Lake Tahoe Total Maximum Daily Load

Technical Report

June 2009

California Regional Water Quality Control Board, Lahontan Region
2501 Lake Tahoe Boulevard
South Lake Tahoe, California 96150

Contact Person:
Douglas F. Smith, P.G.
Senior Engineering Geologist
Telephone: (530) 542-5453
DFSmith@waterboards.ca.gov

Nevada Division of Environmental Protection
901 South Stewart Street, Suite 4001
Carson City, Nevada, 89701-5249

Contact Person:
Jason Kuchnicki
Environmental Scientist IV
Telephone: (775) 687-9450
jkuchnic@ndep.nv.gov

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List of Acronyms and Abbreviations

These acronyms and abbreviations appear in various chapters of the report. Most of these are initially spelled out individually in each chapter, but this list is provided for ease of reference.

AnnAGNPS	Agricultural Non-Point Source Pollutant Version 3.30
BAP	Biologically Available Phosphorus
BF	Baseflow
BME	Bradu-Mundlak Estimator
BMP	Best Management Practice
C	Carbon
^{o}C	Degrees Celsius
CARB	California Air Resources Board
CDM	Camp Dresser and McKee
CDOM	Colored dissolved organic matter
CFR	Code of Federal Regulations
cfs	cubic feet per second
CICU	Commercial/Institutional/Communications/Utilities
CO	Carbon monoxide
CONCEPTS	Conservational Channel Evolution and Pollutant Transport System
CTC	California Tahoe Conservancy
CWA	Clean Water Act
DCNR	Nevada Department of Conservation and Natural Resources
DEM	Digital Elevation Model
DIN	Dissolved Inorganic Nitrogen
DLM	Dynamic Lake Model
DON	Dissolved Organic Nitrogen
DOP	Dissolved organic phosphorus
DOQs	Digital Orthophotographic Quadrangles
DRI	Desert Research Institute
DYRESM	Dynamic Reservoir Model
D-team	TMDL Development Team
EMC	Event Mean Concentration
EP	Erosion Potential
ET	Evapotranspiration
ft	Feet
GIS	Geographic Information System
GQUAL	Lake Tahoe Watershed General Water Quality Module
HIC	Hard Impervious Cover
HSPF	Hydrologic Simulation Program – FORTRAN
HYSEP	USGS hydrograph separation algorithms
I_B	Bank-stability index
IVZ	Intervening Zones
IWQMS	Integrated Water Quality Management Strategy

L	Liter
LA	Load Allocation
LC	Loading Capacity
LCM	Lake Clarity Model
LSPC	Loading Simulation Program in C++(Lake Tahoe Watershed Model)
LTADS	Lake Tahoe Atmospheric Deposition Study
LTBMU	Lake Tahoe Basin Management Unit
LTIMP	Lake Tahoe Interagency Monitoring Program
MOS	Margin of Safety
MVUE	Minimum Variance Unbiased Estimator
m	Meter
µm	Micrometer
mg	milligrams
mL	Milliliter
MFR	Multi-family Residential
MT	Metric Ton
NAC	Nevada Administrative Code
NADP	National Atmospheric Deposition Program
NCDS	National Climatic Data Center
NDEP	Nevada Division of Environmental Protection
NDOT	Nevada Department of Transportaiton
NHD	National Hydrography Dataset
NH_4^+	Ammonium
NO_x	Oxides of Nitrogen
NO_3^-	Nitrate
NRCS	National Resource Conservation Service
NTU	Nephelometric Turbidity Units
n/y	Number of Particles per Year
OM	Organic Matter
ONRW	Outstanding National Resource Water
PEVT	Potential Evapotranspiration
PM	Particulate Matter
PN	Particulate Organic Nitrogen
PO_4^{-3}	orthophosphate
PON	Particulate organic nitrogen
PP	Particulate Phosphorus
PPr	Primary Productivity
Q-wtd	Flow weighted
RGAs	Rapid Geomorphic Assessments
RMHQs	Requirements to Maintain Higher Quality
RO	storm-flow
ROG	Reactive organic gases
SAG	Source Analysis Group
s.d.	Standard deviation
SFR	Single-family Residential
SNOTEL	SNOwpack TELemetry

SNPLMA	Southern Nevada Public Lands Management Act
SRP	Soluble Reactive Phosphorus
SWE	Snow Water Equivalent
SWQIC	Storm Water Quality Improvement Committee
SWRCB	State Water Resources Control Board
S-XRF	Synchroton-X-Ray Fluorescence
TDP	Total Dissolved Phosphorus
TERC	Tahoe Environmental Research Center
THP	Total Acid-Hydrolyzable-Phosphorus
TKN	Total Kjeldahl Nitrogen (all organic nitrogen plus NH_4^+)
TKN + nitrate	Total Dissolved Nitrogen
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TON	Total Organic Nitrogen
TP	Total Phosphorus
TRG	Tahoe Research Group
TROA	Truckee River Operating Agreement
TRPA	Tahoe Regional Planning Agency
TSS	Total Suspended Sediment
UC Davis	University of California Davis
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USFS	United States Forest Service
USGS	United States Geological Survey
VEC	Vertical Extinction Coefficient
WLA	Waste Load Allocation
WQS	Water Quality Standard
WVLL	Ward Valley Lake Level
XRF	X-ray Fluorescence

Acknowledgments

The science conducted in direct support of this document involved of numerous academic institutions, state and federal agencies, and environmental/engineering consulting firms. Over 100 individuals participated in the field work, information collection, modeling and research contained in this report. Many more have contributed to our understanding of water quality at Lake Tahoe during the past four decades, and we hope that we did not miss any of the key citations. The dedication, long hours, and extraordinary efforts of all these individuals are greatly appreciated. Specific acknowledgement goes to Dave Roberts and Dr. John E. Reuter, whose efforts made this document possible. The degree of commitment to this effort demonstrated by these individuals and entities underscores a commitment to water quality improvement and watershed restoration in the Lake Tahoe basin.

Numerous projects were funded as part of the Lake Tahoe TMDL and were intended for direct use in this Technical Report. In some cases, the language from portions of those project reports was directly used in this document with minor editing. For areas where new information was not collected, the most recent and comprehensive analyses were used. In particular, the following reports were conducted in direct support of the Lake Tahoe TMDL and, at least portions of which are specifically incorporated into the text of this Technical Report.

Groundwater
USACE (United States Army Corps of Engineers). 2003. *Lake Tahoe Basin Framework Study: Groundwater Evaluation*. U.S. Army Corps of Engineers, Sacramento District.

Stream Channel
Simon, A., E.J. Langendoen, R.L. Bingner, R. Wells, A. Heins, N. Jokay and I. Jaramillo. 2003. *Lake Tahoe Basin Framework Implementation Study: Sediment Loadings and Channel Erosion*. USDA-ARS National Sedimentation Laboratory Research Report. No. 39.

Simon, A. 2006. *Estimates of Fine-Sediment Loadings to Lake Tahoe from Channel and Watershed Sources*. USDA-Agricultural Research Service, National Sedimentation Laboratory. Oxford, MS.

Atmospheric
CARB (California Air Resources Board). 2006. *Lake Tahoe Atmospheric Deposition Study (LTADS)*. Final Report – August 2006. Atmospheric Processes Research Section, California EPA, Sacramento, CA.

Upland

Tetra Tech, Inc. 2007. *Watershed Hydrologic Modeling and Sediment and Nutrient Loading Estimation for the Lake Tahoe Total Maximum Daily Load*. Final modeling report. Prepared for the Lahontan RWQCB and University of California, Davis.

Shoreline Erosion

Adams, K.D. and T.B. Minor. 2001. *Historic Shoreline Change at Lake Tahoe from 1938 to 1998: Implications for Water Clarity.* Desert Research Institute, Reno, NV. Prepared for the Tahoe Regional Planning Agency.

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Lake Clarity Modeling

Sahoo, G.B., S.G. Schladow and J.E. Reuter. 2006. Technical support document for the Lake Tahoe Clarity Model. Tahoe Environmental Research Center, John Muir Institute of the Environment, University of California, Davis. 56 p.

Sahoo, G.B., S.G. Schladow and J.E. Reuter. 2007. *Linkage of Pollutant Loading to In-lake Effects.* University of California, Davis – Tahoe Environmental Research Center. Prepared for the Lahontan RWQCB.

We would also like to thank all the organizations and individuals that provided technical information or who engaged in important scientific discussions in direct support of this document. We recognize and appreciate the contributions of all these colleagues and apologize if we inadvertently omitted anyone from this list.

University of California Davis, TERC: John Reuter, Geoff Schladow, Goloka Sahoo, Scott Hackley, Tom Cahill, Steve Cliff, Ted Swift, Joaquim Perez-Losada, Alan Jassby, Bob Richards, Charles Goldman, Jenny Coker, Alex Rabidoux, Mark Grismer, Andrea Parra, Colin Strasenburgh, Raph Townsend, Lev Kavvas, Michael Anderson, Patty Arneson, Mark Palmer, Tina Hammell, George Malyj, David Jassby, Brant Allen, Debbie Hunter

University of Nevada Reno: Jerry Qualls, Joseph Ferguson, Anna Panorska, Wally Miller

Desert Research Institute: Alan Heyvaert, Jim Thomas, Ken Adams, Ken Taylor, Todd Mihevc, Gayle Dana, Rick Susfalk, Melissa Gunter, Alan Gertler, Tim Minor, Paul Verburg, Mary Cablk

California Air Resources Board: Eileen McCauley, Leon Dolislager, Tony VanCuren, Jim Pederson, Ash Lasgari, Bart Croes, Richard Corey, Dongmin

Luo, William Vance, Clinton Taylor, Steve Mara, Deborah Popejoy, Michael Fitzgibbon, Jerry Freeman, Pat Vaca

California Tahoe Conservancy: Judy Clot, Kim Carr

Nevada Tahoe Conservation District: Chad Praul

Tahoe Regional Planning Agency: Larry Benoit, Sean Dougan, John Stanley

United States Army Corps of Engineers: Meegan Nagy, Melissa Kieffer, Lewis Hunter, Timothy Crummett, Teresa Rodgers, John Baum, Elizabeth Caldwell, Scott Gregory, Suzettee Ramirez, Glenn Cox, Richard Meagher

United States Environmental Protection Agency: Jacques Landy, Jane Freeman

United States Geological Survey: Tim Rowe, Kip Allander

USDA, ARS, National Sedimentation Laboratory: Andrew Simon, Eddie Langendoen, Ron Bingner, Brian Bell, Loren Klimetz, Danny Klimetz, Mark Griffith, Charlie Dawson, Robert Wells, Amanda Heinz, Nick Jokay, Igor Jaramillo

USDA, USFS, Lake Tahoe Basin Management Unit: Sue Norman, Denise Downey, German Whitley, Joey Keeley

USDA, NRCS: Woody Loftis

Tetra Tech Inc.: John Riverson, Leslie Shoemaker, Clary Barreto, Andrew Parker, John Craig

United States National Park Service: Lee Tarnay

Geosyntech: Eric Strecker, Jim Howell, Andi Thayumanavan, Marc Leisenring

Hydroikos: Bob Coats, Matt Luck

Environmental Incentives: Jeremy Sokulsky

Reviewed and Edited by:

Lahontan Water Board: Kim Gorman, Lauri Kemper, Robert Larsen, Robin Mahoney, Hannah Schembri, Eric Shay, Carly Nilson, and Douglas Smith

Nevada Division of Environmental Protection: Jason Kuchnicki

Tetra Tech: Eugenia Hart

1 Introduction

This report focuses on the evaluation of pollutant sources and the amount of pollutant load reduction that needs to occur, to achieve water quality objectives protecting the optical properties of water in Lake Tahoe. This is the first step towards completion of Final Lake Tahoe Total Maximum Daily Load (TMDL) for fine sediment, nitrogen and phosphorus which are the pollutants responsible for the continued loss of deep water transparency in Lake Tahoe.

Clarity vs. Transparency

While annual Secchi disk measurements are commonly referred to as clarity, this measurement is actually defined as transparency in regulatory documents. Clarity is defined as vertical extinction of light in regulatory documents. Collectively, these measurements are referred to as optical properties in this report.

The information contained in this report is intended to provide the framework for the evaluation of various pollutant control opportunities during the development of an Integrated Water Quality Management Strategy (IWQMS). This strategy will articulate how the restoration of lake transparency will be accomplished. The development of the IWQMS involved extensive public participation for input regarding the potential opportunities for implementation of pollutant control measures. Ultimately through the IWQMS process, pollutant load reduction allocations were developed along with implementation and monitoring plans that are part of the Final Lake Tahoe TMDL.

A TMDL is a written, quantitative assessment of water quality problems and contributing pollutant sources. It identifies one or more numeric targets based upon existing water quality standards and specifies the maximum amount of pollutant a waterbody can receive while remaining in attainment of water quality objectives. The goal of the TMDL, when implemented, is that the waterbody fully attain its designated beneficial uses by meeting existing water quality objectives. Consequently, a completed TMDL provides the scientific basis and framework for a comprehensive water quality restoration plan.

The Lake Tahoe TMDL is being developed cooperatively between the States of California and Nevada and is intended to meet the planning and regulatory needs of both states. It is also anticipated that the Final Lake Tahoe TMDL will meet the planning requirements of the United States Environmental Protection Agency (USEPA) and the Tahoe Regional Planning Agency (TRPA). The organization and implementation of this multi-agency effort is being coordinated through a process called Pathway in the Lake Tahoe basin for the Lahontan Water Board, Nevada Divison of Environmental Protection, Tahoe Regional Planning Agency, and the United States Forest Service, Lake Tahoe Basin Management Unit. The Pathway planning process was initiated to update and make consistent all the various resource management documentation covering the Lake Tahoe basin. Additional information on the Pathway process can be obtained from the Pathway2007.org website.

The Federal Clean Water Act (CWA) requires the development of TMDLs for the protection of beneficial uses and attainment of established water quality objectives for impaired waterbodies as designated under Section 303(d) list of the CWA. Lake Tahoe has been identified as not meeting established water quality objectives intended to protect its famed water clarity and transparency. When finalized, the Lake Tahoe TMDL will provide a comprehensive quantitative evaluation of (1) major pollutant loading sources, (2) effect of these pollutants on Lake Tahoe's transparency, (3) degree of pollutant load reduction needed and (4) how load reductions can be achieved.

TMDLs are generally limited to the evaluation of a single pollutant-waterbody combination. However, the declining transparency of Lake Tahoe is the result of a complex interaction of different pollutants originating from diverse sources. The Lake Tahoe TMDL specifically addresses the three pollutants responsible for transparency reduction (fine sediment particles, nitrogen, and phosphorus), as it is the interaction of these pollutants that are responsible for the impairment of the Lake Tahoe's transparency. Because of this complex interaction, it was necessary to evaluate the three pollutants simultaneously.

Research and information collection in support of this document was initiated in 2001 and this report is the culmination of several years of effort to initiate, develop and synthesize new and historical information regarding the impairment of Lake Tahoe's transparency. This effort included contributions from numerous state, federal, academic and private entities that involved the participation of over 100 contributing scientists. Significant combined funding from state and federal agencies has allowed the most comprehensive and thorough evaluation of pollutant sources and lake effect ever completed in the Tahoe basin.

1.1 Overview of TMDL Program

This section provides background on the Federal TMDL Program and how these requirements are being fulfilled by the Lake Tahoe TMDL Program. This section includes a discussion of federal water quality requirements that provide the framework for protecting and restoring the nation's waters. Central to this framework is the Federal Clean Water Act which provides the regulatory authority for the development of TMDLs.

1.1.1 Federal Water Quality Requirements

The United States Congress enacted landmark legislation in 1972. This statute, the Federal Water Pollution Control Act, referred to as the Clean Water Act of 1972 (CWA), expanded and built upon existing laws. The goal of the CWA is to restore and maintain the chemical, physical and biological integrity of the nation's waters. Thus, the CWA established a regulatory framework for protecting and restoring surface waterbodies to conditions that attain existing water quality standards. The framework begins with adoption by states (subject to USEPA approval) of appropriate numeric or narrative water quality standards for the subject waterbody. The CWA defines "water quality standards” to include: (1) beneficial uses, (2) water quality criteria (i.e. water quality objectives) and (3) application of an antidegradation objective (i.e. nondegradation objective).

Beneficial uses identify appropriate uses of that water that are to be achieved and protected. The primary beneficial use relevant to this TMDL is non-contact water recreation, which protects the aesthetic enjoyment of Lake Tahoe’s historical clarity, in both the pelagic (deep) and littoral (near shore and shallow) zones of the lake.

Water quality criteria (or objectives) are limits on a particular pollutant or on a condition of a waterbody designated to protect and support the identified beneficial uses. These criteria can be expressed either as numeric or narrative criteria. When criteria are met, water quality is sufficient for the protection of identified beneficial uses. The deep water transparency standard for Lake Tahoe is not being met, therefore, Lake Tahoe is impaired by nitrogen, phosphorus, and fine sediment.

As mentioned above, an antidegradation policy is one of the minimum elements required to be included in a state’s water quality standards. The antidegradation policy does not strictly prohibit degradation of water quality, except in a very limited circumstance. The antidegradation policy can be expressed as one of three tiers.

A Tier One policy states that any existing use and the water quality necessary to protect that use, must be maintained and protected. This means that whatever the existing use of the waterbody is, you are not allowed to make it worse. If water quality needs to be improved to meet the standards then control programs must be put into place to meet the water quality standard. This can be considered the most basic level of water quality protection under the CWA.

Tier Two antidegradation, or maintenance of high-quality water, says that if water quality is better than needed to protect beneficial uses, the water quality can be allowed to deteriorate to a level that still maintains the beneficial use. However, it is up to the state to make the decision whether or not to allow the degradation. In all cases, the state is required to involve the public, and other federal agencies, as necessary. The decision to allow deterioration in water quality is based on the finding that a lower water quality is necessary to support important economic and social development in the area in which the water is located.

Tier Three affords the highest level of protection under the CWA with the designation of Outstanding National Resource Water (ONRW). This is a classification created by the USEPA which does not allow any degradation if the state classifies a waterbody as an ONRW. This designation is usually reserved for exceptional waters with unique ecological and/or social significance needing special protection. Temporary water quality degradation is allowed in an ONRW only if “temporary” is defined in terms of weeks and months, and not years. Lake Tahoe has been designated an ONRW by the State of California since 1980.

1.2 National TMDL Program

Section 303(d) of the CWA and the USEPA Water Quality Planning and Management Regulations (Title 40 of the *Code of Federal Regulations* [CFR] Part 130) require states to: 1) identify impaired waters where required pollution controls are not stringent enough to attain water quality standards and 2) establish TMDLs for such waters for the pollutants that are contributing to the water quality impairments even if pollutant sources have implemented technology-based controls.

The impaired waters requiring the development of TMDLs are included on the states' Section 303(d) lists, which are submitted to USEPA every two years for approval. A TMDL establishes the maximum allowable load (mass per unit of time) of a pollutant that a waterbody is able to assimilate and still support its designated uses. The maximum allowable load is determined on the basis of the relationship between pollutant sources and the water quality of the specific water body. A TMDL provides the scientific basis for a state to establish water quality-based controls to reduce pollution from both point and nonpoint sources to restore and maintain the quality of the states' water resources (USEPA 1991). Point sources of pollutants are discrete, conveyed pollutant sources such as stormwater, while non-point sources of pollutants are diffuse pollutant sources such as atmospheric deposition.

Furthermore, TMDLs provide a means to integrate the management of both point and nonpoint sources of pollution through the establishment of wasteload allocations (WLAs) for point source discharges, and load allocations (LAs) for nonpoint sources. TMDLs are to be established at levels necessary to attain and maintain applicable narrative and numeric water quality standards with consideration given to seasonal variations and a margin of safety (MOS). The goal of the TMDL, when implemented, is that the waterbody fully attain its designated beneficial uses and water quality objectives.

The general equation describing the TMDL, the allocation and margin of safety components is as follows (USEPA 1991):

$$TMDL = LC = \sum WLA + \sum LA + MOS \qquad \textbf{Equation 1}$$

Where:
- $\sum$ = sum of
- LC = loading capacity, or the greatest loading a waterbody can receive without exceeding water quality standards;
- WLA = wasteload allocation, or the portion of the TMDL allocated to existing or future point sources;
- LA = load allocations, or the portion of the TMDL allocated to existing or future nonpoint sources and natural background;
- MOS = margin of safety, or an accounting of uncertainty about the relationship between pollutant loads and receiving water quality.

The margin of safety can be provided implicitly through conservative analytical assumptions or explicitly by reserving a portion of loading capacity. In addition to the above equation, the federal TMDL program requires that certain elements be included in a TMDL evaluation. The required elements and a brief explanation of each are provided in Table 1-1.

Table 1-1. Required TMDL elements.

Required Element	Definition
Problem Statement	The problem statement describes the impairment of the identified waterbody in terms of which currently designated beneficial use is not being attained. In other words, the Problem Statement explains which standards are being exceeded in that lake, stream or river. In the case of Lake Tahoe, it is the non-attainment of the established clarity objectives that has caused the lake to be listed for not meeting the non-contact beneficial use, or 'aesthetic standard'.
Numeric Targets	A Numeric Target needs to be established for each TMDL in order to quantify pollutant load reductions necessary to support beneficial uses designated for that waterbody. In some instances the Numeric Target needs to be determined based upon the evaluation of a narrative standard that does not specifically determine a numeric goal for the protection of beneficial uses. In the case of Lake Tahoe, a specific numeric standard for clarity currently exists.
Source Assessment	This element of TMDL development is intended to identify the location, type, frequency and magnitude of all known loading sources (both point and nonpoint). The principle product of the Source Assessment is the development of an accurate estimate, or budget, of the total pollutant load currently entering a waterbody.
Linkage Analysis	The Linkage Analysis is performed to understand what effect the identified pollutant sources and their respective loads are having on the identified waterbody. Once this is performed, a determination of the waterbody's assimilative capacity is identified. The assimilative capacity is the estimation of the maximum amount of pollutant a water body can assimilate without exceeding the existing water quality objectives. The linkage analysis is then able to quantify future pollutant loading levels that will be necessary to achieve the numeric targets identified in the target analysis.
Load Allocations	The assimilative capacity defines the amount of pollutant load reduction needed to achieve applicable water quality standards. Once the overall load reduction has been estimated, it then needs to be distributed or "allocated" among the significant sources of the pollutant identified in the source analysis. The determination and development of load allocations will be completed as part of the Integrated Water Quality Management Strategy (IWQMS). The development of the IWQMS is part of Phase Two of TMDL development. Consequently Load Allocations have not been developed for this report.
Margin of Safety	A Margin of Safety (MOS) must be included in the analysis to account for uncertainties in (a) the relationship between effluent limitations and the water quality of the receiving water and (b) the estimation of existing pollutant sources. The MOS may be provided implicitly through the use of conservative analytical assumptions or explicitly as an unallocated portion of the allowable loading. The MOS must also consider and provide an allocation for the potential loading resulting from the impacts associated with future growth. The MOS will be part of the Final TMDL and is not included in this document.
Monitoring and Review Plan and Schedule of Revision	The TMDL monitoring plan will track source load reductions, indicators and milestones over time, accounting for variability and including regular progress reports to inform decision-makers on the need for TMDL and/or Implementation Plan revision. This is to be developed for Lake Tahoe through the Pathway process and is not included in this report.
Implementation Plan (Required in California only)	Although not currently required by USEPA guidance, TMDLs adopted by the state of California must include an Implementation Plan. The Implementation Plan will present a detailed process for achieving load reductions beginning with current loads and resulting in the TMDL over an agreed-upon timeframe. Milestones will include interim load reductions at specified, regular intervals. This effort is currently being completed through the Pathway process and is not included in this report.

1.3 Lake Tahoe TMDL Program

Lake Tahoe's exceptional characteristics combined with its unique resource management/regulatory setting, presented particular challenges and opportunities that are illustrated in this section. The multi-agency approach taken to develop the Tahoe TMDL Program provided a vast range of expertise that was particularly valuable given the scheduling needs required for inclusion within the Pathway process. This section describes the scope of the Lake Tahoe TMDL, the phases of TMDL development for Lake Tahoe and the research program developed to support the Lake Tahoe TMDL.

1.3.1 Scope of Lake Tahoe TMDL Program

The Section 303(d) listing of Lake Tahoe identifies the lake as impaired for not attaining applicable water quality objectives. Specifically, the Lake Tahoe TMDL is being developed by California and Nevada to address pollutant loading from all sources to achieve existing water quality objectives for deep water clarity and transparency. This TMDL only addresses the pollutants impacting deep water transparency in Lake Tahoe, namely the loading of nitrogen, phosphorous and fine sediment.

The Lake Tahoe TMDL addresses only the pelagic (deep water) waters of Lake Tahoe and does not address the nearshore waters. The nearshore is defined as the area of the lake that is close to shoreline where the bottom of the lake is visible (LRWQCB 1995). The pelagic area of the lake is where the bottom is no longer visible from the surface. This TMDL report summarizes data from studies in the nearshore but does not address the water quality objectives for the nearshore. Though additional research is needed to better understand the relationship between upland activities and effects in the nearshore, this TMDL assumes that efforts to prevent pollutants from entering surface discharge for the protection of pelagic lake clarity should also benefit conditions in the nearshore. An exception to this may be isolated "hot spots" (i.e. marinas) in the nearshore area. These areas should be identified and addressed as needed as part of ongoing restoration efforts.

1.3.2 Phases of TMDL Development

For planning purposes, the development of the Lake Tahoe TMDL has been divided into three distinct phases. Phase One involved the research to develop loading estimates from major sources and estimate the amount of pollutant load reduction needed to attain applicable standards. The results of that evaluation are contained in this Technical Report. Phase Two of TMDL development includes a public process to determine the required load reduction allocations and to develop an implementation plan that outlines how pollutant load reductions will be achieved. The work to complete Phase Two is collectively referred to as the Integrated Water Quality Management Strategy (IWQMS). Once completed in 2008, the IWQMS formed the framework for water quality restoration planning and updating of regulatory documents through the Pathway process. The Pathway process also developed an adaptive management framework for the Tahoe basin and is expected to be the cornerstone of Phase Three of the TMDL process which identified the need for continuous updating and evaluation of TMDL loading estimates and models. The products of each phase are summarized in Table 1-2 and are discussed in greater detail below.

Table 1-2. TMDL Phased Development.

TMDL phase	Questions	Products
Phase One — Pollutant Capacity and Existing Inputs	**What pollutants are causing Lake Tahoe's clarity loss?**	Research and analysis of fine sediment, nutrients and meteorology
	How much of each pollutant is reaching Lake Tahoe?	Existing pollutant input to Lake Tahoe from major sources
	How much of each pollutant can Lake Tahoe accept and still achieve the clarity goal?	Linkage analysis and determination of needed pollutant reduction
		Document: TMDL Technical Report
Phase Two — Pollutant Reduction Analysis and Planning	**What are the options for reducing pollutant inputs to Lake Tahoe?**	Estimates of potential pollutant input reduction opportunities **Document:** Pollutant Reduction Opportunity Report
	What strategy should we implement to reduce pollutant inputs to Lake Tahoe?	Integrated strategies to control pollutants from all sources **Document:** Integrated Water Quality Management Strategy Project Report
		Pollutant reduction allocations and implementation milestones
		Implementation and Monitoring Plans
		Document: Final TMDL
Phase Three — Implementation and Operation	**Are the expected reductions of each pollutant to Lake Tahoe being achieved?**	Implemented projects & tracked pollutant reductions
	Is the clarity of Lake Tahoe improving in response to actions to reduce pollutants?	Project effectiveness and environmental status monitoring
	Can innovation and new information improve our strategy to reduce pollutants?	TMDL continual improvement and adaptive management system, targeted research
		Document: Periodic Milestone Reports

Phase One

The first phase of TMDL development initiated a significant research effort. In July of 2001, a budget request made by the Governor of California was approved by the State Legislature and provided funding for an ambitious 5-year program to investigate pollutant sources and the magnitude of load reductions needed to restore lake clarity. This initial round of funding provided to the Water Board and the California Air Resources Board (CARB) initiated significant research efforts to fill information gaps and develop the tools needed to perform a basin-wide evaluation of pollutant sources and their affect on Lake Tahoe.

To compliment this initial research effort and secure funding to complete Phase Two of the TMDL, the project team wrote numerous funding proposals that resulted in significant additional funding contributions from the federal government and both states. This partnership is nationally significant, reflecting both on the importance of Lake Tahoe as a resource and the dedication of state, regional and federal agencies to better understand and protect Lake Tahoe.

The research objectives of Phase One of TMDL development were to:

- Identify the significant sources of pollutants impacting the transparency and clarity of Lake Tahoe,
- Provide quantitative estimates of pollutant loading from the identified sources,
- Provide a linkage between those pollutants and response by optical properties within the lake,
- Provide quantitative estimates of the load reductions needed to achieve applicable water quality objectives protecting the optical properties of Lake Tahoe, and
- Summarize the results of the research and applied science used to achieve these objectives in a Technical Report.

Descriptions and summaries of the research and applied science used to achieve these objectives are contained in this report. This information is intended to assist in development of scientifically informed decisions needed as part of Pathway, IWQMS and development of the Final Lake Tahoe TMDL.

Phase Two

The second phase of TMDL development facilitated agency and stakeholder discussion on load reduction opportunities. This phase of TMDL development explored various pollutant control opportunities, packaged these opportunities into integrated implememation strategies, and developed a single Recommended Strategy for TMDL implemenation. The development of this strategy is the cornerstone of the Phase Two effort and provides a solid planning platform for the management of water quality and the restoration of Lake Tahoe's clarity and transparency. Phase Two also developed the remaining elements for the Final TMDL, including Recommended Strategy details, source-specific pollutant load allocations, waste load allocations for NPDES-permitted urban jurisdictions, along with implementation and monitoring plans to achieve water quality objectives.

Phase Three

The continuous incorporation of future research efforts, monitoring data and improved understanding is a fundamental intention of the Lake Tahoe TMDL Program. The estimates developed for this report provide a comprehensive evaluation of all pollutant sources and their effect on lake clarity. Many factors can affect these estimates including, data form and availability, quality of information, variability of complex ecosystems, unavoidable need for assumptions, and certainty of estimates all have the potential to impact the estimates developed. The project team minimized these effects as much as possible by drawing on the wealth of scientific information and expertise available in the Tahoe basin, but the need for continuous re-evaluation, interpretation and improvement was recognized early in the process. Phase Three of the Lake Tahoe TMDL will specifically address these needs by completing several tasks:

- Develop an adaptive management system to integrate new information, research and understandings,
- Provide a framework for the modification and tracking of pollutant load estimates and pollutant load reduction allocations over time,
- Identify additional research and information to improve quantified estimates,
- Explore opportunities for greater integration between pollutant source categories, agencies, funding, monitoring and direct application of future efforts.

The scientific framework developed by the TMDL program will allow for timely application of new information as well as the ability to evaluate the potential outcome of management actions in the future. This will allow for an increased ability to incorporate new information, evaluate potential implications of change, and estimate lake response in a much more timely and efficient manner.

1.3.3 TMDL Associated Research

Given its national significance, Lake Tahoe and its watershed have benefited from decades of research and scientific attention. Consequently, Lake Tahoe is a well-studied ecosystem with a rich database for TMDL application. Literally, hundreds of peer reviewed journal papers, and reports have been written on many aspects of Lake Tahoe and its watershed since studies first began over 40 years ago (Reuter and Miller 2000). Much of this information was used to address a series of questions associated with three critical issues relevant to the Lake Tahoe TMDL:

1) Identify major pollutant sources and where possible, quantify loading of nutrients and fine sediments to Lake Tahoe,
2) Determine the extent, to which the load of fine sediment and nutrients from the watershed and air basin can be effectively reduced by management and/or restoration activities,
3) Understand how Lake Tahoe's clarity will respond to environmental improvement and pollutant control efforts.

Many of the researchers who have studied Lake Tahoe and its environment for the past 10-20 years (and longer) are still very active in the scientific community. This has allowed TMDL researchers the ability to establish inter-disciplinary and inter-institutional science teams. Another key benefit to the rich database is that the many models that have been used in the Lake Tahoe TMDL effort were able to incorporate rate coefficients and other parameters which are developed with site specific data rather than depending on literature data. Moreover, the extensive monitoring data from the

Lake Tahoe Interagency Monitoring Program provides key intra- and inter-annual time series data sets for model population, calibration and validation.

Initiated in 2001, research associated with the development of the Lake Tahoe TMDL was specifically intended to build on the wealth of information available in the Tahoe basin. Key Management Questions relevant to the Lake Tahoe TMDL where evaluated and information gaps were identified that required additional evaluation for application in TMDL development. The development of these information needs was based on many events/efforts, including but not limited to: guidance from previous and ongoing research; Presidential Forum at Lake Tahoe in 1997; Lake Tahoe Watershed Assessment; Lake Tahoe Science Symposia; establishment of the Lake Tahoe Science Consortium; and the Pathway process.

Dr. John Reuter from the UC Davis Tahoe Environmental Research Center (UC Davis - TERC) was contracted as Research and Science Coordinator for the Lake Tahoe TMDL Program. Dr. Reuter developed, in coordination with the project team, a Science Plan for the Lake Tahoe TMDL that identified information gaps and tools needed for TMDL development. This plan greatly benefited from rich literature on Lake Tahoe, its watersheds, and its air basin. Significant contributions were provided from multiple academic, state, federal, and private consulting entities to complete the research and applied science contained in this report. The use of sound science continues into Phase Two and will be continuously improved thru Phase Three.

The following section provides brief descriptions of the research and applied science projects completed as part of the TMDL. This overview also includes some research projects completed since 2001 that directly applied to the TMDL. The collection and application of this information has provided a framework for the integration of science and information and its translation into management application through the TMDL program.

Sources of scientific information used to address these TMDL issues include:

- Historic Tahoe data and analyses
- Scientific literature
- New and existing monitoring data
- Laboratory experiments
- Field experiments
- Demonstration projects
- Statistical analyses
- Modeling – with calibration and validation
- Best professional judgment

Brief descriptions, by category, of the major, new TMDL science projects that were done in support of Phase One of the Lake Tahoe TMDL are provided below:

Watershed Model – In direct support of the TMDL, Tetra Tech has developed the Lake Tahoe Watershed Model using the Loading Simulation Program in C++ (LSPC). The watershed modeling system includes algorithms for simulating hydrology, sediment and water quality from over twenty land-use types in 184 subwatersheds. This model was used to estimate the current pollutant loading to the lake from surface runoff and will be used for the exploration of various scenarios during development of the IWQMS. An independent study was also conducted to determine the statistical relationship between land-use characteristics and loading.

Lake Clarity Model – The University of California, Davis (UC Davis), has been developing the Lake Tahoe Clarity Model (Lake Clarity Model) for several years based on the extensive data collected on lake processes by the Tahoe Environmental Research Center (TERC) (formerly Tahoe Research Group) and others over the last forty years. The Lake Clarity Model is a unique combination of sub-models including a hydrodynamic model, an ecological model, a water quality model and an optical model. This model was developed to specifically identify Lake Tahoe's response to pollutant loading and the pollutant reductions necessary for the protection of lake clarity.

Atmospheric Transport and Deposition – The California Air Resources Board (CARB) recently completed a large and significant effort to better characterize atmospheric pollutant sources, transport and deposition (*Lake Tahoe Atmospheric Deposition Study* – LTADS). This two year monitoring and modeling effort has provided updated and new information on the amount of nutrients and particulate matter generated in the basin (and out-of-basin) and the amount of deposition onto the lake surface resulting from these processes. LTADS, for the first time, quantified the deposition of particulate matter onto Lake Tahoe. Current and previous studies by the UC Davis-TERC, UC Davis DELTA Group, and the Desert Research Institute (DRI) were also used in quantifying atmospheric deposition.

Groundwater Loading – On the basis of currently available nutrient data from existing wells, an assessment of likely inflow and nutrient loading from five regions comprising the entire shoreline of Lake Tahoe was completed by the US Army Corps of Engineers.

BMP Feasibility Report – Using both national and local data, Geosyntech Consultants, evaluated the performance of urban runoff BMPs, and for the first time took a basin-wide approach to evaluating BMP performance.

Stream Channel Erosion – The U.S. Department of Agriculture's (USDA's) National Sedimentation Laboratory evaluated the significance of stream channel erosion as a source of fine sediment. This project quantified the significance of stream channel erosion relative to other major sources. This increased understanding will enable stream channel erosion to be treated as a discrete source of pollution in the Lake Tahoe TMDL.

Urban Stormwater Monitoring – Sixteen auto-samplers were deployed throughout the basin as part of the TMDL-funded Stormwater Monitoring Program in 2003 and 2004. These stations plus three stations already in operation were used to measure water quality in runoff from different urban land-uses. All storm events were measured for two consecutive years to better inform watershed modeling estimates of loading from different land-uses. This work was completed collaboratively between the DRI and UC Davis - TERC. This was the first time a comprehensive effort has been made at Lake Tahoe to characterize and quantify urban stormwater quality based on land-use. California Department of Transportation and Nevada Department of Transportation also conducted companion studies during the period 2001-2004 to determine the water quality of runoff from primary roads.

Biologically Available Phosphorus (BAP) – Measurements of ortho-phosphorus and total phosphorus underestimate and overestimate the phosphorus available for algal growth, respectively. However, monitoring programs rarely measure BAP. In a study conducted at the University of Nevada-Reno, researchers measured BAP from various sources in the Tahoe basin. This information was used in the Lake Clarity Model to estimate nutrients from stream channel erosion.

Nearshore Clarity – The DRI measured nearshore turbidity values through whole lake transects and focused study along the south shore. Real time measurements of turbidity where taken during different weather conditions to measure differences in nearshore turbidity. These studies indicate that nearshore turbidity is negatively impacted during surface flow events associated with snowmelt and rainfall runoff in urban areas.

Sources and Fate of Fine Particles – The importance of fine particles to Lake Tahoe's clarity only was first recognized in 1999 (Jassby et al. 1999). A series of in-lake investigations commenced in 1999 that have help characterize particle distribution and dynamics in Lake Tahoe. As part of the TMDL science program additional research and monitoring was done to investigate particle loading from the channelized tributaries. Additional investigations were also made to better understand the processes of particle aggregation, settling and ultimate removal from the water column.

Lake Tahoe Interagency Monitoring Program (LTIMP) - LTIMP is a cooperative program including both state and federal partners and is operationally managed by the U.S. Geological Survey (USGS), UC Davis - TERC, and the Tahoe Regional Planning Agency (TRPA). It was formed in 1979 (Leonard and Goldman 1981) and one of its main missions is to monitor flow, nutrient load and sediment loads from representative streams that flow into Lake Tahoe. The following streams are currently monitored and have been monitored since 1988: Trout Creek, Upper Truckee River, General Creek, Blackwood Creek, Ward Creek, Third Creek, Incline Creek, Glenbrook Creek, Logan House Creek and Edgewood Creek (Rowe et al. 2002). Because of variation in watershed characteristics around the basin and significant 'rain shadow' effects along the west-to-east direction across the lake, no single location is representative of all watersheds. Cumulative flow from these monitored streams comprises about 50 percent of the total discharge from all tributaries. Each stream is monitored on 30-40 dates each year and sampling is largely based on hydrologic events. Nitrogen and phosphorus loading calculations are performed using the LTIMP flow and nutrient concentration database. LTIMP also includes measurements of atmospheric deposition using wet/dry collectors and measurement of Secchi depth and associated limnological parameters (e.g., Byron and Goldman 1988).

Brief descriptions of the current TMDL projects that are being done in support of Phase Two of the Lake Tahoe TMDL are provided below:

Integrated Water Quality Management Strategy – The goals of the Integrated Water Quality Management Strategy project were twofold. First, the project considered the feasibility and potential effectiveness of different pollutant control measures for reducing pollutant loads from the major pollutant source categories. Second, the project packaged various load reduction opportunities into integrated implementation strategies. With feedback from the Pathway Forum and other stakeholders, the sample strategies were refined into a single Recommended Strategy for TMDL implementation.

Pollutant Load Reduction Model – A team of consultants lead by Northwest Hydrologic Consultants, Inc. and GeoSyntec is working to develop a modeling tool to estimate pollutant load reductions from water quality improvement actions at a subwatershed scale. It is expected that this tool will provide a uniform approach to calculating expected pollutant load reductions from infrastructure improvements, roadway management actions, and operations and maintenance practices. Load reduction estimates will help inform Lake Clarity Credit assignment assist in measuring progress towards achieving required pollutant load reductions.

Water Quality Crediting, Incentives, and Trading Feasibility Study – Environmental Incentives, LLC is working on behalf of the Lake Tahoe TMDL effort to establish a Lake Clarity Crediting Progam that will link water quality improvement actions to pollutant load reductions. The crediting system will primarily be used to evaluate and track load reductions from the urban source category. The program will ensure consistent water quality benefit assessments and will offer greater regulatory flexibility to municipal jurisdictions in selecting and implementing water quality improvement actions. The Crediting Program will also provide a consistent metric to determine compliance with municipal storm water regulations.

Load Reduction Accounting and Tracking System – A pollutant reduction tracking system is critical to water quality restoration in that it provides resource managers and project implementers with an up-to-date assessment of progress towards meeting the Lake Tahoe TMDL and associated pollutant load reduction allocations. These systems will allow for the tracking of trends and for modification of the implementation timeline based upon new information. In partnership with the United States Army Corp of Engineers, the Lahontan Water Board is developing a comprehensive Accounting and Tracking System database to support the Lake Tahoe TMDL and the Lake Clarity Crediting Program information storage and reporting needs. The Accounting and Tracking System will account for water clarity credits, track load reduction estimates, and provide ready access to tables and charts to document progress toward meeting pollutant load reduction goals. 2nd Nature, Inc. is leading the Accounting and Tracking System project team.

1.4 Problem Statement

Lake Tahoe is a unique environmental treasure, and designated by the State of California and the USEPA as an Outstanding National Resource Water (ONRW) under the Clean Water Act. However, Lake Tahoe's hydrologic and air basins are part of a changing landscape, with significant portions of this once pristine region now urbanized. Studies during the past forty years have shown that many factors have interacted to degrade the Lake Tahoe Basin's air quality, terrestrial landscape and water quality, such as land disturbance, increasing resident and tourist population, habitat destruction, air pollution, soil erosion, roads and road maintenance and loss of natural landscapes capable of detaining and infiltrating rainfall runoff (Goldman 1998, Reuter et al. 2003). Cumulatively, these factors have impacted the famed transparency of Lake Tahoe as indicated by the loss of approximately 8 meters of Secchi depth clarity since the early 1970s.

1.4.1 Nature of Impairment to Water Quality

Continuous long-term evaluation of water quality in Lake Tahoe between 1968 and 2007 has documented a decline of deep water transparency (commonly referred to as clarity) from an annual average of 31.2 meters to 21.4 meters, respectively (Jassby et al. 1999, 2003, UC Davis - TERC 2008). Transparency is expressed as Secchi depth and is the depth to which an observer can see a 25 centimeter diameter white disk lowered into the water from the surface. This long-term loss of transparency is both statistically significant ($p < 0.001$) and visually apparent.

Based on the most recent Secchi depth data for 2007 and applying a more sophisticated statistical approach known as a *generalized additive model*, it was recently reported that between 2001 and 2007 there was an apparent slowing in the rate of clarity loss (UC Davis - TERC 2008). Researchers caution that the trend developed by the current analysis could change depending on what future measurements show and the seven years of most recent data is insufficient to declare with certainty that the apparent slowing will be sustained into the future. Since even the most recent annual Secchi depth value of 21.4 meters as measured in 2007 is 8.3 meters less than the 1967-1971 average annual Secchi depth of 29.7m, the loss of transparency is a significant water quality impairment.

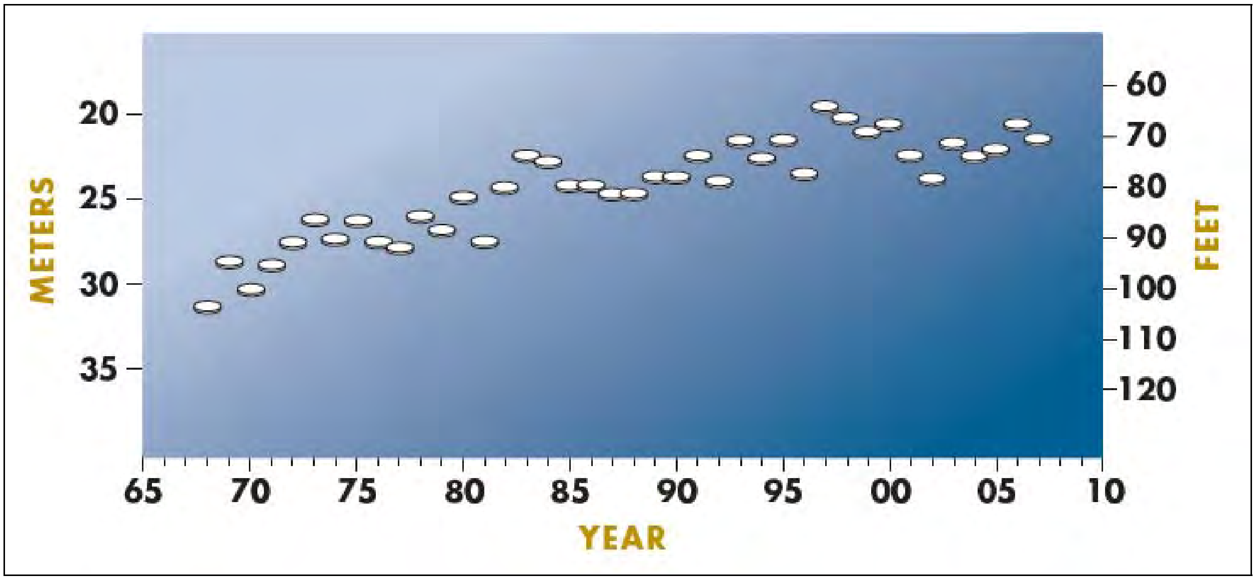

Figure 1-1. Average Annual Secchi Depth measurements (UC Davis – TERC unpublished).

Further signs of impairment to the waters of Lake Tahoe include these examples that add evidence that the water quality of Lake Tahoe has undergone significant changes:

- algal growth rate or primary productivity has increased since 1958 (e.g. Goldman 1998, Jassby et al. 2001, UC Davis - TERC 2008);
- the depth at which the deep chlorophyll maximum occurs has generally been getting shallower over time – presumably linked to the decline in clarity (UC Davis - TERC 2008);
- nuisance growth of attached algae is found in the urbanized nearshore region (e.g. Hackley et al. 2007);
- turbidity in the nearshore is elevated in the vicinity of urban regions compared to undeveloped land-uses (Taylor et al. 2003); and
- changes in lake biology and food web dynamics (e.g. Hunter et al. 1990, Vander Zanden et al. 2003, Hunter 2004, Chandra et al. 2005).

The measurements shown in Figure 1-1 represent annual averages of Secchi depth measurements; Table 1-3 provides the specific data for each year in the long-term record. However, Secchi depth exhibits distinct seasonal changes. The mean seasonal pattern over the period of record is bimodal, with a strong annual minimum Secchi depth (reduced clarity) in May-June and a weaker local minimum in December (Jassby et al. 1999). The clearest water is typically observed in February with a secondary period of clear water in October.

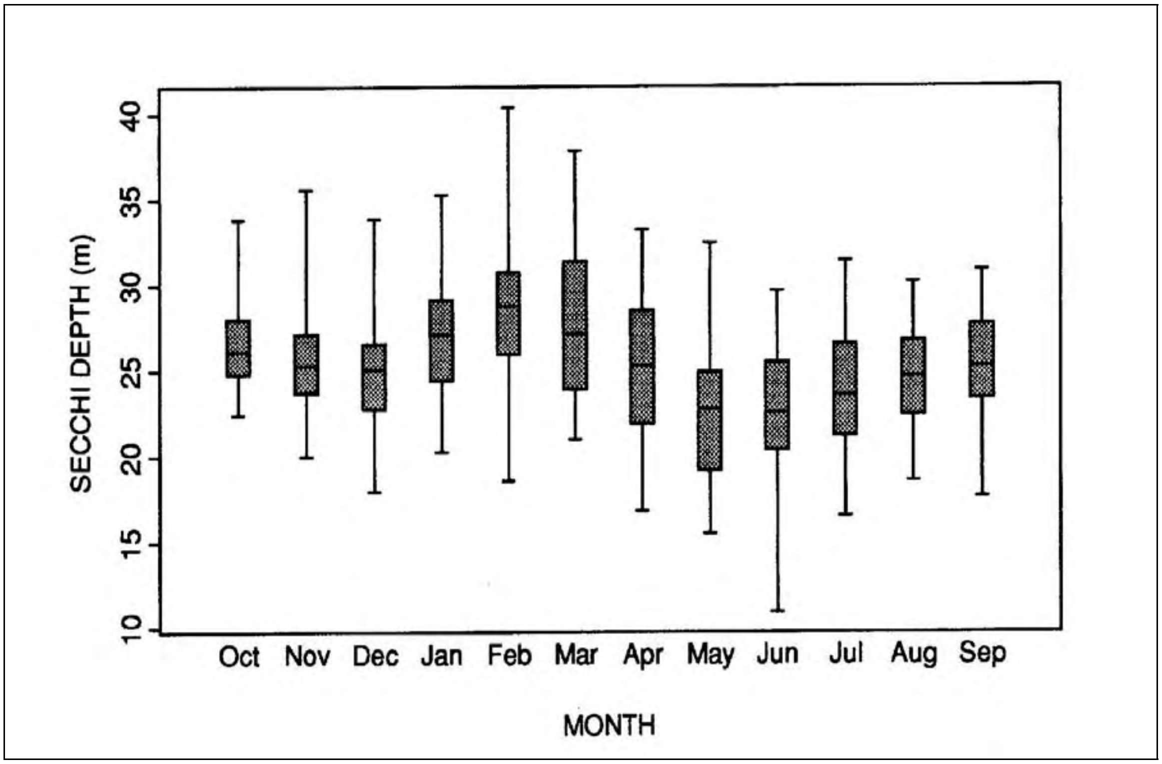

Figure 1-2. Seasonal pattern of Secchi depth from 1968 - 1996 (Jassby et al. 1999).

Jassby et al. (1999) considered the decreased Secchi depth in June to be due to the cumulative discharge of suspended sediment following melting of the seasonal snowpack. This is consistent with the measured seasonal pattern of suspended sediment discharge and with visual observations of sediment plumes entering the lake. The sediment load typically diminishes in June and thermal stratification with-in the lake intensifies. From June to October, the balance between watershed inputs and loss of particles from upper waters due to sedimentation begins to shift, resulting in the gradual increase in clarity. The December clarity minimum is attributed to the deepening of the mixed layer as the thermocline erodes at that time of year and passes through layers of phytoplankton and other light-attenuating particles that reach a maximum below the summer mixed layer (e.g., the deep chlorophyll maximum typically found between 40 – 60 meters in Lake Tahoe).

Table 1-3. Annual Average Secchi Depth values for the period of record (UC Davis – TERC unpublished).

Year	Secchi Depth (m)	Year	Secchi Depth (m)
1968	31.22	1988	24.66
1969	28.57	1989	23.64
1970	30.21	1990	23.64
1971	28.74	1991	22.43
1972	27.41	1992	23.89
1973	26.08	1993	21.47
1974	27.21	1994	22.57
1975	26.11	1995	21.47
1976	27.38	1996	23.45

1977	27.75	1997	19.53
1978	25.95	1998	20.14
1979	26.72	1999	21.04
1980	24.82	2000	20.53
1981	27.39	2001	22.44
1982	24.31	2002	23.78
1983	22.38	2003	21.62
1984	22.79	2004	22.42
1985	24.20	2005	22.05
1986	24.08	2006	20.63
1987	24.65	2007	21.37

In addition to the change in Secchi depth (transparency), there have been documented changes in the vertical transmission or penetration of light into the water (clarity). Light penetration (euphotic zone) in Lake Tahoe has been as deep as about 100 meters, but over the past decade it has largely ranged from 50 – 70 meters. Swift (2004) reported that the reduction in this deep-light transmission has caused an important upward shift of the deep chlorophyll maximum in Lake Tahoe from 60 – 90 meters in the early 1970's to 40 – 70 meters more recently. In addition to documenting changes to water quality, the gradual change to the euphotic zone affects pelagic and benthic food webs, (Chandra et al. 2005) as well as lake trout spawning habitat in deep-water aquatic plant communities (Beauchamp et al. 1992).

The declining transparency resulted in the inclusion of Lake Tahoe as water quality-limited in California's biennial report on water quality, as mandated by CWA Section 305(b), in 1998. That same year, Lake Tahoe was included on California's Section 303(d) list of waterbodies requiring development of TMDLs (SWRCB 2003). Lake Tahoe was also placed on Nevada's 2002 Section 303(d) list of impaired waters (NDEP 2002) as a result of clarity loss.

2 Numeric Target

The Clean Water Act (CWA) establishes a regulatory framework to restore degraded surface waterbodies. The framework begins with adoption by states, subject to USEPA approval, of appropriate numeric or narrative water quality standards for the subject waterbody. This includes designating the beneficial uses of the water, setting criteria necessary to protect the uses, and preventing degradation of water quality by means of antidegradation provisions. States adopt water quality standards to protect public health or welfare, to enhance the quality of water and to serve the purposes of the CWA by helping to "restore and maintain the chemical, physical and biological integrity" of state waters (CWA section 101(a)).

2.1 Applicable State and Regional Water Quality Standards

Consistent with the requirements of the CWA, beneficial uses, water quality criteria and antidegradation objectives have been established for Lake Tahoe by the States of California and Nevada. Additionally, the Lake Tahoe basin has water quality thresholds, programs and regulations as developed and implemented by the Tahoe Regional Planning Agency (TRPA). This section of the report summarizes the water quality standards of these regulatory agencies.

The primary responsibility for the protection of water quality in California rests with the State Water Resources Board (State Board) and nine Regional Water Quality Control Boards (Water Boards). The State Board sets statewide policy for the implementation of state and federal laws and regulations. The Regional Boards adopt and implement Water Quality Control Plans (Basin Plans). Basin Plans set forth water quality standards for the surface and groundwaters of the region, which include both designated beneficial uses of water and the narrative and/or numerical objectives that must be maintained or attained to protect beneficial uses. The Basin Plan implements a number of state and federal laws, the most important of which are the federal CWA and the State Porter-Cologne Water Quality Control Act (California Water Code § 1300 et seq). The jurisdiction of the California Regional Water Quality Control Board, Lahontan Region (the Water Board responsible for the Lake Tahoe basin) extends from the Oregon boarder to the northern Mojave Desert and includes all of California east of the Sierra Nevada crest.

The Nevada Water Pollution Control Law designated the Department of Conservation and Natural Resources (DCNR) as the State Water Pollution Control Agency for all purposes of the CWA. The statute authorizes the DCNR to assume the responsibilities delegated by federal water pollution control legislation and to develop comprehensive plans and programs for reducing or eliminating water pollution. Within DCNR, these functions and authorities are carried out by the Nevada Division of Environmental Protection (NDEP), which is the agency responsible for implementation of water quality protection programs and CWA requirements in the Lake Tahoe basin for the State of Nevada.

The Tahoe Regional Planning Compact was adopted in 1969 when the California and Nevada legislatures agreed to create the TRPA to protect Lake Tahoe. The Compact, as amended in 1980, defines the purpose of the TRPA (TRPA 1980):

> *To enhance governmental efficiency and effectiveness of the Region, it is imperative there be established a Tahoe Regional Planning Agency with the powers conferred by this compact including the power to establish environmental threshold carrying capacities and to adopt and enforce a regional plan and implementing ordinances which will achieve and maintain such capacities while providing opportunities for orderly growth and development consistent with such capacities.*

2.1.1 State Beneficial Uses

Table 2-1 provides a comparison of Lake Tahoe's beneficial uses as designated by California and Nevada. The two states' beneficial use designations are entirely consistent for purposes of establishing a TMDL to protect Lake Tahoe's transparency. Both California and Nevada have identified the aesthetic of Lake Tahoe's clarity as a beneficial use, "non-contact water recreation" in California and "recreation not involving contact with water" in Nevada.

Table 2-1. Comparison of Nevada and California beneficial uses for Lake Tahoe (Water Board 1995, Nevada Administrative Code).

Nevada	California
Irrigation	AGR – Agricultural Supply
Watering of Livestock	AGR – Agricultural Supply
Recreation not involving contact with the water	REC-2 – Non-contact Water Recreation
Recreation involving contact with the water	REC-1 – Water Contact Recreation
Industrial Supply	None
Propagation of wildlife	WILD – Wildlife Habitat
Propagation of aquatic life, including a coldwater fishery	COLD – Cold Freshwater Habitat
	BIOL – Preservation of Biological Habitats of Special Significance
	MIGR – Migration of Aquatic Organisms
	SPWN – Spawning, Reproduction and Development
Municipal or domestic supply, or both	MUN – Municipal and Domestic Supply
Water of extraordinary ecological or aesthetic value	Although not a Beneficial Use, California has designated Lake Tahoe an "Outstanding National Resource Water."
None	GWR – Groundwater Recharge
	NAV – Navigation
	COMM – Commercial and Sport Fishing

2.1.2 State Water Quality Objectives

Several water quality objectives serve to protect the non-contact recreation beneficial use, including clarity, transparency, algal productivity, and concentrations of nitrogen and phosphorus (LRWQCB 1995). Table 2-2 contains a comparison between California and Nevada's numeric water quality objectives related to clarity, and those factors that affect clarity and transparency.

Table 2-2. Comparison of Nevada and California numeric objectives for parameters related to lake clarity in Lake Tahoe (Water Board 1995, Nevada Administrative Code).

Parameter	Nevada[a]	California[b]
Soluble Phosphorus (mg/L)	Annual Average ≤ 0.007	NA[c]
Total Phosphorus (mg/L)	NA[c]	Annual Average ≤ 0.008
Total Nitrogen (as N) (mg/L)	Annual Average ≤ 0.25 Single Value ≤ 0.32	Annual Average ≤ 0.15
Total Soluble Inorganic Nitrogen (mg/L)	Annual Average ≤ 0.025	NA[c]
Algal Growth Potential	The mean annual algal growth potential at any point in the lake must not be greater than twice the mean annual algal potential at a limnetic reference station and using analytical methods determined jointly with the EPA, Region IX	The mean annual algal growth potential at any point in the lake must not be greater than twice the mean annual algal potential at a limnetic reference station. The limnetic reference station is located in the north central portion of Lake Tahoe. It is shown on maps in annual reports of the Lake Tahoe Interagency Monitoring Program. Exact coordinates can be obtained from the UC Davis Tahoe Research Group.
Plankton Count (No./mL)	Jun – Sep Average ≤ 100 Single Value ≤ 500	Mean seasonal ≤ 100 Maximum ≤ 500
Biological Indicators	NA[c]	Algal productivity and the biomass of phytoplankton, zooplankton, and periphyton shall not be increased beyond the levels recorded in 1967-71 based on statistical comparison of seasonal and annual means. The "1967-71 levels" are reported in the annual summary reports of the "California-Nevada-Federal Joint Water Quality Investigation of Lake Tahoe" published by the California Department of Water Resources. [Note: The numeric criterion for algal productivity (or Primary Productivity, PPr) is 52 g C m^{-2} y^{-1} as an annual mean.]
Clarity	The vertical extinction coefficient must be less than 0.08 per meter when measured at any depth below the first meter. Turbidity must not exceed 3 NTU at any point of the lake too shallow to determine a reliable extinction coefficient.	The vertical extinction coefficient must be less than 0.08 per meter when measured at any depth below the first meter. Turbidity must not exceed 3 NTU at any point of the lake too shallow to determine a reliable extinction coefficient. In addition, turbidity shall not exceed 1 NTU in shallow waters not directly influenced by stream discharges. The Regional Board will determine when water is too shallow to determine a reliable vertical extinction coefficient based upon its review of standard limnological methods and on advice from the UC Davis Tahoe Research Group.
Transparency	NA[c]	The Secchi disk transparency shall not be decreased below the levels recorded in 1967-71, based on a statistical comparison of seasonal and annual mean values. The "1967-71 levels" are reported in the annual summary reports of the "California-Nevada-Federal Joint Water Quality Investigation of Lake Tahoe" published by the California Department of Water Resources. [Note: the 1967-71 annual mean Secchi depth was 29.7 meters.]

[a]Provision in State Regulation: Nevada Administrative Code 445A.191
[b]Provision in State Regulation: Water Quality Control Plan for the Lahontan Region (Water Board 1995).
[c]No applicable numeric water quality objectives

Secchi disk clarity is best considered as a measure of visibility; that is, the depth to which one can see down into the water. The Secchi depth is the depth at which a 25 centimeter white disk is no longer visible from the surface as it is lowered into a waterbody. An observer lowers the Secchi disk into the water and records the depths at which it disappears then re-appears upon retrieval. The average of those two depths is considered the Secchi depth. The historical trend of declining transparency has been made using a 25 centimeter, all white, Secchi disk. The clear water of Lake Tahoe yields Secchi depths on the order of 20-30 meters and, therefore, this measure of transparency is not used in shallow, near-shore environments where the disk would be seen on the lake bottom.

The Vertical Extinction Coefficient (VEC) represents the fraction of light held back (or extinguished) in water per meter of depth by absorption and scattering. Thus, higher VEC values indicate less clarity. The vertical transmission or penetration of light down the water column extends beyond the Secchi depth and in Lake Tahoe very small amounts of light can be measured at depths greater than 100 meters (Swift 2004). Limnologists and aquatic ecologists often refer to the depth of 1 percent transmission as the lower boundary of the euphotic zone. This is considered an important depth since net phytoplankton growth (i.e., positive biomass accrual) generally occurs above this depth. The VEC numeric objective also protects deep light penetration (from 30 meters to approximately 100 meters), which is important for protecting deep living aquatic rooted plants (macrophytes) that serve as lake trout spawning and rearing grounds (Beauchamp et al. 1992). From 1967 to 2002 the VEC at Lake Tahoe, as measured by the UC Davis - TERC, has ranged from approximately 0.04-0.11/meter.

2.1.3 State Nondegradation Objectives

All California waterbodies are subject to an antidegradation objective that requires continued maintenance of high quality waters. In 1980 California's State Water Resources Control Board (SWRCB) designated Lake Tahoe as subject to the highest level of protection under the antidegradation objective, that of an ONRW, both for its recreational and its ecological value. The Water Board's Basin Plan states (LRWQCB 1995):

> *Viewed from the standpoint of protecting beneficial uses, preventing deterioration of Lake Tahoe requires that there be no significant increase in algal growth rates. Lake Tahoe's exceptional recreational value depends on enjoyment of the scenic beauty imparted by its clear, blue waters. Likewise, preserving Lake Tahoe's ecological value depends on maintaining the extraordinarily low rates of algal growth which make Lake Tahoe an outstanding ecological resource.*

Section 114 of the federal CWA also indicates the need to "preserve the fragile ecology of Lake Tahoe." The water quality of an ONRW must be maintained and protected under 40 CFR 131.12(a)(3). No permanent or long-term reduction in water quality is allowable for an ONRW.

Rather than designating Lake Tahoe an ONRW, Nevada has adopted the following beneficial use of Lake Tahoe: “water of extraordinary ecological or aesthetic value (Nevada Administrative Code (NAC) 445A.1905.).” There are significant differences between California’s ONRW designation and Nevada’s “water of extraordinary value” designation.

Nevada’s numeric criteria for Lake Tahoe are essentially Requirements to Maintain Higher Quality (RMHQs). RMHQs are intended to protect water quality higher than that strictly necessary to support beneficial uses. According to CWA regulations at 40 CFR 131.12(a)(2), the RMHQ criteria “shall be maintained and protected unless the State finds that allowing lower water quality is necessary to accommodate important economic or social development in the area in which the waters are located.” Therefore Nevada’s antidegradation designation of Lake Tahoe affords less protection than does California’s. However, the difference between California’s and Nevada’s designations does not diminish the prohibition against water quality reduction required by California’s ONRW designation, because Lake Tahoe is an interstate waterbody where more stringent protections by one state dictate the overall requirements that pertain throughout the basin. This is because of 40 CFR Part 131.10(b), which states: "In designating uses of a waterbody and the appropriate criteria for those uses, the State shall take into consideration the water quality standards [WQS] of downstream waters and shall ensure that its WQS provide for the attainment and maintenance of WQS of downstream waters.”

2.1.4 Tahoe Regional Planning Agency Water Quality Objectives

Article V(c)(1) of the Tahoe Regional Planning Compact calls for a “land use plan for the…standards for the uses of land, water, air space and other natural resources within the Region…” The Land Use Element includes the Water Quality sub-element, which is introduced with the following language (TRPA 1980):

> *The purity of Lake Tahoe and its tributary streams helps make the Tahoe basin unique. Lake Tahoe is one of the three clearest lakes of its size in the world. Its unusual water quality contributes to the scenic beauty of the Region, yet it depends today upon a fragile balance among soils, vegetation, and man. The focus of water quality enhancement and protection in the basin is to minimize man-made disturbance to the watershed and to reduce or eliminate the addition of pollutants that result from development.*

The TRPA Compact established several policies related to water quality planning and implementation programs. Relative to standards, the Compact states that the Regional Plan shall provide for attaining and maintaining federal, state or local water quality standards, whichever are the most stringent.

In addition to the establishment of Numerical, Management and Policy standards for water quality, there are two water quality goals:

> *GOAL #1: Reduce loads of sediment and algal nutrients to Lake Tahoe; Meet sediment and nutrient objectives for tributary streams, surface runoff, and sub-surface runoff, and restore 80 percent of the disturbed lands.*
>
> *GOAL #2: Reduce or eliminate the addition of other pollutants that affect, or potentially affect, water quality in the Tahoe basin.*

To achieve these goals, the TRPA established a number of supporting standards and indicators that include numeric objectives for protection of lake clarity. The relevant standards and indicators are listed below.

WQ-1 Littoral (Nearshore) Lake Tahoe

> Threshold Standard: Decrease sediment load as required to attain turbidity values not to exceed 3 NTU in littoral Lake Tahoe. In addition, turbidity shall not exceed 1 NTU in shallow waters of Lake Tahoe not directly influenced by stream discharge.
>
> Indicator: Turbidity offshore at the 25-meter depth contour at 8 locations, both near the mouths of tributaries and away from the tributaries.

WQ-2 Pelagic Lake Tahoe, Deep Water

> Threshold Standard: Average Secchi depth, December – March, shall not be less than 33.4 meters.
>
> Indicator: Secchi depth, winter average; Tahoe Research Group index stations (meters).

It should be noted that there is a difference between the California and TRPA objectives for clarity relevant to Secchi measurement. The TRPA uses a winter (December – March) average while California uses a statistical comparison of seasonal and annual mean values.

2.2 Comparison of Water Quality Objectives and Determination of Numeric Target

The objective of the Lake Tahoe TMDL is to restore the deep water transparency and clarity of Lake Tahoe to levels protected by California, Nevada and TRPA water quality standards (Table 2-2). As described in Sections 2.1.1 and 2.1.4, all three of these agencies have identified the aesthetic quality of Lake Tahoe's deep water clarity as a beneficial use and all three accord Lake Tahoe a high level of protection against degradation. Section 2.2 compares these water quality objectives and provides an appropriate numeric target for the TMDL.

2.2.1 Comparison of Lake Tahoe Transparency and Clarity Objectives

Clarity and transparency standards are both used to protect the aesthetic beneficial use of water in Lake Tahoe (Table 2-2). Clarity standards, in both California and Nevada, are expressed as the VEC of light as it penetrates down into the Lake's water column, and as turbidity in littoral (nearshore) areas too shallow to reliably determine a VEC. California also has adopted a transparency objective for the deep water lake that is based on Secchi disk measurements. Nevada has not yet adopted a numeric objective for Secchi depth transparency; however, it has committed to begin addressing such an adoption following the TMDL process.

The State of California's transparency objective for Lake Tahoe is based on a statistical comparison of the seasonal and annual mean Secchi depth values measured between 1967-1971. The TRPA has an objective of 33.4 meters Secchi depth, winter average (December – March). The States of California and Nevada have adopted the same clarity objectives for the pelagic portion of the lake, which is a VEC that must be less than 0.08/meter when measured at any depth below the first meter. Given that the California transparency objective protects the lake's historical condition that predates both the CWA and applicable dates established in federal regulation for protection of existing uses (November 28, 1975, per 40 CFR 130.26), the TMDL will assume that achieving the transparency objective, whichever is more protective, will also satisfy antidegradation requirements.

To determine the most appropriate numeric target for the Lake Tahoe TMDL, it was necessary to determine the relationship between Secchi depth and VEC values and evaluate which is more protective. The difference between California and TRPA clarity objectives was also assessed.

The relationship between VEC and Secchi depth readings in Lake Tahoe was examined for the periods 1967-2002 (Swift 2004). Between 1967-1971, the period upon which transparency objectives are based, Secchi depths were in the range of 28.5-32.5 meters and, in general, corresponded to VEC values between approximately 0.045-0.065/meter. During 1967-1971 a VEC of ≥ 0.08/meter was measured only three times in close to 100 observations. From 1972 to 2002, VEC in the deep water has varied from about 0.04 to 0.11 per meter, with no apparent trend or pattern. At no time between 1967 and 2002 did a VEC of 0.08/meter correspond to a Secchi depth of 30 meters. A more appropriate value for VEC that reflects actual conditions between 1967-1971 would be on the order of 0.05-0.06/meter. These observations show that the California water quality objective for average annual transparency (i.e., Secchi depth) is more protective than the California and Nevada clarity objective (VEC).

The TRPA winter Secchi depth objective of 33.4 meters (December-March) reflects the observation that measured light transmission is at its maximum during this season

(Jassby et al. 1999). While it is acknowledged that the winter threshold is protective of water clarity at that time, it does not include the entire year. There is no reason why the winter period represents a special time when it would be more desirable to be protective of clarity. For the purpose of aesthetic enjoyment, the summer is the season when most visitors view the lake.

The seasonal variability in Secchi depth measurements is complicated by several factors unrelated to seasonal pollutant loading. Due to the limited amount of seasonal stormwater data available, the challenges associated with estimating loads and load reductions on a seasonal basis, and the complexity of Lake Tahoe's thermal and hydro dynamic properties, the numeric target for the Lake Tahoe TMDL relies on the average annual value and not seasonal average values.

2.2.2 Determination of Numeric Target

The objective of this Lake Tahoe TMDL is to achieve the transparency (Secchi depth) and clarity (VEC) standards, but the California deep water transparency standard is the most protective. The Lake Tahoe TMDL numeric target is 29.7 meters average annual Secchi depth, which is the most protective target for deep water to approximately 30 meters of depth. For that area between 30 meters and approximately 100 meters, the UC Davis - TERC data shows that by attaining the 29.7 meter numeric target for transparency, the VEC (clarity) should always be < 0.08/meter. Therefore a 29.7 meter Secchi depth should be protective of both transparency and clarity for Lake Tahoe's deep water.

3 Watershed and Lake Characteristics

This section of the report is intended to provide background information on Lake Tahoe and its watershed. This section is intended to help inform the reader about watershed and lake characteristics and how these characteristics influence pollutant loading and ultimately lake clarity. The first half of this section focuses on watershed and climactic conditions of the Tahoe basin while the second half focuses on how pollutants affect the optical properties of the lake.

3.1 Study Area

Lake Tahoe is situated near the crest of the Sierra Nevada mountains at an elevation of 6,224 feet (1,897 meters) above sea level. It is approximately 22 miles (35.5 km) at its longest point from north to south and 12 miles (19.3 km) at its maximum width, east to west. The drainage area is 200,650 acres (812 km^2) with a lake surface area of 123,800 acres (501 km^2) producing a watershed-to-lake ratio of only 1.6:1, much smaller than the 10:1 value found for a typical watershed. Consequently, a significant amount of precipitation falls directly on Lake Tahoe. The California–Nevada state line splits the Lake Tahoe basin, with about three-quarters of the basin's area and about two-thirds of the lake's area lying in California (Figure 3-1). The geologic basin that cradles the lake is characterized by mountains reaching over 4,003 feet (1,220 meters) above lake level, steep slopes and erosive, granitic soils, although volcanic rocks and soils are also present in some areas. Slopes rise quickly from the lake's shore, reaching 30 to 50 percent in many places.

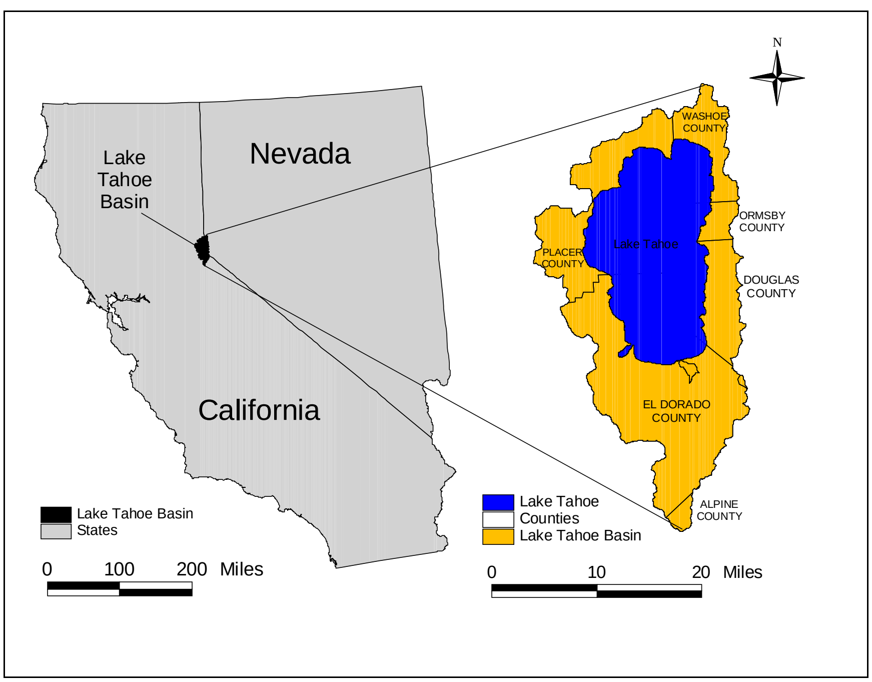

Figure 3-1. Location of the Lake Tahoe basin.

Lake Tahoe is the eleventh-deepest lake in the world with a maximum depth of 1,657 feet (505 meters). The average depth of the lake is 1,027 feet (313 meters). The surface area of the lake covers nearly two-fifths of the Lake Tahoe basin, and the lake holds nearly 39 trillion gallons of water. The hydraulic residence time is 650 years, which means that it takes, on average, 650 years for water that enters the lake to leave the lake. As a result of its volume, depth and geographic location, Lake Tahoe remains ice-free year-round, though Emerald Bay has frozen over during some extreme cold spells.

Lake Tahoe’s current trophic status is oligotrophic, although clarity measurements and calculations of its vertical light extinction indicate the onset of cultural eutrophication (Goldman 1988).

Lake Tahoe is fed by 63 tributary streams. The largest tributary to Lake Tahoe is the Upper Truckee River, which contributes approximately 25 percent of the annual flow. The Lake Tahoe basin also has 52 intervening zones that drain directly to the lake without first entering streams. The lake has one outlet on its northwest side, forming the start of the Truckee River, which ultimately drains to Pyramid Lake, a terminal lake located in Nevada.

In 1874, a timber dam was built to regulate water outflow at the Truckee River outlet in Tahoe City, California. The timber dam was partially removed in 1909 and construction began on a new concrete dam. The concrete dam was completed in 1913 and later in 1988 it was seismically retrofitted and enlarged to its current configuration. In 1915, a federal court placed the dam under federal control. Up to the level of the natural rim (6223, Lake Tahoe datum), Tahoe water is unavailable for downstream use. The maximum water level was set at 6,229.1 feet and the lake’s natural rim elevation was set at 6,223.0 feet (Lake Tahoe Datum) in 1935 pursuant to the Truckee River Operating Agreement (TROA). These elevations were affirmed through a court case that resulted in the Orr Ditch Decree (September 8, 1944). According to Boughton et al. (1997) the upper six feet of the lake forms the largest storage reservoir in the Truckee River basin, with an effective capacity of 240 billion gallons (745,000 acre-feet). Since 1987, lake levels have fluctuated from 6,220.26 feet (about 3 feet below the rim), during a prolonged drought in 1992 to 6,229.39 feet (about 0.2 feet above the legal maximum), during the flood of January 1997(Boughton et al. 1997).

The lake’s montane-subalpine watershed is predominantly vegetated by mixed coniferous forests, although bare granite outcrops and meadows are also common features. Most urban development exists along the lake’s shoreline, with the largest concentrations occurring at South Lake Tahoe in the southeast, Tahoe City in the northwest and Incline Village in the northeast. The north and west shores are less densely populated, and the east shore is mostly undeveloped.

3.2 Watershed Characteristics

3.2.1 Geology and Soils

The Lake Tahoe basin was formed approximately 2 to 3 million years ago by geologic faulting that caused large sections of land to move up and down. Uplifted blocks created the Carson Range on the east and the Sierra Nevada on the west while down-droppedblocks created the Lake Tahoe basin in between. About two million years ago, lava from Mt. Pluto on the north side of the basin blocked and dammed the northeastern end of the valley and caused the Lake Tahoe basin to gradually fill with water. As the lake water level rose, the Truckee River eroded an outlet and a stream course through the andesite (volcanic rock) flows down to the Great Basin hydrologic area to the east. Subsequent glacial action (between 2 million and 20,000 years ago) temporarily dammed the outlet causing lake levels to rise as much as 600 feet above the current level. A detailed account of the basin's geology and its effect on groundwater flow and aquifer characteristics is given by USACE (2003).

Nearly all the streams in the Tahoe basin lie on bedrock, with the exception of the south shore area and some other aquifers associated with the lower reaches of some streams. While Loeb (1987) found that the aquifers for the Ward Creek, Trout Creek and Upper Truckee River watersheds were sloped toward the lake (implying a net flow into the lake), some recent studies in the Pope Marsh area of the south shore indicate that under the influence of water pumping and seasonal effects, the net flow in some areas may be from the lake into the adjacent aquifer system (Green 1998, Green and Fogg 1998).

Lake Tahoe basin soils are generally low nutrient granitic soils, with more nutrient rich volcanic soils located in the north and northwestern parts of the basin. Soils near the lake consist of alluvial wash deposits (Crippen and Pavelka 1970). Soils in the basin have a wide range of erosion potential and soil permeability ranges from moderate to very rapid, with the lowest permeabilities found in the northwest quadrant of the basin (Tetra Tech 2007). Figure 3-2 presents a map of the general geology of the Lake Tahoe basin.

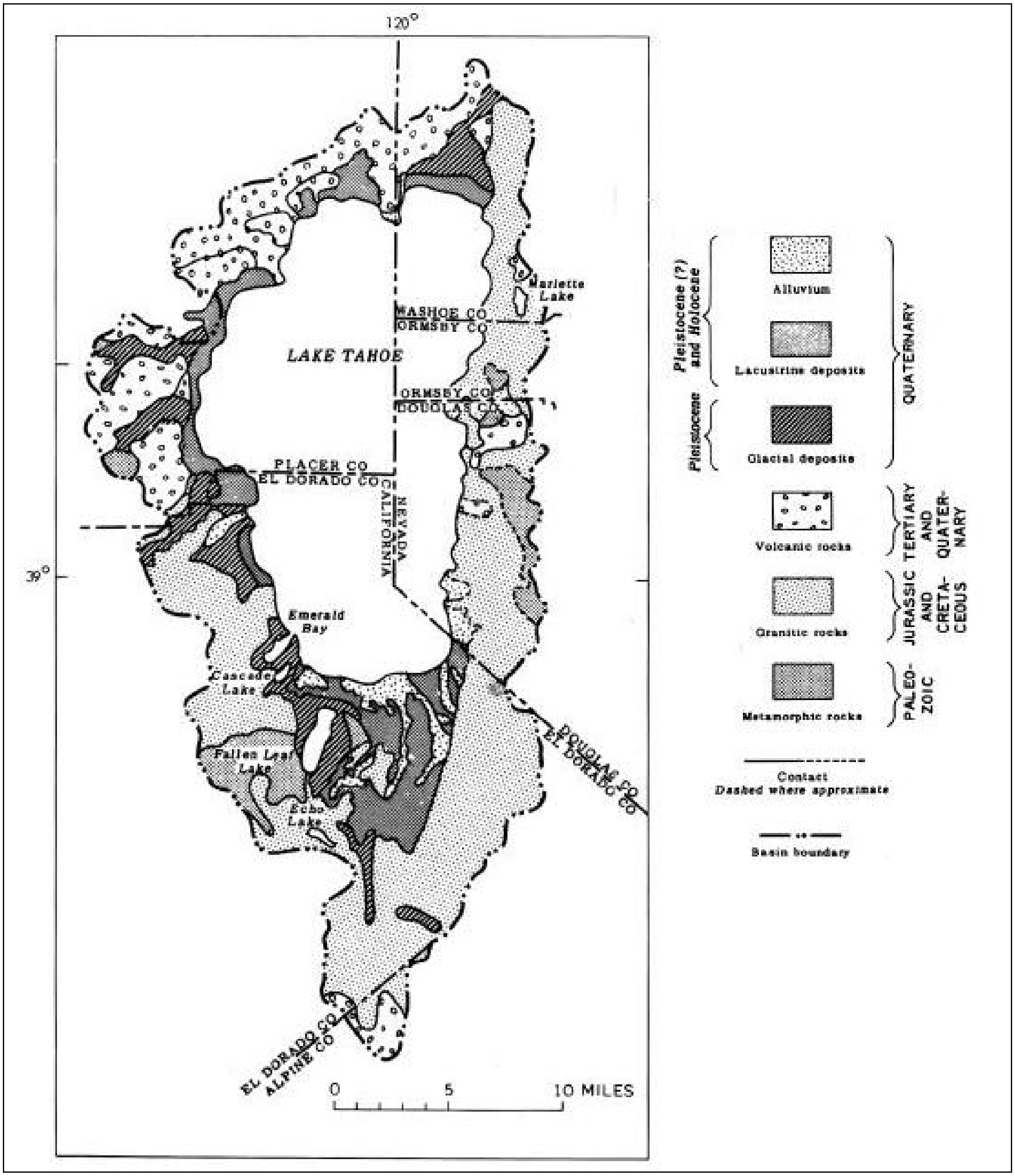

Figure 3-2. General geology of the Lake Tahoe basin (Crippen and Pavelka 1970).

3.2.2 Land-uses

Land-uses in the Lake Tahoe basin have an influence on the watershed, lake clarity, and other environmental attributes. A detailed natural and human history of the basin is provided in the *Lake Tahoe Watershed Assessment* (USDA 2000). Several significant, anthropogenic influences in the watershed followed its discovery by European-American explorers in 1844: clear-cut logging of an estimated 60 percent of the basin during the Comstock-era (1870's-1910's), livestock grazing (1900's-1950's), gradual urbanization of the lakeshore and lowest-lying parts of the basin beginning in the 1950's (USDA 2000), and public acquisition and protection of thousands of acres of sensitive lands since the mid-1960's. As of 1996 public ownership represented 85 percent of the total land area of the basin.

Based on available information, the land-uses in the basin were divided into six general categories:

- Single-family residential (SFR)
- Multi-family residential (MFR)
- Commercial/Institutional/Communications/Utilities (CICU)
- Roads (primary, secondary and unpaved)
- Vegetated
- Waterbody

The first three land-use categories (SFR, MFR, and CICU) were additionally broken down to pervious and impervious land-uses based upon IKONOS™ satellite imaging (Minor and Cablk 2004). The vegetated land, which makes up more than 80 percent of the watershed, was further broken down into undeveloped forest, turf, recreational, ski areas, burned and harvested vegetation. Simon, et al. (2003) divided the undeveloped forest into five erosion potential classes. A GIS layer, developed as part of this report (Figure 3-3), shows that two percent of the total basin land area is impervious. This equates to over 5,000 impervious acres (Minor and Cablk 2004), many of which are adjacent to the lake or its major tributaries. At the same time, 14 of the 63 individual watersheds have 10 percent or more of their total land area as impervious coverage. The land-use map (Figure 3-3) and associated information in a geographic information system (GIS) database is available in more detail in Tetra Tech (2007).

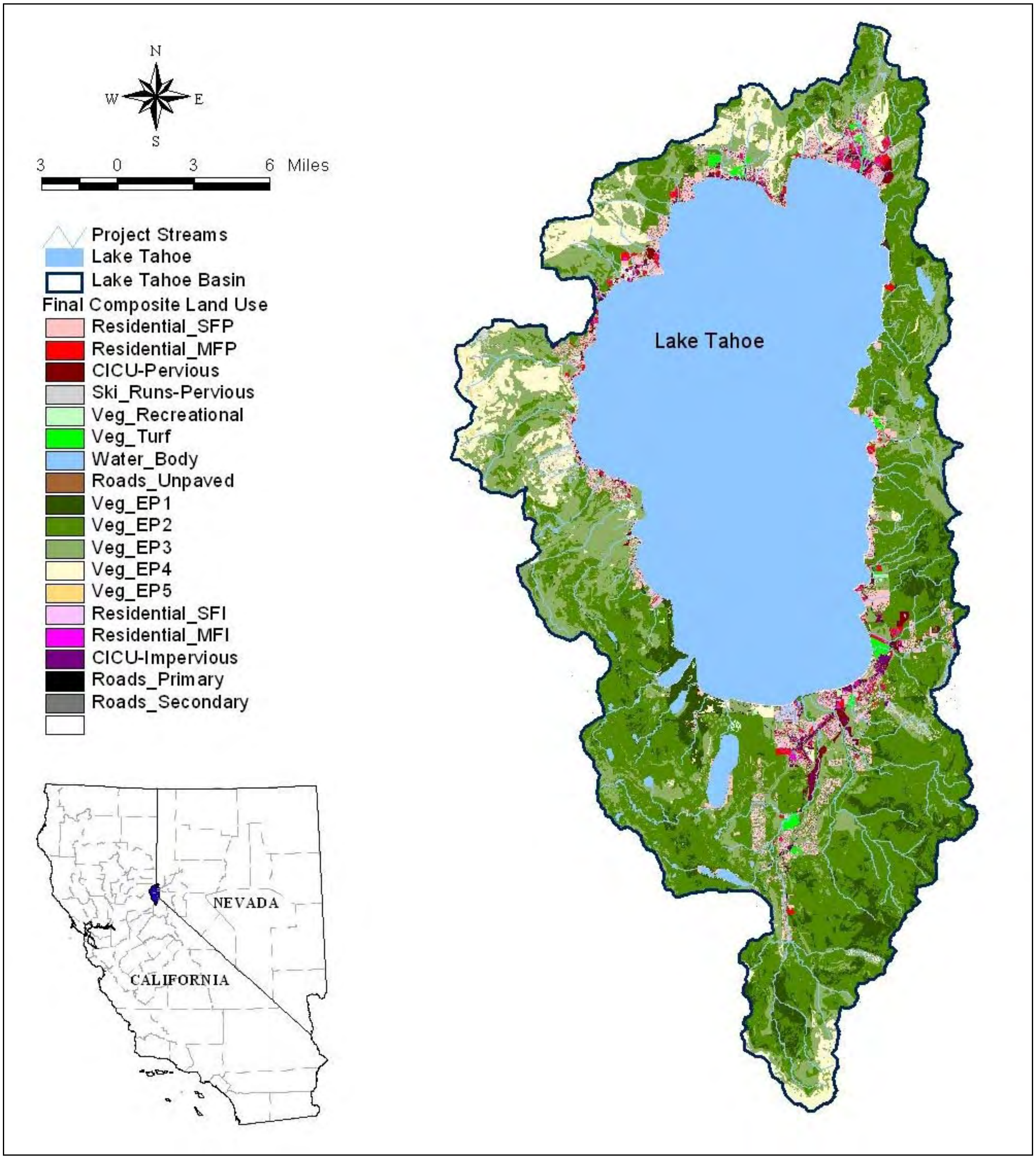

Figure 3-3. Land-uses in the Lake Tahoe basin (Tetra Tech 2007).

