- Determine how changes in lake level affect near-shore processes, including shoreline erosion.
- Evaluate how hardening (reinforcement) of shore zones affects the near-shore environment. For example, how are erosion, deposition, and transport of near-shore sediments, hydraulics of wave run-up, and geomorphic processes affected by shore zone hardening?
- Develop a coarse-sediment mass budget for the near-shore environment. Is enough sediment being delivered to maintain beaches and near-shore habitat characteristics?

Define and assess the linkages between on-shore, near-shore, and mid-lake processes that affect water quality, clarity, and ecology—

- Define and create the tools to (1) simulate the transport of pollutants within the near shore and around the lake and (2) predict the ability of the near shore to buffer and propagate pollutant loading from onshore activities to mid-lake.
- Further refine/quantify the role of the near shore as an integrator of watershed, atmospheric, and mid-lake processes. Can a change in near-shore characteristics be used as an indicator for short-term, neighborhood-scale activities or as a long-term indicator for water impairment?
- Develop analytical approaches for generating quantitative water quality standards, thresholds, and indicators for the near-shore region.

Pollutant Loading From Urban Sources

Results of water quality monitoring show that for some urban land uses (e.g., roads and commercial development), the concentrations and loads of pollutants in surface runoff can be substantial. Although estimated flow from urban areas is only part of that from nonurban areas, the inputs of pollutants from these areas are 50, 60, and 72 percent of the total annual loads to Lake Tahoe for N, P, and fine particles (<16 µm), respectively (LRWQCB and NDEP 2008a).

Relative Contribution of Sediment Loading From Urban Sources

A number of studies have been completed over the past 30 years to address sediment delivery issues from various watersheds in the Tahoe basin. However, these studies have (1) generally focused on only a few streams within the watershed (Glancy 1988, Kroll 1976, Nolan and Hill 1991, Stubblefield 2002), and (2) usually considered only the larger category of total suspended sediments, rather than focusing on the finer fractions. More recently, studies have begun to examine the loading of total suspended sediment mass, along with suspended sediment mass for material <63 µm, and the number of particles for <16 µm sediment fractions (LRWQCB and NDEP 2008a, Sahoo et al. 2007, Simon et al. 2003, Tetra Tech 2007).

It is instructive to compare estimates of sediment loading to the lake from all sources, including the urban landscape (table 4.1). These results illustrate the importance of fine-sediment particle loading (number of particles) derived from urban sources.

Table 4.1—Total suspended sediment (TSS) and fine particle loading to Lake Tahoe for the major pollutant sources[a]

Pollutant source	TSS		TSS <63 µm		Particle number[b]	
	Metric tons/year	*Percent*	*Metric tons/year*	*Percent*	*<20 µm/year*	*Percent*
Urban upland runoff[c]	5,200	17	4,430	31	34.80×10^{19}	72
Nonurban upland runoff[c]	11,700	40	4,670	33	4.11×10^{19}	9
Stream channel erosion[d]	5,500	19	3,800	27	1.67×10^{19}	4
Atmospheric deposition[e]	NA	NA	750	5	7.45×10^{19}	15
Shoreline erosion[f]	7,200	24	550	4	0.11×10^{19}	<1
Total	29,600	100	14,200	100	48.14×10^{19}	100

[a] Values are expressed as metric tons/year (metric tons = 1000 kg) except for particle number, which is expressed as number of particles <16 µm/year (taken from LRWQCB and NDEP 2008a).
[b] Percentage values refer to the relative portion of total basinwide load.
[c] Upland runoff (urban and nonurban) is the annual mean value from measurements collected between 1994 and 2004.
[d] Stream channel erosion is the annual mean value from measurements collected between 1983 and 2002.
[e] Atmospheric deposition is a combined estimate of wet deposition (annual mean value from measurements collected between 1992 and 2003) and dry deposition (measured in 2003 only).
[f] Shoreline erosion represents a 60-year mean annual value.
NA = not applicable.

The total suspended sediment (TSS) loading from all major pollutant sources was estimated to be approximately 29,600 metric tons per year (MT/yr) (LRWQCB and NDEP 2008a). Upland watersheds, including stream channel erosion, account for 22,400 MT/yr, and represent 75 percent of the TSS load. Upland watersheds without the contribution from stream channel erosion, deliver 16,900 MT/yr, of which 5,200 MT/yr or 30 percent was generated from the urban portion of these watersheds. Shoreline erosion contributes on average about 7,200 MT/yr; however, it is likely that this source is highly variable from year to year, and the total erosion rate between 1938 and 1998 was affected by some very large events (Adams and Minor 2002). Stream channel erosion from both urban and nonurban stream sections combined was independently estimated at 5,500 MT/yr (Simon et al. 2003).

For the TSS <63 µm size fraction ($TSS_{<63\ \mu m}$), it was estimated that average annual loading to Lake Tahoe was 14,200 MT/yr from all sources (LRWQCB and NDEP 2008a). This accounts for nearly 50 percent of the total TSS loading. Upland runoff contributed 9,100 MT/yr, or 63 percent of the $TSS_{<63\ \mu m}$ load. The $TSS_{<63\ \mu m}$ loadings from urban and nonurban areas were virtually identical, at about 4,500 MT/yr. However, the loading ratio of TSS to $TSS_{<63\ \mu m}$ differed between urban and nonurban land use categories. For urban areas, approximately 85 percent of TSS load was in the $TSS_{<63\ \mu m}$ fraction, whereas only 40 percent of the TSS load from nonurban areas was contributed by this smaller size fraction. The contribution of TSS and $TSS_{<63\ \mu m}$ from the other major measured sources is shown in (table 4.1).

The first estimates of fine particle loading to Lake Tahoe in terms of particle numbers have only recently become available (LRWQCB and NDEP 2008a). These estimates were based on studies by Heyvaert et al. (2008), Rabidoux (2005), CARB (2006), Tetra Tech (2007), Sahoo et al. (2009), and Adams (2002). As discussed previously, although loading estimates for TSS and the $TSS_{<63\ \mu m}$ fractions are of interest, it is the fine particles <16 µm that are of greatest concern, as these have the most effect on lake water clarity.

The average annual load of fine particles <16 µm from all major sources was on the order of 5×10^{20}. Table 4.1 shows the estimated breakdown of loading by source categories for particle numbers in the <16-µm size range. Approximately 85 percent of the <16-µm size particle loading into Lake Tahoe is associated with surface runoff from urban and nonurban upland sources, including stream channel erosion. By far the most significant contributor was urban runoff, accounting for 72 percent of total lake loading for fine particles <16 µm. In contrast, the nonurban uplands only accounted for 9 percent of the fine particle loading, and stream channel erosion only accounted for 4 percent. It is very interesting to note that as the sediment size classification becomes smaller (i.e., from TSS to <63 µm to <16 µm particles), the relative contribution from urban areas increases substantially. Urban TSS load was estimated to be 17 percent. This nearly doubled to 31 percent for the <63-µm fraction and more than doubled again to 72 percent for the <16-µm particle number loads. Relative contributions from nonurban sources generally declined with decreasing particle size, except atmospheric deposition where loading from <16-µm size particles increased to 15 percent of the total.

Sources of fine sediments in urban areas of Lake Tahoe also include gully erosion from roadside ditches, upstream sediments that are more efficiently passed through urban drainage systems and concentrated in discharges, fine particulates washed off urban surfaces (including applied sanding materials, break-pad wear, or air deposition), and downstream erosion caused or accelerated by urban runoff discharges that exceed natural runoff conditions.

Urban Hydrology

Much of the existing urban stormwater drainage system around Lake Tahoe was installed as part of subdivision development many decades ago, when the main purpose of drainage system design was to provide efficient stormwater conveyance and flood control, with minimal design considerations given toward downstream water quality effects. Currently, insufficient hydraulic retention exists within many urban drainages. Instead, culverts and ditches generally concentrate and expedite runoff from urban watersheds into receiving waters. As a consequence, peak flows at most storm frequencies are much higher than would occur without urban development; these higher peak flows not only facilitate pollutant transport, they also enhance erosion within urban watersheds.

