$ g/L) in stormwater samples are for seven samples of standing detention basin water from PA1, but concentrations in filtered samples collected at the same time had the smallest mean concentrations of nitrate plus nitrite nitrogen (110  $\mu$ g/L), ammonium nitrogen (17  $\mu$ g/L), and phosphorus (49  $\mu$ g/L). Relatively small concentrations of filtered nitrate plus nitrite, ammonium, and phosphorus indicate that these more biologically available nutrients are assimilated during photosynthesis by aquatic plants in PA1.

Ninety-five samples of ground water from 11 observation wells had the largest statistical-distribution variables (mean, median, maximum, and minimum) of filtered nitrogen concentrations and, except for the anomalous maximum concentration (420  $\mu$ g/L), had the smallest distribution of phosphorus concentrations for all filtered water samples.



**Figure 12.** Statistical distribution of nitrogen and phosphorus concentrations in water samples grouped by source, Park Avenue detention basin, South Lake Tahoe, California.

**Table 6.** Statistical summary of nitrogen and phosphorus concentrations in water samples grouped by source, Park

 Avenue stormwater collection and detention system, South Lake Tahoe, California, water years 2006–07.

[The term "water year" means a 12-month period beginning October 1 and ending September 30. Sample collection sites described in <u>table 1</u>. **Abbreviation:** mg/L, microgram per liter; PA1, Park Avenue basin 1; n, sample count. **Symbol:** –, data not collected]

Statistic	Nitro (mg	ogen I/L)	Phospl (mg	horus /L)
_	Unfiltered	Filtered	Unfiltered	Filtered
	Stormwa	ater inflow (PA1_inletA an	d PA1_inletB [n=22])	
Mean	1,500	_	380	94
Minimum	390	_	79	30
Median	1,200	_	270	60
Maximum	7,400	_	1,500	380
	De	etention-basin water at PA	A1_stage (n=7)	
Mean	1,500	_	570	48
Minimum	530	_	69	17
Median	890	_	380	43
Maximum	3,600	-	1,200	92
	S	tormwater outflow from F	PA1_out (n=7)	
Mean	720	_	200	99
Minimum	220	_	66	27
Median	780	_	240	80
Maximum	970	-	310	260
	Grou	nd water at all 11 observa	tion wells (n=95)	
Mean	_	1,100	_	39
Minimum	_	82	_	3
Median	_	580	_	20
Maximum	_	7,700	-	420
	(	Ground water upgradient	of PA1 (n=28)	
Mean	_	1,700	_	20
Minimum	_	82	_	3
Median	_	2,000	_	18
Maximum	_	4,600	-	61
	Gr	ound water downgradien	t of PA1 (n=64)	
Mean	_	740	_	48
Minimum	_	82	_	6
Median	_	510	_	23
Maximum	_	7,700	-	420
		All stormwater sample	es (n=37)	
Mean	1,300	_	380	86
Minimum	220	_	66	17
Median	900	_	250	56
Maximum	7,400	-	1,500	380



**Figure 13.** Relations among net change in the volume of stormwater accumulated in PA1, precipitation, and unfiltered concentrations of nitrogen and phosphorus in sampled stormwater inflow, Park Avenue detention basin, South Lake Tahoe, California.

Concentrations of filtered nitrogen and phosphorus in ground water averaged 1,100 and 39 µg/L, respectively. Nitrogen ranged from 82 to 7,700 µg/L and phosphorus ranged from 3 to 420 µg/L. Nitrogen concentrations measured in individual wells varied 380  $\mu$ g/L (410–790  $\mu$ g/L) for samples from site MW198A to 4,200 µg/L (200-4,400 µg/L) for samples from site MW201A (figs. 3 and 14A). The maximum nitrogen concentration from site MW201A was measured in a sample collected November 7, 2005. Phosphorus concentrations measured in individual wells varied 9  $\mu$ g/L (13–22  $\mu$ g/L) for samples from site MW198B to 410  $\mu$ g/L (7–420  $\mu$ g/L) from site MW199A (fig. 14B). The maximum phosphorus concentration was measured in a sample collected on May 9, 2006, from site MW199A. During well purging of almost 16 gal, the discharge water frothed as if it contained detergent or other surfactants, such as naturally occurring dissolved organic carbon. One other filtered sample from site MW199A had phosphorus concentration greater than 100 µg/L and six of the nine samples were 20 µg/L or less.

### **Ratios of Oxygen and Hydrogen Stable Isotopes**

The isotopic composition of water, expressed as oxygen-18 relative to oxygen-16 (18O/16O) and deuterium relative to hydrogen-1 (<sup>2</sup>H /<sup>1</sup>H), of local ground water was shown to be different from that of Lake Tahoe due to evaporative fractionation of lakewater that has an estimated residence time of 700 years (Thodal, 1997). By convention, each ratio is related mathematically to the comparable ratio for an international reference standard known as the Vienna Standard Mean Ocean Water (VSMOW) and expressed as "delta oxygen-18" ( $\delta^{18}$ O) and "delta deuterium" ( $\delta^{2}$ H); the units of measure are parts per thousand (abbreviated permil). A negative delta value indicates that the sample water is lighter isotopically than the standard (depleted). Evaporation preferentially removes the lighter isotopes (<sup>16</sup>O and <sup>1</sup>H) as water vapor and the heavier isotopes (18O and 2H) remain in the liquid water. Figure 15 shows the relation of stable-isotope values for samples from Lake Tahoe, shallow ground water near the Park Avenue stormwater collection system, and two samples of interstitial water that fall along a linear mixing line  $(\delta^2 H = 26.19 + (5.59 (\delta^{18}O)))$  between lakewater and ground water. The meteoric water line ( $\delta^2 H = 26.19 + (5.59 (\delta^{18}O))$ ; Craig, 1961) also is shown.

Eight water samples were collected from five nearshore locations in Lake Tahoe, July 26 and August 2, 2007, that averaged -5.2 permil  $\delta^{18}$ O (-5.6 to -5.1 permil  $\delta^{18}$ O) and

-55.9 permil  $\delta^2$ H (-59.0 to -54.4 permil  $\delta^2$ H). One water sample collected from Lake Tahoe in 1980 was -5 permil  $\delta^{18}$ O and -56 permil  $\delta^{2}$ H. The five samples collected from the lakebed/lakewater interface averaged -5.2 permil  $\delta^{18}$ O and -55.9 permil  $\delta^2$ H compared to three samples collected 1 ft beneath lakewater surface that averaged -5.1 permil  $\delta^{18}$ O and -54.8 permil  $\delta^2$ H. The isotopic composition of 11 shallow ground-water samples averaged -13.94 permil  $\delta^{18}O$  (-15.05 to -12.70 permil  $\delta^{18}$ O) and -104.0 permil  $\delta^{2}$ H (-110.4 to -97.6 permil  $\delta^2$ H) and are comparable to 32 samples of ground water collected from wells and a spring in the Lake Tahoe Basin in 1990 that averaged -14 permil  $\delta^{18}$ O and -104 permil  $\delta^2$ H (Thodal, 1997). Isotopic compositions of two samples of interstitial water, collected 0.8 ft beneath the lakebed using a 0.5-in. diameter minipeizometer, were -13.85 permil  $\delta^{18}$ O; -102.5 permil  $\delta^{2}$ H and -9.76 permil  $\delta^{18}$ O; -80.8 permil  $\delta^2$ H. Both interstitial-water samples fall on a linear mixing line between lakewater and ground water, with the isotopic signature for the interstitial water sample collected from site L3 (fig. 3) falling in the middle of values measured in wellwater samples (fig. 15).