3.2.3 Climate and Hydrology

Climate is the single most important factor influencing pollutant delivery to Lake Tahoe as precipitation drives mobilization and transport of pollutants off the watershed and into tributaries and/or the lake. Most of the precipitation in the Lake Tahoe basin falls between October and May in the form of snow at higher elevations and snow/rain at lake level, which typically melts and runs off in May and June. However, precipitation timing can vary significantly from year to year (Coats and Goldman 2001, Rowe et al. 2002). Figure 3-4 is a plot of the monthly flow from the Upper Truckee River as an example of runoff seasonality. Watershed elevations differences also have a significant influence on the type of precipitation (snow or rain) and the timing of snow melt. For example, snow pack at lower elevations near the lake shore typically melts earlier, and can even melt off mid-winter if air temperatures and solar radiation conditions are right. It is common for the lower elevation snow pack to have melted completely before the tributaries crest with snowmelt from the higher and colder elevations.

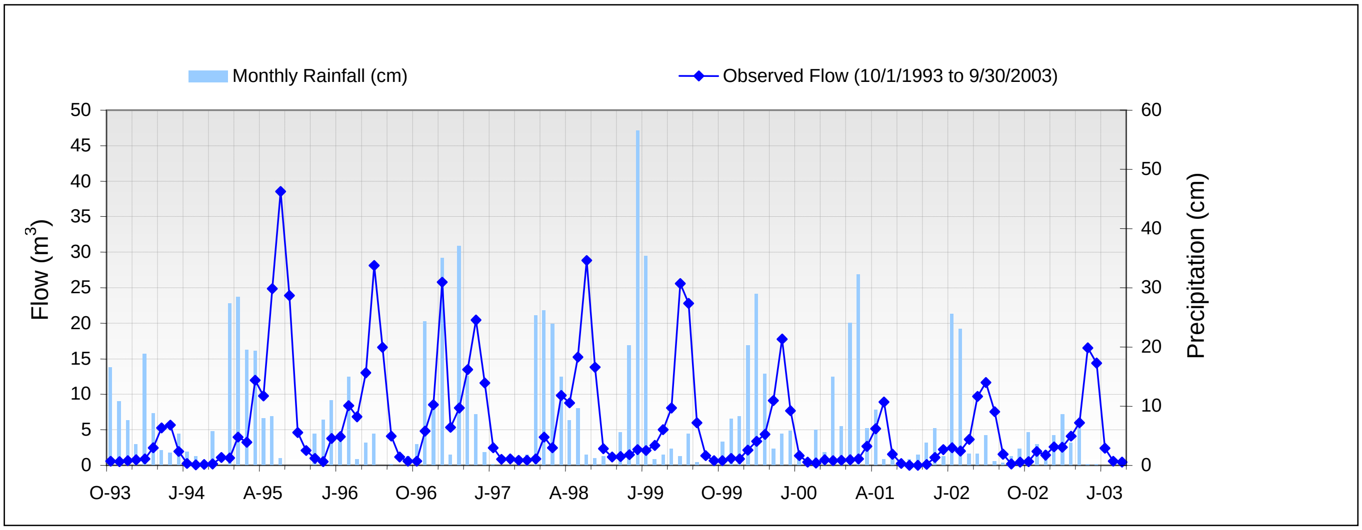

Figure 3-4. Monthly flow from the Upper Truckee River.

Summer thunderstorms, fall rain storms on bare ground, and rain-on-snow events also contribute to erosion, runoff, and pollutant transport into Lake Tahoe tributaries and/or the lake. The most significant hydrologic events typically accompany large rain-on-snow events, such as what happened in January 1997 when stream channels underwent major geomorphic changes (Simon et al. 2003) from the high runoff volume in a short time. Compared to spring snow melt and rain-on-snow events, summer thunderstorms typically are not responsible for significant pollutant loads to the tributaries (Hatch et al. 2001, S. Hackley unpublished data). Thunderstorms, however, can be intense and are capable of generating large loads for short periods of time, typically in isolated geographic locations.

Because the lake surface area is relatively large compared to its watershed area, a significant amount of precipitation (36.2 percent) enters the lake directly as snow or rain. Over 75 percent of the basin's precipitation is delivered by frontal weather systems from the Pacific Ocean between November and March. Topography largely determines the spatial distribution of precipitation and whether winter precipitation occurs as rain or snow. Lower elevations receive about 20 inches (500 mm) of annual precipitation, but the upper elevations on the west side of the basin receive about 59 inches (1,500 mm) (USDA 2000). Future climate change could cause both the relative distribution of snow versus rain and the distribution and extent of precipitation to change.

3.3 Precipitation Characteristics

This section briefly describes seasonal patterns in annual rain and snowfall, synoptic differences over the lake, and characteristics of the long-term data set.

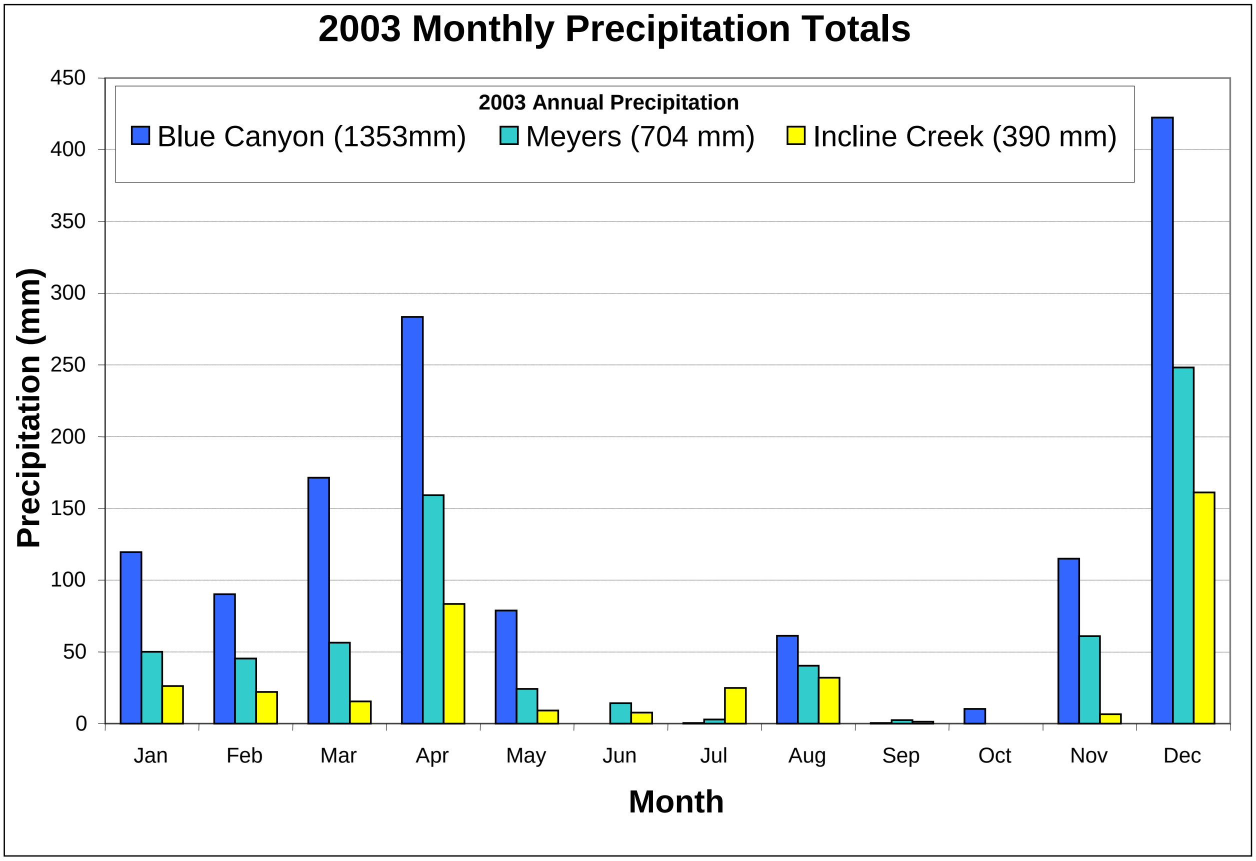

Figure 3-5. Monthly precipitation (2003) showing wet winters and dry summers (modified from CARB 2006).

Figure 3-5 presents precipitation from the CARB (2006) studies for 2003 showing the seasonal distribution of precipitation. Blue Canyon is on the west slope of the Sierra Nevada at an elevation of approximately 5,000 feet (outside the Tahoe basin). Meyers and Incline Creek are both located in the basin. All three stations exhibit the Mediterranean-type climate characterized by wet winters and dry summers. Even though intensive, short-duration thunderstorms occur during the summer, the July through September events contribute little to annual precipitation.

The isohyetal map (Figure 3-6) shows contours of mean annual precipitation in the basin, as well as, spatial differences in precipitation. A well-defined rain-shadow exists across the lake from west to east (Crippen and Pavelka 1970, Sierra Hydrotech 1986, Anderson et al. 2004). Precipitation over the lake declines from a value of about 35 inches/year (90 cm/year) along the west shore to 20 inches/year (51 cm/year) on the east shore. Annual averages include both snow and rain combined.

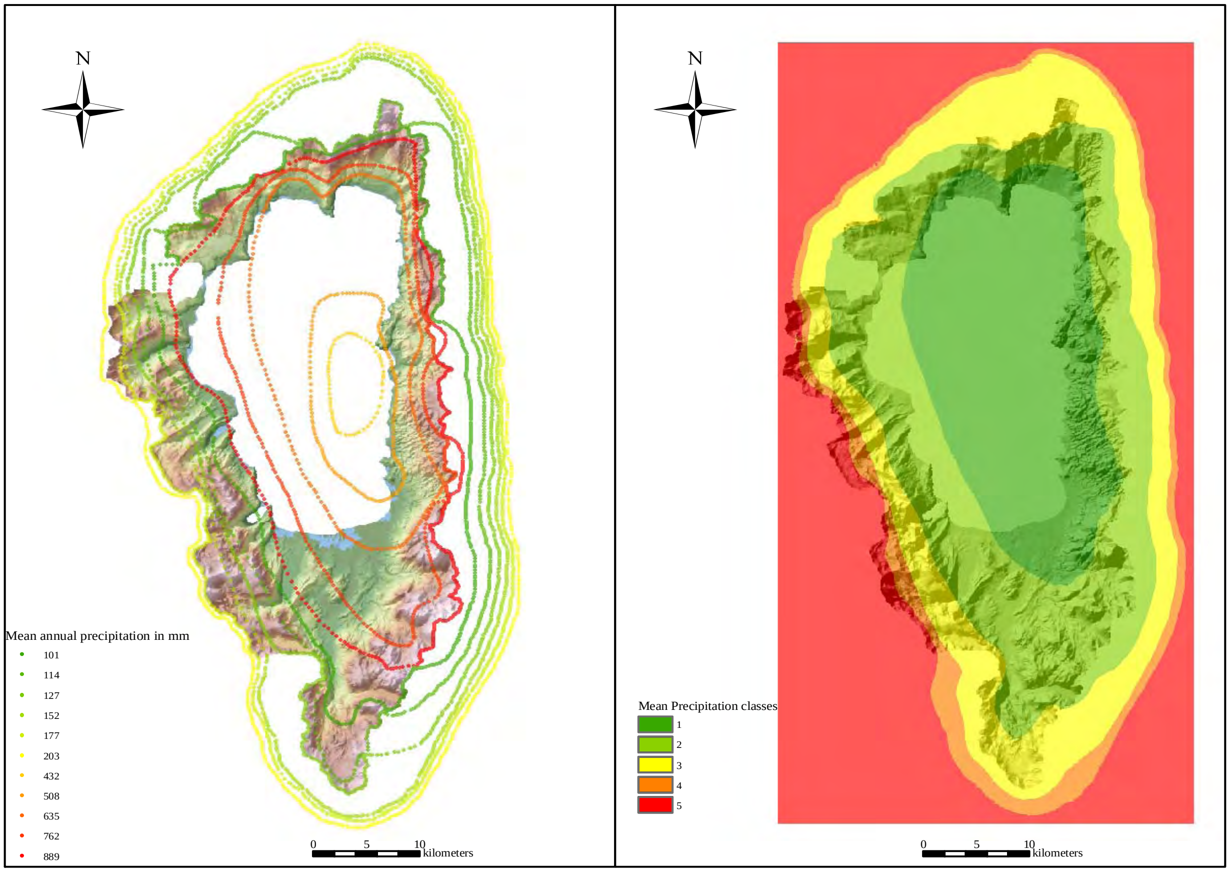

Figure 3-6. Isoheytal map for the Lake Tahoe basin showing contours of equal annual precipitation (Simon et al. 2003).

Year-to-year patterns of precipitation at Lake Tahoe can be seen from the 96-year data record (1910-2005) at Tahoe City, located in the northwest quadrant of the basin adjacent to the Truckee River outlet (Figure 3-7). Interannual and decade-scale patterns can be seen, which illustrate the variation that can occur from year to year. Typically, values are presented as precipitation totals in a water year, which is October 1 to September 30.

Mean annual precipitation during this period is 31.5 inches (80 cm) with a very similar median value of 30 inches (77 cm). The middle quartile values (25 – 75 percent of observations) are 3 – 38 inches/year (8.5 – 96.5 cm/year). Years with greater than 30 inches (77 cm) of precipitation occur regularly and typically not more than three consecutive years elapse without annual precipitation exceeding the median of approximately 30 inches/year (77 cm/year).

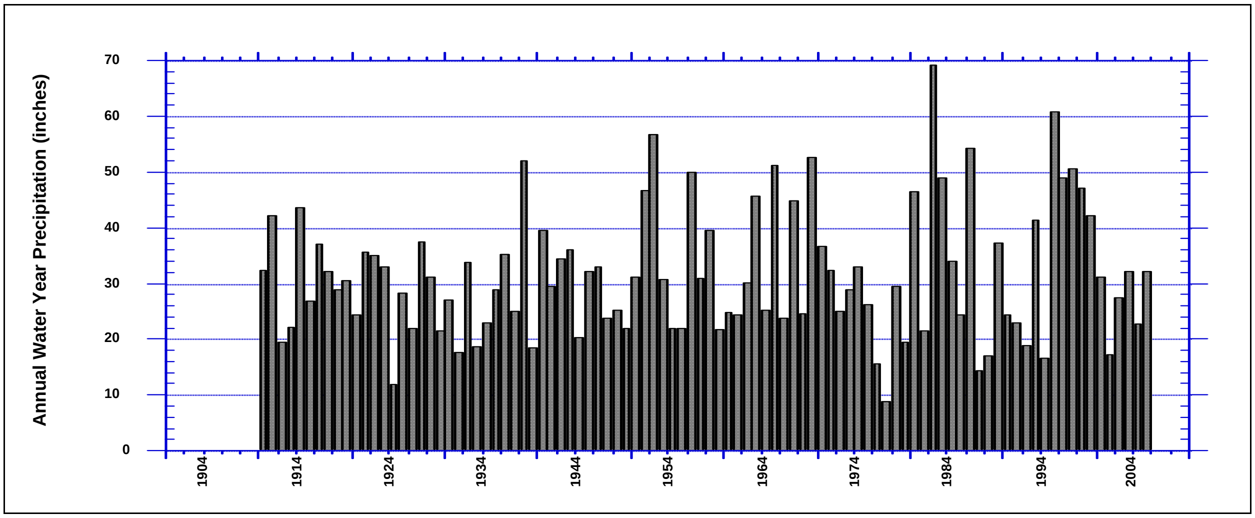

Figure 3-7. Precipitation over the 96-year record at Tahoe City.

3.4 Limnology and Optical Properties of Lake Tahoe

Limnology is the study of lakes and is concerned with the fundamental relationships and productivity of aquatic communities as they are affected by their physical, chemical and biotic environment (Wetzel 1983). The limnology of Lake Tahoe has been the subject of extensive research and the clarity has been a focus for many years. Lake clarity is a function of the water column's optical properties. This section focuses on some of the important issues related to the optical properties affecting Lake Tahoe's water clarity: nutrients, floating algae or phytoplankton, inorganic particles, and lake mixing.

3.4.1 Optical Properties in the Open Water of Lake Tahoe

The optical properties of water can be divided into apparent and inherent properties. Apparent optical properties are a function of natural lighting and are influenced by sun angle, cloud cover and water surface conditions such as waves. Inherent optical properties depend on the water and the material contained in the water column. An important inherent optical property of water is light attenuation, which is a result of absorption and scattering of light.

Particles in water both absorb and scatter light. In Lake Tahoe, light scattering and absorption are caused by mineral and organic particles (Figure 3-8). Absorption occurs from dissolved organic material, such as naturally occurring tannins, and anthropogenic compounds that enter the lake (Taylor et al. 2003, Swift 2004). Also, water molecules themselves absorb light.

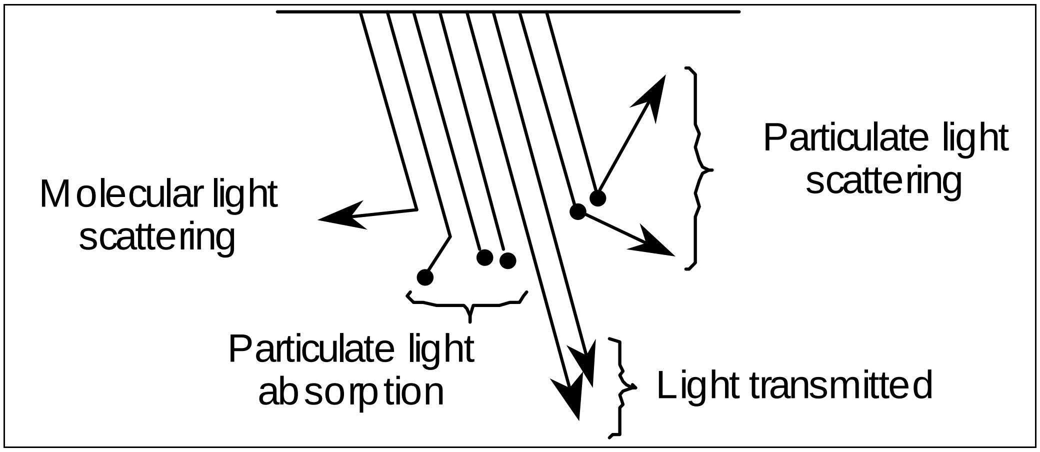

Figure 3-8. Conceptual model of the pathway of light in water (Swift 2004).

Secchi depth in Lake Tahoe has long been known to be controlled by both absorption and scattering of light by particles. This can be seen in recent Secchi depth data collected in Lake Tahoe (Figure 3-9) (Swift 2004). These data show the significant, albeit non-linear, relationship between the measured number of particles in Lake Tahoe and the corresponding Secchi depth.

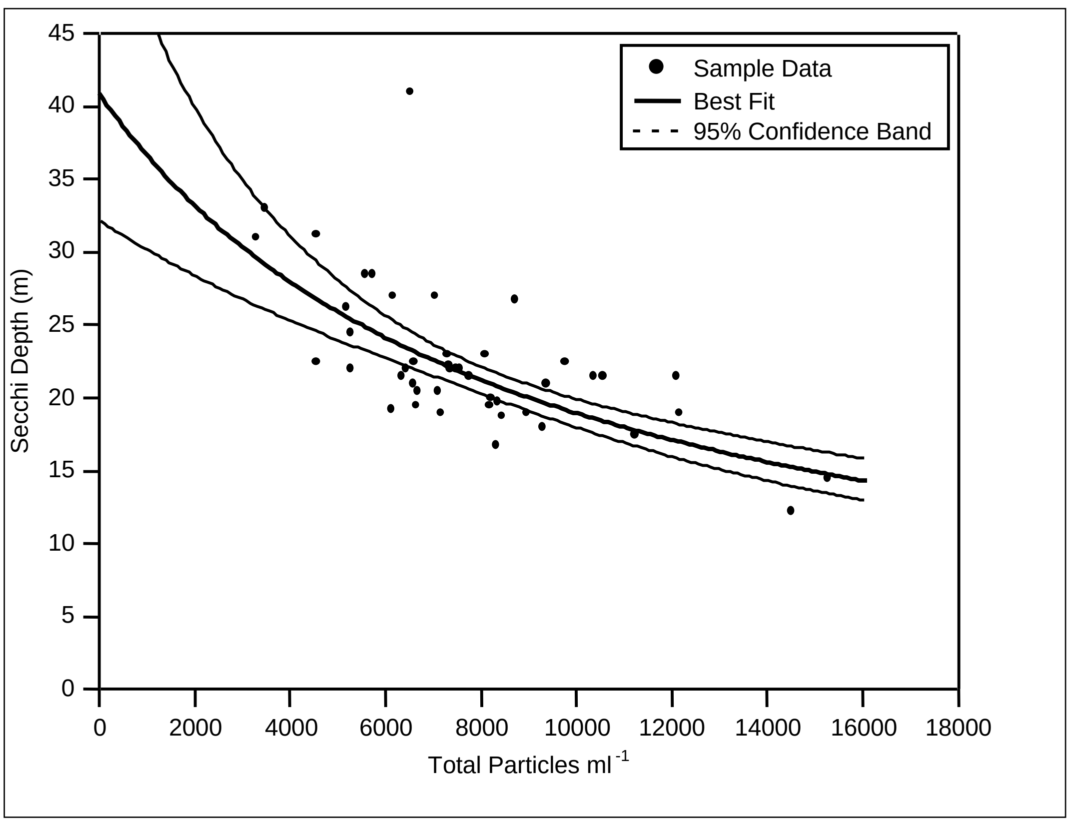

Figure 3-9. Relationship between in-lake particle number and Secchi depth (modified from Swift 2004).

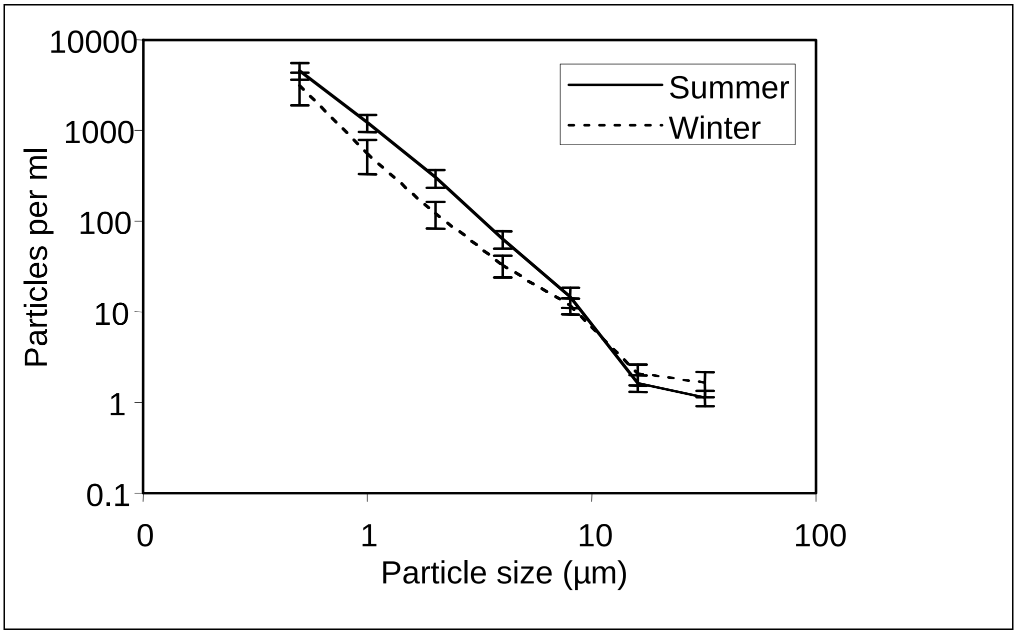

Figure 3-10. Particle size distribution in Lake Tahoe showing dominance of particles <16 µm in diameter (Swift et al. 2006).

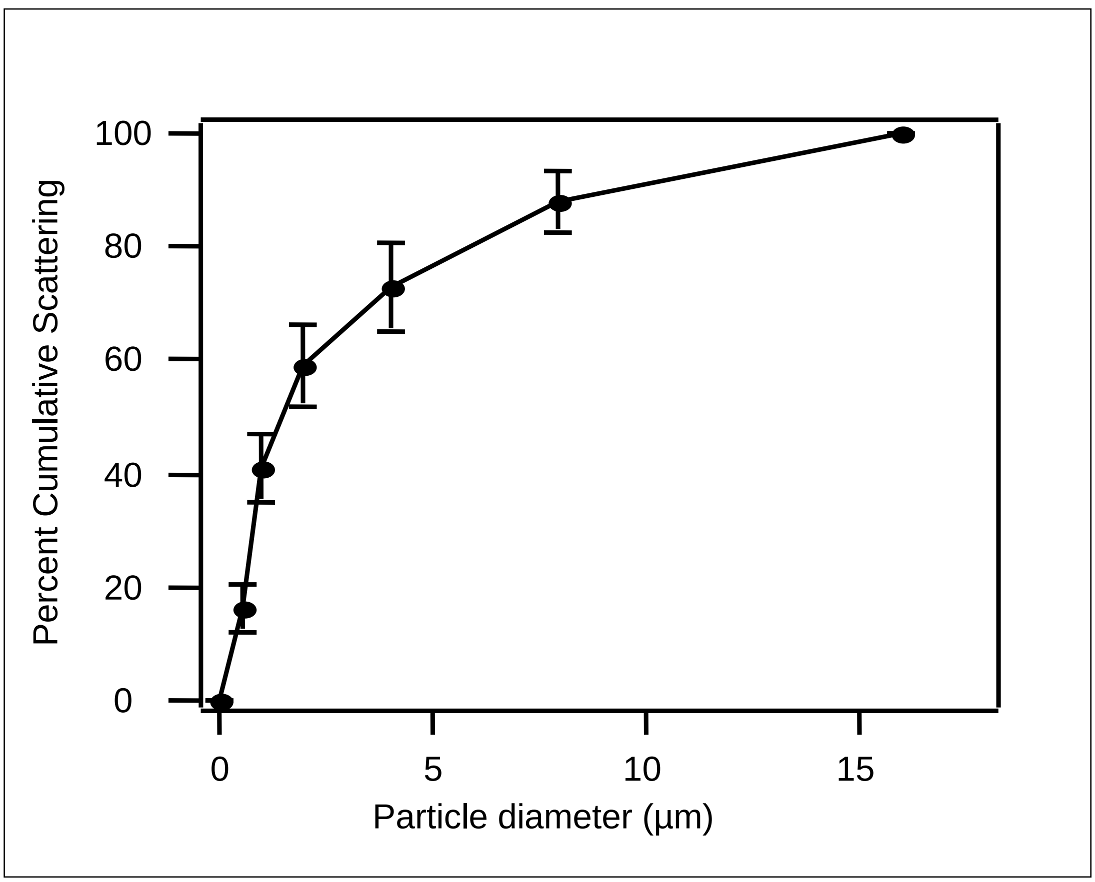

Figure 3-11. Influence of particle size on light scattering (modified from Swift et al. 2006).

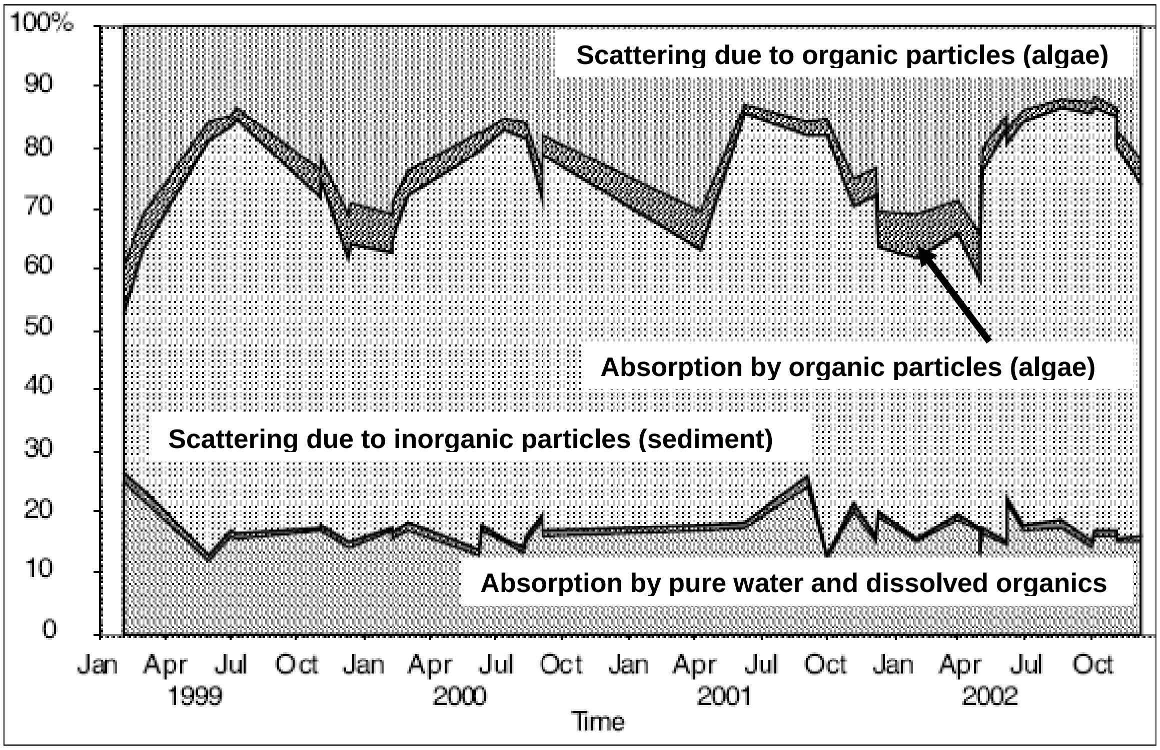

Figure 3-12. Results of an optical sub-model that predicted Secchi depth from particle number, size and composition (modified from Swift et al. 2006).

Earlier investigations focused primarily on increased phytoplankton productivity and the onset of cultural eutrophication as the primary source of these particles (e.g., Goldman 1974, 1994). The long-term increase of primary productivity in Lake Tahoe has been attributed to increased nutrient loading acting in concert with the efficient recycling of nutrients (Goldman 1988). Mean settling velocities for particulate nitrogen and phosphorus as measured with large sediment traps deployed in Lake Tahoe were 54 and 39 feet/year (16.4 and 12.0 meters/year), respectively (A.C. Heyvaert *In:* Reuter and Miller 2000). These correspond to settling times on the decadal scale. With an average depth of over 984 feet (300 meters) and a maximum depth of over 1,640 feet (500 meters), many of the nutrients associated with particles are mineralized by bacteria and effectively recycled before settling to the bottom (Paerl 1973).

The hypothesis that fine inorganic particles from soil and dust (<16 µm diameter) contribute to measurements of lake clarity loss was first published in 1999 (Jassby et al. 1999). This was immediately followed by the first comprehensive study of particle number, size and composition in Lake Tahoe during 1999-2000 (Coker 2000). Typical particle size distributions for over 40 samples from lake sampling stations are shown in Figure 3-10. It can be seen that the very fine particles dominate and that in the 10 – 16 µm range, particle numbers are almost negligible. The lower number of particles typically seen in the winter agrees with the observed higher Secchi depth readings during that season.

The original 1999 – 2000 investigation of particle size distribution has been followed up by a series of studies including the spatial and temporal distribution of particle concentration and composition in Lake Tahoe (Sunman 2001), characterization of biotic particles and limnetic aggregates in Lake Tahoe (Terpstra 2005), lake particles and optical modeling (Swift 2004, Swift et al. 2006) and distribution of fine particles in Lake Tahoe streams (Rabidoux 2005). Of the inorganic particles, the finer fraction (1 – 10 µm) has the greatest impact on clarity (Figure 3-11).

Particle loss to the bottom through sedimentation is an important parameter in any mass balance consideration of particle concentration in the water column. This was confirmed by Jassby (2006) who studied particle aggregation and developed a preliminary version of a particle loss model. Data from Sunman (2001) suggest that fine sediment particles (< 20 µm diameter) can be transported through the upper 329 feet (100 meters) of the water column in approximately three months.

Swift (2004) and Swift et al. (2006) developed an optical model for Lake Tahoe to link fine sediment particles and Secchi depth. The model takes into account algal concentration, suspended inorganic sediment concentration, particle size distribution and dissolved organic matter to predict Secchi depth and diffuse attenuation. Both biological (e.g., phytoplankton and detritus) and inorganic (terrestrial sediment) particulate matter are important contributors to clarity loss in Lake Tahoe (Figure 3-12). The high scattering cross-section of inorganic particles results in their often being the dominant cause of reduced light transmission, despite their numerical minority most of the year. This research suggested that currently (1999 – 2002) light scattering by inorganic particles contributed greater than 55 to 60 percent of total light attenuation; about 25 percent was due to organic particles; with the remaining 15 to 20 percent due to absorption by water and, to a much lesser extent, dissolved organic matter. Specifically for Lake Tahoe, these findings lend support to the earlier hypothesis (Jassby et al. 1999) that inorganic particles dominate clarity for most of the year, but that winter mixing of the deep chlorophyll layer results in greater attenuation by organic particles.

Coupling organic and inorganic particle concentrations in the lake to a predicted Secchi depth provides useful relationships that can be used to guide restoration efforts in the Tahoe basin. The Lake Clarity Model used for Lake Tahoe TMDL development is a combination of the optical model (results presented above), a hydrodynamic model customized for Lake Tahoe, an ecological model and particle fate models developed as part of the Lake Tahoe TMDL science plan (Perez-Losada 2001, Reuter and Roberts 2004, Sahoo et al. 2006). Chapter 6 focuses on the Lake Clarity Model and its initial results.

Lake Tahoe's annual average clarity can vary significantly from year-to-year based on nutrient and fine sediment loading (Jassby et al. 2003). For example, in the three years from 2000 through 2002 during lower total precipitation, lake Secchi depth increased by 3 meters. This level of Secchi depth change has been observed in the long-term data and suggests that lake response time to load reduction can be rapid. As reported by Heyvaert (1998), Lake Tahoe water quality was fully restored to historic conditions in about 20 to 25 years following the mass disturbance to the basin from the timber clear-cut activities in the late 1800's. As the basin was allowed to heal, lake clarity improved (Figure 3-13). These findings suggest that nutrient and fine sediment reduction can lead to an increased Secchi depth clarity, and in a relatively shorter time period than previously considered. Although lake clarity improved during this "Intervening Era" from 1901 to 1970, that historic recovery does not guarantee the current lake clarity conditions will be restored to the levels seen in the early 1970's.

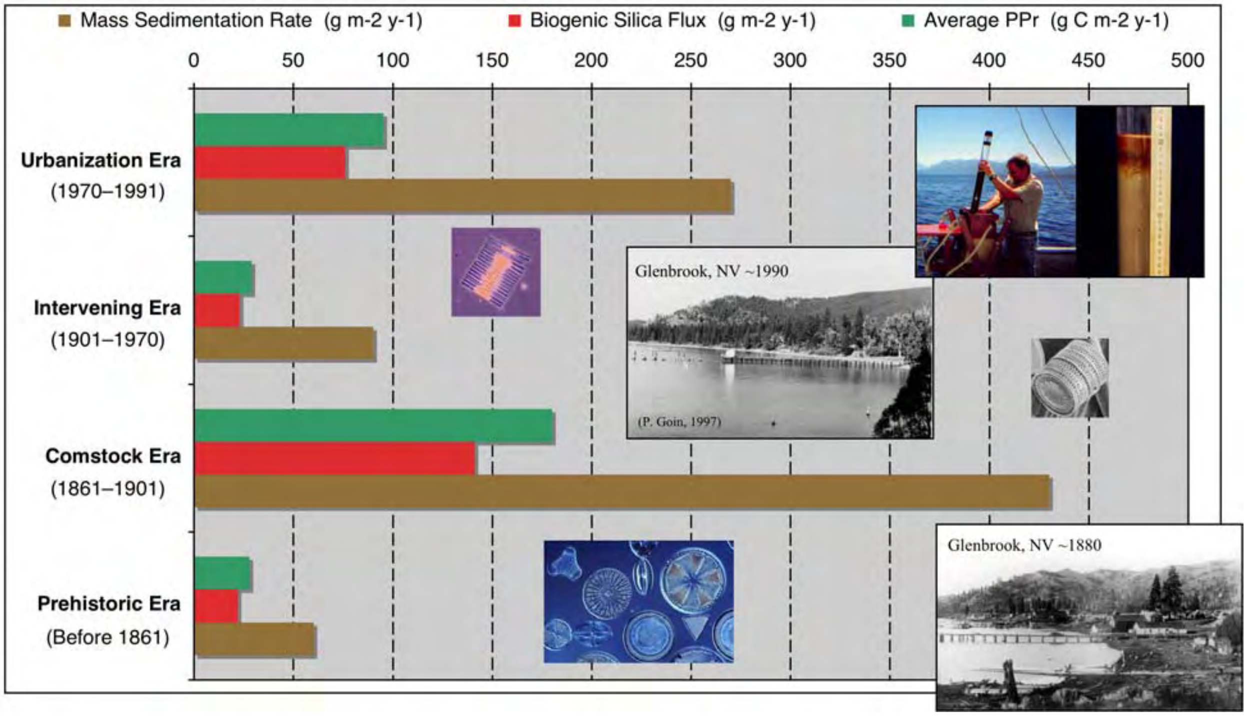

Figure 3-13. Summary of paleolimnologic studies that reconstruct the recent water quality history of Lake Tahoe. PPr indicates primary productivity (A.C. Heyvaert *In*: Tahoe Science Consortium 2007).

3.4.2 Water Quality in the Open Water of Lake Tahoe

The pelagic zone is the lake's deepest water column, where sunlight only penetrates through the uppermost part and the lake bottom cannot be seen. The vast majority of the lake's water is contained in the pelagic zone which acts a reservoir for pollutants that enter the lake. The gradual accumulation of these pollutants over time has caused the decline in lake clarity and transparency. The lake's transparency is a function of the water's optical properties, and the stressors to the lake's transparency are nutrient input and algal growth.

Nutrients

The nutrients that stimulate algal growth (primary productivity) in Lake Tahoe are nitrogen and phosphorus. However, the forms in which these nutrients are present have a large affect on how they are used by algae. This discussion will describe the forms of nitrogen and phosphorus, their bioavailability, and the concentration of these nutrient forms in the lake.

Nutrient Forms and Bioavailability

Algae require a nitrogen:phosphorus ratio of 7:1 (by weight). Nutrient limitation occurs when the nitrogen:phosphorus ratio in the water deviates from 7:1. At ratios greater than 7:1, nitrogen is in 'abundance' and phosphorus is considered limiting. At ratios less than 7:1, phosphorus is considered in abundance and nitrogen would be considered limiting. However, not all nitrogen and phosphorus in water is available for algal growth.

The forms of nitrogen typically measured in lake water include nitrate (NO_3^-), ammonium (NH_4^+) and total Kjeldahl nitrogen (TKN). The organic nitrogen can be further divided into particulate and dissolved components. Dissolved organic nitrogen (DON) includes a wide array of chemical compounds, ranging from some of the more labile, or easily broken down, compounds, such as certain amino acids, to more refractory nitrogen-containing compounds that resist bacteria breakdown. Lake Tahoe is similar to most other lakes in that it also contains large portions of its total nitrogen pool as DON. Typically, nitrate and ammonium are directly available for algal uptake and growth. Organic nitrogen can be mineralized by bacteria to ammonium and some algae can use organic nitrogen directly as a source of nitrogen. Research in this area is generally limited. A study by Seitzinger et al. (2002) looking at nitrogen bioavailability in runoff from forest, pasture and urban land-uses in the northeastern United States found that 0 to 73 percent of the DON could be used by algae. Similarly, working in a montane stream, Kaushal and Lewis (2005) reported that use of DON by algae ranged from 15 to 73 percent. These are complex studies that have not been conducted at Lake Tahoe.

Phosphorus in lake water is typically defined by the method of analysis. While ortho-phosphate (PO_4^{-3}) is typically considered the form of phosphorus used by algal cells, measurements of phosphorus in water commonly include soluble reactive phosphorus (SRP), total dissolved phosphorus (TDP) and total phosphorus. SRP is the form of phosphorus that is considered mostly bioavailable. Part of the TDP includes SRP and part dissolved organic-phosphorus. Total phosphorus includes phosphorus from organic phosphorus as well as phosphorus associated with inorganic sediments. In a study conducted for the Lake Tahoe TMDL, Ferguson and Qualls (2005) found that about 20 percent of the total phosphorus associated with suspended sediment in selected Lake Tahoe tributaries was bioavailable and that about 35 percent of the total phosphorus in sediment from urban runoff was bioavailable. Based on Ferguson and Qualls (2005) bioavailable phosphorus measurements and the distribution the various measured phosphorus forms in atmospheric deposition (Hackley et al. 2004), it was estimated that about 40 percent of the total phosphorus in atmospheric deposition was bioavailable. This agrees with the work of Dillion and Reid (1981) that found a range of 16 to 56 percent for the amount of bioavailable phosphorus in total phosphorus from atmospheric deposition in Canada. Ferguson and Qualls (2005) found the bioavailability of dissolved organic phosphorus in Lake Tahoe streams to be negligible.

Nutrient Concentrations in Lake Tahoe

The mean whole-lake concentration of total nitrogen for Lake Tahoe was calculated as 65 micrograms per liter (µg/L) from Jassby et al. (1995). Monitoring and research data summarized by Marjanovic (1989) indicate that particulate nitrogen comprises nearly 15 percent of total nitrogen, or in this case, 9 µg/L. The majority (85 percent) of total nitrogen occurs in the dissolved form either as DON or dissolved inorganic nitrogen (DIN). DIN consists of nitrate (15 µg/L) and ammonium (1 – 2 µg/L) and accounts for approximately 25 percent of total nitrogen. At a mean concentration of approximately 40 µg/L, DON constitutes the largest nitrogen fraction at 60 percent.

Mean, whole-lake total phosphorous concentration at the same time was 6.3 µg/L (Jassby et al. 1995). Particulate phosphorus, at a calculated concentration of 0.6 µg/L, was approximately 10 percent of the whole-lake total phosphorus. As was observed for nitrogen, most of the lake's phosphorus is in the dissolved form; TDP, at 5.7 µg/L. Further dividing TDP, SRP was 2.1 µg/L, and dissolved organic phosphorus (DOP) was 3.6 µg/L. Total acid-hydrolyzable-phosphorus (THP) represents that portion of total phosphorus (TP) converted to ortho-phosphorus following a relatively mild acid digestion during chemical analysis. THP is intended to represent the potentially bioavailable-phosphorus. The whole-lake average THP concentration was 2.6 µg/L and, as expected, the THP portion of TP is greater than particulate phosphorus (PP).

A comparison of the mean annual concentrations of nitrate and THP in the euphotic zone at the UC Davis - TERC mid-lake and index stations indicated that both locations were similar. The index station is positioned on the lake's western shelf, approximately two kilometers off-shore. For the period 1985 through 1993, nitrate at the index station was 4.9 ± 0.8 µg nitrogen/L and slightly higher than the average concentration of 4.5 ± 1.0 µg nitrogen/L at the mid-lake station (average of mean annual concentrations). The largest annual difference in nitrate between these two locations was in 1992, when nitrate at the index station was 3.6 µg nitrogen/L as compared to 2.8 µg/L at mid-lake. THP was virtually identical at these two stations, with the average of the mean annual concentrations equal to 2.9 µg/L for mid-lake and 3.0 µg/L for the index station.

Primary Productivity, Phytoplankton and Algal Growth Bioassays

The first measurements of phytoplankton (free floating algae) growth in Lake Tahoe were made in 1959 (Goldman 1974). At that time, the annual phytoplankton growth rate was slightly less than 40 g chlorophyll *a* (C)/m^2/year and typical of an ultra-oligotrophic lake. For the years prior to 1959, average annual primary productivity was reconstructed from an analysis of sediment cores. Heyvaert (1998) determined that the baseline pre-disturbance (prior to 1850) primary productivity was 28 g C/m^2/year. Interestingly, the calculated value for 1900-1970, the period between the effects of the Comstock logging era in the late 1800's and the onset of urbanization of the Tahoe basin, was almost identical at 29 g C/m^2/year.

The rates of primary productivity recorded in 1959 were only about 30 percent more than the estimated baseline rates. Annual primary productivity of Lake Tahoe has increased by a factor of approximately five-fold since 1959 with a measurement of 203 g C/m^2/year made in 2005 (Figure 3-14). Although there is year-to-year variation, the productivity data shows a highly significant upward trend that continues at a rate of approximately 5 percent per year. The largest single-year increases were found between 1982 and 1983 (28 g C/m^2/year or 32 percent), 1988-1989 (30 g C/m^2/year or 25 percent), 1992-1993 (33 g C/m^2/year or 22 percent) and 1997-1998 (25 g C/m^2/year or 15 percent). The magnitude of each of these large annual increases was similar to baseline productivity during the early part of the 20th century; highlighting the impact that nutrient loading has had on Lake Tahoe. These increases typically occur when complete lake mixing is accompanied by heavy precipitation and runoff.

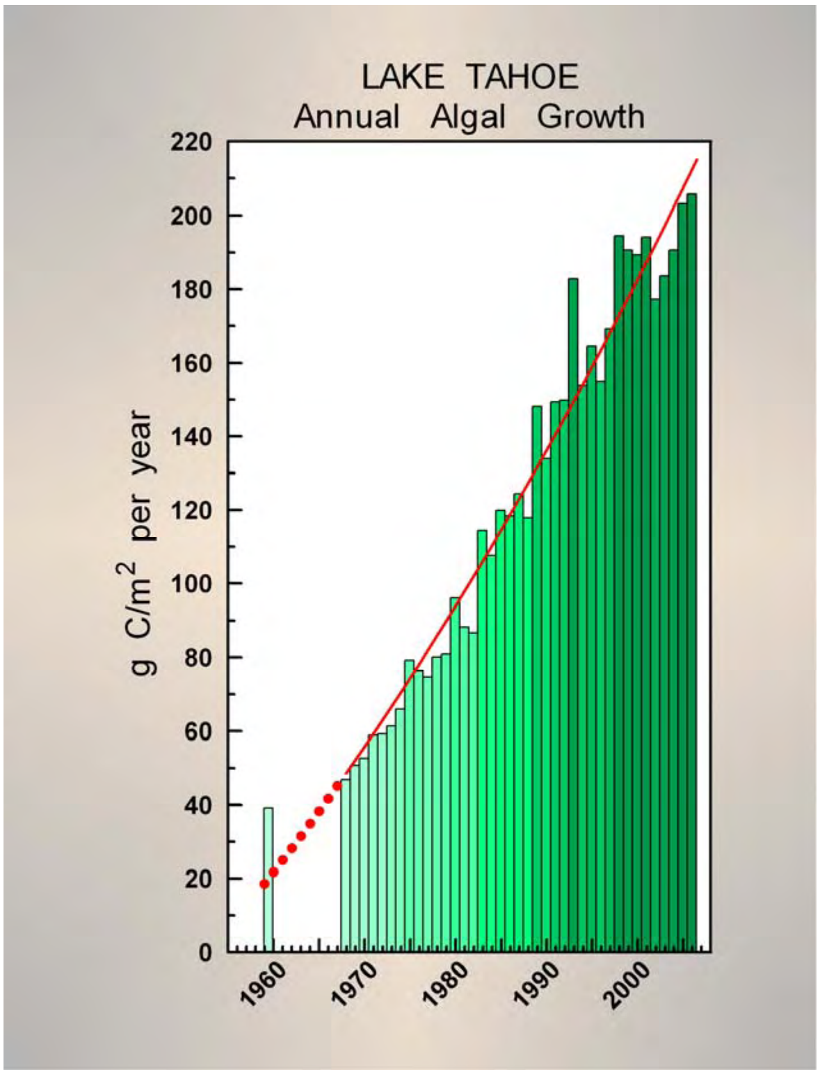

Figure 3-14. Annual primary productivity in Lake Tahoe. Values represent annual means from approximately 25-30 measurements per year (UC Davis - TERC 2007).

The long-term increase of primary productivity in Lake Tahoe is attributed to increased nutrient loading acting in concert with the lake's long hydraulic retention time (650 years) and efficient recycling of nutrients (Goldman 1988). With an average depth of over 984 feet (300 meters) and a maximum depth of over 1,640 feet (500 meters), many of the nutrient-bearing particles either remain suspended in the water column by lake mixing or the nutrients are mineralized by bacteria and effectively recycled before settling to the bottom (Paerl 1973). Year-to-year variability in primary productivity is directly related to the depth of mixing (Goldman et al. 1989).

Results from long-term algal growth response bioassay experiments show a clear shift from co-limitation by both nitrogen and phosphorus, to predominant phosphorus limitation (Goldman et al. 1993). This shift began in the early-mid 1980's, and has been explained by the accumulation of anthropogenic nitrogen from atmospheric deposition directly on to the lake surface (Jassby et al. 1994). Supporting evidence can be found in the phytoplankton species data. Atmospheric deposition provides most of the dissolved inorganic nitrogen (DIN) and total nitrogen in the annual nutrient load. Increased amounts of atmospheric nitrogen have caused an observed shift from co-limitation by nitrogen and phosphorus to persistent phosphorus limitation in the phytoplankton community (Jassby et al. 1994, 1995, and 2001).

The most recent algal growth bioassays (2002 – 2005) continue to show more frequent phosphorus-stimulation relative to nitrogen-stimulation (Hackley et al. 2005). When added individually, nitrogen was found to significantly increase algal biomass in 17 percent of experiments performed each year. In contrast, phosphorus stimulation caused an increase in algal biomass 57 percent of the time. Most importantly, when nitrogen and phosphorus are added in combination, algal growth was significantly higher in all of the experiments. Consequently, the control of both nitrogen and phosphorus is important.

Studies of phytoplankton species composition have helped to corroborate the shift in nutrient limitation and other changes in the lake. There is now a validated phytoplankton dataset that spans a 37 year period (the most recent data on phytoplankton distribution can be found in Hackley et al. 2005). Over the last four decades, changes have occurred in the standing crop, species composition and richness, and patterns of dominance (Hunter et al. 1990, Hunter 2004). The overall decline in relative abundance of diatoms is indicative of Lake Tahoe's eutrophication, as is an observed increase in araphid pennate diatoms at the expense of centric diatoms. In addition, the disappearance of *Fragilaria crotonensis* after 1980 is attributed to its inability to compete well in phosphorus limited waters.

Lake Tahoe has a deep-chlorophyll maximum, a common feature in the summer and early autumn, at a depth of 197- 328 feet (60-100 meters) below the surface (Coon et al. 1987). While this biomass does not directly influence Secchi depth (20-30 meters deep), it was discussed above that these particles can affect clarity during the initial periods of lake mixing when they are swept up into the surface waters. Over the years the deep-chlorophyll maximum has risen in the water column to a shallower depth (Goldman 1988, Swift 2004).

Deep Lake Mixing

Vertical stratification and mixing affect lake clarity. Stratification, or layering of waters, is created by layers of differing densities that impede top-to-bottom movement of water and pollutants. These density differences are primarily the result of varying temperature throughout the water column. Lake depth, size, shape, wind and other meteorological conditions also influence mixing and the stratification process. Stratification occurs during spring and summer due to heating by the sun. There are three layers in a stratified lake: (1) the epilimnion – a warm, lower density surface layer, (2) the metalimnion – a middle layer that contains the thermocline, which is the region where temperature changes most rapidly with depth, and (3) the hypolimnion – a cool, dense lower layer.

Thermal stratification in Lake Tahoe begins during the period February/March to April and reaches its maximum in August. The thermocline is strongest in late July/early September at a depth of approximately 66 feet (20 meters). As the summer progresses into fall, surface temperature is reduced and the thermocline weakens and deepens slowly until the winter when vertical mixing or turnover occurs. Deep mixing occurs when the water column is isothermal. Mixing or de-stratification generally occurs during autumn and winter, due to cooling air temperatures and wind (Pamlarsson and Schladow 2001). The depth of vertical mixing in Lake Tahoe varies from 328 feet (100 meters) to the bottom (approximately 500 meters), depending on the intensity of winter storms. On average, Lake Tahoe mixes to the bottom once every four years. This is a statistical average and mixing does not happen on a regular schedule.

Mixing is an important part of nutrient cycling and particle dynamics in Lake Tahoe. Mixing brings nutrient-rich waters from deeper portions of the lake to the epilimnion (surface) where, together with pollutants introduced by surface and subsurface runoff and atmospheric deposition, they can be utilized by algae and contribute to reduced lake clarity. There is a positive correlation showing that increased depth of mixing during the winter results in increased algal growth the following summer (Goldman and Jassby 1990a, b). Lake mixing and vertical circulation patterns also act to help position particles in the water column. The vertical distribution of these particles sets the conditions for clarity. Additionally, vertical circulation affects the settling rates for particles and limnetic aggregates. The UC Davis - TERC Lake Clarity Model includes a complete hydrodynamic sub-model to account for lake mixing and circulation processes on a 2-hour time scale.

Research and lake monitoring shows that significant vertical mixing can occur during summer months in addition to the annual mixing event (Pamlarsson and Schladow 2000). During sustained summer wind events, surface water can be forced downward and, in response, colder deeper water rises to the surface due to a process termed upwelling. During summer upwelling events, the Secchi depth often exceeds 30 meters due to the fact that deeper water lower in fine particle concentrations is brought to the surface.

Another important mixing process in Lake Tahoe occurs as streams discharge to the lake. Recent investigations have shown that water temperature, associated water density and stream flow have a profound impact on the depth at which influent stream water mixes in the lake (Perez-Losada and Schladow 2004). Because the influent streams carry significant sediment loads to Lake Tahoe, the insertion depth of the stream water has the potential to significantly affect lake clarity.

Since 1970, Lake Tahoe has warmed at an average rate of 0.015 ^{o}C per year (Coats et al. 2006). This has increased the thermal stability and resistance to mixing of the lake, reduced the depth of the October thermocline and shifted the timing of stratification onset toward earlier dates. The warming trend is correlated with both the Pacific Decadal Oscillation and the Monthly El Nino-Southern Oscillation Index, but it results primarily from increasing air temperature and secondarily from increased downward long-wave radiation from the sun. The biological and water quality impacts of the changes in lake thermal structure have been the subject of discussion, but have yet to be documented in detail.

3.4.3 Nearshore Water Quality

This TMDL does not directly address restoring the nearshore clarity of Lake Tahoe. Rather, the Lake Tahoe TMDL focuses solely on restoring the deep water clarity and transparency. However, relevant research in the nearshore is summarized in this section to highlight the nature of the nearshore conditions. The nearshore is the area that connects the deep water to the upland and, though some research has been completed, the relationship between the lake's deep water clarity and the nearshore conditions is not well understood and additional research is planned to hopefully bridge that gap. Research on the lake's nearshore is presented in this Section to highlight some complexities and lack of understanding the relationship between the upland activities and the conditions in the nearshore.

For the purposes of the Lake Tahoe TMDL, the nearshore extends from the lake shoreline to about 66 feet (20 meters) of water depth, typically where the bottom can no longer be seen from above. The nearshore is the area of the lake where clarity is most obvious to the casual observer because the lake bottom can be seen. This TMDL-definition for the nearshore is different than the Tahoe Regional Planning Agency (TRPA) Code of Ordinances definition for "nearshore", which states, "the zone extending from the low water elevation of Lake Tahoe (6,223.0 feet Lake Tahoe Datum) to a lake bottom elevation of 6,193.0 feet Lake Tahoe Datum, but in any case, a minimum lateral distance of 350 feet measured from the shoreline."

The nearshore area is affected by surface loading either as direct discharge to the nearshore, tributary inflow, and groundwater loading. Water quality is historically measured in the nearshore as turbidity which is a measurement of water murkiness. Turbidity is expressed as nephelometric turbidity units (NTU) with higher values indicating less clarity, or greater murkiness (Taylor et al. 2003). Another indicator of nearshore water quality is the abundance and distribution of periphyton, or attached filamentous algae. Both of these nearshore indicators are discussed in this section.

Turbidity

A study by Taylor et al. (2003) explored near shore clarity by collecting field measurements of turbidity between September 2001 and August 2003. Turbidity mesaurments made during this study are in Figure 3-15. It showed that California's near shore numeric clarity objective for turbidity was exceeded in several areas. The study showed moderate to extremely elevated near-shore turbidity in the south shore area. Specifically, the mouth of the Upper Truckee River was characterized as having extremely elevated turbidity, while the Al Tahoe intervening zone, Bijou Creek, Tahoe Keys Marina and Ski Run Marina showed moderate levels of turbidity. These areas had maximum observed turbidities above 3 (NTU) or typical values near or above 1 NTU (i.e., above or near the numeric objectives).

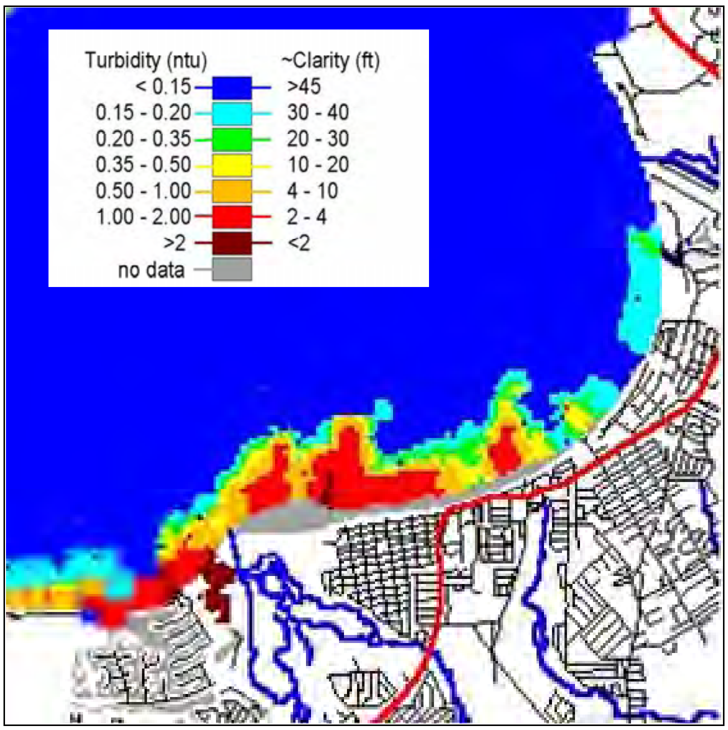

Figure 3-15. Measurements of near shore turbidity along Lake Tahoe's South Shore on April19, 2003 following a lake level rain event (Taylor et al. 2003).

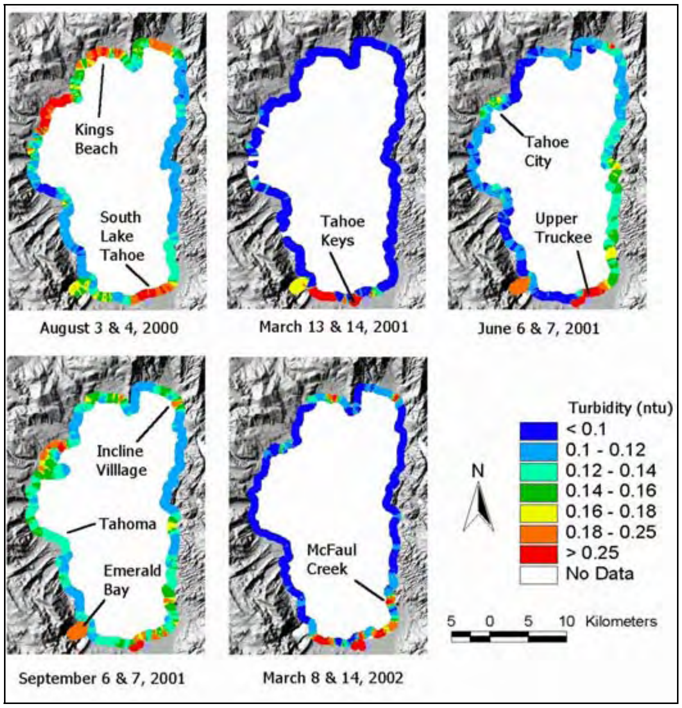

Figure 3-16. Synoptic monitoring of near shore turbidity in Lake Tahoe showing seasonal and spatial variation (Taylor et al. 2003).

Approximately 0.93 miles (1.5 km) of the 71 miles (114 km) total shoreline (near the outlet of the Upper Truckee River) had extremely or moderately elevated turbidity. Extremely elevated turbidity was defined as a 123.5 acres (0.5 km^2) area with typical turbidity above 0.5 NTU and maximum turbidity above 2.5 NTU. Moderately elevated turbidity was defined as a 123.5 acres (0.5 km^2) area with typical turbidity above 0.35 NTU and maximum turbidity above 1.5 NTU. Four km of the total shoreline (further east on the south shore to the vicinities of Bijou Creek and Ski Run Marina, and near Tahoe Keys) had moderately elevated turbidity and 5.6 miles (9 km) further east had slightly elevated turbidity. The highest measurements coincided with spring snowmelt and runoff, and also had the highest ratios of mineral to algal particle content. Summer thunderstorms had a lesser but still discernable effect on near shore clarity. Figure 3-16 provides a synoptic view of near shore turbidity. Areas associated with chronically elevated turbidity occur most frequently in proximity to urbanized areas during periods of surface water discharge.

Attached Algae

Some of the first visible evidence of eutrophication of Lake Tahoe was the increased amount of attached algae or periphyton growth along the shoreline in the 1960’s. The accumulation of attached algae on rocks, piers, boats and other hard-bottomed substrates is a striking indicator of Lake Tahoe’s declining water quality for the largely shore-bound population. Thick, green or white expanses of periphyton biomass often coat the shoreline in portions of the lake during the spring. When this material dies and breaks free, beaches can be littered with mats of algae. The near shore periphyton can significantly impact the aesthetic beneficial use of the shorezone.

Under the current periphyton monitoring program, collections are made at 10 stations (five each in California and Nevada), nine of which have historical data on periphyton biomass. Samples of natural periphyton are collected directly from rocks at 1.6 feet (0.5 meter) depths, approximately monthly during the peak growth season (January-June) and less frequently during the remainder of the year (July-December). The units of biomass are chlorophyll *a* per square meter of lake bottom area (Hackley et al. 2004, 2005).

Measures of annual maximum, average annual and baseline chlorophyll *a* were determined for 2000 – 2003 and these values were compared with historical data collected from 1982 – 1985 (Figure 3-17). The average annual maximum biomass measured as chlorophyll *a* concentration was clearly higher in areas of high development in the northwest portion of the lake during both periods. In contrast, the average maximum biomass was consistently lower at undeveloped east shore sampling locations.

Attached algae also exhibit a distinct seasonal pattern (Figure 3-18) of high biomass accrual in the spring and early summer, followed by a die-off and sloughing of biomass in mid-summer. Periphyton biomass returns to near its annual baseline level by July. Periphyton growth is stimulated by the elevated nitrogen and phosphorus loading associated with the spring surface runoff and groundwater flow (Loeb 1986, Reuter and Miller 2000).

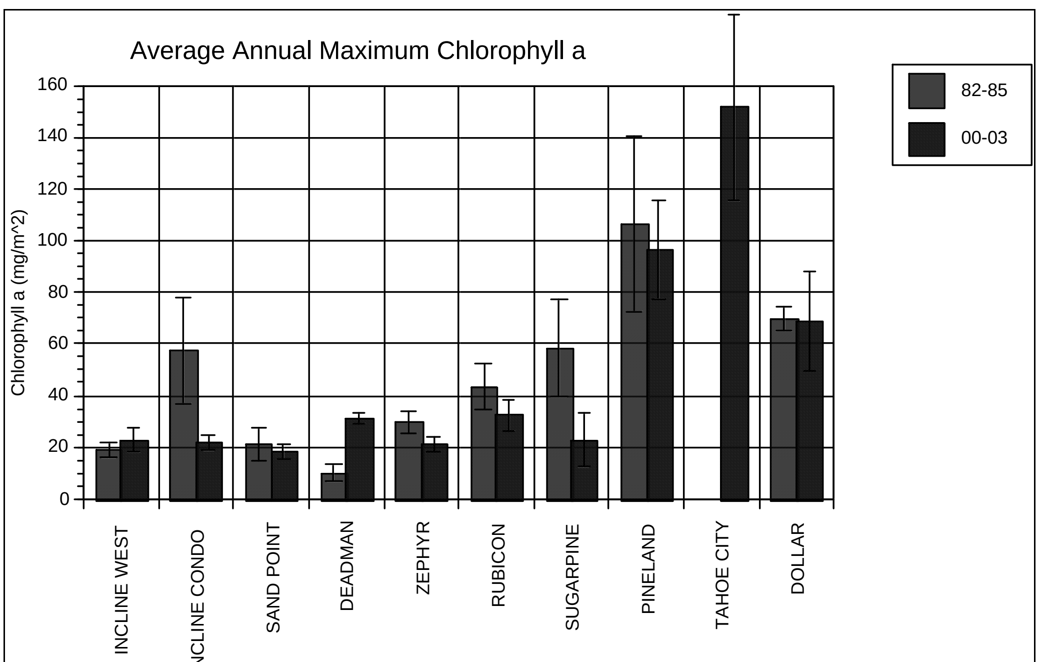

Figure 3-17. Synoptic distribution of attached algae at 10 monitoring sites in Lake Tahoe (Hackley et al. 2004).

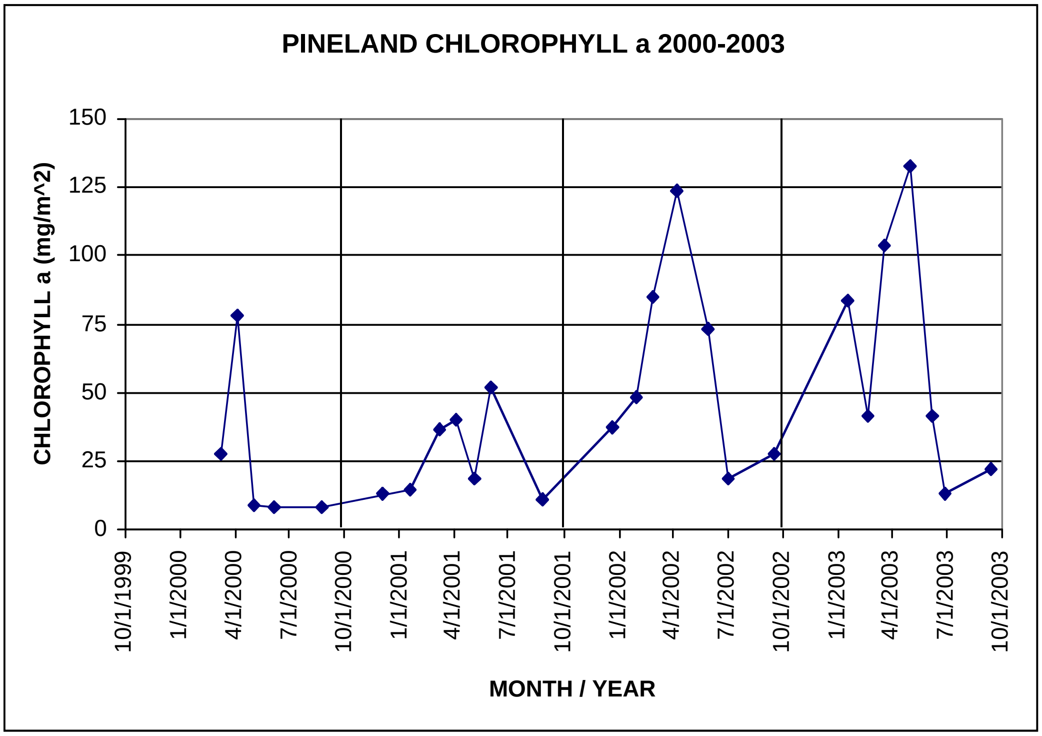

Figure 3-18. Seasonal distribution of attached algae from a depth of 0.5 meter at the Pineland sampling site located on the west shore in the vicinity of Ward Creek (Hackley et al. 2004).

4 Source Analysis

Significant research on pollutant sources has been completed as part of the Lake Tahoe TMDL development. This research has greatly improved our understanding of individual pollutant sources, distribution of sources, magnitude of pollutant load, and specific pollutant species. This section of the report provides detailed summaries of work done to better understand and evaluate sources of pollutants to Lake Tahoe. This work was specifically designed to build on the research, data, and information available in the Tahoe basin.

Pollutant source information in the Tahoe basin has typically focused on individual site evaluations or specific sources within a subwatershed. A notable exception is the Watershed Assessment (USDA 2000) and Reuter et al. (2003) which identified major source categories of pollutants, including:

- Stream loading (from tributaries)
- Intervening zones (areas that discharge directly into the lake)
- Atmospheric deposition
- Groundwater
- Shoreline erosion

Using information available at the time, Reuter et al. (2003) developed the first pollutant budget for Lake Tahoe in 1998 (Table 4-1). The Budget focused on nitrogen and phosphorus as it was thought that phytoplankton were the principal cause of clarity loss. It wasn't until 1999 (Jassby et al. 1999) that serious concern was raised about the impact of fine grained sediment on lake clarity. Consequently, initial pollutant budgets did not thoroughly evaluate fine sediment.

Table 4-1. Pollutant loading estimates for Lake Tahoe (metric tons per year) as revised in 2000 (Reuter et al. 2003).

Source Categories		Total Nitrogen	Total Phosphorus
Upland Runoff	Stream Loading	82 (20%)	13.3 (31%)
	Intervening Zones	23 (5%)	12.3 (28%)
Atmospheric Deposition		234 (59%)	12.4 (28%)
Groundwater		60 (15%)	4 (9%)
Shoreline Erosion		1 (1%)	1.6 (4%)
TOTAL		400	43.6

Initial results from modeling the optical properties of water in Lake Tahoe highlighted the significant impact that fine particles have on clarity and transparency. It is estimated that approximately 60-70 percent of clarity loss is the result of fine particle interaction with light and water (Swift et al. 2006). Consequently, estimating the contribution of fine sediment from identified sources was a significant effort associated with the Lake Tahoe TMDL related research. Additionally, research focused on providing information on the specific forms of pollutants from each source, and to the extent possible, additional refinement to the major source categories. Stream channel erosion was identified and evaluated as a source of pollutants. Table 4-2 lists the source areas evaluated in this document to develop an updated pollutant budget for Lake Tahoe.

Table 4-2. Listing of pollutant sources evaluated as part of the Source Assessment.

Urban Areas	Single Family Residential
	Multi-family Residential
	Primary Roads
	Secondary Roads
	Commercial/Institutional/ Communications/Utilities
	Turf Areas
Forest Areas	Unpaved Roads
	Ski Areas
	Recreational Areas
	Burned Areas
	Timber Harvest Areas
	Five Different Erosion Potential Areas
Groundwater	South Lake Tahoe/Stateline
	Tahoe City/West Shore
	Tahoe Vista/Kings Beach
	Incline Village
	East Shore
Stream Channel Erosion	Stream Channel Loading Estimates for all 63 Tributaries
Atmospheric Deposition	
Shoreline Erosion	

The urban areas identified in Table 4-2 also include loading estimates from pervious and impervious surfaces areas. Estimates of fine sediment loading and fine sediment particle counts were also developed for each source category. Each source evaluation used Tahoe specific data and information. When literature values were applied, similar climates and settings were selected. In most instances, new data was collected in the Tahoe basin as part of the evaluations.

The source loading estimates were applied to the Lake Clarity Model for evaluating the lake's response to the pollutant loading conditions. The urban and forest upland loading estimates were developed for the Lake Tahoe Watershed Model with the use of the Loading Simulation Program C++ (LSPC). The stream channel loading estimates were also applied to the Lake Tahoe Watershed Model to better represent stream channel loading. This allowed for the development of individual estimates of in-channel and upland pollutant sources. These combined estimates were then used as input to the

Lake Clarity Model, while pollutant loading estimates from groundwater, atmospheric deposition, and shoreline erosion were used as direct inputs to the Lake Clarity Model.

Table 4-3 provides the updated pollutant loading estimates for Lake Tahoe.

Table 4-3. Updated Pollutant loading estimates based upon work completed as part of the Lake Tahoe TMDL development.

Source Category		Total Nitrogen (metric tons/year)	Total Phosphorus (metric tons/year)	Number of Fine Sediment Particles ($x10^{18}$)
Upland	Urban	63	18	348
	Non-Urban	62	12	41
Atmospheric Deposition	(wet + dry)	218	7	75
Stream Channel Erosion		2	<1	17
Groundwater		50	7	NA**
Shoreline Erosion		2	2	1
TOTAL		397	46	481

**NA=Not Applicable since it was assumed that groundwater does not transport fine sediment particles.

Numerous projects were funded as part of the Lake Tahoe TMDL and were intended for direct use in this Technical Report. In some cases, the language from portions of those project reports was directly used in this document with minor editing. In particular, the following studies were conducted in direct support of the Lake Tahoe TMDL, and portions of their reports are incorporated into the text of this Technical Report.

Groundwater
USACE (United States Army Corps of Engineers). 2003. *Lake Tahoe Basin Framework Study: Groundwater Evaluation*. U.S. Army Corps of Engineers, Sacramento District.

Stream Channel
Simon, A., E.J. Langendoen, R.L. Bingner, R. Wells, A. Heins, N. Jokay and I. Jaramillo. 2003. *Lake Tahoe Basin Framework Implementation Study: Sediment Loadings and Channel Erosion*. USDA-ARS National Sedimentation Laboratory Research Report. No. 39.

Simon, A. 2006. *Estimates of Fine-Sediment Loadings to Lake Tahoe from Channel and Watershed Sources*. USDA-Agricultural Research Service, National Sedimentation Laboratory. Oxford, MS.

Atmospheric
CARB (California Air Resources Board). 2006. *Lake Tahoe Atmospheric Deposition Study (LTADS)*. Final Report – August 2006. Atmospheric Processes Research Section, California EPA, Sacramento, CA.

Upland

Tetra Tech, Inc. 2007. *Watershed Hydrologic Modeling and Sediment and Nutrient Loading Estimation for the Lake Tahoe Total Maximum Daily Load*. Final modeling report. Prepared for the Lahontan RWQCB and University of California, Davis.

Shoreline Erosion

Adams, K.D. and T.B. Minor. 2002. *Historic Shoreline Change at Lake Tahoe from 1938 to 1998: Implications for Water Clarity.* Desert Research Institute, Reno, NV. Prepared for the Tahoe Regional Planning Agency.

Adams, K.D. 2004. *Shorezone Erosion at Lake Tahoe: Historical Aspects, Processes, and Stochastic Modeling.* Desert Research Institute, Reno, NV. Prepared for the Tahoe Regional Planning Agency.

Each of these reports reviewed available information and, in most cases, built upon research previously conducted on more limited scales. For additional detail and description of research conducted on each source category, each of the above reports should be referenced individually. The content of these reports was largely summarized in this document with enough detail included to allow the reader to fully understand the methods, scope, and detail of research conducted for each source category. For areas where new information was not collected, the most recent and comprehensive analyses were used.

Figure 4-1, Figure 4-2, and Figure 4-3 are pie charts of the relative pollutant loading from each source category. The loading values presented in this report are based on data collected largely since 2000 and reflect relatively recent development and land-use conditions. Note the urban upland sources are estimated to contribute more than two-thirds of all the fine sediment particles to Lake Tahoe. This information highlights the significance of urban uplands as a primary pollutant source of fine sediment.

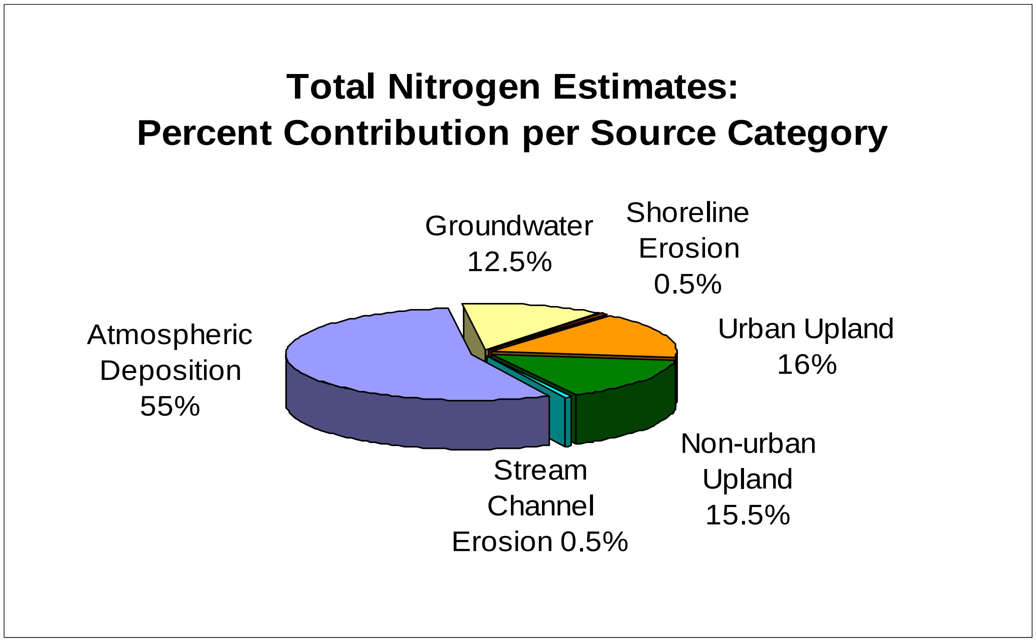

Figure 4-1. Relative Nitrogen Mass Loading by Source Category.

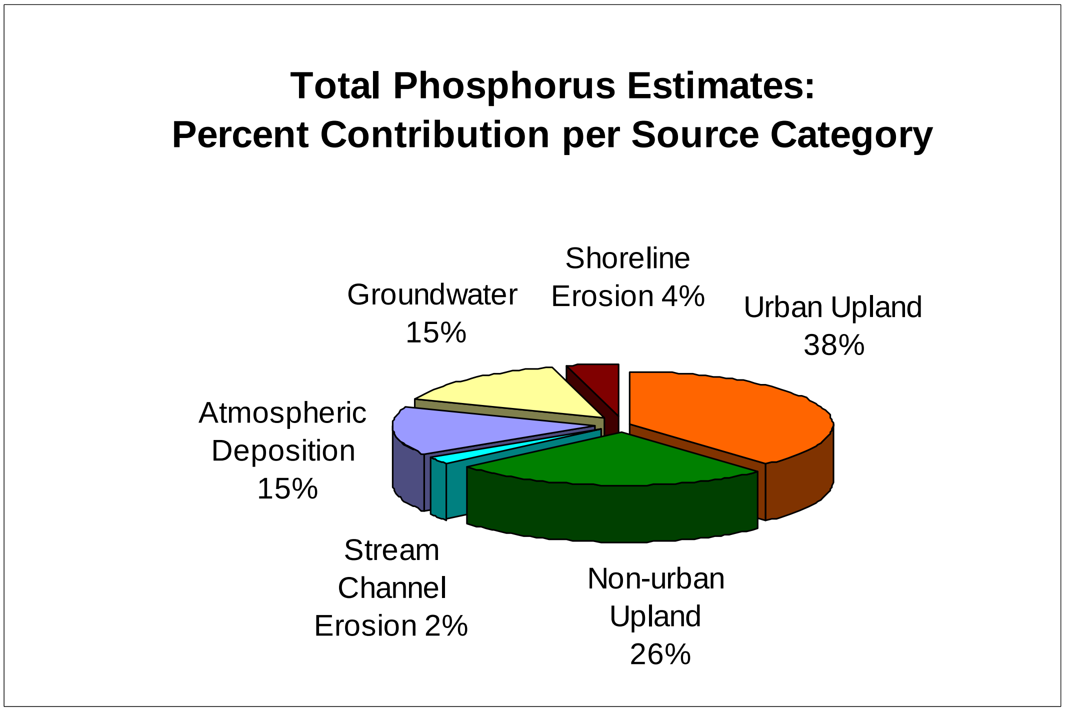

Figure 4-2. Relative Phosphorus Mass Loading by Source Category.

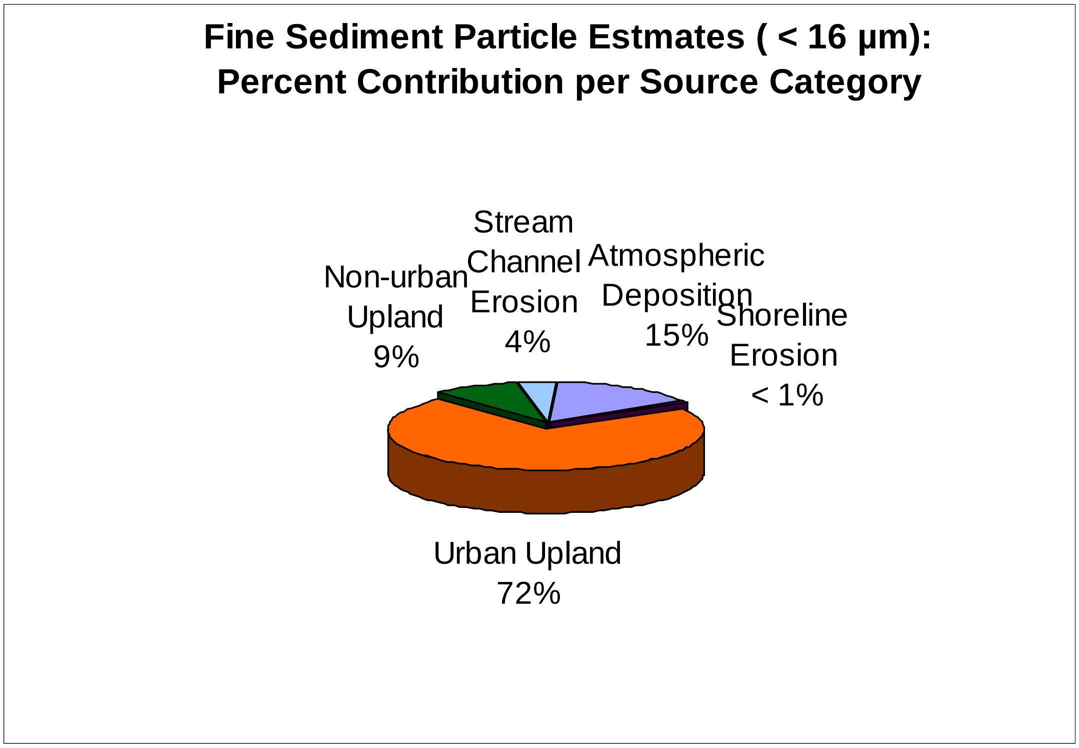

Figure 4-3. Relative Fine Sediment Particle Loading by Source Category.

4.1 Groundwater

Groundwater is an important nutrient source to Lake Tahoe. Nutrient-rich groundwater reaches Lake Tahoe when rainfall and snowmelt infiltrate the upland basin, fill deposits and fractured rock and travel down-gradient toward the lake. The groundwater may become enriched with soluble nutrients as it mixes with groundwater that has infiltrated through subsurface areas in both developed and undeveloped land-uses. Ultimately, this groundwater flow is discharged to Lake Tahoe directly or via interflow to tributaries and/or is lost to the atmosphere by evapotranspiration. Nutrient loading from groundwater by streamflow is included in Section 4.3 as part of the upland source analysis. This section focuses on groundwater loading resulting from direct groundwater discharge into Lake Tahoe at the aquifer-lake interface.

A study of the groundwater quality in three major aquifers in the Lake Tahoe basin (Ward Creek, Upper Truckee River, and Trout Creek) (Loeb 1987) concluded that groundwater became enriched with nutrients as it moved toward Lake Tahoe through developed regions of the watersheds. Potential sources of nutrients in groundwater are residual effluent from past sewage disposal sites, fertilizer, effluent from leaky sewage conveyance lines, and infiltrating urban stormwater runoff. The degradation or retardation of nutrients as groundwater flows towards the lake can occur as a result of physical, chemical and biological processes within the aquifer. Groundwater is not considered a source of sediment loading to Lake Tahoe (Tyler 2003 personal communication, Fogg 2003 personal communication).

To better understand groundwater processes and nutrient loading to Lake Tahoe, the USACE completed the *Lake Tahoe Basin Framework Study Groundwater Evaluation* (USACE 2003) in support of TMDL development. This study refined estimates of nitrogen and phosphorus loading from this source. The USACE's Groundwater Evaluation (2003) is the primary information source for this portion of the report.

4.1.1 Groundwater as a Pollutant Source

Thodal (1997) reported that nitrogen and phosphorus loading via groundwater accounted for approximately 15 and 10 percent, respectively, of the overall nutrient loading to the lake. Nitrate (NO_3^-) is the primary form of nitrogen that leaches into groundwater (Follett 1995). Nitrate is highly soluble and moves freely through most soils. Nitrate is repelled by negatively charged clay surfaces, causing it to mobilize rather than attach to soils. Consequently, nitrate travels at the same rate as groundwater flow. Soluble reactive phosphorus (SRP) moves much more slowly, as it is easily taken up by plants and adsorbed to soil particle surfaces (Sharpley 1995).

Groundwater nutrients can affect the water quality of tributary streams. A recent USGS study (Rowe and Allander 2000) found that the Upper Truckee River and Trout Creek supply about 40 percent of all water that flows into Lake Tahoe and that 40 percent of the Upper Truckee River's flow is derived from shallow groundwater. Watershed modeling completed as part of the Lake Tahoe TMDL development indicates even greater percentages of groundwater contribution to tributary flows. The contribution of this very shallow groundwater flow into the tributaries is included as part of the calculations for watershed stream loading. This current section on groundwater focuses on loading from deeper aquifers that discharge directly into Lake Tahoe through the under-water slope faces.

4.1.2 Existing Groundwater Information at Lake Tahoe

Early studies of hydrogeology in the Lake Tahoe basin include McGauhey et al. (1963), Crippen and Pavelka (1970), and Loeb and Goldman (1979). Loeb and Goldman (1979) estimated the total groundwater flow from the Ward Creek watershed into Lake Tahoe from basic hydraulic principles. Later, Loeb (1987) investigated groundwater flow and groundwater quality in the Ward Creek, Upper Truckee River, and Trout Creek aquifers. These studies suggested groundwater nutrient loading in the Ward Creek watershed accounted for 60 percent of the total Dissolved Inorganic Nitrogen (DIN) loading and 45 percent of the watershed’s total dissolved phosphorus loading. Woodling (1987) and Loeb (1987) investigated the hydrogeologic aspects of groundwater and lake interactions in the southern portion of the Lake Tahoe basin. They concluded that groundwater loading of DIN from the Upper Truckee-Trout Creek drainage accounted for only 5-20 percent of the total loading from both groundwater and tributaries. The contribution of groundwater to total watershed loading of soluble phosphorus was also low at 2 percent. Ramsing (2000) focused on measuring groundwater seepage into Lake Tahoe. In estimating nutrient transport from the Incline Creek watershed, Ramsing reported DIN from groundwater to be 14 percent of the total watershed budget; while the contribution of soluble phosphorus was insignificant.

The differing nutrient contributions noted in these studies highlight that groundwater aquifers in different regions of the basin do not all behave identically and any comprehensive evaluation of groundwater nutrient loading must account for regional differences.

Thodal (1997) published the first basin-wide evaluation of groundwater quality and quantity from 1990 to 1992. This study established a monitoring network of 32 sample sites that provided information about the relative significance of groundwater to the nutrient budget of Lake Tahoe. Nitrate represented 85 percent of the total nitrogen, ammonia represented 5 percent and organic nitrogen represented 10 percent. The distribution of mean phosphorus concentration was about 55 percent ortho-phosphorus and 42 percent organic phosphorus. Phosphorus was the only constituent found to be statistically different between the fall and spring seasons.

Thodal’s 1997 study also includes detailed evaluations of hydraulic gradient, hydraulic conductivity, and recharge-precipitation relationships. Based on these assessments, Thodal estimated annual groundwater contributions directly to the lake for nitrogen and phosphorus were 54 metric tons (metric ton = 1,000 kg) and 3.6 metric tons, respectively.

4.1.3 New Information – Groundwater Evaluation Report

The Groundwater Evaluation conducted by the USACE (2003) serves as an independent assessment of Thodal's (1997) analysis. The 2003 report differs from Thodal's 1997 report in that it divides the basin into geographic regions, rather than providing a single basin-wide value for groundwater loading. Data collected by the USGS and other entities were used to update Thodal's nutrient loading evaluation. In addition, sufficient data were available to develop a groundwater flow model for the South Lake Tahoe area and provide better estimates of groundwater discharge from this region. The USACE groundwater evaluation also provided the contribution of ambient nutrient to Lake Tahoe. Ambient loading represents the nutrient flux in groundwater from undisturbed areas.