Runoff rates and volumes are sensitive to the amount of impervious surface area and its connectivity to drainage systems. Existing regulations on new development focus on the onsite retention and infiltration of runoff from impervious surfaces, and substantial investments are being made to retrofit existing development with new best management practices (BMPs) and public drainage improvements.

Alan Heyvaert

Urban stormwater discharge to the Upper Truckee River at Highway 50.

These BMPs are usually designed to accommodate the 20-year storm (equivalent to about 2.54 cm of precipitation in 1 hour). Although this approach may be adequate for designing individual BMPs, managing urban stormwater quality at Lake Tahoe will depend on a fully integrated understanding of the existing pathways of urban drainage on a subwatershed scale. Without a better understanding of the degree of connectedness between pervious and impervious parcels within the drainage in a subwatershed, estimating load reduction for the purpose of the TMDL will be done for individual projects in isolation and will ignore the connectivity along the pollutant pathway defined by regional hydrology.

Land Use and Runoff Water Quality Relationships

Our understanding of land use-water quality relationships in the Tahoe basin is based on five sources (1) the data collected since 1978 by the LTIMP (Coats et al. 2008, Rowe et al. 2002); (2) the recently completed Lake Tahoe TMDL Stormwater Monitoring Study (Coats et al. 2008, Gunter 2005); (3) the Tetra Tech LSPC (Loading Simulation Program in C++) hydrology-water quality model recently developed for the Lake Tahoe TMDL (Riverson et al. 2005), (4) the Pollutant Load Reduction Model (NHC 2009), and (5) process-based studies of nutrient and sediment sources and transport in subalpine watersheds in and near the Tahoe basin (e.g., Coats and Goldman 2001; Hatch et al. 2001; Heyvaert and Parra 2005; Heyvaert et al. 2006; Johnson et al. 1997; Merrill 2001; Miller et al. 2005; Murphy et al. 2006a, 2006b; Sickman et al. 2002; Simon et al. 2003; USFS 2004).

The designation of land use groups was a critical first step in developing watershed-scale estimates of pollutant loads under the Tahoe TMDL (LRWQCB and NDEP 2008a). Land uses have been grouped into 20 categories for the Tahoe basin. The second critical step in characterization of land use-runoff relationships was the estimation of runoff volumes for each land segment. This estimation was done using the Tetra Tech LSPC watershed model with hourly weather data and land-segment-specific hydrologic parameters that have been measured, estimated, or calibrated to reflect the unique characteristics of watersheds around the lake. In the Lake Tahoe watershed LSPC model, event mean concentration data from the TMDL Stormwater Monitoring study were used to model characteristic runoff water quality from different urban land use types. An event mean concentration (EMC) is a calculation used to provide a flow-weighted concentration for a pollutant in question that summarizes conditions during a defined stormwater runoff event. The EMC multiplied by total flow during a stormwater runoff event is taken as the estimated load during the event. For primary roads, the EMCs were developed using a combination of Caltrans and Nevada Department of Transportation (NDOT) monitoring data. Runoff sediment and nutrient loads were estimated by applying EMCs to modeled runoff volumes. The characteristic EMCs and load estimates can differ substantially by land use, region, soil type, and season of the year (e.g., Coats et al. 2008).

Based on the studies described above, it is known that compared to undisturbed and naturally functioning forested lands, the urbanized areas produce much higher concentrations of ammonium-N, nitrate-N, total N, orthophosphate, total P, and also in some cases, suspended sediment. There are also large differences in the yield rates (loading per unit area) of nutrients and sediment for different watersheds in the basin (LRWQCB and NDEP 2008a, Tetra Tech 2007).

In general, for the 10 watersheds sampled as part of the LTIMP (Rowe et al. 2002) the relative concentrations of N and P forms decrease in order: organic-N > nitrate-N > ammonium-N; and total P > dissolved P > orthophosphate. In some urbanized areas, the ammonium-N can be a significant fraction of total N load, whereas it is generally insignificant for watersheds containing little urbanization (Coats et al. 2008, Gunter 2005).

The concentrations and loads of nutrients and sediment are directly related to impervious surface area. In developed areas, the concentrations of P (orthophosphate and dissolved P) are generally related to percentage of residential impervious area, although N concentrations (nitrate-N, ammonium-N, and organic-N) are directly related to the density of multifamily residential lots (LRWQCB and NDEP 2008a). Suspended sediment concentrations are directly related to percentage of area in commercial-industrial-communications-utilities land uses (Coats et al. 2008, Gunter 2005).

Stream channel erosion is a source of TSS in the Tahoe basin streams (see table 4.1), and as noted above, channel erosion can be exacerbated by increased runoff from urbanized areas. Discharge-concentration relationships in basin streams differ greatly among constituents, and with season (Rowe et al. 2002). This variability strongly influences the accuracy and precision of load estimates. Orthophosphate concentrations are strongly controlled by equilibrium reactions with the substrate, and do not change greatly with discharge. Nitrate-N is influenced by biological release and uptake, and by an annual washout cycle, with high autumn and low spring concentrations. The concentrations of particulate constituents (e.g., total P and TSS) are both flow and supply-driven, and vary by orders of magnitude throughout the year.

Role of Highway Surfaces and Shoulders on Pollutant Runoff

Highway surfaces represent about 15 percent of total impermeable surface area in the Tahoe basin. Yet, because of the large number of vehicle miles traveled on these surfaces and the hydraulic connectivity that these routes provide, they often contribute stormwater runoff concentrations that are much higher than observed from other distributed land use types. This is particularly true for fine-particle concentrations in roadside runoff. The Lake Tahoe TMDL has identified that over 50 percent of the fine particles (<16 µm) may originate from the basin's extensive network of primary and secondary roads.

Highway and road runoff typically contain high concentrations of fine sediment, presumably from the abrasive action of traffic on roads and roadside soils and on winter traction materials applied to road surfaces. Traffic and parking on road shoulders in particular, causes considerable damage to the vegetation and the soils surrounding most roads. This compaction increases runoff as well as the loads of sediments and fine particles.

The optimal conditions for fine particle settling include long hydraulic residence time and minimal water movement. Unfortunately, the size/area requirements for construction of optimal BMPs are usually not feasible alongside most roadways, given their limited rights-of-way, terrain constraints, and sensitive environments. Installation of large underground vaults generally is not practical either because of utilities, traffic, and maintenance requirements. These systems also require ready access and easy maintenance to ensure effective long-term functioning. Therefore, new approaches are being sought for treating highway runoff to the level required in the Lake Tahoe basin.

Source control measures are necessary to help prevent sediment from becoming entrained in highway and urban runoff. Revegetation and soil restoration success, however, can be limited by factors that include the dry summer climate at Lake Tahoe, steeper topography, and nutrient-poor soils. In some cases, armoring of highway cut and fill slopes is a successful alternative with appropriate applications and dispersed runoff flows.

Recreational Impacts

There are three types of recreational facilities that can result in accelerated erosion and runoff. These consist of native-surface roads and trails, developed recreational facilities (e.g., visitor centers and trail heads), and established recreation sites (e.g., campgrounds and ski areas). Developed recreational facilities generally exhibit the same features and impacts typical of other urban development (e.g., parking lots and buildings). Forest roads and trails, ski runs, and campgrounds, however, all have unique characteristics that increase their potential sediment and nutrient loading into receiving waters if appropriate BMPs are not properly installed and maintained.

The major risks to water quality from forest road and trail networks exist on those road segments that are hydrologically connected to stream crossings. So proximity of roads and trails to stream channels is the single greatest concern related to road/trail impacts on water quality. Between 2002 and 2005, the Forest Service implemented a forest road BMP retrofit program to reduce the connected length of roads, particularly at stream crossings. This program has decommissioned approximately 150 km of roads, and has conducted BMP retrofits on 241 km of roads. In 2005, the USFS initiated a similar retrofit program for trails. The effectiveness of both programs has been under evaluation (USFS 2002). Based on this work, it is now understood that maintaining the efficacy of the BMPs typically applied to native surface roads and trails requires a high frequency of maintenance. However, preliminary monitoring results also indicate a substantial reduction in the potential for erosion and transport of sediments as a result of efforts to retrofit, upgrade, and decommission forest roads in the Tahoe basin.

