Nutrient and Sediment Transport in Streams of the Lake Tahoe Basin: A 30-Year Retrospective[1]

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Lake Tahoe, widely renowned for its astounding clarity and deep blue color, lies at an elevation of 1,898 meters (m) in the central Sierra Nevada, astride the California-Nevada border. The volume of the lake is 156 cubic kilometers (km^3), and its surface area is 501 square kilometers (km^2), 38 percent of the total basin area of 1,313 km^2. The eutrophication of the lake has been studied intensively since the early 1960s (Goldman 2000), when scientists and farsighted political leaders and private citizens began to recognize that human activities, especially the accelerated input of nutrients and sediment, could cause long-term changes in the lake.

To provide an understanding of nutrient and sediment sources in the Lake Tahoe Basin, long-term monitoring programs were established in the 1970s. These monitoring programs included measuring stream discharge and sampling nitrogen, phosphorus, iron, and suspended sediment to calculate total watershed loads delivered to the lake and measuring both wet and dry atmospheric deposition of nitrogen and phosphorus. The programs have led to a better understanding of the causes of eutrophication and clarity loss of Lake Tahoe and, in some cases, have caused refocusing of programs aimed at restoring desired lake conditions. This paper reviews what we have learned from the stream-monitoring program and related research and suggests directions for future work.

Long-Term Changes at Lake Tahoe

The documented ecological changes in Lake Tahoe have been dramatic. Between 1968 and 1997, primary productivity in the lake (measured as the rate of carbon fixation) increased from 48 to 170 grams per square meter per year ($g/m^2/yr$), and clarity (measured by Secchi depth) decreased from to 31 to 20 m. In spite of increased land-use controls and export of treated sewage effluent from the basin, primary productivity of the lake continues to increase by more than 5 percent annually, and clarity continues to decrease at an average rate of 0.25 m/yr (Goldman 2000).

Scientists have documented major changes at all levels in the food web, some resulting from changes in the trophic status of the lake and some resulting from introduction of exotic species or extirpation of native species (Richards and others 1991).

Moreover, the accelerated influx of nitrogen has caused a shift in the limiting nutrient status of the lake. Until the early 1980s, nutrient limitation studies showed that primary productivity was nitrogen-limited. Since then, the same experimental procedures have shown that the lake is phosphorus-limited most of the time, and co-limited by nitrogen and phosphorus during July and August (Goldman and others 1993). Such a profound change in a lake with a volume of 156 km^3 is astounding and has major implications for policies and strategies aimed at controlling eutrophication.

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Lessons from Stream and Precipitation Monitoring

Since 1980, the Lake Tahoe Interagency Monitoring Program (LTIMP) has been measuring stream discharge and nutrient and sediment concentrations in up to 10 tributary streams in the Lake Tahoe Basin. The objectives of the LTIMP are "to acquire and disseminate the water quality information necessary to support science-based environmental planning and decision making in the basin" (Boughton and others 1997). The LTIMP data set comprises more than 16,000 samples, representing about 300 station-years of records for up to seven water quality constituents.

In the early years of the stream monitoring program, much emphasis was placed on measuring the concentrations and loads of nitrate-N and ammonium-N. This was partly due to the ready biological availability of dissolved inorganic nitrogen (DIN) as well as its ease of measurement. Reliable techniques for measuring concentrations of total Kjeldahl nitrogen (TKN) were not operational until the late1980s. When data on dissolved and particulate organic nitrogen became available, however, it became obvious that more than 90 percent of the nitrogen load from the watersheds was organic and about 50 percent of it dissolved (DON). Evidence indicates that much of the DON is biologically available, possibly as much as 28 percent of it during low-flow periods and 50 percent during early spring runoff (Stepanauskas and others 2000).

Total runoff explains most of the variation in total nitrogen yield, among both watersheds and years. For the 10 watersheds, regression of average annual total N load versus runoff has an r^2 of 0.79 and standard error (s.e.) of 0.28 kilograms per hectare per year (kg/ha/yr); for the 10 years, the regression of N load versus runoff (averaged over the 10 watersheds) has an r^2 of 0.96 and s.e. of 0.14 kg/ha/yr.