Delineation of Major Aquifer Limits

The USACE (2003) report divided the Lake Tahoe basin study area into five main regions based on jurisdictional boundaries and major aquifer limits. The five major regions included South Lake Tahoe/Stateline, East Shore, Incline Village, Tahoe Vista/Kings Beach and Tahoe City/West Shore (Figure 4-4). The South Lake Tahoe/Stateline region was further divided into six subregions extending from Emerald Bay to Stateline (Figure 4-5).

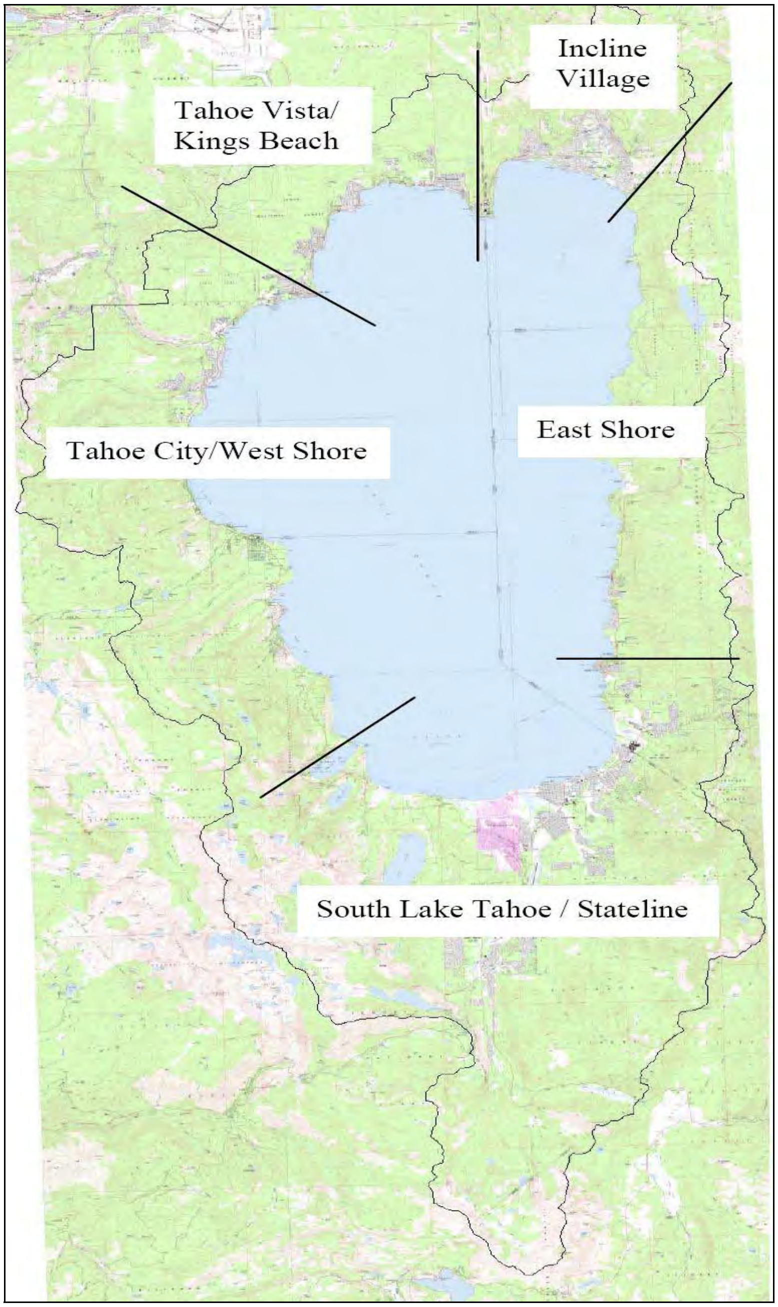

Figure 4-4. Five groundwater evaluation regions in the Lake Tahoe basin (USACE 2003).

Both data collection and a literature review were conducted for the groundwater evaluation. Existing data were obtained for 219 wells from a number of federal, local, and State agencies in California and Nevada. Some data necessary to fully evaluate regional groundwater flow still do not exist. The USACE 2003 report details the sources of data used in that evaluation.

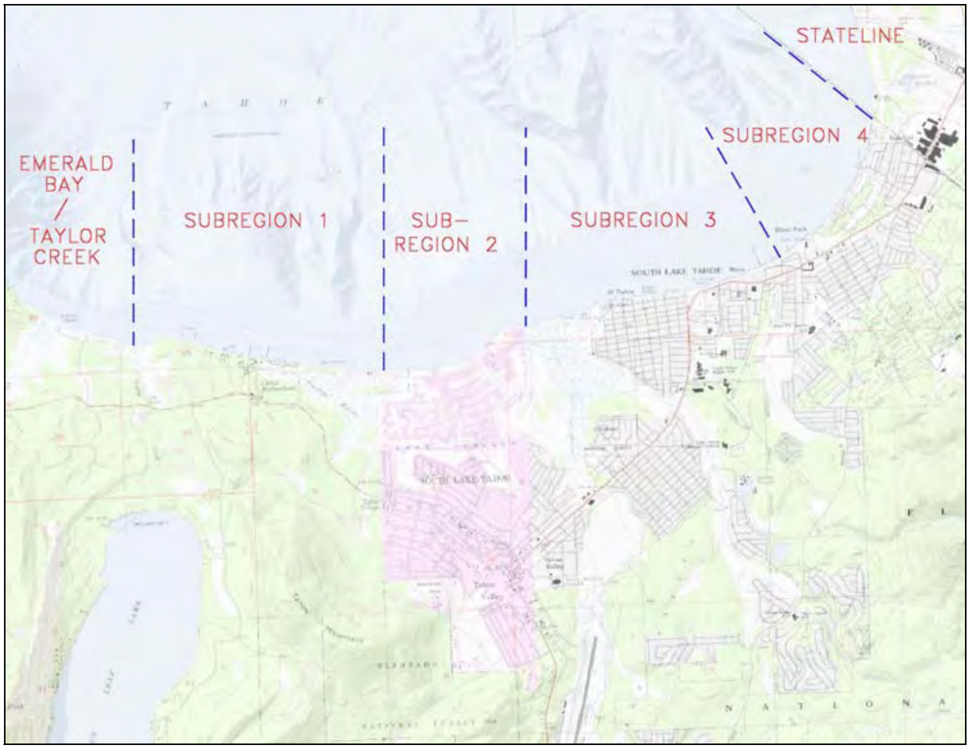

Figure 4-5.The six subregions of the South Lake Tahoe/Stateline region of the Lake Tahoe basin (USACE 2003).

Nutrient Loading Methodology and Estimates

Groundwater discharge for the South Lake Tahoe region was estimated using numerical modeling (Fenske 2003) while Darcy's Law principals were applied to estimate groundwater discharges from other regions.

In applying Darcy's Law, the USACE predicted an average hydraulic conductivity for each region, and then estimated aquifer cross sectional area and hydraulic gradient to calculate flow. Average hydraulic conductivity was estimated from available drill logs. Each well log was partitioned into stratified units and each unit assigned a hydraulic conductivity range, based on published values for similar subsurface material. In some areas, such as portions of the East Shore, few well logs were available and geologic maps and aerial photographs were used to infer subsurface conditions. Aquifer depths were estimated from well logs in proximity to the shoreline and stratigraphic interpretation from geologic maps and aerial photographs. Aquifer lengths were estimated from the bedrock outcrops along the shoreline portrayed in aerial photographs and geologic maps. The lengths of the aquifers were measured from topographic maps.

Using Darcy's Law, the USACE assumed no water is added to or taken away from the system and the aquifer is homogeneous. This simplified approach can give a reasonable estimation of groundwater flow. While it is known that the aquifers in the basin are not homogeneous, the USACE Groundwater Evaluation considered the

Darcy’s Law approach to be the most reasonable method to obtain estimated groundwater flow given the lack of available well data.

The USACE estimated groundwater nutrient loads by multiplying estimated flow (volume per time) by nutrient concentration (mass per volume). The nutrient evaluation included: dissolved ammonia + organic nitrogen (dissolved TKN), dissolved nitrate including nitrite, total dissolved nitrogen (TKN + nitrate), dissolved ortho-phosphorus and total dissolved phosphorus (including ortho-phosphorus, organic phosphorus and hydrolyzable phosphorus).

The USACE selected nutrient concentrations by one of the following approaches: (1) average concentration, (2) downgradient concentration, or (3) land-use weighted concentration. The ultimate selection was based on data availability and best professional judgment, each approach is briefly described below.

The average concentration method takes into consideration monitoring data collected from all wells in a region. The average dissolved nitrogen and dissolved phosphorus concentrations were calculated for the cluster of wells located in each region.

The downgradient concentration method takes advantage of groundwater monitoring data collected from wells close to the lake and should reflect groundwater nutrient concentrations expected to reach the lake. This method was used in each area where wells were located near the lake and represented the major upgradient land-uses. The average dissolved nitrogen and dissolved phosphorus concentrations were determined for these downgradient wells only. The nutrient concentrations in the downgradient wells can be used to evaluate whether attenuation is occurring or, conversely, if nutrients are accumulating. This method did not take into account the depth of the aquifer monitored.

The land-use weighted concentration method considers the type of development in the well vicinity. This method was used for areas that did not groundwater wells. Average nutrient concentrations were calculated from all the basin-wide data then categorized by land-use. The study authors then evaluated each groundwater region using GIS to determine area land-uses. The average nutrient concentrations were then applied to appropriate land-use categories to estimate average groundwater nutrient loads. In cases where land-use types had no associated groundwater quality data, assumptions based on best professional judgment were made by the USACE (2003) report scientists on how specific land-use types affect nutrient loading.

The primary land-uses of concern in the USACE Groundwater Evaluation were residential, commercial and recreational as these land-use types can be sources of nutrients to the groundwater system (USACE 2003). Residential and commercial land-use includes nutrient input from fertilization, stormwater infiltration, leaking sewage lines and/or inactive septic tanks. The primary nutrient source in the typical recreational land-uses is fertilization, although leaking sewage systems may also be in these areas. Because many of the regions did not have adequate monitoring networks at the time of the study, basin-wide average concentrations for specific land-use types were developed. For this analysis, each of the wells located in the Lake Tahoe basin was assigned a land-use code based on its location and basin-wide concentrations for four land-use types were determined by compiling and averaging the analytical results for all wells of the same land-use code (Table 4-4). These values were used for nutrient concentration when the land-use weighted concentration method was employed.

Table 4-4. Average nutrient concentrations of groundwater wells based on land-use types (USACE 2003).

Land-use	Nitrogen Ammonia + Organic Dissolved (mg/L)	Nitrogen Nitrite plus Nitrate Dissolved (mg/L)	Total Dissolved Nitrogen (mg/L)	Dissolved Orthophosphorus (mg/L)	Total Dissolved Phosphorus (mg/L)
Residential	0.26	0.37	0.63	0.081	0.11
Commercial	0.16	0.51	0.67	0.092	0.12
Recreational	0.40	1.2	1.6	0.073	0.10
Ambient	0.16	0.11	0.27	0.040	0.049

Ambient conditions represent the concentration of nutrients that would be naturally occurring in the groundwater without the added impact of human development. It was assumed that these conditions were best represented by nutrient concentrations observed in undeveloped and undisturbed areas (vegetated and forested).

Subregional Flow and Nutrient Loading

The USACE developed regional groundwater discharge and nutrient loading estimates throughout the basin. Each of the major groundwater regions has unique characteristics that warranted region-specific nutrient loading estimates. These regional values were combined to evaluate the overall estimates of groundwater nutrient loading to Lake Tahoe. Table 4-5 provides a range of loading values and an estimate of what is considered a reasonable loading value for groundwater in each area.

The loading percentage estimates at the bottom of Table 4-5 are presented on a regional basis. The contribution of both nitrogen and phosphorus from the South Lake Tahoe/Stateline region was less than five percent of the basin-wide total. The shallow hydraulic slope on the South Shore and aquifer pumping in this region are the main factors in the lower groundwater discharge rate in the South Shore/Stateline area.

Table 4-5. Subregional Groundwater Loading Estimates (USACE 2003).

Constituent		Region										Total Groundwater Loading to Lake Tahoe
		South Lake Tahoe/Stateline						Incline Village	Tahoe Vista/Kings Beach	Tahoe City/West Shore	East Shore	
		Emerald Bay to Taylor Creek	Subregion 1	Subregion 2	Subregion 3	Subregion 4	Stateline					
Dissolved Ammonia + Organic (kg/yr)	Min	10	110	11	0	86	180	200	1,700	1,400	1,300	
	Max	130	710	330	20	460	550	2,100	6,400	17,000	2,300	
	Estimate	70	340	250	9	170	550	1,600	2,700	9,800	2,300	
Average Concentration (mg/L)		0.045	0.71	0.21	0.19	0.23	0.64	0.24	0.27	0.26	0.47	
Dissolved Nitrate (kg/yr)	Min	10	12	92	0	15	34	400	1,600	1,300	1,800	
	Max	140	64	1,100	68	650	840	11,000	8,600	31,000	3,900	
	Estimate	80	30	530	13	290	95	2,600	6,800	18,000	3,900	
Average Concentration (mg/L)		0.051	0.057	0.44	0.26	0.40	0.11	0.39	0.70	0.47	0.81	
Total Dissolved Nitrogen (kg/yr)	Min	20	130	100	1	230	370	60	4,800	2,700	3,100	12,000
	Max	270	770	1,300	80	1,300	1,200	13,000	15,000	48,000	6,200	87,000
	Estimate	150	370	780	22	450	650	4,200	9,400	28,000	6,200	50,000
Average Concentration (mg/L)		0.096	0.77	0.65	0.45	0.63	0.75	0.63	0.97	0.73	1.28	
Dissolved Orthophosphate (kg/yr)	Min	20	8	4	0	24	7	6	390	1,000	500	
	Max	200	43	140	10	72	17	720	1,300	5,400	1,100	
	Estimate	110	15	100	3	60	17	550	820	3,100	900	
Average Concentration (mg/l)		0.071	0.032	0.086	0.062	0.084	0.020	0.082	0.084	0.082	0.019	
Total Dissolved Phosphorus (kg/yr)	Min	20	11	7	0	19	11	10	670	1,500	80	2,400
	Max	240	59	190	10	100	30	1,000	2,200	7,600	150	12,000
	Estimate	140	28	140	4	83	30	770	1,100	4,400	140	6,800
Average Concentration (mg/L)		0.085	0.055	0.12	0.083	0.12	0.034	0.12	0.11	0.11	0.029	
Discharge Rate (m^3/yr)	Min	250,000	230,000	250,000	1,200	370,000	490,000	99,000	6,400,000	14,000,000	2,700,000	
	Max	2,800,000	990,000	1,600,000	120,000	860,000	860,000	8,800,000	9,700,000	66,000,000	4,800,000	
	Estimate	1,600,000	470,000	1,200,000	49,000	720,000	860,000	6,700,000	9,700,000	38,000,000	4,800,000	
% of Total Groundwater Total Dissolved Nitrogen Loading		0.30%	0.74%	1.56%	0.04%	0.90%	1.30%	8.40%	18.80%	56.00%	12.40%	
% of Total Groundwater Total Dissolved Phosphorus Loading		2.06%	0.41%	2.06%	0.06%	1.23%	0.44%	11.32%	16.18%	64.71%	2.06%	

4.1.4 Basin-wide Flow and Nutrient Loading from Groundwater

The USACE estimated total dissolved nitrogen and total dissolved phosphorus loading to Lake Tahoe from groundwater to be approximately 50,000 kg/yr and 6,800 kg/yr, respectively. These estimates were very similar to those of Thodal (1997) (Table 4-6). Estimated basin-wide groundwater volume discharge to Lake Tahoe ranged from 4.9×10^7 m^3/yr to 6.4×10^7 m^3/yr. Fogg (2002) estimated a similar value for basin-wide ground water flow into Lake Tahoe (3.7×10^7 m^3/yr).

Table 4-6. Basin-wide nutrient loading and groundwater discharge estimates (USACE 2003).

Constituent	USACE 2003	Thodal 1997
Total Dissolved Nitrogen (kg/yr)	50,000	60,000
Total Dissolved Phosphorus (kg/yr)	6,800	4,000
Discharge Rate (m^3/yr)	6.4×10^7	4.9×10^7

The methods used to develop the discharge rates and ultimately nutrient loading are inherently uncertain. This uncertainty is discussed in more detail in the Thodal (1997) and USACE (2003) reports. While there may be the potential for error using the methods presented, the similarity between independent analysis supports the discharge estimates. On the basis of these findings, the mean of the Thodal (1997) and USACE (2003) studies were used as inputs to the Lake Clarity Model as part of the TMDL Linkage Analysis.

Generally, the highest loading comes from the west shore aquifers. These loads are high primarily because the groundwater discharge rate is the highest of all subregions.

Ambient Nutrient Loading to Lake Tahoe from Groundwater

Natural groundwater nutrient loading estimates were provided in the USACE (2003) Groundwater Evaluation report. These estimates do not signify if a well in a relatively undisturbed location may be influenced by a possible upgradient source in an urbanized area. Annual ambient loads for total dissolved nitrogen and total dissolved phosphorus from the different regions are provided in Table 4-7. The estimated ambient groundwater nutrient loading to Lake Tahoe represents approximately 46 percent and 34 percent of the phosphorus and nitrogen loading, respectively. This suggests anthropogenic sources are more likely to influence subsurface nitrogen concentrations more than phosphorus levels.

Table 4-7. Ambient groundwater nutrient loading to Lake Tahoe by region (USACE 2003).

Constituent	Region										Total Groundwater Loading to Lake Tahoe
	South Lake Tahoe / Stateline						Incline Village	Tahoe Vista / Kings Beach	Tahoe City / West Shore	East Shore	
	Emerald Bay to Taylor Creek	Sub-region 1	Sub-region 2	Sub-region 3	Sub-region 4	State-line					
Average Ambient Total Dissolved Nitrogen (kg/yr)	150	127	330	13	190	230	1,800	2,600	10,390	1,300	17,000
Average Ambient Total Dissolved Phosphorus (kg/yr)	80	23	59	2	35	30	330	480	1,890	140	3,100

4.1.5 Groundwater Nutrient Sources

This section identifies the known and potential nitrogen and phosphorus sources to groundwater and is integral in determining ground water load reduction alternatives. The key sources evaluated include fertilized areas, sewage, infiltration basins, and urban infiltration. It is important to note there are insufficient data and scientific understanding at this time to directly link these sources to the estimated groundwater nutrient load values presented above. Rather than make a direct correlation between potential sources and groundwater quality, this section provides information on those sources that might be contributing to groundwater nutrient pollution. For example, while fertilizer application rates can be estimated, there is no information on the relative contribution of nitrogen fertilizer in the estimated 50 metric ton basin-wide groundwater nitrogen loading value. Nutrients are also present in the natural system and will contribute to the concentrations in groundwater. There are certain research techniques that could be promising in this regard (e.g., stable isotope tracing, chemical fingerprinting). However, there are currently no comprehensive, field-based measurements that quantify the amount of nutrients from trace fertilizer, sewer line exfiltration or urban infiltration that directly enter the lake by groundwater.

Fertilizer

Fertilizer use has received increasing attention as a potential source of nutrient loading to Lake Tahoe. Historical fertilizer use in the Lake Tahoe basin has not be comprehensively documented and, more importantly, not well understood in terms of nutrient flux to the lake. In 1972, Mitchell and Reisnauer conducted what is considered the first survey to assess fertilizer use in the Lake Tahoe area. He found the principal areas of fertilizer use in the Lake Tahoe basin were golf courses, school grounds, and landscaped areas around motels, condominiums and permanent resident homes. This report also estimated fertilizer use by homeowners from application instructions and land areas. Mitchell and Reisnauer (1972) reported that fertilizer use added approximately 48 metric tons of nitrogen and 7 metric tons of phosphorus to the basin annually. Approximately a decade later, Loeb (1986) estimated that topical application of fertilizer added 79.3 – 84.6 metric tons of nitrogen and 26.4 – 28.2 metric tons of phosphorus into the Tahoe basin. Other than providing a quantity range for fertilizer nutrient loading to the entire Lake Tahoe basin, Loeb (1986) supplied no other details concerning fertilizer application nor was a reference provided for the quantity information.

In the USACE (2003) Groundwater Evaluation, fertilized areas were broken down into residential neighborhoods, recreational facilities, institutional sources, commercial sources and livestock/agriculture. Residential and recreational sources were assumed to be the most significant in the basin as livestock/agriculture is very limited and commercial and institutional sources are typically small, improved areas covered largely by impervious surfaces. Residential neighborhoods consist of both single family and multi-family homes. The *Home Landscaping Guide for Lake Tahoe and Vicinity* (UNR 2001) was used to evaluate potential loading from residential neighborhoods. A scenario using “off the shelf” fertilizers was also considered as a “worst case” loading estimate. Recreational facilities were separated into golf courses and urban parks. The loading estimates from these two sources are based on fertilizer management plans developed for several golf courses and communication with local Public Utility Districts. Institutions consisted of schools, cemeteries and all other institutional establishments. Commercial and agricultural land-uses were not categorized into more specific regions.

To quantify the amount of fertilizer applied in the Lake Tahoe basin, several steps were taken. First, the USACE designated several area categories based on land-use (TRG 2002) and potential for fertilization. Since only a portion of each land-use area receives fertilizers, the area fertilized in each land-use category was determined or estimated. The method for determining the percent fertilized land area for each category was based on historical reports (Mitchell and Reisnauer 1972) and best professional judgment. Next, typical fertilizer application rates were applied according to land-use. From the loading rate and the land area of application values, the mass of fertilizer applied was then determined. Finally, the loading rates for single-family homes and golf greens were applied to a simplified phosphorus leaching model to determine the amount of phosphorus available for leaching into groundwater. Single-family home areas and golf greens were specifically modeled because of their potential to include both regular watering and fertilizer application. Refer to Chapter 10 in the USACE (2003) Groundwater Evaluation report for more details associated with these nutrient loading estimates and the phosphorus leaching model. Table 4-8 presents the resulting fertilized areas.

Table 4-8. Fertilized areas in the Lake Tahoe basin (USACE 2003).

Land-use Category	Specific Use	Land Area (km^2)	Percent of Area Estimated to be Fertilized (%)	Area Fertilized (km^2)
Residential	General	0.021	20	0.0045
	Single-family Residential	45	21	9.4
	Multi-family Residential	13	20	2.7
	Subtotal	59		12
Recreational	Golf Courses	4	95	3.8
	Urban Parks	0.29	50	0.14
	Subtotal	4.3		3.9
Institutions	General	2	20	0.41
	Schools	0.88	50	0.44
	Cemeteries	0.015	95	0.014
	Subtotal	2.9		0.86
Commercial	Commercial	18	10	1.8
Agriculture	Agriculture/ Livestock	0.54	100	0.54
Total		**84**		**19**

Current fertilizer application rates as calculated by the USACE (2003) are much higher than estimates determined in 1972 (Table 4-9). Based on the USACE estimates, the annual soil loading of nitrogen in the Lake Tahoe basin has potentially tripled from approximately 48 metric tons in 1972 to a range of 143-295 metric tons today. The potential annual soil loading of phosphorus has increased from approximately 7 metric tons in 1972 to at least 45 metric tons or even higher today. The range of phosphorus addition due to fertilizer application ranged from 45 to 429 metric tons per year. Even at the recommended application rates, the potential amount of fertilizer applied by individual property owners is large. While the USACE (2003) Groundwater Evaluation report liberally assigned fertilizer use to a portion of the land area of all single-family homeowners in the Lake Tahoe basin, the values from the remaining land-use areas were considered by the authors to be based on realistic rates. When considering only the application rates from recreational, institutional and commercial areas, nitrogen application may have increased roughly 230 percent while phosphorus use has increased over 400 percent. Note the highest degree of uncertainty associated with the USACE (2003) estimates is associated with fertilizer use in the residential land-use category.

Sewage Exfiltration and Abandoned Septic Tanks

Another potential source of groundwater nutrient pollution may be active sewage line exfiltration or residual contamination from abandoned septic tanks and treated sewage infiltration areas. Exfiltration is the incidental outflow, or leakage, from sewer collection/flow pipes due to joints, cracks, holes or breaks in the pipe. Collection systems are typically designed to account for a certain amount of leakage (e.g., average new construction allowable leakage rates range from 90 to 280 liters/day/cm-diameter/kilometer (100 to 300 gallons/day/inch-diameter/mile) of pipe).

A study conducted by Camp Dresser and McKee (CDM 2002) for the USACE (2003) concluded that exfiltration did not appear to be a major source of nutrients to Lake Tahoe when compared to all sources.

Table 4-9. Estimated annual nitrogen and phosphorus application rates in the Lake Tahoe basin in 1972 (Mitchell 1972) versus the application rate estimated for recent conditions by the USACE (2003). The load presented in the column labeled 2003 is best considered as an estimate over the period 2000-2003. (USACE 2003)

Land-use Category	Specific Use	Metric Tons of Nitrogen		Metric Tons of Phosphorus	
		1972	2003	1972	2003
Residential	General	-	0.027	-	0.009
	Single-family Residential	-	49.1-200.6	-	17.1-401
	Multi-familiy Residential	-	14.4	-	5.1
	Subtotal	13.6	64-215	1	22.2-406
Recreational	Golf Courses	26	51.8	4	16.7
	Urban Parks		2		0.27
	Subtotal	26	53.8	4	17
Institutions	General		5.8		0.8
	Schools	1.8	6.2	<0.36	0.9
	Cemeteries		0.18		0.027
	Subtotal	1.8	12.2	<0.36	1.7
Commercial	Commercial	2.3	8.9	<0.36	3.1
	Subtotal	2.3	8.9	<0.36	3.1
Agriculture	Agriculture/ Livestock	4.5	4.5	0.9	0.9
	Subtotal	4.5	4.5	0.9	0.9
Total		~48	143-294	~7	45-429

Infiltration Basins and Urban Infiltration

Infiltration basins and urban infiltration can also contribute nutrients to groundwater. Infiltration basins are constructed specifically to collect stormwater runoff and allow it to slowly percolate into the groundwater aquifer(s) below. These basins are intended to prevent untreated nutrient loads from directly entering the lake via sheet flow or storm drainage outfalls, and to prevent concentrated nutrient loads from entering streams that flow into the lake.

A 2006 study by 2NDNATURE provided a synthesis of existing research on performance of dry detention basins, constructed wetlands, and mechanical treatment structures in the Lake Tahoe basin. The study found that typical Tahoe urban stormwater poses little risk of migrating hydrophobic hydrocarbons into the underlying groundwater from the detention or infiltration facilities provided there is adequate separation between the underlying soils and the groundwater surface. From a limited nutrient sampling, analyses suggest that a nitrate plume may pulse into shallow groundwater from dry detention basins during spring snow melt conditions.

4.2 Shoreline Erosion

Lake Tahoe's shoreline is a dynamic environment where wave action and lake level fluctuation are dominant forces. Many shoreline sections can change shape on an annual basis as sediment is eroded, transported and deposited. Depending on location along the shoreline, these processes occur at different rates. Figure 4-6 shows fallen trees, which is evidence of relatively recent shoreline erosion. Waves in the nearshore area also help redistribute eroded sediment. Prior to 2000, the extent of shoreline erosion had been roughly estimated (Reuter and Miller 2000) but did not adequately quantify nutrient and sediment loading.

Figure 4-6. Photograph looking north at Sugar Pine Point State Park (Adams 2004).

This section of the report summarizes a detailed study performed by researchers with the Desert Research Institute that incorporated georectified historical air photos into a GIS database combined with field observations and nutrient sampling to determine the amount and processes affecting nitrogen, phosphorus and sediment inputs to Lake Tahoe from shoreline sources (Adams and Minor 2002). A supplementary analysis of particle size distributions of Lake Tahoe shorezone sediment included in *Shorezone Erosion at Lake Tahoe: Historical Aspects, Processes, and Stochastic* Modeling (Adams 2004) was also completed on this subject.

The research team acquired historic aerial photographs and digital orthophotographic quadrangles (DOQs) spanning a 60-year time frame (1938-1998) from the TRPA, the United States Forest Service Lake Tahoe Basin Management Unit (USFS LTBMU), and the USGS, respectively. This data was available for 1938, 1939, 1940, 1952, 1992, 1995 and 1998 with aerial photographs of the entire basin taken in 1992 and 1998. Almost all the shoreline was mapped from the 1938-1940 images. The images were scanned and rectified using ground control points common to both the aerial photographs and the USGS DOQs. By calculating the relative measure of accuracy between the predicted and observed control point locations, spatial error between photographic and map data was estimated to be with within two meters. These calculated accuracy values exceed National Mapping Accuracy Standards (USGS 1941).

After the maps and photographs were digitally scanned and rectified, the former shoreline position was delineated based on consistent observable shoreline features. During the 1990's, Lake Tahoe experienced the most dramatic lake-level changes in recorded history, fluctuating between its historic low of 6,220.26 feet in late 1992 to a high of approximately 3.5 inches above the legal limit (6,229.1 feet) in early January 1997 (Boughton et al. 1997). Since the result of lake level fluctuations is an apparent shoreline migration (Adams and Minor 2002), the research team made corrections so that their analysis reflected actual changes to the shoreline configuration with no interference resulting from lake level changes.

Since the aerial photographs literally only provide a 'snapshot in time', and based on the assumption that most shoreline change likely happens when the lake is at or near its legal limit, the research team devised a technique to estimate the position of the shore through time by correcting for different water levels based on the concept that on a stable, sloping shoreline the shore-water interface will migrate laterally in a predictable way depending on water level. Four different situations were noted in comparing the various historical shorelines to the present condition: (1) no change; (2) erosion; (3) accretion; and (4) oscillation. Oscillation is where both erosion and accretion have taken place along this shore over the last 60 years. In each situation (with the exception of an unchanged shoreline), simple trigonometry was used to estimate the amount of net shoreline change. A constant shoreline slope was assumed.

Sediment grab samples were collected from multiple shoreline locations to analyze the nutrient content of the lost shorezone material. Typically, samples were collected from the beach, wave-cut scarps (steep slopes that result from erosion) (Figure 4-7), and in the backshore area from depths ranging from ten centimeters on the beaches to three meters on exposed wave-cut exposures. Samples were analyzed for total phosphorus and total Kjeldahl nitrogen (TKN).

Figure 4-7. Photograph looking west along well-developed wave cut scarp at Lake Forest shoreline.

Study results indicate both shoreline erosion and accretion have occurred over the last 60 years. A total of 22 erosion areas were identified, the largest of which encompasses an area of 32,000 m^2. In calculating the load of sediment and associated nutrients, the research team estimated the thickness of each eroded area using large-scale Bureau of Reclamation topographic maps dating from 1918 and 1919 and assumed a sediment bulk density of 1.5 grams per cubic centimeter. Based on these calculations, the total mass of sediment eroded into Lake Tahoe from the shorezone since 1938 amounts to approximately 429,000 metric tons.

A follow-up study was conducted to assess the particle size distribution of collected shoreline sediment samples (Adams 2004). This work determined that of the 429,000 metric tons of material eroded into the lake, approximately 92 percent of that material is composed of sand-sized sediment (≥ 63 µm), roughly 6 percent was in the silt size fraction (3 – 62.5 µm), with the remaining 2 percent < 3 µm in size. When averaged over the 60 year erosion period, these values equate to about 6,600, 440, and 110 metric tons of sand, silt and clay per year, respectively.

Nutrient analysis of shoreline sediments indicates sediment from around the lakeshore is generally higher in phosphorus than nitrogen. Based on the nutrient sampling data, approximately 117 metric tons of phosphorus and 110 metric tons of nitrogen have been introduced into the lake because of shoreline erosion over the last 60 years. These volumes equate to roughly two metric tons per year of phosphorus and 1.8 metric tons per year of nitrogen. These loading values were used as inputs to the Lake Clarity Model.

4.3 Upland Sources

Upland sources are those that originate from the watershed and are delivered to the lake either by streamflow through one of the 63 major tributaries around the lake or by direct inflow from intervening zones. While the majority of the basin's individual watersheds contain a permanent channel that discharges into Lake Tahoe at a stream mouth, surface runoff in some of these watersheds flows directly to the lake without first entering a channel. These are referred to as intervening zones.

Upland sources include products of anthropogenic influence as well as products of natural surface erosion and groundwater processes. Upland sources include both urban and non-urban (vegetated) land-uses, and the full spectrum of variation within each of these two generalized categories. A watershed model is a tool designed to assist in capturing and assimilating multiple influences to provide spatial and temporal resolution to the science of source characterization. When adequately configured, a watershed model also provides a robust framework for disaggregating and quantifying the relative impact of individual influences or practices (and potential changes to those practices) relative to an established baseline condition. This section describes the development, application, and summary of results for the specific model that was used to characterize upland sources in the Lake Tahoe watershed. Sediment and nutrients that originate in stream channels are considered separately in Section 4.4 since that material is not directly reflective of land-use characteristics in the watershed.

4.3.1 Lake Tahoe Watershed Model Description

This section summarizes the upland source loadings and the watershed model used to determine those loadings. Results from the Lake Tahoe Watershed Model were used as input data (representing watershed inputs) for the Lake Clarity Model as developed by the University of California at Davis (UC Davis). For additional information regarding the watershed model please refer to the modeling report titled *Watershed Hydrologic Modeling and Sediment and Nutrient Loading Estimation for the Lake Tahoe Total Maximum Daily Load* (Tetra Tech 2007).

A watershed model is essentially a series of algorithms that integrate meteorological data and watershed characteristics to simulate upland and tributary routing processes, including hydrology and pollutant transport. Once a model has been adequately set up and calibrated, and the dominant unit processes are deemed representative of monitored conditions, it becomes a useful tool to predict flows and quantify loads from the upland tributaries. Additionally, it can be used to simulate changes in load expected from changes in land-use, and can serve as the platform for estimating basin-wide pollutant reduction resulting from BMP/restoration strategies.

Loading Simulation Program C++ (LSPC) (http://www.epa.gov/athens/wwqtsc/html/lspc.html) was selected to develop the Lake Tahoe Watershed Model. LSPC is a USEPA-approved modeling system that includes Hydrologic Simulation Program – FORTRAN (HSPF) algorithms for simulating watershed hydrology, erosion and water quality processes, as well as in-stream transport processes.

LSPC was developed to facilitate large scale, data intensive watershed modeling applications. A relational Microsoft Access database serves as the framework for watershed data management. A key advantage of the LSPC development framework is that it has no inherent limitations in terms of modeling size or upper limit of model operations imposed by the original FORTRAN architecture. LSPC is currently maintained by the USEPA Office of Research and Development in Athens, Georgia and is a component of USEPA's National TMDL Toolbox (http://www.epa.gov/athens/wwqtsc/index.html). A detailed discussion of HSPF-simulated processes and model parameters is available in the HSPF User's Manual (Bicknell et al. 1997).

4.3.2 Modeling Approach Overview

Usefulness of the Watershed Model

The advantages of choosing LSPC to develop the Lake Tahoe Watershed Model for the Lake Tahoe basin include:

- It simulates the necessary constituents and applies to non-urban and urban watersheds
- Its comprehensive modeling framework can facilitate development of TMDLs not only for this project but also for potential future projects to address other impairments throughout the Lake Tahoe basin
- It allows for customization of algorithms and subroutines to accommodate the particular needs of the Lake Tahoe basin
- The time-variable nature of the modeling will enable a straightforward evaluation of the relationship between source contributions and water body response, as well as direct comparison to relevant water quality criteria
- The proposed modeling tools are in the public domain and approved by USEPA for use in TMDLs
- The model includes both surface runoff and base flow (groundwater) conditions
- It provides storage of all physiographic, point source/withdrawal data and process-based modeling parameters in a Microsoft Access database and text file formats to provide for efficient manipulation of data
- It presents no inherent limitations regarding the size and number of watersheds and streams that can be modeled
- It provides flexible model output options for efficient post-processing and analysis designed specifically to support TMDL development and reporting requirements
- It can be linked to the Lake Tahoe receiving water model (Lake Clarity Model)

How the Tahoe-Specific Model Works

LSPC is a comprehensive watershed and receiving water quality modeling framework. The LSPC framework is developed in a modular fashion with many different components that can be assembled in different ways, depending on the objectives of the individual project. The relevant modules applied for the Lake Tahoe Watershed Model are presented in Table 4-10.

Table 4-10. Description of LSPC modules applied to the Lake Tahoe Watershed Model.

Module	Module Components
LAND – for simulating watershed processes on pervious and impervious land segments	ATEMP / SNOW / WATER – for simulating air temperature/elevation lapse rate, snowfall and snowmelt, and pervious/impervious hydrology
	SEDIMENT – for simulating erosion, production, and removal of sediment and particles from land surfaces
	QUAL – for simulating generalized pollutant generation from surface and subsurface land segments
RCHRES – for simulating processes in streams and vertically mixed lakes	SEDTRN – for simulating in-stream transport, deposition, and scour of sediment
	RQUAL – for simulating in-stream nutrient transformations and transport

The pollutants of concern for the Lake Tahoe TMDL are fine sediment and nutrients (specifically nitrogen and phosphorus.) Fine sediments (particles < 63 µm) are represented as a fraction of the total suspended sediment (TSS) observed in the tributaries. Different potential sources of pollutants are associated with each of the various land-uses in the Lake Tahoe basin and each land-use affects the hydrology of the basin in a different way. Some of these sources contribute relatively constant discharges of pollutants while others are heavily influenced by snowmelt and rain events.

In the Lake Tahoe Watershed Model, a watershed is spatially divided into a series of subwatershed and reach networks. Each subwatershed represents the immediate drainage area for a reach segment. Each subwatershed is further subdivided into land-use segments. For urban developed areas, the land-use segments are further divided into pervious and impervious segments. During a simulation run, the model links the surface runoff and groundwater flow contributions from each of the land segments and subwatersheds and routes them through the network of stream reaches as water moves toward Lake Tahoe. Each stream segment also considers precipitation and evaporation from water surfaces, as well as flow contributions from the watershed, tributaries and upstream stream reaches. The stream network is constructed to represent all of the major tributary streams, as well as different portions of stream reaches where significant changes in water quality occur. Figure 4-8 graphically shows the information/processes that the Lake Tahoe Watershed Model uses to simulate the upland sources to Lake Tahoe.

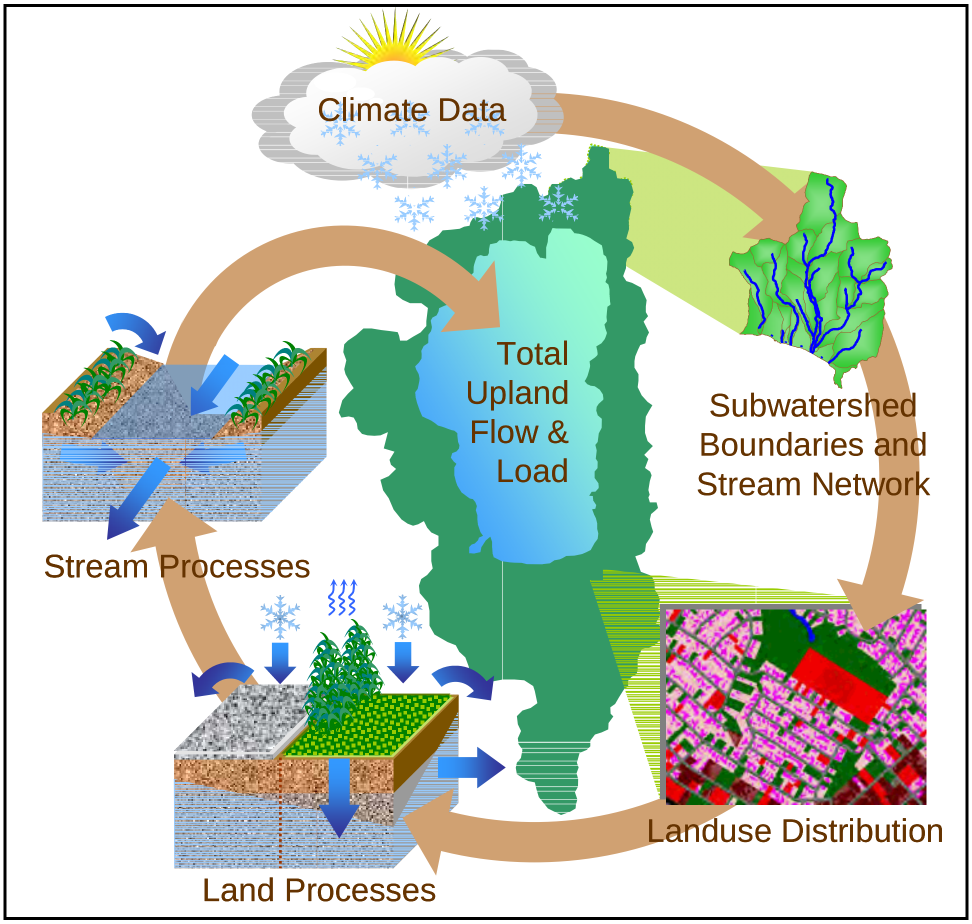

Figure 4-8. Processes simulated by the Lake Tahoe Watershed Model (Tetra Tech 2007).

The Lake Tahoe Watershed Model framework is flexible and allows different combinations of constituents to be modeled depending on data availability and the objectives of the study. Lake Tahoe tributaries are generally fast moving systems which remain well mixed. Therefore, nutrient transport tends to remain relatively conservative. For this approach, a hybrid approach employed to deliver the required nutrient speciation to the Lake Clarity Model. Sediment, total nitrogen and total phosphorus were simulated from land, while observed nutrient distributions were used to partition nutrients into orthophosphate (expressed as soluble reactive-P), organic phosphorus, ammonia, nitrate+nitrite, and organic-N for in-stream transport. No in-stream transformations or biological interactions were simulated given the short duration of transport in the stream channel and to the lake.

4.3.3 Model Set-Up

Developing and applying the Lake Tahoe Watershed Model to address the project objectives involved the following important steps:

1. Watershed segmentation
2. Water body representation
3. Configuration of key model components—meteorological data, land-use representation, and soils

4. Model calibration and validation (for hydrology, sediment, and nutrients)
5. Model simulation for existing conditions and scenarios

Watershed Delineation

The Lake Tahoe Watershed Model was configured to simulate the entire Lake Tahoe basin as a series of hydrologically connected subwatersheds. The delineation of subwatersheds was based primarily on topography, but it also considered spatial variation in sources, hydrology, jurisdictional boundaries, and the location of water quality monitoring and stream flow gauging stations. The spatial division of the watersheds allowed for a more refined resolution of pollutant sources and a more representative description of hydrologic variability.

Representing elevation change in gradual increments was an important consideration for subwatershed delineation since air temperature at a monitoring station is adjusted to mean watershed elevation during snow versus rain simulation. The great variation in topography and land-uses in the Lake Tahoe basin required that the subwatersheds be small enough to minimize these averaging effects and to capture the spatial variability. Lake Tahoe's drainage area was divided into 184 subwatersheds representing 63 direct tributary inputs to the lake. The average size of each subwatershed was 1,100 acres. Figure 4-9 shows the subwatershed delineation for the Lake Tahoe Watershed Model.

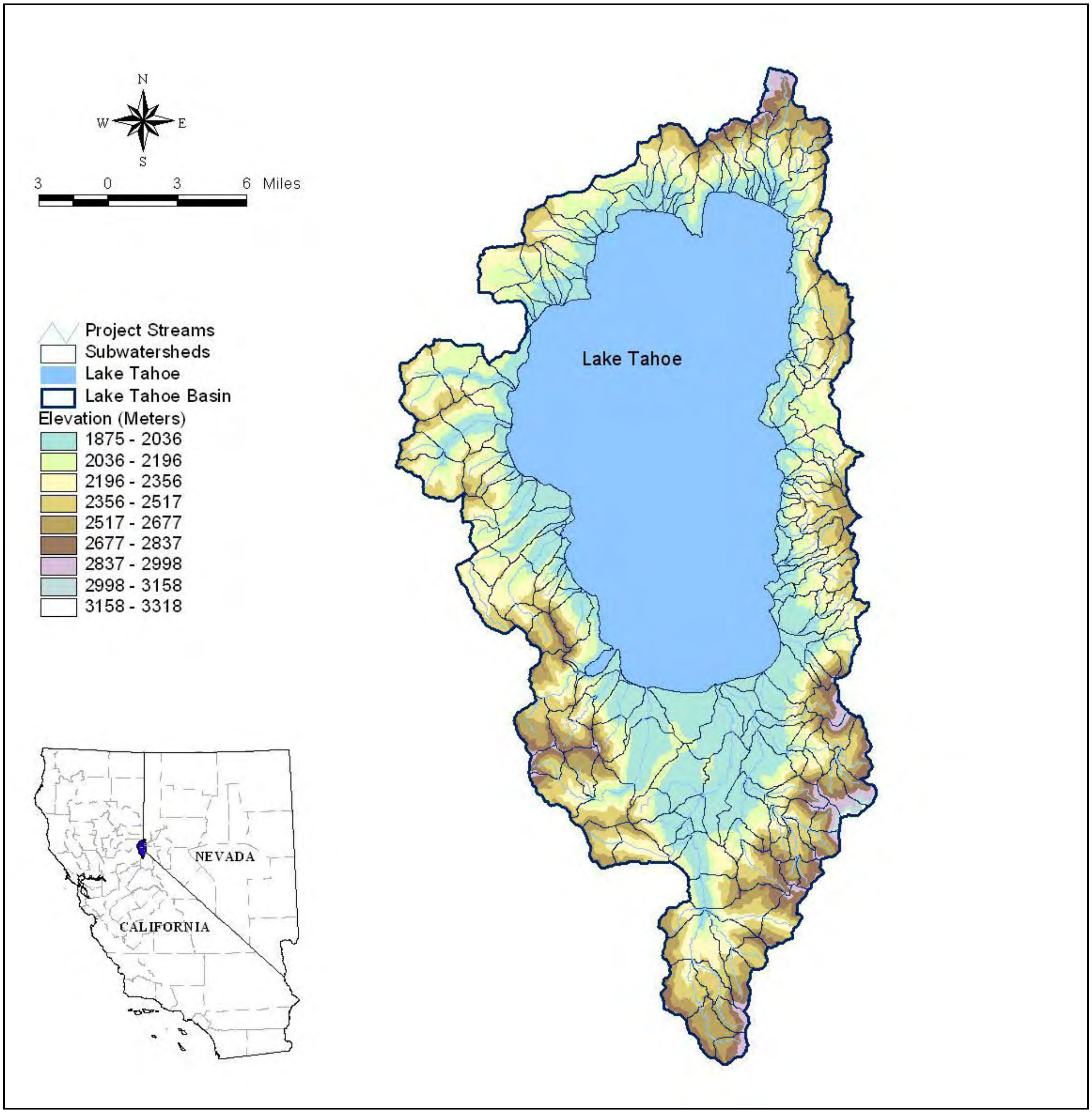

Figure 4-9. Subwatershed delineation and elevation (in meters) (Tetra Tech 2007).

Areas between stream mouths that directly drain into the lake (intervening zones) were modeled separately. The intervening zones represent both urban and forested land-uses. Nine groups of intervening zones were represented in the model as shown in Figure 4-10. The intervening zones were placed into a group corresponding to one of the monitored LTIMP streams based on proximity, similarity of land-use and other considerations, to see which LTIMP stream data was applied, see Table 5-4 (Tetra Tech 2007).

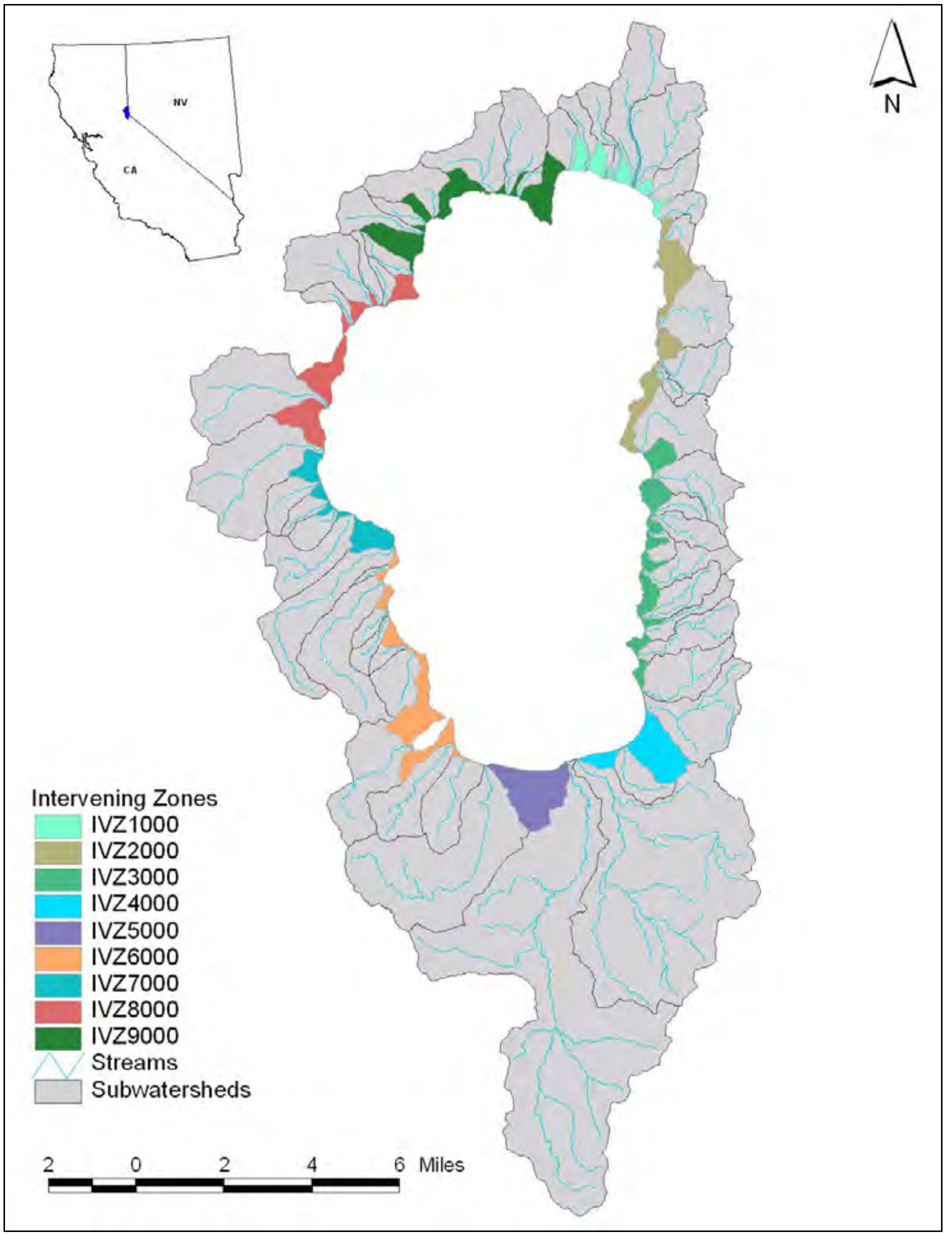

Figure 4-10. Map of intervening zones grouped as simulated in the Lake Tahoe Watershed Model (Tetra Tech unpublished).

Stream Reach Representation

Each delineated subwatershed in the Lake Tahoe Watershed Model is conceptually represented; a single stream is assumed to be a completely mixed, one-dimensional segment with a constant trapezoidal cross-section. The National Hydrography Dataset (NHD) stream reach network was used to determine the representative stream length for each subwatershed. Once the representative reach was identified, slopes were calculated based on Digital Elevation Model (DEM) data and stream lengths were measured from the original NHD stream coverage. Mean depths and channel widths for a number of segments were available from field surveys conducted by the United States Department of Agriculture (USDA)–Agricultural Research Service (Simon et al. 2003). Assuming representative trapezoidal geometry for all streams, mean stream depth and channel width were estimated, using regression curves that relate upstream drainage area to stream dimensions, and were compared with stream surveys at selected locations—General Creek (a wetter west shore of the basin) and Logan House Creek (a drier east shore of the basin). The rating curves consisted of a representative depth-outflow-volume-surface area relationship. An estimated Manning's roughness coefficient of 0.02 was applied to each representative stream reach based on typical literature values (Schwab et al. 1993).

Weather Stations and Data

Hydrologic processes are time-varying and depend on changes in environmental conditions including precipitation, temperature and wind speed. As a result, meteorological data are a critical component of watershed models.

Meteorological conditions are the driving force for nonpoint source transport processes in watershed modeling. Generally, the finer the spatial and temporal resolution available for meteorology, the more representative the modeled watershed hydrology will be. Precipitation and evapotranspiration are required as input for most watershed models. For the Lake Tahoe basin, where the snowfall/snowmelt process is the most significant factor in basin-wide hydrology, additional data (temperature, dew point temperature, wind speed and solar radiation) were required for snow simulation. This section discusses both local observed weather data used for model calibration and observed data customization to account for local influences.

Local Weather Data

An hourly time step for weather data was required to properly reflect diurnal temperature changes. For snow simulation, the model uses temperature to decide whether precipitation should be considered as rainfall or snowfall. Proper prediction of this trigger is required to ensure proper timing of water delivery to the rest of the hydrologic cycle. The timing of rainfall and snowmelt events directly relates to the timing of predicted sediment and nutrient loading. Likewise, the Lake Clarity Model requires proper timing of watershed boundary conditions for predictive accuracy.

There were two primary data sources for locally observed weather data. One source was a series of nine SNOwpack TELemetry (SNOTEL) gages in and around the Lake Tahoe basin maintained by USDA's Natural Resources Conservation Service (NRCS). The SNOTEL sites record air temperature, precipitation, and snow water equivalent data (used for snowfall/snowmelt calibration). The other data source was the National Climatic Data Center (NCDC), which maintains a network of long-term weather stations in the region. South Lake Tahoe Airport was the only hourly surface air gage inside the basin.

Table 4-11 lists the weather datasets used to generate the weather forcing files for watershed modeling and Figure 4-11 shows the location of the SNOTEL and NCDC weather stations in the watershed.

Table 4-11. Table of weather stations and associated data used to simulate weather conditions.

Station Name	Code	Agency[a]	Data Type[b]	Elevation (ft)	Available Data
Echo Peak	ECOC1	NRCS	SNOTEL	7800	Precipitation, Temperature
Fallen Leaf	FLFC1	NRCS	SNOTEL	6300	Precipitation, Temperature
Hagan's Meadow	HGNC1	NRCS	SNOTEL	8000	Precipitation, Temperature
Heavenly	HVNC1	NRCS	SNOTEL	8850	Precipitation, Temperature
Marlette	MRLN2	NRCS	SNOTEL	8000	Precipitation, Temperature
Mount Rose Ski[c]	MRSN2	NRCS	SNOTEL	8850	Precipitation, Temperature
Rubicon	RUBC1	NRCS	SNOTEL	7500	Precipitation, Temperature
Tahoe Crossing	THOC1	NRCS	SNOTEL	6750	Precipitation, Temperature
Ward Creek	WRDC1	NRCS	SNOTEL	6750	Precipitation, Temperature
South Lake Tahoe AP	93230	NCDC	Hourly	6314	Dew point, Wind, Solar Radiation
Reno AP[c]	23185	NCDC	Hourly	4410	Dew point, Wind, Solar Radiation
Emigrant Gap AP[c]	23225	NCDC	Hourly	5276	Dew point, Wind, Solar Radiation

[a]NRCS is the National Resource Conservation Service; NCDC is the National Climatic Data Center
[b]SNOTEL are SNOwpack TELemetry stations (available as daily and hourly)
[c]These weather stations are located outside the Lake Tahoe basin

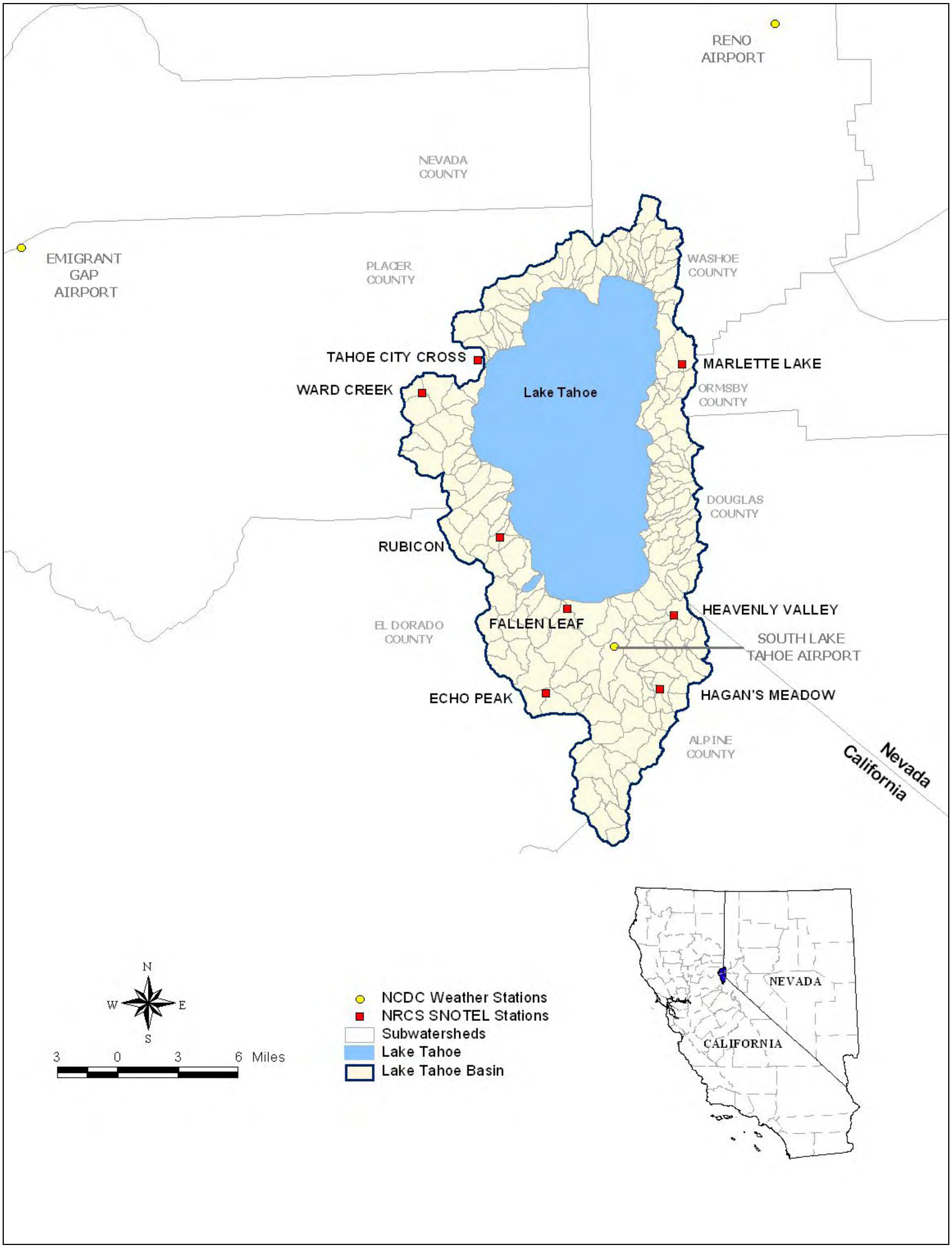

Figure 4-11. Location of SNOTEL and NCDC weather stations in the Lake Tahoe basin (Tetra Tech 2007).

Lapse Rate Calculations

A critical model parameter for snow simulation is the temperature correction for elevation changes (lapse rate). Temperature lapse rate–the rate at which temperature decreases with increasing elevation–significantly influences snowfall prediction, especially when extrapolating snow behavior to ungaged subwatersheds. This rate is particularly important in the Tahoe basin where elevation changes rapidly with distance from the lake. The Tahoe-specific lapse rate averages about 0.0022 degrees Fahrenheit (ºF) per foot difference in elevation, as observed from the weather data analysis (Riverson et al. 2005, Tetra Tech 2007). The Lake Tahoe Watershed Model estimates lapse rate as a function of the elevation difference between the mean subwatershed elevation and the elevation at the location where temperature is gaged.

Evapotranspiration Calculations

Following snowfall/snowmelt simulation, evapotranspiration is arguably the second most important factor influencing Lake Tahoe basin hydrology. Evapotranspiration in the model is used to represent the sum of the evaporation and transpiration that occurs due to plants in their natural environment. The Lake Tahoe Watershed Model requires, as a weather input, the potential evapotranspiration (PEVT), which is the maximum naturally achievable amount at any given moment.

Three widely used methods to estimate evapotranspiration (ET) are the Hamon method (1961), the Jensen-Haise method (1963) and the Penman Pan-Evaporation method (1948). The Penman method, which is the earliest of these three methods, computes evaporation as a function of temperature, solar radiation, dewpoint or relative humidity, and wind movement. The other two methods, Hamon and Jensen-Haise, are simplified empirical representations that require fewer observed datasets to compute. The Hamon method is only a function of temperature, while the Jensen-Haise method requires solar radiation and temperature. The Penman method (1948) was deemed most suitable for Lake Tahoe (Riverson et al. 2005). An average vegetation (crop) factor of 0.875 (based on calibration to observed Tahoe City reference ET) was used to translate Penman pan-evaporation to PEVT.

4.3.4 Land-use Representation

The Lake Tahoe Watershed Model requires a physical basis for representing the variability in hydrology and pollutant loading throughout the basin, which are both related to land-use. Land-use typically represents the primary unit for computing water quantity and quality. Non-urban and/or urban land-use areas in individual subwatersheds contribute runoff containing pollutant loads to a stream that flows to the lake. Lands adjacent to the lake route flow and pollutants directly to the lake.

Developing the Lake Tahoe land-use layer required a major effort relying on significant input from several local experts and agencies responsible for land management around the basin. A TMDL Development Team (D-Team) was formed and included key staff from the Water Board, NDEP, USFS, TRPA, California Tahoe Conservancy (CTC), the TMDL

Science Coordinator and Tetra Tech. The D-team located and compiled the most current and representative GIS land-use coverage layers available, identified advantages and limitations inherent with each data source, and produced a composite layer that maximized the overall accuracy for representing land-use throughout the Lake Tahoe basin.

The final land-use layer was based on three primary sources of spatial data: (1) an updated parcel boundaries layer from a number of agencies comprising the Tahoe basin GIS User's Group, (2) a detailed one-square-meter resolution Hard Impervious Cover (HIC) layer that was developed using remote sensing techniques from IKONOS^{TM} satellite imagery (Minor and Cablk 2004), and (3) a map of upland erosion potential developed by USDA National Sedimentation Lab (Simon et al. 2003). Tetra Tech (2007) provides greater detail on land-use layer development.

Land-use Categorization / Reclassification

The D-Team determined the land-use categories based on collective agreement from the various participating agencies. This involved areas with relatively similar response from a water quality modeling perspective and areas for which local or national pollutant runoff reference information could support model representation. The 140 original land-use types indicated by the parcel boundary codes were reclassified into the following six general land-use categories:

- Single-family residential (SFR)
- Multi-family residential (MFR)
- Commercial/Institutional/Communications/Utilities (CICU)
- Transportation
- Vegetated
- Waterbody

The general category of transportation includes separate subcategories for primary roads, secondary roads and unpaved roads. Primary roads were defined as the major highways that ring the lake shore with secondary roads as those city and county roads that feed into the highways. The D-Team further recognized that vegetated (non-urbanized) areas deserved special attention because they constitute over 80 percent of the basin area. Furthermore, the general vegetated lands category included a number of different land-uses (e.g., ski resorts and other recreational areas), management activities (e.g., harvesting to control overgrowth and fire hazard), and/or natural conditions (e.g., naturally burned forests) that have differing hydrologic and sediment and nutrient loading characteristics. As a result, six subcategories of vegetated land-use were defined:

1. *Unimpacted*: Forested areas that have been minimally affected in the recent past.
2. *Turf*: Land-use types with large turf areas and little impervious coverage, such as golf courses, large playing fields, and cemeteries, with potentially similar land management activities.
3. *Recreational*: Lands that are primarily vegetated and are characterized by relatively low-intensity uses and small amounts of impervious coverage. These include the unpaved portions of campgrounds, visitor centers, and day use areas.

4. *Ski Areas*: Lands within otherwise vegetated areas for which some trees have been cleared to create a run.
5. *Burned*: Areas that have been subject to controlled burns and/or wildfires in the recent past.
6. *Harvested*: Lands that management agencies have thinned in the recent past for the purpose of forest health and defensible space (areas cleared to reduce the spread of wildfire).

GIS Layering Process

To produce the land-use grid that forms the framework for the Lake Tahoe Watershed Model, a layering and intersecting process for the various land-use GIS data sources in the Tahoe basin was performed. The objective of this effort was to develop one composite grid layer that maximized the overall accuracy in representing land-use areas in the Lake Tahoe basin. Table 4-12 shows the modeling land-use categories derived from the composite land-use layer. Impervious, hard surfaces, significantly affects the capacity of surface runoff to be infiltrated, Figure 4-12 illustrates an example area with a large percentage of impervious area in the South Shore of Lake Tahoe. The impervious cover was developed by DRI using spectral mapping and transformation techniques on IKONOS™ satellite images from 2002 (Minor and Cablk 2004). The impervious cover is a one-meter resolution grid map of all anthropogenic impervious surfaces throughout the basin including rooftops and paved roads in both urbanized and rural or vegetated areas.

Table 4-12. Modeling land-use categories derived from the composite land-use layer.

Land-use Description	Pervious/Impervious	Subcategory Name
Waterbody	Impervious	Water_Body
Single Family Residential	Pervious	Residential_SFP
	Impervious	Residential_SFI
Multi Family Residential	Pervious	Residential_MFP
	Impervious	Residential_MFI
Commercial/Institutional/ Communications/Utilities	Pervious	CICU-Pervious
	Impervious	CICU-Impervious
Transportation	Impervious	Roads_Primary
	Impervious	Roads_Secondary
	Impervious	Roads_Unpaved
Vegetated	Pervious	Ski_Areas-Pervious
	Pervious	Veg_Unimpacted *
	Pervious	Veg_Recreational
	Pervious	Veg_Burned
	Pervious	Veg_Harvest
	Pervious	Veg_Turf

** This subcategory was further refined into five new subcategories based on erosion potential as defined by Simon et al. (2003).*

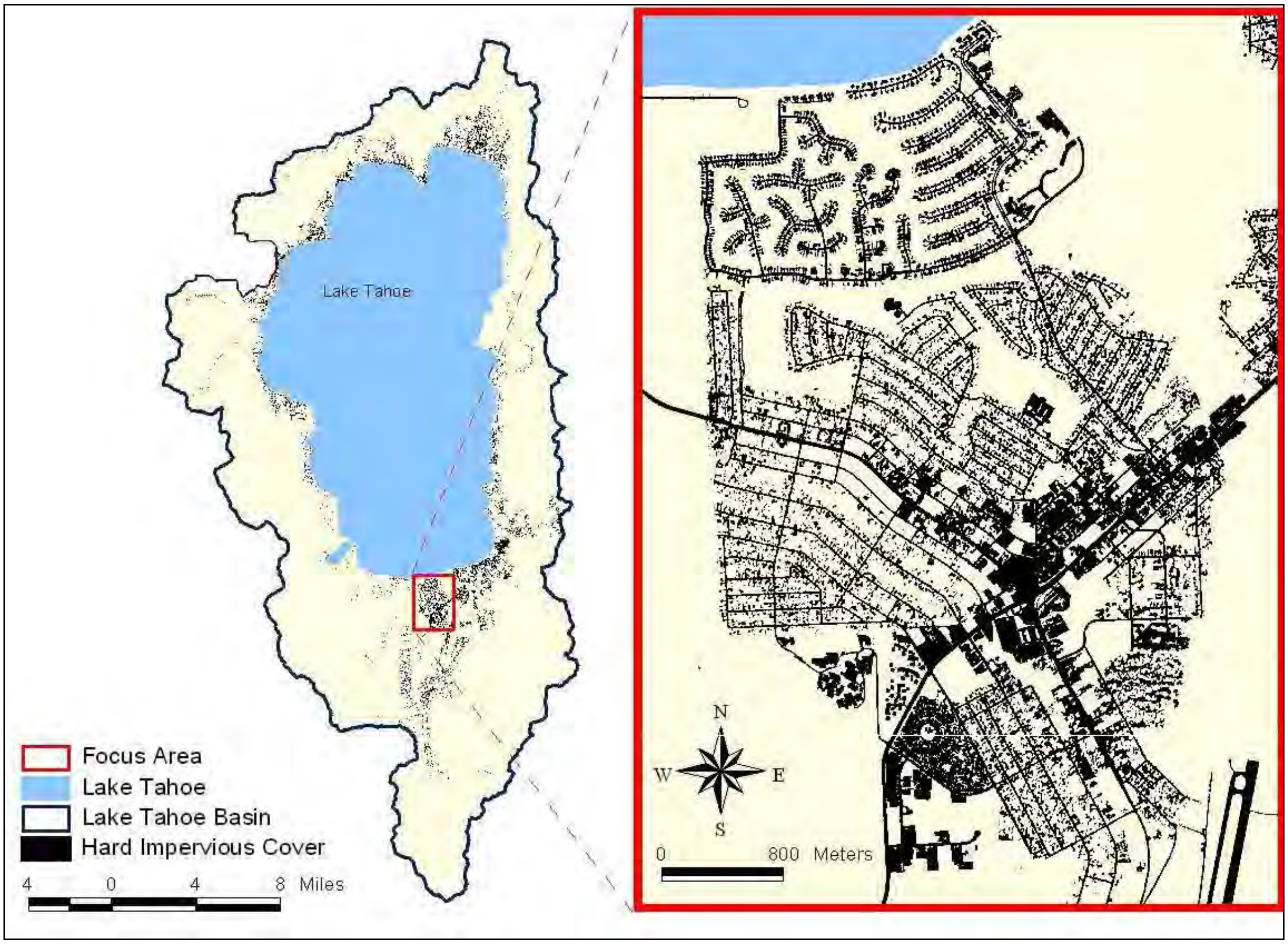

Figure 4-12. Hard impervious cover for the Lake Tahoe basin, an example focus area (Tetra Tech 2007).

Incorporating Erosion Potential for Vegetated Areas

During model development, it became evident that the land-use category classified as vegetated-unimpacted was too broad, and did not reflect significant differences in the erodibility of the soils. Further definition of this category became necessary for successful model calibration. Using the GIS coverage of upland-erosion potential for the Lake Tahoe basin developed by Simon et al. (2003), the land area initially categorized as the vegetated-unimpacted land-use was further subdivided into five erosion potential categories.

The map of upland-erosion potential for the Lake Tahoe basin (Figure 4-13) was developed independently of the TMDL land-use layer using an upland-erosion potential index based on the following parameters (Simon et al. 2003):

- Soil erodibility factor (k factor)
- Land-use
- Paved and unpaved roads, trails and streams
- Surficial geology
- Slope steepness

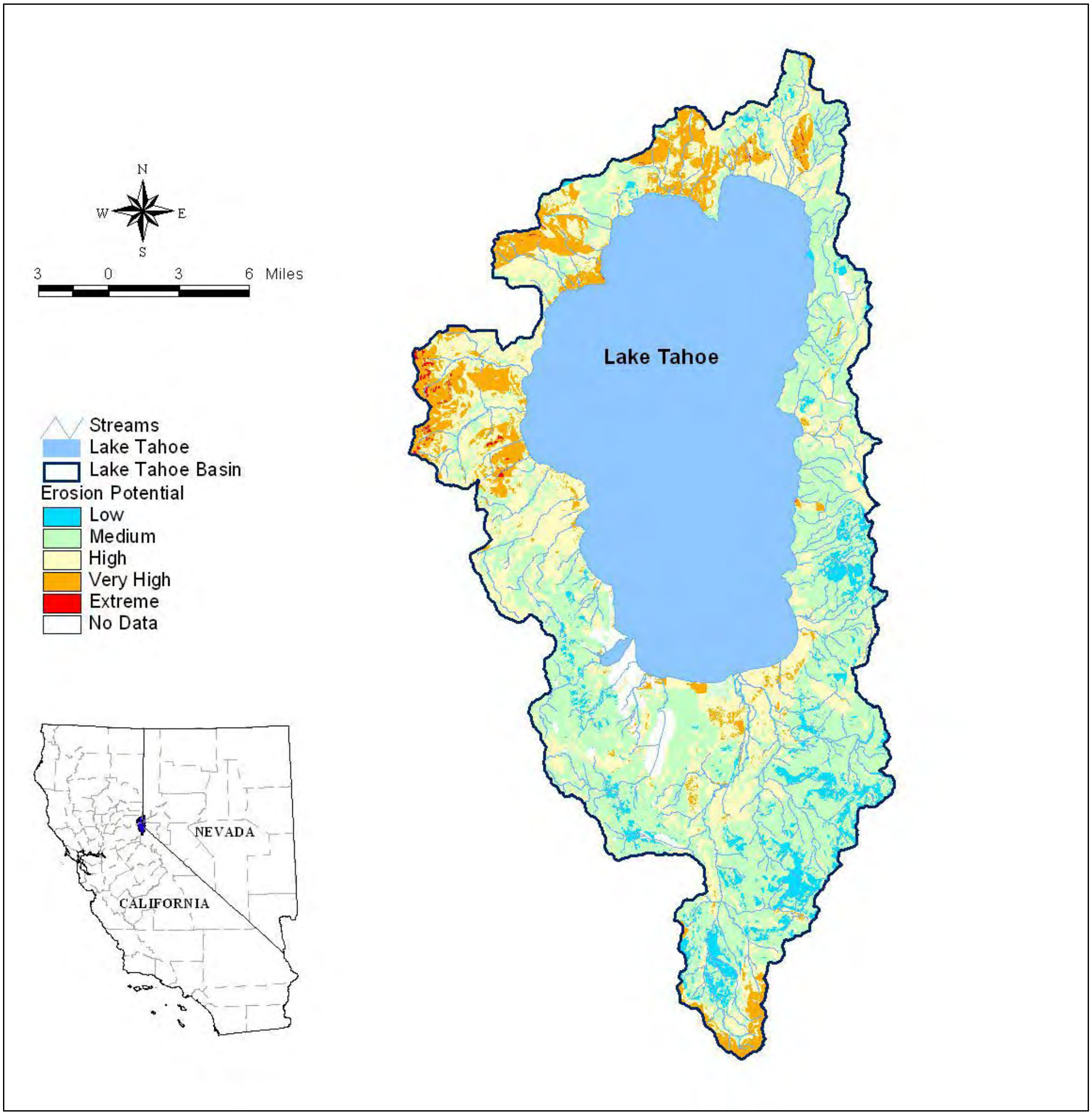

Figure 4-13. Map of upland erosion potential for the Lake Tahoe basin (Tetra Tech 2007).

The erosion potential ability of the soil was scaled numerically from 1 to 5, with the higher values indicating greater erosion potential of the soil. The map of upland erosion potential was used to subdivide the land within the broad vegetated-unimpacted category into 5 vegetated land-use categories. Table 4-13 shows the resulting breakdown of coverage in the Tahoe basin for the 5 categories. Figure 4-14 shows the land-use distribution map before the subdivision of the vegetated unimpacted areas into representative erosion potential categories, while Figure 4-15 shows the land-use distribution map after the sub-division.

Table 4-13. Percent cover of the five vegetation erosion categories (Tetra Tech 2007).

Vegetated Land-use	Percent Cover (%)
Veg_EP1	5.72
Veg_EP2	46.28
Veg_EP3	26.14
Veg_EP4	8.88
Veg_EP5	0.22
Total	**87.02**

Finally, Table 4-14 presents the final land-use distribution for the Lake Tahoe basin.

Table 4-14. Final land-use distribution for the Lake Tahoe basin (Tetra Tech 2007).

Land-use	Percent of Watershed Area (%)	Land-use	Percent of Watershed Area (%)
Veg_EP2	46.28%	Veg_Turf	0.55%
Veg_EP3	26.14%	Ski_Runs	0.54%
Veg_EP4	8.88%	CICU-Impervious	0.48%
Veg_EP1	5.72%	Residential_MFI	0.38%
Residential_SFP	4.00%	Roads_Primary	0.28%
Water_Body	1.70%	Veg_EP5	0.22%
Roads_Secondary	1.34%	Veg_Burned	0.20%
Residential_MFP	1.00%	Veg_Harvest	0.20%
Residential_SFI	0.89%	Veg_Recreational	0.17%
CICU-Pervious	0.86%	Roads_Unpaved	0.15%

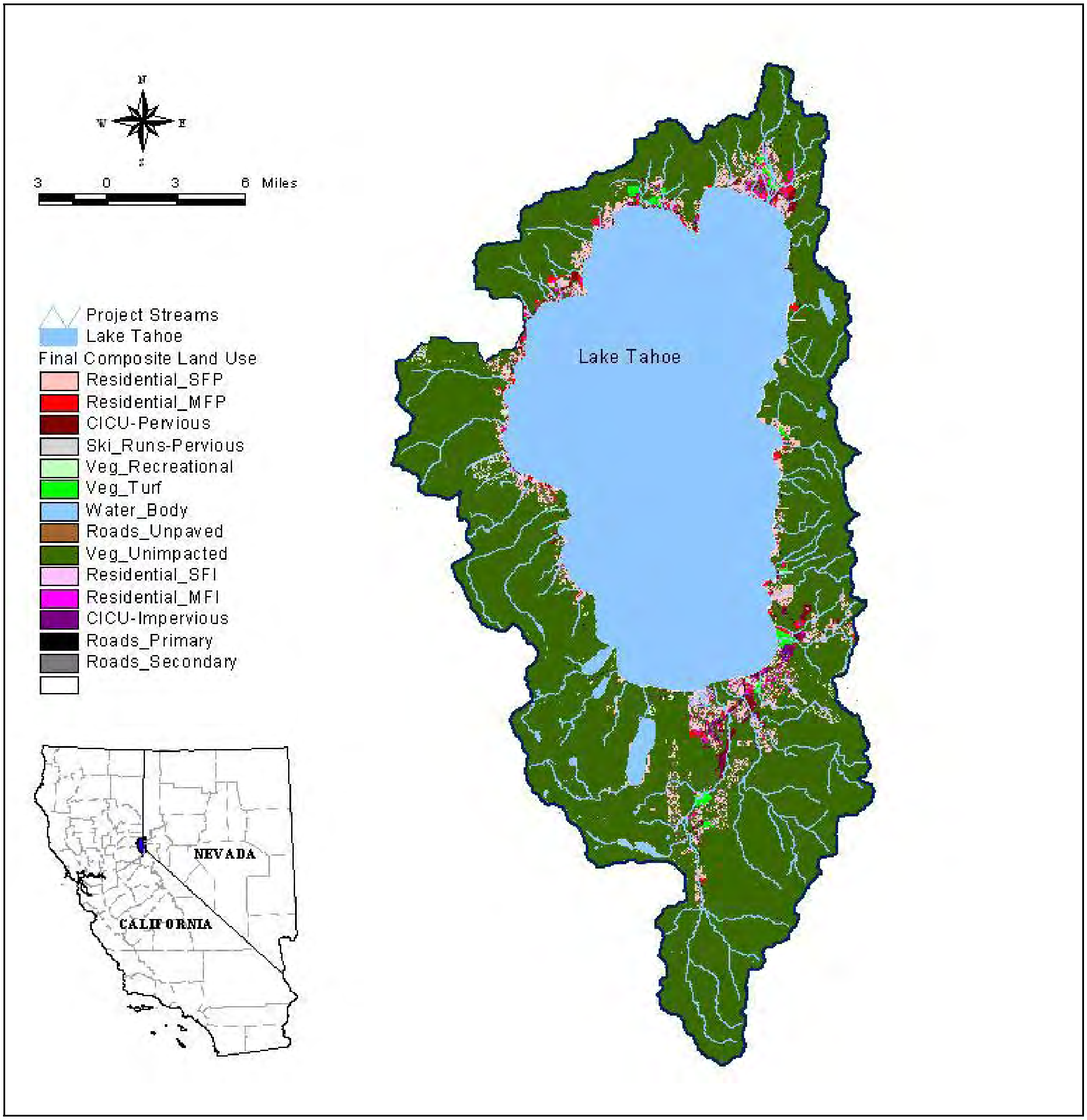

Figure 4-14. Map of land-use coverage with one classification for Vegetated Unimpacted (Tetra Tech unpublished).

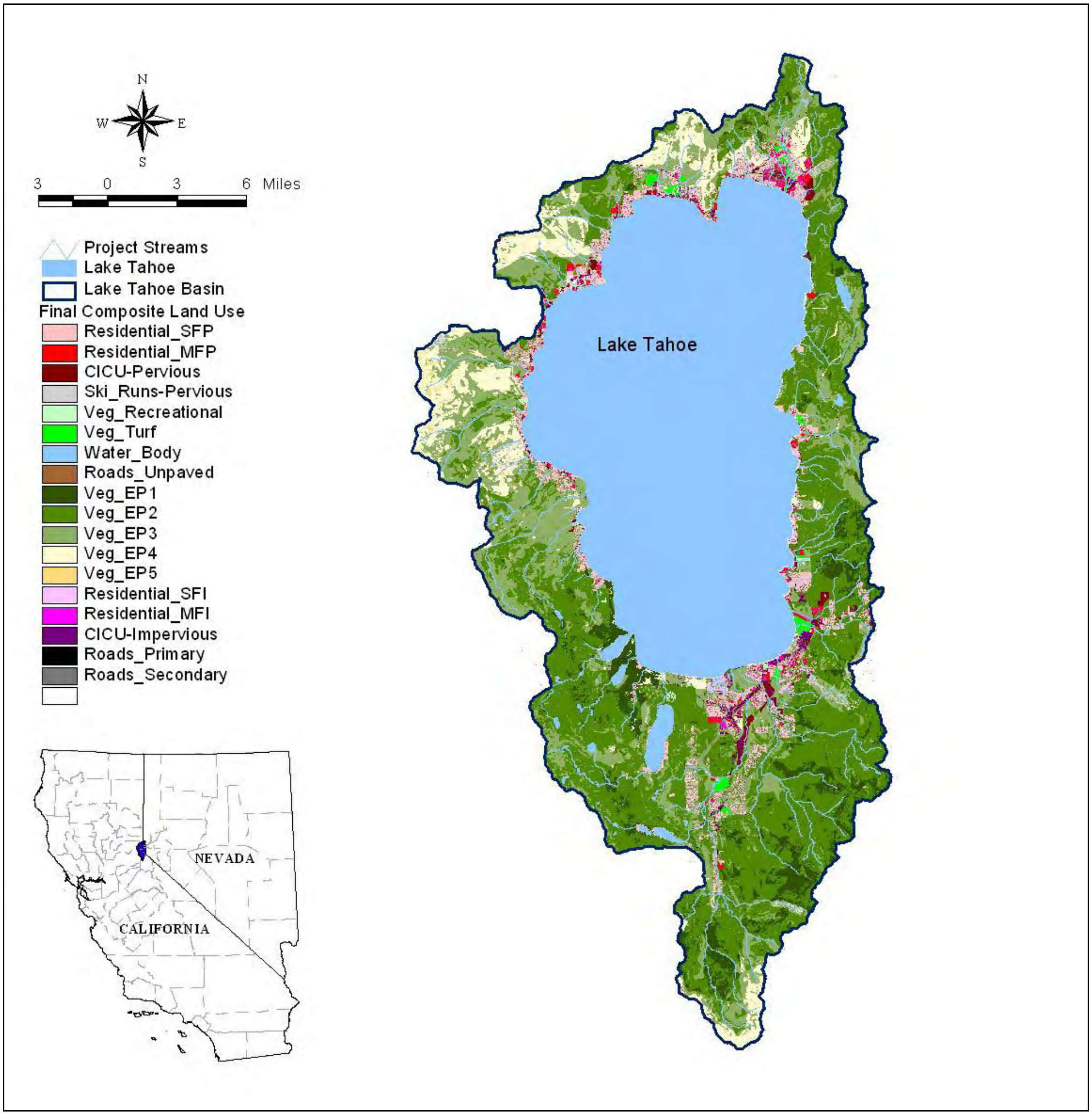

Figure 4-15. Map of land-use coverage after sub-dividing the Vegetated Unimpacted into 5 Erosion categories (Tetra Tech 2007).

4.3.5 Model Calibration

Calibration refers to the adjustment or fine-tuning of modeling parameters to reproduce observations based on field monitoring data. The goal of the calibration was to obtain physically realistic model prediction by selecting parameter values that reflect the unique characteristics of the watersheds around the lake. Spatial and temporal aspects were also evaluated through the calibration process.

Calibration was an iterative procedure that involved comparing simulated and observed values of interest. Calibration of the Lake Tahoe Watershed Model for the basin followed a sequential, hierarchical process that began with hydrology, followed by calibration of water quality.

Hydrology

Because inaccuracies in the hydrology simulation propagate forward into the water quality simulation, the accuracy of the hydrologic simulation has a significant effect on the accuracy of the water quality simulation. Hydrologic calibration was performed after configuring the Lake Tahoe Watershed Model and was based on several years of simulation to be able to capture a variety of climatic conditions. The calibration procedure resulted in parameter values that produce the best overall agreement between simulated and observed streamflow values throughout the calibration period. Calibration included a time series comparison of daily, monthly, seasonal and annual values, and individual storm events. Composite comparisons (e.g., average monthly streamflow values over the period of record) were also made. The Lake Tahoe Watershed Model was calibrated using both historical LTIMP stream-monitoring data and locally observed stormwater runoff monitoring data (Heyvaert et al. 2007).

The general Lake Tahoe Watershed Model hydrology algorithm follows a strict conservation of mass, with various compartments available to represent different aspects of the hydrologic cycle. Sources of water are direct rainfall or snowmelt. Potential sinks from a land segment are total evapotranspiration, flow to deep groundwater aquifers and outflow to a reach. Flow from land is routed through a network of reaches. From the individual-reach perspective, sources include land outflow (runoff and baseflow), direct precipitation and flow routed from upstream reaches. Sinks include surface evaporation, mechanical withdrawals, and reach outflow.

Ten United States Geological Survey (USGS) stream flow gages and 11 LTIMP water quality gages around the perimeter of Lake Tahoe were used for model calibration (Figure 4-16). Calibration graphs for Ward Creek are included as examples (Figure 4-18).