## Chemical Composition of Bottom-Sediment Samples

One 2 ft core of bottom sediment was collected from PA1 (fig. 4A; site PA1) and divided into two samples for laboratory analyses to assess pollutant retention by the infiltration basin (tables B1 and B2). Laboratory determinations of selected chemicals of potential concern associated with urban stormwater runoff included chromium, copper, lead, mercury, nickel, organic carbon, phosphorus, and zinc. Sediment samples also were analyzed for selected polycyclic aromatic hydrocarbons (PAHs). These compounds are found in petroleum products and tar, and are produced by combustion of petroleum as well as by forest fires and wood-burning stoves (Smith and others, 1988, p. 64-67). Comparison of concentrations in surface sediment to those in sediment collected from depth provides a qualitative evaluation of the ability of the detention-basin sediment to retain contaminants, the potential for adverse environmental effects to wet basin ecology, and economic and regulatory considerations for contaminated-sediment disposal. Selected published sediment toxicity screening values also are provided for comparison with data from PA1 (table 7).



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ИТКОGEN СОИСЕИТКАТІОИ, ІИ МІСКОGRAMS РЕЯ LITER



Figure 14.—Continued



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РНОЗРНОВИЗ СОИСЕИТВАТІОИ, ІИ МІСВОВВАМА РЕВ LITER



**Figure 15.** Relation between stable isotopes of hydrogen and oxygen in lake-water and ground-water samples collected near Park Avenue stormwater collection system, South Lake Tahoe California, 2005–07.

Table 7.Concentrations of selected chemicals of potential concern in bottom sediment collected on August 31, 2005 from ParkAvenue detention basin 1, South Lake Tahoe, California, and sediment toxicity screening values for protection of benthic aquaticlife.

[**Probable effect level:** From Smith and others, 1996. **Effective range:** From Long and Morgan, 1991. **Severe effect level:** From Persaud and others, 1993. **Consensus-based probable effect concentration:** From Ingersoll and others, 2000. **Abbreviations:**  $\mu$ g/g, microgram per gram; ft, foot; <, less than]

Constituent	Sediment co (µg	ncentration /g)	Probable	Effect range,	Severe	Consensus-based probable effect
Constituent	0–0.2 ft depth sample	1.5–1.7 ft depth sample	effect level (µg/g)	(µg/g)	effect level (µg/g)	concentration (µg/g)
Cadmium	0.62	0.22	3.53	9	10	4.98
Copper	120	38	197	390	110	149
Lead	54	19	91.3	110	250	128
Mercury	0.12	.04	0.486	1.3	2	1.06
Nickel	27	12	36	50	75	48.6
Zinc	480	79	315	270	820	459
Anthracene	0.3	< 0.01	_	0.96	3.7	0.845
Benz[a]Anthracene	0.4	< 0.01	0.385	1.6	1.48	1.05
Benzo[e]Perylene	0.6	< 0.01	_	_	_	-
Benzo[g,h,i]Perylene	0.4	< 0.01	_	_	_	-
Chrysene	0.5	< 0.01	0.862	2.8	4.6	1.29
1,6-dimethyl Naphthalene	0.2	< 0.01	_	_	_	-
2,6-dimethyl Naphthalene	0.2	< 0.01	_	_	_	-
2-ethyl Naphthalene	0.1	< 0.01	_	_	_	-
Fluoranthene	1.0	< 0.01	2.355	3.6	10.2	2.23
4,5-methylene Phenanthrene	0.2	< 0.01	_	_	_	-
1-methyl Phenanthrene	0.2	< 0.01	_	_	_	-
Perylene	0.4	< 0.01	_	_	_	-
Phenanthrene	0.8	< 0.01	0.515	1.38	9.5	1.17
Pyrene	1.0	< 0.01	0.875	2.2	8.5	1.52
2,3,6-trimethyl Naphthalene	0.2	< 0.01	_	_	_	_

Concentrations of organic carbon, cadmium, copper, lead, mercury, nickel, phosphorus, sulfur, and zinc in the surface sample are all at least twice as large as concentrations in the deeper sample (6.4, 2.8, 3.2, 2.8, 3, 2.2, 3.2, more than 7.2 and 6.1 times, respectively), but chromium in the surface sample was only 1.1 times more than the deeper sample. Cadmium, copper, lead, nickel, and zinc are metals used in the fabrication of tires and brake linings (Hjortenkrans and others, 2007, p. 5224–5225). Other studies in the Lake Tahoe basin also demonstrate increased concentrations of metals in shallower sediments compared with deeper samples. Concentrations of lead and mercury in sediment core-samples collected from Lake Tahoe (Heyvaert and others, 2000) were 6 and 5 times larger, respectively, in samples estimated to have been deposited in the mid-20th century compared to sediment deposited prior to 1850, indicating regional atmospheric sources of these contaminants. Concentrations of 28 PAHs were all less than laboratory reporting limits in the deeper sample, but 15 compounds were quantified and the concentration of an additional compound, acenaphthalene, was estimated in the surficial sample.

No constituents measured in the deeper (1.5-1.7 ft) bottom-sediment sample exceeded concentrations for chemicals of potential concern for protection of benthic aquatic life, but concentrations in the surface sample (0-0.2 ft) exceeded the severe effect level for copper and the median effect, probable effect, and consensus-based probable effect levels for zinc. Probable effect levels also were exceeded for benz[a]anthracene  $(0.4 \ \mu g/g)$ , phenanthrene  $(0.8 \ \mu g/g)$ , and pyrene  $(1.0 \ \mu g/g)$ ; table 7) in the surficial bottom sediment sample.

#### Processes Affecting Water Quality in and Near Detention Basins

Settling of suspended particles, accumulation of chemicals of potential concern, and biological assimilation of dissolved nutrients are the primary stormwater treatments achieved by the Park Avenue detention basins. Suspended particulates may include suspended micro-organisms (algae, bacteria, and fungi), organic detritus, and suspended inorganic sediment particles to which ammonium, phosphate, metals, and hydrophobic organic compounds have sorbed. Dissolved nutrients are available for biological assimilation by algae, bacteria, fungi, and aquatic vascular plants. Additionally, bacteria and fungi can decompose particulates to derive energy from carbon and assimilate nutrients.

Contributions of the species of phosphorus (suspended phosphorus and filtered orthophosphate and hydrolyzable phosphorus) relative to total concentrations indicate that most of the phosphorus is associated with particles that are larger than 0.45 µm (nominal pore size of cartridge filter; fig. 16). Suspended phosphorus, estimated as the difference between unfiltered and filtered phosphorus values, had mean concentrations that averaged 67 percent of the total phosphorus (range: 26-94 percent). Suspended phosphorus in samples from detention basin PA1 averaged 86 percent of total phosphorus (range: 71-96 percent) and outflow samples averaged 55 percent of total phosphorus (range: 16–74 percent). The phosphorus concentration  $(1,400 \,\mu g/g)$ in the surface sample of bottom sediment supports the observation that about half of unfiltered phosphorus in stormwater inflow to detention basin PA1 settles out and is retained by the stormwater-control system. However, assuming that the phosphorus concentration in one sample of bottom sediment is representative of sediment throughout detention basin PA1, about 50 lb of phosphorus has accumulated in the top 0.2 ft of sediment in PA1 while almost 200 lb of phosphorus is estimated to be associated with inflow to PA1.