Estimated nutrient loads from watersheds that drain into the lake must be considered in the context of all sources of loading to the lake. Dugan and McGauhey (1974) called attention to the importance of direct atmospheric deposition on the lake surface. A recording and sampling precipitation gage was installed at the head of Ward Valley in November 1972, and a gage near the mouth of Ward Creek was operated in the late 1970s as part of the National Atmospheric Deposition Program (NADP). When Jassby and others (1994) compiled data from these stations with data from collectors mounted on buoys in the lake and compared the resulting deposition estimates, it became clear that atmospheric deposition was the dominant source of nitrogen and a major source of phosphorus input to the lake.

Direct atmospheric deposition to the lake is the dominant source of nitrogen input for two reasons. First, the lake is large relative to its drainage basin. Second, the soil-vegetation systems in the monitored watersheds are relatively efficient at scavenging and retaining nitrogen. A comparison of the loading rates above with DIN deposition for the period 1989 through 1992 (from Jassby and others 1994) shows that Ward Creek retained about 97 percent and Blackwood about 90 percent of the wet plus dry DIN atmospheric deposition.

Sediment Loads to the Lake

Suspended sediment contributed from Lake Tahoe basin watersheds has long been of interest. Glancy (1988) called attention to increased sediment yield associated with development in the Incline area, and suspended sediment was included in the suite of water quality parameters measured by the LTIMP program from its inception. Paerl (1973) showed that suspended sediment particles provide a substrate for microbial activity, which enhances particle aggregation and settling and accelerates the release and mobilization of inorganic nitrogen and phosphorus. Because surface soils are potentially an important source of nutrients, surface soil erosion was the focus of much of the early work on sediment sources in the Lake Tahoe basin.

The sediment budget approach, however, reveals that surface soil erosion is a relatively minor source of suspended sediment to Lake Tahoe. In a study of Blackwood, General, Edgewood, and Loganhouse Creeks, Nolan and Hill (1991) found that erosion of the beds and banks of stream channels accounts for more than 90 percent of the suspended sediment load to the lake. This suggests that runoff changes associated with roads and urban development in the basin may play an important role in increasing sediment production offsite and downstream.

A recently developed model of water clarity in Lake Tahoe has called attention to the fine fraction of suspended sediment in Tahoe basin streams (Schladow and others 2001). It turns out that the clarity of Lake Tahoe is very sensitive to the input of fine sediment (less than 63 micrometers [µm]). Because of its slow settling rate and the long hydraulic residence time in the lake, the impact of fine sediment on water clarity is persistent: a 2-µm particle takes 2 years to settle out of the water column. The actual rate at which sediment settles from the water column is influenced by particle aggregation (a function of particle density and biological activity) as well as internal circulation and mixing.

The shift in nutrient limitation from nitrogen toward phosphorus has also increased the significance of fine sediments as a factor in lake eutrophication. Relatively large sediment particles (sand) may settle near tributary mouths and have little impact on phosphorus availability. Fine particles, with a high surface-to-volume ratio, however, may be a significant potential source of phosphorus. As fine sediment particles enter the lake, where orthophosphorus concentration is lower than in basin streams, adsorbed phosphorus may be released and become available to algae over months or years (Froelich 1988; Hatch and others 1999).