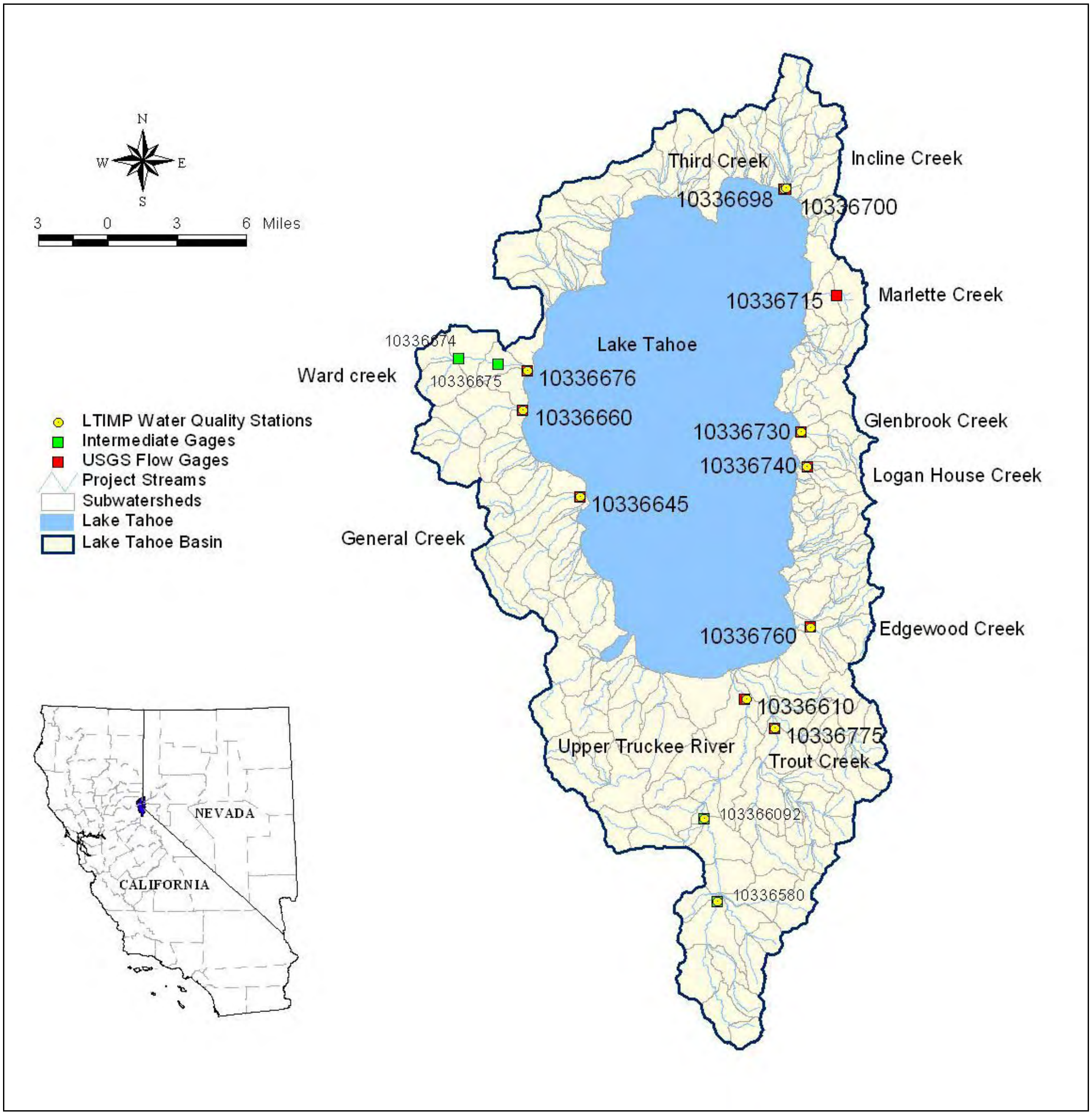

Figure 4-16. Hydrology and water quality calibration locations (Tetra Tech 2007).

Snow Processes

Snowfall and snowmelt have a dominant impact on hydrology, water quality, and management practice requirements in the Lake Tahoe basin. Therefore, calibrating snow hydrology was critical to the accuracy of the overall hydrology calibration for the basin.

An energy balance approach was used to simulate snow behavior. The Lake Tahoe Watershed Model SNOW module uses the meteorological information to determine whether precipitation falls as rain or snow, how long the snowpack remains, and when snowpack melting occurs. Heat is transferred into or out of the snowpack through net radiation heat, convection of sensible heat from the air, latent heat transfer by moist air condensation on the snowpack, from rain, and through conduction from the ground beneath the snowpack. Figure 4-17 provides the snow simulation schematic. The snowpack essentially acts like a reservoir that has specific thermodynamic rules for how water is released. Melting occurs when the liquid portion of the snowpack exceeds the snowpack's holding capacity; melted snow is added to the hydrologic cycle.

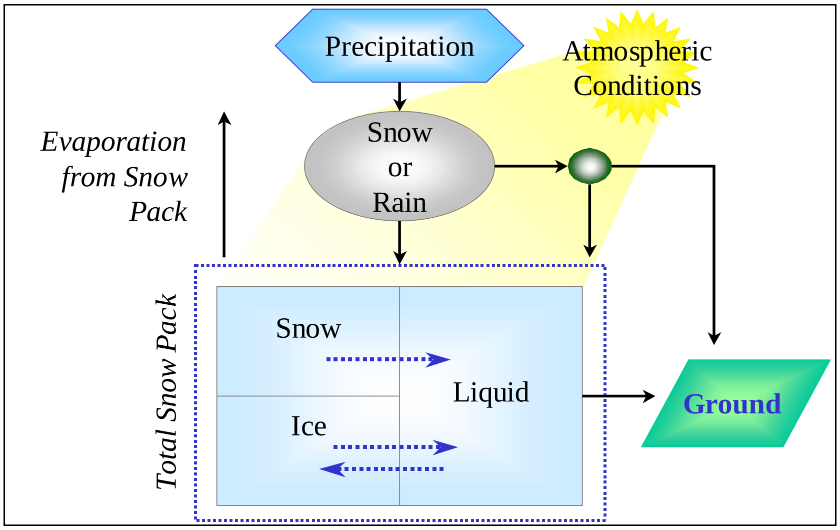

Figure 4-17. Snow simulation schematic used in the Lake Tahoe Watershed Model (Tetra Tech 2007).

Daily average snow water equivalent (SWE) data at the SNOTEL sites were directly compared with modeled SWE output. Emphasis was given to overall volumes and the shape of the SWE curve. Figure 4-18 shows an example of modeled versus observed daily average temperatures and SWE depths at Ward Creek**.** The upper graph shows temperature (right axis), volume (left axis), and precipitation type. When the temperature falls below the solid brown line, precipitation becomes snowfall; rainfall volumes are the dark blue bars, and snowfall volumes are the light blue bars. The lower graph, which shows modeled SWE in gray and observed SWE as blue dots, demonstrates consistently good agreement year after year through eight annual snowfall/snowmelt cycles.

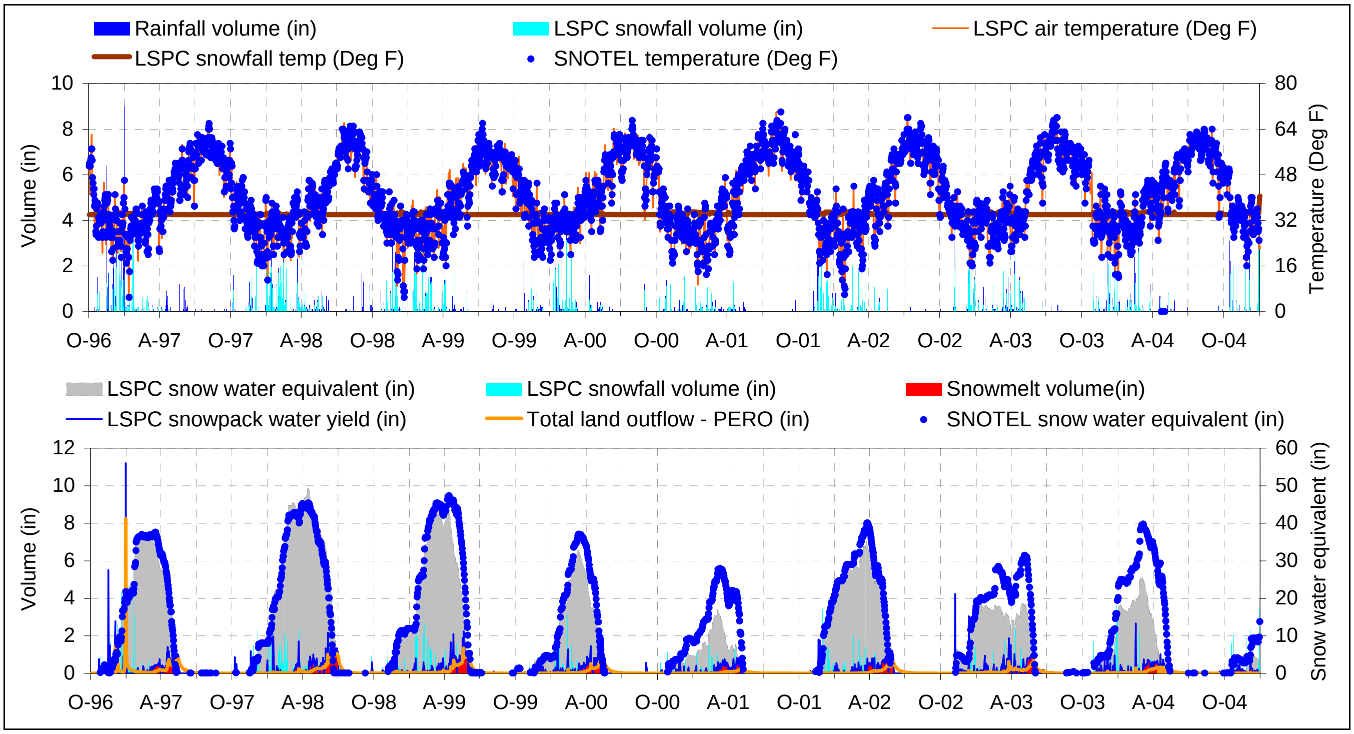

Figure 4-18. Modeled vs. observed daily average temperatures and snow water equivalent depths at Ward Creek SNOTEL site from October 1996 – December 2004, note LSPC is the Lake Tahoe Watershed Model output (Tetra Tech 2007).

During model testing and calibration, it became evident that the most important factor influencing the model snow predictions was not the calibration parameters, but the quality of the input temperature time series. The SNOTEL quality assurance process for temperature, together with the lapse rate correction, noticeably reduced overall model error. The calculation of the lapse rate (the rate at which temperature decreases with increasing elevation) in the Lake Tahoe basin was critical to the accuracy of the Lake Tahoe Watershed Model because it influences snowfall prediction, which significantly affects the hydrology of the basin.

Discharge

During calibration, agreement between observed and simulated stream flow data was evaluated on an annual, seasonal, and daily basis using quantitative and qualitative measures. Specifically, annual water balance, groundwater volumes and recession rates, and surface runoff and interflow volumes and timing were evaluated. The hydrologic model was calibrated by first adjusting model parameters until the simulated and observed annual and seasonal water budgets matched. Then the intensity and arrival time of individual events were calibrated. This iterative process was repeated until the simulated results closely represented the system and reproduced observed flow patterns and magnitudes. The model calibration was performed using the guidance of error statistics criteria specified in HSPEXP (Lumb et al. 1994). Output comparisons included mean runoff volume for simulation period, monthly runoff volumes, daily flow time series, and flow frequency curves.

Lake Tahoe Watershed Model hydrology algorithms follow a strict conservation of mass. The sources of water to the land surface are either direct precipitation or snowmelt. Some of this water is intercepted by vegetation, man-made structures, or by other means. The interception is represented in the model like a land-use-specific “reservoir” that must be filled before any excess water is allowed to overflow to the land surface. The water in the “reservoir “is also subject to evaporation. The size, in terms of inches per unit of area, of this reservoir can be varied monthly to represent the level of each compartment (both above and below the land surface).

Water that is not intercepted is placed in surface detention storage. If the land segment is impervious, no subsurface processes are modeled, and the only pathway to the stream reach is through direct surface runoff. If the land segment is pervious, the water in the surface detention storage can infiltrate, be categorized as potential direct runoff or be divided between runoff and infiltration. This decision is made during simulation as a function of soil moisture and infiltration rate. The water that is categorized as potential direct runoff is partitioned into surface storage/runoff, interflow, or kept in the upper zone storage. Surface runoff that flows out of the land segment depends on the land slope and roughness, and the distance it has to travel to a stream. Interflow outflow recedes based on a user-defined parameter.

Water that does not become runoff, interflow, or lost to evaporation from the upper zone storage will infiltrate. This water will become part of the lower zone storage, active groundwater storage or be lost to the deep/inactive groundwater. The lower zone storage acts like a reservoir of the subsurface. Within the Lake Tahoe Watershed Model, this reservoir needs to be full in order for water to reach the groundwater storage. Groundwater is stored and released based on the specified groundwater recession, which can be made to vary non-linearly.

The model attempts to meet the evapotranspiration demand by evaporation of water from baseflow (groundwater seepage into the stream channel), interception storage, upper zone storage, active groundwater, and lower zone storage. How much of the evapotranspiration demand is allowed to be met from the lower zone storage is determined by a monthly variable parameter. Finally, within the Lake Tahoe Watershed Model water can exit the system in three ways: evapotranspiration, deep/inactive groundwater, or entering the stream channel. The water that enters the stream channel can come from direct overland runoff, interflow outflow, and groundwater outflow.

Some of the hydrologic parameters can be estimated from measured properties of the watersheds while others must be estimated by calibration. Model parameters adjusted during calibration are associated with evapotranspiration, infiltration, upper and lower zone storages, recession rates of baseflow and interflow, and losses to the deep groundwater system.

During hydrology calibration, land segment hydrology parameters were adjusted to achieve agreement between daily average simulated and observed USGS stream flow at selected locations throughout the basin, as previously shown in Figure 4-16. The average of the 24 hourly model predictions per day was compared to daily mean flow values measured at USGS streamflow gauges throughout the basin. The four-year calibration period was from 10/01/1996 to 9/30/2000. Although the model was run from January 1996 through December 2004, the first 9 months are disregarded to allow for model predictions to stabilize from the effects of estimated initial conditions.

Insights gained from calibration are that about 70 percent of the total annual water budget arrives during spring snowmelt and that as a basin-wide average, baseflow (which includes water that infiltrates into the subsurface regime from the surface) accounts for more than 90 percent of the annual stream water budget. This distribution changes in the more urbanized intervening zones, where runoff percentage is proportional to the impervious area. Most of the groundwater is from snowmelt, which has the ability to infiltrate rather than immediately enter the stream channel as surface runoff because the snowmelt process occurs relatively slowly. The timing of the hydrograph was directly related to the modeling of the snow component. It became clear that the level of detail achieved in the snow calibration was necessary for a good calibration of stream flows.

Groundwater recession rates had spatial and seasonal variability. The rates were found to be nonlinear, with a steeper curve during the spring that tapered off during summer and fall. The use of a model parameter that allows for nonlinear recession rates was necessary to represent this variability in the recession rates.

Figure 4-19 shows example results over the model calibration period at Ward Creek, with emphasis on water year 1997. Figure 4-19 also shows that the model is robust enough to predict an extreme 100-year rain-on-snow event (January 1, 1997) while also capturing low-flow variability, as seen by exaggerating low flows using a log-scale. Validation was performed for a longer time period (10/1/1996 through 12/31/2004). Figure 4-20 shows model results for the full validation period at Ward Creek. Results are month-aggregated to evaluate the model's ability to reproduce consistent seasonal trends. Model performance statistics are shown in Table 4-15.

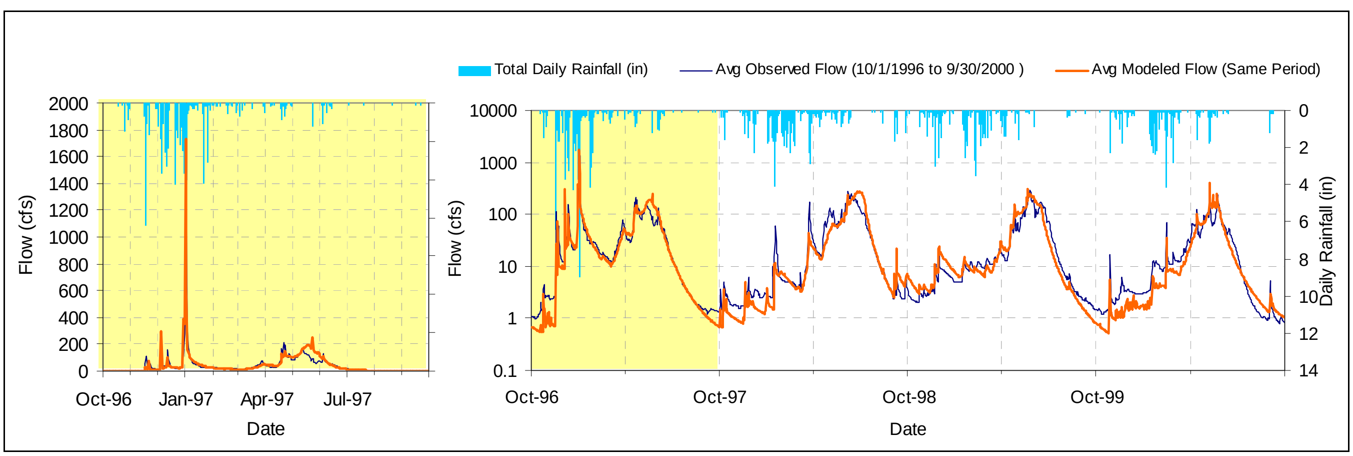

Figure 4-19. Hydrology calibration for Ward Creek with emphasis on water year 1997 (Tetra Tech 2007).

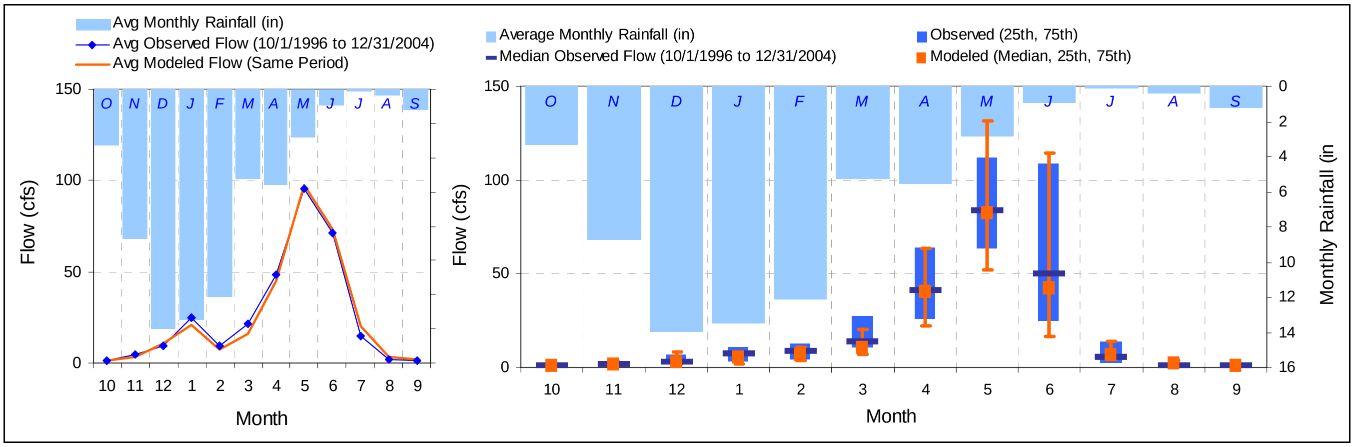

Figure 4-20. Hydrology validation for Ward Creek with seasonal mean, median and variation (Tetra Tech 2007).

Table 4-15. Hydrology validation summary statistics for Ward Creek (note: LSPC is the Lake Tahoe Watershed Model) (Tetra Tech 2007).

LSPC Simulated Flow		**Observed Flow Gage**	
REACH OUTFLOW FROM SUBBASIN 8060 8.25-Year Analysis Period: 10/1/1996 - 12/31/2004 Flow volumes are normalized, with total observed as 100		**USGS 10336676 WARD C AT HWY 89 NR TAHOE PINES CA** Placer County, California Hydrologic Unit Code 16050101 Latitude 39°07'56", Longitude 120°09'24" NAD27 Drainage area 9.70 square miles	
Total Simulated In-stream Flow:	**99.19**	Total Observed In-stream Flow:	**100.00**
Total of simulated highest 10% flows:	**58.50**	Total of Observed highest 10% flows:	**53.93**
Total of Simulated lowest 50% flows:	**4.54**	Total of Observed Lowest 50% flows:	**4.21**
Simulated Summer Flow Volume (months 7-9):	**8.49**	Observed Summer Flow Volume (7-9):	**6.02**
Simulated Fall Flow Volume (months 10-12):	**5.70**	Observed Fall Flow Volume (10-12):	**5.59**
Simulated Winter Flow Volume (months 1-3):	**14.46**	Observed Winter Flow Volume (1-3):	**18.24**
Simulated Spring Flow Volume (months 4-6):	**70.54**	Observed Spring Flow Volume (4-6):	**70.15**
Total Simulated Storm Volume:	**7.03**	Total Observed Storm Volume:	**8.29**
Simulated Summer Storm Volume (7-9):	**0.54**	Observed Summer Storm Volume (7-9):	**0.40**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-0.81	10		
Error in 50% lowest flows:	7.32	10		
Error in 10% highest flows:	7.80	15		
Seasonal volume error - Summer:	29.12	30		
Seasonal volume error - Fall:	2.01	30		
Seasonal volume error - Winter:	-26.12	30		
Seasonal volume error - Spring:	0.55	30		
Error in storm volumes:	-18.06	20		
Error in summer storm volumes:	26.03	50		

In general, the model produced excellent snow and hydrology results when model inputs were spatially derived from site-specific data and when weather data quality were validated. Performance statistics show that the model reproduced observed trends very well. Table 4-16 shows the validation summary statistics for the other flow gages in the Lake Tahoe basin.

Table 4-16. Hydrology validation summary statistics for USGS flow gages in the Lake Tahoe basin (Tetra Tech 2007).

Watershed	USGS Station ID	Location	Drainage Area (sq-mi)	% Error in Total Volume	% Error in 50% Lowest Flows	% Error in 10% Highest Flows
Upper Truckee	10336610	Upper Truckee River at South Lake Tahoe, CA	54.9	4.1	-14.6	5.0
Upper Truckee	103366092	Upper Truckee River at Hwy 50 above Meyers, CA	34.3	9.1	-26.0	9.7
Upper Truckee	10336580	Upper Truckee River at South Upper Truckee Rd nr Meyers, CA	14.1	0.8	2.6	-13.0
Blackwood	10336660	Blackwood Creek near Tahoe City, CA	11.2	-6.2	-8.7	7.4
Ward	10336676	Ward Creek at Hwy 89 near Tahoe Pines, CA	9.7	-0.8	7.4	7.8
General	10336645	General Creek near Meeks Bay, CA	7.4	-4.3	-7.3	1.0
Incline	10336700	Incline Creek near Crystal Bay, NV	6.7	1.7	-2.6	8.8
Edgewood	10336760	Edgewood Creek at Stateline, NV	5.6	2.1	0.7	21.8
Glenbrook	10336730	Glenbrook Creek at Glenbrook, NV	4.1	7.8	-0.6	3.4
Logan House	10336740	Logan House Creek near Glenbrook, NV	2.1	10.7	30.1	6.1

As a final validation, the annual hydrologic budget estimates from streamflow into Lake Tahoe were compared to previously published estimates. Table 4-17 shows the results of this comparison. The Lake Tahoe Watershed Modeled stream flows fall right in between the other estimates.

Table 4-17. Hydrologic Budget Estimates for Lake Tahoe (Stream-flow Component) (Tetra Tech 2007).

Reference	Period Considered	Estimate Annual Streamflow into Lake Tahoe (acre-ft)
McGauhey and others, 1963	1901-62	308,000
Crippen and Pavelka, 1970	1901-66	312,000
Dugan and McGauhey, 1974	1960-69	372,000
Myrup et al. 1979	1967-70	413,000
Marjanovic, 1987		379,562
Lake Tahoe Watershed Model (LSPC) Tetra Tech 2007	**1990-2002**	**376,211**

Water Quality

The water quality component of the Lake Tahoe Watershed Model is dependent on the modeled hydrology. Sediment production is directly related to the intensity of surface runoff and its yield varies by spatially land-use throughout the basin. Besides meteorology and the resulting hydrology, sediment yield is also influenced by factors including, but not limited to, soil type, surface cover and soil erodibility. Sediment is delivered to the tributaries and to Lake Tahoe through surface runoff erosion and in-stream bank erosion.

Nutrients are delivered to the tributaries with surface runoff and subsurface flow. They may be observed in both organic and inorganic forms, and may exist in both dissolved and particulate forms. Some nutrient forms, such as phosphorus are also associated with sediment. The Lake Tahoe Watershed Model provides mechanisms for representing these various pathways of pollutant delivery.

A detailed water quality analysis was performed using statistically-based load estimates with observed flow and in-stream monitoring data. The confidence in the calibration process increases with the quantity and quality of the monitoring data. The LTIMP stream database provides very good spatial and temporal coverage that focuses primarily on nutrients and sediment. This analysis provides the necessary information to inform the model parameterization and calibration.

This section describes the statistical analysis, model parameterization and model calibration process for water quality.

Estimating Sediment Loads through Log-Transform Regression

Since a primary objective of the Lake Tahoe Watershed Model is to estimate pollutant loads for use in the lake clarity model, accurate estimates of loads based on the LTIMP monitoring data had to be developed to aid in the water quality calibration process.

Suspended sediment loads are typically estimated using linear regression of observed sediment load versus stream flow datasets. Since sediment load and stream flow are storm driven, observed values for both often span several orders of magnitude. For this reason, the in-stream sediment load versus flow relationship tends to be linear when plotted on logarithmic scales. For practical application of the regression model, estimated loads must be re-transformed from the log transformations back to the original units. Since this retransformation process may be statistically biased, one of the methods that the USGS recommended for bias correction is the Minimum Variance Unbiased Estimator (MVUE) (Cohn and Gilroy 1991). The objective of this method is to yield an unbiased estimate with the smallest possible variance.

Many years of research have refined this statistical retransformation method and made it practical for estimating loads for environmental engineering applications (Finney 1941, Bradu and Mundlak 1970, and Cohn et al. 1989). In addition to sediment, the MVUE re-transformation has also been applied in numerous studies to other pollutants that exhibit log-normal relationship including total and dissolved nitrogen and phosphorus species (e.g. MDNR and USGS 2001, Green and Haggard 2001). It is important to note that this method is only unbiased if the regression errors are normally distributed when presented as logs.

An estimate of in-stream sediment loads from upland and channel or stream sources was developed for each of the 10 calibration watersheds using this method. Table 4-18 shows the annual estimates of TSS loads for calibration streams (NOTE: values given the tables associated with this section are for the 10 LTIMP streams only and do not represent basin-wide loading estimates. The basin-wide loading estimates from the Lake Tahoe Watershed Model are given in Section 4.3.6).

Table 4-18. Annual estimates of TSS loads for calibration streams developed using the MVUE.

Watershed	TSS (metric tons)	TSS Contribution by Modeled Watershed (%)
Third Creek	819	5.3%
Incline Creek	419	2.7%
Glenbrook Creek	40	0.3%
Logan House Creek	10	0.1%
Edgewood Creek	49	0.3%
General Creek	388	2.5%
Blackwood Creek	5,127	33.0%
Ward Creek	3,166	20.4%
Trout Creek	422	2.7%
Upper Truckee River	5,091	32.8%
TOTAL	**15,531**	**100%**

Once the annual average TSS loads were determined using the MVUE, the next step was to quantify the portion of the load composed of particles finer than 63 µm in diameter. Percent of total load contributed by fines for each of the 10 calibration watersheds was obtained from *Estimates of Fine-Sediment Loadings to Lake Tahoe from Channel and Watershed Sources* (Simon 2006). The fine sediment percentage, together with the previous total load estimates, was multiplied to estimate total fine sediment by watershed (Table 4-19). As a result, the final estimate is consistent with the MVUE total load estimate while maintaining the relative distribution (in terms of percentage) as published by Simon (2006).

Table 4-19. Annual average total fine sediment outlet loads (upland and stream channel loads) estimate by calibration watershed.

Watershed	Annual Average TSS Load (metric tons/year)	Fines < 63µm[a] (%)	Annual Average Total Fines Load (metric tons/year)	Fine Sediment by Modeled Watershed (%)
Third	819	31%	254	3.7%
Incline	419	67%	281	4.1%
Glenbrook	40	80%	32	0.5%
Logan House	10	75%	7	0.1%
Edgewood	49	59%	29	0.4%
General	388	29%	113	1.6%
Blackwood	5,127	45%	2,307	33.4%
Ward	3,166	47%	1,488	21.5%
Trout	422	38%	160	2.3%
Upper Truckee	5,091	44%	2,240	32.4%
TOTAL	**15,531**	**44%**	**6,911**	**100.0%**

[a]From Simon (2006)

Because stream channel erosion is being considered discretely from the upland source category, the third step involved estimating the annual average channel fines load. Simon (2006) presents fine sediment from channel stream banks relative to total fines load at the stream outlet. This percentage was applied to the total outlet fines estimate from the previous step to estimate the channel fines contribution (Table 4-20).

Table 4-20. Annual average channel fine sediment outlet load estimate by calibration watershed.

Watershed	Annual Average Total Fines Load (metric tons/yr)	Fine Grained Contribution from Stream banks (%)	Channel Fines Load (metric tons/yr)	Percent TSS Contribution (%)
Third	253.9	10%	24.6	0.8%
Incline	280.9	4%	10.3	0.3%
Glenbrook	32.1	46%	14.8	0.5%
Logan House	7.2	1%	0.04	0.0%
Edgewood	28.9	19%	5.4	0.2%
General	112.6	45%	50.5	1.6%
Blackwood	2,307.0	51%	1,176.1	38.2%
Ward	1,487.9	25%	375.1	12.2%
Trout	160.4	2%	2.4	0.1%
Upper Truckee	2,240.1	63%	1,418.2	46.1%
TOTAL	**6,911.0**	**45%**	**3,077.4**	**100.0%**

The upland fine sediment load entering tributaries that reaches the outlet of the watershed, consequently, becomes the difference between the total fines load and the channel fines load (Table 4-21). A target value for upland fine sediment load was derived using the model's estimate of the percent of the upland fine sediment load that reaches the lake for each tributary.

Table 4-21. Annual average upland fine sediment outlet load estimate by calibration watershed.

Watershed	Annual Average Total Fines Load (metric tons/year)	Channel Fines Load (metric tons/year)	Upland Fines Loads Reaching the Lake (metric tons/year)	Percent TSS Contribution (%)
Third	253.9	24.61	229.3	6.0%
Incline	280.9	10.29	270.6	7.1%
Glenbrook	32.1	14.82	17.3	0.5%
Logan House	7.2	0.04	7.2	0.2%
Edgewood	28.9	5.42	23.5	0.6%
General	112.6	50.45	62.1	1.6%
Blackwood	2,307.0	1,176.10	1,131.0	29.5%
Ward	1,487.9	375.06	1,112.8	29.0%
Trout	160.4	2.43	158.0	4.1%
Upper Truckee	2,240.1	1,418.22	821.9	21.4%
TOTAL	**6,911.0**	**3,077.4**	**3,833.7**	**100.0%**

As shown in the tables above, a majority of the TSS loading from upland sources is from Blackwood Creek, Ward Creek and the Upper Truckee River watersheds.

Pollutant Export Analysis Using Regression and Hydrograph Separation

Hydrology is the driving force for the Lake Tahoe Watershed Model general water quality module (GQUAL). Since wastewater is exported out of the Tahoe basin, nonpoint sources represent the major source of pollutant loading to Lake Tahoe streams. Stream bank erosion has also been shown to represent another source of sediment loading (and associated nutrients) to Lake Tahoe. There are no known point source pollutant dischargers in the basin. The GQUAL module requires that loading rates or concentrations are specified for groundwater, interflow, and surface runoff for each land-use in each subwatershed. A statistical data 'mining' exercise was performed to 1) understand the seasonality and trends observed in both in-stream and stormwater monitoring data, 2) represent nutrient species distribution and loading patterns in baseflow versus stormflow samples, 3) estimate organic and inorganic nutrient quantities, 4) characterize particulate and sediment associated nutrient mass and 5) derive land-use specific loading rates to apply in the Lake Tahoe Watershed Model.

The primary source of in-stream monitoring is a high-resolution historical water quality dataset collected at numerous sites by the LTIMP. The constituents that have been monitored include ammonia (NH_4), total Kejdahl nitrogen (TKN), nitrate (NO_3), soluble reactive phosphorus (SRP), total phosphorus (TP), and total suspended sediment (TSS). For the purpose of this investigation, the data have been aggregated into five categories: TSS, TN, TP, dissolved inorganic-N (NO_3 + NH_4) and soluble-P. Nitrite levels, while measured, are so low that they are of no consequence to inorganic nitrogen loading in the Tahoe basin.

Hydrograph separation used in conjunction with log-transform regression allows the assessment of baseflow and surface runoff volumes and associated nutrient yield. Again, baseflow is defined as flow that enters a tributary through its bottom or channel walls. Baseflow can occur at any time. During the summer when precipitation is negligible, most all of the flow in the stream channels comes from baseflow; but as shown in Figure 4-21, baseflow occurs throughout the year. The USGS hydrograph separation algorithms (HYSEP) were used to perform hydrograph separation on the observed flow time series (Sloto and Crouse 1996). Figure 4-21 presents the results of the hydrograph separation and shows that streamflow in the Lake Tahoe basin tends to be groundwater-dominant.

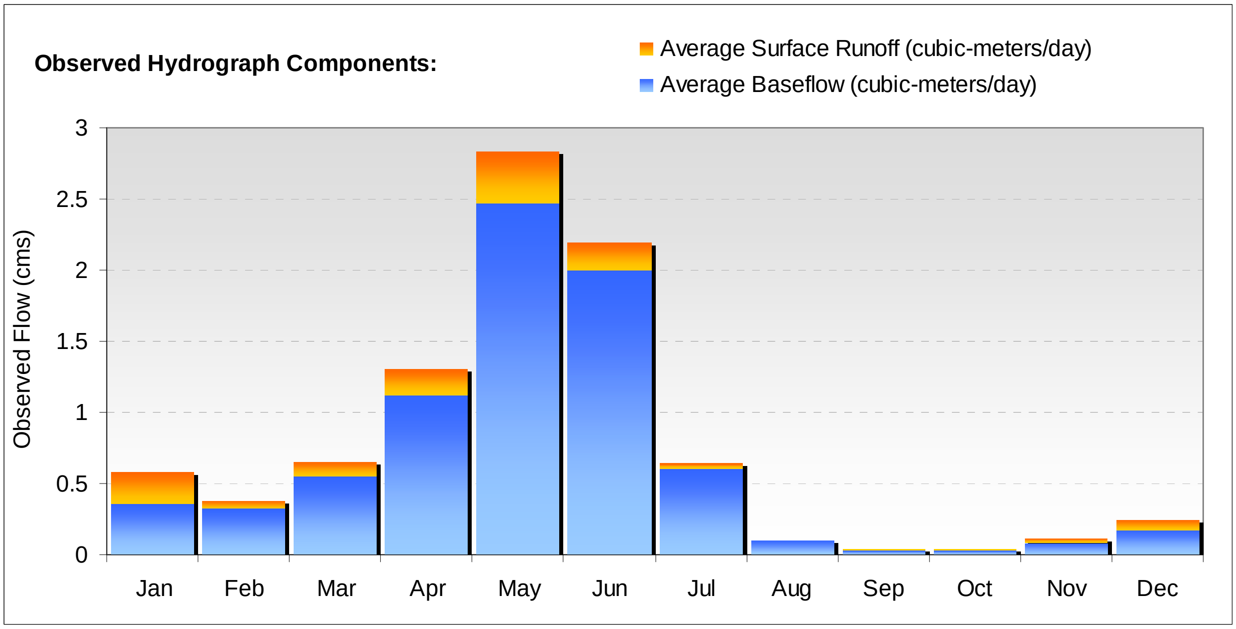

Figure 4-21. Hydrograph separation for Ward Creek (USGS 10336676) using historical flow data collected between 10/1/1972 and 9/30/2003 (Tetra Tech 2007).

Since there are no direct point source contributions of nutrients to the streams, the sediment and nutrient yields at the monitoring station are assumed to have come from upstream nonpoint sources. The following assumptions were applied for this analysis:

- Reasonable baseflow and surface runoff volumes can be obtained using the HYSEP sliding-interval method, as defined by Sloto and Crouse (1996)
- Since flow-versus-load regressions have errors that are normally distributed in log space, it is reasonable to use rating curves in conjunction with MVUEs to develop baseflow and surface runoff load relationships in linear space
- TN and TP represent all transportable nitrogen and phosphorus from upstream sources
- Baseflow pollutant load is primarily groundwater driven and storm-flow pollutant load is primarily surface runoff driven
- Baseflow associated samples are composed primarily of dissolved inorganic nutrients (dissolved nitrogen and dissolved phosphorus)
- TN and TP baseflow samples represent total dissolved nutrients, which include both organic and inorganic forms
- TSS, which is primarily associated with surface runoff, includes organic material that contains nutrients
- Baseflow rating curves can be used in conjunction with total flow rating curves to back-calculate surface runoff nutrient loading
- Surface runoff pollutant mass is composed of primarily particulate constituents
- Particulate nutrient mass is primarily composed of organic material
- Particulate-nutrient-mass to sediment-mass ratios represent sediment-associated nutrients

For each LTIMP gage, a set of ten regression rating curves were developed using the monitoring data. For each water quality constituent, a baseflow (BF) and storm-flow (RO) curve was derived using the separated hydrograph. A set of example equations are presented in Table 4-22. For the development of the rating curves, each instream sample had to be classified as either a BF sample or a RO sample using the daily separated hydrograph timeseries. It was reasonable to assume that BF classification could be potentially assigned to any sample where the base-flow-to-total-flow ratio was greater than 50 percent. Therefore, this sample classification analysis was performed for each threshold value between 50 and 100 percent to see which threshold value resulted in the best correlation for both the BF and RO rating curves. The R^2 correlation value served as the performance measure for goodness of fit.

Table 4-22. Baseflow and storm-flow sediment and nutrient rating curves summary for Ward Creek (Tetra Tech 2007).

Constituent and Sample Type[1]		Number of Samples	Base-flow Threshold	Log of Intercept	Slope	R^2
Sediment	BF	77	98%	6.326	1.354	0.863
	RO	457	98%	7.473	1.769	0.811
Total Nitrogen	BF	69	99%	2.165	1.149	0.915
	RO	337	99%	2.609	1.144	0.880
Total Phosphorus	BF	90	96%	0.571	0.982	0.940
	RO	312	96%	1.339	1.211	0.829
Dissolved Inorganic Nitrogen	BF	76	98%	-0.213	1.066	0.907
	RO	328	98%	0.220	1.081	0.843
Dissolved Inorganic Phosphorus	BF	295	58%	-0.659	0.856	0.925
	RO	107	58%	-0.098	0.870	0.900

[1] BF indicates baseflow samples and RO indicates storm-flow samples (collected during runoff events)

The rating curves were used to develop loading estimates and summarized to produce seasonal trends and loading distributions. Figure 4-22 is an example of the results. As an independent validation of this methodology, dissolved organic nitrogen (DON) values were compared against independently computed fractions (Coats and Goldman 2001), and were found to be in agreement.

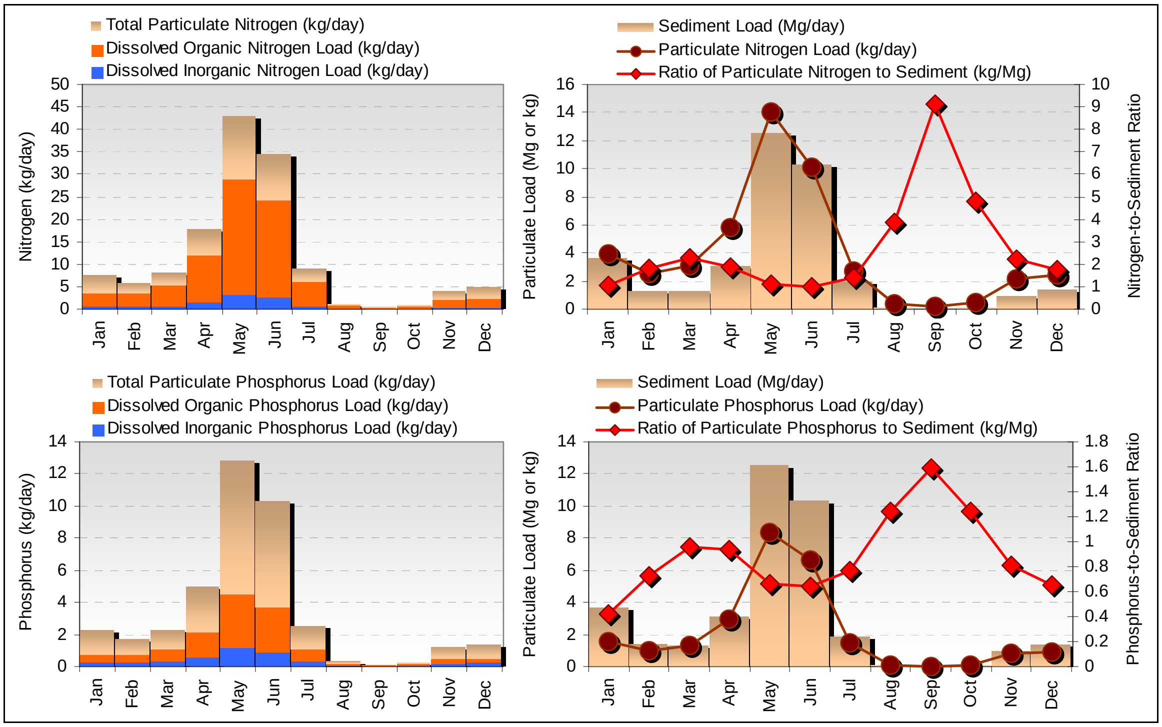

Figure 4-22. Seasonal nitrogen and phosphorus constituent distribution for Ward Creek water quality samples for data collected between 1972 and 2003, derived from hydrograph separation and regression (Tetra Tech 2007).

The insights gained from this statistical data 'mining' exercise provide guidance for selecting appropriate source loading parameters for a deterministic watershed simulation model. Some interesting observations from reviewing the results are presented below:

- About 70 percent of the total annual sediment, nitrogen and phosphorous loads are delivered to the streams during the snowmelt months of April, May and June.
- On average, 8.5 percent of TN is dissolved inorganic-N and 12 percent of TP is dissolved inorganic-P. In support of these modeling results, Coats and Goldman (2001) reported that dissolved inorganic-N was roughly 10 percent of TN. Also, analysis of the 1991-2004 LTIMP database for the 10 stream mouth stations showed that the ratio of soluble reactive-P was 18 ± 8 percent of TP.
- While the months of August, September and October yield the lowest amount of sediment and nutrients, the ratio of particulate nutrient mass to total sediment mass shows a distinct 2 to 4 times increase, suggesting that the organic matter in terms of percent composition of total sediment increases during these months; likely contributed in part as a result of increased attached algal growth/decay during the summer months.
- Comparison of total nitrogen distribution and loading to an independent analysis performed using the same dataset shows excellent agreement in estimated loads for Ward Creek (Coats and Goldman 2001, estimate about 1.5 kg-N/ha/yr for Ward Creek, compared to 1.6 kg-N/ha/yr for this analysis).

Model Parameterization by Land-use

Following the data 'mining' analysis, monthly variable baseflow and surface concentrations were directly computed using the various loading components and their associated flow volumes. Particulate nutrient mass was modeled as a sediment-associated fraction using the derived nutrient-to-sediment mass ratios.

Water quality parameters are specified at the land-use level for each subwatershed. The primary objective of this parameterization is to represent the influence and relative contribution of each upstream land-use on the total observed loads at the mouth of the tributary. The first step is to characterize the total runoff volumes for each land segment. This is done using the process-based hydrologic component of the Lake Tahoe Watershed Model, which uses hourly meteorological forcing data and land-segment specific hydrologic parameters derived by observation, estimation, and calibration. Each tributary outflow is evaluated to see how well it reflects the unique characteristics of its component watershed response. The second step is to determine and assign representative runoff concentrations for each land-use.

Stormwater runoff often represents a significant source of nutrients and sediment. Pollutants, such as nutrients, that have accumulated on watershed surfaces or are part of the soils within the watershed (subject to erosion) are readily transported by way of the stormwater drainage systems and/or overland flow during rain/snow melt events. Increases in impervious cover associated with urbanization (e.g., streets and parking lots) decrease the natural capacity to absorb rainfall and remove pollutants by filtering and treating the runoff through vegetative cover and the soil matrix. Urbanized areas in the Tahoe basin generate substantial pollutant concentrations (e.g. Reuter et al. 2001, Heyvaert et al. 2006). Additionally, there are typically higher runoff volumes and peak flow rates in developed urban areas due to greater impervious cover; i.e. less opportunity for infiltration. In general, decreased water quality treatment and increased stormwater runoff volumes and peak flow rates associated with urbanization increase sediment and nutrient loading (Schueler 1987).

Event mean concentrations (EMC) represent the average concentration of constituents in land-use runoff. EMCs for most urban land-uses were developed based upon stormwater monitoring information collected from 19 autosamplers distributed around the basin (Figure 4-23)(Heyvaert et al. 2007). At 10 of the 19 sites, continuous real-time data including specific conductance, water temperature, stage, and turbidity were conducted. The autosamplers were triggered by a predetermined stage height or preset volume. The height, volume, and frequency to which sampling is triggered differs at each site depending on typical site flow conditions. The relative land-use characteristics at each monitoring sites are shown in Figure 4-24. This stormwater monitoring program was conducted in water years (Oct 1st – Sept 30th) 2003 and 2004 as part of the Lake Tahoe TMDL research effort conducted by the DRI and UC Davis - TERC. Results are reported in Gunter 2005 and Coats et al. 2008. It proved to be very difficult to design the stormwater monitoring program to target each individual land-use. Flow was typically any combination of mixed land-uses since the impacted areas are relatively small.

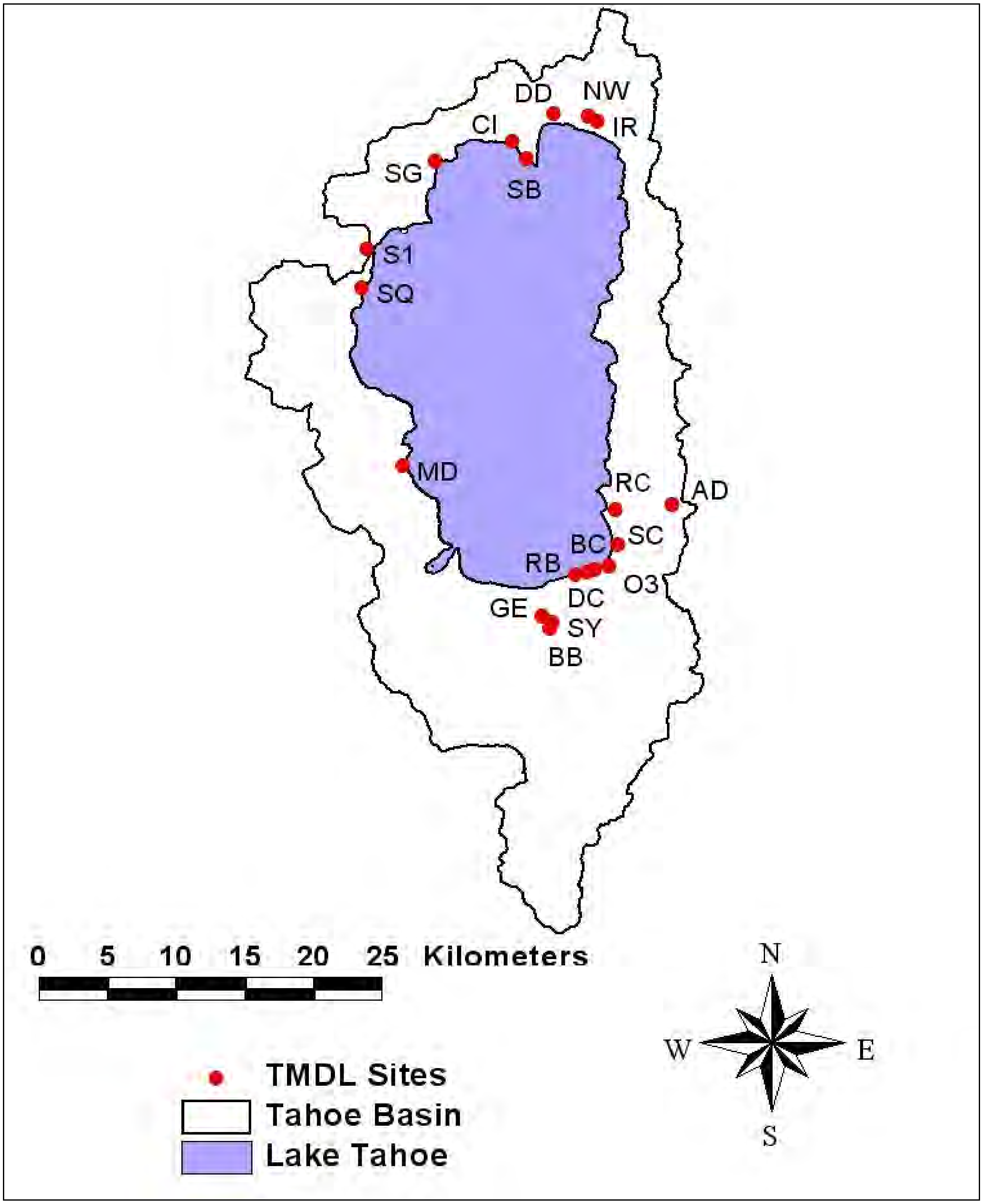

Figure 4-23. Location of TMDL stormwater monitoring sites during 2003-2004 (modified from Gunter 2005). [AD=Andria Drive, BB=Bonanza Avenue, BC=Bijou Creek, CI=Coon Street, DC=Don Cheapos, DD=Dale Drive, GE=Glorene and Eighth, IR=Incline Village Raley's, MD=Mountain Drive, NW=Northwood Boulevard, O3=Osgood Avenue, RB=Regan Beach, RC=Roundhill CDS, S1=Tahoe City Wetlands Treatment System, SB=Speedboat Avenue, SC=SLT Casinos, SG=Shivagiri, SQ=Sequoia Avenue, SY=SLT-Y]

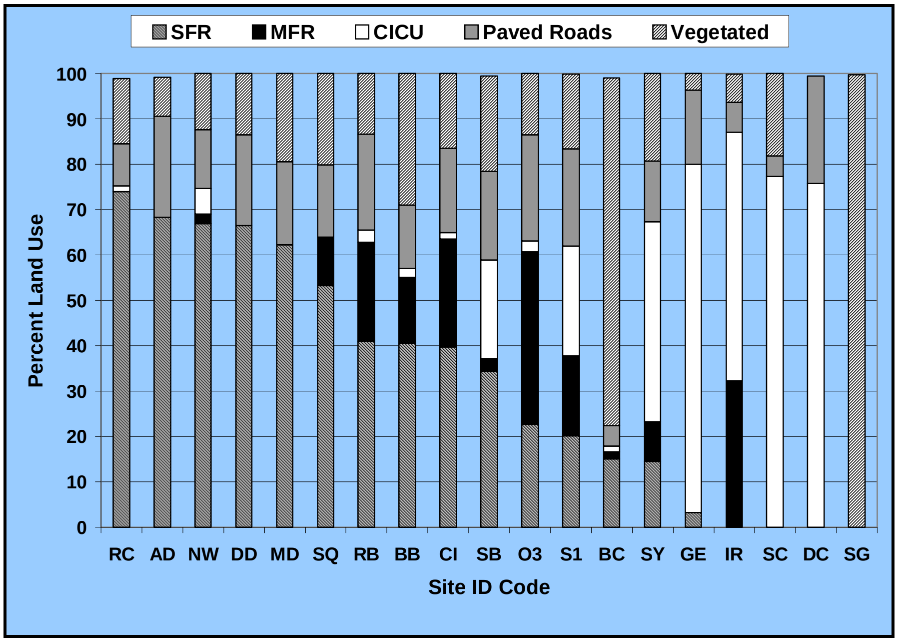

Figure 4-24. Relative land-use characteristics at each of the 19 autosampler locations used for stormwater monitoring. SFR – single family residential, MFR – multiple family residential, CICU – commercial industrial, communications and utilities, paved roads and vegetated undeveloped (Heyvaert et al. unpublished).

Reliable EMCs were obtained for the following land-uses; commercial, mixed urban, high density residential, and low density residential. While some data was collected from vegetated, undeveloped areas, the primary focus of this monitoring program was to collect information from urban areas. EMC for primary roads were collected by independent monitoring programs operated by Caltrans (2003) and NDOT (Jones et al. 2004). EMC data were not available for other, more specific land-uses (ski runs, vegetated recreational, vegetated turf, roads secondary, vegetated burned, vegetated harvest, and Vegetated EP1 - EP5). In some instances, relative evaluations between other land-uses were used to develop EMCs, while in other instances, available grab sample data, literature information, or in-stream concentrations were used to develop EMCs. After the initial EMC estimates by land-use were developed, a margin of safety of 20 percent was added. The following bullets describe how the initial target EMCs by land-use were obtained:

- Residential Single Family, Residential Multiple Family, and CICU, Pervious and Impervious – Concentrations were taken from EMC analysis of runoff data from the DRI/UC Davis-TERC Stormwater Monitoring Dataset (Gunter 2005). In this study, runoff mean concentrations were related to watershed characteristics and land-use through multiple linear regression analyses. The study showed that particulate species of nitrogen and phosphorus were the most abundant sources of nutrients in stormwater, and they were especially high in commercial land-uses. Population density and typical activities associated with these areas are directly related to increases in nutrient and sediment concentrations for residential land-uses (Gunter 2005). No distinction was made between runoff concentrations from pervious and impervious areas.

- Ski Runs Pervious – This land-use includes lands within otherwise vegetated areas for which trees have been cleared to create a run. The three ski areas in the watershed with available data, Heavenly, Homewood, and Diamond Peak, have very different runoff characteristics and, consequently, are modeled separately. The concentrations are based on stream data at each ski area, background values, and the area of the ski runs.

- Vegetated Recreational – This land-use includes lands that are primarily vegetated and are characterized by relatively low-intensity uses and small amounts of impervious coverage. These include the unpaved portions of campgrounds, visitor centers and day use areas. Final values calculated assume that the areas are represented by 40 percent roads, and 60 percent forest.

- Vegetated Turf - This land-use includes large turf areas with little impervious coverage, such as golf courses, large playing fields, and cemeteries, with potentially similar land management activities. EMCs are based on application ratios and land turf areas for golf course vs. residential. According to the USACE (2003) groundwater report, the ratio of fertilizer application for nitrogen and phosphorus for Golf Courses relative to Residential was approximately 2.5 to 1, assuming the Home Landscaping Guide instructions are followed, which is a reasonable assumption. With the assumption that most nitrogen/phosphorus runoff from residential land comes from fertilizer applied to lawns and the estimate of total residential areas to lawns is 1.25:1.0, these values represent 1.25 x 2.5 = 3.125 times the mean of Single Family Residential. Estimates do not account for infiltration of nitrogen and phosphorus. The recommended TSS concentration is based on the best professional judgment of the modelers.

- Roads Primary – EMCs were obtained from data in the Caltrans (2003) monitoring report and a report from NDOT and DRI that looked at highway stormwater runoff and BMP effectiveness on portions of SR 28 and US 50 in Nevada (Jones et al. 2004).

- Roads Secondary – No direct data was available for secondary roads. EMCs from this land-use are assumed to be the same as those developed/estimated for the multiple family residential land-use.

- Roads Unpaved – EMCs are based on data from McKinney Rubicon Rd USFS data. EMCs shown are the median of 20 samples taken from the road drainage. Independent calculation for this EMC, based on the Sierra Nevada Ecosystem Project (McGurk et al. 1996) sediment loadings by road slope, returned 955 mg/L for TSS.

- Vegetated Burned – These are areas that have been subject to controlled burns and/or wildfires during the 1996 – 2004 modeling time period. A six-year linear recession curve to zero-impact is used to compute the diminishing effects of the burn over time.

- Vegetated Harvest – These are lands that management agencies have thinned for the purpose of forest health and to reduce the spread of wildfire. The EMCs used are the same as unpaved roads, but the impact areas are adjusted based on the Equivalent Road Area obtained from USFS for each event. To account for the diminishing impact of the harvesting activity through time during the calibration years, a recession curve was used.

- Vegetated EP1 through EP5 – EMCs for each of the five erosion potential categories were initially estimated by running the model with all the land-uses set at their target EMCs described above, and performing a multi-regression optimization analysis resulting in the best estimate EMC for each of the five erosion potential categories.

Table 4-23 presents the final runoff EMCs that were developed for each of the land-uses. Figure 4-25 indicates that in most cases, the higher concentrations are associated with urban runoff as compared to those measured in the LTIMP streams.

Table 4-23. Derived EMCs for runoff by modeled land-use categories (mg/L).

Land-use Name	TN	DN	TP	DP	TSS
Residential_SFP	1.752	0.144	0.468	0.144	56.4
Residential_MFP	2.844	0.420	0.588	0.144	150.0
CICU-Pervious	2.472	0.293	0.702	0.078	296.4
Ski_Runs-Pervious	0.360	0.132	0.120	0.038	270.7
Veg_EP1	0.164	0.011	0.034	0.029	14.0
Veg_EP2	0.164	0.011	0.034	0.029	37.6
Veg_EP3	0.164	0.011	0.034	0.029	100.9
Veg_EP4	0.164	0.011	0.034	0.029	270.7
Veg_EP5	0.164	0.011	0.034	0.029	726.6
Veg_Recreational	1.035	0.012	0.629	0.209	459.6
Veg_Burned	2.340	0.014	1.524	0.480	1015.2
Veg_Harvest	2.340	0.014	1.524	0.480	1015.2
Veg_Turf	5.475	0.450	1.463	0.450	12.0
Water_Body	0.000	0.000	0.000	0.000	0.0
Residential_SFI	1.752	0.144	0.468	0.144	56.4
Residential_MFI	2.844	0.420	0.588	0.144	150.0
CICU-Impervious	2.472	0.294	0.702	0.078	296.4
Roads_Primary	3.924	0.720	1.980	0.096	951.6
Roads_Secondary	2.844	0.420	0.588	0.144	150.0
Roads_Unpaved	2.340	0.014	1.524	0.480	1015.2

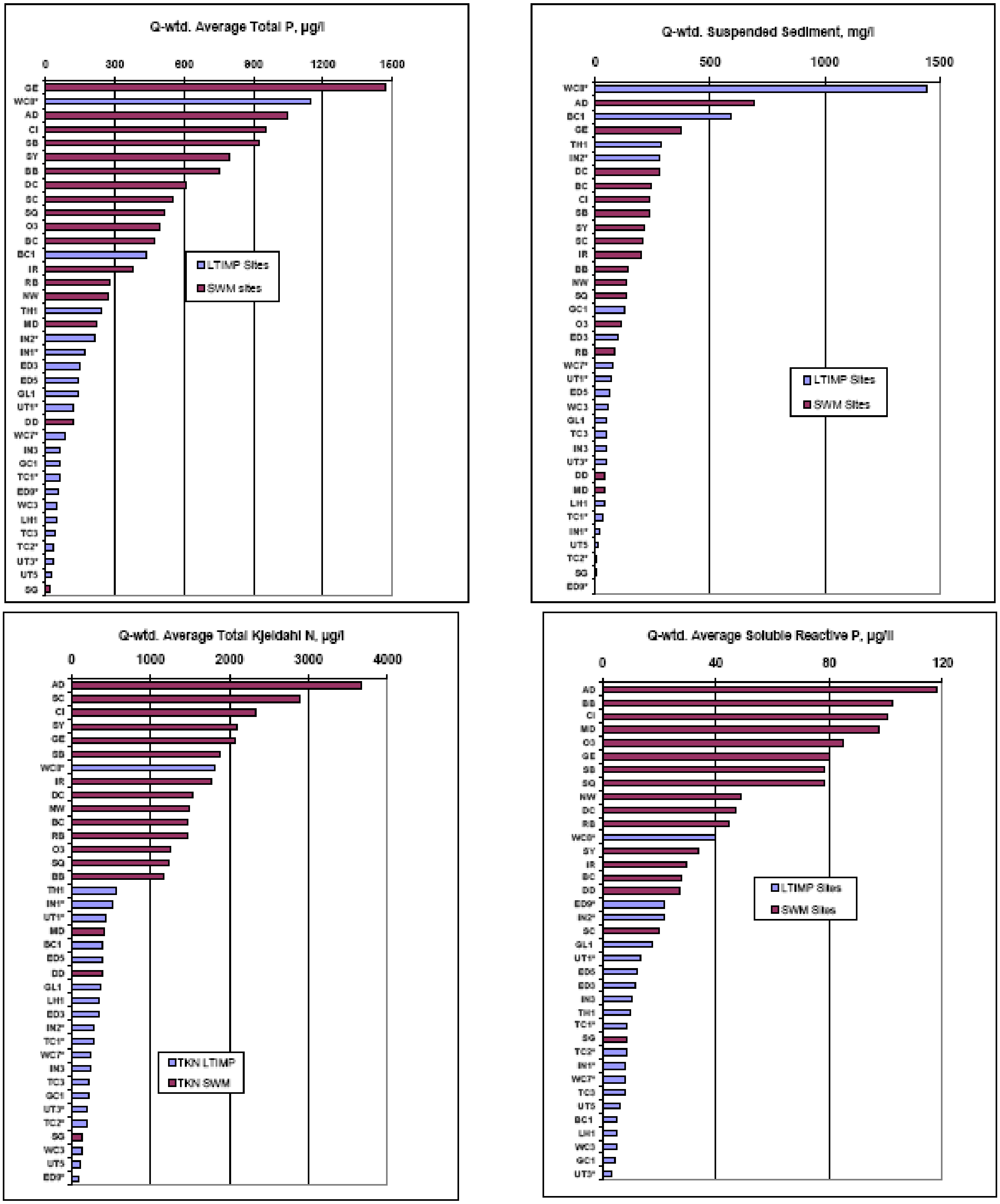

Figure 4-25. Summary of flow-weighted (Q-wtd.) concentrations for TP, TSS, total Kjeldahl-N and soluble-P for stormwater monitoring sites and LTIMP (mouth) sites for period 2003-2004 (Coats et al. 2008).

In addition to the EMCs, the fraction of the TSS comprised of fine sediment (< 63 µm) was estimated for each urban land-use category using available stormwater sampling information. The same urban sediment distribution was applied to all land-uses of the same type in all subwatersheds. The remaining non-urban land-uses were assigned a uniform distribution of fine sediment based on in-stream sediment distributions that varied by subwatershed. Table 4-24 shows the fine sediment distributions by land-use and subwatershed.

Table 4-24. Percent fines by land-use and subwatershed as applied in the Lake Tahoe Watershed Model (Tetra Tech 2007).

Land-use Type	Land-use Name or Subwatershed	Runoff Fines Distribution		
		(< 63 µm)	(20 - 63 µm)	(< 20 µm)
Urban	Residential_SF	76.3%	40.6%	35.7%
Urban	Residential_MF	88.4%	30.7%	57.7%
Urban	CICU	85.4%	22.3%	63.1%
Urban	Roads_Primary	85.4%	22.3%	63.1%
Urban	Roads_Secondary	85.4%	22.3%	63.1%
Non-Urban	Third Creek	31.0%	21.5%	9.5%
Non-Urban	Incline Creek	67.0%	46.6%	20.4%
Non-Urban	Glenbrook Creek	80.0%	55.4%	24.6%
Non-Urban	Logan House Creek	75.0%	51.6%	23.4%
Non-Urban	Edgewood Creek	59.0%	41.2%	17.8%
Non-Urban	General Creek	29.0%	20.3%	8.7%
Non-Urban	Blackwood Creek	45.0%	31.4%	13.6%
Non-Urban	Ward Creek	47.0%	32.3%	14.7%
Non-Urban	Trout Creek	38.0%	26.3%	11.7%
Non-Urban	Upper Truckee River	44.0%	30.6%	13.4%

Water Quality Calibration Process

Once the water quality parameters were initially set-up in the model, the model was run and the results of the annual average loads by calibration watershed were compared with the annual loads obtained using the available LTIMP data. After this initial comparison was made, two things were noted. First, the modeled fine sediment loads were too low for those areas with a large percent of volcanic soils and second, fine sediment loads were too high for those areas dominated by granitic soils. A regression was developed that correlates the required multiplying factor for the pervious land-uses and the percent volcanic soils in the watershed. This regression is presented in Figure 4-26. Each point in the graph represents a calibration watershed. It can be observed that the higher the fraction of volcanic soils in the watershed, the higher the multiple required for the TSS EMCs.

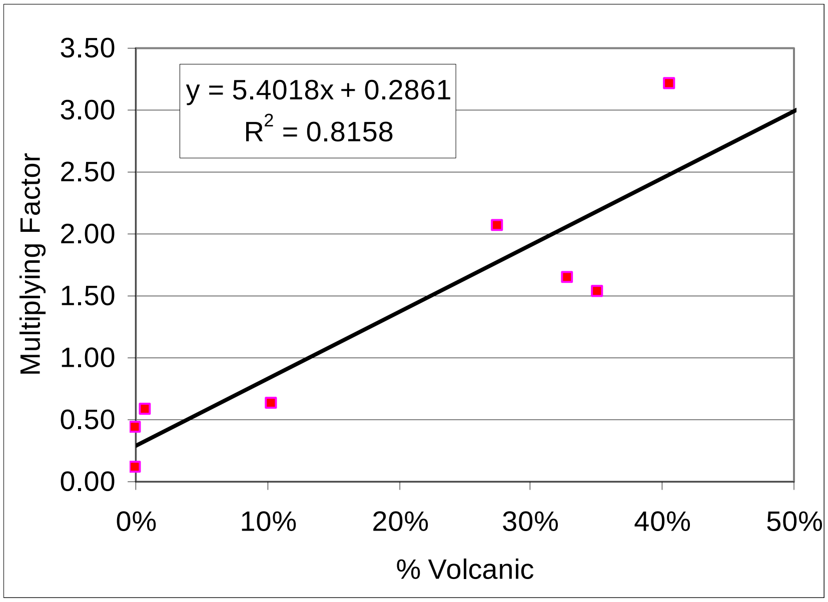

Figure 4-26. EMC multiplying factor for pervious land-uses relative to percent volcanic (Tetra Tech 2007).

After the soil variability was taken into account, the model was run again, and a second observation was made. This observation was related to the differences in the fine-load estimates by quadrant of the watershed. The model's estimate was low for the northern and western quadrants and high for the southern and eastern ones. This error was minimized by applying the following scaling factors to the EMCs for all land-uses (Table 4-25). Similar scaling factors were also derived for total nitrogen and total phosphorus following the quadrant method.

Table 4-25. Scaling factor for EMCs by quadrant (modified from Tetra Tech 2007).

Quad ID	Quad Name	Ratio TSS	Ratio nitrogen	Ratio phosphorus
1	North	1.59	0.986	0.483
2	East	0.11	0.409	0.628
3	South	0.74	0.823	0.757
4	West	1.45	1.535	1.558

A summary of the results of the water quality calibration is shown in Table 4-26, Table 4-27, and Table 4-28.

Table 4-26. Results of water quality calibration for upland fine sediment (modified from Tetra Tech 2007).

Name	Overland Flow, 1000 m^3/year	Baseflow, 1000 m^3/year	Modeled: Upland Fines (metric tons/year)	Target: * Upland Fines (metric tons/year)	Fines Ratio (target / modeled)
Third Creek	1,070	5,600	190	229	**1.21**
Incline Creek	1,270	6,380	357	318	**0.89**
Glenbrook Creek	587	3,220	25	17	**0.71**
Logan House Creek	258	1,210	4	7	**2.02**
Edgewood Creek	1,430	2,630	21	24	**1.16**
General Creek	3,390	11,700	60	62	**1.04**
Blackwood Creek	3,730	25,700	837	1,150	**1.38**
Ward Creek	4,980	18,900	1,430	1,110	**0.78**
Trout Creek	3,980	28,400	205	189	**0.92**
Upper Truckee River	22,900	78,800	1,010	1,030	**1.02**
TOTAL	**43,600**	**183,000**	**4,140**	**4,140**	**1.00**

* Upland targets adjusted to account for net transport losses

Table 4-27. Results of water quality calibration for total nitrogen (modified from Tetra Tech 2007).

Name	Overland Flow, 1000 m^3/year	Baseflow, 1000 m^3/year	Modeled: Total Nitrogen (kg/year)	Target: Total Nitrogen (kg/year)	Ratio TN (target / modeled)
Third Creek	1,070	5,600	2,820	3,930	**1.39**
Incline Creek	1,270	6,380	3,300	2,190	**0.66**
Glenbrook Creek	587	3,220	383	638	**1.67**
Logan House Creek	258	1,210	157	241	**1.53**
Edgewood Creek	1,430	2,630	1,370	1,030	**0.75**
General Creek	3,390	11,700	3,150	3,160	**1.01**
Blackwood Creek	3,730	25,700	8,400	9,170	**1.09**
Ward Creek	4,980	18,900	6,440	5,660	**0.88**
Trout Creek	3,980	28,400	6,540	5,390	**0.82**
Upper Truckee River	22,900	78,800	24,100	25,300	**1.05**
TOTAL	**43,600**	**183,000**	**56,700**	**56,700**	**1.00**

Table 4-28. Results of water quality calibration for total phosphorus (modified from Tetra Tech 2007).

Name	Overland Flow 1000 m^3/year	Baseflow 1000 m^3/year	Modeled: Total Phosphorus (kg/year)	Target: Total Phosphorus (kg/year)	Ratio TP (target / modeled)
Third Creek	1,070	5,600	843	1,170	**1.38**
Incline Creek	1,270	6,380	877	553	**0.63**
Glenbrook Creek	587	3,220	143	137	**0.96**
Logan House Creek	258	1,210	26	21	**0.80**
Edgewood Creek	1,430	2,630	203	214	**1.05**
General Creek	3,390	11,700	517	398	**0.77**
Blackwood Creek	3,730	25,700	2,320	2,710	**1.17**
Ward Creek	4,980	18,900	2,030	1,760	**0.87**
Trout Creek	3,980	28,400	1,000	954	**0.95**
Upper Truckee River	22,900	78,800	4,110	4,160	**1.01**
TOTAL	**43,600**	**183,000**	**12,100**	**12,100**	**1.00**

Once the upland model was calibrated, a summary of average annual upland loads was obtained for each modeled stream. Simon (2006) provided an estimate of total fine sediment load vs. channel fine sediment load for each stream. From this information, the ratio of channel fines to total fines was applied to the modeled upland load as follows to obtain an estimate of total fine sediment loads for all streams:

Total Fine Sediment Load = Upland Fines Load / (1 – [Channel Fines / Total Fines])

From there, the channel fine sediment load becomes:

Channel Fines Load = Total Fines Load x [Channel Fines / Total Fines]

Time series comparison revealed that the timing of streambank erosion was not linearly related to the timing of upland fines. Therefore, it was not representative to simply multiply the modeled upland fines load by the stream fines ratio. However, streambank erosion frequency appeared to vary closely with streamflow. Assuming a linear relationship between streambank erosion and stream flow, estimated channel loads were distributed according to modeled flows from the Lake Tahoe Watershed Model to generate time series of channel fines sediments. This time series was superimposed over the original upland fines time series, resulting in a complete total fines time series representation.

After selecting appropriate water quality parameters for the Lake Tahoe Watershed Model, modeled results were compared against both the observed data points. Figure 4-27, Figure 4-28, and Figure 4-29 show Lake Tahoe Watershed Model results versus observed data for TSS, TN and TP for Ward Creek which is used as an example.

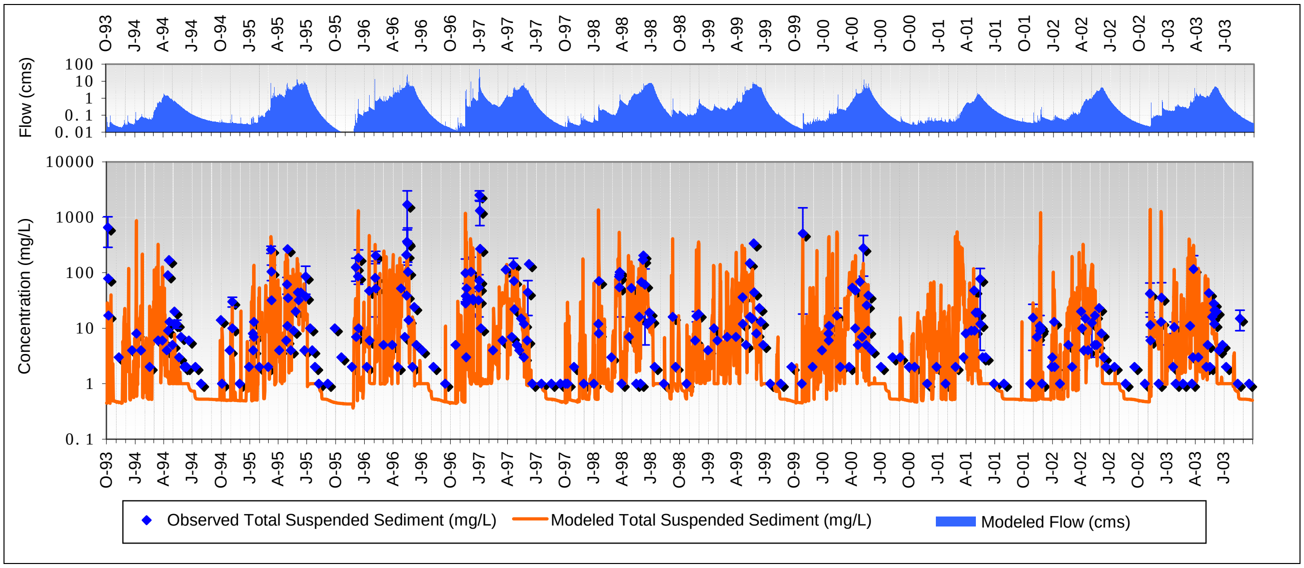

Figure 4-27. Lake Tahoe Watershed Model results vs. observed data for TSS at Ward Creek (cms = m^3/sec) (Tetra Tech 2007).

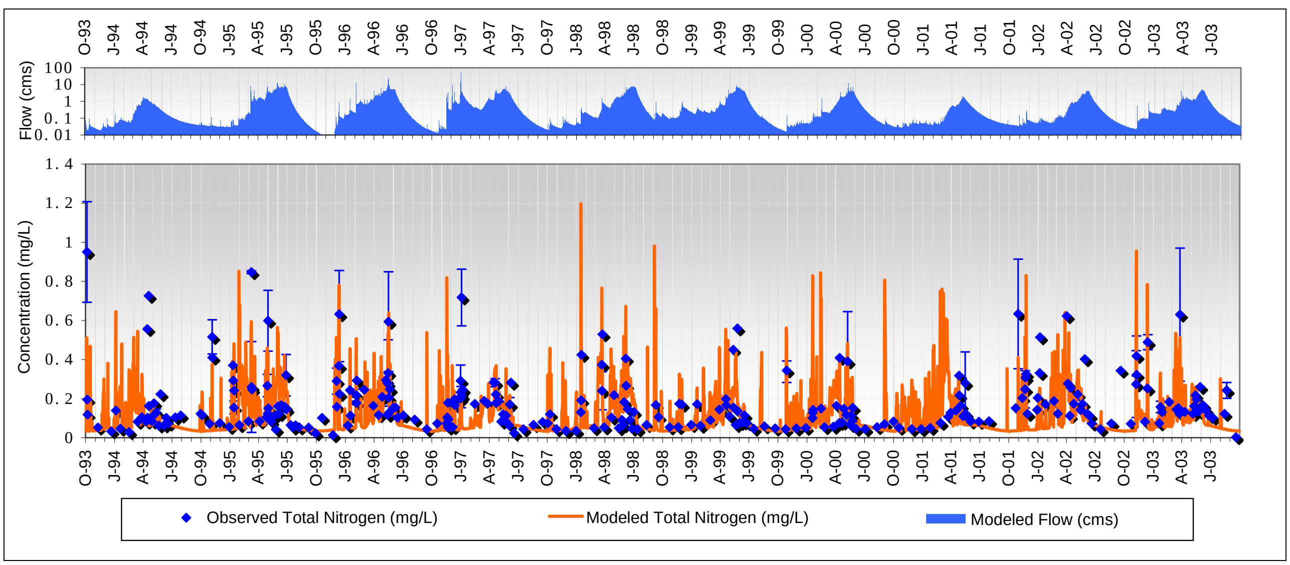

Figure 4-28. Lake Tahoe Watershed Model results vs. observed data for TN at Ward Creek (cms = m^3/sec) (Tetra Tech 2007).

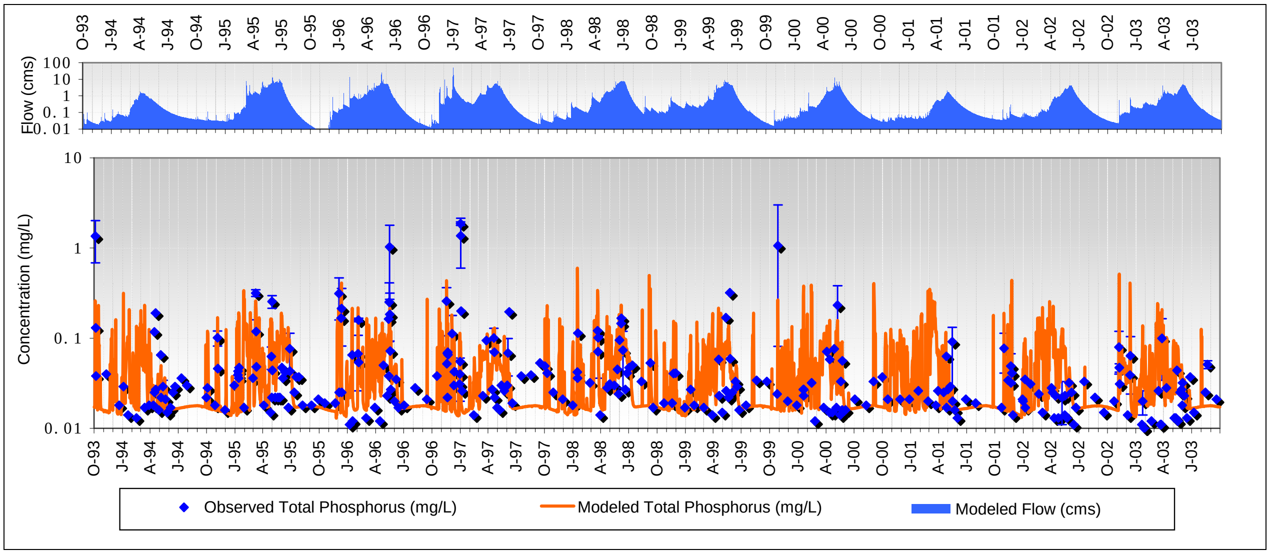

Figure 4-29. Lake Tahoe Watershed Model results vs. observed data for TP at Ward Creek (cms = m^3/sec) (Tetra Tech 2007).

4.3.6 Results

This section is not intended to provide an exhaustive description and discussion of the model output. Rather, the objective herein is to (1) present a summary of the model output over the 1994-2004 period, (2) provide flow volume, TSS, fine sediment (< 63 µm), TN and TP output for each of the watersheds and modeled intervening zone units, and (3) distinguish between urban and non-urban areas, and specific land-uses when considering loads. Some general observations are described below regarding the influence of elevation, location, and land-use on the model predicted results for water yield, sediment, and nutrient loads. The period 1994-2004 was characterized by a wide range of precipitation conditions including very wet and very dry years. The range of annual precipitation amounts (as measured at Tahoe City as part of the approximately 100 year data record) was 17 – 61 inches with a mean ± standard deviation of 36 ± 15 inches. For reference the lowest annual precipitation measured at this location was approximately nine inches in 1977 and the highest annual precipitation was 69 inches in 1982. Mean annual precipitation at the Tahoe City location since 1910 has been approximately 32 inches.

General observations

Elevation

Elevation has the biggest effect on predicted water yield. Higher elevations tend to receive higher amounts of snowfalls. In general, for subwatersheds in the same region, unit-area flow increases as elevation increases. Total flow volume, location, and land-use are factors that directly influence model-predicted loads.

Location

The Lake Tahoe watershed has distinct orographic features that vary spatially. By categorizing the watershed into north, south, east, and west quadrants; one can see distinct spatially variable patterns. Unit area water yield varies by quadrant. The west quadrant is wettest while the east is the driest. The prevailing weather patterns in the basin are significantly influenced by the topographic relief. If one considers two subwatersheds with the same elevation on the west side and east side, the western subwatershed will typically experience over two times the volume of precipitation and water yield as its eastern counterpart. Total flow volume has a direct effect on the predicted model load.

Land-use

Table 4-31 shows the percent of total contribution for Upland TSS, Upland Fines, Nitrogen and Phosphorus from each of the 20 land-use categories. Marked in bold are values for which a single land-use category contributes greater than 10 percent of the total load. A cursory review shows a fairly consistent correlation of flow yield with area. Table 4-31 also shows that the largest contributors are generally vegetated areas and roads. While roads represent a relatively small amount of area, they are impervious surfaces which tend to serve as conduits for flow from surrounding areas. As modeled, concentrations from road surfaces are higher than those from other pervious and impervious areas. In general, while urban areas represent a relatively small percentage of the watershed area, they exhibit a disproportionately higher level of fine sediment and nutrient loads. Finally, it's noteworthy to mention that the "Water_Body" land-use was retained in the land-use list to complete the water balance. There are several smaller high elevation lakes that were not explicitly modeled. The associated water surface areas contribute flow from direct precipitation, but do not directly generate pollutant loads.

Flow volumes

A summary of average flow volume from each of the modeled intervening zones and individual streams over the 1994-2004 period is given in Table 4-29. The total annual flow volume was modeled at 4.48×10^8 m^3 with approximately 25 percent entering the stream directly by flow over the land surface. The remaining approximately 75 percent infiltrates through the shallow soils prior to entering the stream (i.e. termed baseflow). As presented in Table 4-17 the Lake Tahoe Watershed Model (LSPC) estimate of streamflow agreed well with previous estimates. The largest individual stream contributor to total flow was the Upper Truckee River at 25 percent of total stream contribution. Combined, the Upper Truckee River, Trout Creek, Blackwood Creek and Ward Creek accounted for 46 percent of the total stream flow. Flow from the intervening zones contributed 10 percent of the total flow volume with 90 percent coming from stream discharge. This estimate is nearly identical to that made by Marjanovic (1989) and used by Reuter et al. (2003) in the initial estimate of pollutant loading from intervening zones.

Table 4-29. Summary of annual surface, base and total flow volumes by watershed as determined using the Lake Tahoe Watershed Model. Values represent means over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Tributary	OUTLET SWS	Surface Flow (m^3)	Baseflow (m^3)	Total Flow (m^3)
INTERVENING ZONE RUNOFF				
IVZ1000	1000	1.13E+06	1.66E+06	2.80E+06
IVZ2000	2000	7.55E+05	3.63E+06	4.39E+06
IVZ3000	3000	1.42E+06	3.45E+06	4.87E+06
IVZ4000	4000	1.99E+06	2.21E+06	4.21E+06
IVZ5000	5000	2.20E+06	2.62E+06	4.81E+06
IVZ6000	6000	7.68E+05	3.99E+06	4.75E+06
IVZ6001	6001	8.05E+05	1.42E+06	2.23E+06
IVZ7000	7000	1.61E+06	2.86E+06	4.47E+06
IVZ8000	8000	1.56E+06	2.96E+06	4.51E+06
IVZ9000	9000	1.47E+06	4.79E+06	6.26E+06
TOTAL		1.37E+07	2.96E+07	4.33E+07
STREAM FLOW				
MILL CREEK	1010	3.69E+05	1.92E+06	2.29E+06
INCLINE CREEK	1020	1.27E+06	6.38E+06	7.64E+06
THIRD CREEK	1030	1.07E+06	5.60E+06	6.67E+06
WOOD CREEK	1040	3.87E+05	1.81E+06	2.20E+06
BURNT CEDAR CREEK	1050	1.93E+05	2.23E+05	4.16E+05
SECOND CREEK	1060	1.96E+05	1.29E+06	1.49E+06
FIRST CREEK	1070	1.84E+05	1.68E+06	1.87E+06
SLAUGHTER HOUSE	2010	9.35E+05	3.73E+06	4.67E+06
BLISS CREEK	2020	8.24E+04	4.27E+05	5.09E+05
SECRET HARBOR CREEK	2030	4.17E+05	2.68E+06	3.10E+06
MARLETTE CREEK	2040	1.54E+06	3.31E+06	4.85E+06
BONPLAND	2050	1.10E+05	6.73E+05	7.83E+05
TUNNEL CREEK	2060	1.09E+05	1.22E+06	1.33E+06
MCFAUL CREEK	3010	5.11E+05	2.12E+06	2.63E+06
ZEPHYR CREEK	3020	2.22E+05	9.55E+05	1.18E+06
NORTH ZEPHYR CREEK	3030	3.16E+05	1.51E+06	1.83E+06
LINCOLN CREEK	3040	2.89E+05	1.43E+06	1.72E+06
CAVE ROCK	3050	9.91E+04	4.16E+05	5.15E+05
LOGAN HOUSE CREEK	3060	2.58E+05	1.21E+06	1.46E+06
NORTH LOGAN HOUSE CREEK	3070	1.34E+05	8.40E+05	9.74E+05
GLENBROOK CREEK	3080	5.87E+05	3.22E+06	3.81E+06
BIJOU CREEK	4010	7.66E+05	1.45E+06	2.22E+06
EDGEWOOD CREEK	4020	1.43E+06	2.63E+06	4.06E+06
BURKE CREEK	4030	4.20E+05	1.79E+06	2.21E+06
UPPER TRUCKEE RIVER	5010	2.29E+07	7.88E+07	1.02E+08

Tributary	OUTLET SWS	Surface Flow (m^3)	Baseflow (m^3)	Total Flow (m^3)
TROUT CREEK	5050	3.98E+06	2.84E+07	3.24E+07
GENERAL CREEK	6010	3.39E+06	1.17E+07	1.51E+07
MEEKS	6020	4.13E+06	1.25E+07	1.67E+07
SIERRA CREEK	6030	4.39E+05	1.33E+06	1.77E+06
LONELY GULCH CREEK	6040	5.73E+05	1.64E+06	2.21E+06
PARADISE FLAT	6050	2.95E+05	9.55E+05	1.25E+06
RUBICON CREEK	6060	1.38E+06	4.37E+06	5.75E+06
EAGLE CREEK	6080	2.35E+06	1.01E+07	1.25E+07
CASCADE CREEK	6090	2.37E+06	6.53E+06	8.90E+06
TALLAC CREEK	6100	6.30E+05	3.35E+06	3.98E+06
TAYLOR CREEK	6110	1.78E+07	2.77E+07	4.55E+07
UNNAMED CK	6120	1.46E+05	3.97E+05	5.42E+05
BLACKWOOD CREEK	7010	3.73E+06	2.57E+07	2.94E+07
MADDEN CREEK	7020	1.09E+06	3.21E+06	4.29E+06
HOMEWOOD CREEK	7030	5.62E+05	1.57E+06	2.13E+06
QUAIL LAKE CREEK	7040	7.73E+05	2.23E+06	3.00E+06
MKINNEY CREEK	7050	2.62E+06	7.10E+06	9.72E+06
DOLLAR CREEK	8010	9.17E+04	9.58E+05	1.05E+06
UNNAMED CK LAKE FOREST 1	8020	2.15E+05	5.62E+05	7.77E+05
UNNAMED CK LAKE FOREST 2	8030	1.13E+05	8.78E+05	9.91E+05
BURTON CREEK	8040	2.58E+05	4.57E+06	4.83E+06
TAHOE STATE PARK	8050	8.43E+04	9.11E+05	9.95E+05
WARD CREEK	8060	4.98E+06	1.89E+07	2.39E+07
KINGS BEACH	9010	9.47E+04	3.62E+05	4.57E+05
GRIFF CREK	9020	2.72E+05	3.74E+06	4.01E+06
TAHOE VISTA	9030	5.60E+05	3.97E+06	4.52E+06
CARNELIAN CANYON	9040	2.25E+05	2.63E+06	2.86E+06
CARNELIAN BAY CREEK	9050	4.89E+04	7.71E+05	8.20E+05
WATSON	9060	1.27E+05	1.94E+06	2.07E+06
TOTAL		8.81E+07	3.16E+0	4.05E+08
GRAND TOTAL		1.02E+08	3.46E+08	4.48E+08
CONTRIBUTION FROM IZ		13%	9%	10%
CONTRIBUTION FROM STREAMS		87%	91%	90%

The contribution of urban land-use areas to total flow volume was also calculated to be 10 percent (Table 4-30). This is coincidentally the same percentage contributed by intervening zones; however, the two are not directly related since the percent urban area in the intervening zones ranges from 3 percent in IZ 6000 to 72 percent in IZ 1000. Table 4-30 also shows the contributions by specific land-use category as does Figure 4-30. By far the largest flow volume came from the vegetated land-use that was made up of the five erosion potential sub-units (EP1-EP5). Flow volume from this source was 83 percent of total (Table 4-31). The next largest contributor was the combination of pervious plus impervious single family residential parcels (5 percent of total flow volume). It is interesting that a minimal volume of the non-urban flow entered via surface flow (6 percent), while for the parcels in the urban area this value was 4-times higher at 25 percent. This reflects both the higher proportion of impervious area in the urban setting and the good infiltration capacity of native Tahoe basin soils.