Suspended plus organic nitrogen in six samples from detention basin PA1 were 96 percent of total nitrogen (range: 91-99 percent) but suspended plus organic nitrogen in seven outflow samples averaged 73 percent of total nitrogen (range: 54–90 percent). However, organic nitrogen was not determined in filtered stormwater samples. Suspended plus organic nitrogen, estimated by subtracting mean filtered concentrations of ammonium and nitrate plus nitrite from total nitrogen, measured in 22 samples of inflowing stormwater averaged almost 78 percent of the total nitrogen (range: 8-97 percent). Concentrations of filtered nitrogen and phosphorus probably are decreased due to photosynthesis and assimilation by suspended biomass (algae, bacteria, and fungi) as well as by attached aquatic vegetation. However, because concentrations of filtered organic nitrogen in stormwater samples were not determined, it is not known how much of the total nitrogen was suspended nitrogen and how much was filterable organic nitrogen.

Concentrations of filtered nitrogen (440  $\mu$ g/L) and phosphorus (20  $\mu$ g/L) in ground-water samples from site MW194 (upgradient of most development) predominately are organic nitrogen and hydrolyzable phosphorus (fig. 15). The mean concentration of nitrogen is larger than values for samples from three other wells and phosphorus concentration is larger than values for two other wells. Nutrient-enriched surface runoff in the Lake Tahoe basin has been attributed to accumulation of forest litter due to fire suppression (Miller and others, 2005). Recharge from an intermittent stream near this site may be the source of nitrogen and phosphorus in samples from this well.

Sites MW196 and MW197 are upgradient of detention basin PA1 and have the two largest mean concentrations of filtered nitrogen (2,000  $\mu$ g/L and 2,700  $\mu$ g/L, respectively) that are more than 90 percent nitrate plus nitrite. This indicates that nitrate contamination of the regional shallow aquifer, possibly by past wastewater-disposal practices, continues to persist since its early recognition in low-flow stream samples (Perkins and others, 1975) and ground-water monitoring results (Thodal, 1997). Filtered concentrations of phosphorus (19  $\mu$ g/L and 23  $\mu$ g/L) are comparable to concentrations for site MW194, with hydrolyzable phosphorus slightly more dominant.

Filtered nitrogen concentrations in samples from sites immediately downgradient of detention basin PA1 average much less than concentrations in the two upgradient sites, with ammonium and organic nitrogen accounting for 84-99 percent of the average filtered nitrogen concentrations. This indicates that a recharge mound beneath detention basin PA1 has displaced the regional ground water with infiltrated stormwater with a lower mean concentration of nitrate  $(44 \mu g/L)$  that also has diluted the high nitrate concentrations and introduced elevated concentrations of ammonium and organic nitrogen. Mean concentrations of filtered phosphorus for the four downgradient wells (17–24  $\mu$ g/L) are comparable to the concentrations in upgradient wells (19–23  $\mu$ g/L) with hydrolyzable phosphorus contributing more than 70 percent of the filtered phosphorus. However, the mean phosphorus concentration for site MW199A (fig. 3) was 72 µg/L and only one sample of the nine collected from site MW199A had orthophosphate accounting for more than 40 percent of filtered phosphorus. The anomalous sample collected on May 9, 2006, had 420 µg/L of filtered phosphorus with 90 percent as orthophosphate. The mean phosphorus concentration for site MW200 was 39 µg/L, but seven of nine samples were less than 30 µg/L. The largest concentrations of filtered phosphorus (260  $\mu$ g/L) and filtered orthophosphate (240  $\mu$ g/L) in the outflow from detention basin PA1 was in a sample collected on May 10, 2006. The second largest concentration of filtered phosphorus (84  $\mu$ g/L) and filtered orthophosphate (68 µg/L) was measured in samples from site MW200 and also was collected on May 10, 2006. MW199A has the largest measurement of hydraulic conductivity (20 ft/d; table 2). Attempts to slug test at site MW200 were unsuccessful because the stressed water level recovered too quickly for quantification. The rapid recovery indicates that the hydraulic conductivity of the aquifer material tapped at site MW200 is greater than 20 ft/d, and may represent localized deposits that permit preferential flow of stormwater to ground water.



**Figure 16.** Relative contribution of nutrient species that constitute mean concentrations of nitrogen and phosphorus, South Lake Tahoe, California and Nevada.



Figure 16.—Continued.



Figure 16.—Continued.

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Concentrations of filtered nitrogen (560–1,300 µg/L) in samples from sites downgradient of detention basin PA2 (sites MW201A, MW201B, and MW202) are dominated by nitrate (63–92 percent) because detention basin PA2 only received stormwater inflow during flooding due to a warm rain-on-snow events that spanned December 17, 2005, through January 7, 2006. Therefore, nitrate in the shallow regional ground water is only diluted and displaced intermittently. Sites MW201A and MW202 are completed at 13 ft below land surface and site MW201B was completed at 23 ft. Samples from the deeper well had a mean filtered nitrogen concentration of 1,300 µg/L compared to 890 µg/L for site MW201A and 560 µg/L for site MW202. Mean concentrations of filtered phosphorus (29–120  $\mu$ g/L) for these three wells are all at least 69 percent orthophosphate and are among the five largest mean concentrations.

## **Ground-Water Discharge and Nutrient Loading to Lake Tahoe**

In order to estimate the load of nutrients discharged to Lake Tahoe directly from detention basin PA1, an estimate of the amount of stormwater infiltrated from the detention basin was needed. Detention basin PA1 was not instrumented to record basin outflow; therefore, a calibrated-infiltration rate from the ground-water flow model of 73 ft<sup>3</sup>/d was used. Thus, an estimated 18 ft<sup>3</sup>/d of stormwater that infiltrated through the bed of detention basin PA1 discharges to Lake Tahoe based on particle tracking results of 25 percent direct discharge. The remaining 55 ft<sup>3</sup>/d (0.46 acre-ft/yr) of infiltrated stormwater discharged to stormdrains that discharge into Lake Tahoe by way of a wet meadow or was evapotranspired by riparian vegetation. The volume of infiltrated stormwater that discharges to Lake Tahoe as ground water represents about 0.1 percent (0.15 acre-ft/yr) of the total volume of groundwater discharge from the study area (256 acre-ft/yr). Assuming a mean filtered nitrogen concentration in ground water of 1,100 µg/L and filtered phosphorus concentration of 39  $\mu$ g/L, it is estimated that ground water within the study area contributes 765 lb of nitrogen and 27 lb of phosphorus each year to Lake Tahoe and infiltrated stormwater from detention basin PA1 contributes less than 0.45 lb of the nitrogen load and less than 0.1 lb of the phosphorus load to the lake.

The distribution of ground-water discharge across the lake sediment is important because heterogeneity of aquifer permeability can "focus" ground-water discharge, such as ground-water discharge to springs. The calibrated ground-water flow model was used to calculate zones of discharge to the lake (fig. 9). About 41 acre-ft/yr (16 percent) of total ground-water discharge to Lake Tahoe occurs within about 60 ft of the shoreline. Approximately 55 acre-ft/yr also discharges in a zone between 60 ft and 600 ft offshore.

Particle tracking was used to observe where infiltrated stormwater into the Park Avenue detention basins would discharge. Nearly 9,000 particles were placed in model cells representing detention basin PA1. The number of particles placed in each model cell was proportional to the groundwater flux through that particular cell. Results indicate that 75 percent of infiltrated stormwater discharges to nearby stormdrains northwest of detention basin PA1 while the remaining 25 percent discharges to Lake Tahoe within 60 ft of the shoreline. Ground water discharged to stormdrains is conveyed to nearby wet meadows and directly to Lake Tahoe depending on diversion-dam configuration.