A decade of monitoring at Heavenly Ski Area indicates substantial improvement can be achieved at ski areas in relation to water quality, soil condition, erosion control, and sediment transport (USFS 2004).

Knowledge Gaps

Urban hydrology—

Urban hydrology in the Tahoe basin is complicated by the fact that developed communities are relatively small, and highly influenced by runoff from wildland regions that are immediately adjacent and often located within the urban boundaries. Although models are used for uniform runoff computations for designing specific BMPs and runoff conveyance features in the Tahoe basin, no attempt has been made to comprehensively model flow from its upland source through all the urban features (including specific BMPs and water conveyance features) and finally into Lake Tahoe or one of its tributaries. Furthermore, project-specific models for BMP-related runoff computations are generally not well calibrated, and the effects of rain on snow have been difficult to estimate. Precipitation and flow monitoring data are scarce in urban areas of the basin. Our understanding of snow hydrology in urban areas and its contribution to seasonal runoff patterns also is limited. The Pollutant Load Reduction Model is a recent attempt to more accurately estimate runoff from project areas. However, it would benefit from more specific data.

Land use and runoff water quality relationships—

The uncertainty associated with estimates for loads and concentrations is not well-determined. Specifications for two kinds of error are recommended. The first is sampling error associated with taking instantaneous samples of continuous concentration variables. The second is prediction error associated with regression estimates based on the relationships between concentration and discharge. Despite some published data (e.g., Loupe 2005, Meidav 2008, Miller et al. 2005) there is also considerable uncertainty associated with the runoff from vegetated land use categories, representing a large part of the Tahoe basin.

Role of highway surfaces and shoulders on pollutant runoff—

The contribution of highway stormwater runoff and pollutant generation is not well-defined relative to total watershed impervious surface areas and the percentages of pollutants generated specifically within the road and rights-of-way. Although curb and gutter installations reduce road shoulder compaction and erosive runoff scouring, these structures generate larger runoff volumes at higher velocities. So effective alternative designs are needed to disperse roadway flows while preventing erosion. These designs also need to reduce the migration of soils and fine particles onto road surfaces, and their subsequent transport to receiving waters.

Sources and transport of fine sediment—

Because the reduction of fine particles is considered key to improving the clarity of Lake Tahoe (LRWQCB and NDEP 2008a, 2008b, 2008c), more detailed information is needed on the specific sources of fine particles and the relationships between natural watershed characteristics (e.g., geology, aspect, slope, vegetation cover), anthropogenic features (e.g., roadways, transportation/traffic, land use), and fine sediment loads from watershed drainages in urban areas.

Recreational impacts—

Increasing use and prevalence of trails around urbanized areas may be of concern, especially where hikers and mountain bikes are causing hillslope erosion, meadow disturbance, or streambank degradation. Roads may present even greater water quality concerns owing to their larger disturbance area, greater traffic volume, and larger stream crossings. Although ski run restoration has provided substantial increases in overall effective soil cover (and subsequent reductions in erosion), monitoring indicates that some areas of the mountain do not respond to current restoration practices. Therefore, better methods are still needed for maintaining vegetative cover in difficult conditions.

Pollutant transport from urban areas—
Hydrologic adjustments are still being accommodated from historical disturbances in most drainages receiving runoff from urban land uses. We need a better understanding of stable equilibrium conditions in urban drainages and streams. On a basinwide or regional scale, the extent of specific urban area erosion problems (hot spots) and their relative contribution to long-term pollutant loads is unclear. Better spatial information is needed for all urban drainage systems in the Tahoe basin, especially for those that discharge directly to the lake or to potentially erosive channels, streams, and overland flow areas.

Research Needs

Urban hydrology—

- Review and compile data from local runoff monitoring so that a Tahoe basin urban hydrologic monitoring network can be designed and implemented to provide consistent, comparable, and continuous urban flow data.
- Implementation of a Tahoe basin meteorological network is recommended to supplement existing long-term monitoring sites (SNOTEL, National Climate Data Center) and improve the utility of hydrologic monitoring and modeling.
- Conduct modeling studies of monitored catchments to identify sensitive parameters and develop appropriate calibration and parameter estimation techniques.
- Develop a coordinated modeling approach to simplify regional relationships for estimating runoff flow-duration characteristics and time series of flows from urban areas.

Land use and runoff water quality relationships—

- Conduct research to quantify fine particle and nutrient loading from nonurbanized, vegetated areas.
- With regard to urban stormwater flow, gain a better understanding of the temporal-and spatial-scale processes associated with hydrology and pollutant transport between pervious and impervious areas.
- Better assess relative contributions from specific land use sources for particular pollutants of concern, including fractionalization into the dissolved, bioavailable, and total constituent concentrations.
- Develop refined pollutant load estimates for the various land uses with a comparison of continuous and event-based modeling approaches for application to drainage and water quality project design.

- Conduct comparative water quality modeling studies in catchments where monitoring data are available or where monitoring is planned to improve our understanding of the relative importance of spring snowmelt, "first flush," and extreme events.
- Validate models that estimate sediment and nutrient loading/load reduction from urban land uses.

Role of highway surfaces and shoulders on pollutant runoff—

- Continue monitoring stormwater from highway runoff, including assessment of sediment loads and particle size distributions, to better understand spatial and temporal variability.
- Conduct quantitative evaluations to guide appropriate curb and gutter designs or alternatives that will reduce runoff volumes and pollutant loads while limiting roadside parking and soil compaction. These recommendations could address differences in roads at higher versus lower elevations, and between urban and rural areas, as well as between different types of road surfaces.
- Conduct studies on the effectiveness of different source control measures, such as paving of roadside ditches, placing riprap on cut and fill slopes, or the revegetation of disturbed areas, especially as these practices relate to mobilization and transport of fine sediments.
- Develop better estimates for the pollutant load reduction of maintenance associated with road sand collection, sweeping, and sediment removal. Better estimates are particularly needed for fine sediments <16 µm.
- Research the development of highway runoff treatment BMPs that remove fine sediment from stormwater runoff. This research could include methods that increase fine sediment capture with new types of hydraulic structures and with the retrofit of existing structures, e.g., drop inlets and small settling basins.
- Conduct research to determine the specific size range for fine-grain sediments that are best targeted in treating highway runoff, and the amount of P that can be removed with this sediment.
- Gather more systematic information on the effectiveness of infiltration systems, given characteristics of Tahoe basin soils, and where these basins are optimally located to best treat highway runoff.

Sources and transport of fine sediment—

- Conduct comparative assessments of the various methods for determining and reporting particle-size distribution, with the goal of developing recommended uniform protocols for data analyses and for reporting results.
- Ascertain relationship between turbidity and the number of fine particles for monitoring load reduction.
- Compile and review the available monitoring data for particle-size distribution to improve estimates of loading by land use category, by drainage characteristics, and by catchment conditions.
- Conduct studies to expand understanding of particle-size distribution loads from all land use categories, including source-specific studies on anthropogenic activities that produce and mobilize fine sediments.
- Conduct trend analyses of particle-size data to describe the temporal and spatial contributions of fine-sediment loadings from dominant sources, including relative contributions.
- Complete studies on the mass of particles contributed annually from abrasive wearing of road surfaces, including the characterization of size distribution and the chemical properties of this material.
- Increase measurements of the percentage of snow traction material removed by street sweeping activities, and the amount of material remaining. Conduct studies to better understand the drainage characteristics of primary and secondary roads as this flow transports fine particles and other pollutants to receiving waterbodies. Determine how road sand is pulverized by tires and quantify the conversion of large particles into smaller, more environmentally relevant sizes (i.e., <16 µm).