Table 4-30. Summary of annual surface, base and total flow volumes by land-use and urban versus non-urban category. Determined using Lake Tahoe Watershed Model and values represent mean over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Urban/Non-urban Category	Land-use	Surface Flow (m^3)	Baseflow (m^3)	Total Flow (m^3)
U	Residential_SFP	2.61E+06	1.44E+07	1.70E+07
U	Residential_MFP	4.65E+05	3.37E+06	3.84E+06
U	CICU-Pervious	3.70E+05	2.76E+06	3.13E+06
U	Residential_SFI	5.74E+06	0.00E+00	5.74E+06
U	Residential_MFI	2.24E+06	0.00E+00	2.24E+06
U	CICU-Impervious	3.04E+06	0.00E+00	3.04E+06
U	Roads_Primary	1.81E+06	0.00E+00	1.81E+06
U	Roads_Secondary	8.97E+06	0.00E+00	8.79E+06
NU	Ski_Runs-Pervious	8.19E+05	2.41E+06	3.23E+06
NU	Veg_EP1	3.35E+06	2.03E+07	2.37E+07
NU	Veg_EP2	2.68E+07	1.57E+08	1.84E+08
NU	Veg_EP3	1.87E+07	1.02E+08	1.21E+08
NU	Veg_EP4	6.07E+06	3.79E+07	4.40E+07
NU	Veg_EP5	2.60E+05	1.25E+06	1.51E+06
NU	Veg_Recreational	1.27E+05	6.07E+05	7.34E+05
NU	Veg_Burned	2.01E+05	8.61E+05	1.06E+06
NU	Veg_Harvest	9.37E+04	6.64E+05	7.58E+05
NU	Veg_Turf	2.19E+05	1.72E+06	1.94E+06
NU	Water_Body	1.98E+07	0.00E+00	1.98E+07
NU	Roads_Unpaved	1.64E+05	6.88E+05	8.52E+05
U	**TOTAL FLOW**	**2.52E+07**	**2.05E+07**	**4.58E+07**
NU	**TOTAL FLOW**	**7.66E+07**	**3.25E+08**	**4.02E+08**
			í	
	GRAND TOTAL	1.02E+08	3.46E+08	4.48E+08
	CONTRIBUTION FROM URBAN	25%	6%	10%
	CONTRIBUTION FROM NON-URBAN	75%	94%	90%

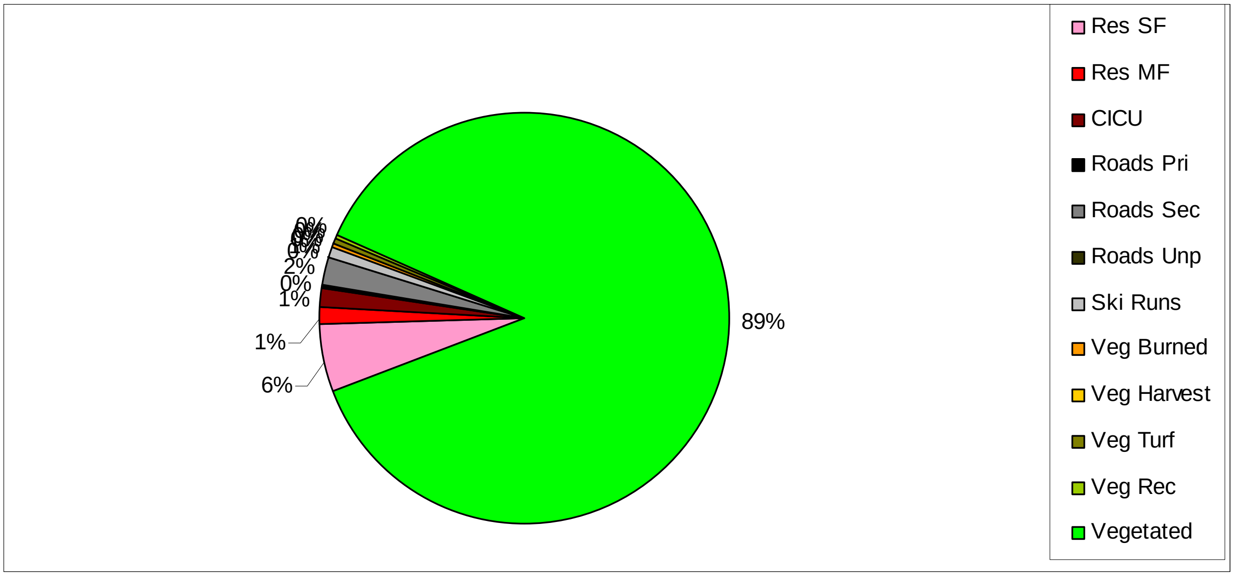

Figure 4-30. Relative contribution of major land-use types to total flow volume during the 1994-2004 model calibration/validation period (Tetra Tech 2007).

Table 4-31. Land-use area distribution and percent contribution to the model predicted outputs (Tetra Tech unpublished).

Land-use	Area	Flow	Upland TSS	Upland Fines (>63µm)	Total Nitrogen	Total Phosphorus
Residential_SFP	4.0%	3.8%	1.7%	2.3%	5.4%	7.5%
Residential_MFP	1.0%	0.9%	1.3%	1.9%	1.5%	2.2%
CICU-Pervious	0.9%	0.7%	1.3%	1.9%	1.0%	1.5%
Ski_Runs-Pervious	0.5%	0.7%	4.1%	2.5%	0.6%	1.3%
Veg_EP1	5.7%	5.2%	0.1%	0.1%	2.3%	1.4%
Veg_EP2	**46.3%**	**41.1%**	4.0%	3.2%	**20.9%**	**13.4%**
Veg_EP3	**26.1%**	**27.0%**	**17.6%**	**13.5%**	**16.4%**	**12.4%**
Veg_EP4	8.9%	9.7%	**33.1%**	**25.9%**	6.4%	6.3%
Veg_EP5	0.2%	0.3%	4.0%	3.2%	0.2%	0.4%
Veg_Recreational	0.2%	0.2%	0.2%	0.2%	0.2%	0.3%
Veg_Burned	0.2%	0.2%	1.0%	0.8%	0.4%	0.8%
Veg_Harvest	0.2%	0.2%	0.8%	0.6%	0.2%	0.5%
Veg_Turf	0.5%	0.4%	0.0%	0.0%	0.9%	2.0%
Water_Body	1.7%	n/a	n/a	n/a	n/a	n/a
Residential_SFI	0.9%	1.3%	2.0%	2.7%	7.6%	8.4%
Residential_MFI	0.4%	0.5%	2.3%	3.5%	4.8%	4.0%
CICU-Impervious	0.5%	0.7%	5.0%	7.4%	5.2%	5.3%
Roads_Primary	0.3%	0.4%	**10.8%**	**16.2%**	5.4%	**12.2%**
Roads_Secondary	1.3%	2.1%	8.6%	**12.9%**	**20.2%**	**18.1%**
Roads_Unpaved	0.2%	0.2%	2.0%	1.4%	0.4%	2.0%

Figure 4-31 shows the higher unit-area flows (i.e. flow volume per area of land surface) along the west shore.

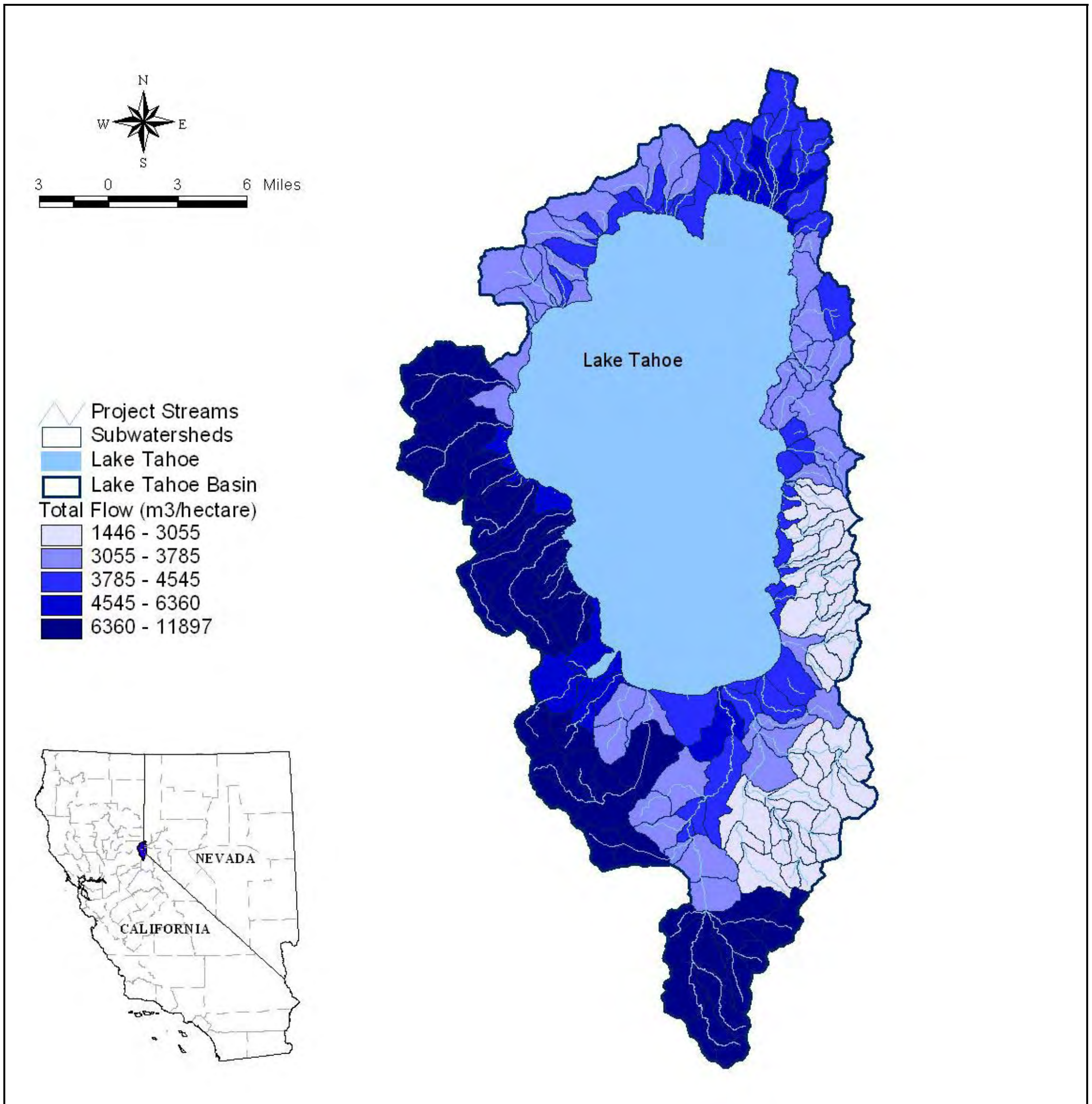

Figure 4-31. Unit-area annual water yield (m^3/ha) by subwatershed (Tetra Tech 2007).

Suspended sediment

Summary results from the Lake Tahoe Watershed Model for sediment loads from upland TSS, upland fines (< 63 µm), channel fines (< 63 µm) and total fines (< 63 µm expressed as the sum of upland and channel) are given in Table 4-32. Values designated as upland loads do not include sediment from stream channel erosion. Total upland TSS over the 1994-2004 period of record was nearly 17,000 metric tons per year with 83 percent coming from overland flow into streams and 17 percent from intervening zones. Of the total upland TSS load (streams + intervening zones), an estimated 9,100 metric tons or approximately 65 percent were in the < 63 µm size range. For the streams, approximately 50 percent of the TSS load was < 63 µm while that proportion increased to 75 percent within the intervening zones. When this same comparison is made between urban and non-urban areas the difference is even more pronounced with approximately 85 percent of the TSS load from urban land-uses associated with the < 63 µm size class. The contribution of upland fines to upland TSS in the non-urban areas was only 40 percent. This demonstrates the importance of upland fine sediment loading from urban areas. Overall, 31 percent of the upland TSS load (16,921 metric tons/year) came from urban sources while approximately 50 percent of the upland fines came from urban land-uses (Table 4-33).

Channel fines come only from stream channels, therefore values for intervening zones are not applicable. It was estimated that a total of 3,768 metric tons of fine sediment (< 63 µm) came from this source. This represents nearly 30 percent of the 12,872 metric tons/year load of total fines. The contribution of upland fines (9,100 metric tons/year) represents the remaining 70 percent of the total fines load (Table 4-32).

Table 4-32. Summary of annual upland TSS, upland fines, channel fines and total fines loads by watershed as determined using the Lake Tahoe Watershed Model. Channel fines were not explicitly modeled using the Lake Tahoe Watershed Model (see text on model calibration). Values represent means over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Tributary	OUTLET SWS	Upland TSS Load (metric tons)	Upland Fines Load (metric tons)	Channel Fines (metric tons)	Total Fines (metric tons)
INTERVENING ZONE LOAD					
IVZ1000	1000	435	336	NA	336
IVZ2000	2000	114	97	NA	97
IVZ3000	3000	28	23	NA	23
IVZ4000	4000	292	248	NA	248
IVZ5000	5000	150	122	NA	122
IVZ6000	6000	122	96	NA	96
IVZ6001	6001	129	103	NA	103
IVZ7000	7000	469	304	NA	304
IVZ8000	8000	524	405	NA	405
IVZ9000	9000	679	468	NA	468
TOTAL		2942	2202	NA	2202
STREAM LOAD					
MILL CREEK	1010	114	94	0	94
INCLINE CREEK	1020	546	420	16	436
THIRD CREEK	1030	292	211	23	234
WOOD CREEK	1040	98	70	0	71
BURNT CEDAR CREEK	1050	80	60	4	64
SECOND CREEK	1060	51	26	0	26
FIRST CREEK	1070	79	29	0	30

Tributary	OUTLET SWS	Upland TSS Load (metric tons)	Upland Fines Load (metric tons)	Channel Fines (metric tons)	Total Fines (metric tons)
SLAUGHTER HOUSE	2010	11	9	1	10
BLISS CREEK	2020	10	8	0	9
SECRET HARBOR CREEK	2030	28	23	0	23
MARLETTE CREEK	2040	28	23	2	25
BONPLAND	2050	3	2	0	2
TUNNEL CREEK	2060	4	3	0	3
MCFAUL CREEK	3010	2	1	0	2
ZEPHYR CREEK	3020	1	1	0	1
NORTH ZEPHYR CREEK	3030	1	1	0	1
LINCOLN CREEK	3040	3	2	0	2
CAVE ROCK	3050	1	0	0	0
LOGAN HOUSE CREEK	3060	5	4	0	4
NORTH LOGAN HOUSE CREEK	3070	2	1	0	1
GLENBROOK CREEK	3080	32	26	22	47
BIJOU CREEK	4010	85	71	0	71
EDGEWOOD CREEK	4020	26	22	5	27
BURKE CREEK	4030	7	6	0	6
UPPER TRUCKEE RIVER	5010	2219	1309	2259	3569
TROUT CREEK	5050	257	205	3	208
GENERAL CREEK	6010	160	59	48	107
MEEKS	6020	137	54	12	66
SIERRA CREEK	6030	35	23	0	23
LONELY GULCH CREEK	6040	36	25	0	25
PARADISE FLAT	6050	11	7	0	7
RUBICON CREEK	6060	90	59	3	62
EAGLE CREEK	6080	40	22	0	22
CASCADE CREEK	6090	20	13	0	13
TALLAC CREEK	6100	52	31	0	32
TAYLOR CREEK	6110	272	137	3	139
UNNAMED CK	6120	16	11	0	11
BLACKWOOD CREEK	7010	1816	839	873	1712
MADDEN CREEK	7020	918	268	0	269
HOMEWOOD CREEK	7030	908	272	0	272
QUAIL LAKE CREEK	7040	405	123	0	123
MKINNEY CREEK	7050	192	88	0	88
DOLLAR CREEK	8010	113	51	1	51
UNNAMED CK LAKE FOREST 1	8020	92	65	0	65
UNNAMED CK LAKE FOREST 2	8030	92	47	0	47
BURTON CREEK	8040	366	117	1	118
TAHOE STATE PARK	8050	57	32	0	32
WARD CREEK	8060	2994	1439	485	1924
KINGS BEACH	9010	57	29	0	29

Tributary	OUTLET SWS	Upland TSS Load (metric tons)	Upland Fines Load (metric tons)	Channel Fines (metric tons)	Total Fines (metric tons)
GRIFF CREEK	9020	300	114	5	119
TAHOE VISTA	9030	489	223	2	225
CARNELIAN CANYON	9040	168	70	0	70
CARNELIAN BAY CREEK	9050	39	14	0	14
WATSON	9060	119	39	0	39
TOTAL		13979	6898	3768	10670
GRAND TOTAL		16921	9100	3768	12872
CONTRIBUTION FROM IZ		17%	24%	0%	17%
CONTRIBUTION FROM STREAMS		83%	76%	100%	83%

Table 4-33. Summary of annual upland TSS loads, upland fines loads and associated flow-weighted average concentration by land-use and urban versus non-urban category. Determined using the Lake Tahoe Watershed Model and values represent means over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Urban/Non-urban Category	Land-use	Upland TSS (metric tons/year)	Upland Fines (metric tons/year)	Upland TSS Concentration (mg/L)	Upland Fines Concentration (mg/L)
U	Residential_SFP	269	205	103	78
U	Residential_MFP	194	172	418	370
U	CICU-Pervious	205	175	555	474
U	Residential_SFI	319	243	56	42
U	Residential_MFI	358	316	160	141
U	CICU-Impervious	788	673	260	222
U	Roads_Primary	1,720	1,470	950	811
U	Roads_Secondary	1,380	1,180	154	131
NU	Ski_Runs-Pervious	695	227	848	278
NU	Veg_EP1	20.9	8.93	6	3
NU	Veg_EP2	3,050	290	26	11
NU	Veg_EP3	3,050	1,230	163	66
NU	Veg_EP4	5,810	2,360	957	388

Urban/Non-urban Category	Land-use	Upland TSS (metric tons/year)	Upland Fines (metric tons/year)	Upland TSS Concentration (mg/L)	Upland Fines Concentration (mg/L)
NU	Veg_ep5	686	288	2640	1110
NU	Veg_Recreational	41.3	17.2	326	135
NU	Veg_Burned	189	68.7	941	342
NU	Veg_Harvest	142	54.1	1520	577
NU	Veg_Turf	7.49	2.72	34	12
NU	Roads_Unpaved	354	126	2150	770
U	**TOTAL LOAD**	**5233**	**4434**		
NU	**TOTAL LOAD**	**11687**	**4673**		
	GRAND TOTAL	16920	9107		
	CONTRIBUTION FROM URBAN	31%	49%		
	CONTRIBUTION FROM NON-URBAN	69%	51%		

An examination of upland TSS and upland fine sediment loading by specific land-use category is presented in Table 4-31, Table 4-33 and Figure 4-32. The largest contributors in decreasing order were, vegetated-erosion potential-4, vegetated-erosion potential-3, primary roads, secondary road, CICU commercial, and ski runs. These contributed nearly 80 percent of the upland TSS load. Single and multiple family residential contributed 7 percent of the total upland TSS load. Within the urban category, primary and secondary roads plus CICU commercial accounted for about 75 percent of the upland TSS load.

For upland fine sediment (< 63 µm), the top six contributors in descending order were vegetated-erosion potential-4, primary roads, vegetated-erosion potential-3, secondary roads, CICU commercial and single family residences. These accounted for > 80 percent of the total 9,107 metric tons/year load from upland fines. Estimated concentrations for upland TSS and upland fines are also given in Table 4-33.

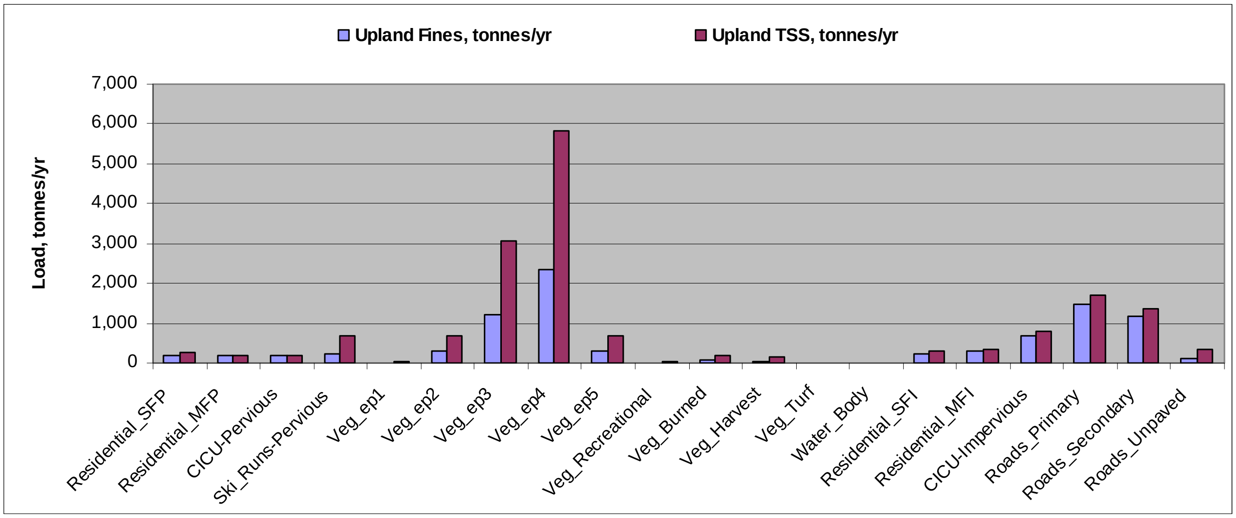

Figure 4-32. Upland TSS and upland fine sediment loading by land-use category as determined by the Lake Tahoe Watershed Model over the 1994-2004 calibration/validation period (note: tonnes is referred to as metric tons in this report) (Tetra Tech 2007).

The loads in Figure 4-32, Table 4-31, and Table 4-32 are dependent upon flow volume, concentration and area. Figure 4-33 provides an example of the relative load for upland TSS when expressed on a per unit area basis. As can be seen a very large amount of TSS comes from each hectare of primary road surface with minimal values for turf, vegetated and single family residential land-uses. It is important to keep in mind that a unit area load may be high but if the total area of that land-use is small; its contribution to basin-wide loading is likely to be low. Figure 4-34 and Figure 4-35 show modeling results for unit-area TSS and fine sediment around the basin.

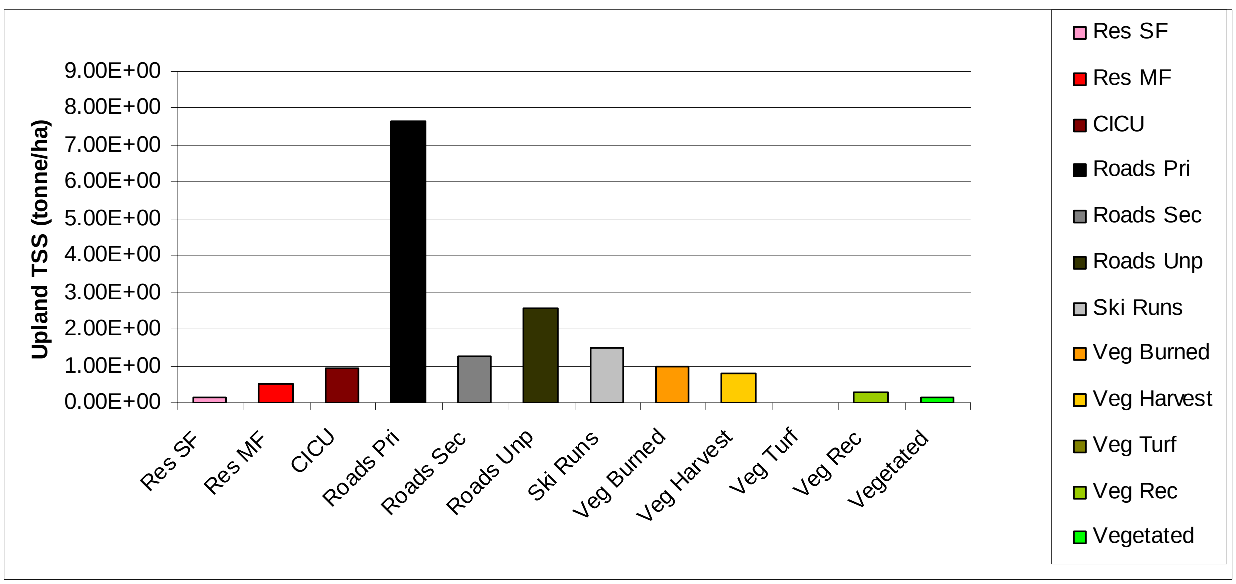

Figure 4-33. Relative upland TSS load from selected land-use categories as compared on a per unit area (per hectare) basis (note: tonne is referred to as metric ton in this report) (Tetra Tech 2007).

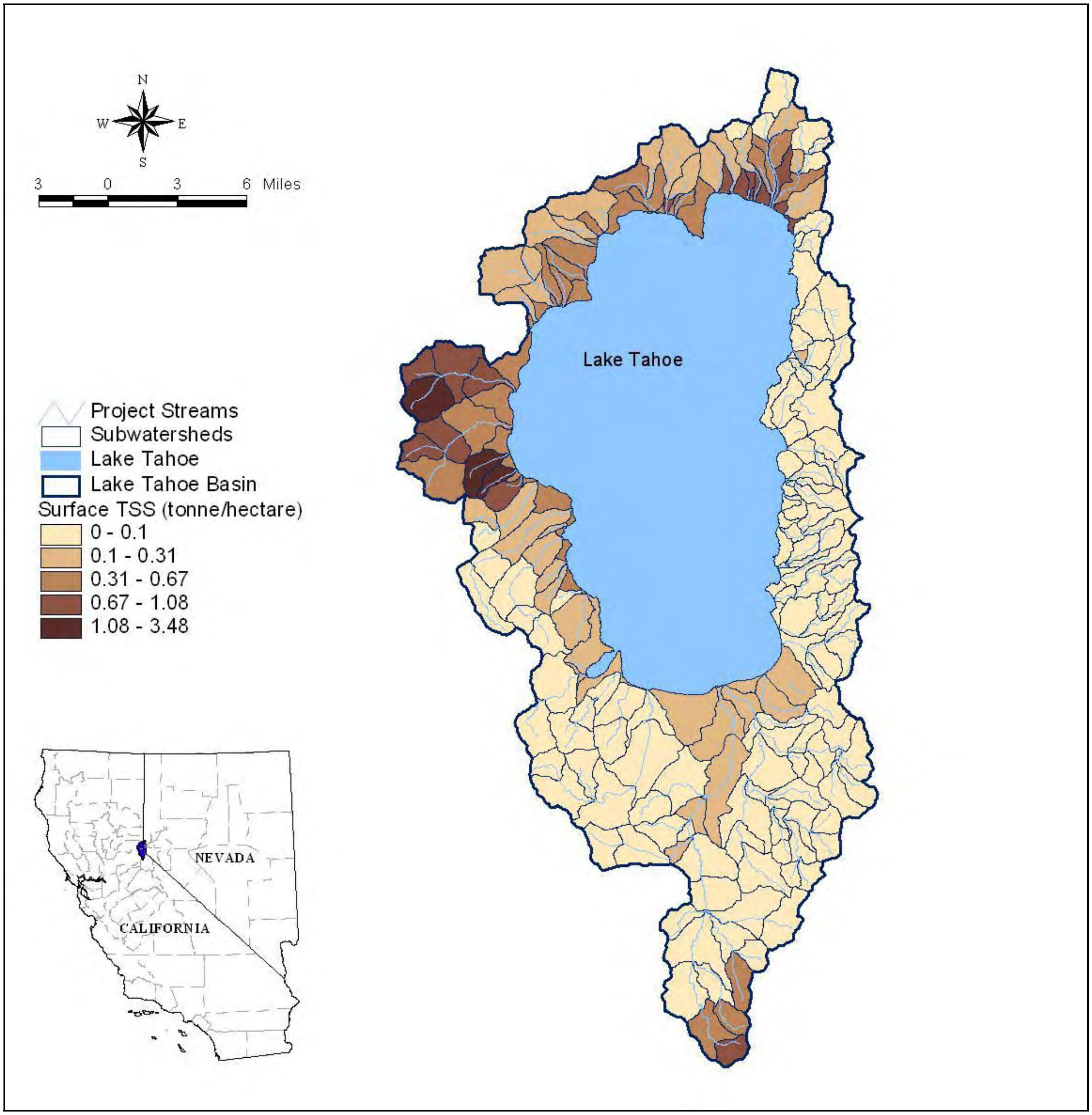

Figure 4-34. Unit-area annual total sediment yield (metric tons/ha) by subwatershed (note: tonnes is referred to as metric tons in this report) (Tetra Tech 2007).

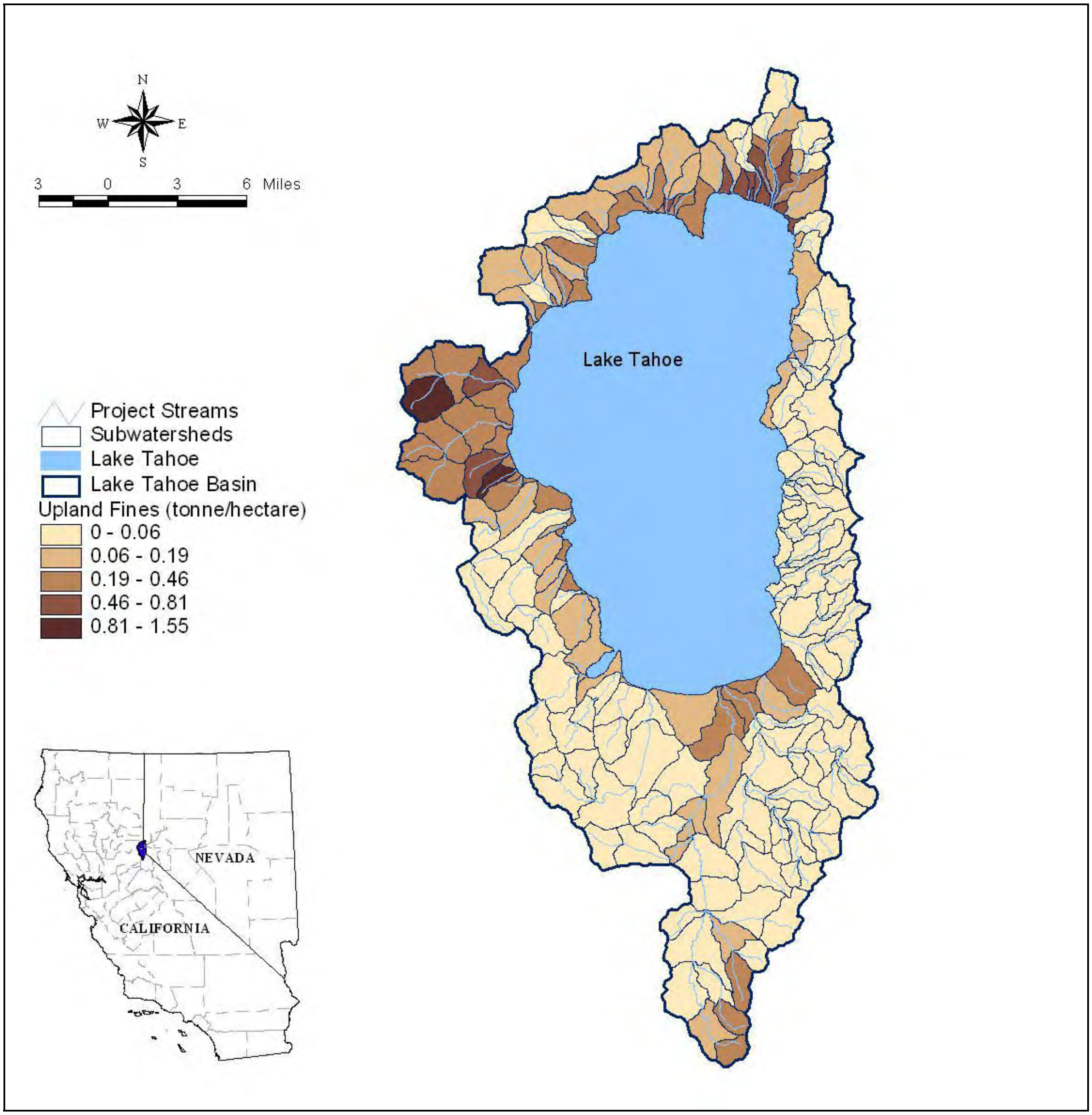

Figure 4-35. Unit-area annual fine sediment yield (metric tons/ha) by subwatershed (note: tonne is referred to as metric ton in this report) (Tetra Tech 2007).

Nitrogen

The load of total nitrogen (TN) from watershed sources was estimated by the Tahoe Watershed Model to be approximately 125 metric tons/year over the 1994-2004 calibration period (Table 4-34)(note: that in this discussion all values refer to just the nitrogen content of the compounds; i.e. expressed in units of nitrogen). This agrees well with the value of 105 metric tons for TN reported using data collected prior 1993 (Reuter et al. 2003). The later estimate was not based on modeling, but rather on extrapolation of the LTIMP or other even more limited databases to the whole basin.

Given the different time periods for each estimate and the fact that the applied methods of calculation were so different, the similarity of results is noteworthy.

Of the 125 metric tons total load, 25 percent was estimated to come from intervening zones and 75 percent from stream flow (Table 4-34). Again, using different and less sophisticated methodologies the reported contributions from stream flow and intervening zones were nearly identical at 78 percent and 22 percent, respectively Reuter et al. (2003). As expected based on flow, the Upper Truckee River was the largest single contributor with a load of about 24 metric tons/year or 25 percent of all streams.

Table 4-34. Summary of annual surface, base and total nitrogen by watershed as determined using the Lake Tahoe Watershed Model. Values represent means over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Tributary	OUTLET SWS	Surface TN Load (kg)	Baseflow TN Load (kg)	Total TN Load (kg)
INTERVENING ZONE RUNOFF				
IVZ1000	1000	2631	280	2911
IVZ2000	2000	502	582	1084
IVZ3000	3000	1039	229	1268
IVZ4000	4000	4062	192	4254
IVZ5000	5000	2484	316	2800
IVZ6000	6000	870	929	1799
IVZ6001	6001	1990	232	2221
IVZ7000	7000	4390	462	4852
IVZ8000	8000	5588	514	6102
IVZ9000	9000	3196	823	4019
TOTAL		26752	4559	31310
STREAM FLOW				
MILL CREEK	1010	593	341	934
INCLINE CREEK	1020	2173	1127	3300
THIRD CREEK	1030	1846	978	2824
WOOD CREEK	1040	651	311	962
BURNT CEDAR CREEK	1050	465	38	502
SECOND CREEK	1060	230	220	450
FIRST CREEK	1070	118	285	403
SLAUGHTER HOUSE	2010	140	249	389
BLISS CREEK	2020	33	69	102
SECRET HARBOR CREEK	2030	108	438	546
MARLETTE CREEK	2040	132	541	673
BONPLAND	2050	20	109	129
TUNNEL CREEK	2060	23	218	240

MCFAUL CREEK	3010	131	217	349
ZEPHYR CREEK	3020	52	98	150
NORTH ZEPHYR CREEK	3030	33	156	189
LINCOLN CREEK	3040	31	147	179
CAVE ROCK	3050	20	43	63
LOGAN HOUSE CREEK	3060	34	124	157
NORTH LOGAN HOUSE CREEK	3070	12	56	69
GLENBROOK CREEK	3080	166	216	383
BIJOU CREEK	4010	1455	126	1581
EDGEWOOD CREEK	4020	1154	217	1371
BURKE CREEK	4030	350	189	539
UPPER TRUCKEE RIVER	5010	13981	10133	24115
TROUT CREEK	5050	4046	2492	6538
GENERAL CREEK	6010	1201	1944	3145
MEEKS	6020	1376	2084	3460
SIERRA CREEK	6030	380	221	601
LONELY GULCH CREEK	6040	578	273	851
PARADISE FLAT	6050	175	159	334
RUBICON CREEK	6060	982	725	1707
EAGLE CREEK	6080	444	2479	2923
CASCADE CREEK	6090	213	853	1067
TALLAC CREEK	6100	291	421	712
TAYLOR CREEK	6110	1872	3512	5384
UNNAMED CK	6120	188	65	254
BLACKWOOD CREEK	7010	1850	6553	8402
MADDEN CREEK	7020	419	533	952
HOMEWOOD CREEK	7030	360	260	619
QUAIL LAKE CREEK	7040	364	371	735
MKINNEY CREEK	7050	1949	1177	3126
DOLLAR CREEK	8010	111	166	277
UNNAMED CK LAKE FOREST 1	8020	487	97	584
UNNAMED CK LAKE FOREST 2	8030	196	152	348
BURTON CREEK	8040	61	805	866
TAHOE STATE PARK	8050	108	160	268
WARD CREEK	8060	2883	3561	6444
KINGS BEACH	9010	191	62	254
GRIFF CREEK	9020	308	669	978
TAHOE VISTA	9030	1078	695	1773
CARNELIAN CANYON	9040	267	463	730
CARNELIAN BAY CREEK	9050	28	135	164
WATSON	9060	66	350	416
TOTAL		46423	48083	94511
GRAND TOTAL		73175	52646	125821
CONTRIBUTION FROM IZ		37%	9%	25%
CONTRIBUTION FROM STREAMS		63%	91%	75%

The contribution of dissolved inorganic-N (nitrate + ammonium; and those forms most readily used by algae) is presented in Table 4-35. Combined annual DIN loading from streams flow and intervening zones was modeled at 11.8 metric tons/year over the 1994-2004 calibration period. The ratio of DIN to TN was 9 percent, with organic-N accounting for the vast majority of TN. This finding from the Tahoe Watershed Model was identical to the finding in Coats and Goldman (2001) that for Lake Tahoe streams the discharge weighted concentration of organic-N was usually 10 times that of inorganic-N. Model results suggested that TN load from the intervening zones were 31 percent of the total combined load with 69 percent contributed from stream flow (Table 4-35). As for the other pollutants considered in this study, the contribution of the intervening zones was approximately 2 − 3 times that of flow. This highlights the fact that many of the urban areas – with elevated pollutant concentrations – are located in the intervening zones. Finally, while baseflow and surface TN loads were nearly the same for the stream flow sources, surface TN load exceed baseflow TN load in the intervening zones by factor of nearly 6-fold.

Table 4-35. Summary of annual loads for dissolved inorganic-N (sum of nitrate and ammonium) and soluble reactive-P by watershed as determined using the Lake Tahoe Watershed Model. Values represent means over the 1994-2004 calibration/validation period (Tetra Tech unpublished).

Tributary	Soluble Reactive-P (kg)	DIN (kg)
INTERVENING ZONE RUNOFF		
IVZ1000	129	356
IVZ2000	51	90
IVZ3000	59	140
IVZ4000	89	552
IVZ5000	70	340
IVZ6000	100	159
IVZ6001	89	245
IVZ7000	251	561
IVZ8000	395	761
IVZ9000	189	463
TOTAL	1423	3667
STREAM FLOW		
MILL CREEK	45	91
INCLINE CREEK	172	338
THIRD CREEK	173	2844
WOOD CREEK	46	102
BURNT CEDAR CREEK	20	63
SECOND CREEK	23	42
FIRST CREEK	26	30
SLAUGHTER HOUSE	44	30
BLISS CREEK	5	8
SECRET HARBOR CREEK	26	36
MARLETTE CREEK	32	44

Tributary	Soluble Reactive-P (kg)	DIN (kg)
BONPLAND	6	8
TUNNEL CREEK	15	14
MCFAUL CREEK	14	26
ZEPHYR CREEK	6	11
NORTH ZEPHYR CREEK	9	12
LINCOLN CREEK	9	11
CAVE ROCK	3	5
LOGAN HOUSE CREEK	8	10
NORTH LOGAN HOUSE CREEK	10	4
GLENBROOK CREEK	42	31
BIJOU CREEK	34	199
EDGEWOOD CREEK	41	160
BURKE CREEK	14	56
UPPER TRUCKEE RIVER	833	2283
TROUT CREEK	183	663
GENERAL CREEK	129	221
MEEKS	140	241
SIERRA CREEK	25	54
LONELY GULCH CREEK	32	82
PARADISE FLAT	13	26
RUBICON CREEK	73	140
EAGLE CREEK	146	180
CASCADE CREEK	47	69
TALLAC CREEK	30	57
TAYLOR CREEK	227	389
UNNAMED CK	10	26
BLACKWOOD CREEK	668	573
MADDEN CREEK	91	66
HOMEWOOD CREEK	87	50
QUAIL LAKE CREEK	48	58
MKINNEY CREEK	117	283
DOLLAR CREEK	22	23
UNNAMED CK LAKE FOREST 1	26	69
UNNAMED CK LAKE FOREST 2	21	33
BURTON CREEK	69	52
TAHOE STATE PARK	19	23
WARD CREEK	456	508
KINGS BEACH	11	29
GRIFF CREK	70	76
TAHOE VISTA	133	174
CARNELIAN CANYON	52	59
CARNELIAN BAY CREEK	13	11

Tributary	Soluble Reactive-P (kg)	DIN (kg)
WATSON	31	28
TOTAL	4646	8158
GRAND TOTAL	6069	11825
CONTRIBUTION FROM IZ	23%	31%
CONTRIBUTION FROM STREAMS	72%	69%

The previous observation regarding elevated nitrogen concentrations in urban areas is supported by the nitrogen load estimates separated on the basis of urban versus non-urban land-use (Table 4-36). Despite the finding that urban zones only contributed 10 percent of the total flow volume (Table 4-30), the TN loads from urban and non-urban land-use areas were identical with each representing 50 percent of the total load. Notice the much higher TN concentrations for surface flow coming from urban land-uses (Table 4-36). Baseflow concentrations were relatively uniform because much of the organic load could be trapped as the flow infiltrated into and through the natural soils.

Table 4-36. Summary of annual upland surface, base, and total nitrogen loads, and associated flow-weighted average concentration by land-use and urban versus non-urban category. Determined using the Lake Tahoe Watershed Model and values represent means over the 1994-2004 calibration period (modified from Tetra Tech 2007).

Urban/Non-urban Category	Land-use	Surface TN (kg/year)	Baseflow TN (kg/year)	Total TN (kg/year)	Surface TN Concentration (mg/L)	Baseflow TN Concentration (mg/L)
U	Residential_SFP	4,920	1,980	6,900	1.88	0.14
U	Residential_MFP	1,310	484	1,790	2.81	0.14
U	CICU-Pervious	891	373	1,260	2.41	0.14
U	Residential_SFI	9,440	0	9,440	1.64	NA
U	Residential_MFI	5,860	0	5,860	2.62	NA
U	CICU-Impervious	6,380	0	6,380	2.10	NA
U	Roads_Primary	6,740	0	6,740	3.72	NA
U	Roads_Secondary	25,100	0	25,100	2.79	NA

Urban/Non-urban Category	Land-use	Surface TN (kg/year)	Baseflow TN (kg/year)	Total TN (kg/year)	Surface TN Concentration (mg/L)	Baseflow TN Concentration (mg/L)
NU	Ski_Runs-Pervious	415	352	767	0.51	.0.15
NU	Veg_EP1	459	2,530	2,990	0.14	0.13
NU	Veg_EP2	4,430	22,100	26,500	0.17	0.14
NU	Veg_EP3	3,840	17,000	20,800	0.21	0.17
NU	Veg_EP4	1,300	6,910	8,210	0.21	0.18
NU	Veg_eEP5	64.9	246	311	0.25	0.20
NU	Veg_Recreational	153	89.1	242	1.21	0.15
NU	Veg_Burned	431	110	541	2.14	0.13
NU	Veg_Harvest	165	81.7	247	1.76	0.12
NU	Veg_Turf	842	232	1,070	3.85	0.14
NU	Roads_Unpaved	470	106	576	2.86	1.15
U	**TOTAL LOAD**	**60641**	**2837**	**63478**		
NU	**TOTAL LOAD**	**12569**	**49757**	**62326**		
	GRAND TOTAL	73210	52594	125804		
	CONTRIBUTION FROM URBAN	83%	55%	50%		
	CONTRIBUTION FROM NON-URBAN	17%	95%	50%		

The TN loading data contained in Table 4-35 are plotted in Figure 4-36. Upland total nitrogen loading by land-use category as determine by the Lake Tahoe Watershed Model over the 1994-2004 calibration/validation period (Tetra Tech 2007). and summarized in Table 4-31. It was estimated that 50 percent of the TN coming from urban land-uses came from primary (approximately 10 percent) and secondary (approximately 40 percent) roads; or 26 percent from all land-uses. Single and multiple family residences combined 38 percent of the TN load from urban areas and 20 percent from all land-uses. More than 95 percent of the TN load from non-urban areas came from the vegetated forest (EP1-EP5); this source was 46 percent of the total watershed TN load.

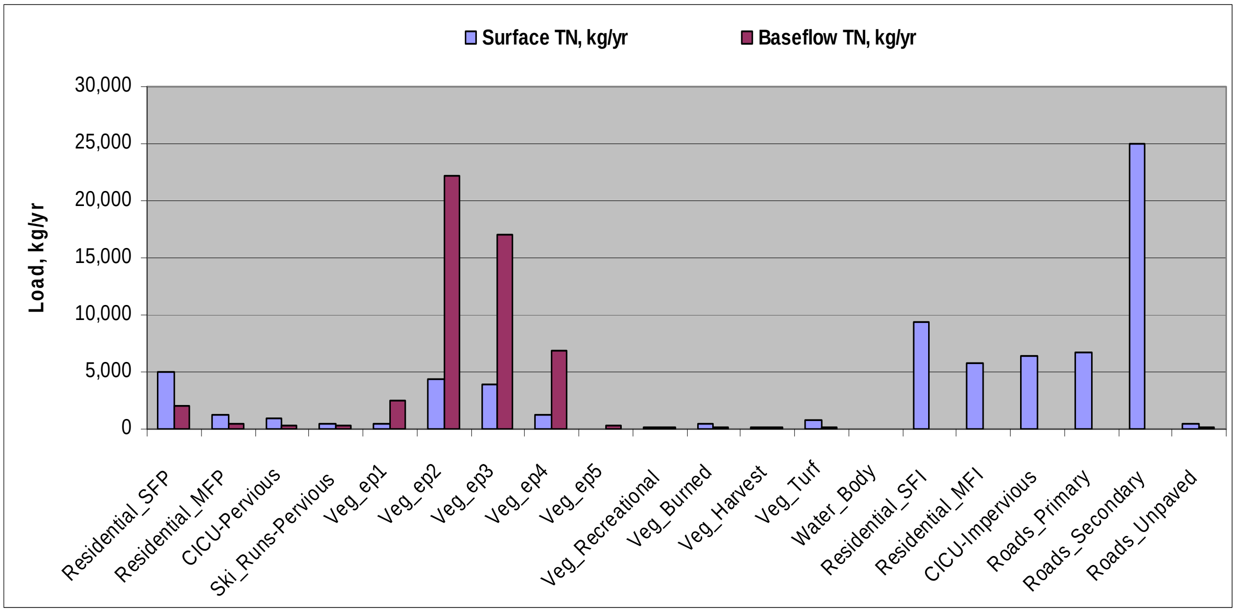

Figure 4-36. Upland total nitrogen loading by land-use category as determine by the Lake Tahoe Watershed Model over the 1994-2004 calibration/validation period (Tetra Tech 2007).

Figure 4-37 demonstrates that as found for TSS, the primary roads deliver the most TN per unit area, followed closely by secondary roads. Again, it is important to note that while the per unit TN load from the vegetated forest is the lowest, when the extent of forested land area and runoff is considered, it becomes the most significant contributor. Figure 4-38 shows the distribution of unit-area loading for TN around the basin.

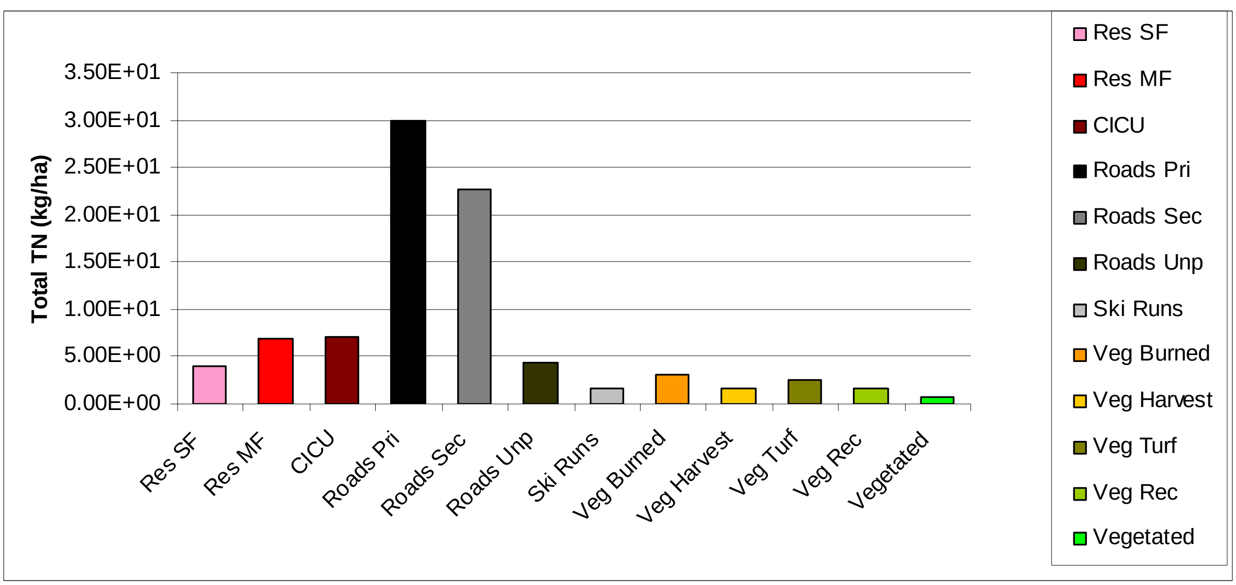

Figure 4-37. Relative upland nitrogen load from selected land-use categories as compared on a per unit area (per hectare) basis (Tetra Tech 2007).

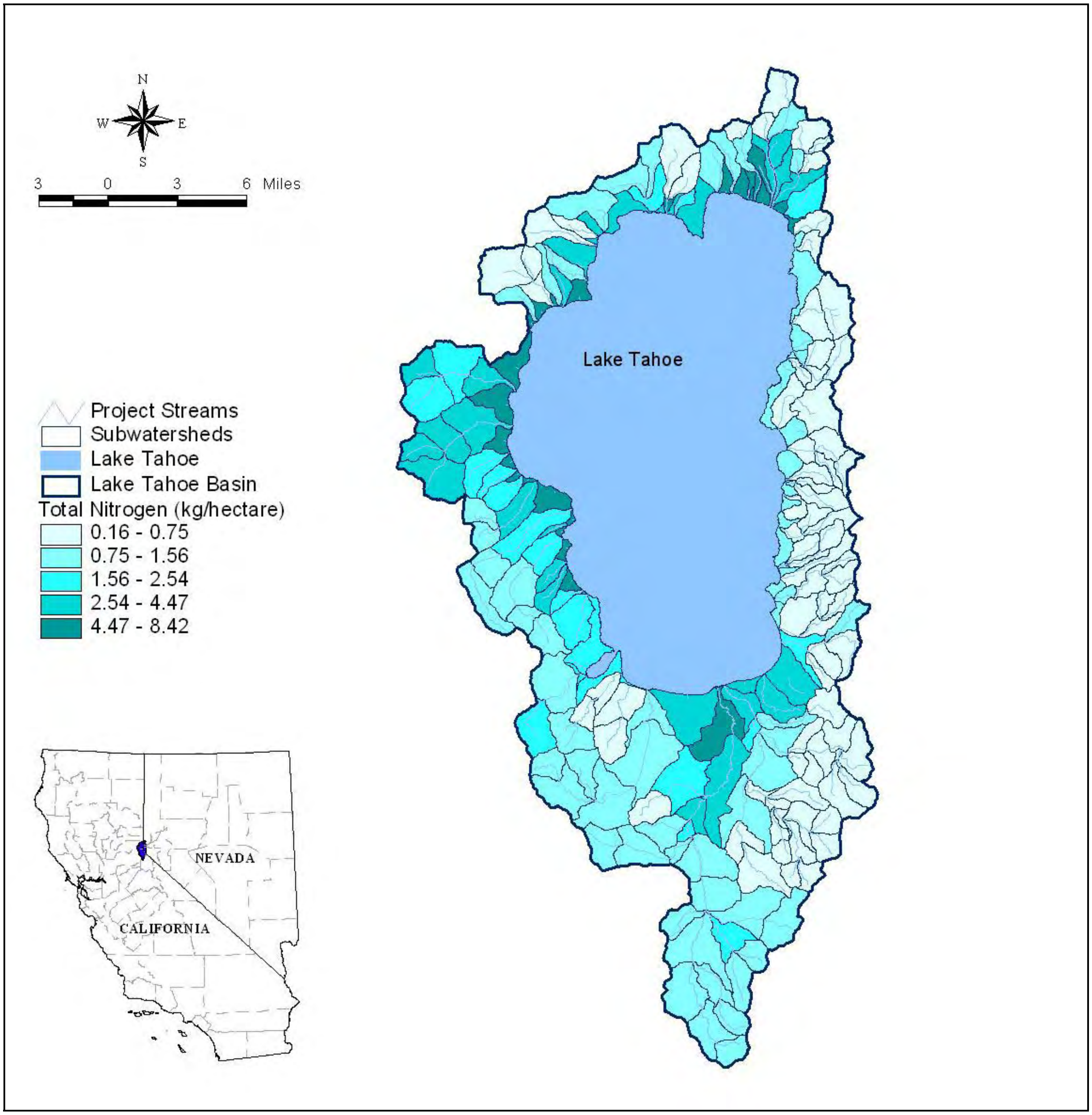

Figure 4-38. Unit-area total nitrogen yield (kg/ha) by subwatershed (Tetra Tech 2007).

An analysis of DIN loading by land-use is summarized in Table 4-37. Average annual loading attributed to urban land-uses was approximately 8 metric tons compared to 3.9 metric tons for the non-urban land-uses. The 2:1 ratio of DIN load from urban versus no-urban was higher than the 1:1 ratio seen for TN loading from these two land-use categories, respectively. This identifies the urban areas as an important source of DIN. Within the urban land area, secondary (43 percent) and primary roads (11 percent) accounted for greater than half the urban DIN load with single and multiple family residental accounting for 34 percent of the urban DIN load. Commercial/industrial land-use contributed about 12 percent.

Of the 3.9 metric tons/year for DIN estimated to come from non-urban land-uses, 90-95 percent was attributed to the vegetated, undeveloped regions (EP1-EP5). Negligible amounts of DIN appeared to results from the remaining land-uses within the non-urban classification (e.g. veg-recreational, veg-turf, burned, harvested, ski runs).

Table 4-37. Summary of annual upland dissolved inorganic-N (nitrate+ammonium) and soluble reactive-P loads, and associated flow-weighted average concentration by land-use and urban versus non-urban category. Determined using Lake Tahoe Watershed Model and values represent means over the 1994-2004 calibration/validation period (Tetra Tech unpublished).

Urban/Non-Urban	Land-use	Soluble Reactive-P (kg/yr)	DIN (kg/yr)	Soluble Reactive-P Concentration (mg/L)	DIN Concentration (mg/L)
U	Residential_SFP	515	512	0.0304	0.0302
U	Residential_MFP	147	133	0.0383	0.0348
U	CICU-Pervious	100	93	0.0320	0.0298
U	Residential_SFI	272	1275	0.0475	0.2220
U	Residential_MFI	126	791	0.0562	0.3533
U	CICU-Impervious	171	862	0.0563	0.2841
U	Roads_Primary	396	910	0.2185	0.5023
U	Roads_Secondary	588	3386	0.0655	0.3774
NU	Ski_Runs-Pervious	93	54	0.0288	0.0166
NU	Veg_EP1	138	182	0.0058	0.0077
NU	Veg_EP2	1328	1624	0.0072	0.0088
NU	Veg_EP3	1205	1281	0.0100	0.0106
NU	Veg_EP4	595	500	0.0135	0.0114
NU	Veg_EP5	32	19	0.0213	0.0128
NU	Veg_Recreational	23	17	0.0311	0.0238
NU	Veg_Burned	54	41	0.0510	0.0388
NU	Veg_Harvest	31	18	0.0410	0.0238
NU	Veg_Turf	123	81	0.0637	0.0420
U	**TOTAL LOAD**	2320	7960		
NU	**TOTAL LOAD**	3750	3860		
	GRAND TOTAL	6070	11820		
	CONTRIBUTION FROM URBAN	38%	67%		
	CONTRIBUTION FROM NON-URBAN	62%	33%		

Phosphorus

The load of total phosphorus (TP) from watershed sources was estimated by the Tahoe Watershed Model to be approximately 30 metric tons/year over the 1994-2004 calibration period (Table 4-38). Again, this agrees well with the overall value of 26 metric tons for TP reported using data collected prior to 1993 (Reuter et al. 2003). As noted above for TN, the later estimate was not based on modeling, but rather on extrapolation of the LTIMP data to the whole basin. Given the different time periods for each estimate and the fact that the applied methods of calculation were so different, the results are none the less very similar.

Of the 30 metric tons total load for TP, 32 percent was estimated to come from intervening zones with 68 percent from stream flow (Table 4-38). This differs from Reuter et al. (2003) who reported an equal contribution from each source. In fact, it was the identified uncertainty associated with the intervening zones loads (Reuter and Miller 2000, Reuter et al. 2003) that prompted more detailed studies to be undertaken as part of the TMDL effort. The Upper Truckee River was the largest single contributor with a load of about 4 metric tons/year or 20 percent of all streams. Combined, the Upper Truckee River and Trout Creek contributed just over 5 metric tons/year, while the west shore tributaries of Ward Creek and Blackwood Creek were not far behind with a combined load of > 4 metric tons/year.

The modeled combined load for ortho-P and SRP from both streams and the intervening zone sources was 6 metric tons/year with 23 percent from intervening zones and the remaining 72 percent from upland stream flow (Table 4-35). For the purposes of this document, ortho-phosphorus and SRP are indistinguishable, as they are both considered immediately available for algal growth. The calculated ratios of SRP:TP were 20 percent for all sources, 15 percent for intervening zones and 23 percent for stream flow. The 20 percent value for SRP:TP was higher than the approximately 10 percent value for DIN/TN. While Tahoe-specific studies have not been done, it is likely that this is related to the fact that SRP can be readily leached into water from particulate-phosphorus associated with sediment.

Table 4-38. Summary of annual surface, base and total phosphorus by watershed as determined using the Lake Tahoe Watershed Model. Values represent means over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Tributary	OUTLET SWS	Surface TP Load (kg)	Baseflow TP Load (kg)	Total TP Load (kg)
INTERVENING ZONE RUNOFF				
IVZ1000	1000	772	60	831
IVZ2000	2000	180	82	263

Tributary	OUTLET SWS	Surface TP Load (kg)	Baseflow TP Load (kg)	Total TP Load (kg)
IVZ3000	3000	169	102	270
IVZ4000	4000	739	21	760
IVZ5000	5000	477	42	519
IVZ6000	6000	439	135	574
IVZ6001	6001	639	26	665
IVZ7000	7000	1717	53	1770
IVZ8000	8000	2858	92	2950
IVZ9000	9000	951	176	1127
TOTAL		8941	789	9729
STREAM FLOW				
MILL CREEK	1010	159	66	224
INCLINE CREEK	1020	657	221	877
THIRD CREEK	1030	632	211	843
WOOD CREEK	1040	166	67	232
BURNT CEDAR CREEK	1050	131	8	139
SECOND CREEK	1060	49	47	96
FIRST CREEK	1070	29	61	90
SLAUGHTER HOUSE	2010	31	110	141
BLISS CREEK	2020	14	10	23
SECRET HARBOR CREEK	2030	29	62	91
MARLETTE CREEK	2040	33	76	109
BONPLAND	2050	3	15	18
TUNNEL CREEK	2060	4	42	45
MCFAUL CREEK	3010	22	30	52
ZEPHYR CREEK	3020	9	14	23
NORTH ZEPHYR CREEK	3030	7	21	29
LINCOLN CREEK	3040	8	20	28
CAVE ROCK	3050	4	6	9
LOGAN HOUSE CREEK	3060	9	17	26
NORTH LOGAN HOUSE CREEK	3070	4	25	29
GLENBROOK CREEK	3080	47	96	143
BIJOU CREEK	4010	260	14	273
EDGEWOOD CREEK	4020	134	69	203
BURKE CREEK	4030	43	26	69
UPPER TRUCKEE RIVER	5010	2782	1328	4110
TROUT CREEK	5050	728	272	1000
GENERAL CREEK	6010	302	215	517
MEEKS	6020	324	231	555
SIERRA CREEK	6030	125	24	149
LONELY GULCH CREEK	6040	163	30	193
PARADISE FLAT	6050	45	18	62

Tributary	OUTLET SWS	Surface TP Load (kg)	Baseflow TP Load (kg)	Total TP Load (kg)
RUBICON CREEK	6060	311	80	391
EAGLE CREEK	6080	112	356	468
CASCADE CREEK	6090	45	111	156
TALLAC CREEK	6100	69	55	125
TAYLOR CREEK	6110	367	462	829
UNNAMED CK	6120	60	7	67
BLACKWOOD CREEK	7010	821	1503	2324
MADDEN CREEK	7020	351	59	410
HOMEWOOD CREEK	7030	398	29	427
QUAIL LAKE CREEK	7040	183	41	224
MKINNEY CREEK	7050	508	130	638
DOLLAR CREEK	8010	53	36	88
UNNAMED CK LAKE FOREST 1	8020	136	21	157
UNNAMED CK LAKE FOREST 2	8030	65	33	98
BURTON CREEK	8040	34	174	209
TAHOE STATE PARK	8050	41	35	76
WARD CREEK	8060	1443	591	2034
KINGS BEACH	9010	48	13	61
GRIFF CREEK	9020	117	146	263
TAHOE VISTA	9030	489	150	640
CARNELIAN CANYON	9040	99	100	199
CARNELIAN BAY CREEK	9050	14	29	43
WATSON	9060	23	77	100
TOTAL		12740	7690	20425
GRAND TOTAL		21681	8479	30154
CONTRIBUTION FROM IZ		41%	9%	32%
CONTRIBUTION FROM STREAMS		59%	91%	68%

TP load from urban land-uses was modeled at approximately 18 metric tons/year (59 percent) and somewhat higher than the approximately 12 metric tons/year (41 percent) estimated to come from non-urban land-uses (Table 4-31, Table 4-39). Within the urban areas, primary and secondary roads contributed approximately 45 percent of the TP load or 30 percent to the TP load from both intervening zones and upland stream sources. Both single family and multiple family residences combined contributed 35 − 40 percent of the TP from urban land-uses and 22 percent of the TP from both intervening zones and upland stream sources (Figure 4-39). For the non-urban land-uses, the vegetated forest areas contributed 80 − 85 percent of the TP load. This amounted to approximately 35 percent of the total TP load.

The calculated TP based on a unit area approach (Figure 4-40) was very similar to that seen for TSS (Figure 4-33) with primary roads as the largest contributor. This is not surprising given the close relationship between TSS and TP in the Tahoe basin (Hatch 1997, Hatch et al. 2001). Figure 4-41 provides the basin-wide distribution of unit-area TP loading.

Table 4-39. Summary of annual upland surface, baseflow and total phosphorus loads, and associated flow-weighted average concentration by land by use and urban versus non-urban category. Determined using Lake Tahoe Watershed Model and values represent means over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Urban/Non-urban Category	Land-use	Surface TP (kg/year)	Baseflow TP (kg/year)	Total TP (kg/year)	Surface TP Concentration (µg/L)	Baseflow TP Concentration (µg/L)
U	Residential_SFP	1,950	343	2,290	0.75	0.02
U	Residential_MFP	565	92.4	657	1.22	0.03
U	CICU-Pervious	384	63.2	447	1.04	0.02
U	Residential_SFI	2,500	0	2,500	0.44	NA
U	Residential_MFI	1,160	0	1,160	0.52	NA
U	CICU-Impervious	1,570	0	1,570	0.52	NA
U	Roads_Primary	3,640	0	3,640	2.01	NA
U	Roads_Secondary	5,400	0	5,400	0.60	NA
NU	Ski_Runs-Pervious	370	51.3	421	0.45	0.02
NU	Veg_EP1	76.9	344	421	0.02	0.02
NU	Veg_EP2	780	3,290	4,070	0.03	0.02
NU	Veg_EP3	910	2,870	3,780	0.05	0.03
NU	Veg_EP4	700	1,270	1,970	0.12	0.03
NU	Veg_EP5	82.1	43.7	126	0.32	0.04
NU	Veg_Recreational	90.3	13.0	103	0.71	0.02
NU	Veg_Burned	234	19.1	253	1.17	0.02
NU	Veg_Harvest	126	15.9	142	1.34	0.02
NU	Veg_Turf	528	47.1	575	2.41	0.03
NU	Roads_Unpaved	614	17.7	632	3.74	0.03
U	**TOTAL LOAD**	**17169**	**499**	**17688**		
NU	**TOTAL LOAD**	**4511**	**7982**	**12493**		
	GRAND TOTAL	21680	8480	30161		
	FROM URBAN	79%	6%	59%		
	FROM NON-URBAN	21%	94%	41%		

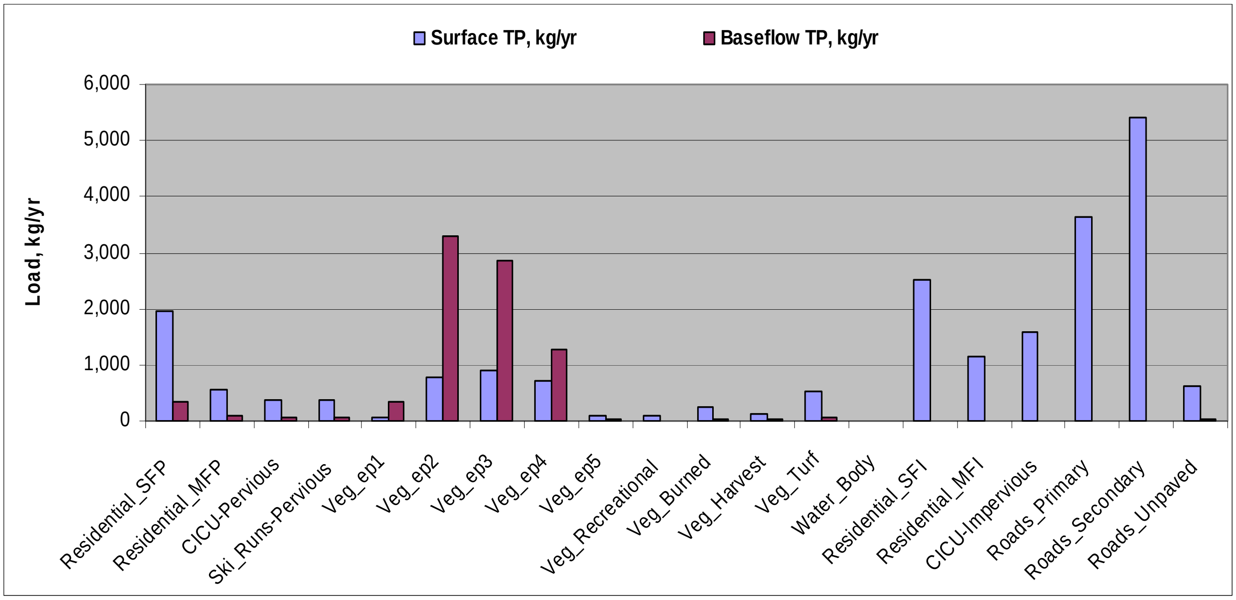

Figure 4-39. Upland total phosphorus loading by land-use category as determine by the Lake Tahoe Watershed Model over the 1994-2004 calibration/validation period (Tetra Tech 2007).

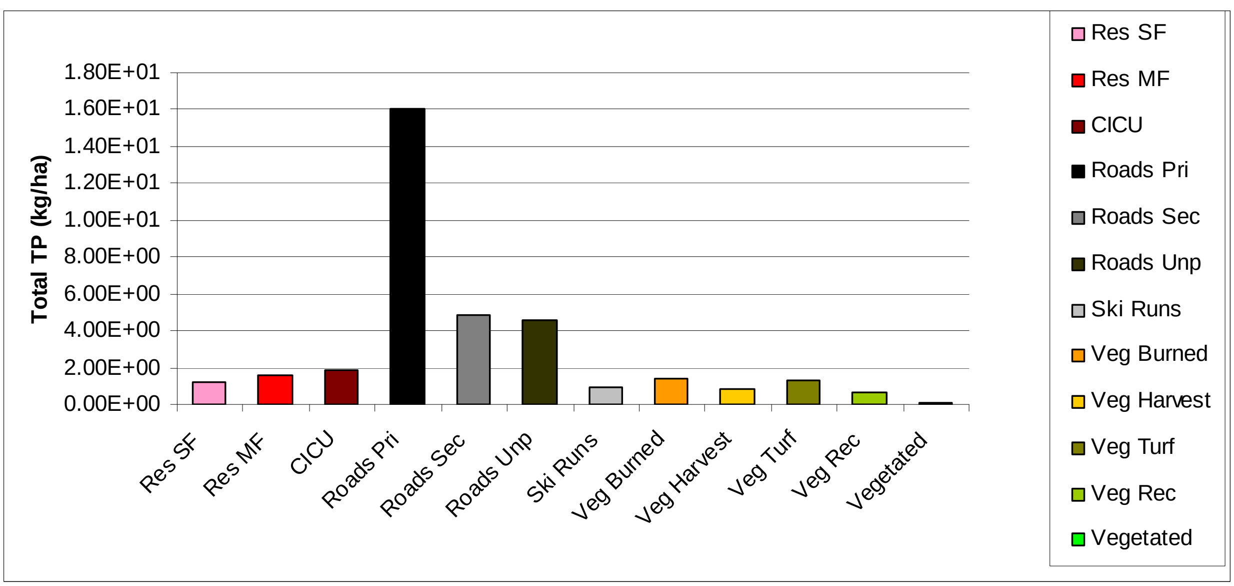

Figure 4-40. Relative upland phosphorus load from selected land-use categories as compared on a per unit area (per hectare) basis (Tetra Tech 2007).

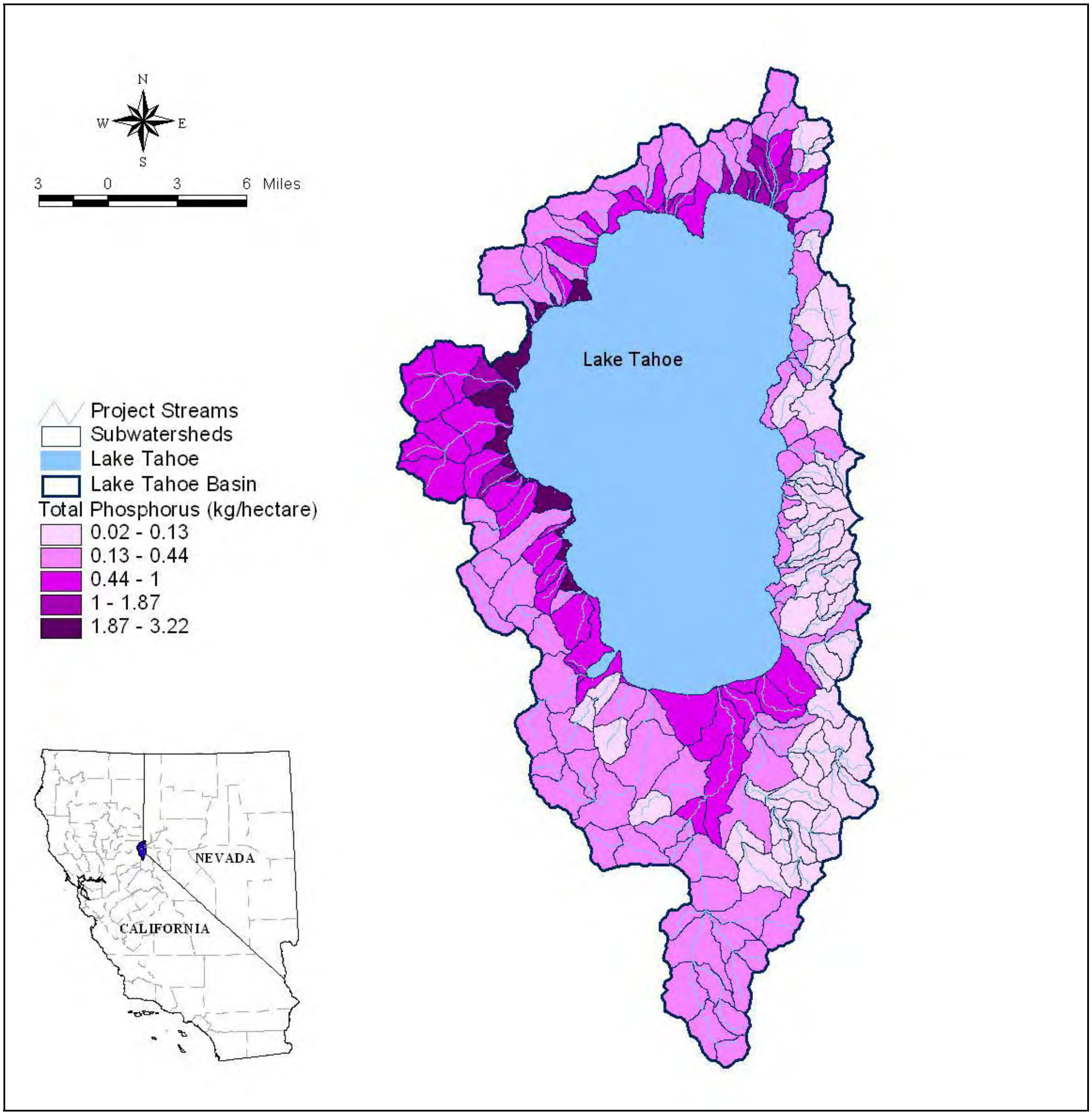

Figure 4-41. Unit-area total phosphorus yield (kg/ha) by subwatershed (Tetra Tech 2007).

An analysis of soluble reactive loading by land-use is summarized in Table 4-37. Average annual loading attributed to urban land-uses was 2.3 metric tons compared to 3.8 metric tons for the non-urban land-uses. The larger contribution of SRP estimated from non-urban land-uses (approximately 60 percent) was the opposite of that found for TP here TP from non-urban sources was approximately 40 percent. Within the urban land area, secondary (25 percent) and primary roads (17 percent) accounted for 40 − 45 percent of the urban SRP load with single and multiple family residential accounting for approximately 45 percent of the urban SRP load. Commercial/industrial land-use contributed about 12 percent. Of the 3.8 metric tons/year for SRP estimated to come from non-urban land-uses, 85 − 90 percent was attributed to the vegetated, undeveloped regions (EP1-EP5) (Table 4-37).

Summary of loads from urban and non-urban land-uses

As discussed above, the urban land-uses were taken as single family and multiple family residential, CICU-Commercial and primary/secondary roads. Both the pervious and impervious parcels within the residential and commercial categories were considered. Non-urban land-use were taken as vegetated (EP1-EP5), unpaved roads, ski runs, and vegetated areas with the following uses, recreational, harvested, prescribed burns, ski runs, turf and unpaved roads. Table 4-40 summarizes the finding presented earlier that while flow volume from the urban areas was relatively low, i.e. 10 percent of the total combined overland flow, the contribution of the urban areas to pollutant load was proportionately much higher. Upland contribution of TSS by urban areas was approximately 30 percent; however, the urban contribution increased for upland fine sediment increased to nearly 50 percent. The same was observed for TN with the urban contribution to total TP load the highest at almost 60 percent. These modeled load not only reflect the higher pollutant concentrations associated with urban land-uses, but also indicates that the non-urban areas contribute roughly half the nutrient and sediment load from the watershed.

Table 4-40. Summary of relative loads from urban (U) versus non-urban (NU) land-use categories as modeled for the Tahoe basin using the Lake Tahoe Watershed Model. Values represent means over the 1994-2004 calibration/validation period (modified from Tetra Tech 2007).

Urban/Non-urban Category	Total Flow Volume (m^3)	Upland TSS (Metric tons/yr)	Upland Fines (metric tons/year)	Total Nitrogen (metric tons/year)	Total Phosphorus (metric tons/year)
U	4.58×10^7	5,233	4,434	63.5	17.7
	10%	31%	49%	50%	59%
NU	40.2×10^7	11,687	4,673	62.3	12.5
	90%	69%	51%	50%	41%
Total	44.8×10^7	16,920	9,107	125.8	30.2

Lake Tahoe Watershed Model versus LTIMP loading comparison

As discussed in detail above with regard to model development, the Lake Tahoe Watershed Model was calibrated based on 11 years (1994-2004) of field data collected as part of the Lake Tahoe Interagency Monitoring Program (LTIMP). The LTIMP collects on the order of 30 − 40 depth-integrated samples across the width of each stream station each year. These field samples are analyzed for nitrogen, phosphorus and suspended sediment and annual loads are calculated based on the continuous flow hydrographs recorded at each site (Rowe et al 2002). Table 4-41 presents a comparison between mean annual loads as calculated by the LTIMP program and the Lake Tahoe Watershed Model (LSPC) output for nitrogen, phosphorus and TSS over the 11-year calibration period. The standard deviations presented along with the LTIMP provides a sense of interannual variability, primarily related to annual precipitation.

While there is some difference between the LTIMP and Lake Tahoe Watershed Model (LSPC) values for certain tributaries and for certain nutrient species (e.g. Blackwood Creek DIN, Ward Creek SRP), there was very good agreement, especially when considering the combined sum for the 10 tributaries (Table 4-41). The relative percent difference (=[LSPC-LTIMP)/mean of LSPC and LTIMP]) was between 10 − 14 percent with the exception of SRP which was much higher at 60 percent. The difference between LTIMP field data and LSPC modeled output for SRP was greatest for the Upper Truckee River, Ward Creek and Blackwood Creeks. While these differences require further investigation, the Lake Clarity Model considers biologically available phosphorus which is derived from both SRP and a fraction of TP. Assuming all SRP is bioavailable and that approximately 20 percent of the remaining phosphorus is bioavailable (Ferguson 2005), an approximation of bioavailable-phosphorus from the10 monitored streams shows the relative percent difference between LTIMP and LSPC reduced to 25 percent.

Table 4-41. Mean annual loading values for the 10 streams monitored as part of LTIMP. Data under the LTIMP label refers to load calculations made by UC Davis-TERC as part of LTIMP reporting. LSPC are modeled results from the Lake Tahoe Watershed Model (Tetra Tech 2007). Mean ± standard deviations refer to model calibration/validation period of 1994-2004. Standard deviations reflect interannual variability with differences in precipitation and flow.

LTIMP Tributaries	DIN (kg) LTIMP	DIN (kg) LSPC	TN (kg) LTIMP	TN (kg) LSPC
Incline Creek	287 ± 164	339	2548 ± 2076	3300
Third Creek	159 ± 132	284	2899 ± 2905	2824
Logan House Creek	13 ± 12	10	184 ± 132	157
Glenbrook Creek	41 ± 28	31	469 ± 328	383
Edgewood Creek	146 ± 93	160	881 ± 392	1371
Upper Truckee River	1818 ± 110	2382	20066 ± 13424	24115
Trout Creek	546 ± 337	663	7638 ± 4853	6538
General Creek	153 ± 88	221	2872 ± 1649	3145
Blackwood Creek	1040 ± 578	573	8500 ± 5501	8402
Ward Creek	450 ± 289	507	5067 ± 3126	6444

Total	4653	5170	51124	56679
PHOSPHORUS (kg)	**SRP** LTIMP	**SRP** LSPC	**TP** LTIMP	**TP** LSPC
Incline Creek	95 ± 61	172	657 ± 516	877
Third Creek	70 ± 44	173	900 ± 1166	843
Logan House Creek	2 ± 2	8	18 ± 15	26
Glenbrook Creek	30 ± 23	42	126 ± 109	143
Edgewood Creek	50 ± 21	42	191 ± 114	203
Upper Truckee River	492 ± 358	833	4037 ± 2898	4110
Trout Creek	307 ± 184	183	1529 ± 1072	1000
General Creek	69 ± 39	89	427 ± 321	517
Blackwood Creek	145 ± 93	667	3417 ± 4172	2324
Ward Creek	164 ± 103	457	2518 ± 3583	2034
Total	1424	2666	13820	12077
TOTAL SUSPENDED SEDIMENT (metric tons)		LTIMP	LSPC	
Incline Creek		410 ± 483	419	
Third Creek		967 ± 1733	819	
Logan House Creek		11 ± 22	10	
Glenbrook Creek		36 ± 33	40	
Edgewood Creek		44 ± 32	40	
Upper Truckee River		3189 ± 2572	5091	
Trout Creek		806 ± 836	422	
General Creek		774 ± 1610	388	
Blackwood Creek		4325 ± 6335	5127	
Ward Creek		2952 ± 5009	3166	
Total		13514	15531	

4.4 Stream Channel Erosion

Streams transport water, sediment and pollutants from their drainage basins to the ocean. When watersheds are left undisturbed, in-stream processes reflect a balance that has developed over millennia and function within a state of dynamic equilibrium. However, this balance can be disturbed by changes to flow and/or sediment transport. When these changes occur they manifest themselves most obviously as increased stream channel erosion (Figure 4-42).

Figure 4-42. Photograph of stream channel erosion along the Upper Truckee River.

Traditional development activities (e.g. increasing impervious and disturbed areas) cause increases in the flow and sediment a stream must transport, thereby exacerbating the natural rates of stream channel erosion. Soon after disturbances within a watershed occur, streams will begin to adjust their pattern, profile and cross section. Simon and Hupp (1986) describe this as a process of “stream channel evolution” which can be illustrated by six stages of channel evolution (Figure 4-43). Stage I represents a pre-disturbance condition with Stage VI representing the establishment of a new quasi-equilibrium achieved once conditions have been modified to accommodate the energy shift. Stages III-V are of specific interest to managers in the Lake Tahoe basin, as these stages represent channel instabilities, and mass failures of streambanks (Simon et al. 2003).

Stream systems influenced by watershed disturbance typically illustrate greater instability as a result of shifts in the stream system energy balance. Examples of these disturbances in the Tahoe basin include: changes in hydrologic and sediment contributions from urbanization, direct stream channel modifications and stream channel constrictions. Stream evaluations and modeling completed in the basin by Simon el al. (2003) support these conclusions. Simon et al. (2003) estimated that 79 percent of the annual total suspended sediment load was from the Upper Truckee River, a relatively disturbed stream system, originates from in-channel sources, as compared to 53 percent of the annual total suspended sediment load from General Creek, a relatively undisturbed stream system. Similarly, for fine sediments < 63 µm in diameter, in-channel sources accounted for 51 percent and 28 percent of the load for the Upper Truckee River and General Creek, respectively.

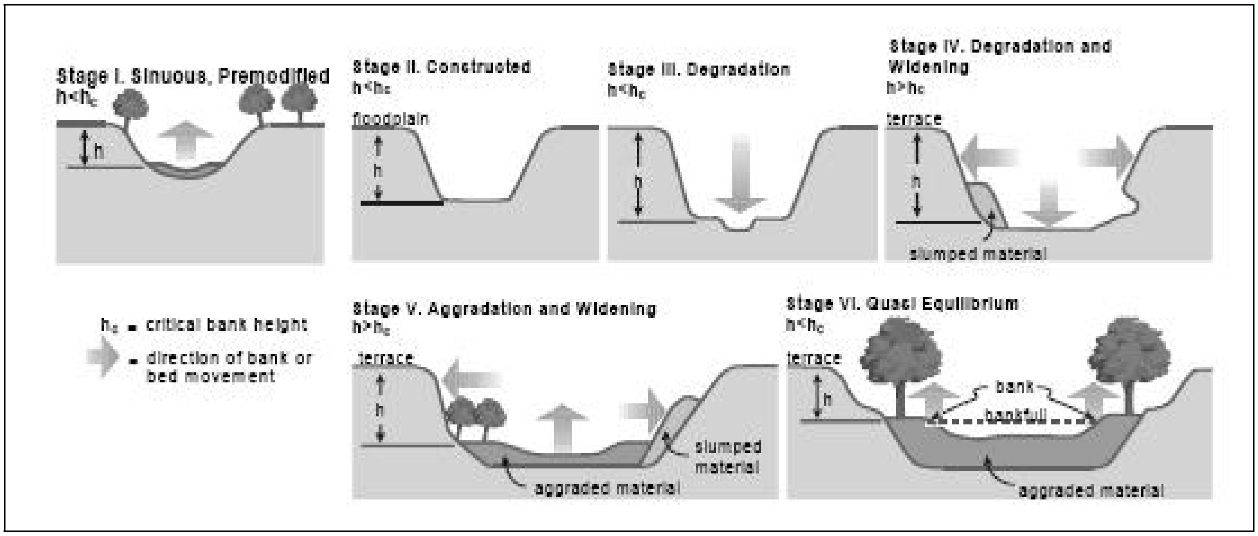

Figure 4-43. Six stages of channel evolution (Simon and Hupp 1986, Simon 1989).

4.4.1 Stream Channel Erosion as a Pollutant Source

Phosphorus and nitrogen are pollutants commonly attached to sediment, which itself is also considered a pollutant. Some of the sediment and nutrients transported by streams is generated from the upland portion of the watershed (described in Section 4.3) and some is generated from stream channel erosion. The distinction between in-channel and upland sources is important for implementation planning, as methods to control pollutants for each are different. This section focuses solely on the pollutant loading from stream channel erosion.

4.4.2 Existing Information

A number of studies have been completed in the past 25 years to address the larger topic of sediment delivery from various watersheds in the Lake Tahoe basin. Many of these studies were focused on individual streams or limited sets of streams, depending on data availability and the scope of the investigation (e.g. Kroll 1976, Glancy 1988, Hill and Nolan 1990, Hill et al. 1990, Stubblefield 2002). Recent analyses by Reuter and Miller (2000) and Rowe et al. (2002) used suspended-sediment transport data from the Lake Tahoe Interagency Monitoring Program (LTIMP), which brought together data from 10 streams all around the basin. These evaluations have indicated that Incline, Third, Blackwood, and Ward Creeks and the Upper Truckee River are the largest contributors of suspended sediment to Lake Tahoe, in ascending order. Although these studies have been valuable for providing quantitative estimates of sediment loading and insight into the spatial and temporal variability of loading, they were not intended to specifically address the relative contribution from in-channel/upland sources. While some early investigations suggested that stream channel erosion could play an important role as a source to the suspended sediment load in some basin streams (Leonard et al. 1979, Hill and Nolan 1990, Hill et al. 1990), this hypothesis was never fully evaluated.

4.4.3 New Information and Additional TMDL-Related Research

In 2002, the National Sedimentation Laboratory in Oxford, Mississippi initiated a study to evaluate the contribution of sediment from stream channel erosion processes as part of the Lake Tahoe TMDL Program. The report, entitled *Lake Tahoe Basin Framework Study: Sediment Loadings and Channel Erosion* (Simon et al. 2003), was designed to combine detailed geomorphic and numerical modeling investigations of several representative watersheds with reconnaissance level evaluation of approximately 300 sites located around the entire Lake Tahoe basin.