Other methods were attempted to determine locations of ground-water discharge to Lake Tahoe. Differences in the temperature and electrical conductivity of ground water compared to the receiving lake water have been used to locate submerged ground-water discharge for subsequent measurement of limnologic responses (Lee, 1985). Paired thermocouples attached to a data logger were dragged behind a boat along the Lake Tahoe shoreline, but wave action and airtemperature variations affected the data logger performance, preventing useful results.

An attempt was made to apply Raman Spectra fiber optic distributed temperature sensing technology in collaboration with researchers from the University of Nevada, Reno; Oregon State University; and others in June 2007. The system precisely measures temperature ( $\pm 0.05^{\circ}$ C) along a 3,000 ft length of standard optical communication cable with 3-ft spatial resolution (Hausner and others, 2007). Unfortunately, the equipment was available only during early June 2007 when a cold front moved in with wind and snow that again obscured any differences in lakebed temperatures.

On July 26 and August 2, 2007, a multiparameter water-quality probe was again dragged along the nearshore lakebed. However, no variations in temperature or electrical conductivity were observed. Thick mats of attached algae were observed in a linear pattern parallel to the lakeshore that indicated focused ground-water discharge. A seepage meter and minipiezometer were inserted into the lakebed sediment, and lake level and intercepted ground-water levels were compared using transparent tubing. Two samples of interstitial water and eight samples of lake water were collected for laboratory determination of stable isotopes of hydrogen and oxygen and for filtered concentrations of nitrogen and phosphorus.

Three lake samples were collected 1 ft beneath the lake surface and five were collected at the lakebed-water contact. Relations between the two isotopic ratios (fig. 14) indicate that the lake water was well mixed with a slight groundwater signature in the samples collected at site L4B, near the lakebed (table A7). One interstitial water sample was nearly all ground water (site L3C) and the other (site L1C) falls along a linear mixing line between ground water and lake water. Filtered concentrations of nitrogen and phosphorus were less than laboratory reporting limits for all lake water samples except for one sample collected near the lakebed (site L3B) that had 71  $\mu$ g/L of nitrogen. The sample of interstitial water indicated a mixture of lake and ground water (site L1C). This sample had 143 µg/L of nitrogen and 36 µg/L phosphorus comprised mostly of organic nitrogen and orthophosphate, respectively. The other sample (site L3C) had 720 µg/L of filtered nitrogen comprised of 65 percent ammonium, 35 percent organic nitrogen and detectable nitrite  $(3 \mu g/L)$ , and  $40 \mu g/L$  filtered phosphorus comprised of 72 percent orthophosphate and 28 percent hydrolyzable phosphorus. Filtered nitrogen concentrations in ground-water samples collected from wells averaged 1,000 µg/L with nitrate representing nearly 70 percent of the concentration and ammonium only 10 percent. Nitrate was less than reporting levels in the interstitial water (estimated as 10 µg/L from site L1C) indicating a dissimilative nitrate reduction to ammonium by sediment micro-organisms (Sørensen, 1978).

### **Summary and Conclusions**

Clarity of Lake Tahoe, California and Nevada, has been decreasing, in part due to inflows of sediment and nutrients associated with stormwater runoff. Constructed stormwater detention basins are considered effective best management practices for mitigation of suspended sediment and nutrients associated with runoff, but consequences of infiltrated stormwater to shallow ground water are not known. This report documents 2005-07 hydrogeologic conditions in a small part of a shallow aquifer and how it interacts with a stormwater-control system and with nearby Lake Tahoe. Descriptions of the basin-fill aquifer and a stormwater-control system; quantification of components of the ground-water budget; and characteristics of the quality of stormwater, bottom sediment from a stormwater detention basin, ground water, and nearshore lake and interstitial water are included. Results of a three-dimensional, finite-difference, numerical model also are presented, coupled with chemical data to evaluate responses of ground-water flow to stormwater runoff accumulation in the stormwater-control system.

Ground-water flow in the basin-fill aquifer was modeled using five layers of constant thickness (5, 10, 15, 10 and 10 ft thick, respectively), from land surface to 50 ft and a sixth layer that varied in thickness from the bottom of layer 5 to bedrock. The large and varying thickness of this deepest layer is assumed to have no effect on the simulation of shallow ground-water movement. Information indicates lacustrine layers may be interspersed within sand and gravel deposits, but enough evidence was not available to support a continuous confining layer in this model. Bedrock underlying layer 6 represents a basal no-flow boundary and boundaries to the northeast and southwest were aligned along hydrographic basin boundaries and were represented as no-flow boundaries. Model cells exposed to Lake Tahoe in the northwest were simulated using a constant-head boundary of 6,225 ft, which is the average stage of Lake Tahoe. The southern Park Avenue detention basin also was simulated using a constant-head boundary because it was never observed to completely drain.

Model layers 1–5 were assigned hydraulic conductivity values of 2 ft/d for the simulations. Recharge was applied to the modeled area as precipitation (areal recharge) and mountain-front recharge. Areal recharge was estimated during model calibration and applied to about 62 percent of layer 1 model cells that were determined not to be impervious. Mountain-front recharge was applied to all cells along the southeast boundary, as well as two zones that extend downgradient from the mountain front. Annual precipitation averaged 4,400 acre-ft in the watersheds upgradient of the model area between 1971 and 2000, of which 2 percent was estimated to be in-place recharge, 54 percent is consumed by evapotranspiration, and the remaining 44 percent is attributed to potential runoff. The percentage of the potential runoff that actually becomes recharge was estimated during model calibration.

A network of stormwater drainage ditches and sewers scattered across South Lake Tahoe were simulated as drains. These drains were placed 5 ft below land surface. In this way, if the simulated ground-water surface came within 5 ft of land surface, ground water would be able to discharge to the stormwater ditches, and then directly to Lake Tahoe.

The steady-state model was calibrated to water-level measurements in 18 wells and a mean ground-water discharge from the model domain was estimated to be 256 acre-ft/yr to Lake Tahoe. About 0.61 acre-ft/yr infiltrates from detention basin PA1 to ground water and particle tracking indicated 25 percent (0.15 acre-ft/yr) of this infiltration ultimately discharges to Lake Tahoe within 60 ft of the shoreline. The remaining 0.46 acre-ft/yr discharged to local stormdrains that convey water to nearby wet meadows and directly to Lake Tahoe, depending on diversion-dam configuration.

Settling of suspended nutrients and sediment, biological assimilation of dissolved nutrients, and accumulation of chemicals of potential concern are the primary stormwater treatments achieved by the detention basins. Comparison of mean concentrations of unfiltered nitrogen and phosphorus in stormwater samples indicate that 55 percent of nitrogen and 47 percent of phosphorus is trapped in the detention basin. Cadmium, copper, lead, mercury, nickel, organic carbon, phosphorus, and zinc in the uppermost 0.2 ft of bottom sediment from the detention basin were all at least twice as concentrated compared to sediment collected from 1.5 ft deeper. Similarly, concentrations of 28 polycyclic aromatic hydrocarbon compounds were all less than laboratory reporting limits in the deeper sample, but 15 compounds were measured in the uppermost 0.2 ft of bottom sediment. Published concentrations determined to affect benthic aquatic life were exceeded for benz[a]anthracene, copper, phenanthrene, pyrene, and zinc in the uppermost 0.2 ft of bottom sediment.