Recreational impacts—

- Revisit high- and moderate-risk road segments that did not improve with BMP retrofits to identify the causes of failure and possible improvements. This could also address the amount of maintenance required to maintain efficacy of BMP retrofits over the long term.
- More intensively monitor ski resort impacts throughout the Tahoe basin, as is done currently at Heavenly Ski Resort. Ideally, this monitoring also would include the evaluation of soil restoration approaches being developed through the California Alpine Resort Environmental Cooperative.
- Evaluate water quality effects from low-impact techniques currently used and proposed by ski resorts in removing trees to create new glades and runs.

- Assess the distribution of impacts from trail development and use near urban areas (especially with respect to mountain bike use).
- Assess the distribution and impacts from fertilizer applications on recreational areas such as ball fields, golf courses, and public lawns.

Pollutant transport from urban areas—

- Conduct process-based studies to describe the sources, transport mechanisms, and sinks for nutrients and sediments on their journey from urban landscapes to Lake Tahoe.
- Conduct studies to better understand pollutant accumulation, transformation, and transport processes in snow and snowmelt, especially for roadway, roadside, and parking lot snowpacks. These snow and snowmelt studies could include monitoring to better evaluate pollutant release from roadside snowpack under various settings and management strategies (e.g., highway versus secondary streets, heavy versus light traction abrasive application, shade versus sun, plowing and blowing versus hauling or moving).
- Understand how new improvements will affect drainages, and what improvements are needed to allow watersheds to reach their desired equilibrium states is important. In addition to the hierarchical approach of source control, hydrologic design, and treatment is generally recommended, but alternative or complementary strategies also could be evaluated. Furthermore, it is recommended that monitoring, modeling, and project construction all occur on equivalent time scales to obtain validation data from “real” projects.
- Develop a field classification scheme for identification of specific erosion problem areas (hot spots) as sources of sediment and nutrients. Watershed and drainage inventories that map the type, extent, and condition of hot spots according to an established classification scheme would help target mitigation projects. This would lead to research and monitoring to develop estimation techniques for evaluation of erosional hot spots as sources of sediment and nutrients to downstream waters. It would be useful to understand how much of the loads and concentrations measured in monitoring data (e.g., the land use-based characteristic concentrations) are associated with erosional hot spots versus distributed sources.
- Complete of a basinwide inventory to provide detailed spatial information on the distribution of drainage systems and discharges, as well as existing downstream conditions. This inventory could address legacy as well as modern drainage and conveyance routes, and BMP installations. Local agencies have started this work.

- Develop better predictive models for evaluating the effects from disturbance and mitigation projects that change runoff paths, volumes, velocities, and patterns, especially as this relates to the potential loading of fine particulates from accelerated channel, stream, and overland flow erosion. These models could provide comprehensive watershed analysis for evaluating the best methods to reduce peak flows and pollutant loads from urban watersheds.

Peter Goin

Active streambank erosion along the Upper Truckee River, south of Highway 50.

Stream Channel Erosion

In addition to affecting lake clarity, sediment derived from stream channels can affect localized hydrology, instream habitat for lotic aquatic biota, and stream-water quality. Streambank erosion has been identified as a source of TSS from several watersheds as a result of extensive reconnaissance-level field work throughout the Tahoe basin, and by resurveying monumented cross sections originally established in the 1980s (Hill et al. 1990, Simon et al. 2003). In particular, streambank erosion in Blackwood and Ward Creeks, and the Upper Truckee River was found to be the major contributor of TSS from these watersheds (fig. 4.7) (Simon et al. 2003). Overall, the contribution of sediment (<63 µm in diameter) from streambank erosion was estimated by developing an empirical relationship between measured or simulated bank-erosion rates (adjusted for the content of silt and clay in the bank material) with a field-based measure of the extent of bank instability along given reaches and streams (Simon 2006). Measured unit values of fine sediment erosion rates ranged from 12.2 $m^3 \cdot y^{-1} \cdot km^{-1}$ for Blackwood Creek to 0.002 $m^3 \cdot y^{-1} \cdot km^{-1}$ for Logan House Creek (Simon 2006). Based on this empirical relationship, the Tahoe Watershed Model (Tetra Tech 2007) predicted that the contribution of stream channel erosion to total sediment loading from all sources was 19 percent, although the contribution of stream channel erosion to the number of fine sediment particles <16 µm in diameter (the pollutant of concern for water clarity) is currently estimated to be <5 percent of that from all sources (see "Lake Tahoe Water Clarity" section).

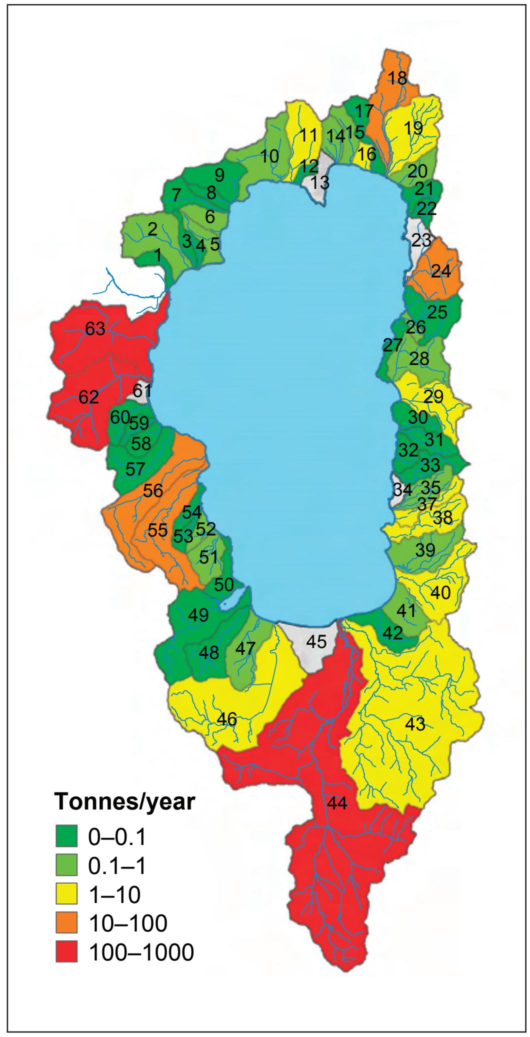

Figure 4.7—Fine-sediment loadings from streambank erosion (from Simon 2006).

Knowledge Gaps

The following discussion focuses on uncertainties and research needs associated with estimates of fine-sediment loadings from streambanks.

Stream channel cross sections—

- Estimates of sediment (<63 µm) loadings from streambanks are based on limited time-series cross-section surveys from a handful of streams and numerical simulations of three streams that were then extrapolated basin-wide based on observations of the extent of bank erosion at about 300 sites across the watershed. Although these data represent good estimates based on available data, additional time series and site observation data could reduce levels of uncertainty.

Fine sediment sources and channel processes—

- The influence that urbanization in the Tahoe basin has on runoff and stream hydrology and ultimately stream channel erosion is not fully understood.
- Uncertainties exist in the ability to quantify rates and volumes of bank erosion on stream segment and river-wide scales under historical, current, and future conditions. For example, measurements of flood-plain deposition rates in downstream areas of the Upper Truckee River and other streams will aid in determining the fate of fine sediment eroded from upstream areas.
- A better understanding of flood-plain processes, channel overbanking frequency and dynamics, and other geomorphic processes is needed to help guide restoration planning.
- The legacy impacts upon current rates of stream channel erosion and sediment transport from major watershed disturbance that occurred during the timber clearcut in the late 1800s are not well understood.

Model improvement—

- The CONCEPTS model needs to be further calibrated (for specific conditions at Lake Tahoe) and validated to demonstrate its effectiveness in providing useful guidance for design-level planning at the project scale.
- Improved erosion routines in the upland flow and sediment transport models are needed as they serve as the upstream boundary condition for running the CONCEPTS channel-evolution model and predicting upland contributions.