Numerical modeling of upland- and channel-erosion processes was conducted using Annualized Agricultural Non-Point Source Pollutant Version 3.30 (AnnAGNPS) and Conservational Channel Evolution and Pollutant Transport System (CONCEPTS) on three representative watersheds: General and Ward Creeks and the Upper Truckee River. GIS-based analysis of land-use, land cover, soil erodibility, steepness, and geology was used to evaluate upland-erosion potential across the basin. Channel contributions to sediment loading were determined by comparing cross-sectional geometries of channels originally surveyed in either 1983 or 1992, including sites along General, Logan House, Blackwood and Edgewood Creeks and the Upper Truckee River, which were re-surveyed in 2002. Historical flow and sediment-transport data from more than 30 sites were used to determine bulk suspended-sediment loads (in metric tons per year) and yields (in metric tons/yr/km^2 of stream channel) for sites all around the lake. Results were reported for both total suspended sediment and fine-grained suspended sediment (< 63 µm in diameter).

Eighteen index stations, defined as those located in a downstream position with long periods of flow and sediment-transport data, were selected. These stations were used to make comparisons between sediment production and delivery from individual watersheds and between different regions of the lake. Fine-grained sediment transport was determined from historical data obtained from 20 sites based on relations derived from particle-size distributions across the range of measured flows.

To better quantify the contributions of fine sediment from stream channel erosion in all 63 tributary stream systems, the National Sedimentation Laboratory completed additional work contained in *Estimates of Fine Sediment Loading to Lake Tahoe from Channel and Watershed Sources* (Simon 2006). Primarily, this study provides valuable information on the average, annual fine-sediment (< 63µm) loadings in metric tones per year from streambank erosion and the relative contribution of each of the basin's 63 streams. Secondarily, it provides additional estimates of average, annual fine-sediment (< 63µm) loadings and average, annual fine-sediment (< 16 µm) loadings in number of particles per year. A summary of the methods applied in these evaluations is provided in the following sections.

Study Methodology & Data Collection

In support of TMDL development, the magnitude and extent of channel erosion was determined using five methods (Simon et al. 2003, Simon 2006):

(1) Direct comparison of monumented, historical stream channel cross-section surveys on Blackwood, Edgewood, General, and Logan House Creeks and the Upper Truckee River
(2) Identification of unstable reaches contributing fine-grained sediment via bank erosion during reconnaissance surveys of geomorphic conditions along Blackwood, Edgewood, Logan House, Incline, General and Ward Creeks and the Upper Truckee River
(3) Rapid geomorphic assessments (RGAs) at 304 locations across the Lake Tahoe basin
(4) Numerical modeling of General Creek, Ward Creek and the Upper Truckee River
(5) Basin-wide evaluation of stream channel erosion based upon results of the above methods and development of a statistically valid (R^2=0.99) empirical relationship between a bank-stability index (I_B) and the measured/modeled rate of streambank erosion.

A summary of the first four of these methods is provided below. The basin-wide evaluation of stream channel erosion is presented following the first four channel erosion methods.

Comparison of Historical Cross-section Surveys

One of the simplest, yet most powerful, ways of estimating channel erosion is by direct comparison of time-series cross-sections. An example of overlain surveys from the Upper Truckee River is provided in Figure 4-44. To obtain a relatively good degree of accuracy it is best to apply historical cross-sections with available measurements taken in both the horizontal and vertical dimensions. Cross sections on Blackwood, General, Logan House and Edgewood Creeks were monumented and labeled (Hill et al. 1990) by the USGS in 1983 and 1984. Original survey notes were obtained from the USGS and new surveys were conducted at as many of these sites as could be located during the USDA survey in the fall of 2002. Time-series cross sections of the Upper Truckee River were originally surveyed in 1992 with additional surveys in 1994 and 1997 (C. Walck 2003 unpublished data) and had been recently re-surveyed in 2001 (Simon et al. 2003), thus providing a ten-year record of channel changes.

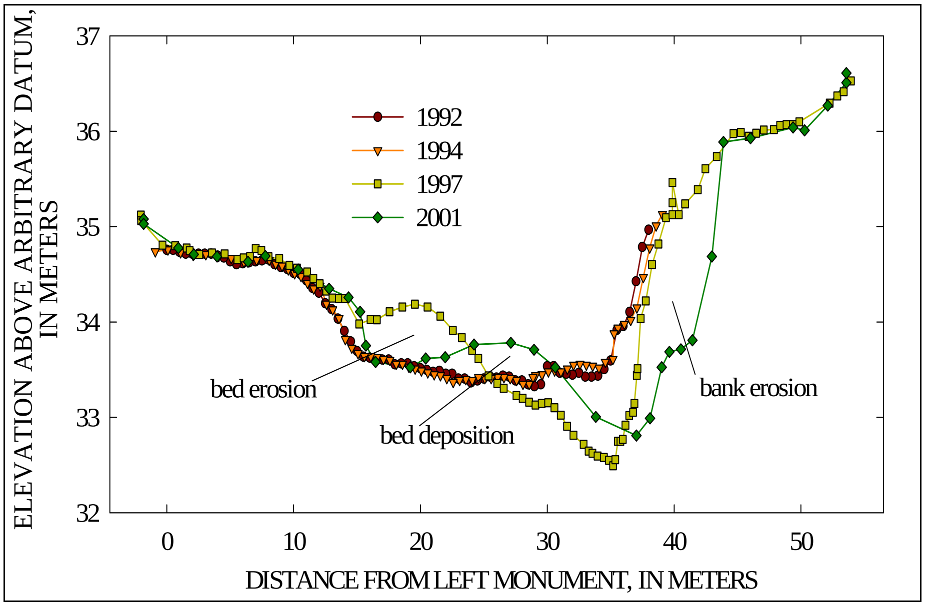

Figure 4-44. Example of overlain surveys from the Upper Truckee River (Simon et al. 2003).

The change in cross-sectional area for a given time period was determined by overlaying time-series cross sections and calculating the area between the channel profiles. The location of the bank toe was determined for the original and 2002 surveyed sections and used to discriminate between erosion and deposition from the bed and banks. Unit rates of streambank erosion were derived from the numerical simulations by: (1) calculating the area eroded in each cross section (the number of cross sections matched for the five streams with available data ranged from 10 for Logan House Creek to 24 for the Upper Truckee River with a mean of 17), (2) taking the average eroded area between successive cross sections, (3) multiplying by the distance between the midpoint of successive cross sections, (4) dividing by the number of years of simulation to obtain a rate in m^3/yr, and (5) dividing by the total reach length to obtain a rate in m^3/yr/km of channel. This provided a unit streambank erosion rate in the same units as those calculated from time-series cross section calculations. The average percentage of fines determined from samples of bank material was multiplied by the volume of material eroded from the channel banks to determine loading rates and yields of fine-grained materials delivered by streambank erosion. Because fines were not found in measurable quantities on streambeds, bed erosion was assumed not to be a contributor of fine sediments.

Reconnaissance Surveys of Stream Channel Stability

From September through November 2002, Simon et al. (2003) identified unstable reaches contributing fine-grained sediment via bank erosion based on reconnaissance surveys of geomorphic conditions along Blackwood, Edgewood, Logan House, Incline, General and Ward Creeks and the Upper Truckee River. The stream channels were assessed based on direct field evidence of stream stability trends throughout each of the watersheds. Evaluations were carried out through field reconnaissance surveys of each main-stem channel. Typically, the lower 80 percent of the main channel length was covered during each survey. At approximate 100 meter intervals, notes and photographs were taken to document eroding reaches and assess their potential for supplying fine sediment. The levels of erosion were divided into four classes: (1) none to negligible, (2) low, (3) moderate and (4) high. The classes were determined through an objective evaluation based on bank height ratio, length of bank instability, vegetation root density, and relative amount of fine-grained materials in the channel bed. The eroding reaches for each stream were then tabulated and mapped to show bank erosion “hotspots” and overall geomorphic trends along the channel. These data were combined with geomorphic data derived from rapid geomorphic assessments (RGAs) of point locations that were conducted not only along the seven intensely studied streams, but throughout the entire basin.

Rapid Geomorphic Assessments

To determine the relative stability and stage of channel evolution for sites in the Lake Tahoe basin, RGAs were conducted throughout the basin at 304 specific locations on a total of 63 streams (Figure 4-45).

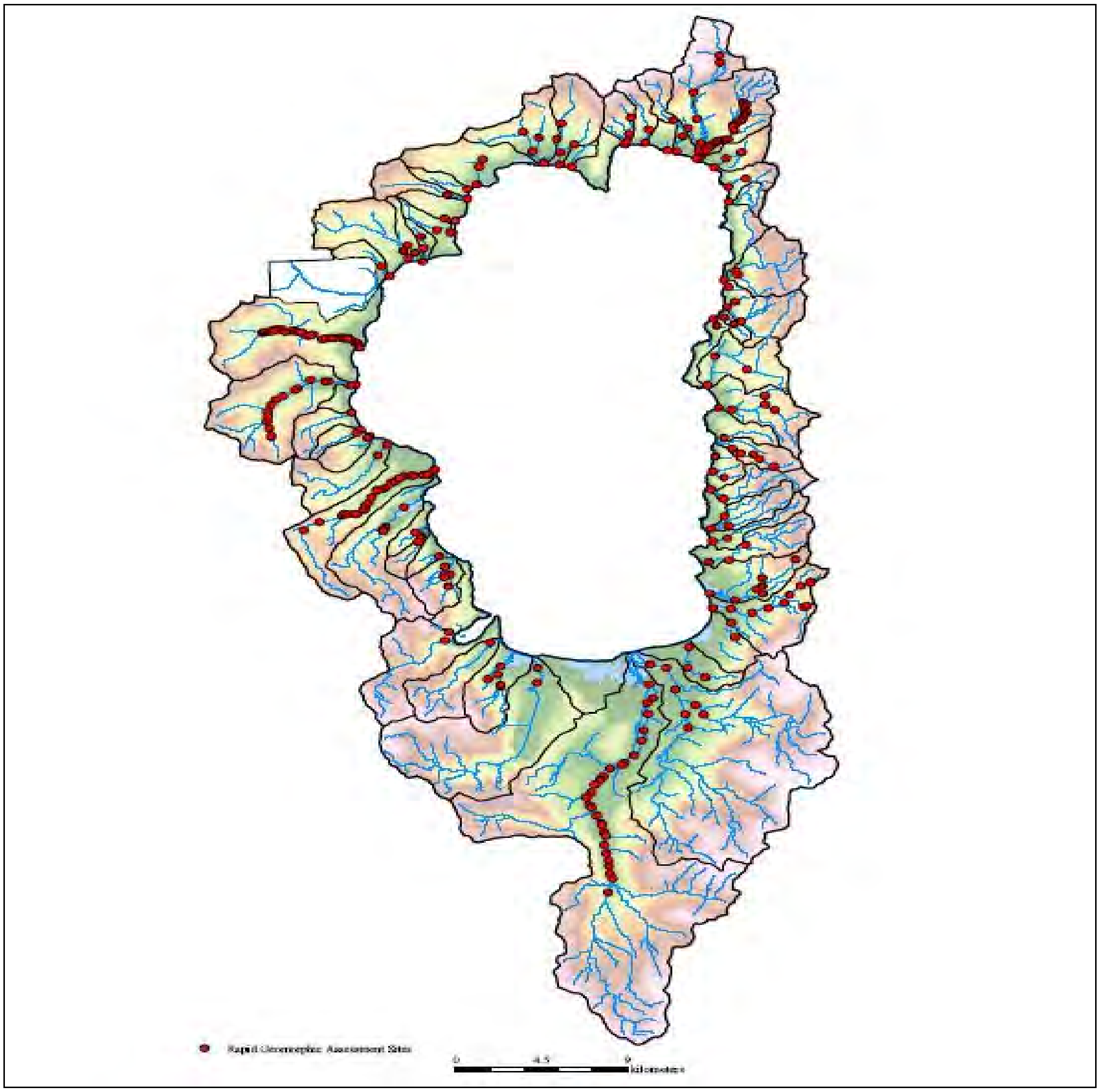

Figure 4-45. Locations of the 304 RGAs conducted in the Lake Tahoe basin between September and November 2002 (Simon 2006).

RGA techniques utilize diagnostic criteria of channel form/conditions to infer dominant channel processes and the general magnitude of channel instabilities. The RGA procedure for sites in the Lake Tahoe basin consisted of three steps; (1) take photographs looking upstream, downstream and across the reach, (2) take samples of bed and bank material for particle size distribution analysis, and (3) make quasi-quantitative assessment of channel conditions based on diagnostic criteria (Simon et al. 2003). This approach has been used successfully in a variety of physiographic environments to rapidly determine system-wide geomorphic conditions of large fluvial networks (Simon et al. 2003). Because they provide information on dominant channel processes rather than only channel form, they can be used to identify disturbances and critical areas of erosion and deposition.

Numerical Modeling

Numerical simulations of upland and channel processes using the AnnAGNPS watershed simulation model (Cronshey and Theurer 1998) and CONCEPTS (Langendoen 2000), respectively, were carried out on three representative watersheds comprising General and Ward Creeks and the Upper Truckee River. The models were used to determine the relative contributions of sediment from upland and channel sources; simulate the effects of the January 1997 runoff event on future sediment loads; and evaluate 50-year trends in suspended sediment delivery to Lake Tahoe from the three watersheds. Each module provides information needed by other modules to enhance the predictive capabilities of each. AnnAGNPS is used to supply the upland sediment load, while CONCEPTS is used to simulate in-stream sediment loading.

AnnAGNPS is a watershed-scale, continuous-simulation, pollutant loading computer model designed to quantify and identify the source of pollutant loadings anywhere in the watershed for optimization and risk analysis. CONCEPTS is a set of stream network, corridor, and water quality computer models designed to predict and quantify the effects of bank erosion and failures, bank mass wasting, bed aggradation and degradation, burial and re-entrainment of contaminants, and streamside riparian vegetation on channel morphology and pollutant loadings.

Basin-Wide Evaluations

Without the resources to conduct detailed numerical simulations of channel processes for each individual stream, as was done for the Upper Truckee River, Ward Creek, and General Creek, a combination of empirical methods were used to estimate channel erosion for the remaining streams. Determination of fine-sediment (< 63 µm) loadings (metric ton/year) was straightforward for the LTIMP streams with historical flow and concentration data. However, estimating fine-sediment loadings from streams with no historical monitoring information required the development of an extrapolation methodology. Simon (2006) developed an extrapolation methodology based upon measured and simulated rates of streambank erosion, the average percentage of fines in the channel banks, diagnostic information obtained from the RGAs, and the bank-stability index (I_B) that represents the percent of reach length with failing banks. A summary of the methods and results from Simon (2006) are provided below.

Extrapolation of Measured and Simulated Streambank Erosion Rates

In general, the technique to estimate basin-wide fine-sediment contributions from streambank erosion relied on extrapolating rates of streambank erosion obtained from time-series measurements of monumented cross sections and from numerical simulations with the CONCEPTS channel evolution model (Nolan and Hill 1991, Simon et al. 2003, Simon 2006).

To obtain the rate of streambank erosion of fine sediment (< 63 µm) from the measured and simulated unit erosion rates for total sediment, values were multiplied by the average percentage of silt-clay in the channel banks. The resulting rates of streambank erosion are expressed in m^3/yr/km of fines (< 63 µm) and listed in Table 4-42.

Table 4-42. Measured and simulated average annual rates of streambank erosion for index streams.

Stream	Bank Composition (% < 63 µm)[a]	Erosion Rate (m^3/yr/km)	Type of Data	Source of Data
Blackwood Creek	5.6	12.2	Measured	Simon et al. 2003
Edgewood Creek	4.9	0.09	Measured	Nolan and Hill 1991
General Creek	7.4	0.92	Simulated	Simon et al. 2003
Logan House Creek	-	0.002	Measured	Nolan and Hill 1991
Upper Truckee River	9.5	9.50	Simulated	Simon et al. 2003
Ward Creek	10.4	4.40	Simulated	Simon et al. 2003

[a]Data from Simon et al. 2003

To extrapolate this limited data set to the entire Lake Tahoe basin, diagnostic information obtained during the RGAs was used. Results from the RGA analysis described above, evaluated relative bank instability as the percentage (longitudinally) of each side of the channel that has experienced recent mass failure. Observed conditions ranged from 0 percent (stable banks) to 100 percent (where the entire reach contained failing streambanks). Each bank was assigned a numerical value based on the extent of failures. This value was termed the bank-stability index (I_B). The index attempts to synthesize more quantitative evaluations of streambank stability that might include parameters such as bank height, bank angle, geotechnical strength, and bank-toe erodibility. A summary of all field data and the average I_B values for each stream can be found in Simon (2006).

Relationship between Bank-Stability Index and Streambank Erosion Rate

With an average bank-stability index (I_B) available for each stream, a relationship between this parameter and streambank erosion rates was required for extrapolation to streams without measured data. Using data from the six streams with measured or simulated data (Table 4-42), a regression was performed using a sigmoidal 3-parameter equation based on the general shape of the relation (Simon 2006). Equation 2 (R^2=0.99) and the relation between average, annual streambank erosion rates are expressed in Figure 4-46.

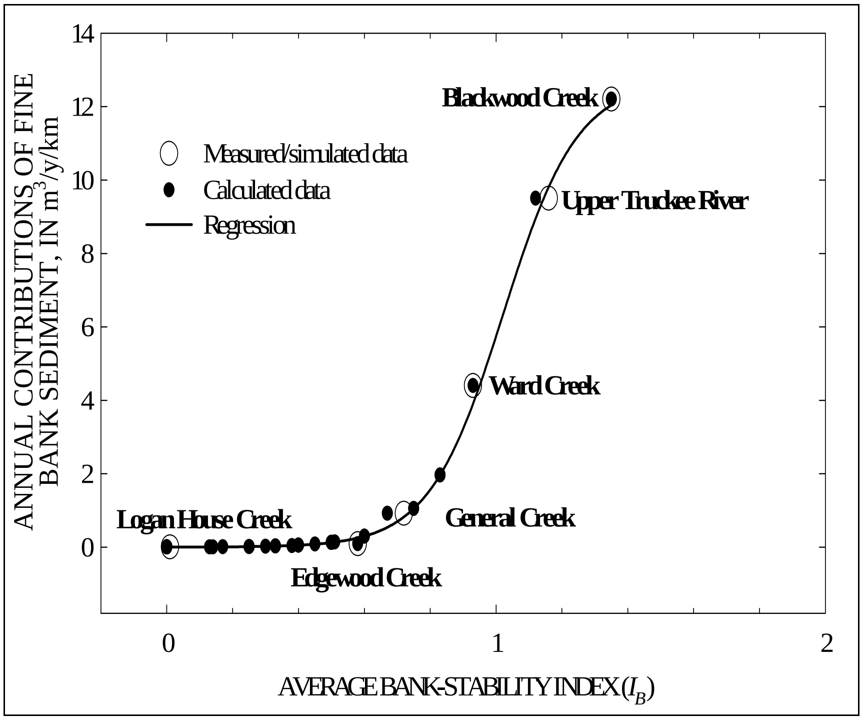

Figure 4-46. Three-parameter sigmoidal equation and the Relation between average, annual streambank erosion rates and average bank-stability index (I_B) (Simon 2006).

$$E_r = \frac{12.6939}{1 + e^{-\frac{(I_B - 1.0217)}{0.1129}}}$$ **Equation 2**

Where:

E_r = erosion rate of fine (< 63µm) bank sediment in m^3/y/km of channel
I_B = average bank–stability index (percent of reach length with failing banks).

An erosion rate for each stream channel was obtained by substituting the stream's bank stability index value into the above regression equation to provide an average annual erosion rate of fine sediment per unit length of channel. The average annual loading of streambank erosion for each stream was then determined by multiplying this value by the total length of main channels.

Basin-Wide Estimate of Fine-Sediment Loading from Streambank Erosion

Using the above procedures, average annual erosion and delivery of fine sediment to Lake Tahoe were calculated for each stream. (Table 4-42 and Figure 4-47). Specific values for each stream are presented in Simon (2006). Summing the values calculated for each of the 63 watersheds gives an annual average of 1,305 metric tons/year of fine sediment delivered to Lake Tahoe from streambank erosion. The three largest contributors of fine streambank sediment are the Upper Truckee River (639 metric tons/year), Blackwood Creek (431 metric tons/year) and Ward Creek (104 metric tons/year) (Simon 2006).

According to Simon (2006), about 25 percent of the fine sediment delivered to the lake from upland sources (not including the flow coming directly to the lake from intervening zones) emanates from streambank erosion when compared to the calculated total fine sediment loadings. About 22 percent of all fine sediment delivered to Lake Tahoe from upland sources comes from the banks of the Upper Truckee River, Blackwood Creek and Ward Creek (Figure 4-34 and Figure 4-35).

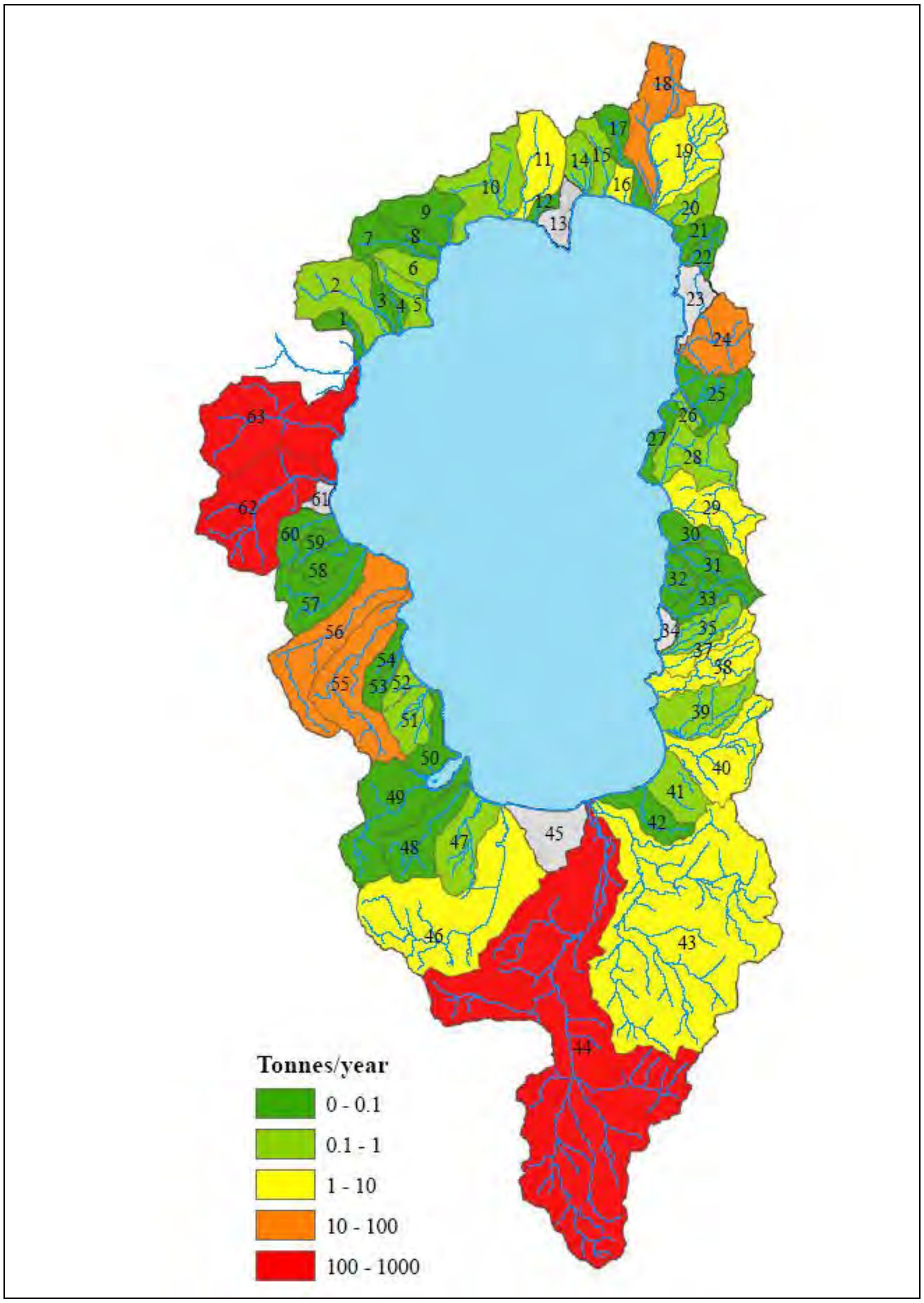

Figure 4-47. Loadings of fine sediment (< 63 µm) from streambank erosion (gray shading indicates no data available; note: tonnes is referred to as metric tons in this report) (Simon 2006).

Refer to Section 4.3 on upland sources and particularly to Section 4.3.5 on sediment loads for a specific discussion as to how these values for stream channel sediment (mass of material < 63 µm) were modified for application within the Lake Tahoe Watershed Model. Channel fines < 63 µm were estimated using the Lake Tahoe Watershed Model to be 3,800 metric tons per year based on calibration to actual LTIMP monitoring data.

Estimates of Nutrient Loading Associated with Streambank Erosion

In addition to the soil particles delivered to stream flow by channel erosion, phosphorus and nitrogen may also accompany this eroded material. To estimate the phosphorus load contributed from stream channel erosion, data from the Ferguson and Qualls (2005) and Ferguson (2005) bioavailable phosphorus study were used. As part of that work, the authors analyzed samples of composite stream channel sediment from areas considered potentially erodable (Simon et al. 2003, R. Wells 2003 personal communication). Samples of these representative, composite samples were taken from nine LTIMP streams (all monitored tributaries except Logan House) and were chemically analyzed for total phosphorus. Results ranged from 0.075 − 0.199 µg total phosphorus/mg sediment (< 63 µm) with a mean of 0.153 µg total phosphorus/mg sediment and a 95 percent confidence interval of 0.096 − 0.197 µg total phosphorus/mg sediment (< 63 µm). This mean value was applied to all streams and was multiplied by sediment load from channel erosion to obtain phosphorus loading. Based on the fine-sediment load of 3,800 metric tons/year from stream channels obtained from the Lake Tahoe Watershed Model, this yielded a total phosphorus load of 0.6 metric tons/year. For the purpose of this evaluation, it was assumed that nitrogen loading from stream channel erosion was proportional to the ratio of stream channel-phosphorus to stream load-phosporus from upland runoff. This yielded a stream channel total nitrogen load of approximately 2 metric tons/year. While the uncertainty of this estimation is high, it only accounts for less than one percent of the total nitrogen budget from all sources. Therefore, the potential error associated with this estimate is negligible.

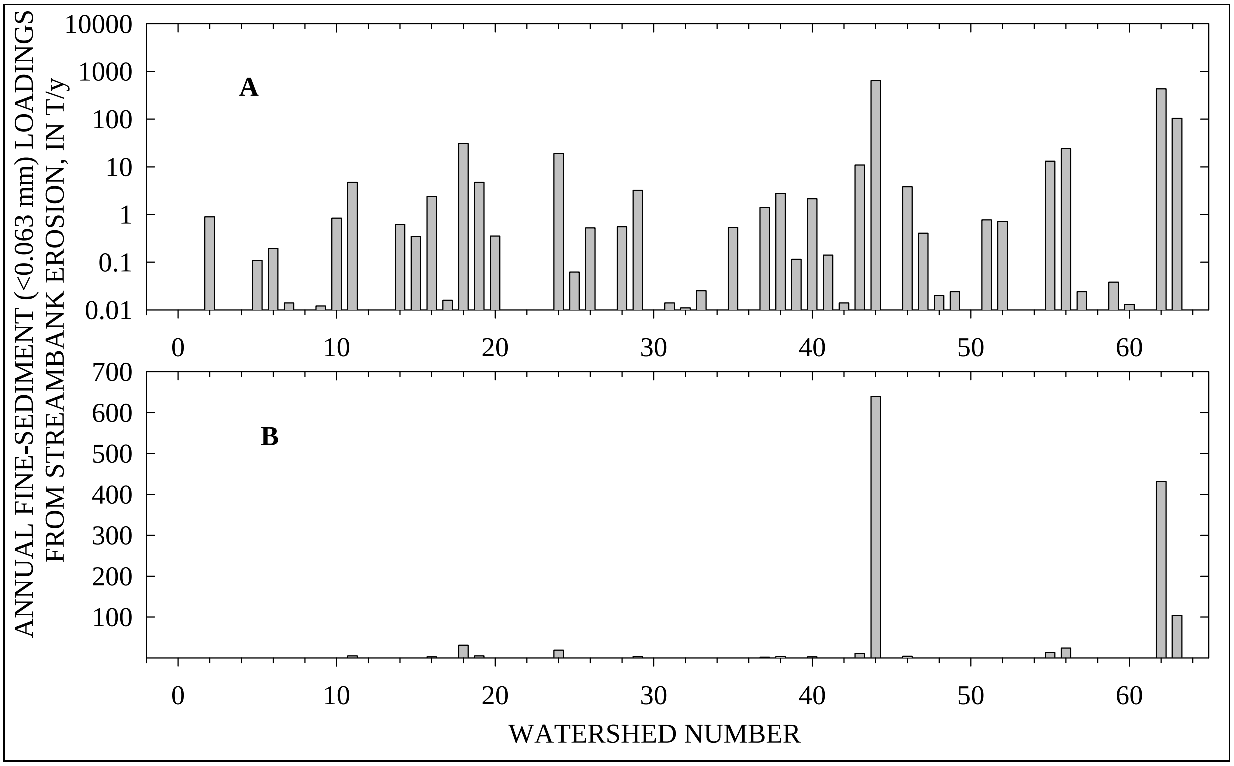

Figure 4-48. Annual, fine-sediment (0.063 mm) loadings in metric tons per year from streambank erosion plotted with log scale (A) and arithmetic scale (B). Note the relatively large contributions from the Upper Truckee River (#44), Blackwood Creek (#62), and Ward Creek (#63). Watershed numbers correspond with Figure 4-47 (Simon et al. 2006).

4.5 Atmospheric Deposition

4.5.1 Overview

Because of the large surface area of the lake (501 km^2) in comparison to its drainage area (812 km^2), it is not unreasonable to expect that loading of nutrients and particulate matter directly to the surface waters of Lake Tahoe through the process of atmospheric deposition loading might be important. For the purpose of discussion, atmospheric deposition only refers to dry fallout or precipitation (as rain or snow) that lands on the lake surface directly. Nutrients and particulate matter deposited over the land portion of the drainage basin may or may not enter Lake Tahoe depending on uptake by vegetation, sequestration within the soil layers, etc. Pollutants that fall onto the land are included in the evaluation of groundwater and upland loading.

The first comprehensive estimate of the contribution by atmospheric deposition of nitrogen and phosphorus to the annual nutrient budget of Lake Tahoe was made by Jassby et al. (1994). This study analyzed atmospheric deposition from both wet (rain and snow) and dry fallout in comparison to loading from stream inflow. This was the first published research to conclude that atmospheric deposition provides a majority of the dissolved inorganic nitrogen (DIN; defined as nitrate plus ammonium) and total nitrogen to the annual nutrient load of Lake Tahoe. It was further concluded that atmospheric deposition also contributes significant amounts of soluble reactive phosphorus (SRP) and total phosphorus loading, but to a lesser extent than nitrogen.

Reuter et al. (2003) used the data from Jassby et al. (1994) to estimate total nitrogen and total phosphorus loading directly to Lake Tahoe via atmospheric deposition. The resulting loading rates were approximately 230 metric tons per year for total nitrogen and 12 metric tons per year for total phosphorus. Atmospheric deposition of total nitrogen accounted for nearly 60 percent of the nitrogen budget while total phosphorus accounted for 25 – 30 percent of the phosphorus budget. While measurements of the chemical content of atmospheric deposition were assumed to be accurate, there were acknowledged uncertainties associated with extrapolating to the whole-lake surface from a limited sampling network.

In 1999, a cooperative effort began between the TRPA and scientists at UC Davis and the Desert Research Institute (DRI), which resulted in publication of the *Lake Tahoe Air Quality Research Scoping Document* (Cliff et al. 2000). As part of this investigation, it was hypothesized that phosphorus present in wet and dry fallout could have resulted from local sources, i.e. road dust and aeolian (wind) transport from disturbed land, as well as wood smoke (fires in the forest and wood stove use). This agreed with the conclusions of Jassby et al. (1994) that phosphorus would most likely originate from an in-basin, terrestrial source. It was further hypothesized by Cliff et al. (2000) that the presence of large amounts of gaseous nitrogen species from locally generated roadways and vehicle exhaust, could dominate over out-of-basin sources. Acknowledging that: 1) the estimated contributions of atmospheric deposition from Jassby et al. (1994) and Reuter et al. (2003) required additional verification and 2) no data regarding the contribution of atmospheric deposition to fine particle loading to the whole-lake existed, the Water Board and the California Air

Resources Board (CARB) began a multi-year science program focusing on topics for which insufficient data/understanding were available. *The Lake Tahoe Atmospheric Deposition Study* (LTADS) (CARB 2006) was CARB's contribution to this effort.

The primary goal of LTADS was to quantify the contribution of dry atmospheric deposition to Lake Tahoe as an input to modeling lake clarity. Wet deposition is also an important input to the lake, but was not a major focus of the LTADS field study. LTADS did not emphasize observations of wet deposition and it was acknowledged that the long-term wet deposition data being collected by the UC Davis - TERC would suit this purpose. However, to support these existing wet deposition measurements and to provide estimates of particulate matter deposition, LTADS presented estimated wet deposition onto Lake Tahoe during 2003 based on a first principles analysis of seasonal air quality concentrations and the number of hours when precipitation fell (CARB 2006).

The LTADS estimate of dry deposition included all optically and biologically significant materials in the air over the lake, including gas- and particle-phase nitrogen and phosphorus and non-soluble (inert) particulate matter that, once deposited in the lake, would scatter light. Secondary goals of LTADS included identification and ranking of emissions sources, and consideration of the relative impacts of local emissions relative to out-of-basin sources.

Other significant research has been conducted at Lake Tahoe in the areas of air quality and atmospheric deposition. This work is also referenced in this section. In the past, research directly linking air quality, atmospheric deposition and lake clarity was sporadic. The analysis in this section provides the current state of knowledge. However, uncertainties still exist (e.g., spatial distribution and potential falloff of atmospheric deposition in nearshore versus open-lake regions, contribution of atmospheric deposition to fine particle loading, extrapolation of limited sampling locations to the entire lake surface). Science plans and funding sources are being developed to address these issues.

Sections 4.5.2 and 4.5.3 provide information on characteristics and loading values for dry and wet deposition, respectively. Section 4.5.4 summarizes this information and presents loading values for various forms of nitrogen, phosphorus and particulate matter used in the Lake Clarity Model. Section 4.5.5 summarizes the LTADS findings for regionally transported versus local sources.

It is important to note that the final values for atmospheric deposition of nitrogen, phosphorus and particulate matter reported in this section came from a variety of studies including those by CARB (LTADS), UC Davis -TERC, UC Davis - DELTA Group and DRI.

4.5.2 Dry Atmospheric Deposition

Sampling Design and Methodologies

The LTADS investigation employed an ambient air monitoring program in concert with a pollutant deposition model to estimate atmospheric deposition to the surface of Lake Tahoe. Alternatively, the UC Davis -TERC approach consisted of the deployment of wet/dry and bulk (wet plus dry) collectors to directly estimate atmospheric deposition. A brief overview of the LTADS and UC Davis Lake Tahoe Interagency Monitoring Plan (LTIMP) approaches are presented here, the reader is referred to CARB (2006) and Hackley et al. (2004, 2005) for further details for these two programs, respectively. These are the only two investigations to quantify atmospheric deposition over the entire annual cycle. Additionally, data on phosphorus and nitrogen deposition and phosphorus deposition reported by the UC Davis - DELTA Group and Desert Research Institute, respectively were also used.

Lake Tahoe Atmospheric Deposition Study (LTADS)

Figure 4-49 shows the location of air quality and meteorological (aloft or above the land/lake surface) monitoring sites used as part of LTADS, as well as the location of the UC Davis on-lake deposition monitoring sites. Ambient concentrations of phosphorous, nitrogen and particulate matter (PM) were measured by LTADS at the land-based monitoring sites, generally located near the shoreline.

Filter-based measurements of atmospheric pollutants were obtained between November 2002 and March 2004 using two types of samplers: two-week samplers (TWS) and mini-volume samplers (MVS). The TWS collected integrated samples representing total suspended particulates (TSP), PM_{10} and $PM_{2.5}$, nitric acid and ammonia. The mini-volume samplers were stationed on lake buoys and on land.

UC Davis – Lake Tahoe Interagency Monitoring Program (LTIMP)

As part of the Lake Tahoe Interagency Monitoring Program (LTIMP), UC Davis - TERC monitors atmospheric deposition of nitrogen and phosphorus at two locations on the lake. The first, designated as the mid-lake buoy (TB-1), is located in the northern, middle portion of the lake (Figure 4-49). The second location, designated as the northwest lake buoy (TB-4), is located between the mid-lake station and Tahoe City. From April 2002 to June 2005, 83 buoy bucket samples (both wet and dry collected simultaneous as bulk) from TB-1 were analyzed for nutrient chemistry. At TB-4 a total of 78 buoy bucket samples were analyzed over the same time period. Measured parameters include pH, nitrate (NO_3^-), ammonium (NH_4^+), total Kjeldahl nitrogen (TKN), soluble reactive phosphorus (SRP), total dissolved phosphorus (TDP; persulfate digestion of a filtered sample), and total phosphorus (persulfate digestion of an unfiltered sample). Measurements were initially reported as aqueous concentrations (in units of µg/L) then converted to estimates of dry deposition on a per unit area basis.

Sampling protocols for atmospheric deposition can be found in the TERC Standard Operating Procedures (Janik et al. 1990). Wet and dry deposition was captured directly using both a wet/dry collector that independently collects both forms of fallout or a bucket-collector that captures both wet and dry fall at the same time as bulk deposition (Hackley et al. 2004, 2005). Analytical methodologies and standard QA/QC practices are found in Janik et al. (1990) and Jassby et al. (1994).

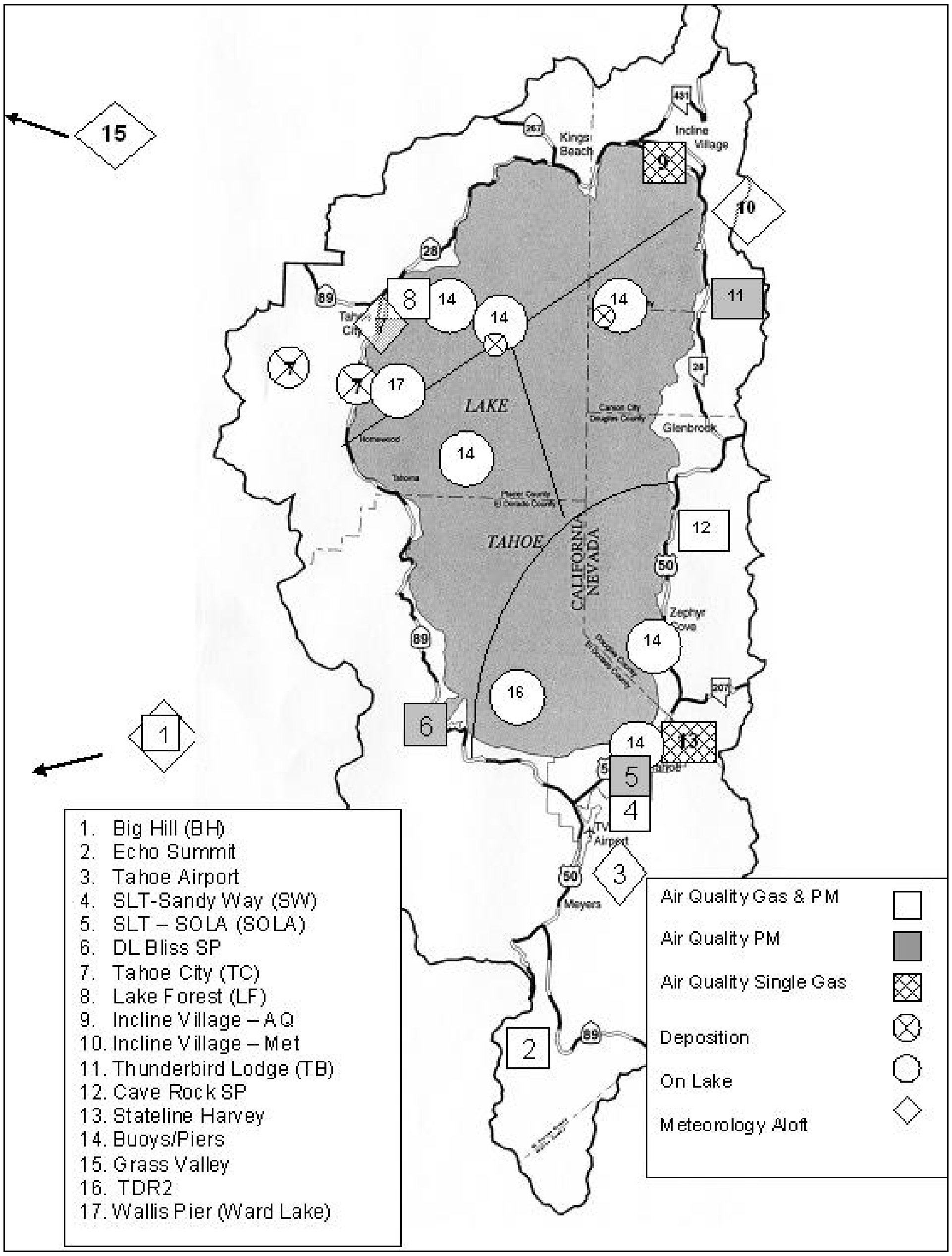

Figure 4-49. LTADS map of study sites and activities at each site (November 2002 to March 2004) (CARB 2006).

Atmospheric Concentrations of Particulate Matter, Nitrogen and Phosphorus

This section provides a summary of the ambient air concentrations used in estimating atmospheric deposition of particulate matter, nitrogen and phosphorus directly to the surface of Lake Tahoe. When appropriate, comparisons to other air monitoring data at Lake Tahoe are provided. A summary of the deposition estimate methodologies and the deposition estimates are presented in Section 4.5.3. These ambient concentration measures were used when modeling atmospheric deposition; they are independent of the deposition-bucket approach employed by UC Davis - TERC.

Ambient Concentrations: Particulate Matter

Data used in the calculation of particulate matter deposition (both dry and wet) were taken entirely from LTADS (CARB 2006). CARB (2006) presented the annual averages for TWS TSP, PM_{10} and $PM_{2.5}$ mass concentrations from November 2002 to December 2003 at the Big Hill, Lake Forest, Thunderbird, Sandy Way and SOLA sites. Note that for discussions specifically related to the TSP, PM_{10} and $PM_{2.5}$ fractions there is measurement overlap. By definition, PM_{10} is the total weight of material less than 10 µm in size and therefore it includes the $PM_{2.5}$ fraction (less than 2.5 µm in size); similarly, TSP includes PM_{10} and $PM_{2.5}$.

Throughout this section, the terms fine particulate matter (PM Fine), coarse particulate matter (PM Coarse) and large particulate matter (PM Large) are used. PM Fine is the measured aerosol mass < 2.5 µm in aerodynamic diameter. PM Coarse is defined as that fraction between $PM_{2.5}$ and PM_{10}. PM Large is that fraction greater than PM_{10}. Therefore, $PM_{2.5}$ and PM Fine are identical, whereas PM_{10} ≠ PM Coarse and TSP ≠ PM Large. As much as possible, the data are presented in terms of PM Fine, PM Coarse and PM Large since they each represent distinct and non-overlapping size ranges.

Annual Particulate Matter Summary

The highest annual average concentration of total suspended particles (TSP) was found at SOLA (21.2 µg/m^3) and Sandy Way (21.1 µg/m^3) followed by Lake Forest (17.9 µg/m^3) (Table 4-43). Big Hill (out-of-basin) and Thunderbird were lower and more similar to the on-lake annual average TSP concentrations of 7.1 and 6.7 µg/m^3 measured at buoys TB-1 (east) and TB4 (west), respectively. Annual average PM_{10} concentration was highest at the SOLA site (18.8 µg/m^3), followed by the Sandy Way (16.8 µg/m^3), Lake Forest (14.0 µg/m^3), Big Hill (8.8 µg/m^3) and Thunderbird (6.0 µg/m^3) sites. For comparison, between 1990 and 1994, Cliff and Cahill (2000) reported nearly identical average values for PM_{10} of about 20 µg/m^3 and about 7 − 8 µg/m^3 at South Lake Tahoe and D.L. Bliss State Park, respectively. The highest annual average $PM_{2.5}$ (same as PM Fine) concentration was found at the Sandy Way site (8.0 µg/m^3), followed by SOLA (7.1 µg/m^3), Big Hill (4.8 µg/m^3), Lake Forest (4.7 µg/m^3) and Thunderbird sites (3.6 µg/m^3) (Table 4-43). Again, during the period 1990-1994, Cliff and Cahill (2000) reported similar average values for $PM_{2.5}$ of about 11 µg/m^3 and 4 µg/m^3 at South Lake Tahoe and D.L. Bliss State Park, respectively. These results agree with the assumed characteristics of the sites identified for LTADS: the Thunderbird site represents a local background site and the SOLA and Sandy Way sites represent heavy urban sites.

The relative contribution of each size categories depended on location. In general, large particulate matter accounted for approximately 15 − 25 percent of TSP. The only exception was at Thunderbird where large particulate matter did not contribute much to TSP. Coarse particulate matter accounted for approximately 35 − 50 percent of TSP with Lake Forest and SOLA both at ≥ 50 percent. Fine particulate matter showed the widest range at 26 percent (Lake Forest) to 58 percent (Thunderbird). On average the relative contributions of fine and coarse particulate matter were similar.

Table 4-43. Annual average concentration of air-borne particulate as measured by the LTADS two week samplers (modified from CARB 2006).

Location	Fine Particulate Matter[a] ($\mu g/m^3$)	Coarse Particulate Matter[b] ($\mu g/m^3$)	Large Particulate Matter[c] ($\mu g/m^3$)	Particulate Matter TSP[d] ($\mu g/m^3$)
Big Hill	4.8	3.9	2.8	11.5
Thunderbird	3.6	2.2	0.2	6.0
Lake Forest	4.7	9.1	4.1	17.9
Sandy Way	8.0	8.4	4.7	21.1
SOLA	7.1	11.0	3.1	21.2

[a]Fine particulate matter is concentration of particles < 2.5 µm in aerodynamic diameter
[b]Coarse particulate matter is concentration of particles 2.5-10 µm in aerodynamic diameter
[c]Large particulate matter is concentration of particles > 10 µm in aerodynamic diameter
[d]Particulate matter TSP = ∑ Fine PM +Coarse PM + Large PM

Temporal Variation

The measured size classes of particulate matter also varied seasonally. TSP concentrations at the Thunderbird site, the local background site, were generally about 5 $\mu g/m^3$ during winter and spring but increased by a factor of approximately three in the summer. Peaks in winter values were observed at both the Sandy Way and SOLA sites located on the south shore (Table 4-44). Cliff and Cahill (2000) found a distinct winter peak in each of four years for PM_{10} and $PM_{2.5}$ at South Lake Tahoe. Moreover, Cahill et al. (2003) reported that ambient air concentrations for silicon (an indictor for the fine sediments that affect lake clarity) were elevated in both the winter and summer; this was also demonstrated by LTADS (CARB 2006).

Table 4-44. Seasonal average concentrations of particulate matter (modified from CARB 2006).

Location/Particulate Matter Size	Winter ($\mu g/m^3$)	Spring ($\mu g/m^3$)	Summer ($\mu g/m^3$)	Fall ($\mu g/m^3$)	Annual Mean ($\mu g/m^3$)
Big Hill					
Fine Particulate Matter	1.4	3.7	6.6	5.0	4.8
Coarse Particulate Matter	0.4	1.8	5.5	4.9	3.9
Large Particulate Matter	1.4	0.9	4.0	3.7	2.8
TOTAL (=TSP)	3.2	6.4	16.1	13.6	11.5
Thunderbird					
Fine Particulate Matter	2.3	2.4	5.8	3.7	3.6
Coarse Particulate Matter	1.0	2.1	3.3	2.5	2.2
Large Particulate Matter	0.3	0.2	0	0.3	0.2
TOTAL (=TSP)	3.6	4.7	9.1	6.5	6.0
Lake Forest					
Fine Particulate Matter	5.0	3.0	6.1	4.8	4.7
Coarse Particulate Matter	10.8	8.7	7.8	9.1	9.1
Large Particulate Matter	1.8	4.5	5.7	4.3	4.1
TOTAL (=TSP)	17.6	16.2	19.6	18.2	17.9
Sandy Way					
Fine Particulate Matter	10.2	4.9	7.1	9.8	8.0
Coarse Particulate Matter	11.6	7.8	6.2	7.9	8.4
Large Particulate Matter	7.5	3.1	5.3	3.1	4.7
TOTAL (=TSP)	29.3	15.8	18.6	20.8	21.1
SOLA					
Fine Particulate Matter	9.0	4.0	7.0	8.2	7.1

Coarse Particulate Matter	15.4	9.1	10.5	9.4	11.0
Large Particulate Matter	5.5	2.0	0.1	4.4	3.1
TOTAL (=TSP)	29.9	15.1	17.6	22.0	21.2

24-Hour Profiles

Hourly data for particulate matter were also measured using a beta attenuation monitor; this provided greater time resolution than the TWS (CARB 2006). Figure 4-50 provides representative diel (24-hour) profiles during the summer at Thunderbird and Lake Forest. Results for other seasons and other locations are given in (CARB 2006). The profiles at Lake Forest reflect human activity patterns. This pattern was much less noticeable at the lower impacted Thunderbird site.

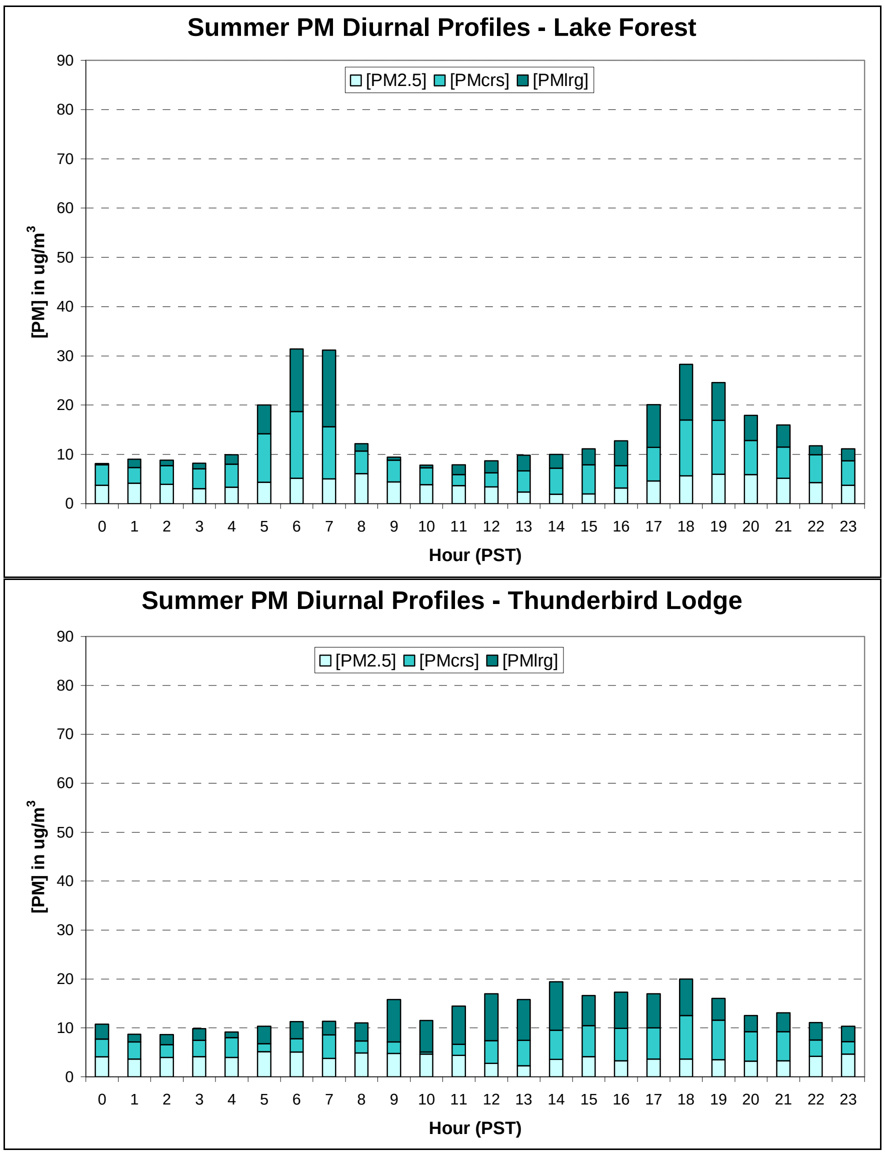

Figure 4-50. Summer diel profiles of particulate matter concentrations at Lake Forest and Thunderbird (CARB 2006).

Targeted Studies of Particulate Matter Distribution

Since particle size resolution in the LTADS baseline monitoring was limited to three, larger size ranges (< 2.5 µm, 2.5 − 10 µm and > 10 µm), additional information on size distribution was desirable to confirm that deposition calculations based on the simplified LTADS size data would reasonably represent the deposition environment at Lake Tahoe (CARB 2006). This section describes only the salient findings of a series of experiments conducted during LTADS, using optical particle counters, to better characterize the temporal and spatial variation of a more resolved series of particle size distributions. The reader is referred to CARB (2006) for a complete presentation of these results. The information presented here is most meaningful when viewed qualitatively, showing how particle concentrations and size distributions vary at Lake Tahoe. Although the sampling periods were chosen to represent conditions typical of the Lake Tahoe basin, the actual particle concentrations measured in these experiments may not be representative of long-term conditions (i.e. LTADS measurements were limited to a few sampling times during a single year).

The particle count experiments addressed: 1) spatial variation among monitoring environments (e.g., urban versus rural), 2) spatial variation between lakeshore and mid-lake areas, and 3) dilution and deposition of roadway emissions.

Sampling for particle size distribution at the pristine D.L. Bliss State Park showed that mass was dominated by larger particles. Fine particulate matter (< 2.5 µm) was less than 5 percent of the estimated mass, while large particles (> 10 µm) were nearly two-thirds of the total. The larger sizes (> 2.5 µm) were composed of mechanically generated material (primarily soil dust), while the fines (< 2.5 µm) were dominated by chemically generated materials (combustion products and secondary aerosols formed in the atmosphere from gaseous precursors). The fine particles generally constitute a large fraction of the total in urban and industrial areas, such as San Francisco or Sacramento, while the reverse is true in rural locations such as the Tahoe region.

The populated sites in the Lake Tahoe basin exhibit a wide range of particle concentrations due to effects of location, season and proximity of human activity. The SOLA site provided a unique opportunity to examine the variation in particle concentration along a populated segment of the shoreline. During night and morning hours, cold air drainage causes air to flow from the urban area across the highway and out over the lake. During midday, solar heating of the land induces a lake breeze that brings air from the lake onshore. Thus, SOLA experiences diel oscillation between the high urban aerosol concentrations associated with a population center and heavily traveled arterial highway (land breeze) and very clean air drawn off the lake under conditions of deep atmospheric mixing (lake breeze). The contrast in particle size distributions for these two extremes is shown in Figure 4-51. The combination of urban emissions (smoke, dust, etc.) with roadway emissions from Highway 50 drove the TSP (mean ± 1 standard deviation) to 274 ± 51 mg/m^3). The midday onshore flow from Lake Tahoe was much lower, with TSP at 9.6 ± 2.7 mg/m^3. TSP concentrations range by a factor of approximately 30, necessitating the logarithmic scale in the plot.

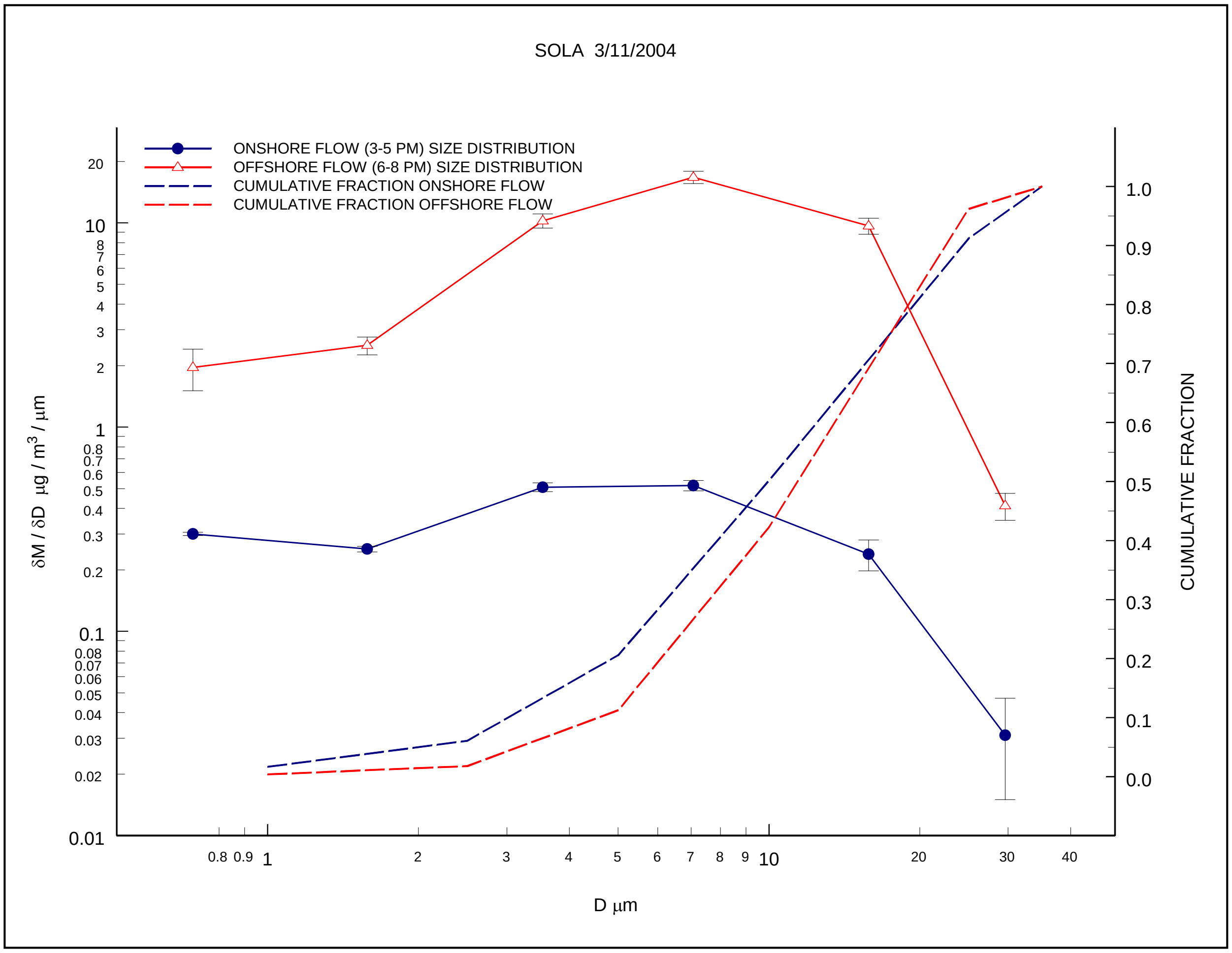

Figure 4-51. Extremes of the diel aerosol cycle at SOLA (CARB 2006).

The strong difference between the composition of air under different flow regimes observed at SOLA suggests that air flowing from land out onto the lake is not only diluted, but is also deposited onto the lake surface (CARB 2006). This pattern suggests that there is a zone of terrestrial influence near-shore that grades outward to a well mixed mid-lake environment. CARB (2006) also found that the particle size distribution from the unpopulated shoreline approximated the "background" as measured at the remote D.L. Bliss State Park site.

Roads are an important source of atmospheric particles in the Lake Tahoe basin and a significant portion of the material emitted from roads is re-deposited downwind (CARB 2006, Gertler et al. 2006). To understand dispersion and loss as a function of distance from a likely source such as motor vehicle traffic, CARB (2006) designed and executed the SOLA dust experiments. Figure 4-52 provides the results. The concentrations of particles emitted by traffic on Highway 50 in the evening diminishes with downwind distance. The magnitude of this reduction was related to particle size.

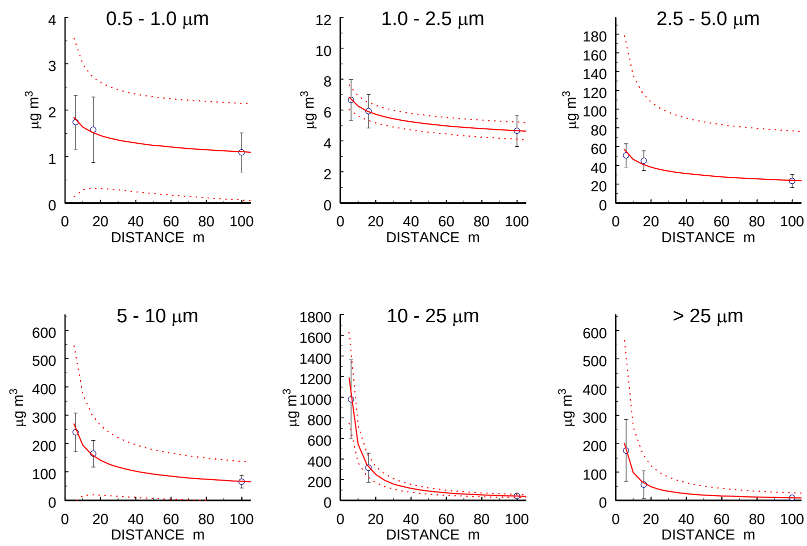

Figure 4-52. Particle concentration change and fitted power functions downwind of Highway 50 at SOLA (evening of March 11, 2004) (CARB 2006). (Note: Dotted lines are 95 percent confidence bounds for the fits)

Even for particles in the smallest size fraction (0.5 − 1 µm in aerodynamic diameter), there was nearly a 40 percent loss in the number of particles due to dispersion, deposition and interactions with tree canopies between the roadway and the lakeshore at the SOLA site. For the heavier particles (10 to 25 µm and > 25 µm in diameter), there was approximately a 90 percent loss. However, since Lake Tahoe is considered to be well-mixed due to wind-generated currents; atmospheric deposition anywhere on the lake surface is considered a direct load that influences lake clarity. The results of these experiments, taken together with the findings of the near-shore boat sampling, indicate that downslope winds deliver concentrated particle plumes to the lake from the heavily developed urban and residential portions of the lake shore and that these plumes diminish in intensity fairly quickly with increasing distance.

Estimated Particle Number and Deposited Fraction

While a variety of particle types enter Lake Tahoe directly through atmospheric deposition to the lake surface, the efficiency at which they scatter light in the water is strongly dependent on their size and chemical composition. The actual numbers of particles in the aerosol mass that affect lake clarity is not well known, but particle count data, when combined with particle chemical data from the LTADS and IMPROVE (Interagency Monitoring of Protected Visual Environments; http://vista.cira.colostate.edu/improve/Default.htm) filter records, were used by CARB to generate a rough estimate. There is uncertainty with these estimates, both from the perspective of mass deposition and the estimated particle numbers that the mass represents. However, the values are adequate first estimates and more detailed research is warranted to refine these values.

An important size range of concern for light scattering by particles in the lake is the $PM_{2.5}$ fraction. In that fraction, there are three general classes of chemical materials based on their effect on lake optical properties: (1) soluble species (e.g., sulfates and nitrates) that dissolve into the lake water and have no residual optical effect, (2) organic materials which, although largely insoluble, have refractive indices near that of water and are, therefore, optically unimportant and (3) inert materials (e.g., soot and soil minerals) that persist in the water column after deposition and affect lake clarity.

Computing the inert soil fraction of deposited particle numbers requires converting particle mass to particle numbers, then allocating the numbers to the three particle types listed above. Since there is such a large range of counts between the 0.5 − 1 µm and 1 − 2.5 µm size bins, $PM_{2.5}$ allocation is subdivided based on size distributions for "typical" aerosols to estimate where each chemical type lies in the size-number distribution. The allocation for LTADS species was based in part on limited size-resolved chemical data available from Mt. Lassen (CARB 2006). Using a combination of calculated regression analysis for particle count versus mass at SOLA (CARB 2006) and inferences drawn from the Mt. Lassen data, a species allocation scheme was developed for the LTADS $PM_{2.5}$ data (Table 4-45).

When expressed on an annual basis the contribution of inert soil particles, soluble particles and particles composed of organic matter comprised 36.4, 16.5 and 47.2 percent of the $PM_{2.5}$ mass, respectively (Table 4-45). Over the same annual period the relative contribution of the 1.0-2.5 µm size class was twice that of the 0.5 − 1.0 µm size class. The seasonal contributions of the inert soil fraction remained uniform at 33 − 39 percent. However, both soluble particles and particulate organic matter (OM) varied seasonally. Soluble particles also varied seasonally, from a low near 10 percent in winter to almost double (22 percent) in summer. Organic particles also varied between a winter peak of over half (56 percent) to a summer minimum of less than half (39 percent). Particle count fractions were similar.

The last columns in Table 4-45 show the concentration model converted into particle counts. The optical implications of these calculations are that strongly scattering fine inert particles constitute about 30 percent of $PM_{2.5}$ particles, regardless of season, while most of the variation is in the optically weak organic and soluble particles.

The influence of black carbon (carbon that is not fully combusted) was not evaluated either by LTADS or in the Lake Clarity Model. This adds a degree of uncertainty and new research is needed to evaluate this process in Lake Tahoe. Collecting this data was beyond the scope of LTADS.

Table 4-45. Allocation of particle types to seasonal data from SOLA based on the $PM_{2.5}$ fraction only (modified from CARB 2006).

Fraction of $PM_{2.5}$ (%)				Particle Count Fraction (%)
Annual	**0.5-1.0 µm**	**1.0-2.5 µm**	**All $PM_{2.5}$**	
Inert	10.2	26.1	36.4	31
Soluble	9.2	7.3	16.5	24
OM	15.6	31.6	47.2	45
Percent	35.0	65.0	100	100
APR-OCT	**0.5-1.0 µm**	**1.0-2.5 µm**	**All $PM_{2.5}$**	**Count Fraction (%)**
Inert	10.0	29.0	39.0	31
Soluble	12.2	9.6	21.8	32
OM	12.9	26.3	39.2	37
Percent	35.1	64.9	100	100
NOV-MAR	**0.5-1.0 µm**	**1.0-2.5 µm**	**All $PM_{2.5}$**	**Count Fraction (%)**
Inert	10.6	23.0	33.6	31
Soluble	6.1	4.8	10.8	16
OM	18.3	37.3	55.6	53
Percent	35.0	65.0	100	100

Ambient Concentrations: Nitrogen

Three research groups have been active in quantifying the atmospheric deposition of nitrogen directly to Lake Tahoe. These include CARB, UC Davis - TERC and DRI. CARB and DRI have employed ambient air measurements coupled with deposition modeling. TERC employed directly estimating deposition using dedicated bucket sampling. Given that the bucket deposition approach does not require measurements of ambient air concentrations, this section of the report only presents the results from the DRI studies and LTADS. While there are other databases on ambient air nitrogen concentrations (e.g., IMPROVE and monitoring programs conducted by the states of California and Nevada and the TRPA), these were limited and therefore not directly used to estimate rates of atmospheric deposition to the lake surface.

Nitrogen deposition may occur via two distinct forms. Nitrate (NO_3^-) and ammonium (NH_4^+) are considered particulate (i.e. aerosol) forms of nitrogen. Ammonia (NH_3) and nitric acid (HNO_3) are gaseous forms. Organic nitrogen can occur as both a gas and aerosol.

Desert Research Institute Ambient Nitrogen Measurements

Nitrogen deposition to Lake Tahoe was estimated as dry deposition during the summer and early fall season (July-September only) by Tarnay et al. (2001, 2002, and 2005). Tarnay et al. (2001) hypothesized that HNO_3, NH_3 and NH_4NO_3 (ammonium nitrate) were the primary sources of dry nitrogen deposition during the summer dry season. Ambient concentrations of HNO_3 and NH_3 were measured at two sites with open terrain to represent ambient concentrations above forest canopies. These included D.L. Bliss State Park (adjacent to Desolation Wilderness) and Incline Village Overlook, Nevada (southwest exposure of Mt. Rose). These ambient air nitrogen measurements were conducted in 1997 and 1998 and reported in Tarnay et al. (2001). The NH_4NO_3 data were obtained from the IMPROVE network (1990-1996) (Cahill 1999 *In:* Tarnay et al. 2001).

Tarnay et al. (2005) also reported measured summer HNO_3 and NH_4 concentrations through 2000 and from a more extensive series of sites including Barker Pass, D.L. Bliss State Park, Echo Summit, SOLA, Thunderbird and Incline. Organic nitrogen and particulate nitrogen were not measured. Table 4-46 presents the mean day and night air concentrations.

Table 4-46. Mean day and night concentrations for various nitrogen species (modified from Tarnay et al. 2005).

Nitrogen Species	Mean Concentration - Day (μg N/m^3)	Mean Concentration - Night (μg N/m^3)
HNO_3	0.24 ± 0.02 [a]	0.18 ± <0.02
NH_3	0.30 ± 0.07	0.14 ± 0.09
NH_4NO_3 [b]	0.10 ± <0.01	0.10 ± <0.01
NO_2 [c]	2.66 ± 0.14	1.34 ± 0.45

[a]Values represent ± 1 standard error
[b]NH_4NO_3 values from Tarnay et al. (2001)
[c] Tarnay et al. cites these as reported values from co-located NO_x sampler at Incline, Echo Summit and SOLA (CARB)

UC Davis Aircraft Based Ambient Nitrogen Measurements

Zhang et al. (2002) collected air samples from an airplane, at an elevation of approximately 300 meters above the surface of Lake Tahoe, during July and August of 2001 (flights only during the daytime) and monitored them for nitrogen, among other parameters. A total of 12 sampling flights were made over Lake Tahoe on six dates. As part of the study, measurements were also taken from a mid- and low-elevation on the west slope of the Sierra Nevada as well as from the plume of a forest fire in the vicinity of Truckee, California during slightly smoky conditions.

A July 2002-March 2003 aircraft sampling was also completed as part of the LTADS program using the same methodology as cited above (Carroll et al. 2003). Table 4-47 summarizes the findings from these related studies.

Organic nitrogen was higher in samples taken under slightly smoky conditions. Otherwise the remaining nitrogen species were similar. The 2001 and the July 2002-March 2003 sampling events produced similar results.

Table 4-47. Average (± standard deviation (s.d.)) for ambient air concentrations of nitrogen species sampled aloft (data from Zhang et al. 2002, Carroll et al. 2003).

Nitrogen Species	2001[a]		July 2002 – March 2003[b]
	Clear ($\mu g\ N/m^3$)	Slightly Smoky ($\mu g\ N/m^3$)	All Conditions ($\mu g\ N/m^3$)
HNO_3 (g)	0.31	0.35	0.34 ± 0.17
NH_3 (g)	1.08	0.99	0.88 ± 0.78
ON (g)	0.20	0.91	0.25 ± 0.33
TN (g)	1.59	2.25	1.38 ± 0.89
NO_3^- (p)	0.10	0.09	0.04 ± 0.04
NH_4^+ (p)	0.18	0.22	0.18 ± 0.12
ON (p)	0.06	1.78	0.15 ± 0.20
TN (p)	0.34	2.09	0.29 ± 0.23
HNO_3 (g) + NO_3^- (p)	0.41	0.43	0.38
NH_3 (g) + NH_4^+ (p)	1.26	1.22	1.06
ON (g) + ON (p)	0.25	2.69	0.40
TN (g) + (p)	1.96 ± 0.46 (1 s.d.)	4.34 ± 0.80 (1 s.d.)	1.67

[a]Data source: Zhang et al. (2002)
[b]Data source: Carroll et al. (2003)
(g) = gaseous form
(p) = particulate
ON = organic nitrogen
TN = total nitrogen

LTADS Ambient Nitrogen Measurements

The most comprehensive monitoring of ambient air nitrogen concentrations used to support modeled estimates of atmospheric deposition was conducted as part of LTADS. According to (CARB 2006), several nitrogen species can be deposited from the atmosphere in both aerosol (suspension of particles in air) and gaseous forms. The most common nitrogen-containing aerosol species are ammonium nitrate (NH_4NO_3) and ammonium sulfate ($(NH_4)_2SO_4$). Both are water soluble and readily deposited to water.

Based on nitrate and ammonium measurements, CARB (2006) calculated the atmospheric concentrations of particulate and gaseous nitrogen (Table 4-48). There was a wide variation across the sites. In the winter, the populated sites in the basin (Lake Forest, Sandy Way and SOLA) showed elevated ambient air concentrations of nitrogen. In the summer, the south shore was still elevated, but the difference between sites was less pronounced than the winter. The unpopulated east shore (Thunderbird) showed the least seasonal signal and had the lowest concentrations year-round. The study average of 0.57 $\mu g\ N/m^3$ at Thunderbird was approximately three times lower than more populated areas.

Table 4-48. Gaseous and aerosol nitrogen from the LTADS network (µg N/m^3) (modified from CARB 2006).

Site	Nitrogen Particulate and Gas (µg N/m^3)				
	Winter	Spring	Summer	Fall	Study Average
Big Hill	0.22	0.76	1.95	1.52	1.33
Lake Forest	0.93	0.67	1.17	1.20	0.97
Sandy Way	1.47	1.24	2.83	1.94	1.63
SOLA	2.73	1.38	1.88	2.30	2.13
Thunderbird	0.32	0.47	0.82	0.67	0.57
Maximum Basin-Wide (excludes Big Hill)					3.84
Average Basin-Wide (excludes Big Hill)					1.35
Median Basin-Wide (excludes Big Hill)					1.28
Minimum Basin-Wide (excludes Big Hill)					0.15

The relative contribution of gas and aerosol species is also highly variable across the network. Total nitrogen distributions are shown in Table 4-49. The aerosol fraction (nitrate + ammonium) is greatest at the less-populated sites (Thunderbird and Big Hill), while the ammonia gas fraction peaks in the populated areas (SOLA, Sandy Way and Lake Forest). Nitric acid, by contrast, is a relatively constant fraction at all sites. On average, 70 percent or more of total nitrogen is from ammonia plus ammonium, with over 50 percent of total nitrogen from ammonia alone. Thus, total atmospheric nitrogen is primarily determined by the supply of ammonia, regardless of its site-specific aerosol-gas partitioning. Of these nitrogen species, NH_3 and NH_4^+ are both highly water soluble.

Table 4-49. Relative contributions of nitrogen species nitrate, ammonium (NH_4^+), nitric acid (HNO_3) and ammonia (NH_3). The rows labeled NH_4^++NH_3 and HNO_3+NO_3^- are composites for the individual nitrogen species (CARB 2006).

Site	Nitrates (p)	NH_4^+ (p)	HNO_3 (g)	NH_3 (g)	NH_4^+ + NH_3	HNO_3 + NO_3^-	Total Nitrogen (µg N/m^3)
	Percent of Total	Percent of Total	Percent of Total	Percent of Total	Percent of Total	Percent of Total	Study Average
Big Hill	21	32	11	36	68	32	1.333
Lake Forest	11	21	11	57	78	22	0.973
Sandy Way	15	24	14	48	72	28	1.627
SOLA	9	14	10	67	81	19	2.125
Thunderbird	21	40	13	26	66	34	0.566

(p) = particulate
(g) = gaseous

LTADS (CARB 2006) reported total nitrogen values based on the aerosol and gaseous nitrogen data presented in Table 4-49. Organic nitrogen was not measured during the LTADS program. Based on the aircraft sampling of Zhang et al. (2002) over Lake Tahoe during clear conditions, organic nitrogen comprised 10 to 15 percent of total nitrogen during summer sampling. This value increased to 60 to 65 percent during slightly smoky conditions.

Comparison of Lake Tahoe Ambient Air Nitrogen Measurements

This section provides a summary comparison of the ambient air nitrogen measurements as presented in the studies described above. All values were converted to µg nitrogen/m^3 to make results directly comparable (Table 4-50).

Table 4-50. Comparison of ambient air nitrogen measurements from Lake Tahoe.

Nitrogen Species	**DRI 1997-2000**[a]		**LTADS 2002-03**
	Mean Day (µg N/m^3)	**Mean Night (µg N/m^3)**	**Study Median (µg N/m^3)**
HNO_3	0.24	0.18	0.13
NH_3	0.29	0.14	0.63
NH_3NO_3	0.10[b]	0.10[b]	0.05[c]
Nitrogen Species	**UC Davis Aircraft**[d]		**LTADS**
	2001	**2002-03**	**2005**
	Clear Air Average (µg N/m^3)	**All Conditions Average (µg N/m^3)**	**Study Median (µg N/m^3)**
HNO_3 (g)+NO_3 (p)	0.41	0.38	0.29
NH_3 (g)+NH_4 (p)	1.26	1.06	1.02
ON (g)+ON (p)	0.25	0.40	Not Measured
TN (g)+TN(p)	1.96	1.67	1.28

[a]Tarnay et al. (2005) provided an update to the preliminary measures reported in Tarnay et al. (2001); includes data for summer period only
[b]Taken from IMPROVE network at D.L. Bliss State Park and SOLA, summer-fall 1990-1996
[c]MVS average as reported in CARB (2006), based on only 6 samples
[d]Zhang et al. (2002) and Carroll et al. (2003)

Nitric acid (HNO_3) concentrations observed during LTADS were in the range, albeit lower, to those reported by Tarnay et al. (2001 and 2005). LTADS data from the remote site at D.L. Bliss State Park also agreed with ammonium nitrate concentrations reported by Tarnay et al. (2001). However, despite similar sampling protocols, LTADS observed substantially higher ammonia concentrations than were reported by Tarnay et al. (2005). No comprehensive evaluation of interannual variation in these nitrogen species is available.

Zhang et al. (2002) reported aircraft sampling in and near the Lake Tahoe basin. These measurements were variable, but were within the range of LTADS reported concentrations (Table 4-50). Carroll et al. (2003) performed detailed air and boat sampling over and on Lake Tahoe in coordination with LTADS. The ammonium nitrate and gaseous nitrogen concentration range from the Carroll et al. (2003) study were between the reported median and maximum values (CARB 2006). The ammonia fraction of nitrogen species from Carroll et al. (2003) and the LTADS agree quite well.

Concentrations of organic nitrogen were only measured during the UC Davis aircraft sampling. Organic nitrogen in the gaseous and $PM_{3.5}$ components accounted for 13 to 22 percent of all nitrogen species combined (Table 4-50). This would be an underestimate to the extent that organic nitrogen is present in the > 3.5 µm fraction.

Ambient Concentrations: Phosphorus

Phosphorus is not commonly a focus of air quality monitoring. The IMPROVE network reports phosphorus concentrations for $PM_{2.5}$, but does not use it in computing aerosol composition statistics or quality assurance calculations. However, Cahill et al. (2003) found that at South Lake Tahoe, phosphorus is predominantly seen in size modes above 2.5 µm. LTADS attempted to measure/analyze aerosol phosphorus, but the analytical measurements were limited and there was considerable uncertainty associated with the data. Perhaps the best data set on ambient concentrations of atmospheric phosphorus comes from the UC Davis-TRPA studies at SOLA (Cahill et al. 2004); however, this is a highly urban site and not representative of lake-wide conditions.

Difficulties Associated with Measuring Phosphorus

The University of California conducted a Peer Review of the LTADS Report and acknowledged that measurement of atmospheric phosphorus is not routine and is very difficult. The relatively clean air in the Lake Tahoe basin further accentuates the phosphorus detection problem. Low phosphorus concentrations and interferences from other elements in ambient samples makes detecting phosphorus concentrations using most X-ray fluorescence (XRF) systems difficult to achieve even in the best of circumstances.

Aerosol phosphorus levels at Lake Tahoe are low enough that standard sampling/analytical methods are often ineffective. Phosphorus is a geochemically rare element, which contributes to its status as a limiting nutrient for algal growth. In ambient aerosols, phosphorus detection is hampered by small phosphorus concentrations and by strong interference from two common elements, sulfur and silicon.

The sulfur interference is driven by three factors: 1) the strongest spectral fluorescence lines for phosphorus and sulfur are separated by only a little more than the minimum energy resolution of typical fluorescence detectors, 2) sulfur fluoresces more strongly than phosphorus, and 3) sulfur is usually present at several times the concentration of phosphorus. Together, these factors often cause the sulfur signal to overwhelm the phosphorus signal. The silicon interference is not as intrinsically strong, but silicon is generally present in much higher concentrations than phosphorus and the large concentration peaks have wider electronic “noise” footprints. Furthermore, phosphorus x-rays self-absorb in the standard detectors, losing x-rays to heat and avoiding measurement as phosphorus. Additionally, x-ray methods that try to detect phosphorus in a soil (alumino-silica) matrix are subject to very significant self-absorption; again under-estimating actual phosphorus concentrations.

Addressing the Difficulties Associated with Measuring Phosphorus

During the LTADS sampling program, 604 filters were analyzed by XRF. Based on the significant difficulties in measuring low-level aerosol phosphorus concentrations, a 70-sample subset of these filters was run by Dr. Steve Cliff (UC Davis) using the much more sensitive Synchrotron-X-Ray Fluorescence (S-XRF) instrumentation (Cliff 2005). Of this 70 filter-subset, a total of 56 (80 percent) actually showed concentrations above the detection limit. While only about 10 percent of all the filters were analyzed with S-XRF, they included both summer and winter samples and came from numerous sampling sites including the on-lake buoys, SOLA and Sandy Way (South Lake Tahoe), Zephyr Cove, Thunderbird, Lake Forest and a lakeshore location in Ward Valley. Although this is a reduced data set, these phosphorus measurements do provide a credible first estimate of lake area averages (T. Cahill 2006a personal communication).

Ambient Air Phosphorus Concentrations

Figure 4-53 shows phosphorus aerosol data measured at SOLA (Cahill et al. 2004 and revised in 2005 based on the S-XRF analysis discussed above) and provides a clear summary of size-resolved phosphorus concentrations. While aerosol phosphorus was found in size class <$PM_{2.5}$, concentrations were extremely low. Past studies did not focus on the PM_{10} and greater categories. This is likely the explanation as to why the historical phosphorus data for ambient air quality at Lake Tahoe show very little airborne phosphorus. Aerosol phosphorus concentrations were somewhat lower in the winter than the summer, but both were similar in magnitude. According to Cahill et al. (2003), phosphorus in the > 2.5 µm size classes is associated with soils and the 0.09 − 0.26 µm class represents phosphorus in diesel and car exhaust. The summer values in the 0.26 − 0.34 µm and 0.34 − 0.56 µm size classes were associated with wood smoke.

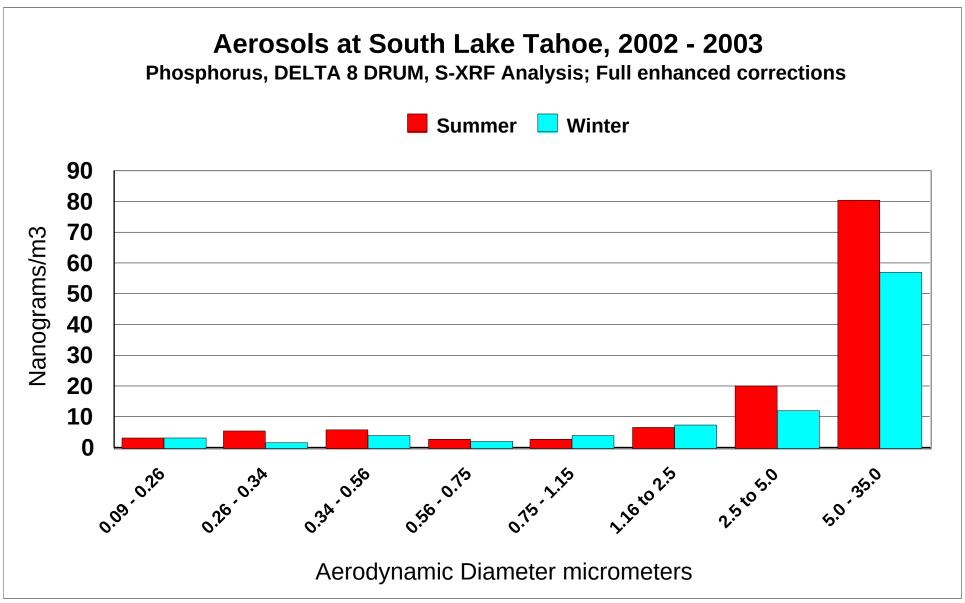

Figure 4-53. Airborne phosphorus at SOLA (Cahill et al. 2004, figure revised 2005).

Further analysis of the SOLA data indicates that the winter is associated with materials brought in for road sanding operations (Cahill et al. 2004). Concentrations of airborne phosphorus were subject to rapid increases and decreases, presumably the results of the following common sequence of events: snow – application of road sand – warming air temperature – roadway snow melt – drying of road surface with residual sand – transport as wind blown dust (Figure 4-54).

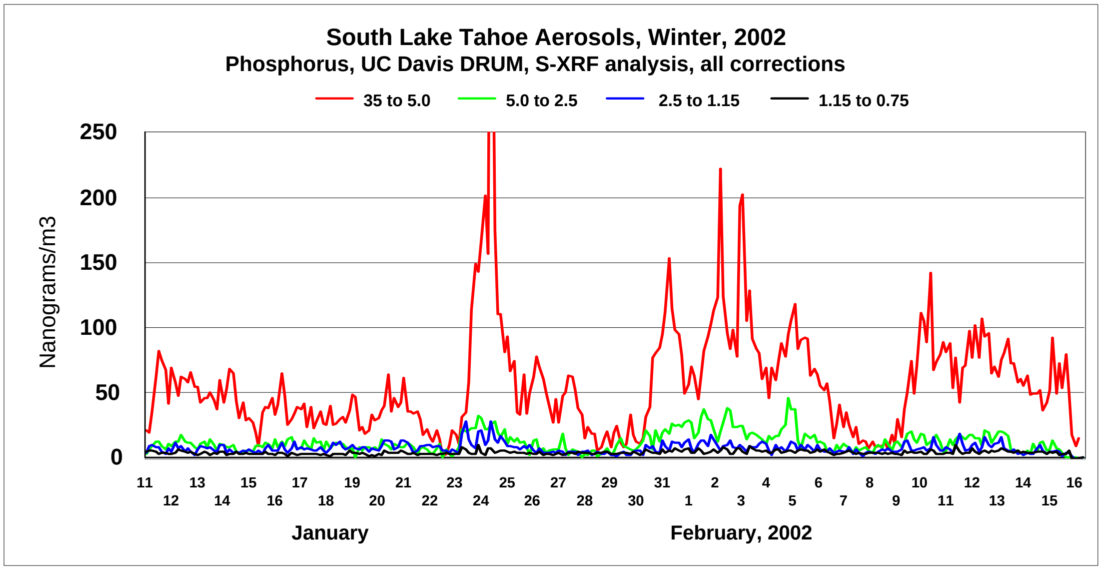

Figure 4-54. Aerosol phosphorus collected during the winter (Cahill et al. 2004, revised 2005). Note the highest phosphorus concentrations in the 5 − 35 µm size fraction.

In contrast, summer airborne phosphorus exhibited a more steady day-to-day profile at South Lake Tahoe (Figure 4-55). In early September, there was a “clean” period that coincided with a frontal system passing through the basin. Summer airborne phosphorus at SOLA was somewhat higher than during the winter. While the exact cause is unknown, it could be related to increased traffic on the roadways and soft shoulders, and other summertime activities (e.g. OHV vehicle use, construction, unpaved yet exposed soils, wind erosion from disturbed soils, etc.).