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Concentrations of filtered major ions indicate that upgradient ground water is a mixed cation-bicarbonate type with 152 mg/L total solutes that evolves to a mixed cation/ mixed anion, sodium-chloride type and sodium-bicarbonate type waters with up to 390 mg/L total solutes, possibly due to residual leachate from abandoned septic-tank systems and recharged stormwater runoff. Concentrations of filtered nitrogen ranged from 82 to 4,600 µg/L and phosphorus ranged from 4 to 420 µg/L. Coupling mean concentrations of phosphorus (39 µg/L) and nitrogen (1,100 µg/L) with the steady-state ground-water flow model yields annual estimates of 26 lb of phosphorus and 770 lb of nitrogen that may be transported with ground water to Lake Tahoe from the modeled area (1.5 percent of the total area that is tributary to the lake).

The isotopic composition of water, expressed as ratios of oxygen-18 relative to oxygen-16 (delta oxygen-18) and deuterium relative to hydrogen-1 (delta deuterium), of local ground water is different from that of Lake Tahoe due to evaporative fractionation of lake water that has an estimated residence time of 700 years. Comparison of delta oxygen-18 and delta deuterium ratios for samples of shallow ground water, lake water, and interstitial water from Lake Tahoe indicates the lake water was well mixed with a slight groundwater signature in two of five lake-water samples collected near the lakebed. One of two interstitial water samples from 0.8 ft beneath the lakebed was nearly all ground water and concentrations of nitrogen and phosphorus were comparable to concentrations in shallow ground-water samples. The other interstitial sample fell along a mixing line between ground water and lake water, and nutrient concentrations appeared diluted with lake water. Nitrate was less than laboratory reporting levels in both interstitial samples, indicating a dissimilative nitrate reduction to ammonium by micro-organisms. Based on average nitrogen and phosphorus concentrations of interstitial-water samples and ground-water discharge to Lake Tahoe directly from detention basin PA1, it is estimated that PA1 contributes loads of less than 0.3 lb of nitrogen and less than 0.1 lb of phosphorus per year.

### **Acknowledgments**

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# Appendix A. Water-Quality Data

Table A1.—Concentrations of nitrogen, phosphorus, and suspended solids in surface-water samples collected from Park Avenue stormwater collection and detention system, South Lake Tahoe, California, water years 2006-07.

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Phosphorus, filtered (µg/L as P)	380	64	180	50	120	38	200	52	41	98	130	20	86	56	30	42	30	110	56	44	82
Phosphorus, unfiltered (µg/L as P)	750	160	360	150	250	089	260	230	280	1,500	210	120	240	80	170	370	80	490	200	620	340
Nitrate + nitrite, filtered (µg/L as N)	320	260	48	470	120	210	270	79	220	620	250	74	27	560	46	270	55	100	92	82	78
Ammonia, filtered (µg/L as N)	480	57	39	75	24	8	370	59	460	220	55	29	26	84	9	8	20	36	28	6	10
Organic nitrogen, unfiltered (µg/L as N)	1,100	400	710	570	009	1,300	008	1,200	2,100	6,600	720	470	820	60	530	1,200	310	1,700	1,100	2,300	1,300
Nitrogen, unfiltered (µg/L)	1,900	710	800	1,100	750	1,500	1,400	1,300	2,800	7,400	1,000	570	870	710	590	1,500	390	1,800	1,200	2,300	1,300
Time	-	1450	1400	1450	1200	1545	1340	1620	1400	1210	-	1455	1400	1500	1200	1545	1700	1335	1645	0800	1202
Date	11-25-05	11-29-05	12-01-05	12-07-05	12-28-05	03-06-06	05-10-06	01-04-07	02-01-07	03-02-07	11-25-05	11-29-05	12-01-05	12-07-05	12-28-05	03-06-06	04-18-06	05-10-06	01-04-07	02-10-07	02-10-07
Site No.	PA1_inletA										PA1_inletB					ļ					

		r	r	r	r	r				,		,		,			,
nd detention	Suspended solids, unfiltered (mg/L)	100	-	270	260	260	81	40				9	-	20	21	۷	
ormwater collection ar	Orthophosphate, filtered (µg/L as P)	31	4	26	32	30	41	14	28	69	140	15	84	20	25	240	60
n Park Avenue stu	Phosphorus, filtered (µg/L as P)	120	17	92	09	43	52	28	41	80	150	27	64	39	38	260	69
les collected fror	Phosphorus, unfiltered (µg/L as P)	470	69	1,000	1,200	1,100	380	98	96	240	260	99	240	100	140	310	180
surface-water samp	Nitrate + nitrite, filtered (µg/L as N)	22	15	120	120	3	3	4	490	200	88	400	91	30	100	74	150
ended solids in ontinued.	Ammonia, filtered (µg/L as N)	8	32	25	10	8	9	22	220	130	38	15	6	46	19	99	25
orus, and suspe rs 2006-07C	Organic nitrogen, unfiltered (µg/L as N)	086	490	1,900	3,600	2,000	880	840	560	640	610	480	120	710	700	480	140
rogen, phosph nia, water yea	Nitrogen, unfiltered (µg/L)	066	530	2,100	3,600	2,100	890	870	780	970	730	006	220	780	820	610	320
ns of nit , Califori	Time	1955	1155	0730	1946	2124	2221	1222	1340	1500	1400	1500	1200	1545	1635	1400	1200
Concentratio h Lake Tahoe	Date	02-10-07	12-14-06	02-09-07	02-10-07	02-10-07	02-10-07	04-09-07	02-07-07	11-29-05	12-01-05	12-07-05	12-28-05	03-06-06	04-18-06	05-10-06	12-28-05
Table A1.— system, South	Site No.	PA1_inletB	PA1							PA1_out							PA2

Table A2.—Concentrations of selected species of nitrogen and phosphorus in ground-water samples from observation wells near Park Avenue stormwater collection and detention system, South Lake Tahoe, California, water years 2006-07. [Site locations and numbers are shown in figure 3. The term "water vear" means a 12-month period beginning October 1 and ending September 30.

		1	1	-	-		1	-	-		-	-								
-	Orthophosphate, filtered (µg/L as P)	c	27	11	3	2	5	1	1	3	2	2	4	3	1	4	3	2	5	2
	Phosphorus, filtered (µg/L as P)	11	61	15	21	20	22	8	7	3	52	10	40	13	24	14	25	10	17	12
	Nitrate + nitrite, filtered (µg/L as N)	8	10	130	11	68	230	10	7	2	2,200	1,900	2,200	1,900	2,300	2,000	1,300	1,200	2,400	1,100
u]	Ammonia, filtered (µg/L as N)	8	21	91	17	59	76	41	36	21	26	2	3	9	2	3	5	73	7	4
orus; <, less that	Organic nitrogen, filtered (µg/L as N)	150	50	1,800	280	20	120	160	180	130	40	06	<35	130	<35	<35	<35	170	110	<35
rogen; P, phosph	Nitrogen, filtered (µg/L as N)	170	80	2,000	310	120	420	210	220	150	2,300	2,000	2,200	2,100	2,300	2,000	1,300	1,400	2,500	1,200
s per liter; N, nit	Time	1400	1230	1731	1345	1245	0830	1450	0910	1120	1600	1420	1200	1225	1530	1230	1035	1200	1149	1205
µg/L, microgram	Date	12-07-05	02-13-06	03-06-06	04-18-06	05-10-06	12-14-06	02-01-07	04-09-07	05-07-07	11-07-05	12-07-05	02-14-06	03-06-06	04-18-06	05-09-06	12-14-06	02-01-07	03-02-07	04-09-07
Abbreviations:	Site No.	MW194									MW196									