Research Needs

Stream channel cross-sections—

- Establish, monument, and maintain additional cross sections for annual surveys. Collect field observations along stream courses, particularly in previously unsampled streams. Ideally, these surveys would include determination of the particle-size distribution of stream channel material susceptible to erosion.

Fine sediment sources and channel processes—

- Separate natural from anthropogenic stream channel erosion loading to distinguish between baseline loads and treatable loads.
- Conduct sediment-tracking research using stable radionuclides or other elements to differentiate between the percentage of sediment and fine particles emanating from upland and channel sources.

- Complete additional modeling of streams that are known to contribute substantial quantities of sediment from the channel margin using CONCEPTS to test alternative strategies for erosion control and to predict the amount of load reductions that could be obtained by these strategies.
- Determine the influence of the Comstock logging activities on current stream channel erosion; determine how (if) legacy impacts from the Comstock logging will affect the efficacy of future channel restoration work.
- Establish an understanding of recent (historical and late Holocene) streambank sediment sources, sizes, and relative rates of erosion.
- Link CONCEPTS modeling flood-plain water quality modeling to estimate load removal associated with channel overflow.

Model improvement—

- Develop improved hydraulic routines, in 2- and 3-D to support better channel model (CONCEPTS) predictions of lateral migration, bank erosion, planform change, and slope adjustment.
- Fully integrate the CONCEPTS channel evolution model with the upland flow and sediment-transport models AnnAGNPS and LSPC.
- Test and validate estimates of the shear stress required to entrain upland materials and the associated erodibility coefficient used in the upland models. Ideally, this work would be completed on different soils and geologic units using in situ field-based measurements.
- Collect calibration/validation data regarding ground water, surface water, seasonal ice, and vegetation interactions, with regard to bank failures in selected reaches that have been or are being modeled using CONCEPTS.
- Collect field data regarding the in situ bank strength properties of stabilized or constructed bed/banks associated with recent stream restoration practice, such as excavated channels, placed riffles, or sod revetments.

Water Quality Treatment

Water quality treatment and source control measures are a key focus of management programs aimed at improving water quality in the Lake Tahoe basin. Although important research and monitoring has occurred in the past, future efforts will be most productive if they are hypothesis-driven to answer specific questions on the best methods for water quality treatment and source controls throughout the basin. Further, better integration of the research and monitoring results to date is recommended to address information needs at multiple spatial scales (e.g., at the project, watershed, and basinwide scales).

As with the other subthemes considered in this chapter, fine sediment and the nutrient forms of N and P are the primary pollutants of concern relative to water quality treatment and source control. Fine sediment and nutrients enter the lake from streams, atmospheric deposition, intervening areas, shoreline erosion, and by ground-water inflow (LRWQCB and NDEP 2008a, Reuter and Miller 2000, Reuter et al. 2003). Since 1970, several projects have been undertaken to reduce the quantity of sediment and nutrients entering the lake. Perhaps the most important project has been the pumping of treated effluent out of the Lake Tahoe basin. Additionally, the 1987 Clean Water Act Revision greatly affected transportation agencies by requiring more emphasis on wetland mitigation and stormwater management. Transportation agencies throughout the country began constructing wetlands and stormwater detention basins in response to provisions in the act. Numerous detention basins have been constructed in the Lake Tahoe basin (Fenske 1990, Reuter et al. 1992b). Constructing wetlands in or adjacent to stormwater detention basins has been shown to provide marked improvements in the quality of stormwater runoff (Martin 1986; Scherger and Davis 1982; Reuter et al. 1992a, 1992b). However, some potential exists for degradation of the ground-water quality beneath detention basins and associated wetlands (Church and Friesz 1993, Granato et al. 1995, K.B. Foster Civil Engineering Inc. 1989, 2ndNature 2006a).

Planning for a comprehensive water quality treatment plan for the Tahoe basin has taken a substantial step toward the completion of a pollutant reduction opportunity evaluation (LRWQCB and NDEP 2008b) as part of the Lake Tahoe TMDL. This analysis estimated potential pollutant load reductions and associated costs at a basinwide scale. It was the first comprehensive analysis of possible load reductions from the major source categories of urban runoff and ground water, atmospheric deposition, forested uplands, and stream channel erosion. This analysis was done in three steps including (1) an evaluation of potential pollutant controls applicable within the Tahoe basin, (2) a site-scale analysis that included an evaluation of treatable areas and the potential level of treatment within each, and (3) an extrapolation to the basinwide scale. The uncertainty analyses conducted for each of the major pollutant source categories in that report highlighted where assumptions were made and best professional judgment applied. Much of the research discussed in this section will help fill those types of knowledge gaps and advance the TMDL as a living water quality improvement plan for Lake Tahoe.

BMP Implementation, Operations, and Maintenance for Water Quality Treatment

Implementation of BMPs in the Lake Tahoe basin has generally focused on soil restoration projects and hydrologic controls (installation of basins, culverts, and surface runoff conveyance). The overall effectiveness of these strategies has not been well evaluated for water quality improvements. Although a few individual BMPs have been extensively monitored for performance in the Tahoe basin, these tend to be the exception (e.g., the compilation of published studies in 2ndNature 2006b, Reuter et al. 2001). There is not yet a clear understanding of what BMPs work in subalpine environments like the Tahoe basin. It is likely that continued implementation and management of water quality BMPs in the Tahoe basin will be necessary over the long term. Thus, a better understanding of effective BMP design, operation, and maintenance will be essential for sustained water quality improvements.

Effective BMPs for the protection and restoration of Lake Tahoe clarity will differ in some aspects from standard designs used in other parts of the country, largely owing to the unique climate characteristics in the Tahoe basin (e.g., rain and snow in winter, infrequent thunderstorms, and dry summers), as well as the fairly thin granitic soils, relatively low BMP influent concentrations, and very low desired BMP effluent concentrations. Thus, for Tahoe installations, it has been difficult to use with confidence the BMP design and effectiveness information from other parts of the country. Preliminary results from Tahoe-specific studies suggest, however, that in some cases, the overall effluent concentrations and efficiencies are similar to the national averages (Heyvaert et al. 2006b).

Most annual runoff into Lake Tahoe occurs from snowmelt and rain-on-snow events. These are typically due to large frontal storms that arrive as nominally uniform events around the Tahoe basin, where BMPs are usually designed to meet standards of hourly precipitation intensity (e.g., the 20-yr, 2.54-cm of precipitation in 1-hour storm event). In contrast, high-intensity thunderstorms typical of summer are much more variable in terms of spatial extent and intensity. A short-duration Tahoe summer thunderstorm of only 10 to 15 min can generate very high flows that scour online BMPs and exceed the first-flush capacity of offline BMPs. These summer thunderstorms are frequently a substantial source of sediment loading (Gunter 2005, Jones et al. 2004).

In the Tahoe basin, studies of BMP effectiveness have been largely confined to new or well-maintained projects. These studies may not capture the true range of performance for different types of BMPs or BMPs of different ages. Most treatment BMP designs in the Tahoe basin do not undergo comprehensive scientific or technical review by specialists. Common design problems, such as hydraulic short-circuiting, could be avoided if this review practice were implemented as a standard operating procedure.

Typical BMP evaluations can underestimate total particulate loads, especially the flux of very coarse material and debris that tends to fill basins and vaults. Capturing this information is important for developing maintenance programs. To address this issue, an alternative mass balance approach has been recommended, where feasible, for basins and vault evaluations (Heyvaert et al. 2005). This alternative approach substantially improves estimates of performance and life-cycle costs, particularly as related to maintenance requirements. To date, only limited data are available on the sustainability and life-cycle costs of BMPs. This is especially true for infiltration basins because of their high rates of failure caused by reduced infiltration capacity over time.