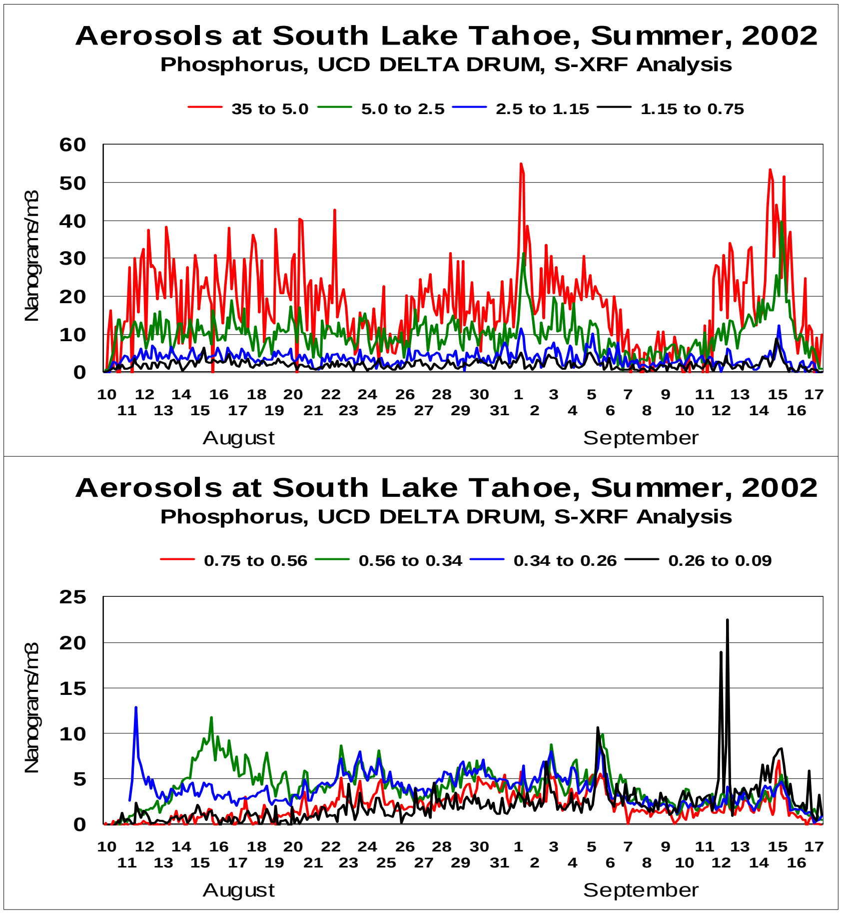

Figure 4-55. Aerosol phosphorus collected during the summer (Cahill et al. 2004, revised 2005).

Estimates of Dry Atmospheric Deposition: Particulate Matter, Nitrogen and Phosphorus

Four research groups have been active in quantifying the atmospheric deposition of nitrogen, phosphorus or particulate matter directly to Lake Tahoe. CARB, the UC Davis DELTA Group, and DRI employed the approach of ambient air measurements coupled with deposition modeling. The data summarized in the previous Sections were used to estimate on-lake atmospheric deposition. UC Davis - TERC directly estimated dry deposition using dedicated bucket sampling.

Overview of Dry Deposition Estimation Methodologies

Desert Research Institute – Nitrogen

Tarnay et al. (2001) estimated nitrogen deposition to the lake surface using the following equation:

$$F_w = V_d \times C_a \quad \textbf{Equation 3}$$

Where:

F_w = deposition to the Lake surface in mol N/m/s

C_a = constituent concentration
V_d = the deposition velocity in units of m/s.

Tarnay et al. (2001) used V_d from four studies; reported values were HNO_3 = 6.4 mm/s, NH_3 = 1.5 − 7.6 mm/s, and NH_4NO_3 = 0.05 − 2.0 mm/s. Using both updated air sampling database and modeling techniques, Tarnay et al. (2005) revised some of the preliminary estimates of dry nitrogen deposition to the lake.

The DRI flux estimates are reported in units of kg nitrogen/hectare/summer and represent the deposition of inorganic nitrogen species during the dry summer period only. Organic nitrogen, summer wet deposition, and annual deposition were not estimated.

UC Davis DELTA Group – Phosphorus

The UC Davis DELTA Group estimated phosphorus deposition to the surface of Lake Tahoe from a range of sources based on the collected ambient air phosphorus concentration data (Cahill 2005; Cahill 2006b; Gertler et al. 2006) using the Lake Tahoe Airshed Model (LTAM) (Cliff and Cahill 2000).

LTAM is an Eulerian array of 1,248 cells each with an area of 2.56 km^2 (1 mi^2) across the basin. The domain is 72 km north to south (Truckee to Echo Summit) and 42 km west to east (Ward Peak to Spooner Summit). LTAM is semi-empirical in design, and incorporates all available air quality measurements at Lake Tahoe, 1967-present, plus aspects of meteorological and aerometric theory. Free variables (traffic flow, acres burned in the forest, population density, etc.) are assumed to have a linear relationship with pollutant emissions. This model is a heuristic tool used to gather the disparate sources of air quality data at Lake Tahoe into a consistent framework. The LTAM developers realized that emission estimates valid in other parts of the state and nation may not, even if available, be relevant to the unique conditions of the Lake Tahoe area. Whenever possible, measured values in the basin were used to establish source emission relationships.

The key factors in LTAM that relate to impacts of atmospheric pollutants are source and sink (deposition) strength, and meteorology. The meteorological conditions are divided into summer day, summer night, and winter (non-storm) conditions. As such, LTAM was used to estimate dry deposition only. Data on wind speed and direction come from UC Davis-TERC data at the north end of Lake Tahoe and TRPA data at the southern end of the lake. Mid-lake meteorology was derived from personal observations (T. Cahill 2006a personal communication) and enhanced by theoretical interpretation of night-time down slope patterns seen at the south end of the lake. Lateral dispersion in urban settings are calculated from the measured US Hwy. 50 transects (Barone et al. 1979), while lake transport is estimated from the same parameters modified by the relative z_o obstruction ratio (trees versus a flat lake) giving an estimated one-fifth decrease per grid dimension of 2.56 km^2. This is approximately confirmed by photographs taken in early winter mornings, showing the South Lake Tahoe haze extending 2-5 miles over the lake. Night winds were assumed to follow topography, moving from the highest points, the watershed boundary, down slope to the lowest elevation, the lake surface. Every evening, air is moved from land to water and trapped close to the water surface.

Modeling is accomplished by a three-cell average centered on the mean wind direction. This gives a representation of the geographic variability of the wind direction. As sources are encountered, the values are added. Mixing of air from adjacent cells is modeled by mathematical averaging of the meteorological output.

The fall out of particles downwind of a local line or area source is modeled as logarithmic, based upon the observed fall off of fine particles at South Lake Tahoe (Barone et al. 1979). Fall out over the lake, however, was assumed to be less rapid due to the much lower surface roughness parameter (z_o) over the water. In the total absence of these data, this parameter is set 3 to 5 times less than in forest conditions.

It has been shown that pollutants emitted near ground level, and especially in inversions at night and winter, are quite local in character (Cliff and Cahill 2000). A correlation between local traffic, lead, sulfate, and ozone and also for soils and road salt indicated that a uniform distribution of transported pollutants exists in the basin and that local sources are quite variable depending on source strength (Cliff and Cahill 2000). Emission estimates are discussed in further detail in published and unpublished research (Cliff and Cahill 2000, Cahill et al. 2004).

LTADS Program – Nitrogen, Phosphorus and Particulate Matter

The general approach taken by CARB (2006) to estimate atmospheric dry deposition rates for nitrogen, phosphorus and particulate matter involved the use of observed atmospheric concentrations in conjunction with theoretical deposition velocities. Concentration measurements were used to provide mean seasonal concentrations. The seasons were defined as winter (December, January and February), spring (March, April and May), summer (June, July and August) and fall (September, October and November). These seasonal concentrations were then refined to daily-24-hour concentrations based on ancillary hourly data (e.g., particulate matter data, gas measurements). These hourly, seasonally-averaged concentration data were then merged with hourly deposition velocities defined by the hourly meteorological data (e.g., wind speed and direction, air temperature, water temperature) to produce hourly deposition rates that were summed seasonally and annually. Assumptions associated with the calculation of deposition velocities (e.g., mean particle size within size fractions, limits on maximum deposition velocities) were varied over a range of feasible values to provide bounding estimates of the atmospheric deposition of nitrogen, phosphorus and particulate matter.

The seasonal average deposition rates were associated with a specific area of the lake. Deposition to the lake surface was calculated as an unweighted average of seasonal deposition rates in four air quality quadrants representing equal areas of the lake (Figure 4-56). Those quadrants were chosen based on air quality measurements and similar densities of population and activity (CARB 2006). Deposition rates were also summed over four seasons to provide an annual estimate for each quadrant of the lake and summed across all quadrants to provide rates of deposition to the lake as a whole. The reader is advised to consult directly with the LTADS Final Report (CARB 2006) for a much higher level of detail. For unknown or poorly known parameters associated with ambient concentrations or deposition velocities, upper and lower estimates of the parameters enable bounding limits for the deposition.

Because population, roads, and other activities that generate emissions in the Lake Tahoe basin are generally located near the shore of the lake, the daily patterns of airflow are important to spatial variations in concentrations and source-receptor relationships. In addition, the deposition velocity over the near-shore waters depends on the wind direction because the roughness elements over land are much larger than over water and affect the amount of turbulence for some distance downwind. For these and other reasons, the meteorological observations presented in the LTADS Report are of practical importance and were used in the calculation of dry deposition (CARB 2006).

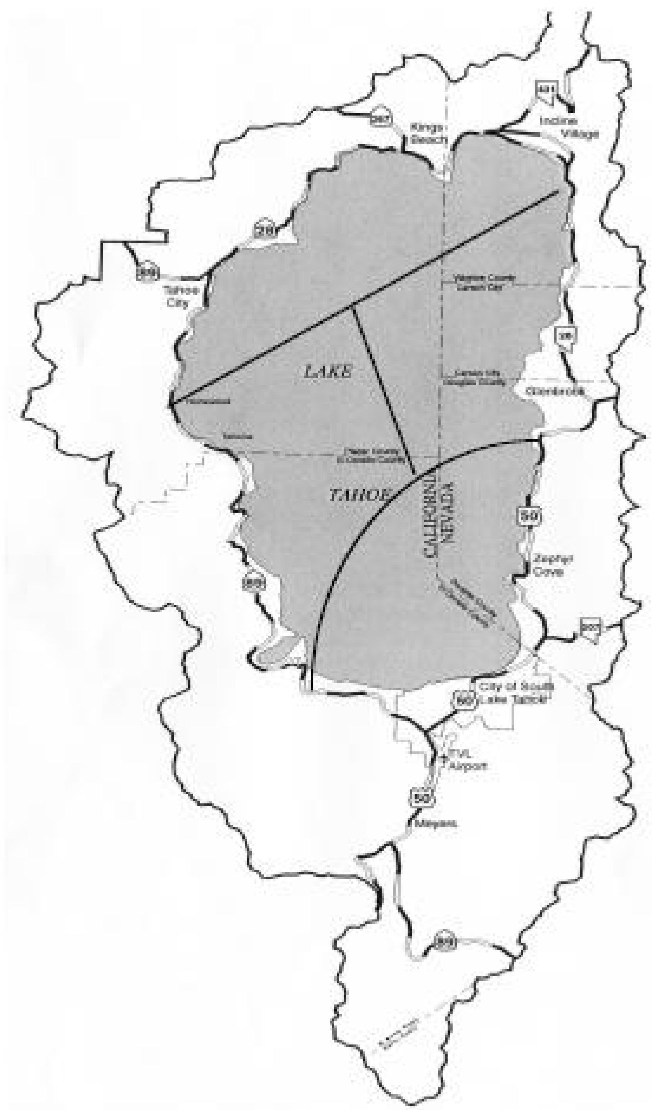

Figure 4-56. Conceptual view of lake quadrants utilized to represent the spatial variations in ambient concentrations and deposition rates over Lake Tahoe (CARB 2006).

Deposition velocities for gases and particles were modeled for each hour of 2003 for which meteorological data were available at a representative site. The methods of calculating deposition velocity are explained in detail in CARB (2006).

UC Davis TERC – Nitrogen, Phosphorus

Measurements of bulk deposition at the two open-lake sites (TB-1 and TB-4) were converted to aerial deposition based on the geometry of the collection bucket and reported as grams of nitrogen or phosphorus/hectare/day. These deposition rates were calculated for each dry sampling period and summed over the entire year. During the period of record (2002-2005), these were the only operational lake-based buoys that supported this type of sampling. The TERC buoys measured flux of bulk nutrient deposition (i.e., wet plus dry). Dry deposition was estimated by subtracting the wet deposition rates from the bulk deposition rates.

Results of Dry Deposition Estimates

LTADS Results

Seasonal and spatial variations in dry deposition rates are presented in CARB (2006). Summary graphs for nitrogen and particulate matter are provided in Figure 4-57 and Figure 4-58. It is presumed that CARB did not provide a similar figure for phosphorus deposition due to the uncertainty associated with the phosphorus measurements.

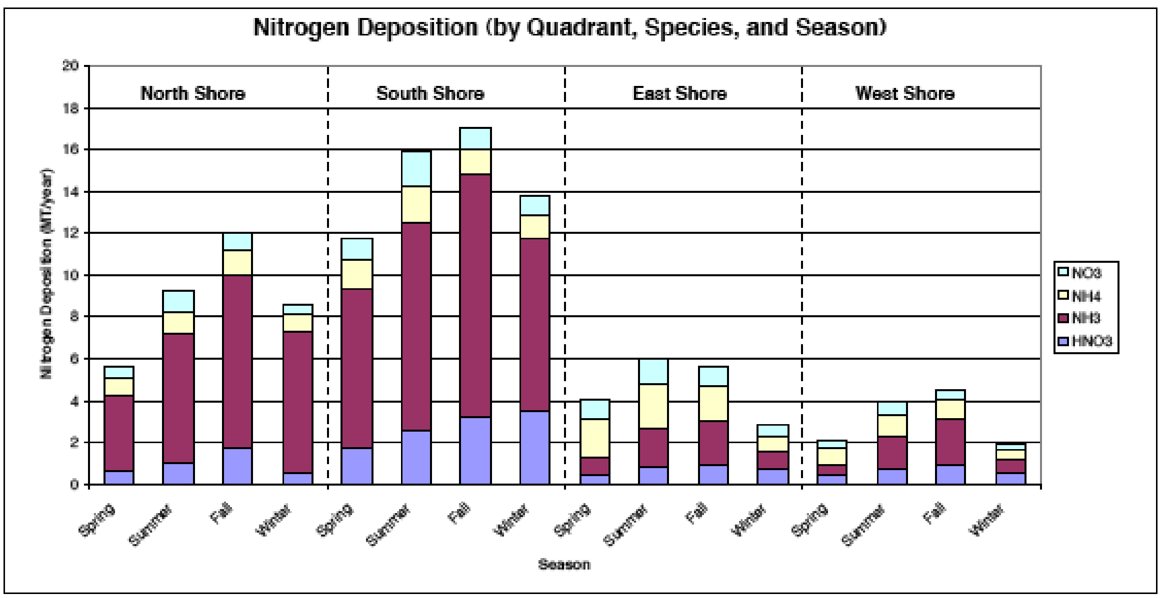

Figure 4-57. Total nitrogen dry deposition by quadrant, chemical species and season (CARB 2006).

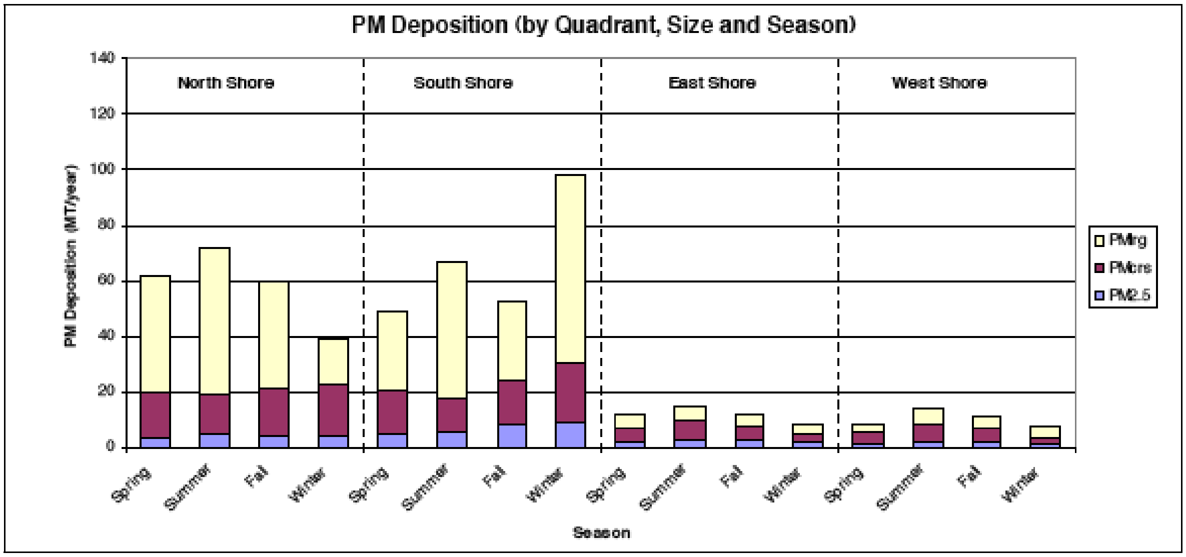

Figure 4-58. Particulate matter contributions to dry deposition by quadrant, season and particle size (CARB 2006).

A summary of the LTADS estimates for dry deposition to the entire surface of Lake Tahoe is presented in Table 4-51. Organic nitrogen was not estimated.

Table 4-51. Central estimates of dry deposition to the entire surface of Lake Tahoe in 2003 (CARB 2006).

Parameter	Size	Winter (metric tons)	Spring (metric tons)	Summer (metric tons)	Fall (metric tons)	Annual (metric tons)
TSP-NH_4	Total	1.1	3.0	3.2	2.5	10
NH_3	Total	17.7	12.8	19.4	26.4	76
TSP-NO_3	Total	1.0	2.0	3.0	2.1	8
HNO_3	Total	5.8	3.3	5.0	7.4	22
Total Nitrogen[a]	Total	25.6	21.1	30.6	38.4	116
Phosphorus[b]	Total	0.6	0.6	0.6	0.6	2.2
Particulate Matter[c]	PM Fine	17	11	15	17	60
	PM Coarse	44	42	40	43	170
	PM Large	92	78	110	77	360
	Total	153	131	167	135	590

[a]Total nitrogen does not include organic nitrogen
[b]Phosphorus concentration is 40 ng/m^3 in all zones
[c]The dry deposition calculation assumed a reduced deposition of particulate matter mass in N and S zones to account for fall-off in concentrations at mid-lake – with reduction for N and S zones equal to 25 percent of the difference between deposition in N or S zone relative to the deposition in the E zone (TB). This reduction is calculated individually for each particulate matter size fraction and season. No fall-off of concentration was assumed for the W and E zones. Fall-off phosphorus for the N and S zones was scaled to the estimated fall-off of particulate matter for each size fraction and season.

Comparison to Other Estimates

The UC Davis DELTA Group (Gertler et al. 2006; Cahill 2006b) estimated phosphorus loading from various sources to the surface of Lake Tahoe. Phosphorus-flux to the surface of Lake Tahoe was estimated at 5.4 metric tons per year (using a V_d = 0.45 cm/sec) (Cahill 2006b). This estimate was made for the period 2001-2002. Estimates were made a second time based on ambient air measurements of phosphorus made during the winter of 2003-2004; the resultant lake deposition estimate was similar, albeit less at 3.5 ± 0.5 metric tons per year. The UC Davis DELTA Group has also reported that local sources contribute approximately 95 percent to the total phosphorus load (Table 4-52). Sources related to vehicle traffic contributed 65 to 70 percent. The possible contribution from vehicle exhaust (i.e., phosphorus in lubricating oil) has only recently been considered.

Table 4-52. Percent contribution of transported and local phosphorus (Gertler et al. 2006).

Transported	Percent Contribution (%)
Asian dust	3
Sacramento Valley dust	2
Oregon forest fire smoke (2002)	<1
Local	**Percent Contribution (%)**
Highway road dust (winter)	47
Local soils (spring to fall)	21
Vehicle exhaust	21
Local wood smoke	6

The estimate of dry deposition to Lake Tahoe, based on the buoy collectors maintained by UC Davis-TERC, yielded an overall mean of 2.8 metric tons of phosphorus per year. Both TERC buoys are located in the mid-lake region on the northern portion of the lake. The coefficient of variation (mean ÷ standard deviation) for the TB-1 and TB-4 stations during the two years (October 2002 – September 2003 and July 2004 – June 2005) was low at 9 percent. Between 1986 and 1988, TERC operated an additional buoy located 2 − 3 km off the south shore (Jassby et al. 1994). Only nitrate, ammonium and SRP were measured. For these nutrients the ratio of the TB-1 site to the south shore sites was 1.25, 1.30 and 0.70, respectively. Without a sampling network in the nearshore, there is some uncertainty that the mid-lake sites adequately reflect deposition closer to the shoreline. If deposition of particles and associated phosphorus decline lakeward from the land, the TERC values could underestimate whole-lake deposition

Nitrogen deposition estimated by CARB did not include organic nitrogen compounds. This leaves only the inorganic nitrogen fraction available for a CARB versus TERC comparison. TERC measurements for inorganic nitrogen included dissolved nitrate and ammonium in the water layer in the buoy buckets. Combined, these nitrogen species constitute DIN, a form of nitrogen readily available for algae uptake and a form used in the Lake Clarity Model. Dry DIN calculated from the buoy buckets in 2002-2003 and extrapolated to the lake surface was 101 metric tons. In 2004-2005 dry DIN deposition was estimated to be 76 metric tons. This shows good replication between the two sites and provides some information on the potential interannual variability. Both sampling periods combined, the DIN deposition to the lake surface based on TERC buoy buckets was 89 metric tons. Given that the buoy bucket and CARB modeling approaches were fundamentally different with no sharing of data sets and extrapolating to a 500 km^2 surface area from limited measurement points, the agreement between the 116 metric tons CARB estimate and the 89 metric tons TERC estimate is excellent.

Nitrogen deposition modeling by DRI to the lake surface was only done for the summer period (June through September). Whole-lake deposition of HNO_3 and NH_3 was estimated to range from 16 − 78 metric tons depending on model selection. CARB's estimate for these nitrogen species during the summer was 23 metric tons. Finally, taking CARB's estimates of HNO_3+NH_3+NH_4^++NO_3^-, a value of 31 metric tons was calculated. This was directly comparable to the TERC measurement of 34 metric tons for NO_3^-+NH_4^+. Note that the TERC summer value did not include wet deposition. While there are uncertainties associated with individual portions of the deposition analyses, the similarity of the results show that the final deposition values are reasonable.

There is not a detailed understanding of particle deposition directly to the lake surface. Liu (2002), during the summer of 2000, measured particle size distribution and particle numbers from a series of water-filled buckets placed on piers and at other near-lake locations along the north shore of Lake Tahoe. That study provided initial data on the number of particles per square meter deposited per summer day for a range of size classes. It does not; however, provide adequate data for a direct comparison with the CARB particulate matter deposition values. Based on the data presented above, there is still uncertainty associated with the whole-lake particulate matter deposition values. However, these are the only data available for use at this time and future research and monitoring is warranted.

4.5.3 Wet Atmospheric Deposition

Sampling Design and Methodologies

Wet atmospheric deposition represents nutrients and fine particles that enter the lake surface directly during rain and snowfall events. Regular measurements of wet deposition have been made by the UC Davis - TERC as part of LTIMP. Wet deposition, completely separated from dry deposition, has not been collected directly from the lake surface (i.e. at lake buoy stations) due to technical constraints and funding availability. Wet and dry deposition are captured simultaneously at the buoys as bulk deposition.

The wet deposition data used in this analysis comes largely from the Ward Valley Lake Level (WVLL) station. This station is located 400 meters west of the mouth of Ward Creek about 100 meters from the lakeshore (Figure 4-49). A dual-bucket (Aerochem Metrics) wet/dry sampler installed at this station independently collects wet and dry deposition. Further details on collection methodologies and analytical chemistry protocols can be found in Jassby et al. (1994) as updated in Hackley et al. (2004 and 2005). However, as previously stated, approximately 30 − 40 precipitation events are measured during a typical year.

Limited data on wet deposition were also collected from stations at Incline Village, Glenbrook and Meyers during water year 1982 (Axler et al. 1983). In 1983-1984, a study was done in which monitoring was done for nitrate, ammonium and soluble reactive phosphorus (SRP) at two sites: Tahoe Vista and Bijou, South Lake Tahoe (Byron et al. 1984). The wet deposition data from these other stations around the lake were used to provide an estimate of historical spatial patterns in comparison to the long-term WVLL record.

A data record of nearly 25 years is available for nitrate, ammonium and SRP at the WVLL station. Nitrate and ammonium, taken together) is defined as dissolved inorganic nitrogen (DIN), a form of nitrogen that is readily available for algal growth; SRP is also considered to be bioavailable. Data for other species of nitrogen and phosphorus are less comprehensive. Total Kjeldahl nitrogen (TKN) and total dissolved phosphorus data have been collected since water year 1992. Total phosphorus was measured during the periods 1992-1994 and 2000-present. The record includes average annual concentration (in units of µg/L), total annual loading (in units of grams/hectare/year) and precipitation (in units of inches of rain/snow). Data from 1992 through 2003 were used in this analysis. However, wet deposition data from 2004 and 2005 are provided for comparison.

Fine particles have never been directly measured in wet deposition at Lake Tahoe. As described in Section 4.5.3, and in much more detail in CARB (2006), wet deposition of particles is an estimate with a high degree of uncertainty that requires future research/monitoring.

Nutrient Concentrations

Ward Valley Lake Level

Average annual SRP concentrations over the two-decade period of record ranged from 1.5 (1998) to 5.5 (1987) µg P/L with mean concentrations of 3.2 ± 1.1 µg P/L (Figure 4-59). From 1985-1990, concentrations were somewhat higher ranging from 3.6 to 5.5 µg P/L with a mean of 4.8 ± 0.7 µg P/L. Prior to that period, from 1981-1984, the mean annual average concentration was less at 2.7 ± 0.2 µg P/L. Over the 12-year period considered in the calculation of atmospheric loading (1992-2003), annual average concentrations have remained steady with a mean of 2.7 ± 0.8 µg P/L and a range of 1.5 − 3.7 µg P/L. The periods 1981-1984 and 1991-2005 provided similar results. Taking the entire 24-year record into account, and including SRP concentrations in 2004 and 2005, the trend exhibits approximately a 1.5 µg P/L decline over the past 25 years because of elevated values in the mid-to-late 1980’s. A comparison between mean annual concentrations during the period 1981-2005 and the period used in the wet deposition evaluation (1992-2003) showed the mean ± standard deviation (s.d.) very similar at 3.2 ± 1.1 µg P/L and 2.7 ± 0.8 µg P/L, respectively.

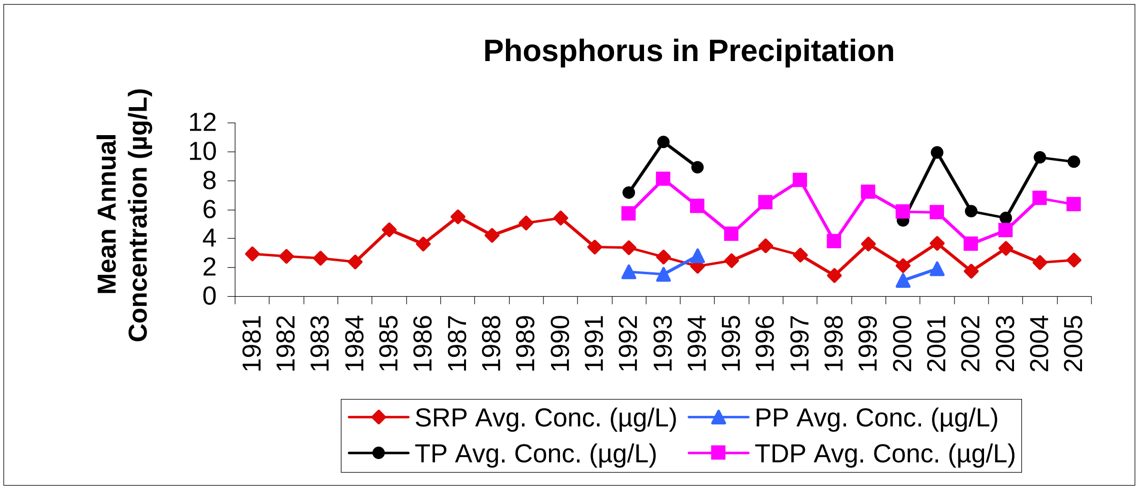

Figure 4-59. Long-term record of phosphorus species concentration in precipitation collected at the Ward Valley Lake Level sampling site (Hackley unpublished data).

Only five years of estimates for annual particulate phosphorus are available. The mean ± s.d. was 1.8 ± 0.6 µg P/L and all values were similar. These particulate phosphorus values are best viewed as what remains associated with particles after an initial leaching period between the time of deposition into the buckets and collection for analysis. Kinetic studies of bioavailable phosphorus (BAP) from Lake Tahoe stream sediments suggest that in approximately 20 days, 80 to 90 percent of the BAP had been leached (Ferguson 2005).

Total dissolved phosphorus (TDP) represents that fraction of soluble phosphorus that breaks down to SRP following a persulfate digestion. For Lake Tahoe wet deposition, the ratio of TDP:SRP was 2.1, with a mean ± s.d. for TDP of 5.8 ± 1.5 µg P/L. The mean annual TDP concentration for 2004-2005 was somewhat higher at 6.6 µg P/L. However, mean annual TDP has exceeded 6.0 µg P/L in five other years since 1992. Total phosphorus was measured during seven years in the 1992-2003 period of record with an annual mean concentration of 8.0 ± 2.0 µg P/L. The 2004-2005 values were 9.6 and 9.3 µg P/L, respectively, and not dissimilar to other total phosphorus mean annual concentrations. Since total phosphorus = TDP + particulate phosphorus, the calculated total phosphorus and measured total phosphorus values were compared. Over the period of record when particulate phosphorus was measured (1992-1994, 2000-2001), these values were identical at 7.6 µg P/L. This supports the validity of the particulate phosphorus and total phosphorus data even though there were only five and seven years of measurements, respectively. Table 4-53 provides data on the relative abundance of the measured forms of phosphorus.

Table 4-53. Mean annual phosphorus concentrations (± standard deviation) for wet deposition at Ward Valley Lake Level measured within the period 1992-2003 (Hackley unpublished data).

Phosphorus Species	Mean Annual Concentration (µg P/L)
SRP	2.7 ± 0.8
TDP	5.8 ± 1.5
PP[a]	1.8 ± 0.6
TP[b]	8.0 ± 2.0

[a] Measurements made in 1992-1994 and 1999-2000
[b] Measurements made in 1992-1994 and 1999-2003

From 1981-2003, the mean annual nitrate (NO_3^-) concentration was 71.9 ± 27.7 µg N/L; this was very similar to the 1992-2003 period used for loading calculations (i.e., 67.4 ± 24.8 µg N/L). Similarly, the mean annual ammonium (NH_4^+) concentration was nearly identical at 55.8 ± 25.6 and 53.0 ± 15.9 µg N/L, for these periods, respectively. As can be seen in Figure 4-60 and as indicted by the lower standard deviation value, interannual variation in ammonium was reduced between 1992 and 2003. The ratio of NO_3^--N:NH_4^+-N was approximately 1.3:1 and similar to that reported by Jassby et al. (1994) for Lake Tahoe wet deposition. The interannual variation in nitrate and ammonium are also almost identical.

Average annual DIN concentrations (NO_3^--N:NH_4^+-N) have ranged from 69 (1983) to 273 (1990) µg N/L with a mean of 126 ± 50 µg N/L. Average annual DIN concentrations over the full period of record were characterized by lower values in 1981-1986 (87 ± 16 µg N/L) and increased values during 1987-1994 (179 ± 51 µg N/L).

Average annual DIN concentration has been relatively stable since 1993 (109 ± 24 µg N/L). While there is a generally good relationship between increasing annual precipitation and decreasing annual average DIN concentration (R^2=0.5; with the exclusion of 1990), the increased annual DIN concentrations during 1987-1994 can be partially, but not solely, explained by a decline in precipitation. Both SRP and DIN exhibited an increase in concentrations from about 1987-1991 or 1992. There were no changes to the analytical chemistry program during that time. Currently there is no clear explanation for this pattern.

TKN has been measured since 1992. Over the 12-year period of record, TKN had a mean annual average of 123.2 ± 48.2 µg N/L, similar to DIN. Measured mean annual concentrations for nitrate, ammonium and TKN were nearly identical in 2004 and 2005 as compared to other years. The trendline for these three nitrogen species shows no change. Figure 4-60 depicts the long-term record for each of the three measured nitrogen species.

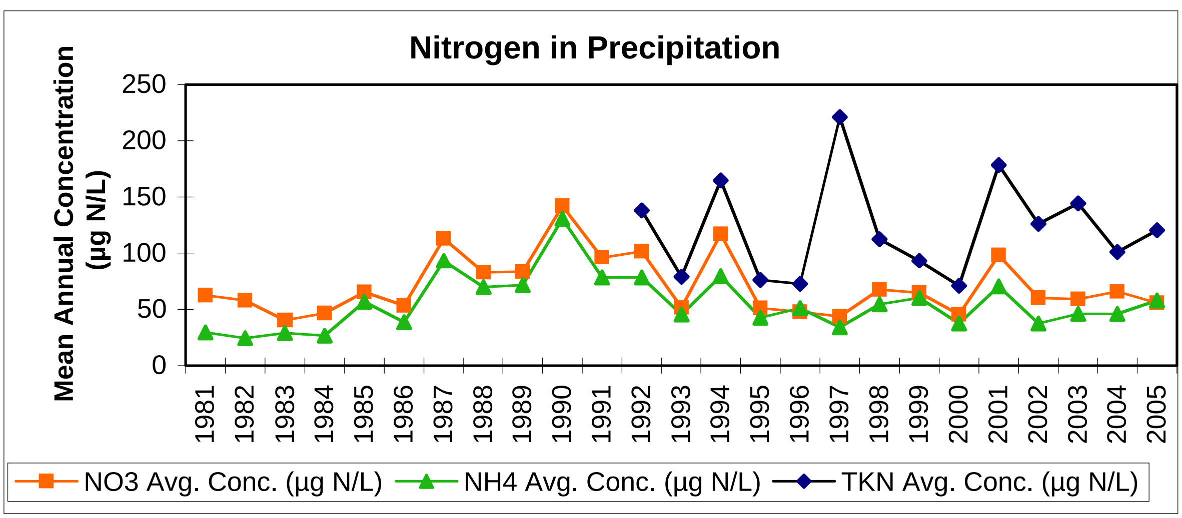

Figure 4-60. Long-term record of nitrogen species concentration in precipitation collected at the Ward Valley Lake Level sampling site (Hackley unpublished data).

Based on the following known relationships, mean annual concentrations for nitrogen species not directly measured (total organic nitrogen, total nitrogen and dissolved organic nitrogen) can be calculated as follows:

TKN = Total Organic Nitrogen (TON) + NH_4^+

Total Nitrogen (TN) = TKN + NO_3^-

Dissolved Organic Nitrogen (DON) = TN – DIN – Particulate Nitrogen (PN)

Particulate nitrogen measurements in wet deposition were only available for a single water year (1992) with a total of 19 samples analyzed. The annual mean concentration was 9 µg N/L and very low compared to the other, measured forms of nitrogen in wet deposition.

Based on the measured nitrogen species and the relationships above, Table 4-54 provides values for mean annual nitrogen concentration (± s.d.) for wet deposition at Ward Valley Lake Level from 1992-2003.

Table 4-54. Mean annual nitrogen concentration (± s.d.) for wet deposition at Ward Valley Lake Level (1992-2003).

Nitrogen Species	Mean Annual Concentration (µg N/L)
NO_3^-	67 ± 25
NH_4^+	53 ± 16
DIN	120 ± 39
DON	61 ± 47
TON	70 ± 47
PN	9[a]
TN	185 ± 63

[a] Measurement made in 1992 only

Synoptic Measurements

The data presented above provide a very good long-term record for wet deposition at a single site (WVLL). This is the only location at Lake Tahoe that supports such an extensive monitoring record. However, during Water Year 1982, wet deposition measurements were also taken from stations at Incline Village, Glenbrook and Meyers as part of a larger synoptic study (Axler et al. 1983). In 1983-1984, a similar study was done in which nitrogen and phosphorus monitoring was performed at two sites – Tahoe Vista and Bijou, South Lake Tahoe (Byron et al. 1984). These historic data are used for comparison with the findings at WVLL.

The data suggest that while there were absolute differences between locations, DIN concentrations associated with precipitation were similar at all sites (Table 4-55). Given that these sampling sites were located synoptically around the basin and within the spectrum of less urban to highly urban, it was concluded that the WVLL wet deposition concentration data were representative of near-shore locations and that the WVLL long-term record could be used for basin-wide deposition estimates. The pattern for SRP deposition around the lake was similar.

Table 4-55. Data from synoptic wet deposition sampling in the Lake Tahoe basin in the early 1980's (Axler et al. 1983, Byron et al. 1984).

Location	NO_3^- (µg N/L)	NH_4+ (µg N/L)	DIN (µg N/L)	SRP (µg P/L)
Oct 1982-Sep 1983[a]				
WVLL	58	24	82	1.3
Meyers	38	26	64	2
Incline Village	55	27	82	2
Glenbrook	62	34	96	3
May 1983-Jun 1984[b]				
WVLL	49	30	79	2.3
Tahoe Vista	61	46	107	2.0
Bijou at South Lake Tahoe	60	62	122	2.8

[a] Axler et al. 1983
[b] Byron et al. 1984

Wet Deposition of Nutrients and Particulate Matter

Nutrients

Hackley and Reuter (2004) calculated wet deposition loading directly to Lake Tahoe using WVLL data; values were expressed as grams/hectare (g/ha), where 1 hectare = 10^4 m^2. Table 4-56 provides a summary of the annual load calculations for nitrogen and phosphorus species that were directly measured using analytical chemistry. Loadings for the other nitrogen species (DON, TON and TN) were calculated using the relationships presented above. Loading values were obtained by multiplying measured nutrients for each storm by the total volume of precipitation collected during that storm. Each storm during the year was summed to determine the cumulative annual load.

Table 4-56. Annual aerial loading for measured nitrogen and phosphorus species associated with wet deposition at Ward Valley Lake Level (Hackley unpublished data).

Year	Precip (in.)	NO_3^-N (g/ha)	NH_4^-N (g/ha)	TKN (g/ha)	PN (g/ha)	SRP (g/ha)	TDP (g/ha)	TP (g/ha)
1992	25.7	667.2	511.6	906.9	9.3	21.9	37.4	46.9
1993	49.7	648.9	570.0	997.1	NA	34.3	102.5	134.9
1994	21.8	648.1	439.0	911.6	NA	11.7	34.6	49.4
1995	73.3	947.5	789.7	1,416.9	NA	46.4	80.1	125.3[a]
1996	60.9	740.8	785.6	1,120.8	NA	54.3	100.7	151.5[a]
1997	63.5	701.1	546.6	NA	NA	45.9	129.3	158.7[a]
1998	56.6	968.1	782.3	1,619.7	NA	21.0	54.4	69.3[a]
1999	51.2	843.6	783.2	1,216.6	NA	47.0	93.6	135.6[a]
2000	41.3	478.3	390.0	741.6	NA	22.5	61.6	55.2
2001	22.1	556.6	395.0	1,005.2	NA	20.7	32.6	55.9
2002	38.7	592.4	368.4	1,238.7	NA	17.2	35.6	57.8
2003	40.8	609.5	478.7	1,498.1	NA	34.5	47.3	87.1
Mean ± s.d.[b]	**45.5 ± 16.8**	**700.2 ± 151.1**	**570.0 ± 170.1**	**1,152.1 ± 274.5**	**9.3**	**31.5 ± 14.2**	**67.5 ± 32.8**	**94.0 ± 43.7**

[a]Total phosphorus (TP) values were estimated using SRP:TP and TRP:TP ratios from other years when TP was measured
[b]Mean for all years of data

Annual precipitation at WVLL during the period 1992-2003 was 45.5 ± 16.8 inches. The range of measured values was wide at 21.8 to 73.3 inches and included both wet and dry years. Based on the isohyetal map for Lake Tahoe (Crippen and Pavelka 1970), precipitation at WVLL is approximately five inches per year higher than Tahoe City. The mean annual precipitation measured at Tahoe City from 1968-2003 was 32.8 inches/year; the adjusted mean annual precipitation for WVLL over the same period was about 38 inches/year. Therefore the 1992-2003 period of record, while somewhat higher than the long-term average, is nonetheless representative.

Loading varies considerably between individual storms (Hackley and Reuter 2004) as influenced by nutrient concentration, precipitation volume and other factors related to deposition. Regression analyses between precipitation volume and nutrient loading showed that, in general, load increased with higher levels of rain and snow as suggested by the good, although moderate R^2-values (0.44-NO_3^-; 0.56-NH_4^+; 0.31-TKN; 0.61-SRP; 0.59-TDP; 0.57-TP). Annual precipitation, alone, was not the only factor affecting wet nitrogen and phosphorus deposition. This was largely because the nutrient concentration in precipitation does not remain uniform, 1) within a storm (e.g., pollutant wash-out effect), 2) between frontal systems during a single year (changing source contributions) and/or 3) between years or multi-year periods. The weak relationship between annual DIN and SRP concentrations over the full data record (R^2=0.2), suggests different sources for the nitrogen and phosphorus in wet deposition.

Since there are no direct measurements of wet deposition over the lake surface, it was necessary to estimate whole-lake loading associated with precipitation. The isohyetal map (Crippen and Pavelka 1970) was used to determine the ratio of precipitation over the whole lake, as compared to the precipitation at WVLL. This value was taken as 0.6 (i.e., higher rain and snow at WVLL). This is confirmed by the annual precipitation data at WVLL and the mid-lake sampling buoy. For 1998, 2001 and 2003, when annual precipitation at WVLL ranged from 22.1 − 56.6 inches, covering a wide range of values, the whole-lake to WVLL ratio was nearly identical at 0.67.

Table 4-57 gives the mean ± s.d. for whole-lake nutrient deposition based on the 1992-2003 database. It also provides estimated whole-lake wet deposition from more recent data for comparison. In this analysis, it was assumed that the nutrient concentrations in rain and snow remain the same over the entire lake surface and that these concentrations were represented by the WVLL data (as suggested by the similarity of concentrations measured during the two synoptic studies as presented in Table 4-55). Synoptic, on-lake measurements of nutrient deposition are needed to more fully evaluate this assumption.

The analysis of whole-lake wet deposition of nitrogen and phosphorus show that recent years (2002-2005) were very similar to the 1992-2003 period of record used for modeling purposes. During 1992-2003, DIN was 65-70 percent of the total nitrogen, with about 30-35 percent of the wet total nitrogen in the organic form. The standard deviation values presented in Table 4-57 signify the inter-annual variation in estimated wet loading values over the period of record. The existing monitoring data are insufficient to compare actual synoptic differences in measurements. Annual wet deposition over the lake was estimated at 56 ± 17 metric tons for total nitrogen and 38 ± 10 metric tons for DIN. These values are comparable to those reported by Jassby et al. (1994) for wet deposition at Lake Tahoe during the 1980's. Jassby et al. (1994) compared the wet deposition rates from Lake Tahoe for nitrate and ammonium to seven sites in California and one in Nevada close to Lake Tahoe, where measurements were taken as part of the National Atmospheric Monitoring Program. The data for Lake Tahoe were judged to be consistent with the other Sierra Nevada stations located in Yosemite and Sequoia National Parks.

Table 4-57. Mean annual nutrient loading extrapolated over the entire lake surface using values from WVLL corrected by the 0.6 factor for synoptic precipitation differences (Hackley unpublished data).

Nutrient Species	Loading (metric tons) 1992-2003[a]	Loading (metric tons) 2002-2004[b]	Loading (metric tons) 2004-2005[c]
NO_3^-	21 ± 5	18	19
NH_4^+	17 ± 5	14	10
DIN	38 ± 10	32	38
DON	17 ± 7	31	16
TON	18 ± 7	31	16
PN	0.5	0.5	0.5
TN	56 ± 17	63	54
SRP	0.7 ± 0.4	1	1
TDP	1.5 ± 1.0	1.4	2.1
TP	2.8 ± 1.3	2.6	3.1

[a]Loading for 1992-2003 represents mean ± s.d. for measured values (NO_3—N, NH_4^+-N and TON [TKN-NH_4^+-N]).
[b]May 2002 – February 2004 (Hackley et al. 2004)
[c]July 2004 – June 2005 (Hackley et al. 2005)
TKN (TON + NH_4^+) is accounted for in the table

Total phosphorus deposition from rain and snow directly to the lake surface was estimated at 2.8 metric tons per year based on the 1992-2003 database (Table 4-57). Total dissolved phosphorus was about 50 percent of that value. The inter-annual variation, based on the standard deviation values, was higher for phosphorus than nitrogen.

Since wet deposition depends on precipitation amount, it was decided that for the purpose of providing input data on nutrient loading to the Lake Clarity Model, a daily loading rate would be calculated from the existing data and applied to each day on which the simulation included precipitation. For each year from 1992 to 2003, the number of days on which precipitation was ≥ 0.1 inches was determined from the daily/storm records. This is referred to as 'precipitation days' in Table 4-58. The amount of total annual nutrient loading from Table 4-57 was divided by the number of precipitation days to yield an annual average for loading (in units of g/ha/precipitation day). For example, the overall mean nitrate loading expressed on the basis of a precipitation day was 13.3 g nitrogen/ha/precipitation day. If there are 50 days in a simulation of the Lake Clarity Model when precipitation occurs, the annual load would be 665.0 g NO_3^--N/ha/year. Since the actual nutrient concentrations for each simulated storm used in the Lake Clarity Model could not be predicted, this was a reasonable approach to account for variation in wet deposition between years of varying precipitation. This approach also allows the introduction of wet deposition loading based on a more defined meteorological time scale (i.e., daily).

Table 4-58. Annual nutrient loading from wet deposition at WVLL based on number of days on which precipitation volume was ≥0.1 inches. The expression 'pd' refers to precipitation day (Hackley unpublished data).

YEAR	Precip. Days	NO_3^--N (g/ha/pd)[a]	NH_4^+-N (g/ha/pd)	TKN (g/ha/pd)	SRP (g/ha/pd)	TDP (g/ha/pd)	TP (g/ha/pd)
1992	29	23.0	17.6	31.3	0.76	1.29	1.62
1993	58	11.2	9.8	17.2	0.59	1.77	2.33
1994	41	15.8	10.7	22.2	0.28	0.84	1.21
1995	79	12.0	11.0	17.9	0.59	1.01	1.59[b]
1996	63	11.8	12.5	17.8	0.86	1.60	2.40[b]
1997	56	12.5	9.8		0.82	2.31	2.83[b]
1998	77	12.6	10.2	21.0	0.27	0.71	0.90[b]
1999	57	14.8	13.7	21.3	0.82	1.64	2.38[b]
2000	49	9.8	8.0	15.1	0.46	1.26	1.13
2001	39	14.3	10.1	25.8	0.53	0.84	1.43
2002	55	10.8	6.7	22.5	0.31	0.65	1.05
2003	55	11.1	8.7	27.2	0.63	0.86	1.58
Mean ± s.d.		13.3 ± 3.5	10.7 ± 2.9	21.8 ± 4.8	0.57 ± 0.21	1.23 ± 0.51	1.70 ± 0.63

[a]g/ha/pd = grams/hectare/precipitation day
[b]These total phosphorus (TP) values were estimated using SRP:TP and TRP:TP ratios from other years when TP was measured

Particulate Matter

There has been no study/monitoring of wet deposition of fine non-biological particles. Given that the importance of these particles to the clarity of Lake Tahoe was not recognized until the late 1990's (Jassby et al. 1999), this lack of data is not unexpected. Liu (2002) investigate particle deposition using buckets from a series of seven pier and nearshore locations along Lake Tahoe's north shore during the summer of 2000. As discussed above, summers in the Lake Tahoe basin are typically dry; consequently the sample collection protocol was designed for dry deposition (i.e., a layer of water was placed in the bucket to simulate the lake surface). Liu (2002) observed an increase in deposition for particles in the 0.5 − 18 µm range at many of the sampling sites following the first measurable precipitation of the summer relative to each site's respective average up to that time.

The LTADS investigation (CARB 2006) provides the most detailed estimates of particle deposition directly to the lake surface. Although measurement of wet deposition of particulate matter was not a component of the LTADS field study, CARB did estimate wet deposition for particles onto Lake Tahoe during 2003 based on a first principles analysis of seasonal air quality concentrations and precipitation frequency. Refer to CARB (2006) for more details on approach and methodology. As noted by CARB this year was drier than normal. This will affect estimates of particle flux in wet deposition as the magnitude of interannual variability is unknown for atmospheric particles. This important uncertainty requires further investigation.

The LTADS wet deposition analysis for particles uses precipitation data collected during 2003 at Incline Creek, located near the northeast shore of Lake Tahoe. Precipitation in this portion of the Lake Tahoe basin is near the basin-wide average for frequency, but below average for quantity. Because much of the pollution washout occurs during the initial phase of a storm, CARB (2006) reported that the frequency of precipitation events is a better indicator of the wet deposition of atmospheric pollutants than the amount of precipitation. Thus, their analysis was based on the assumption that any precipitation, whether light or intense, will cleanse the air of pollutants.

Additionally, LTADS divided the particles wet deposition analysis into two components addressing transported (regional background) pollutants and locally-generated pollutants. Conceptually, the local component was represented by the washout of pollutants observed over Lake Tahoe and extending 700 meters from the lake's surface up to the altitude of the Sierra crest (i.e., local pollutants are trapped in the Tahoe basin by the mountains surrounding the lake). The transport component of the wet deposition was represented by the washout of regional pollutants extending 3,000 meters above the altitude of the Sierra crest (i.e., the air of regional origin essentially flows over the Tahoe basin).

Seasonal air quality concentration data for particulate matter, collected and used in LTADS to estimate wet deposition of particulate matter, are provided in Table 4-59. Again, these represent dry concentrations for total suspended particles and were not a direct measure of wet deposition. While there are large differences between locations, these likely reflect the variation in local sources during dry periods. Without more expansive data, the influence of frontal storm systems bringing particles into the Lake Tahoe basin from the outside cannot be ascertained (CARB 2006).

The highest ambient concentrations were measured at the more urbanized locations at Sandy Way (South Lake Tahoe) and Lake Forest (near Tahoe City). This observation held for each season with the exception of the summer when levels at Big Hill were also higher and the relative difference between the less urbanized Thunderbird site and the urban sites was reduced. Also, the measurements at Lake Forest during the winter were mid-way between Sandy Way and the more pristine Thunderbird and D.L. Bliss State Park locations. Ambient air concentration measurements were typically elevated in the summer and fall at all sampling locations. The higher winter value of 9.27 $\mu g/m^3$ found at Sandy Way, relative to Lake Forest, may have been the result of higher vehicle traffic.

Table 4-59. Seasonal air quality concentration data for particulate matter, collected and used in LTADS to estimate wet deposition of particulate matter (CARB 2006).

Location	Seasonal Concentration ($\mu g/m^3$)			
	Winter	Spring	Summer	Fall
Big Hill[a]	1.59	3.98	15.17	12.78
Sandy Way[b]	9.27	10.67	14.65	21.34
Lake Forest[b]	5.22	9.28	14.76	15.14
Thunderbird[b]	1.65	2.96	10.12	7.76

[a]Outside the Lake Tahoe basin in the adjacent western slope of the Sierra Nevadas
[b]Inside the Lake Tahoe basin

The LTADS project team used factors including ambient pollutant concentration, atmospheric mixing depth, precipitation frequency and washout efficiency to estimate wet deposition of particulate matter directly to the surface of Lake Tahoe. Estimates for fine particulate matter ($PM_{2.5}$), coarse particulate matter ($PM_{>2.5}$-PM_{10}), and large particulate matter ($PM_{>10}$) are included. The sum of these fractions represents total suspended particles (TSP). The seasonal and annual estimates of TSP are presented in Table 4-60. The values in Table 4-60 were used as input data to the Lake Clarity Model. CARB provided lower and upper bounds for their loading estimates. For wet deposition of particulate matter, the upper estimate was approximately 5 times the lower estimate.

Table 4-60. Summary of estimated total wet deposition of particulate matter to Lake Tahoe from all sources (based on CARB 2006 central estimates).

Parameter	Winter (metric tons)	Spring (metric tons)	Summer (metric tons)	Fall (metric tons)	Annual (metric tons)
Fine Particulate Matter	30	31	10	3	74
Coarse Particulate Matter	17	41	8	3	69
Large Particulate Matter	7	8	3	2	20
TOTAL	**54**	**80**	**21**	**8**	**163**

4.5.4 Summary of Annual Loading Values for Nitrogen, Phosphorus and Particulate Matter

Based on the data presented above, Table 4-61 through Table 4-63 present the most reasonable summary of the wet and dry, whole-lake pollutant loading estimates for atmospheric deposition directly to the surface of Lake Tahoe (in metric tons per entire lake surface). They are derived from both UC Davis and LTADS studies as appropriate. Values for nitrogen and phosphorus were presented as those chemical forms of these nutrients that have limnological/water quality significance. LTADS values represent their central estimate.

Dry deposition of particulate matter directly to the surface of Lake Tahoe was estimated at 586 metric tons/year and wet at 163 metric tons/year for a total of approximately 749 metric tons/year (Table 4-61). This is the first such estimate of particulate matter deposition to Lake Tahoe. Two clarifications need to be made: (1) these values represent all forms of particulate matter and, (2) they represent weight of deposited material and not particle numbers. Values were adjusted for inert particulate matter and converted to particle number before being used in the Lake Clarity Model. Again, light scattering due to black carbon was not considered in the Lake Clarity Model.

Table 4-62 came from both LTADS (CARB 2006) and Hackley (unpublished data). CARB (2006) values for dry deposition of inorganic nitrogen were used. LTADS did not estimate organic deposition during either the wet or dry seasons. UC Davis - TERC unpublished data estimates for wet deposition (both inorganic and organic) as well as dry-organic deposition were used. Atmospheric deposition of total nitrogen using multiple sources of data was estimated to be 218 metric tons/year. This was very similar to the initial estimate of 234 metric tons made by Reuter et al. (2003) and lends support to the value. The ratio of dry:wet DIN was 3.6:1. While the total estimate for dry DIN from LTADS and UC Davis - TERC unpublished data was very close (116 metric tons and 89 metric tons, respectively), the relative contribution of NH_3 and NH_4^+ to DIN in the CARB data was much higher at 70 − 75 percent as compared to the UC Davis - TERC data that showed a 45 − 50 percent contribution of these N-species to DIN. This could be due to chemical transformations in the bucket or other unknown factors at this time. Organic nitrogen values in dry deposition were calculated from UC Davis - TERC bulk nitrogen deposition data from the open-water sites minus the estimated open-water DIN values.

Total phosphorus deposition was determined from the data provided by the UC Davis - DELTA Group (Cahill unpublished data). The SRP values were calculated from the bulk total phosphorus estimates at the UC Davis-TERC lake buoys and based on a measured annual ratio of SRP:TP of 0.24:1 at that location. The measured ratio used for TDP:TP was 0.44 (Hackley et al. 2005). Total annual SRP deposition was 2.3 metric tons/year with wet and dry deposition very similar (Table 4-63). TDP deposition was higher at 3.7 metric tons/year dry deposition. Annual deposition of total phosphorus deposition to Lake Tahoe ranged between 6 and 8 metric tons. Dry values were higher than wet values. The 6 − 8 metric tons per year deposition estimate agrees well with the value of 5 − 6 metric tons per year calculated using the annual average TP deposition rate measured from the two lake buoys and extrapolated to the entire lake surface (Hackley et al. 2005). It is expected that the buoy values would be less than the actual whole-lake deposition since some of the particles carrying phosphorus would fall out on to the lake surface before reaching the buoys at mid-lake. CARB's central estimates for total phosphorus were 2.2 metric tons during the dry period and 0.7 metric tons during the wet period for an annual load of 2.9 metric tons.

Table 4-61. Estimates of dry and wet deposition of particulate matter to Lake Tahoe. Values in parentheses denote contribution to total annual PM.

Parameter	Season	Winter (metric tons)	Spring (metric tons)	Summer (metric tons)	Fall (metric tons)	Annual (metric tons)
Fine Particulate Matter	Dry	17	11	15	17	60
	Wet	30	31	10	3	74
	Total	**47**	**42**	**25**	**20**	**134**
Course Particulate Matter	Dry	44	42	40	43	169
	Wet	17	41	8	3	69
	Total	**61**	**83**	**48**	**46**	**238**
Large Particulate Matter	Dry	92	78	110	77	357
	Wet	7	8	3	2	20
	Total	**99**	**86**	**113**	**79**	**377**
Total Particulate Matter	Dry	153	131	165	137	586
	Wet	54	80	21	8	163
	Total	**207** (36%)	**211** (28%)	**186** (25%)	**145** (19%)	**749**

Source: CARB 2006

Table 4-62. Estimates of dry and wet deposition of nitrogen to Lake Tahoe.

Parameter	Season	Winter (Metric Tons)	Spring (Metric Tons)	Summer (Metric Tons)	Fall (Metric Tons)	Annual (Metric Tons)
NO_3^-	Dry	7	5	8	9	29
	Wet[e]					18
	Total					**47**
NH_4^+	Dry	19	16	23	29	87
	Wet[e]					14
	Total					**101**
DIN[a]	Dry	26	21	31	38	116
	Wet[e]					32
	Total					**148**
DON[b]	Dry	13	8	6	4	31
	Wet[e]					31
	Total					**62**
TON[c]	Dry	15	10	8	6	39
	Wet[e]					31.5
	Total					**71**
PN[d]	Dry	2	1	2	2	7
	Wet[e]					0.5
	Total					**8**
Total Nitrogen	Dry	41	31	39	44	155
	Wet[e]					63
	Total					**218**

[a]DIN = dissolved inorganic nitrogen and is the sum of NO_3^-+NH_4^+
[b]DON = dissolved organic nitrogen
[c]TON = total organic nitrogen
[d]PN = particulate organic nitrogen
[e]Seasonal data for wet deposition were not calculated. As discussed in Chapter 4, a value of wet deposition per precipitation day for the entire wet period was calculated for use in the Lake Clarity Model.
Wet deposition values include the period 2002-2004.

Table 4-63. Estimates of dry and wet deposition of phosphorus to Lake Tahoe.

Parameter	Season	Winter[a] (metric tons)	Summer[a] (metric tons)	Annual (metric tons)
SRP	Dry	0.4	0.9	1.3
	Wet[b]			1.0
	Total			**2.3**
TDP	Dry	0.7	1.6	2.3
	Wet[b]			1.4
	Total			**3.7**
Total Phosphorus (2002-03)	Dry	1.7	3.7	5.4
	Wet[b]			2.6
	Total			**8.0**
Total Phosphorus (post-2003)	Dry	1.1	2.4	3.5
	Wet[b]			2.6
	Total			**6.1**

[a]The year was divided into two seasons – winter and summer
Source: Estimates come from UC Davis - DELTA Group (Gertler et al. 2006; Cahill 2006b)
[b]Seasonal data for wet deposition were not calculated. As discussed in Chapter 3, a value of wet deposition per precipitation day for the entire wet period was calculated for use in the Lake Clarity Model. Measurement/calculation of these phosphorus species is provided in Section 3.3.

4.5.5 LTADS Findings on Regionally Transported Versus Local Sources

Wet Deposition

As part of LTADS, CARB (2006) provided estimates for the relative contribution of regional and local sources for nitrogen, phosphorus and particulate matter associated with wet deposition (Table 4-64). In general, the annual contribution of particulate matter primarily comes from local sources. Similarly, both total nitrogen and total phosphorus in wet deposition were largely attributed to local sources. Note that the contribution of the PM Large from local and regional sources is similar. While it is only speculation, the larger atmospheric particles may be transported into the Lake Tahoe basin by storm fronts but not by wind during dry periods. Since nearly 90 percent of the light scattering in Lake Tahoe results from particles < 10 µm in diameter (Swift et al. 2006) this PM size category is not important for lake clarity.

Table 4-64. CARB (2006) estimate on regional background (out-of-basin) and locally generated pollutant load to Lake Tahoe in wet deposition.

Estimate	Source	Winter	Spring	Summer	Fall	Annual
		Percent of Total Deposition (%)				
Fine Particulate Matter	Regional	8	26	83	79	29
	Local	92	74	17	21	71
Coarse Particulate Matter	Regional	9	18	79	79	25
	Local	91	72	21	21	75
Large Particulate Matter	Regional	46	16	93	87	48
	Local	54	84	7	13	52
Total Nitrogen	Regional	13	29	87	86	31
	Local	87	71	13	13	69
Total Phosphorus	Regional	33	25	a	a	29
	Local	67	75	a	a	71

[a]An estimated deposition of zero (0) was reported

Dry Deposition

CARB (2006) provides a summary overview of the Lake Tahoe basin emission inventory. This should be viewed as an initial estimate, as work is still in progress. The following discussion comes directly from CARB (2006).

For each of eight pollutant species, Figure 4-61 lists the total emissions (metric tons/day) from sources in the basin and breaks out the percentage of those emissions from each of 10 source categories. As in many other air basins, mobile sources are a major source category for reactive organic gases (ROG), carbon monoxide (CO), oxides of nitrogen (NO_X), NH_3, and particulate matter. Wood smoke from residential fuel combustion comprises the bulk of the fine particulate matter emissions. The information in Figure 4-61 only reflects the strength of the pollutant source. Factors such as wind speed and direction, local and regional meteorology, atmospheric conditions aloft, and structural and/or vegetation barriers to pollutants transported from their source all affect the contribution of these sources to actual deposition onto the lake surface. Current research being funded as part of the Southern Nevada Public Lands Management Act (SNPLMA) is updating the emission inventory.

As discussed in (CARB 2006), NH_3 was found to be the primary component of nitrogen deposition to Lake Tahoe. Source categories that emit a significant percentage of the NH_3 include farming operations (including golf courses), on-road motor vehicles, waste burning (e.g., prescribed burns), and to a lesser extent, residential wood burning. Nitric acid, which is a product of photochemical reactions that start with NO_x, is another important chemical species with respect to nitrogen deposition. The main sources of NO_x are on-road motor vehicles and other mobile sources.

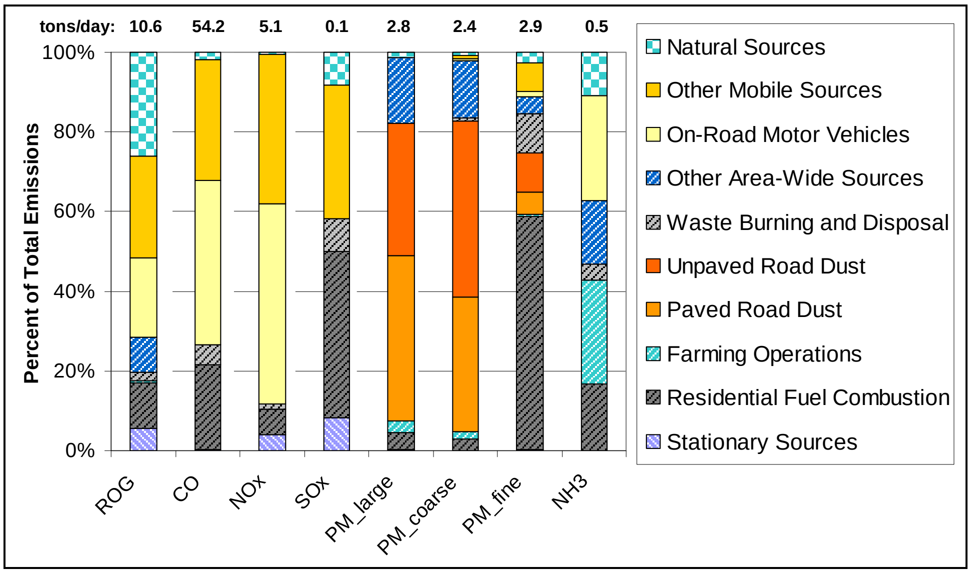

Figure 4-61. Estimated emissions in the Lake Tahoe air basin for 2004 by source category (CARB 2006).

Summary of LTADS Conclusions Regarding Atmospheric Sources

Nitrogen is deposited to Lake Tahoe primarily in the form of ammonia gas and secondarily in the form of nitric acid. Both ambient measurements and the emission inventory suggest that local motor vehicle emissions are a source of ammonia. There is insufficient information to apportion with any certainty the ammonia between local and regional sources. Based on observed concentrations, atmospheric lifetimes, and transport patterns, LTADS also concluded that nitric acid deposited was primarily of local origin.

No conclusions are drawn from the LTADS ambient data about sources of phosphorus. However, the source samples collected prior to and during LTADS indicate that road dust may be the primary source with contributions from the burning of live vegetative material and lubricating oils from motorized vehicles. The UC Davis DELTA Group concluded that approximately 95 percent of the phosphorus deposition likely came from local sources (Gertler et al. 2006).

Road dust is the dominant source of particulate matter concentrations at LTADS monitoring sites and in the immediate vicinity of the lake, as inferred both from ambient concentrations and special source-oriented monitoring results. Road dust as the dominant source of particulate matter is consistent with the inventory estimates of coarse and large particulate matter provided in the current Lake Tahoe air basin emission inventory.

Road dust and wood smoke both appear to be important sources of fine particles. However, fine particles from these two sources likely differ in solubility and this fact may be important to consideration of their potential to impact water clarity. Insoluble particles would obviously have the potential to scatter light and to serve as a substrate for algal growth, while soluble particles would not. The constituents of road dust are generally less soluble than fine particles from wood smoke or other combustion sources.

The location and timing of emissions is important when determining the potential for deposition to Lake Tahoe. Sources located near the lake and at low altitude have much greater potential for deposition to the lake than more distant sources. In general, emissions released during nighttime or early morning hours will have much greater potential for impacting the lake than emissions occurring during morning through afternoon.

4.6 Pollutant Loading Summary & Confidence Levels

The previous sections on groundwater, shoreline erosion, upland runoff, stream channel erosion, and atmospheric deposition (4.1 – 4.5) provided details on (1) how nutrient and sediment loading was estimated from each of these sources and (2) loading results. This section summarizes those results and present values in terms of an average annual load. This is done for total nitrogen (TN) and dissolved inorganic-N (DIN), total phosphorus (TP) and soluble reactive-P (SRP), and total suspended sediment (TSS) and sediment less than 63 µm (smaller than sand). These values are presented in terms of load as metric tons per year. As discussed in Section 3.4, the optical properties of Lake Tahoe are largely affected by the number of particles less than 16 µm in diameter. Therefore, it is the number of particles in this size range that acts as the pollutant and not weight of either TSS or even the ≤ 63 µm fraction. In the next chapter, sediment loading to the lake is presented as the number of inorganic, mineral particles from each of the major sources.

Not all the estimates for annual load in Table 4-66 encompass the same time period; this was due to differences in data variability for the various major sources. For upland runoff the values represent average over the period 1994-2004 as simulated by the Lake Tahoe Watershed Model. To reduce uncertainty, it was important to perform the model loading simulations over a period that included the wide range of precipitation and hydrologic conditions found in the Tahoe basin. As noted in Section 4.3.6, the range of precipitation during 1994-2004 was comparable to the range found in the entire 100-year record taken at Tahoe City. Stream channel erosion, as modeled using AnnAGNPS and CONCEPTS was validated using field data on channel cross sections collected during the period 1983-2002 (Simon et al. 2003). The period for atmospheric deposition varied depending on wet versus dry deposition. Field measurements for wet deposition dating from 1992-2003 were used in the calculation of wet nitrogen and phosphorus loading. Dry nutrient deposition, as modeled in LTADS were primarily representative of 2003; however, the modeled nitrogen and phosphorus dry deposition estimates compared favorably with estimates using different approaches over different time periods. The groundwater evaluation by the USACE (2003) focused on a re-evaluation of existing data and a limited compilation of new data generated since Thodal's 1997 evaluation (Thodal 1997). Thodal's period of record was 1990-1992, which experienced about 70 percent of the precipitation recorded over the 100-year record at Tahoe City. Finally, the loading associated with shoreline erosion was based on an analysis of photographic evidence spanning the 60-year period between 1938 and 1998.

It is important to note that the average values in Table 4-66 are not necessarily intended to represent input to the Lake Clarity Model for each year the model is run. For example, the Lake Tahoe Watershed Model is run for each year capturing the specific characteristics of precipitation and hydrology for each modeled year. Atmospheric deposition of nitrogen and phosphorus as inputs to the Lake Clarity Model also vary depending on the number of wet versus dry days for each modeled year. In contrast, the loading from shoreline erosion used in the Lake Clarity Model is identical for each modeled year and represents the mean calculated by Adams and Minor (2002) over the 60 year period of record. Similarly, the data is insufficient to apply a distinct groundwater loading value for each; therefore a single value is used for all modeled years. With regard to stream channel erosion, the Lake

Clarity Model makes no distinction between nutrients or sediments resulting from stream channel erosion versus uplands runoff. Both are included in overall estimates of stream loading; intervening zones are defined as not having significant channelized flow.

In summary, the values presented below and the ensuing discussion is intended to provide an overview of the relative magnitude of the major pollutant sources. As mentioned above, and also in Chapter 6, interannual variability based on precipitation and hydrology is considered in both the Lake Tahoe Watershed Model and the Lake Clarity Model when possible.

4.6.1 Level of Confidence

A number of major considerations were applied to the estimates of confidence related to nutrient and sediment loading to Lake Tahoe. First the models were calibrated, validated, and supported by loading estimates obtained from field data. Second, the levels of confidence associated with these measurements were considered to be important. Third, extensive scientific literature was used for guidance related to water quality processes and dynamics. Fourth, conclusions that were supported by independent studies at Lake Tahoe, i.e. weight of evidence, were given a higher level of confidence. Fifth, a wide range of scientific expertise was used to help apply the concept of best professional judgment.

As discussed in this document, confidence was viewed from a resource management perspective, i.e. what is the likelihood that science has provided a correct understanding of pollutant loading and is the level of understanding sufficient to support a management decision? Based on these considerations related to resource management, a set of qualitative criteria was developed for evaluating confidence in the pollutant loading estimates (Table 4-65). Green represents a high level of confidence, yellow a moderate level, and red a low level. A further distinction is made within each level with a value of 9 being the greatest level of confidence and a 1 being the lowest level of confidence.

A ranking level of 5 or better was considered adequate to support the initiation of the Integrated Water Quality Management System (IWQMS) for the restoration of Lake Tahoe's lost clarity. It is important to highlight additional studies related to the moderate level of confidence should be carried out within an adaptive management framework. That is, there is a good starting point for data with studies needed that are targeted on specific issues. This is especially true for fine sediment particle numbers. As discussed in Section 3.4, a significant amount of new information has been collected on the source, transport and fate of the fine sediment particles. This provides a good level of understanding from which to base loading estimates however, additional studies to better characterize this pollutant are necessary for defining TMDL performance milestones, evaluating restoration effectiveness, and determining specific pollutant control options for the parcel and sub-watershed scales.

Table 4-65. Criteria for determining level of confidence.

Level	Definition
9 8 7 High	Confidence in estimates is high and uncertainty is low. Estimates based on reliable and extensive field data or modeling supported by extensive field data. Peer-reviewed studies exist specifically for the Tahoe basin are available to support data. Weight of evidence provided by similarity to other independent studies for Lake Tahoe. Scientific reasoning supported by TMDL Team. Additional studies not likely to yield significantly different results.
6 5 4 Medium	Confidence and uncertainty is moderate. Estimates based on reliable field data or modeling supported by field data; however, the supporting database is either not extensive and/or comprehensive. Primarily non peer-reviewed studies exist for the Tahoe basin to support data. Weight of evidence provided by independent studies for Lake Tahoe is limited. Additional studies, conducted within an adaptive management framework, will likely improve our understanding but not likely change broad-based management strategy.
3 2 1 Low	Confidence in estimates is low and uncertainty is high. Estimates based on a single study that was considered preliminary or not enough data was collected. Additional studies are needed to support management decisions.

4.6.2 Pollutant Input Budgets for Major Sources

Sediment

Total Suspended Sediment

The average TSS or total suspend sediment fraction from the major sources was estimated to be approximately 29,600 metric tons per year (Table 4-66). The upland watersheds, including stream channel erosion, accounted for 22,400 or 75 percent of the total. Within the category of upland runoff (not including stream channel erosion), 11,700 metric tons or 70 percent of the load from that source came from the non-urban portion of the watershed. Alternatively, 5,200 metric tons or 30 percent was generated from the urban portions of the watershed. Shoreline erosion contributes, on average, 7,200 metric tons/year; however, it is most likely that this source is highly variable from year-to-year and that the total erosion rate between 1938-1998 was affected by some very large events. The methodologies used in the LTADS atmospheric deposition study measured particulate matter > 30 µm and therefore this dataset was not appropriate for discussions of TSS. It was also assumed that TSS is not transported along with groundwater flow.

Whole-basin estimates of TSS loading are not common for the Tahoe basin, with the LTIMP program the most comprehensive. Given the length of the LTIMP data set and the high level of QA/QC imposed on this program by the US Geological Survey and UC Davis - TERC, that data set is considered to be of high quality and was therefore used for model calibration. For the period of 1972-1974, Kroll (1976) investigated sediment discharge from highway cut-slopes in the Tahoe basin and made whole-basin sediment loading estimates. Based on data from seven streams–45 percent of total inflow (including the Upper Truckee River and Trout Creek but no other LTIMP streams)–a basin-wide TSS loading of nearly 11,000 metric tons can be calculated. This is somewhat less than the 16,900 metric tons value estimated by Lake Tahoe Watershed Model for the period 1994-2004, precipitation in 1972-1974 was only 75 percent of that measured during 1994-2004. With the conservative estimate that load during 1994-2004 should be reduced by 25 percent to account for the difference in precipitation and runoff, the Lake Tahoe Watershed Model results and Kroll (1976) estimates are nearly identical at 12,675 metric tons and 11,000 metric tons respectively. Based on this agreement and the fact that the Lake Tahoe Watershed Model was calibrated to the reliable LTIMP database, our level of confidence is moderate-high (classification of 6-7).

The 5,500 metric tons estimate for TSS from stream channel erosion was calculated from data presented in Simon et al. (2003). In that study TSS was modeled for General Creek, the Upper Truckee River and Ward Creek. Values of 241 metric tons/year, 2,892 metric tons/year and 695 metric tons/year were reported for these streams, respectively. Estimates of whole-basin TSS load were not made since TSS was not directly used as input data to the Lake Clarity Model. Using Simon's later estimate of basin-wide fine sediment loading from stream channel erosion, the three modeled creeks above contributed a total of approximately 60 percent. Taking the sum of stream channel TSS from General Creek, the Upper Truckee River and Ward Creek (3,828 metric tons/year) and scaling to the whole basin based on the 60 percent contribution value, a value of 6,380 metric tons/year was calculated. Also, for those three streams Simon (2006) reported a TSS to fines ratio of approximately 3.6:1. By multiplying that ratio by the whole-basin stream channel fines load reported by Simon (2006) of 1,305 metric tons/year a second stream channel TSS load calculation of approximately 4,700 metric tons/year was made. The mean of these two calculations was on the order of 5,500 metric tons. A confidence classification of 5-6 was assigned since the basin-wide calculations are based on the focused work of Simon and his colleagues who conducted their investigations specifically in the Tahoe basin as part of the TMDL Research Program.

As noted above, the value for TSS coming from shoreline erosion is based on an analysis of shoreline characteristics over a 60-year period. No comparable study has been done at Lake Tahoe. While our level of confidence is in the 6-7 range of classification, this applies to the 60-year period; based on the available data our level of confidence that this long-term average would apply during any single year would be low and in the 2-3 range.

Total nitrogen loading from shoreline erosion was considered minimal based on the values reported by Adams and Minor (2002). At a value of approximately 2 metric tons/year, these sources accounted for < 1 percent of the total nitrogen load. Based on the limited number of samples collected for nitrogen analysis, our confidence classification was moderate at 4-5.

Fine Sediment

Fine sediment (fines) is defined as that material with a diameter for individual particles diameter at < 63 µm. Decreasing the size range from TSS to fines begins to narrow our discussion; however, it should be noted that the < 63 µm range still contains material in the > 16 µm to 63 µm size class that has little direct affect on the clarity of Lake Tahoe (Swift et al. 2006), but which is likely to make a major contribution to the mass (metric tons) of this fraction. The fine, < 63 µm class is included since there was available data, and since it does begin to bring our attention more specifically to the sources of concern.

It was estimated that the average annual load of fine sediment to Lake Tahoe was 14,200 metric tons/year from all sources. This accounts for nearly 50 percent of the combined TSS load. Upland runoff contributed 9,100 metric tons or 63 percent of the fines load from all sources. The fine sediment load from the urban and non-urban portions of the upland were virtually the same at about 4,500 metric tons/year. The ratio of fine sediment to TSS loading varied based on urban versus non-urban land-use category. For the urban areas approximately 85 percent of the TSS load was found in the fine sediment fraction, whereas only 40 percent of the TSS load from the non-urban areas was contributed by the fines. Kroll (1976) found that for streams only fines accounted for 30-40 percent of the total suspended sediment load for the seven streams sampled. The Lake Tahoe Watershed Model predicted that ratio to be approximately 50 percent considering all streams. Kroll's whole-lake estimate for fine loading from streams was 4,000 metric tons/year compared to the 6,900 metric tons/year value modeled in the current study. Again, taking into account the fact that the 1972-1974 study period of Kroll (1976) was 25 percent drier than the 1994-2004 when the Lake Tahoe Watershed Model was run, fine sediment loading from the streams was comparable. Simon (2006) provided another estimate of fine sediment loading for Lake Tahoe. The study focused primarily on streams and did not include the urban portions of the intervening zones that flow directly to the lake without being transported via one of the 63 stream channels. His estimate of approximately 5,200 metric tons (based on a period of record of approximately10-40 years depending on the specific stream), was very similar to the others for the fine sediment load from streams. Based on the discussion above, a confidence classification of 6-7 was made for fine sediments from upland runoff.

As presented below, the relative contribution of the urban areas is even greater with respect to particle numbers for the < 16 µm fraction. Therefore, considering smaller sediment fractions and focus on that fraction that most impacts water clarity, the importance of loading from the urban areas increases. As presented below, the average concentration of particles in the < 16 µm size class (number/mL) from urban land-uses was found to be on the order to 300 times than in stream flow (Heyvaert et al. 2007, Rabidoux 2005). While there are no studies from the Tahoe basin to directly support this, it is suspected that the large amount of vehicle traffic and other human activities in the urban areas result in the breakdown of soil to finer size classes. Given the apparent importance of the urban areas to fine sediment and particle loading, the establishment of long-term monitoring stations–similar to LTIMP–would increase our level of confidence.

The contribution of fine sediment from stream channel erosion was estimated by the Lake Tahoe Watershed Model to be 3,800 metric tons/year, accounting for 27 percent of the total fine sediment load from all sources. As discussed in Section 4.3, the Lake Tahoe Watershed Model does not directly simulate stream channel erosion; rather it is calculated based on the modeled upland fines loads and the ratio of channel fine to total fines as determined by Simon (2006). Simon et al. (2003) and Simon (2006) have conducted detailed investigations of stream channel erosion at Lake Tahoe; the only such studies done to date. They reported a fine sediment load from all stream channels of approximately 1,300 metric tons/year, which is much lower than the 3,800 metric tons/year modeled value. If the 1,300 metric ton value were substituted into Table 4-66, the relative contribution of fines from stream channel erosion would decline from 27 percent to 11 percent. Therefore a confidence classification of 5 is assigned to this source of fines, but it is likely that this can be improved if the CONCEPTS model for stream channel erosion were directly incorporated into the Lake Tahoe Watershed Model.

The estimated value for atmospheric deposition given in Table 4-66 is 750 metric tons/year. This would account for five percent of the total load; however, this is an under-estimate since airborne particles in the 30 − 63 µm size range are much less common in air than in runoff. As emphasized in Section 4.5 and in the LTADS report (CARB 2006), the estimate of fine sediment loading from atmospheric deposition should be viewed as a preliminary value based on limited data. Only one year of incomplete data exists and as noted in CARB (2006) a large number of best professional assumptions were required given the very short time table of this project. This is particularly true for wet deposition of particles, but an elevated level of confidence also exists for the dry deposition values. This was the first time such an investigation has been done at Lake Tahoe. LTADS does provide a wealth of data that can be used to support future studies on fine sediment deposition. In fact, funding from the Southern Nevada Public Lands Management Act (SNPLMA) for research is currently being used to investigate this in more detail. The confidence value assigned to fine sediment associated with atmospheric deposition is 2-3.

The amount of material ≤ 63 µm from shoreline erosion was estimated to be 33,000 metric tons over the 60-year record for a calculated annual mean of 550 metric tons (Adams and Minor 2002). This accounts for < 5 percent of the combine fine sediment load; however, as previously discussed this is not accurate to the extent that shoreline erosion will likely vary considerably from year-to-year. While our confidence in the 60-year estimate is moderate-high, there is not data to estimate a unique annual estimate based on lake conditions.

Particle Numbers in the < 16 µm Size Class

This is the first time an estimate for particle loading to Lake Tahoe has been made based explicitly on particle number (Table 4-66). Discussions of the factors that control lake clarity strongly implicate particles (number, size, composition and location in water column) as a critical driver of Secchi depth (e.g. Swift et al. 2006). Consequently, while loading estimates for total suspended sediment (TSS) and even the $TSS_{< 63\ \mu m}$ fraction is of interest, fine particles (< 16 µm) are the pollutant of concern, as these sized particles have the greatest impact on lake optical properties. Using the research finding that particles greater than 16 µm have little affect on light scattering, estimates of particle loading for the < 16 µm size range were made for each of the major sources based on field measurements and mass balance considerations, modeling or a combination of both. Chapter 5 provides a detailed overview of the approaches taken for each source; in this section a summary of the findings are presented along with a comparison to the TSS and < 63 µm loads. Since the importance of these fine particles to lake clarity was not recognized until the late 1990's (Jassby et al. 1999) and TMDL funding was not available until 2001-2002, the period of record for these estimates was primarily during the period 2002-2004.

The average annual load of particles < 16 µm from all the major sources was on the order of 5×10^{20} particles per year. Table 5-13 shows the estimated break down of loading by source for each of the individual particle size classes in the < 16 µm range. On the order of 85 percent of the particle load to Lake Tahoe is associated with surface runoff associated with urban and non-urban upland sources and stream channel erosion. By far the most significant contributor was urban upland runoff accounting for 72 percent of the total. The non-urban uplands accounted for only 9 percent with 4 percent from stream channel erosion. It is very interesting to note that as the sediment size classification became smaller (i.e. TSS to < 63 µm to < 16 µm particles) the relative contribution from the urban uplands increased dramatically. Urban TSS load was estimated to be 17 percent. This nearly doubles to 31 percent for the < 63 µm fraction and approximately doubled again to 72 percent for the < 16 µm particle number loads. Likewise, the relative contribution from non-urban areas declined with decreasing particle size. Since particle number and size are of primary concern for controlling lake clarity, it can be seen that neither TSS nor the load of < 63 µm sediments (by weight) can be used as substitutes for particle counts. While the research has yet to be done, it is speculated that larger sized particles are broken down into smaller sized particles by human activity, (e.g. motor vehicle abrasion) within the urban regions. Since the residence time for stream water is so short (hours of travel time from headwaters to mouth), in-stream processes that can break particles down are less likely to occur. Once again it supports the concept that the urban areas are critical with respect to pollutant control.

The contribution of particles from atmospheric deposition was taken as 15 percent of the total (Table 4-66,Table 5-13, and Table 5-14). The atmospheric deposition values are based on the upper bound revised wet deposition values provided by CARB staff (L. Dolislager 2007 personal communication).

Figure 5-4 summarizes the data for particle number presented inTable 5-13. As seen for the in-lake particle data (Coker 2000, Sunman 2001, Swift 2004), particle loading declines linearly with increasing size when plotted on a log-log scale. The slopes of each source were the same and the dominance of the extremely small particles (< 8 µm) is evident. To highlight the difference between particle numbers and weight, the weight of a particle 4 µm diameter (2 µm radius) is 64-fold that of a 1 µm diameter particle. Similarly a 16 µm diameter particle is nearly 4,000-fold that of the 1 µm diameter particle.

Based on the percentage data in Table 5-14, it is interesting to note that for the watershed sources, including uplands runoff and stream channel erosion, the relative contribution of the urban areas was high and in the range of 66 – 84 percent until the 16 – 32 µm fraction was reached. At that larger size class the relative importance of non-urban and stream channel sources increased significantly. Again, this highlights the importance of the urban areas as sources of the particles of most concern to Lake Tahoe’s clarity. Also, while there is some deviation to this trend, the smallest size fractions appeared to be the largest contributors to the atmospheric load. Shoreline erosion made negligible contributions to < 16 µm particle loading and once again highlights the conclusion that TSS is a very poor surrogate for sediment loading to Lake Tahoe as it affects clarity.

As noted, the importance of very fine particles (< 16 µm in diameter) was only proposed in 1999 and verified by field research and modeling in the early 2000’s (Perez-Losada 2001, Swift 2004). Consequently, all the supportive data is recent and there is no historical database or previous studies to compare with. This lack of data was recognized at the out-set of the TMDL process and research/monitoring for particle loading from streams, stormwater runoff, stream channel erosion and atmospheric deposition was initiated. While our level of knowledge has increased dramatically in recent years, areas of lower confidence still exist and much more work is still needed. This is especially true for atmospheric deposition of particles which has a very low confidence classification, i.e. 2-3. Based on the initial CARB LTADS data collection, which set the stage for all future work in this area, a more detailed investigation of particle deposition directly to the lake surface was only recently initiated with research/science funds from the SNPLMA Round 6. Results from that study are just beginning to come in and are too early for incorporation into our current analysis. Based on the available data and our best professional judgment an over confidence classification for particle number loading of (moderate) 5 was given, with a range of 5-6 for the upland sources, 2-3 for atmospheric sources and 4-5 for shoreline erosion.

In summary, there is an adequate level of confidence to guide management decisions relative to the overall strategy for restoring water clarity in Lake Tahoe. Much more research, monitoring and modeling is needed to understand fine sediment particle loading and in-lake fate similar to the level and understanding for nutrients. Given that this topic has not been on the scientific ‘radar-screen’ at Lake Tahoe for long, and the paucity of literature-based research in general by the water quality/limnology community in general, progress to date has been significant.

Nitrogen

Total Nitrogen

The estimated average annual total nitrogen loading from the five major sources was 397 metric tons or approximately 400 metric tons (Table 4-66). This was identical to the 390 metric tons estimate made by Thodal (1997) and the 400 metric tons estimate of Reuter et al. (2003). Based on these consistent findings a confidence classification of 7-8 was assigned to the total nitrogen loading value. In further support of this value, Dr. Alan Heyvaert (Desert Research Institute, Reno) deployed large, oceanographic-scale sediment traps in Lake Tahoe and reported that nitrogen sedimentation to the bottom of the lake (the major mechanism for the loss of nitrogen from this system) to be 402 metric tons/year (analysis appears in Reuter and Miller 2000). This value agrees remarkably well with the loading values reported here and increases our confidence that the loading rates are representative.

The combined urban plus non-urban contributions to upland runoff was 125 metric tons/year with an equal amount estimated to come from each of these two major land-use areas. As such, the upland runoff category accounted for about 32 percent of the total nitrogen input budget (16 percent for urban and 16 percent for non-urban). Using the Lake Tahoe Watershed Model, this was the first time urban and non-urban land-uses were differientiated. Previously, the only distinction possible was between the load from stream channels and that from intervening zones. Modeled total nitrogen loading from intervening zones and streams obtained in the current study were approximately 31 metric tons/year and approximately 94 metric tons/year, respectively for a total contribution from urban uplands of 125 metric tons/year as noted above. On the basis of a much simpler approach, Reuter et al. (2003) reported loads of 23 metric tons/year and 82 metric tons/year for intervening zones and streams. Other estimates of total nitrogen loading for Tahoe basin streams have ranged from 55 −110 metric tons/year (Dugan and McGauhey 1974, Marjanovic 1989, Jassby et al. 1994, and Thodal 1997). While there are some differences in the published nitrogen load from streams, it must be noted that these were done at various times over the past 30 years when different levels of precipitation, and extrapolated to the whole-basin from varying sets of monitoring streams. Based on the similarity of all the estimates, a confidence classification of 7-8 was assigned to total nitrogen loading from upland runoff.