Table A2.—Co stormwater col	oncentrations of lection and deter	selected species ntion system, So	s of nitrogen and outh Lake Tahoe,	phosphorus in c California, wate	Iround-water sam r years 2006-07–	nples from observ —Continued.	/ation wells near	· Park Avenue
Site No.	Date	Time	Nitrogen, filtered (µg/L as N)	Organic nitrogen, filtered (µg/L as N)	Ammonia, filtered (µg/L as N)	Nitrate + nitrite, filtered (µg/L as N)	Phosphorus, filtered (µg/L as P)	Orthophosphate, filtered (µg/L as P)
MW196	05-07-07	1330	1,700	180	62	1,500	23	3
MW197	11-07-05	1605	2,800	70	28	2,700	26	4
	12-07-05	1430	2,800	270	က	2,500	12	2
	02-14-06	1320	2,600	40	4	2,500	43	10
	03-06-06	1235	2,800	240	240	2,200	19	4
	04-18-06	1540	2,800	370	21	2,400	30	2
	02-00-00	1100	2,500	70	2	2,500	24	10
	12-14-06	1045	1,900	300	14	1,600	30	3
	02-01-07	1205	2,300	80	65	2,200	11	2
	03-02-07	1200	4,600	150	8	4,400	17	7
	04-09-07	1200	1,200	<35	26	1,500	13	۷
	02-07-07	1320	2,100	240	38	1,800	13	2
MW198A	11-07-05	1628	490	290	200	3	21	3
	02-16-06	1400	470	100	300	76	41	18
	03-06-06	1245	410	55	226	130	14	2
	04-18-06	1550	680	270	170	240	31	2
	02-09-00	0945	790	280	170	330	34	10
	12-14-06	1115	630	340	280	8	19	2
	02-01-07	1240	650	290	350	7	10	1
	03-01-07	1630	560	230	330	2	10	2
	04-09-07	1145	590	260	330	1	6	1
	05-07-07	1313	710	340	370	2	9	8

Table A2.—Concentrations of selected species of nitrogen and phosphorus in ground-water samples from observation wells near Park Avenue stormwater collection and detention system, South Lake Tahoe, California, water years 2006-07—Continued.

Orthophosphate, filtered (µg/L as P)	2		5	2	C	4	15	4	2	380		1	2	3	1	3	10	9	4	26	62
Phosphorus, filtered (µg/L as P)	22	13	61	15	20	10	120	12	23	420	26	10	16	12	L	61	32	20	20	35	68
Nitrate + nitrite, filtered (µg/L as N)	13	9	1	-	c	8	4	-	4	7	10	8	4	3	С	8	-	L	8	26	80
Ammonia, filtered (µg/L as N)	4	18	9	9	250	270	520	400	340	480	540	830	260	440	490	4	7	5	21	Υ	73
Organic nitrogen, filtered (µg/L as N)	160	200	06	75	170	320	160	430	360	300	400	410	310	230	480	200	87	120	230	200	150
Nitrogen, filtered (µg/L as N)	180	230	67	82	420	009	690	830	710	062	950	1,300	570	670	026	210	95	120	260	230	300
Time	1610	1441	1300	1030	1636	1450	1000	1251	1610	1400	1145	1250	1600	1135	1305	1641	1100	1330	1650	1500	1400
Date	11-07-05	12-07-05	02-16-06	02-09-00	11-07-05	12-07-05	02-14-06	03-06-06	04-18-06	02-00-00	12-14-06	02-01-07	03-01-07	04-09-07	02-02-07	11-07-05	02-14-06	02-00-00	11-07-05	12-07-05	02-14-06
Site No.	MW198B				MW199A											MW199B			MW200		

Table A2.—Concentrations of selected species of nitrogen and phosphorus in ground-water samples from observation wells near Park Avenue stormwater collection and detention system, South Lake Tahoe, California, water years 2006-07.—Continued.

		·						
Site No.	Date	Time	Nitrogen, filtered (µg/L as N)	Organic nitrogen, filtered (µg/L as N)	Ammonia, filtered (µg/L as N)	Nitrate + nitrite, filtered (µg/L as N)	Phosphorus, filtered (µg/L as P)	Orthophosphate, filtered (µg/L as P)
MW200	03-06-06	1300	250	200	49	-	44	38
	04-18-06	1620	590	380	210	S	47	28
	05-10-06	1345	580	350	240	-	84	68
	12-14-06	1135	560	280	270	15	30	4
	02-01-07	1300	480	230	250	9	2	1
	03-01-07	1540	370	290	73	9	13	2
	04-09-07	1125	310	250	56	2	13	10
	02-07-07	1300	480	430	74	2	23	11
MW201A	11-07-05	1710	4,400	190	29	4,100	160	140
	02-16-06	1015	265	120	ß	140	85	80
	04-18-06	1800	1,100	240	42	850	18	2
	05-10-06	0945	270	130	2	140	97	91
	12-14-06	1220	200	180	10	9	150	140
	02-01-07	1325	250	240	6	1	110	110
	03-01-07	1457	330	300	15	22	160	160
	04-09-07	1233	320	210	ß	100	160	140
	02-07-07	1412	390	360	9	32	180	158
MW201B	11-07-05	1716	2,500	25	34	2,400	35	13
	12-07-05	1510	1,000	250	3	750	96	87
	02-16-06	1100	380	78	8	290	44	52

Table A2.—Concentrations of selected species of nitrogen and phosphorus in ground-water samples from observation wells near Park Avenue stormwater collection and detention system South Lake Tahoe California water years 2006-07-Continued

	Orthophosphate, filtered (μg/L as P)	22	<b>21</b>	13	22	91	8	9	12	13	18	50	15	2
	Phosphorus, filtered (µg/L as P)	28	29	30	80	20	6	14	19	49	20	30	17	13
0011111000.	Nitrate + nitrite, filtered (µg/L as N)	430	2,200	19	26	077	330	620	370	096	280	140	260	7,700
1 2000 2000 01	Ammonia, filtered (µg/L as N)	9	2	7	3	2	2	13	2	22	38	14	5	10
	Organic nitrogen, filtered (µg/L as N)	81	<35	240	200	130	190	150	120	320	230	220	170	36
זמנוו במואט ומווטט,	Nitrogen, filtered (µg/L as N)	520	2,300	270	300	570	520	800	500	1,300	540	370	440	7,700
יוונוטוו סאסנטווו, טר	Time	1315	1020	1719	1520	1200	1331	1815	1130	1211	1310	1507	1243	1430
ווכניוטון מוומ מכיר	Date	03-06-06	05-10-06	11-07-05	12-07-05	02-16-06	03-06-06	04-18-06	05-10-06	12-14-06	02-01-07	03-01-07	04-09-07	05-07-07
	Site No.	MW201B		MW202										