Management Response to Water Quality Problems

Armed with evidence from research and monitoring programs, local government agencies and land managers have implemented various programs to address the degradation of Lake Tahoe. The first major effort, completed in the early 1970s, was to treat all sewage in the basin and export the treated effluent. With that seemingly accomplished, managers turned their attention to controlling land development. The Tahoe Regional Planning Agency established controls on development in meadows and riparian zones (although not soon enough to save the important wetland complex at the mouth of the Upper Truckee River). The Agency has been through several iterations of land-use control programs. The current program sets limits on allowable impervious surface in new development on the basis of the physical characteristics of a site. Developers may, however, propose off-site mitigation in the same watershed and avoid certain restrictions by contributing to a mitigation fund. The next big "push" will be to develop and implement Best Management Practices (BMPs) to control nutrients and sediment from runoff. Unfortunately, the efficacy of many BMPs (such as developing detention basins, armoring roadcuts and inboard ditches, and revegetating bare slopes) is difficult to document because of the difficulty and cost of sampling (Coats and others 2002).

Future Research Directions

Limnological and watershed research in the Lake Tahoe basin have provided the basis for efforts to deter the degradation of the lake's water quality. Although our understanding of the basic sources, sinks, and impacts of nutrients and sediments has improved substantially over the past three decades, important information gaps remain. Current and future research directions aimed at closing those gaps include:

1. *Research on the role of runoff from urbanized areas*. Most of the area sampled by the LTIMP is undeveloped or lightly developed; the highly urbanized areas at South

Lake Tahoe drain directly to the lake. Preliminary sampling has shown that runoff from commercial and residential areas carries concentrations of suspended sediment, nitrogen, and phosphorus that are 5 to 100 times greater than that from comparable undeveloped areas. A major effort, funded by the Regional Water Quality Control Board's "Total Maximum Daily Load" (TMDL) program, is now under way to sample runoff from developed areas, using automated sampling equipment.

2. *Research on sources and sinks of fine suspended sediment*. Virtually no particle-size data exist for the LTIMP streams. New methods using LASER technology are available to rapidly measure concentrations of small particles in water samples. It would be very interesting and useful to compare the contribution of fine sediment from volcanic soils with that from granitic soils and the contribution of fine sediment from highways and developed areas with that from pristine areas. Work (currently in progress) is also needed to study the aggregation and settling of fine sediment in the lake.

3. *Development of control technologies for fine sediment and nutrients.* Detention basins are effective at trapping bedload and sand-sized suspended particles but ineffective for clay and sometimes silt. Nutrients trapped in a detention basin may infiltrate to the groundwater and continue to move into the lake. New technologies to address the fine-sediment problem need to be developed and experimentally tested. Engineering studies on the integrity of the sewage system, which is now 30 years old, are needed.

4. *Research on biologically available phosphorus (BAP)*. On a time scale of days, the biostimulatory impact of stream water is most closely related to the soluble reactive phosphorus (SRP) concentration (Hatch and others 1999). At longer time scales, however, phosphorus released from sediment may be important. The TMDL project is currently funding work at the University of Nevada to address this problem.

5. *Improved methods for estimating total loads of nitrogen, phosphorus, and sediment.* The LTIMP is currently collecting about 30 samples per year for the major stations and fewer samples for the secondary and miscellaneous stations. With only 30 samples per year, the 95-percent confidence limits on an estimate of total phosphorus load by the regression method would be about ±60 percent (Coats and others 2002). Optical back-scatter turbidity probes have shown promise for *in situ* near-continuous measurement of suspended sediment, which may help with quantitative load estimates for sediment and particulate forms of nitrogen and phosphorus.

6. *Atmospheric sources of nutrient loading to Lake Tahoe.* Direct wet and dry deposition is an important input to the lake; however, it is unknown whether these deposited materials originate within the basin (from wood smoke and automobile exhaust and dust) or in agricultural and urban areas to the west and southwest. Atmospheric modeling and sampling studies are under way to fill this gap.

7. *Implication of climate change for the Lake*. The most likely effect of a warmer climate in the Sierra Nevada will be a shift from snow to rain, a shift in the timing of snowmelt to earlier in the year, and an increase in total winter precipitation (Lettenmaier and Gan, 1990; see also papers from the session on "Climate and Landscape Change Over Time" in this volume). These changes will most likely increase soil erosion and mass wasting in the Lake Tahoe basin. The timing, magnitude, and distribution of these impacts need to be investigated.

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