Detention basins are one of the most common BMPs in the Tahoe basin for removing sediments, nutrients, and other contaminants from urban and highway runoff. Although this type of BMP may abate surface-water loads, any infiltrated stormwater can contaminate shallow ground water and potentially increase the ground water gradient and flows into the lake. In addition, contaminants associated with urban runoff often include organic compounds and metals that are potentially toxic when consumed with drinking water. Processes that affect ground water contamination from stormwater have only just begun to be considered (e.g., Prudic et al. 2005, Thomas et al. 2004), but understanding these details is important because a substantial number of EIP projects are planned that will increase infiltration of urban runoff to comply with TMDL regulations.

Pollutant loads in Lake Tahoe are highly variable under the normal range of annual precipitation and runoff (Heyvaert et al. 2008). Therefore, accurate estimation of long-term benefits from various management strategies will depend upon simulations over the full range of climate conditions and would include phased implementation for improvements, coupled with the effects from variable runoff quantity and quality. The first step toward this approach has been made with development of the LSPC watershed model and the LCM, as part of phase 1 in the Lake Tahoe TMDL program (LRWQCB and NDEP 2008a, 2008b; Perez-Losada 2001; Riverson et al. 2005; Sahoo et al. 2007; Swift et al. 2006). Initial modeling results and monitoring data confirm, for example, that high runoff years are highly correlated with declines in lake water clarity. Better BMP designs, implementation, and maintenance will be needed to help reduce this effect.

Urban Source Control

Hydrologic management is typically one of the first steps in sediment source control for urban landscapes. By reducing runoff intensity and volume, the downstream hydrographs show lower peak flows that are spread over longer periods and generally have lower pollutant loads. Hydrologic management also is an effective form of erosion control; however, some level of soil restoration is often necessary in disturbed areas to remediate compaction, protect surfaces, and restore soil function (see “Key Soil Properties” section in chapter 5). Other forms of source control include structures or materials, such as retaining walls or rock and vegetation coverage of unstable roadcuts or slopes. Hydrologic management in urban areas will be especially important for controling soil erosion from erosional hot spots, areas that produce large sediment loads during stormwater runoff.

New Treatment Technologies and Enhanced BMP Designs

Standard types of BMPs may not adequately achieve the pollutant load reductions necessary for improving Lake Tahoe clarity. A combination of standard BMPs and new types of BMPs will likely be needed to achieve low pollutant effluent concentrations destined for Lake Tahoe. Thus, additional efforts have been made over the last few years to explore alternative approaches and technologies for stormwater treatment in the Tahoe basin. Various mechanical and chemical methods for purifying water are well known. However, they tend to be expensive, energy intensive, and are not well suited for dealing with large volumes of stormwater runoff. In addition, there are certain factors at Tahoe that constrain potential solutions for stormwater runoff quality, including (1) extremely low nutrient and sediment target concentrations and (2) cool subalpine air and water temperatures that limit biological productivity. In wetlands, for example, the nutrient uptake by macrophytes and emergent vegetation tends to be lowest in winter and spring, which are times of maximum storm runoff and snowmelt (Reuter et al. 1992a).

There are three broad areas of research on new BMP technologies that could be applicable to the Lake Tahoe basin. These include studies on (1) unit processes and treatment trains, (2) hybrid systems that provide chemical and mechanical augmentation of natural processes (e.g., co-precipitation of P with aeration and water pumping in constructed wetlands), and (3) novel ecological treatment systems (e.g., cultured periphyton, floating wetlands, submerged aquatic vegetation, clams and other filtering organisms, complex ecologies, and industrial food webs).

Coagulation is beginning to be more tested and applied for reducing stormwater turbidity (e.g., Harper et al. 1999). Laboratory and small-scale coagulations studies for the Tahoe basin have demonstrated that dissolved P and fine particles can be removed effectively with coagulation (e.g., Bachand et al. 2006a, 2006b; Caltrans 2006). Ultimately, the new treatment technologies required to achieve compliance with TMDL and water quality standards in the Tahoe basin may approach or be equivalent to technologies employed in the drinking water and wastewater treatment industries, including reverse osmosis, membrane filtration, flocculation, sedimentation, and filtration.

Phosphorus removal by adsorptive media is another BMP technique currently under investigation, in part because soils in the Tahoe basin have relatively low P adsorptive capacity. Although the use of natural or engineered media (including derivatives of calcium, aluminum, iron, or lanthanum) can greatly increase available adsorptive capacity, they also cause changes in pH and other chemical characteristics of the treated water that may be detrimental (Bachand et al. 2006a, 2006b; Caltrans 2006).

Existing BMP standards tend to result in designs that are not optimized for targeted pollutants in the Lake Tahoe basin. Most BMPs, for example, will not effectively remove fine particles and dissolved P from storm runoff when there is surface outflow through the systems (2ndNature 2006b, Strecker et al. 2005). Simply implementing current BMP designs, therefore, is not likely to meet the ultimate requirements for maintaining or improving lake clarity. Advancing BMP design standards at Tahoe will be important for achieving the TMDL and effluent standards.

Substantial efforts have been completed recently for enhancing BMP design in the Lake Tahoe basin. One such project is the Lake Tahoe Basin Stormwater BMP Evaluation and Feasibility Study (Strecker et al. 2005); another is the Pollutant Load Reduction Model (NHC 2009). These projects have assessed current design standards for BMPs in the Lake Tahoe basin, and have suggested potential refinements to BMP designs that would enhance performance. In addition, they have provided a draft methodology and associated spreadsheet tools for assessing options that maximize BMP effectiveness, both onsite and at the small watershed scale. Together, these projects have applied the latest BMP performance information from both the National BMP Database and from local Tahoe BMP performance studies, along with scientific knowledge on unit processes, to provide a reasonable evaluation of potential enhancements to BMP performance that could improve treatment for the pollutants of concern.

Knowledge Gaps

BMP implementation, operations and maintenance for water quality treatment—

A uniform definition that quantifies BMP effectiveness in treating fine sediment and dissolved fractions of nutrients on an event, seasonal, and annual basis is recommended. This definition would be based on performance studies in the Lake Tahoe basin given the low effluent standards and the primary pollutants of concern. Ultimately, a much better understanding of effective treatment technologies, including treatment train approaches and infiltration practices is recommended to achieve compliance with Lake Tahoe TMDL requirements, particularly in areas of high-density development.

The costs and components of oversight programs to ensure that BMPs are correctly monitored, maintained, or retrofitted to meet the fine particle and nutrient load reduction requirements have not been determined. Particular information needs include the long-term sustainability and life-cycle costs of BMPs, removal costs for particulate residuals, and disposal requirements for each type of BMP.

A better understanding of the interactions among source categories and BMP implementation strategies is needed for accurate model simulations. When appropriately calibrated and verified, these simulations would provide opportunities to investigate the effectiveness of potential management actions on achieving environmental thresholds as part of the TMDL Program. Validating the results from these simulations is recommended to achieve confidence in the predictions of the long-term effects on water quality and lake clarity.

New treatment technologies and enhanced BMP designs—

The potential effectiveness of modified or nonstandard BMP designs is under investigation, including coagulant-enhanced particle settling, filtration, biological treatment, and sorptive media. Anionic polyacrylamides show promise for turbidity treatment, but have not yet been studied for application in the Tahoe basin. Understanding and quantifying the toxicity effects of any potential chemical treatment is recommended before implementation in the Tahoe basin.

With adequate surface area and hydraulic retention time, wetlands can be very effective at removing N, P and sediment from urban runoff. However, conventional designs for treatment of wetlands and detention basins only make use of a relatively small subset of the potentially useful biological and ecological processes. In many wetland and aquatic systems, for example, a higher percentage of

P removal from the water column may occur via algae attached to plant stems and on surface sediments than through uptake by higher plants. Thus, for enhanced design opportunities, the treatment potential of other organisms and their combination in novel ecological systems should be investigated further in the Tahoe basin.