1

Table A3 water yea	. Concentrati r 2007.	ons of selected	l species of nit	rogen and pho	sphorus in sam	ples of lake a	and interstitial w	ater, South Lake Ta	ahoe, California,
[Site locat	ions and num	nbers are show	n in figure 3. T	he term "wate	r year" means	a 12-month	period beginning	October 1 and end	ing September 30.
Abbreviati	ions: µS/cm, is; E, estimat	microsiemens ted to be prese	per centimeter ent at a concen	at 25 degrees tration less tha	Celsius; °C, de In laboratory re	grees Celsiu porting limit	s,, no data; µg/ ; <, less than labo	L, micrograms per pratory reporting lir	liter; N, nitrogen; P, mit.]
Site No.	Date	Nitrogen, filtered (µg/L as N)	Organic nitrogen, filtered (ua/L as N)	Ammonia, filtered (µg/L as N)	Nitrate + nitrite, filtered (ua/L as N)	Nitrite, filtered (µg/L as N)	Phosphorus, filtered (µg/L as P)	Phosphorus, hydrolyzable filtered (ua/L as P)	Orthophosphate, filtered (µg/L as P)
L1A	07-26-07	E43	09>	<20	<16	4	9>	9>	E3
L1B	07-26-07	E35	<60	<20	<16	<2	9>	92	E3
L1C	07-26-07	143	118	E15	E10	<2	36	EB	31
L2A	08-02-07	E39	<60	<20	<16	<2	9>	9>	E4
L2B	08-02-07	E35	<60	<20	<16	<2	9	9	EÐ
L3A	08-02-07	E39	<60	<20	<16	<2	9≻	9>	E4
L3B	08-02-07	17	<60	<20	<16	<2	9≻	9>	EÐ
L3C	08-02-07	720	250	470	<16	3.3	40	11	29
L4B	08-02-07	623	09>	<20	<16	<2	9>	9>	E5
L5B	08-02-07	E34	<60	<20	<16	<2	9>	9>	EÐ

Appendix A 53

[Site location µS/cm, micro	is and numbe siemens per	ers are sho square cei	wn in figure 3. Th ntimeter at 25 deo	e term "water grees Celsius; <sup>*</sup>	year" means a 12- °C, degrees Celsius	month perioc s; mg/L, milliç	l beginning Octol grams per liter;	oer 1 and ending So , no data available	eptember 30. Abbr	eviations:
			Water level	Hq	Specific	Dissolv	ed oxygen	Water	Bicarbonate,	Alkalinity,
No.	Date	Time	(reet below land surface)	(standard units)	conductance (µS/cm)	(mg/L)	(percent)	temperature (°C)	riiterea (mg/L as HCO <sub>3</sub> )	riitered (mg/L as CaCO <sub>3</sub> )
MW194	02-13-06	1230	14.40	5.77	219	1	1	11	89	73
	05-10-06	1245	14.04	6.53	213	4.2	49	11.6	1	1
MW196	02-14-06	1200	10.87	6.73	487	7.3	80	6	115	94
	02-00-00	1230	10.06	6.29	470	2.8	31	9.7	1	1
MW197	02-14-06	1320	5.66	6.63	572	6.4	73	11	117	96
	02-00-00	1100	4.32	6.15	625	4.3	49	10.8	1	1
MW198A	02-16-06	1400	9.52	6.96	460	8.6	93	6	118	97
	02-09-06	945	9.28	6.18	498	1.6	18	11.1	1	1
MW198B	02-16-06	1300	10.14	6.35	141	3.0	34	10	86	71
	02-00-00	1030	9.32	6.12	466	0.4	4	9.4	1	1
MW199A	02-14-06	1000	9.85	6.51	616	0.2	3	7	145	119
	02-09-06	1400	9.59	7.1	562	2.1	23	9.1	-	ł
MW199B	02-14-06	1100	10.57	6.71	376	0.4	2	10	128	105
	02-00-00	1330	9.75	6.62	444	1.7	18	9.6	1	1
MW200	02-14-06	1400	7.32	7.05	512	3.2	31	5	1	1
	05-10-06	1345	6.10	6.39	417	4.4	20	10.5	1	ł
<b>MW201A</b>	02-16-06	1015	9.35	5.8	155	5.2	20	4	1	ł
	05-10-06	945	60.6	5.98	168	5.0	50	6.1	-	-
<b>MW201B</b>	02-16-06	1100	9.03	6.18	185	3.3	34	7	-	-

ection and detention system, South Lake Tahoe, California, we Water level DH	nical constituents in ç ater year 2006—Con <b>Specific</b>	ground-water samples from ol tinued. Dissolved oxygen	bservation wells near Water	ar Park Avenue sto Bicarbonate,	Alkalinity,
------------------------------------------------------------------------------	------------------------------------------------------------------	-------------------------------------------------------------	--------------------------------	------------------------------------	-------------

Alkalınıty, filtered	(mg/L as CaCO <sub>3</sub> )	1
Bicarbonate, /	(mg/L as HCO <sub>3</sub> )	1
Water	temperature (°C)	8.1
ed oxygen	(percent)	6
Dissolv	(mg/L)	0.9
Specific	conductance (µS/cm)	302
Hq	(standard units)	5.87
Water level (feet below	land surface)	8.70
Þ		1020
	Date	05-10-06
Site	No.	MW202

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[Site locatic Abbreviatio	ons and numb ns: °C, degree	oers are show es Celsius; mç	n in figure 3. The 3/L, milligrams pe	eterm "water yer liter; SiO <sub>2</sub> , 5	year" means a silica oxide; <, .	12-month peri less than]	iod beginning	October 1 and	d ending Sept	ember 30.
Site No.	Date	Calcium, filtered (mg/L)	Magnesium, filtered (mg/L)	Sodium, filtered (mg/L)	Potassium, filtered (mg/L)	Sulfate, filtered (mg/L)	Chloride, filtered (mg/L)	Fluoride, filtered (mg/L)	Silica, filtered (mg/L as SiO <sub>2</sub> )	Solids, dissolved, residue at 180° C (mg/L)
MW194	02-13-06	16.5	5.34	15.2	3.24	7.4	4.96	<0.1	37.2	152
MW196	02-14-06	46.7	13.6	45.2	5.4	37.3	92.9	<0.1	31.0	350
791WM	02-14-06	56.4	17	43.2	6.41	54	108	<0.1	29.1	062
MW198A	02-16-06	48.9	8.24	38.8	3.79	10	90.8	<0.1	25.6	767
MW198B	02-16-06	25.3	6.4	53.9	5.79	9.6	86.4	<0.1	26.1	265
MW199A	02-14-06	49.6	7.54	70.2	3.56	1.6	131	<0.1	22.7	386
MW199B	02-14-06	18.3	3.27	59.5	4.91	5.6	57.4	<0.1	20.7	233

<b>ble A6.</b> —Concentrations of filtered trace ar Park Avenue stormwater collection and
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<sup>18</sup> Oxygen/ <sup>16</sup> Oxygen	(ratio, in per mil)	-14.8	-12.7	-13.07	-13.82	-13.87	-14.3	-13.38	-14.6	-15.0	-13.3	-14.2
Deuterium/ Hydrogen	(ratio, in per mil)	-109.4	-97.63	-98.77	-103.06	-103.92	-106.72	-101.43	-110.05	-110.39	-97.81	-104.68
Zinc (µg/L)		15	7	7	9>	9>	9>	E5	1	1	1	1
Nickel (µg/L)	1	2	3	3	3	4	4	E1	-	-	-	1
Lead (µg/L)	1	0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	-	-		1
Chromium	(µg/r)	42	<2	<2	<2	<2	<2	E1	-	-		1
Copper	(µg/r)	42	<2	<2	<2	<2	<2	E2		-		:
lron	(µg/r)	16,000	21	2,500	33	7	9,100	9>	-	-	-	ł
Date		02-13-06	02-14-06	02-14-06	02-16-06	02-16-06	02-14-06	02-14-06	02-14-06	02-16-06	02-16-06	02-16-06
Site	.0N	MW194	MW196	MW197	MW198A	MW198B	MW199A	MW199B	MW200	MW201A	MW201B	MW202

Table A7. —Field measurements of physical properties and chemical constituents, ratios of stable isotopes of hydrogen and oxygen and concentrations of nitrogen and phosphorus in samples of lake and interstitial water, South Lake Tahoe, California, water year 2007. [Site locations and numbers are shown in figure 3. The term "water year" means a 12-month period beginning October 1 and ending September 30. Abbreviations: µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius, --, no

	<sup>18</sup> Oxygen/	"Oxygen (ratio, in permil)	-5.17	-5.11	-9.76	-5.09	-5.09	-5.06	-5.26	-13.85	-5.58	-5.12
	Deuterium/	Hydrogen (ratio, in permil)	-54.96	-54.61	-80.78	-54.97	-55.22	-54.40	-55.56	-102.54	-59.02	-55.32
	Water	temperature (°C)	20.5	20.5	1	21.5	21.0	22.0	21.5	1	22.5	22.5
	ed oxygen	(percent)	122	121		111	133	112	118		115	110
	Dissolve	(mg/L)	8.8	8.8	-	8.1	9.6	8.1	8.6	-	8.4	7.9
	Snecific	conductance (µS/cm)	92	91	164	36	36	35	95	262	64	94
	На	(standard units)	6.8	6.9	5.7	7.9	8.0	7.8	8.0	6.3	8.0	7.9
		Time	1300	1315	1330	1025	1040	1130	1150	1200	1215	1305
		Date	07-26-07	07-26-07	07-26-07	08-02-07	08-02-07	08-02-07	08-02-07	08-02-07	08-02-07	08-02-07
data.]		Site No.	L1A	L1B	L1C	LZA	L2B	L3A	L3B	L3C	L4B	L5B

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# Appendix B. Bottom-Sediment Quality Data

Table B1. detention	. —Concentrati basin, South La	ons of selecteo ike Tahoe, Calii	d chemical const fornia, water yea	ituents and per ır 2005.	cent carbon in bo	ottom sediment s	amples from Par	rk Avenue sto	rmwater
[Site locat Abbreviati	ions and numbe ons: µg/g, micro	ers are shown i ogram per gran	n figure 3. The te n; µm, micron; <,	erm "water yea less than]	ar″ means a 12-m	ionth period begi	nning October 1	and ending S	eptember 30.
Cito			Carbon,	Carbon,	Carbon,	Al minim	Antimonu	Aronio	Darium
No.	Date	Fraction	inorganic (percent)	organic (percent)	total (percent)	(þg/g)	Allulloury (µg/g)	Arsenic (µg/g)	baruur (µg/g)
PA1 shallow	08-31-05	<63um	0.11	7.7	7.8	81.000	со С	2.6	880
PA1 deen	08-31-05	<63um	0.03	1	1.3	85.000	- - -	2 00	780
Site	Beryllium	Bismuth	Cadmium	Calcium	Cerium	Cesium	Chromium	Cobalt	Copper
No.	(b/gл)	(p/g/g)	(b/g/)	(p/g/g)	(b/g/)	(pg/g)	(p/g/)	(pg/g)	(µg/g)
PA1 shallow	1.4	0.62	0.62	28,000	49	5.2	52	17	120
PA1 deep	1.9	0.32	0.22	16,000	43	6.8	47	18	38
Site No.	Gallium (µg/g)	lron (µg/g)	Lanthanum (µg/g)	Lead (µg/g)	Lithium (µg/g)	Magnesium (µg/g)	Manganese (µg/g)	Mercury (µg/g)	Molybdenum (µg/g)
PA1 shallow	19	51,000	29	54	36	14,000	660	0.12	6.7
PA1 deep	22	120,000	37	19	54	8,000	570	0.04	63

Table B1. detention t		ions of selecter ke Tahoe, Cali	d chemical const. fornia, water yea	ituents and per ir 2005—Conti	cent carbon in bo nued.	ottom sediment s	amples from Parl	k Avenue sto	rmwater
Site	Nickel	Niobium	Phosphorus	Potassium	Rubidium	Scandium	Selenium	Silver	Sodium
No.	(6/6rl)	(b/brl)	(b/brl)	(6/6rl)	(b/brl)	(b/g/)	(6/6rl)	(6/6rl)	(b/6rl)
PA1									
shallow	27	10	1,400	17,000	75	12	0.18	$\Diamond$	19,000
PA1									
deep	12	11	430	18,000	120	8.6	0.22	$\heartsuit$	18,000
Site	Strontium	Sulfur	Thallium	Thorium	Titanium	Uranium	Vanadium	Yttrium	Zinc
No.	(6/6rl)	(percent)	(b/brl)	(6/6rl)	(b/brl)	(b/g/)	(b/gl)	(b/brl)	(b/6rl)
PA1									
shallow	480	0.36	0.5	16	5,200	22	170	18	480
PA1									
deep	340	<0.05	0.74	34	5,400	180	520	12	79

<b>Table B2.</b> – detention ba	Concentrations of selv ssin, South Lake Tahoe,	ected polycyclic aromati California, water year 21	c hydrocarbon comp 005.	ounds in bottom sedimer	nt samples from Park Aver	nue stormwater
[Site location Abbreviation	ns and numbers are shc ns: µg/kg, microgram pe	own in figure 3. The term er kilogram; <, less than;	ı "water year" mean mm, millimeter; E, e	is a 12-month period beg sstimated]	inning October 1 and endi	ing September 30.
Site No.	Date	Fraction	Acenaphthene (µg/kg)	Acenaphthylene (µg/kg)	Anthracene (µg/kg)	Benz[a] anthracene (μg/kg)
PA1 shallow	08-31-05	<2mm	E100	<200	300	400
PA1 deep	08-31-05	<2mm	<10	<10	<10	<10
Site No.	Benzo[a]pyrene (µg/kg)	Benzo[b] fluoranthene (µg/kg)	Benzo[e] pyrene (µg/kg)	Benzo[g,h,i] perylene (µg/kg)	Benzo[k] fluoranthene (µg/kg)	Chrysene (µg/kg)
PA1 shallow	<500	009>	600	400	<300	500
PA1 deep	<10	<10	<10	<10	<10	<10
Site No.	dibenz[a,h] anthracene (µg/kg)	1,2-dimethyl Naphthalene (µg/kg)	1,6-dimethyl Naphthalene (µg/kg)	2,6-dimethyl Naphthalene (µg/kg)	2-ethyl Naphthalene (µg/kg)	Fluoranthene (µg/kg)
PA1 shallow	<100	<200	200	200	100	1,000
PA1 deep	<10	<10	<10	<10	<10	<10

<b>Table B2.</b> – detention ba	Concentrations of selvasin, South Lake Tahoe,	ected polycyclic aromatic California, water year 20	hydrocarbon compo 05—Continued.	ounds in bottom sedimen	ıt samples from Park Aveı	nue stormwater	
Site No.	9h-fluorene (µg/kg)	Indeno[1,2,3-cd] pyrene (µg/kg)	2-methyl Anthracene (µg/kg)	4,5-methylene Phenanthrene (µg/kg)	1-methyl-9h- Fluorene (µg/kg)	1-methyl Phenanthrene (µg/kg)	
PA1 shallow	<200	<400	<200	200	<200	200	
PA1 deep	<10	<10	<10	<10	<10	<10	
	1-methylpyrene (µg/kg)	Naphthalene (µg/kg)	Perylene (µg/kg)	Phenanthrene (µg/kg)	Pyrene (µg/kg)	2,3,6-trimethyl Naphthalene (µg/kg)	
PA1 shallow	<300	<100	400	800	1,000	200	
PA1 deep	<10	<10	<10	<10	<10	<10	

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