Research Needs

BMP implementation, operations and maintenance for water quality treatment—

- Improve BMP performance assessments based on standardized methods. It is recommended that these assessments focus on fine particles and nutrients and use our understanding of physical-chemical processes to improve the design of treatment systems through sound engineering principles.
- Although not considered research per se, establishment of a centralized database of Tahoe BMP information support of stormwater and BMP research is recommended. Ideally, this database would include data on BMP location, area, and land uses; the type of BMP installed, its capacity, installation date, inspection dates, and maintenance information; as well as water quality data, and monitoring records. The available data also could include BMP design criteria (hydraulic loading, residence time, width/depth ratio, aspect ratio, vegetation types), where the specified criteria are linked to predictable performance standards for specific pollutants of concern.
- Complete applied research to create better design guidance and specific BMP requirements for the Tahoe basin to achieve uniform treatment and pollutant reduction targets. This could lead to a design manual that would be used to enhance BMP selection and design criteria in the Tahoe basin. This includes a process of standardized scientific review for BMP implementation, operation, and maintenance. Design criteria could link directly to specific BMP functional characteristics and processes that improve performance based on integrated results from monitoring and modeling.
- Characterize the processes that influence nutrient transport from infiltration basins to shallow aquifers. This effort would include evaluating the removal (or addition) of pollutants during infiltration of stormwater into different underlying soils, as well as estimates of long-term seepage and pollutant loading at locations where ground water discharges into Lake Tahoe.

- Identify and characterize emerging pollutants of concern in terms of their removal by and effects on treatment BMPs.
- Conduct additional BMP monitoring to improve the prediction capabilities of models that are under development. Testing these models at a variety of field sites and scales for comparison to actual monitoring data will help validate results and inform design practices.

Urban source control—

- Conduct scientifically based effectiveness evaluations on different types of soil cover and erosion control materials, including longer term studies on soil restoration success and nutrient regimes.
- Develop appropriate metrics for evaluating the long-term success of urban source control projects in terms of their fine sediment particle and nutrient-retention characteristics.

New treatment technologies and enhanced BMP designs—

- Conduct replicated experiments to systematically assess the potential of new treatment technologies. A standardized, comparative approach will be needed to (1) predict and quantify performance; (2) understand the mechanisms of performance; (3) understand or identify ancillary effects, consequences, or benefits; (4) refine the logistics of application; and (5) understand inherent limitations.
- Conduct research on enhanced methods for capturing fine sediment in the 0.5 to 16 µm range, especially for BMPs that can remove substantial sediment loads from surface runoff.
- Evaluate the potential for engineered soil matrices that better adsorb nutrients, remove fine particles, and provide improved infiltration rates.
- Test anionic polyacrylamides in conjunction with other passive treatment technologies to determine their ability to reduce runoff turbidity and hence sediment loads.
- Determine the toxicity of stormwater and different treatment technologies before large-scale implementation of new technologies is authorized for the Tahoe basin.
- Determine what other stormwater pollutants could be treated by standard or enhanced BMPs. Examples of these pollutants include metals (i.e., cadmium, copper, and zinc), polyaromatic hydrocarbons, gasoline products (benzene, toluene, ethylbenzene, and xylenes and methyl tertiary butyl ether) and pesticides (pyrethroids).

- Develop a geographic information system (GIS)-based load reduction model to identify constituents and runoff volumes that could be most effectively addressed by different treatment methods, and to predict the results from different implementation strategies at various locations. It is possible, for example, that large regional advanced treatment systems would yield benefits from economies of scale and greater geographic flexibility compared to stormwater treatment applied through individual BMPs.
- Conduct comprehensive studies to quantify and weigh the risks, benefits, costs, and maintenance requirements associated with new types of BMPs that may be introduced into the basin.

Upland Watershed Function—Hydrology and Water Quality

More than 50 years of development in the Lake Tahoe basin has caused an increased flux of sediments and nutrients into the lake owing in part to soil disturbance and subsequent translocation. Road development and other forms of land disturbance, especially in areas of sloping topography, result in accelerated erosion and the accompanying loss of nutrient-containing topsoil. This is accompanied by the exposure of compacted, readily erodible decomposed granite, or andesitic volcanic subsoils, which are the dominant soil types in the Tahoe basin. Erosion and decreased infiltration rates in uplands are largely a result of soil disturbance by logging, grading, grazing, and related practices that result in loss of top layers of organic matter, established vegetation and nutrients, and subsequent soil compaction. The greater the disturbance in terms of soil impacts, the greater the erosion potential and loss of hydrologic function. As the physicochemical soil quality declines, vegetation growth is limited, soil stability decreases, and protective slope covers are lost that would otherwise minimize erosion. Efforts attempting to slow nutrient input to the lake have taken many forms, most of which focus on sediment source control including onsite retention.

Upland source control is critical for reestablishing hillslope hydrologic function with respect to soil moisture retention and percolation to ground water. Improved hydrologic function enhances plant cover conditions, habitat, flood peak attenuation, and can result in greater amounts of fine sediment particles remaining onsite. For example, using GIS assessment methods, Maholland (2002) evaluated the sediment sources and geomorphic conditions in the Squaw Creek watershed northwest of Lake Tahoe, a mixed granitic and volcanic soils environment. He found that forest road ski runs subject to hillslope rilling were the greatest sources of sediment in the watershed. Unfortunately, and despite years of work, little scientific information exists about the performance of road cut or hillslope erosion control measures employed in the Tahoe basin. However, there are numerous examples of anecdotal or visible failures in erosion control especially along road cut and ski run areas.

The nonurban landscape represents the largest land use in the Tahoe basin (about 90 percent). Although this land largely supports a forest biome, it is by no means unimpacted. The clearcut logging practices from the Comstock Era (1860 to 1890s) affected the composition of forest vegetation: populations of major tree species and forest structure never returned to pre-Comstock conditions (Barbour et al. 2002). Additionally, erosion hot spots are readily visible on the landscape. These areas of increased erosion occur at a variety of spatial scales ranging from the Ward and Blackwood Canyon Badlands (subwatershed scale) to landslide/avalanches (catchment scale) and from large to small gullies.

Although there is an enormous amount of literature related to erosion control in agricultural and relatively humid environments, there are few statistically validated field evaluations of the performance of revegetation/restoration type erosion control efforts in semiarid, subalpine environments. Information that is available is often limited to the "grey" literature or "white" papers from agencies, consultant reports, or professional societies. Although erosion control work is not new in the basin, documented results when available lack the scientific rigor needed to provide credible information for management decisions.

Selected examples of erosion studies that are relevant to the Tahoe basin include those of Fifield et al. (1988, 1989), Fifield and Malnor (1990), and Fifield (1992a,1992b) in western Colorado. In these studies, they evaluated the need for irrigation and runoff and erosion from plots "treated" with a variety of "natural" and geotextile covers on steep slopes. The "natural" treatments included hydroseeding, seed blankets, wood and paper hydromulches, straw, coconut, and jute materials. Generally, both runoff and sediment yields dramatically decreased as compared to bare soil conditions. Not surprisingly, the greatest sediment yield reductions were associated with the largest surface cover biomasses. What remains unknown are the long-term benefits of these erosion control strategies in the field, transferability to other locations, and what effects they have on infiltration rates and soil quality restoration. More recently, other efforts at assessing hydrologic effects of erosion control treatments at higher elevations or in nutrient-deficient soils have been reported. Montoro et al. (2000) described efforts to control erosion from anthropic soils on 40 percent slopes using 30-m^2 plots treated with vegetal mulch, hydroseeding with added humic acids and hydroseeding with vegetal mulch and humic acids. Runoff and erosion from natural rainfall events of 2 to 34 mm/h were significantly reduced from all treatments as a result of "protection against raindrop impact" and "general improvement in soil structure."

In the Tahoe basin, rainfall simulation studies have provided a means by which to standardize evaluation of erosion control measures, in a more controlled setting, through replicated rainfall events of the same intensity (or kinetic energy) on multiple plots enabling statistical evaluation of treatment effects on hydrologic parameters of interest. Grismer and Hogan (2004, 2005a, 2005b) reviewed available literature associated with erosion control measures in subalpine regions and applied rainfall simulation methods to assess runoff and erosion rates for disturbed granitic and volcanic bare soils in the Tahoe basin. The most fragile and easily impacted soils are of volcanic origin. Erosion rates of volcanic soils, and to some degree infiltration rates, are slope dependent. They also found that sediment yield (kilograms per hectare per millimeter runoff) from bare soils is exponentially related to slope after a minimum threshold slope is exceeded. Although rainfall simulation measured infiltration rates were similar in both volcanic and granitic soil types (30 to 60 mm/hr), sediment yields from granitic soils were several times smaller on average (from about 1 to 12 $g \cdot m^{-2} \cdot mm^{-1}$) than that from bare volcanic soils (from about 3 to 31 $g \cdot m^{-2} \cdot mm^{-1}$).

Granitic soil particle sizes were greater than that of volcanic soils in both bulk soil and runoff water samples. Runoff sediment concentrations and yields from sparsely covered volcanic and bare granitic soils could be correlated to slope. Sediment concentrations and yields from nearly bare volcanic soils exceeded those from granitic soils by an order of magnitude across slopes ranging from 30 to 70 percent. Similarly, granitic ski run soils produced nearly four times greater sediment concentration than adjacent undisturbed areas. Revegetation, or application of pine needle mulch covers to both soil types decreased sediment concentrations and yields by 30 to 50 percent. Incorporation of woodchips or soil rehabilitation that includes tillage, use of amendments (e.g., Biosol®,[8] compost) and mulch covers together with plant seeding resulted in little, or no, runoff or sediment yield from both soils. Although mulch and grass covers provide some protection to disturbed bare soils, they alone do not improve hydrologic function and may only minimally reduce erosion and runoff rates depending on the extent or depth of coverage (Grismer and Hogan 2004, 2005a, 2005b).

Repeated measurements of sediment concentrations and yields for 2 years following woodchip or soil rehabilitation treatments showed little or no runoff. Revegetation treatments involving use of only grasses to cover soils were largely

[8] The use of trade of firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of product service.

ineffective owing to sparse sustainable coverage (<35 percent) and inadequate infiltration rates. It was suggested that a possible goal of restoration-erosion control efforts in the basin could be the re-creation of "native"-like soil conditions. "Native" soils below forest canopies with about 10 cm of duff, litter, pine needle mulch, or other organic matter have very high infiltration rates (>75 mm/hr) when the surface is not hydrophobic. When the surface is hydrophobic, runoff commences almost immediately with little infiltration in the first 10 minutes; although the runoff yields negligible mineral sediment, it can contain high nutrient concentrations (Miller et al. 2005). Soil rehabilitation (woodchip or compost incorporation) combined with revegetation appears to provide erosion control, increased infiltration rates, and restoration of hydrologic function for at least 3 years, maybe more.

Knowledge Gaps

In comprehensive reviews of erosion control systems for hill slope stabilization, Sutherland (1998a, 1998b) noted that the "formative years" prior to about 1990 resulted in a mass of information that lacked scientifically credible, standardized data. He argued for standardized evaluation methods that have field applicability and greater emphasis on the study of surface, or near-surface processes controlling erosion. Perhaps better still for the Tahoe basin, would be a greater emphasis on scientifically credible studies on the restoration of soil quality adequate to support hill-slope vegetation.

Scientific information about erosion control and soil stabilization methods is critical to local agencies, planners, and property owners who want to know which methods achieve the greatest reductions in erosion for the least amount of money. Forest management efforts related to water quality restoration planning lack both process-based erosion models (with the expectation of the use of the WEPP model) and the basic soil property/hydraulic information necessary for plausible prediction of streamflows and sediment (TSS) and nutrient concentrations.

Understanding the relationship between mineral fraction particle sizes and fine sediment and nutrient transport is crucial for the design of effective sediment traps/basins. For example, fine particle sizes (<16 µm) settle out extremely slowly and are not trapped in many cases, whereas larger particles of lesser water quality impacts can be trapped in smaller BMPs (e.g., drainage sediment cans or small detention basins). Further, contrary to prevailing thought, vegetation cover alone (e.g., grasses with 30 to 60 percent cover that look good) may have little effect on reducing erosion rates from disturbed soils. Scientists and managers in the Tahoe basin have posed numerous relevant questions, including:

- What types of covers are effective for erosion control?
- How effective are various types of cover relative to the level of effort required for implementation?
- Can effective covers be realistically deployed over large areas?
- What are the maintenance requirements both short and long term?
- How do soil stabilization and erosion control approaches compare when applied at the project, watershed, and basinwide scales?
- Is artificial replenishment necessary when using mulch covers?
- Can soil be "rehabilitated" such that natural processes prevail (e.g., functional soil nutrient and microbial communities, growth of plants that leave a functioning litter layer)?

Research Needs

Erosion and pollutant loading—

- Study runoff particle-size distributions, sediment and nutrient loading from the undeveloped, yet disturbed forest landscape. This includes, but is not limited to (1) the mechanisms at play in the erosional hot spots (at the full spectrum of spatial scales at which this erosion occurs), (2) estimates of pollutant concentrations and loading from forest land and the hot spots, (3) the transport of nutrients and sediments from the forest floor to receiving water bodies that are tributary to Lake Tahoe, (4) the ability to better incorporate these processes into management models, and (5) an understanding of potential load reduction strategies for these pollutant sources.
- Determine the impact of existing and legacy roads, trails (e.g., hiking or biking), and other areas of the forest that have been disturbed to accommodate transportation (including recreation), vis-à-vis hydrology (including baseflow) and sediment/nutrient generation.
- Develop monitoring protocols to identify restoration methods that are the most effective in controlling runoff of fine particles and nutrients. These protocols also would provide data for the development of descriptive relationships between nutrients and particle size (for different soil types including granitic and volcanic).
- Quantify the particle size distribution in runoff from steep disturbed slopes for both granitic and volcanic soils.
- Better characterize the possible effects of extreme hydrologic events and runoff from large tracts of disturbed land on erosion, sediment transport, and nutrient loading, given the risk of wildfire, avalanches/landslides, and other potential natural hazards in the mountainous terrain of the Tahoe basin, as well as future climate change.

- Quantify snowmelt-derived erosion across the basin, including monitoring and characterization of snowmelt-induced erosion rates from the different disturbed soils.
- Define the continuum, or threshold relationship between organic matter content of soil at Lake Tahoe and sediment yield (erodibility). Based on a better understanding of the nature of this relationship, there could be tremendous potential to develop a rapid assessment of potential erodibility based on litter layer thickness or percentage of organic matter in the surface soils.
- Develop process-based erosion models applicable to the basin under rainfall and snowmelt conditions—functional at scales ranging from the project scale to the entire basin—to help inform and guide management decisions related to watershed restoration.
- Quantify nutrient concentrations in shallow interflow on hill slopes under a variety of hydrologic and cover conditions. Subsurface flow in the top 20 to 30 cm of soil on the hill slope can be a major flow factor; however, it is not adequately considered in many erosion models. In the Tahoe basin, research shows significant shallow subsurface flow that essentially filters the "runoff" resulting in negligible sediment yields, but potentially substantial loads of dissolved nutrients.

Processes related to soil rehabilitation—

- Determine what soil shear strengths are associated with rehabilitated soils and how they are affected by vegetative succession.
- Determine how soil rehabilitation affects soil aggregate stability, what aggregate stability occurs in "native" soils, and what aggregate stability value should be achieved in restoration projects.
- Study hydrophobicity of "native" soils to determine the extent of this condition, how rapidly it breaks down in summer storms, and whether "native" soils are a source or a sink of N or P.

Restoration effectiveness—

- Determine the ecologic and economic feasibility of treating erosion hot spots in the forest landscape. A better understanding of the occurrence of natural versus anthropogenic erosion hot spots is needed to assist managers in making decisions on implementation strategies.
- Determine which restoration methods will provide the greatest return in terms of hydrologic function per effort required, followed by how long, or if, the restoration method will last and if it is sustainable or self-sustaining.