Total nitrogen load associated with stream channel erosion was estimated to be very low at 2 metric tons/year, and < 1 percent of the total nitrogen input budget. Direct measurements for this nitrogen source were not made and the estimate is based on a series of assumptions guided by best professional judgment. The low level of confidence (1-2) is offset by the minimal contribution from this source. Even an order of magnitude error (factor of 10) would still result in the conclusion that total nitrogen load from stream channel erosion is minor.

Atmospheric deposition was the largest contributor of total nitrogen with an annual estimated load of 215 − 220 metric tons, accounting for 55 percent of the input budget. Based on the close level of agreement between the UC Davis - TERC and LTADS estimates and all the supporting lines of evidence, a confidence classification of 8 was given to this source for total nitrogen. It is important to note that this higher level of confidence applies to whole-lake deposition. There is less certainty about deposition to any specific area of the lake surface.

The estimated groundwater total nitrogen load was 50 metric tons/year and accounted for 13 percent of the total nitrogen input from all sources. Both Thodal (1997) and the USACE (2003) reported values were very similar at 60 metric tons/year and 50 metric tons/year, respectively. As discussed in Section 4.1, approximately 55 percent of total nirogen loading from groundwater appears to come from the west shore aquifers and is elevated primarily due to higher subsurface flows. Based on the degree of agreement between these two studies and the supportive evidence from a few studies in Ward Valley on the west shore (Loeb and Goldman 1979, Loeb 1987) a confidence classification of 6-7 was assigned.

The contribution of shoreline erosion to whole-lake nitrogen loading was estimated at 2 metric tons/year or < 1 percent of the average annual input budget (Adams and Minor 2002). A confidence classification of moderate (4-5) was assigned.

Dissolved Inorganic-N

Dissolved inorganic-N (DIN) is defined as the sum of nitrate plus ammonium. Since both forms of inorganic nitrogen are considered biologically available for algal uptake, DIN is particularly relevant to phytoplankton growth. DIN loading from all the major sources was estimated at 192 metric tons/year and approximately 48 percent of the total nitrogen (TN) load (Table 4-66). Of the remaining 205 metric tons/year of TN entering Lake Tahoe as organic nitrogen based on budget calculations, about 30 percent consists of particulate nitrogen with 70 percent as dissolved organic nitrogen.

The vast majority of DIN loaded to Lake Tahoe during the period of record used in the calculation of the nitrogen input budget came from atmospheric deposition. The annual load of approximately 150 metric tons comprised 77 percent of the yearly budget. The data for nitrate and ammonium deposition at the Ward Valley Lake Level station from Jassby et al. (1994) is available for comparison. For the period 1989-1991 DIN deposition at that location was within 15 percent of the whole-lake estimates from the current study. In further support that these values are reasonable, Jassby et al. (1994) reported the values from Lake Tahoe were consistent with wet DIN deposition measurements made by the National Atmospheric Deposition Program (NADP) at Yosemite and Sequoia, both in the Sierra Nevada. Based on these considerations a confidence classification of 7 was given to DIN loading from atmospheric deposition.

An estimated 17 percent of the average annual DIN loading was attributed to groundwater input. The 32 metric tons/year value was based on the nitrate loading estimates from the USACE (2003) report and will be underestimated to the extent that ammonium was not directly measured. Based on data in that report, DIN from groundwater (including ammonium) did not exceed 50 metric tons/year. A confidence classification value of 6-7 was given for groundwater DIN–identical to that ascribed for groundwater TN and based on the same considerations.

While the contribution of TN from upland runoff was 125 metric tons/year or 30-35 percent from all sources, DIN from upland runoff was much lower at 12 metric tons/year or just 6 percent of the average annual DIN load from all sources. Of the 12 metric tons/year, 8 metric tons was attributed to urban runoff while 4 metric tons/year were attributed to non-urban runoff. The relative ratios of DIN to TN for both urban and non-urban upland runoff were consistent with values previously reported by Coats and Goldman (2001), Gunter (2005) and Coats et al. (2008). Based on the similarity between the modeled DIN loading values and the published papers and technical reports for nitrogen loading from the watershed, a confidence classification of 7-8 was given.

No data was available for DIN loading from stream channel erosion or shoreline erosion. However, given the estimated contribution of these sources combined for TN was approximately 1 percent of the total, and that DIN is not typically bound to particles, it is reasonable to assume they their contribution to DIN loading basin-wide was negligible.

Phosphorus

Total Phosphorus

The estimated average annual total phosphorus (TP) loading from the five major sources was 46 metric tons (Table 4-66). This was virtually the same as the 43.6 metric tons/year value reported by Reuter et al. (2003) and very similar to the 36 metric tons/year estimate presented by Thodal (1997). As discussed above for total nitrogen loading, Heyvaert also estimated TP loss from Lake Tahoe using sediment traps. His estimate of a 53 metric tons/year loss of TP is again very similar to that for TP loading. These are relatively consistent findings, although not as close as those for total nitrogen. Consequently a confidence classification of 7 was assigned to the TP loading value.

The combined urban plus non-urban contributions to upland runoff was 30 metric tons/year with 18 metric tons/year estimated for urban and 12 metric tons/year for non-urban areas. Combined, the upland runoff category accounted for about 65 percent of the total nitrogen input budget (39 percent for urban and 26 percent for non-urban). The relative amount of phosphorus loading from upland runoff was twice as high as that for total nitrogen where only 32 percent came from upland runoff sources. As mentioned above for nitrogen, using the Lake Tahoe Watershed Model has allowed distinction of phosphorus loading between urban and non-urban land-use for the first time. Previously, the only distinction possible was between the load from stream channels and that from intervening zones.

Modeled TP loading from intervening zones and streams obtained in the current study were approximately 10 metric tons/year and approximately 20 metric tons/year, respectively for a total contribution from urban uplands of 30 metric tons/year as previously noted. On the basis of a much simpler approach, Reuter et al. (2003) reported a TP-load from upland runoff of approximately 25 metric tons/year with contributions of 12 metric tons/year and 13 metric tons/year for intervening zones and streams, respectively. The higher basin-wide TP load found in the present study largely results from an increase in the contribution from the intervening zones. Given the relatively low level of confidence associated with those earlier loading estimates from intervening zones, a modest change in estimates was not unexpected. Indeed, the initiation of the TMDL Stormwater Monitoring Study during 2003-2004 was intended to increase that confidence. Others estimates of total phosphorus loading for Tahoe basin streams have ranged from 9 − 8 metric tons/year (Dugan and McGauhey 1974; Marjanovic 1989; Jassby et al. 1994; Thodal 1997). While there are some differences in the published phosphorus load from streams, it must be noted that these were done at various times over the past 30 years with different levels of precipitation, and extrapolated to the whole-basin from varying sets of monitoring streams. Based on the similarity of all the estimates, a confidence classification of 7-8 was assigned to total phosphorus loading from upland runoff.

Total phosphorus load associated with stream channel erosion was estimated to be very low at < 1 metric tons/year, and < 1 percent of the total phosphorus input budget. Direct measurements of total phosphorus associated with nine of the LTIMP stream channel sediments were made and form the basis for extrapolation to the remaining streams. The low-moderate level of confidence (3-4) is offset by the minimal contribution from this source.

Atmospheric deposition was an important contributor of TP with an annual estimated load of 6 − 8 metric tons or approximately 15 percent of the input budget. The current estimate of total phosphorus from atmospheric deposition is less than the 12 metric tons/year reported by Reuter et al. (2003). This is largely the result of two factors. First, the 12 metric tons/year value was calculated as an extrapolation of the measured wet and dry deposition at the land-based Ward Valley Lake Level station to the whole-lake. It has become clear that land-based stations are not ideally suited for extrapolating to estimates of atmospheric deposition over the water surface because of the land-based nature of the emission sources, especially for phosphorus. The highest levels of atmospheric phosphorus near the land accounted for the original over-estimation. This conclusion was borne out by using data from the on-lake deposition collectors that were made possible with the recent deployment of the NASA-TERC in-lake research buoys. Second, the phosphorus deposition estimates of 6 − 8 metric tons/year were also supported by additional studies using a deposition modeling approach that were recently conducted by the UC Davis - DELTA Group and as part of the LTADS study. Based on the close level of agreement between the various phosphorus loading estimates and the supporting lines of evidence, a confidence classification of 7 was given to this source for total phosphorus. As noted for nitrogen deposition, this higher level of confidence applies to whole-lake deposition. There is less certainty about deposition to any specific area of the lake surface.

The estimated average annual groundwater total phosphorus load was 7 metric tons/year and accounted for 15 percent of the total nitrogen input from all sources. Both Thodal (1997) and the USACE (2003) reported values were similar at 6.8 metric tons/year and 3.6 metric tons/year, respectively. The ionic characteristics of ortho-P (PO_4^{-3}) are such that the transport of this compound is more likely to be impeded in the soil matrix of the aquifer than the less chemically “sticky” nitrate molecule (USACE 2003). Consequently, estimates of phosphorus loading based on concentrations found in wells and calculated flow estimates are more subject to confidence when estimated at a whole-basin scale. However, it is not believed that the difference between these two estimates for total phosphorus loading via groundwater is significant, with respect to management decisions related to control of phosphorus loading, and a confidence classification of 5-6 was assigned.

The contribution of shoreline erosion to whole-lake phosphorus loading was estimated at 2 metric tons/year or approximately four percent of the average annual input budget (Adams and Minor 2002). The higher percent contribution to total phosphorus loading from this source relative to total nitrogen (i.e. approximately four percent of phosphorus loading versus < 1 percent of nitrogen loading) results from the close association between phosphorus and sediment (Hatch 1997). A confidence classification of moderate (4-5) was assigned.

Soluble Reactive-P

Soluble reactive phosphorus (SRP) is considered largely bioavailable for algal uptake (e.g. Wetzel 1983). However, a portion of the particulate phosphorus found in stream flow and urban runoff can also be bioavailable as a result of biochemical and chemical equilibrium reactions. As part of the Lake Tahoe TMDL Research Program, Dr. Jerry Qualls and Joseph Ferguson (University of Nevada, Reno) conducted an investigation specifically using stream flow and runoff from Lake Tahoe to quantify the bioavailable phosphorus in the particulate fraction (Ferguson and Qualls 2005). They found that on average 21 percent (± 12 percent) of the particulate phosphorus in stream flow was bioavailable with a measurement of 36 percent (± 14 percent) for particulate phosphorus in urban runoff. While the amount of bioavailablephosphorus from non-SRP sources is accounted for in the Lake Clarity Model, the SRP values reported below are from chemical analyses and do not include bioavailable phsophorus from all sources.

Direct loading of SRP from all the major sources was estimated at approximately 13 metric tons/year and about 30 percent of the TP load (Table 4-66). This was very similar to the 14 metric tons/year estimate of Reuter et al. (2003). In contrast to DIN, SRP loading from atmospheric deposition directly to the lake surface was not dominant. However, with an estimated contribution of 15 − 20 percent from this source (2.3 metric tons/year), it was considered significant from the perspective of pollutant reduction management. The contribution from upland runoff was a combined 6.1 metric tons/year (46 percent) from urban and non-urban land areas. The SRP load from non-urban sources was approximately 65 percent higher than for urban sources and the opposite of that found for total phsophorus loading from these two major land-use categories. As reported in Table 4-41, the agreement between the modeled SRP loads and monitored SRP loads (LTIMP) was less certain than for total phsophorus. Froelich (1988) reported on a phosphate buffer mechanism that exerted a kinetic control over dissolved phosphate concentrations in natural waters. As part of this process, an important mode of interaction between dissolved phosphate and inorganic suspended sediment particles is an adsorption/desorption step characterized by a rapid time interval of minutes to hours. This buffering mechanism can result in maintaining low “equilibrium phosphate concentrations” in natural waters. The Lake Tahoe Watershed Model does not account for these complex chemical processes– this could be the cause for the lower level of agreement between modeled and observed SRP loading.

Groundwater loading of SRP is subject to the same chemical processes as described above. Further, and as noted in the total phsophorus loading discussion, soluble phosphorus is “chemically sticky” and subject to adsorption/desorption as it travels through the soil matrix of the aquifer. Estimates of phosphorus loading from groundwater based on measurements of phosphorus concentrations in wells and estimated subsurface flow rates should be viewed as estimates, especially when applied to an area the size of the Tahoe basin.

Phosphorus measurements for stream channel erosion and shoreline erosion were made as total phsophorus and did not distinguish between SRP and total phosphorus. Ferguson and Qualls (2005) did measure bioavailable phosphorus in stream bank material and reported that approximately 5 percent ± approximately 4 percent (mean ± standard deviation) of the particulate phsophorus was bioavailable.

The overall confidence classification assigned to SRP was in the high end of the moderate confidence level, i.e. 6 (Table 4-66). One of the primary reasons why the confidence level was lower than that for total phsophorus and in the moderate rather than the higher level was because of the larger contribution made by groundwater loading. As noted above, the groundwater input values were calculated based on modeled groundwater flow (Darcy’s Law) and nutrient concentrations in the sampling wells. Given that soluble phosphorus can be readily adsorbed within the soil matrix, it is not certain that the estimated load is truly reflective of the phosphorus crossing the sediment-water boundary and moving directly into the lake. In addition, because of the ‘phosphate buffering mechanism’ (Froelich 1988) discussed above, there is additional confidence associated with the relationship between the instantaneous SRP concentrations measured from field monitoring samples and the true SRP total. This would not affect total phosphorus since total phosphorus accounts for all forms of phosphorus. While the assigned confidence classification for total phosphorus loading from upland runoff was higher at 7-8, the confidence classification for SRP was lower at 6-7. The inclusion of field measurements of biologically available phosphorus as part of the Lake Tahoe TMDL Research Program was intended to increase the confidence related to SRP.

Table 4-66. Nutrient and sediment loading budget for Lake Tahoe based on analyses for the five major sources. Discussion on period of record appears in accompanying text. DIN refers to dissolved inorganic nitrogen (NO_3^-, NO_2^- and NH_4^+) while SRP refers to soluble reactive phosphorus. Approach used to estimate bioavailable nitrogen and phosphorus is detailed in accompanying text and in Chapter 5. All values (except for particle number) expressed as metric tons (1 metric ton = 1,000 kg) on an average annual basis. Percent values refer to relative portion of total basin-wide load. Numbered, colored boxes represent level of confidence based on supporting lines of evidence and best professional judgment. Red, yellow and green denote low, moderate and high levels of confidence as defined in text. Three numeric values are given for each of the major levels (1, 2, 3 or 4, 5, 6 or 7, 8, 9) depending on confidence within each major classification. Entries with two values (e.g. 6-7) represents a range.

	NITROGEN						PHOSPHORUS						SEDIMENT								
	DIN	%		Total N	%		SRP	%		Total P	%		TSS	%		< 63 µm	%		Particle # [e]	%	
Upland Runoff										-											
Urban	8	4	7-8	63	16	7-8	2.3	17	6-7	18	39	7-8	5200	17	6-7	4430	31	6-7	34.80×10^{19}	72	5-6
Non-Urban	4	2	7-8	62	16	7-8	3.8	29	6-7	12	26	7-8	11700	40	6-7	4670	33	6-7	4.11×10^{19}	9	5-6
Stream Channel Erosion	ND	NA	NA	2	<1	1-2	ND	NA	NA	<1	<1	3-4	5500	19	5-6	3800	27	5	1.67×10^{19}	4	5
Atmospheric Deposition	148	77	7	218	55	8	2.3	17	6-7	7	15	7	NA	NA	NA	750 [a]	5	2-3	7.45×10^{19}	15	2-3
Groundwater	32	17	6-7	50	13	6-7	4.8	36	5	7	15	5-6	NA [c]	NA	NA	NA [c]	NA	NA	NA [c]	NA	NA
Shoreline Erosion	ND [d]	NA	NA	2	<1	4-5	ND [d]	NA	NA	2	4	4-5	7200 [b]	24	6-7	550 [b]	4	5	0.11×10^{19}	<1	4-5
TOTAL	192	100	7-8	397	100	7-8	13.2	<100	6	46	<100	7	29600	100	6	14200	100	6	48.14×10^{19}	100	5

ND = No data

NA = Not applicable

[a] Data availability and sampling methodology only allows for the ≤ 30 µm fraction to be included in this estimate.

[b] Sixty year mean from 1938-1998; each year considered the same (see text for further discussion).

[c] Assumed that fine particles affecting clarity (≥ 0.5 µm) did not have significant transport via groundwater.

[d] Measurements in Adams and Minor (2002) as total-P and total Kjeldahl-N only.

[e] Particles < 16 µm in diameter.

5 Estimation of Fine Sediment Particle Loading from Source Analysis

5.1 Particle Size Distribution as Input to the Lake Clarity Model

Fine, inorganic particles of soil origin have a significant effect on clarity in Lake Tahoe (e.g. Jassby et al. 1999, Perez-Losada 2001, Swift 2004, Swift et al. 2006). The Lake Clarity Model was developed with this understanding and requires input data for fine sediment particles in the seven particle diameter size categories of 0.5 – 1 micrometers (µm), 1 – 2 µm, 2 – 4 µm, 4 – 8 µm, 8 – 16 µm, 16 – 32 µm and 32 – 64 µm (Perez-Losada 2001, Sahoo et al. 2007). Swift et al. (2006) showed that in Lake Tahoe, about 98 percent of the particle scattering of light was due to particles approximately < 16 µm. The two largest particle size classes, 16 – 32 µm and 32 – 64 µm, were included in the Lake Clarity Model for potential application to other aquatic systems, though these large sediment particle size classes had an insignificant effect on lake clarity. The Lake Clarity Model required input values for fine sediment particle loading for each of the major source categories.

This chapter presents the overall approach, including streamflow analysis, used to estimate fine sediment particle loading from upland runoff, stream channel erosion, shoreline erosion and atmospheric deposition sources. The source analysis assumed that groundwater discharge did not contain any fine sediment particles. The last section of this chapter describes the general process used to apportion fine sediment particle loading based on different land-uses.

5.1.1 Overall Approach

The approach to estimate fine sediment particle number and size distribution for the different source categories relied on available data collected in the Tahoe basin. No data was available to distinguish between the relative contribution of organic and inorganic particles. However, given the terrigenous nature of watershed runoff it was assumed that the < 16 µm particles measured in stream flow and urban runoff were soil-based (inorganic). Because the average change in channel altitude from the headwaters to the mouth for the 10 Lake Tahoe Interagency Monitoring Program (LTIMP) streams is 506 meters or 1,660 feet (Rowe et al. 2002), the travel time for sediment in the stream is on the order of hours. Under these conditions it was considered unlikely that allochthanous (watershed-based) vegetation and detritus (organic) could break down to individual particles < 16 µm.

A two-year study by UC Davis measured particles and size distribution at the most downstream stations in the 10 LTIMP steams (Upper Truckee River, Ward Creek, Trout Creek, Third Creek, Logan House Creek, Incline Creek, Glenbrook Creek, General

Creek, Edgewood Creek, and Blackwood Creek) (Rabidoux 2005). The frequency of sample collection ranged from monthly during low flow conditions to several times per week during spring snowmelt (i.e. event based monitoring); the same samples collected by LTIMP were used for fine sediment particle analysis. Samples were collected during Water Year 2002 and 2003.

The other monitoring effort to collect particle distribution data in the Tahoe basin came from the Lake Tahoe TMDL Stormwater Monitoring Study, jointly funded to UC Davis and the Desert Research Institute (Heyvaert et al. unpublished). This work focused on urban stormwater and was conducted in 2003 and 2004. Adams (2004) also directly measured soil size distribution in his evaluation of shoreline erosion at Lake Tahoe. Particle size distribution data for atmospheric particles, as they related to atmospheric deposition on the lake surface, was evaluated as part of the Lake Tahoe Atmospheric Deposition Study (CARB 2006).

The three years from 2002 through 2004 represent the most realiable field measurements of fine sediment particles for stream flow and stormwater runoff. Total annual precipitation, as measured at the National Weather Service - Tahoe City site, during 2002 was 85 percent of the mean value from 1968-2007. Similarly, 2003 was 86 percent and 2004 was 73 percent. Since particle loading input to the Lake Clarity Model is based on projected annual precipitation and modeled discharge, the 2002-2004 data was used to establish a relationship between flow and particle concentration. Ideally, it would have been beneficial if flow during at least one of the monitored years was above average; however, this was not the case.

While aquatic scientists have looked at particle size distributions in selected lakes other than Lake Tahoe, these particle size evaluations are often targeted either towards characterizing bulk composition (e.g. Winkleman et al. 1999), the loss of organic matter from the water column through sedimentation (e.g. Poister and DeGuelle 2005), grazing and food-web dynamics (e.g. O’Sullivan and Reynolds 2005), or pollutant absorption and in particular trace metals (e.g. Effler 1996). Characterizing fine particle loading to lakes and reservoirs, for the purpose of understanding light scattering and modeling light attenuation and Secchi depth clarity, has not been widely reported with the notable exception of Steven Effler, Feng Peng and their colleagues at the Upstate Freshwater Institute in Syracuse, NY (e.g. Effler et al. 2000, Effler et al. 2005, Peng and Effler 2007, Peng et al. 2007).

Particles from urban sources are discharged to both streams that are tributary to the lake and surface runoff that flows directly to the lake without entering the stream channel. The upland flow that directly enters the lake without entering a stream is referred to as an intervening zone. Non-urban sources also deliver fine sediment particles to streams and through runoff in the intervening zones directly to the lake. Since there were fine sediment monitoring programs for stream flow and stormwater runoff (the latter of which represented urban runoff almost exclusively), the generalized approach for distinguishing between particle loading from urban and non-urban upland sources was to use measured fine sediment particle concentrations within these areas in concert with modeled urban and non-urban stormwater flows.

Tetra Tech (2007) was able to distinguish between urban flow and non-urban flow as these two general land-use categories contributed to discharge in both the intervening zones and the channelized streams (Table 5-1). Within the intervening zones, fine sediment particle (as well as nutrient) loading was determined by (1) using the TMDL Stormwater Monitoring Study data and the corresponding modeled flow to calculate loading from the urban portion of the intervening zones and (2) assuming that the LTIMP (stream) fine sediment particle monitoring data could be used with the corresponding modeled flow to calculate loading from the non-urban portion of the intervening zone. While this approach could elevate the non-urban load from intervening zones somewhat (to the extent that urban flow contributes to streams), it was the only actual measured data available. Furthermore, any potential underestimate of fine sediment particle loading from the non-urban landscape does nothing to change the conclusion that the urban regions are by far the largest contributing sources.

Table 5-1. Percentage of flow from urban and non-urban sites of streams as simulated in the Lake Tahoe Watershed Model (Tetra Tech 2007).

No	BASIN ID	Individual Stream/River	% of urban flow	% of non-urban flow
1	1000	Intervening zone	38.67	61.33
2	1010	Mill Creek	10.01	89.99
3	1020	Incline Creek	10.34	89.66
4	1030	Third Creek	9.21	90.79
5	1040	Wood Creek	11.77	88.23
16	1050	Burnt Cedar Creek	44.57	55.43
7	1060	Second Creek	6.23	93.77
8	1070	First Creek	2.15	97.85
9	2000	Intervening zone	3.05	96.95
10	2010	Slaughter House Creek at mouth	1.51	98.49
11	2020	Bliss Creek at mouth	0.94	99.06
12	2030	Secret Harbor Creek	0.27	99.73
13	2040	Marlette Creek	0.25	99.75
14	2050	Sand Harbor	0.05	99.95
15	2060	Tunnel Creek	0.06	99.94
16	3000	Intervening zone	20.19	79.81
17	3010	McFaul Creek	4.86	95.14
18	3020	Zephyr Creek	2.18	97.82
19	3030	North Zephyr Creek at mouth	0.51	99.49
20	3040	Lincoln Creek.	0.63	99.37
21	3050	Cave Rock	2.90	97.10
22	3060	Logan House Creek	0.90	99.10
23	3070	North Logan House Creek	0.12	99.88
24	3080	Glenbrook Creek	2.59	97.41
25	4000	Intervening zone	44.80	55.20

26	4010	Bijou Creek	31.31	68.69
27	4020	Edgewood Creek	25.36	74.64
28	4030	Burke Creek	14.76	85.24
29	5000	Intervening zone	25.43	74.57
30	5010	Upper Truckee River	5.37	94.63
31	5050	Trout Creek	5.63	94.37
32	6000	Intervening zone	3.02	96.98
33	6001	Intervening zone	24.91	75.09
34	6010	General Creek	0.35	99.65
35	6020	Meeks Creek.	0.52	99.48
36	6030	Meeks Bay Creek	4.46	95.54
37	6040	Lonely Gulch Creek	5.75	94.25
38	6050	Paradise Flat	2.67	97.33
39	6060	Rubicon Creek at mouth	2.98	97.02
40	6080	Eagle Creek	0.07	99.93
41	6090	Cascade Creek	0.24	99.76
42	6100	Tallac Creek at mouth	2.27	97.73
43	6110	Taylor Creek at mouth	1.24	98.76
44	6120	Unnamed Creek	7.79	92.21
45	7000	Intervening zone	25.43	74.57
46	7010	Blackwood Creek	0.77	99.23
47	7020	Madden Creek	0.26	99.74
48	7030	Homewood Canyon Creek	1.74	98.26
49	7040	Quail Creek	1.76	98.24
50	7050	McKinney Creek	4.27	95.73
51	8000	Intervening zone	31.62	68.38
52	8010	Dollar Creek	4.08	95.92
53	8020	Unnamed Lake Forest 1 (Lake Forest)	25.42	74.58
54	8030	Unnamed Lake Forest 2 (just E/O of Burton Creek)	7.24	92.76
55	8040	Burton Creek	0.12	99.88
56	8050	Unnamed Creek (near Carnelian Bay)	3.93	96.07
57	8060	Ward Creek at mouth	1.86	98.14
58	9000	Intervening zone	20.35	79.65
59	9010	Baldly Creek	16.87	83.13
60	9020	Griff Creek	2.41	97.59
61	9030	Snow Creek	7.77	92.23
62	9040	Unnamed Crystal Creek (Part/Near First Creek)	3.12	96.88
63	9050	Carnelian Bay Creek	0.81	99.19
64	9060	Watson Creek at Mouth	0.81	99.19

5.1.2 Streamflow

Rabidoux (2005) developed regression equations between particle numbers and streamflow based on the data collected during 2002-2003. He found linear relationships between both log-log (natural logarithms) transformed particle flux (number of particles per second) and stream flow (cubic feet per second), and log-log (natural logarithms) transformed particle concentration (number/ml) and particle size (μm). The daily streamflow data predicted by the Lake Tahoe Watershed Model was used in conjunction with particle-flow relationships to estimate contribution of urban and non-urban loading for number of fine sediment particles (i.e. field measurements of particle size distribution and modeled flow) entering the lake through streamflow.

Rabidoux (2005) used a linear model for estimating particle flux based on streamflow for all seven particles size classes used in the Lake Clarity Model. The generalized form of the linear model is described by Equation 4:

$$P = \beta_1 \times Q^* + \beta_0 \qquad \textbf{Equation 4}$$

Where:

P = natural logarithm of particle flux (number/s)
β_1 and β_0 = the slope and intercept of the log-log linear regression equation
Q^* = the natural logarithm of stream flow (cfs)

Q^* (cfs) is the only input and comes directly from the Lake Tahoe Watershed Model. The parameters β_1 and β_0 are estimated based on data collected from the 10 LTIMP tributaries (Table 5-2) (Rabidoux 2005). Table 5-3 shows the estimated fine particle concentration of the size groups 0.5 – 16 µm (most effect on lake clarity) and 16 – 63 µm (little to no effect on lake clarity) for the 10 LTIMP streams.

Table 5-2. Regression equation parameters of flow (cfs) versus particle flux (number/second) relationships for Lake Tahoe LTIMP tributaries (Rabidoux 2005). N is the number of samples collected, TSS (mg/mL) is the total suspended solids concentration, and R^2 denotes goodness of statistical fit. Data was collected at the 10 LTIMP streams during routine sampling.

Stream	Parameter	Linear regression equation parameters for each particle size bin (No./s) and TSS (mg/mL)							
		0.5 – 1	1 – 2	2 – 4	4 – 8	8 – 16	16 – 32	32 – 64	TSS
BC	β_0	19.786	18.104	16.503	15.142	14.069	12.402	10.962	0.404
	β_1	1.253	1.292	1.325	1.400	1.458	1.502	1.554	0.523
	R^2	0.791	0.750	0.701	0.682	0.672	0.627	0.599	0.310
	N	40	40	40	40	40	40	40	40
ED	β_0	20.373	18.749	16.977	15.595	14.284	12.596	11.062	0.680
	β_1	1.772	1.7150	1.905	2.074	2.310	2.386	2.529	0.513
	R^2	0.701	0.756	0.781	0.718	0.735	0.633	0.578	0.198
	N	19	19	19	19	19	19	19	19
GL	β_0	21.165	19.246	17.435	16.226	15.400	13.529	12.074	1.609
	β_1	1.101	1.097	1.049	1.020	0.991	0.962	0.932	0.055
	R^2	0.770	0.715	0.656	0.632	0.609	0.519	0.452	0.007
	N	33	33	33	33	33	33	33	33

GC	β_0	20.001	18.343	16.87	15.536	14.456	12.872	11.483	0.123
	β_1	1.108	1.105	1.057	1.072	1.090	1.065	1.058	0.399
	R^2	0.906	0.867	0.824	0.795	0.774	0.708	0.658	0.432
	N	38	38	38	38	38	38	38	38
IC	β_0	21.457	19.885	18.418	17.336	16.492	14.974	13.726	0.641
	β_1	1.361	1.380	1.338	1.362	1.428	1.408	1.419	1.174
	R^2	0.459	0.423	0.354	0.332	0.356	0.279	0.244	0.413
	N	40	40	40	40	40	40	40	40
LH	β_0	20.003	18.247	16.898	16.056	15.612	14.072	12.975	1.895
	β_1	1.503	1.529	1.503	1.485	1.481	1.474	1.465	0.687
	R^2	0.942	0.930	0.911	0.881	0.866	0.812	0.765	0.647
	N	32	32	32	32	32	32	32	32
TC	β_0	20.154	18.701	17.282	15.772	14.541	13.043	11.628	1.126
	β_1	1.438	1.380	1.348	1.457	1.561	1.534	1.566	0.910
	R^2	0.825	0.829	0.741	0.702	0.713	0.564	0.485	0.499
	N	35	35	35	35	35	35	35	35
TH	β_0	20.938	19.086	17.289	15.931	14.989	13.130	11.625	0.029
	β_1	1.374	1.467	1.653	1.838	1.922	2.090	2.237	1.318
	R^2	0.686	0.713	0.713	0.709	0.702	0.673	0.651	0.643
	N	23	23	23	23	23	23	23	23
UT	β_0	20.718	19.037	17.371	16.051	14.782	13.135	11.649	0.200
	β_1	1.208	1.241	1.283	1.330	1.393	1.429	1.475	0.543
	R^2	0.864	0.859	0.832	0.805	0.794	0.742	0.704	0.431
	N	39	39	39	39	39	39	39	39
WC	β_0	19.360	17.80	15.979	14.577	13.437	11.729	10.242	0.161
	β_1	1.343	1.3799	1.405	1.4860	1.553	1.591	1.644	0.461
	R^2	0.878	0.856	0.822	0.809	0.806	0.765	0.738	0.404
	N	41	41	41	41	41	41	41	41

BC = Blackwood Creek, ED = Edgewood Creek, GL = Glenbrook Creek, GC = General Creek, IC = Incline Creek, LH = Logan House Creek, TC = Trout Creek, TH = Third Creek, UT = Upper Truckee River, WC = Ward Creek

Table 5-3. Concentration of fine particles (number/mL) in the 10 LTIMP streams (Rabidoux 2005). N is the number of samples collected. Values are grouped according to effect on lake clarity. The associated standard deviations (stdev) reflect seasonal variability.

Stream	Parameter	0.5 – 16 µm Particle Conc. (No./mL)	16 – 63 µm Particle Conc. (No./mL)
BC	Average	1.17×10^5	1.49×10^3
	Median	3.92×10^4	5.03×10^1
	stdev	3.16×10^5	7.68×10^3
	N	40	40
ED	Average	8.79×10^4	1.21×10^2
	Median	7.29×10^4	5.78×10^1

	stdev	5.04×10^4	1.93×10^2
	N	19	19
GL	Average	9.21×10^4	7.49×10^1
	Median	6.67×10^4	3.54×10^1
	stdev	1.03×10^5	1.20×10^2
	N	33	33
GC	Average	3.63×10^4	4.49×10^1
	Median	2.69×10^4	1.82×10^1
	stdev	2.62×10^4	7.69×10^1
	N	38	38
IC	Average	4.64×10^5	3.65×10^3
	Median	1.69×10^5	1.96×10^2
	stdev	1.37×10^6	1.68×10^4
	N	40	40
LH	Average	1.80×10^4	8.93×10^1
	Median	9.78×10^3	2.93×10^1
	stdev	1.58×10^4	2.07×10^2
	N	32	32
TC	Average	1.32×10^5	2.48×10^2
	Median	1.21×10^5	1.12×10^2
	stdev	5.97×10^4	3.35×10^2
	N	35	35
TH	Average	2.06×10^5	1.15×10^3
	Median	1.14×10^5	1.47×10^2
	stdev	3.25×10^5	2.45×10^3
	N	23	23
UT	Average	1.67×10^5	8.09×10^2
	Median	1.08×10^5	1.40×10^2
	stdev	1.82×10^5	3.08×10^3
	N	39	39
WC	Average	7.14×10^4	2.57×10^2
	Median	3.84×10^4	2.75×10^1
	stdev	1.12×10^5	7.08×10^2
	N	41	41
Overall	**Average**	$\mathbf{1.39\times 10^5}$	$\mathbf{7.94\times 10^2}$
	stdev	$\mathbf{2.56\times 10^5}$	$\mathbf{3.16\times 10^3}$

This linear modeling approach is also referred to as the Rating Curve Method. One of the difficulties with rating curves is that they are statistically biased and tend to underestimate the true concentrations (Cohn et al. 1989). Rating curves generated for this study used the Bradu-Mundlak Estimator (BME), which is a more complex method and statistically unbiased (Cohn et al. 1989). The BME uses the linear regression model U, and corrects it by a multiplier g(z) (Bradu and Mundlak 1970). Below is a list of equations and variables used in the current analysis:

$$C_{MVUE} = exp(U) \times g(z) \qquad \textbf{Equation 5}$$

Where:

U = the 2-parameter linear regression model, $(\beta_1 \times Q^*) + \beta_0$
g(z) = the Bradu and Mundlak estimator

C_{MVUE} = the estimated particle flux

$$z = \{[(m + 1) / (2m)] \times \{(1 - V)\, s^2\}\}$$ **Equation 6**

Where:

m = N - k, the degrees of freedom in the error distribution
N = the number of observations
k = the number of parameters estimated (k = 2)
s^2 = the sample variance (from linear regression)

$$V = \{1 / N + Ln^2\,(Q^*) / [\Sigma_{i = 1 - N}\,(Ln(Q_i) - \underline{Ln\ Q})^2]\}$$ **Equation 7**

Where:

V = factor used by Cohen et al. (1989) to minimize the variance associated with flow
Q* = the arbitrary input streamflow
$\underline{Ln\ Q} = \Sigma_{i=1-N}\, Ln\,(Q_i) / N$
Q_i = the streamflow for sample set

For each linear model, s^2, $\underline{Ln\ Q}$, m, and the denominator section of V can be calculated strictly based on the linear regression model and sample data. To use the BME, an input value Q*, is needed. The variable Q* is the natural log of the streamflow. Once Q* is known, V in Equation 7 can be calculated. After V is calculated, z in Equation 6 can be solved. With z and m, the value of g(z) can then be interpolated from Tables 1 and 2 of Bradu and Mundlak (1970). The final output value C_{MVUE} from Equation 5 is the estimated particle flux (number/s).

Within the channelized streams, fine sediment particle (as well as nutrient) loading was determined by using (1) the LTIMP particle monitoring data with the corresponding modeled flow to calculate loading from the non-urban portion of the channelized streams and (2) the LTIMP particle monitoring data with the corresponding modeled flow to calculate loading from the urban portion of the channelized streams. The LTIMP particle monitoring data was used for both the non-urban and urban portions of the channelized streamflow since the measurements at the stream mouths included load from both sources. The urban contributions from the intervening zones and the channelized streams were summed to derive the upland urban particle load input to the Lake Clarity Model and the same for the non-urban land-uses.

Tetra Tech (2007) calibrated the Lake Tahoe Watershed Model parameters comparing model output with measured data for the 10 LTIMP streams. To calculate particle loading from the unmonitored streams, each stream was placed into a group corresponding to one of the monitored LTIMP streams based on proximity, similarity of land-use, and other considerations (Tetra Tech 2007). The calibrated model parameters of the LTIMP streams are applied to the streams and intervening zones in each group listed in Table 5-4. For example, particle loading from Mill Creek (an un-monitored stream) was based on the particle-flow relationship developed from monitoring data on

Incline Creek. The Lake Tahoe Watershed Model estimated the flow for Mill Creek. Applying the Incline Creek particle-flow relationship to the modeled flow produced the particle loading estimate for Mill Creek. Figure 5-1 shows the geographic distribution of the nine major sub-basins (1000-9000) used for this analysis.

Table 5-4. Individual streams categorized into ten major stream groupings based on LTIMP monitoring data. Sub-basin numbers represent the number used in the Lake Tahoe Watershed Model for the stream (Tetra Tech 2007).

No	SUB-BASIN Name	Group Name	Individual Stream/River
1	1000	Third	Intervening zone
2	1010	Incline	Mill Creek
3	1020	Incline	Incline Creek
4	1030	Third	Third Creek
5	1040	Third	Wood Creek
6	1050	Third	Burnt Cedar Creek
7	1060	Third	Second Creek
8	1070	Third	First Creek
9	2000	Glenbrook	Intervening zone
10	2010	Glenbrook	Slaughter House Creek at mouth
11	2020	Glenbrook	Bliss Creek at mouth
12	2030	Glenbrook	Secret Harbor Creek
13	2040	Glenbrook	Marlette Creek
14	2050	Glenbrook	Sand Harbor
15	2060	Incline	Tunnel Creek
16	3000	Glenbrook	Intervening zone
17	3010	Logan House	McFaul Creek
18	3020	Logan House	Zephyr Creek
19	3030	Logan House	North Zephyr Creek at mouth
20	3040	Logan House	Lincoln Creek.
21	3050	Logan House	Cave Rock
22	3060	Logan House	Logan House Creek
23	3070	Glenbrook	North Logan House Creek
24	3080	Glenbrook	Glenbrook Creek
25	4000	Trout	Intervening zone
26	4010	Trout	Bijou Creek
27	4020	Edgewood	Edgewood Creek
28	4030	Logan House	Burke Creek
29	5000	Truckee	Intervening zone
30	5010	Truckee	Upper Truckee River
31	5050	Trout	Trout Creek near confluence with Upper Truckee
32	6000	Truckee	Intervening zone
33	6001	General	Intervening zone
34	6010	General	General Creek
35	6020	General	Meeks Creek.
36	6030	General	Meeks Bay Creek
37	6040	General	Lonely Gulch Creek
38	6050	General	Paradise Flat
39	6060	General	Rubicon Creek at mouth

40	6080	Truckee	Eagle Creek
41	6090	Truckee	Cascade Creek
42	6100	Truckee	Tallac Creek at mouth
43	6110	Truckee	Taylor Creek at mouth
44	6120	General	Unnamed Creek
45	7000	Blackwood	Intervening zone
46	7010	Blackwood	Blackwood Creek
47	7020	Blackwood	Madden Creek
48	7030	Blackwood	Homewood Canyon Creek
49	7040	Blackwood	Quail Creek
50	7050	Blackwood	McKinney Creek
51	8000	Ward	Intervening zone
52	8010	Third	Dollar Creek
53	8020	Third	Unnamed Lake Forest 1 (Lake Forest)
54	8030	Third	Unnamed Lake Forest 2 (just E/O of Burton Creek)
55	8040	Third	Burton Creek
56	8050	Third	Unnamed Creek (near Carnelian Bay) (map code 16)
57	8060	Ward	Ward Creek at mouth
58	9000	Third	Intervening zone
59	9010	Third	Baldly Creek
60	9020	Third	Griff Creek
61	9030	Third	Snow Creek
62	9040	Third	Unnamed Crystal Creek (Part/Near First Creek)
63	9050	Third	Carnelian Bay Creek
64	9060	Third	Watson Creek at Mouth

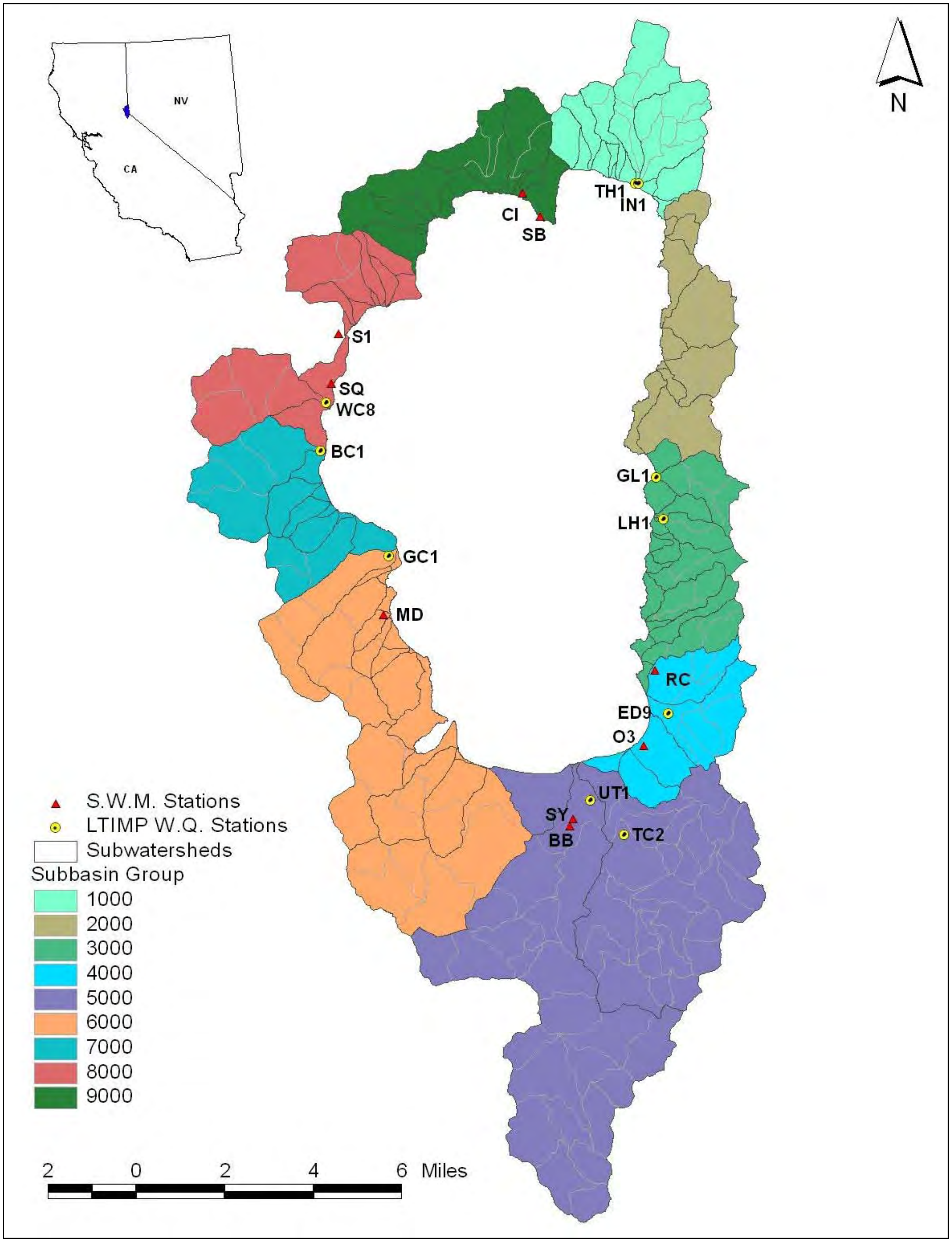

Figure 5-1. Distribution of major sub-basins and intervening zones in the Lake Tahoe Basin as classified for use in the Lake Tahoe Watershed Model. Sample sites for both the LTIMP and the nine TMDL Stormwater Monitoring Sites that included particle size distribution analysis are shown (Tetra Tech unpublished).

5.1.3 Forested Runoff

The forested (non-urban) fine sediment particle loading was estimated based on two loading sources, the streamflow and the intervening zone flow. The daily streamflow estimates from the Lake Tahoe Watershed Model were used in conjunction with the Rabidoux (2005) linear regression equations to determine the contribution of fine sediment particles generated from the forested (non-urban) land-uses using the methodology as in the Streamflow section above. The annual fine sediment particle load entering the lake from streamflow was determined to be 3.72×10^{19} for particles < 16 µm for the calibration period of 1994 – 2004.

The intervening zone flow enters the lake directly and consists of both urban and non-urban land-uses. The daily flow estimates simulated from the Lake Tahoe Watershed Model, originating from the non-uraban intervening zone land-uses (Table 5-1), were used with the Rabidoux (2005) linear regression equations to determine the annual loading values. The annual fine sediment particle load from the forested intervening zone flow was determined to be 0.39×10^{19} for particles < 16 µm for the calibration period of 1994 – 2004. The total average annual contribution from both the streamflow and intervening zone flow from the forested land-uses is estimated to be 4.11×10^{19} for particles < 16 µm.

5.1.4 Urban Runoff

The urban runoff contributions were estimated from the streamflow and intervening zone flow entering Lake Tahoe. The urban fine sediment particle loading to Lake Tahoe from all the channelized streams was estimated using information in Table 5-2 and Table 5-3, the Rabidoux (2005) equations, and the Lake Tahoe Watershed Model estimated stream flow. The methodology used is described in the Streamflow section above. The annual fine sediment particle load from the urban contribution to the streamflow was determined to be 0.18×10^{19} for particles < 16 µm for the calibration period of 1994 – 2004.

As an initial approach to distinguish fine sediment particle loading from urban intervening land-uses, Rabidoux's streamflow-particle regression equations were used in concert with the Lake Tahoe Watershed Model's percent flow estimates from the urban landscape (Table 5-1). This preliminary consideration of urban particle flux was compared to the measured data from the Lake Tahoe TMDL Stormwater Monitoring Study.

The Lake Tahoe TMDL Stormwater Monitoring Study provided the particle concentration data for monitored storm events from nine urban sites around Lake Tahoe (Figure 5-1) (Heyvaert et al. unpublished). The stormwater study measured four size categories (0.49 – 11 µm, 0.49 – 16 µm, 0.49 – 22 µm and 0.49 – 63 µm), which were summarized into two groups: 0.49 – 16 µm and 16 – 63 µm (Table 5-5). Figure 5-2 is a bar chart of the average particle concentration for each of the nine sites for the 0.49 – 16 µm grouping.

Table 5-5. Statistics of particles concentration from nine sites from the Lake Tahoe TMDL Stormwater Monitoring Study refer to Figure 5-1 for sampling locations (modified from Heyvaert et al. 2007).

Site ID*	Statistics**	0.49 – 16 µm Particle Conc. (No./mL)	16 – 63 µm Particle Conc. (No./mL)
SB	Average	2.90×10^7	3.92×10^3
	Median	1.45×10^7	2.41×10^3
	stdev	2.95×10^7	3.50×10^3
	N	37	37
SY	Average	2.79×10^7	3.82×10^3
	Median	1.61×10^7	2.94×10^3
	stdev	3.05×10^7	3.49×10^3
	N	34	34
S1	Average	9.37×10^6	2.52×10^3
	Median	2.56×10^6	8.82×10^2
	stdev	2.26×10^7	6.75×10^3
	N	21	21
O3	Average	9.88×10^6	3.08×10^3
	Median	5.13×10^6	1.35×10^3
	stdev	1.54×10^7	5.76×10^3
	N	27	27
CI	Average	8.20×10^7	1.48×10^4
	Median	3.35×10^7	8.76×10^3
	stdev	9.23×10^7	1.32×10^4
	N	9	9
MD	Average	9.52×10^6	4.07×10^3
	Median	5.42×10^6	1.62×10^3
	stdev	1.12×10^7	5.06×10^3
	N	6	6
SQ	Average	3.35×10^7	7.00×10^3
	Median	1.74×10^7	3.95×10^3
	stdev	2.79×10^7	6.05×10^3
	N	9	9
BB	Average	3.50×10^7	1.11×10^4
	Median	1.25×10^7	3.73×10^3
	stdev	5.92×10^7	2.11×10^4
	N	9	9
RVI (RC)	Average	7.61×10^7	1.94×10^4
	Median	2.33×10^6	9.00×10^2
	stdev	2.44×10^8	6.18×10^4
	N	12	12
Overall	**Average**	**3.47×10^7**	**$7.75\text{x } 10^3$**
	stdev	**5.92×10^7**	**$1.41\text{x } 10^4$**

*SB = Speedboat, SY = SLT-Y, S1 = TCWTS In, O3 = Osgood Ave., CI = Coon Street, MD = Mountain Drive, SQ = Sequoia, BB = B and Bonanza, RVI (RC) = Round Hill.
**stdev = Standard deviation and N = number of events.

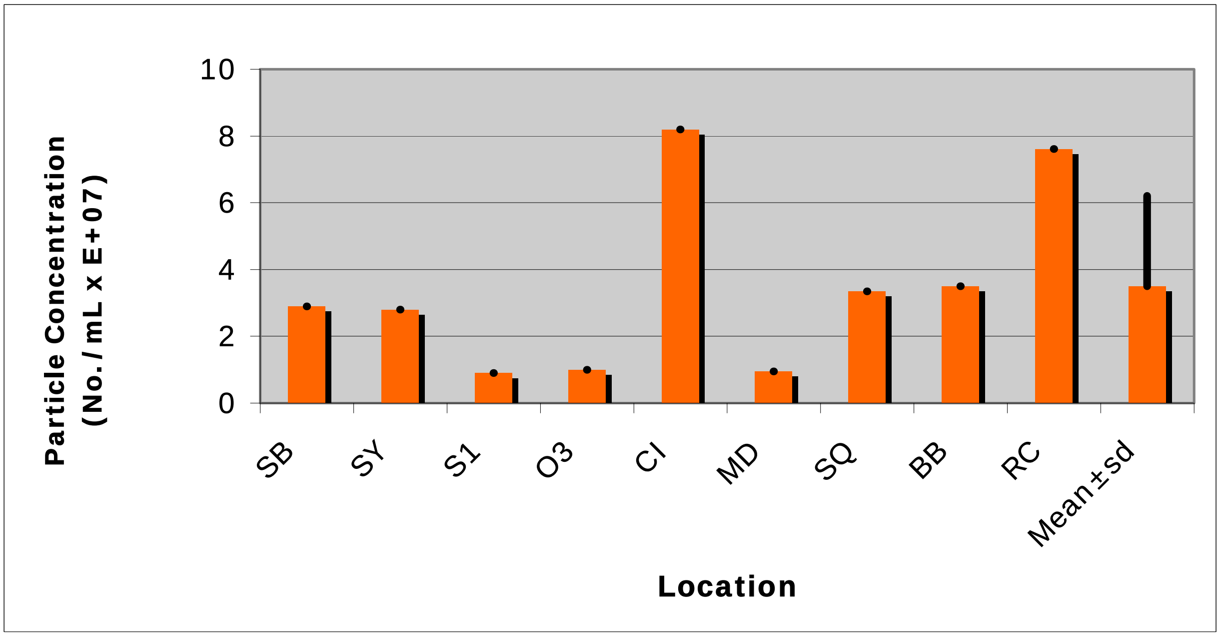

Figure 5-2. Average annual particle concentration for the 0.5 – 16 µm class range. Data from the TMDL Stormwater Monitoring Study data set as presented in Table 5-5 (modified from Heyvaert et al. 2007). The bar to the far right presents average and standard deviation for the nine sites where adequate data were available.

As discussed above, Rabidoux's regression equations were developed using field data on streams. Although the streams include urban and non-urban flow, as indicated in Table 5-1, the urban land-uses produce significantly higher fine particle concentrations (compare Table 5-3 and Table 5-5). Also, in general intervening zones often receive a higher contribution of urban flows compared to streams. Thus, Rabidoux's regression equations will underpredict particle fluxes for the urban portions of intervening zones.

Based on this comparison, the specific streamflow-particle relationships developed for the LTIMP streamflow (refer to Table 5-2) were not considered to be appropriate for describing urban intervening zone runoff without adjustment. First, the concentration of particles in urban runoff (x 10^7 for particles < 16 µm) (Table 5-5) was approximately two orders of magnitude higher than streamflow (x 10^5 for particles < 16 µm) (Table 5-2). Second, the sources of particles are different (e.g. urban particles are impacted by human activities). However, the streamflow-particle relationships developed by Rabidoux (2005) were able to be used after a conversion or multiplication factor was developed and applied to account for the difference between streamflow and urban runoff particle characterization.

Because the detailed data needed to develop regression equations to estimate particle fluxes exclusively for the urban land-uses was not available, a multiplication factor was developed and applied to the intervening zone, leading to the urban particle fluxes estimated using Rabidoux's equations. As mentioned earlier, for the particles flux from the non-urban portion of the intervening zones, it was assumed that Rabidoux's regression equations could be used. This assumption, while based on the best available data, does contribute to uncertainty.

The average annual urban flow from intervening zones during the period 1994 to 2004 as determined by the Lake Tahoe Watershed Model was approximately 9.98 x 10^6 m^3. Thus, using the TMDL Stormwater Monitoring Study measured values for the size range 0.49 – 16 μm (Table 5-5), the average annual particle flux was calculated as approximately 3.47×10^7 particles/mL. This can then be converted to:

$$\frac{3.47 \times 10^7\ particles}{mL} \times \frac{9.98 \times 10^6\ m^3}{year} \times \frac{1 \times 10^6\ mL}{m^3} = \frac{3.46 \times 10^{20}\ particles}{year}$$

Applying the Rabidoux (2005) streamflow versus particle relations to the urban portions of intervening zones, the mean annual particle load for the 0.5 – 16 µm grouping, for years 1994 to 2004, was calculated as 1.086×10^{18} particles/year. For the reasons stated above, it is reasonable and expected that loading value based on the Rabidoux streamflow-particle equations would underpredict the actual measured values. The underprediction difference provided the basis for developing the multiplication factor. This multiplication factor was applied to the estimates of urban particle load for the first five size classes (0.5 – 16 µm) for particle loading from intervening zones based on Rabidoux's study and the Lake Tahoe Watershed Model flow information. The multiplication factor was calculated as $3.46 \times 10^{20}/1.086 \times 10^{18}$ or 318.3. That is, particle loading from the urban landscape could be estimated using the Rabidoux streamflow-particle relationships if a multiplication factor of 318.3 was applied to account for the higher concentrations of fine sediment particles in urban runoff.

Particles fluxes for particle size groups of 16 – 32 µm and 32 – < 63 µm were estimated in a similar manner. Based on the TMDL Stormwater Monitoring Study data, the combined flux for both these size classes was 7.74×10^{16} particles/year; using Rabidoux's regression equations it was again lower, as expected, at 3.53×10^{15} particles/year. Thus, the multiplication factor for the 16 – < 63 µm range is $7.74 \times 10^{16}/3.53 \times 10^{15}$ or 21.9. The annual contribution of fine sediment particles from the urban intervening zone flow was determined to be 34.62 x 10^{19} for particles < 16 µm for the calibration period of 1994 – 2004. The total average annual contribution of fine sediment particles generated from urban land-uses (both streamflow and intervening zone flow) was determined to be 34.80 x 10^{19} for particles < 16 µm.

5.1.5 Stream Channel Erosion

TMDL studies estimated that fine sediment (< 63 µm) from stream bank erosion represents 27 percent of the total fine sediment load to the lake from all sources (Table 4-66). Since the combined watershed sources, including upland runoff and stream channel erosion, contribute 91 percent of the < 63 µm load from all sources, the contribution of stream channel erosion was approximately 27 percent of the watershed contribution to the lake. The LTIMP stream mouth samples analyzed by Rabidoux (2005) contained particles from a mixture of sources including stream channel erosion and upland runoff. Therefore, the total particle loading values for associated stream channel erosion was estimated as 30 percent of the total stream particle load as calculated by the Rabidoux (2005) regression equations as applied to the Lake Tahoe Watershed Model flow estimates. By definition, stream channel erosion does not apply to intervening zones. The urban and non-urban contributions for particle load from stream channel erosion were then partitioned using the relative amount of urban and non-urban flow for each stream (Table 5-1).

5.1.6 Atmospheric Deposition

The LTADS study conducted by CARB (2006) quantified the loading of particulate matter from atmospheric deposition directly to the lake surface. Table 5-6 provides values used in the estimation of total particulate matter (PM) loading from this source. The estimated loading of the fine sediment particle fraction of this total is based on estimates of soil-based particulate matter as described below. CARB (2006) assumed particle diameters of 2 µm, 8 µm and 20 µm for the measured size classes < 2.5 µm, 2.5 – 10 µm, 10 – 35 µm, respectively.

Table 5-6. Atmospheric particulate matter (PM) load into Lake Tahoe expressed as metric tons (based on CARB (2006)). On occasion, total may not be the exact sum of seasonal values due to rounding errors.

Size (µm)	Type	Average seasonal/annual soil load on Lake Tahoe (MT)				
		Winter	Spring	Summer	Fall	Total
2	Dry	17	11	15	17	60
2	Wet	30	31	10	3	74
2	**Subtotal**	**47**	**42**	**25**	**20**	**134**
8	Dry	44	42	40	44	170
8	Wet	17	41	8	3	69
8	**Subtotal**	**61**	**82**	**48**	**47**	**239**
20	Dry	92	78	110	77	360
20	Wet	7	8	3	2	20
20	**Subtotal**	**99**	**86**	**113**	**79**	**380**
	Total	**207**	**210**	**186**	**146**	**749**

The Lake Clarity Model uses particle number, rather than mass, as input data to estimate clarity changes. The CARB (2006) data was converted into fine sediment particle numbers using the following approach:

The mean diameters used for the four class sizes for the CARB data are:

- 0.75 µm for 0.5 – 1 µm,
- 1.5 µm for 1 – 2 µm,
- 5 µm for 2 – 8 µm, and
- 14 µm for 8 – 20 µm.

For particles with an aerodynamic diameter of 1.5 µm, the volume of that sphere is:

$$\frac{4}{3} \times \Pi \times r^3 = 1.767 \mu m^3$$

Where:

Π = 3.14
r = radius of sphere (.75 μm)

Assuming a specific density of 2.56 g/cm^3 for soil (Troeh and Thompson 2005), this calculates into a weight per 1.5 µm fine sediment particle of:

$$1.767\,\mu m^3 \times \frac{2.56\times 10^3\,mg}{cm^3} \times \frac{1.0\times 10^{-12}\,cm^3}{\mu m^3} = 4.52\times 10^{-9}\,mg$$

All particles were assumed to be spherical in shape. This project did not determine the shape of particles deposited from the atmosphere or any of the other sources.

The inert particle mass (soil-based) reported by CARB (2006) was used for the estimation of fine sediment particles since fine organic particles were less important in affecting lake clarity. The term inert particle mass used in the CARB (2006) study is synonymous to inorganic fine sediment mass. CARB (2006) reported that an average of only 10 percent of the $PM_{2.5}$ mass was contributed by inorganic soil-based particles in the range 0.5 – 1 µm and that an average of 27 percent of the $PM_{2.5}$ mass contributed by iinorganic soil-based particles in the range 1 – 2 µm. Thus 37 percent of the $PM_{2.5}$ load was considered to be inorganic and therefore used to model water clarity. It was assumed that in the cases of course and large particles, 100 percent of the particles were inorganic. In summary, there are estimates of inorganic, soil-based particles for four-size classes:

- 10 percent of the $PM_{2.5}$ mass for the 0.5 – 1 µm size class,
- 27 percent of the $PM_{2.5}$ mass for the 1 – 2 µm size class,
- 100 percent of the PM_8 mass for the 2 – 8 µm size class, and
- 100 percent of the PM_{20} mass for the 8 – 20 µm size class.

Therefore, with a known mass (based on percents above for size classes and Table 5-6) of 1.5 µm fine sediment particles (size class 1 – 2 µm) in metric tons (MT) the number of particles were calculated as follows:

$$MT \times \frac{1\times 10^9\,mg}{MT} \times \frac{1\,particle(1.5\mu m)}{4.52\times 10^{-9}\,mg} = \#(1.5\mu m)\,particles$$

The same approach was taken with the 0.5 – 1 µm, 2 – 8 µm, and 8 – 20 µm size classes.

LTADS particulate matter load values were converted to particle numbers for use in the Lake Clarity Model (CARB 2006). However, the Lake Clarity Model requires seven-size classes (i.e. 0.5 – 1 µm, 1 – 2 µm, 2 – 4 µm, 4 – 8 µm, 8 – 16 µm, 16 – 32 µm, and 32 – 64 µm). The number of particles in each of the seven-size classes were estimated from plots of the above four measured size classes. The cumulative particle numbers of the four size classes are plotted against particle-size classes for each season and for both wet and dry conditions; Figure 5-3 provides an example for the spring dry period. The particle number of any particle size class is the difference between corresponding upper and lower range of the particle size class on the plot (e.g. 0.5 and 1 for 0.5 – 1 µm). Figure 5-3 shows that particle numbers are very high within the smallest size classes and decline dramatically as size increases.

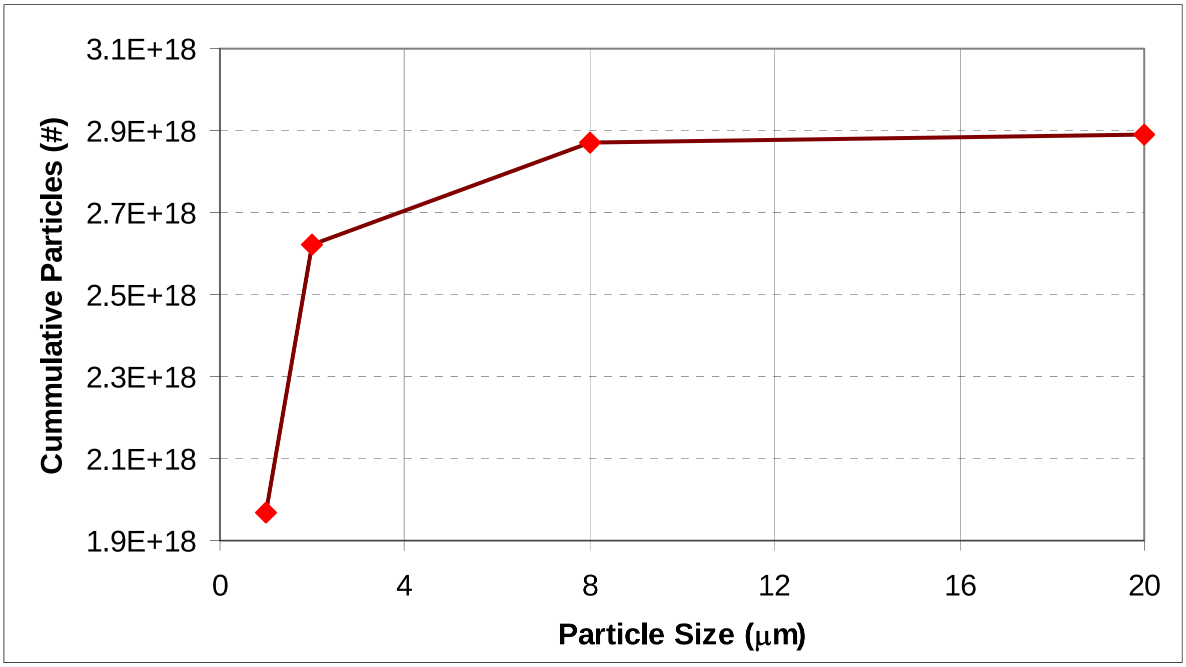

Figure 5-3. Atmospheric cumulative particle curve for different size classes for interpolation and extrapolation of particle number for unmeasured sizes for the spring, dry period.

Using the above approach, the average number of fine sediment particles generated per day for each season, for both wet and dry conditions, was estimated (see Table 5-7 and Table 5-8). This step in the analysis was required for application to the Lake Clarity Model. Since the loading values were different depending on the seasons and wet or dry conditions (based on how the original data was collected), an additional step in the Lake Clarity Model included the daily hydrologic condition. For greater than 0.1 inch of precipitation on a given day, the Lake Clarity Model would use the loading value corresponding to wet conditions for that season (Table 5-8). For less than 0.1 inch of precipitation on a given day, the Lake Clarity Model would use the loading value corresponding to dry conditions for that season (Table 5-7).

Table 5-7. Daily atmospheric dry fine sediment particle load to Lake Tahoe for each season (Note that days when total daily precipitation is less than 0.1 inches are assumed to be dry days).

Size	Range	Winter # particles/day	Spring # particles/day	Summer # particles/day	Fall # particles/day
$PM_{2.5}$	0.5 – 1.0 μm	4.228E+16	2.525E+16	3.160E+16	4.113E+16
	1.0 – 2.0 μm	1.396E+16	8.339E+15	1.043E+16	1.358E+16
PM_8	2.0 – 4.0 μm	1.833E+15	1.616E+15	1.415E+15	1.824E+15
	4.0 – 8.0 μm	1.815E+15	1.598E+15	1.393E+15	1.725E+15
PM_{20}	8.0 – 16.0 μm	2.848E+14	2.336E+14	2.938E+14	2.154E+14
	16.0 – 32.0 μm	5.502E+13	4.522E+13	5.807E+13	4.181E+13
	32.0 – 64 μm	0.000E+00	0.000E+00	0.000E+00	0.000E+00

Table 5-8. Daily atmospheric wet fine sediment particle load to Lake Tahoe for each season (Note that days when total daily precipitation is greater than 0.1 inch are assumed to be wet days).

Size	Range	Winter # particles/day	Spring # particles/day	Summer # particles/day	Fall # particles/day
$PM_{2.5}$	0.5 – 1.0 μm	7.375E+17	7.372E+17	3.515E+17	2.878E+16
	1.0 – 2.0 μm	2.435E+17	2.435E+17	1.161E+17	9.504E+15
PM_8	2.0 – 4.0 μm	7.409E+15	1.759E+16	4.708E+15	5.157E+14
	4.0 – 8.0 μm	7.335E+15	1.743E+16	4.444E+15	5.011E+14
PM_{20}	8.0 – 16.0 μm	2.171E+14	2.347E+14	2.001E+14	2.322E+13
	16.0 – 32.0 μm	4.340E+13	4.763E+13	4.750E+13	5.097E+12
	32.0 – 64 μm	0.000E+00	0.000E+00	0.000E+00	0.000E+00

Each year that is modeled will have a different total loading value of fine sediment particles based on the number of dry and wet days per season for that year. Since the CARB (2006) study was conducted in 2003, the corresponding dry and wet days for that year are included in Table 5-9.

Table 5-9. Total dry and wet days per season for 2003(Hackley unpublished).

	Winter	Spring	Summer	Fall	Total
Dry days	72	78	85	74	309
Wet days	18	13	7	18	56
Total days	90	91	92	92	365

Uncertainty in this approach includes, (1) if the particle diameter would have been used in the lower range (e.g. 1 µm instead of 1.5 µm for the 1 – 2 µm range) then the volume of particles would be four times lower, which corresponds to an increase of four times the particle numbers, (2) the estimated particle number may lie above or below the particle curve presented in Figure 5-3, and (3) the 10 percent for particles ranging from 0.5 – 1 µm and 27 percent for particles ranging from 1 – 2 µm were used for all seasons. While the first uncertainty, (1) above, is important, there is no data available to support a particular approach for estimating the average particle diameter for a specified size class. Additional uncertainty lies in the estimation of the inorganic sediment load into the lake on a year-to-year basis. The inorganic fine sediment particle loads are estimated based on the 2002-2003 atmospheric pollutant loads. Research for particle deposition in the Tahoe basin is ongoing, and is anticipated to reduce the uncertainty with the current estimates in the future.

The relative contribution of fine sediment particles from urban and non-urban areas was based on the loading estimates by CARB (2006) from four lake quadrants selected to represent the spatial variation in ambient concentrations and deposition rates over Lake Tahoe. CARB (2006) estimated particulate matter contributions from the four quadrants (north shore, south shore, east shore and west shore). Particulate matter loading from the north and south shores were > 5 times that from the east and west shores. Because the north and south shores contain most of the concentrated development, the north and south shore were designated as in the urban zone. Both the relative loading contribution and relative geographic contribution of the four quadrants were used to estimate urban and non-urban particle (and nutrient) loading.

5.1.7 Shoreline Erosion

Adams and Minor (2002) reported that both erosion and accretion have occurred along the shore of Lake Tahoe. They estimated that a gross value of 429,350 metric tons of sediment has been lost between 1938 and 1998 through erosional processes, equivalent to about 7,150 metric tons/year. To determine the fine sediment particle load, this value was considered an upper bound to the extent that (1) field observations confirm that some of the areas with documented erosion are currently protected and no longer contribute sediments to the lake (Adams and Minor 2002) and (2) it was beyond the scope of the Adams and Minor (2002) investigation to determine how much of the shoreline accretion of sediment originated from shoreline erosion.

In a subsequent study, Adams (2004) reported that this material from shoreline erosion contained approximately 92 percent sand (62.5 – 2,000 µm), approximately 6 percent silt (3 – 62.5 µm) and approximately 1.5 percent clay (0.5 – 3 µm). These values equate to about 6600, 440, and 110 metric tons/year of sand, silt, and clay, respectively. Overall fine sediment contribution from shoreline erosion loading in the future likely will be lower than over the period 1938-1998, due to the installation of control measures such as sheetpile walls or sloping permeable and dynamic revetments (Adams and Minor 2002).

To estimate a likely reduction in long-term shoreline erosion loading to the lake, the TMDL program assessed each of the eroding shorezone areas' potential to become stabilized since 1998. Adams (2004) determined 7 out of a total of 22 eroded shorezones contributed fine sediment to the lake between 1938 and 1998; the other 15 eroding areas have backshores composed of larger sediment without any measurable silt or clay. The seven eroding areas comprise about one-fourth of all the eroding shorezones around Lake Tahoe, and of these seven eroding areas, only three have potential for stabilization: Al Tahoe-Regan Beach, Sugar Pine Point, and Lake Forest. These three areas have development (such as residential homes, commercial buildings, or public roads) immediately upland of the shorezone, while the remaining four eroding areas are located along undeveloped areas. Without the need to protect development, the erosion will likely continue at the expected rates in these four undeveloped shorezone areas.

However, for the three eroding shorelines along developed areas, there is a strong need to protect property from shoreline erosion. Since 1998, several shoreline protection projects have been built along these three shorelines to protect specific structures. Protecting these shorelines from erosion is anticipated to significantly reduce the expected erosion from those areas. Since the Al Tahoe-Regan Beach shorezone is bordered by dense development, a 75 percent reduction in erosion could be expected. Many areas received shoreline protection since 1998, especially in the five years following the 1997 high lake levels. Assuming the Sugar Pine Point and Lake Forest areas receive only modest shoreline protection since 1998, a 50 percent reduction in erosion could be expected. Applying the 75 percent and 50 percent reductions to estimates on loading from Adams (2004) results in about a 40 percent annual load estimate reduction for total shoreline erosion from the original 1938-1998 estimate. This translates to an assumed annual load of 264 metric tons/year for silt (3 – 62.5 µm) and 66 metric tons/year for clay-sized (0.5 – 3 µm) material. These revised estimates were shown to be reasonable during calibration of the Lake Clarity Model.

For those size classes of importance to the clarity of Lake Tahoe, Adams (2002) provided data for only two composite size distributions, < 3 µm and 3 – 15 µm. However, as noted elsewhere in this document, the Lake Clarity Model requires load estimates in the specific size classes of 0.5 – 1, 1 – 2, 2 – 4, 4 – 8, 8 – 16 and 16 – 32 µm. Since the number of particles associated with the 32 – 64 µm size class are virtually zero as compared with the smaller size class, that size category was not included in this analysis. To go from the two size classes for which data was available (< 3 µm and 3 – 15 µm) to the full suite of size classes needed for the model a two-step process was employed. In the first step, particle number was estimated for the 0.5 – 4 and > 4 – 32 µm categories using the annual loading values of 66 metric tons and 264 metric tons, respectively as revised from Adams and Minor (2002). The conversion from mass to estimated particle number was made using the equations presented in Section 5.1.7. These equations required input for particle radius (diameter divided by 2), sediment density (2.56 g cm^{-3}), and the working assumption that particle shape is approximated by a sphere.

Since volume plays a critical role in estimating particle number, from mass estimates, the mean diameters for particles in the 0.5 – 4 and > 4 – 32 µm categories were calculated using the upper and lower bound for each. For 0.5 – 4 µm the mean particle volume is 16.8 $µm^3$ (0.1 $µm^3$ for 0.5 µm and 33.5 $µm^3$ for 4 µm particles divided by 2 = 16.8 $µm^3$). The equivalent particle diameter for this mean volume was calculated at 3.2 µm. Similarly, for the > 4 – 32 µm category the equivalent particle diameter corresponding to the mean volume is 25.4 µm (33.5 $µm^3$ for 4 µm and 17,157 $µm^3$ for 32 µm particles divided by 2 = 8,595 $µm^3$). Based on model calibration, the representative particle diameters used to estimate particle numbers in the 0.5 – 4 and > 4 – 32 µm categories were set at 3.6 µm and 25.2 µm, respectively. These are very similar to the theoretical mean diameters calculated above. For comparison, the particle volumes corresponding to these latter particle diameters are 24.4 $µm^3$ and 8,379 $µm^3$, for 3.6 µm and 25.2 µm, respectively. Based on the methodology provided above, the total number of particles for the estimated mass of 66 metric tons in the 0.5 – 4 µm category was calculated as 1.06 x 10^{18}. For the 4 – 32 µm category the estimated 264 metric tons yielded a total of 1.23 x 10^{16} particles. The much higher number of particles at the smaller size categories is similar to that found for the other major sources (Figure 5-4).

The second step involved dividing the 0.5 – 4 µm and 4 – 32 µm categories further to estimate the contributions from the 0.5 – 1, 1 – 2 and 2 – 4 µm classes and the 4 – 8, 8 – 16 and 16 – 32 µm classes, respectively. This was accomplished based on the relative proportion of particle number distribution seen for the other land-based source categories (i.e. atmospheric deposition values were not considered since the material and mode of transport to the lake differ significantly from the land-based sources). For fine sediment particles in the 0.5 – 4 µm category, the percentage of distribution of particle number for the 0.5 – 1, 1 – 2 and 2 – 4 µm classes were taken as 75 percent, 22 percent and 4 percent, respectively (rounded to the nearest whole number). These values are partially based on model calibration and supported by the values reported for watershed sources (Table 5-10 original data found in Table 5-13). Values for each size class were calculated by multiplying the 1.06 x 10^{18} estimate for the 0.5 – 4 µm category by 75 percent, 22 percent and 4 percent, respectively.

Table 5-10. Particle percentage distribution among the smallest three classes (0.5 – 1, 1 – 2, and 2 – 4 µm) based on the estimated number for major watershed sources. Data found in Table 5-13.

Particle size	Urban Upland %	Non-Urban Upland %	Stream channel erosion %
0.5 – 1 µm	80	79	79
1 – 2 µm	16	17	17
2 – 4 µm	4	4	4

Similarly, for particles in the 4 – 32 µm category, the total number of estimated particles (1.23 x 10^{16}) was divided into the three classes based on a proportionality of 49 percent (4 – 8 µm), 42 percent (8 – 16 µm) and 9 percent (16 – 32 µm). These percentages were determined by calibration and were somewhat different than the particle size proportions seen in the other watershed sources (Table 5-11). However, given the minimal contribution that the particles in the 4 – 32 µm category from shoreline erosion make in comparison to total particle loading in the full fine sediment particle range (i.e. < 0.0025 percent) these differences are considered trivial.

Table 5-11. Particle percentage distribution among the smallest three classes (4 – 8, 8 – 16, and 16 – 32 µm) based on the estimated number for major watershed sources. Data found inTable 5-13.

Particle size	Urban Upland %	Non-urban Upland %	Stream channel erosion %
4 – 8 µm	67	63	63
8 – 16 µm	32	29	29
16 – 32 µm	1	8	8

Using the approach described above, fine sediment particle loading values per size class used in the Lake Clarity Model to represent shoreline erosion are shown in Table 5-12.

Table 5-12. Shoreline erosion fine sediment particle load to Lake Tahoe.

Size	Range	# particles/year
1	0.5 – 1 μm	7.92×10^{17}
2	1 – 2 μm	2.31×10^{17}
3	2 – 4 μm	4.06×10^{16}
4	4 – 8 μm	6.08×10^{15}
5	8 – 16 μm	5.15×10^{15}
6	16 – 32 μm	1.14×10^{15}
7	32 – 64 μm	Not Applicable
Total		1.08×10^{18}

5.1.8 Summary

The reader is referred to a detailed overview of particle numbers in the < 16 μm size class presented above in Section 4.6.2 under the Sediment heading. A highlight of some of the items most relevant to this section:

- This is the first time a quantitative estimate for particle loading (number of fine sediment particles) to Lake Tahoe has been made (Table 5-13).
- The average annual load of fine sediment particles in the < 16 μm size range from all major sources was approximately 5×10^{20} particles per year.
- Values for particle loading varied based on major source and particle size (Figure 5-4).
- Urban runoff accounted for about 72 percent of the total fine sediment particle load (< 16 μm, see Table 5-14) for all sources making it the most significant contributor. Atmospheric deposition accounted for 15 percent of the total particle load while non-urban upland runoff from the watershed contributed 9 percent.
- These data were used in the Lake Clarity Model with an adequate level of confidence in the particle size distribution data to guide general management decisions; however, a better understanding of particle sources, transport and fate is needed to evaluate the effectiveness of water quality management projects.

Table 5-13. Summary of average annual load and size distribution for fine sediment particles (< 16 µm in diameter) coming from the major source categories. Data is expresses as total number of particles per year for each of the diameters listed. Particles with larger sizes have little effect on lake clarity. Period of record is primarily 2002-2004.

Major Source	0.5-1 µm	1-2 µm	2-4 µm	4-8 µm	8-16 µm	16-32 µm	TOTAL (0.5-16 µm)
Upland Runoff							
Urban	2.71×10^{20}	5.42×10^{19}	1.40×10^{19}	5.76×10^{18}	2.78×10^{18}	5.91×10^{16}	**3.48×10^{20}**
Non-Urban	3.17×10^{19}	6.75×10^{18}	1.67×10^{18}	6.44×10^{17}	2.96×10^{17}	7.94×10^{16}	**4.11×10^{19}**
Stream Channel Erosion	1.29×10^{19}	2.76×10^{18}	6.82×10^{17}	2.62×10^{17}	1.20×10^{17}	3.22×10^{16}	**$1.67 \text{ X } 10^{19}$**
Atmospheric Deposition	5.42×10^{19}	1.79×10^{19}	1.21×10^{18}	1.10×10^{18}	8.59×10^{16}	1.69×10^{16}	**7.45×10^{19}**
Groundwater	NA	NA	NA	NA	NA	NA	**NA**
Shoreline Erosion	7.92×10^{17}	2.31×10^{17}	4.06×10^{16}	6.08×10^{15}	5.15×10^{15}	1.14×10^{15}	**1.08×10^{18}**
TOTAL	**3.71×10^{20}**	**8.18×10^{19}**	**1.76×10^{19}**	**7.77×10^{18}**	**3.29×10^{18}**	**1.88×10^{17}**	**4.81×10^{20}**

Table 5-14. Relative contribution of fine sediment particles (< 16 µm in diameter). Data from Table 5-13 was used to calculate these values.

Major Source	0.5-1 µm	1-2 µm	2-4 µm	4-8 µm	8-16 µm	16-32 µm	TOTAL (0.5-16 µm)
Upland Runoff							
Urban	73 %	66 %	80 %	74 %	84 %	31 %	**72 %**
Non-Urban	9 %	8 %	9 %	8 %	9 %	42 %	**9 %**
Stream Channel Erosion	3 %	3 %	4 %	3 %	4 %	17 %	**4 %**
Atmospheric Deposition	15 %	22 %	7 %	14 %	3 %	9 %	**15 %**
Groundwater	NA	NA	NA	NA	NA	NA	**NA**
Shoreline Erosion	< 1 %	< 1 %	< 1 %	< 1 %	< 1 %	1 %	**< 1 %**
TOTAL	**100 %**	**< 100 %**	**100 %**	**< 100 %**	**100 %**	**100 %**	**100 %**

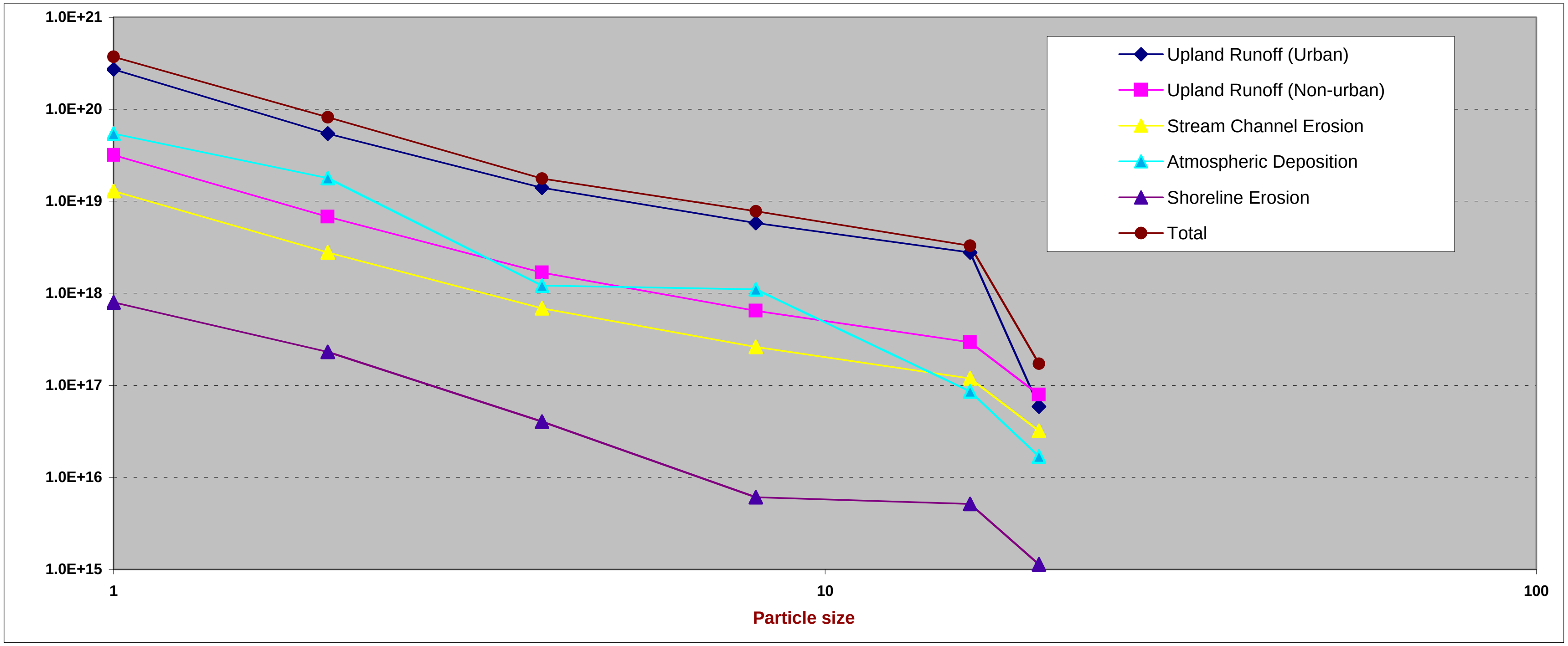

Figure 5-4. Graphic representation of data for average annual particle loading to Lake Tahoe found in Table 5-13 (note the log-log scales).

5.2 Particle Size Distribution as Related to Land-use Characteristics

Section 5.1, above, described the approach taken for particle input to the Lake Clarity Model with the sole purpose to predict the impact of basin-wide loading from the various sources on Secchi depth. During its development, the Lake Clarity Model did not require discrimination of particle loading at the level of specific land-use types.

This section describes the general process used to apportion fine sediment particle loading based on specific land-use characteristics. The approach taken was based on Total Suspended Solids (TSS) loading results from the Lake Tahoe Watershed Model that could be defined on the basis of specific land-use. A series of conversion factors was used to express TSS loading to fine sediment particle loading.

5.2.1 Approach

The primary objective was to characterize the relative magnitudes of pollutant levels among the 20 land-use categories of interest. During calibration to the observed LTIMP values, with scaling factor applied (see Table 4-25), the relative source loading ratios were strictly maintained. The flow chart below highlights the relevant steps in the fine sediment particle number estimation process (Figure 5-5).

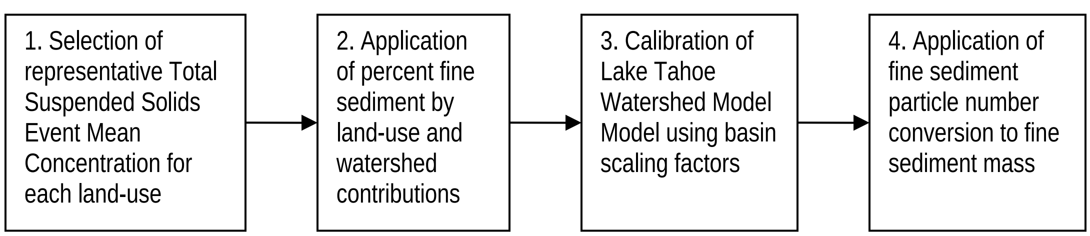

Figure 5-5. Step-wise process to estimate land-use specific particle loading.

Step 1. Total Suspended Solids Event Mean Concentration

The first step used available information to estimate an Event Mean Concentration (EMC) of TSS for overland runoff from the different modeled land-use categories. Section 4.3.5, under the heading of Model Parameterization by Land-use presented the estimated EMCs. For example, the two information sources used to select the primary road EMC was the Caltrans (2003) summary report and a report from the Nevada Department of Transportation (NDOT) and the Desert Research Institute (DRI) looking at highway stormwater runoff and BMP effectiveness on portions of SR 28 and US 50 in Nevada (Jones et al. 2004). Primary roads were assigned an EMC that was the mean of the reported Caltrans (759 mg/L TSS during 2000-2003) and NDOT (827 mg/L TSS during 2002-2004) data, resulting in primary roads being assigned an EMC of 793 mg/L TSS.

Step 2. Particle Size Distribution

The fraction of the TSS comprised of fine sediment (< 63 µm), as mass, was estimated for each urban land-use category using available stormwater monitoring information (Heyvaert et. al 2007). Note that the Lake Tahoe Watershed model used the largest size class as (< 63 µm) since that is the size demarcation of sand. Using primary roads as an example, field monitoring showed that runoff from this source was 85.4 percent of fine sediment. This meant that for every 100 mg of total sediment produced, 85.4 mg were composed of fine sediment < 63 µm. Table 4-24 is a complete list of percent fine sediment by land-use and watershed as applied in the Lake Tahoe Watershed Model. The same urban sediment distribution was applied to all land-uses of the same type in all subwatersheds. The remaining non-urban land-uses were assigned a uniform distribution of fine sediment based on measured in-stream particle size distributions (10 LTIMP streams) and varied by watershed (Simon et al. 2003, Rabidoux 2005).

Step 3. Basin-Wide Factors for Soil Variability and Quadrant

The third step was the development of the basin-wide factors for soil variability and quadrant. These factors calibrated the model to match the loads observed at the LTIMP stream monitoring stations. This step does not affect the relative contribution of each land-use, since they are applied uniformly to the total upland load. Once the model was calibrated, the fine sediment load (mass) was calculated. Section 4.3.5, Water Quality Calibration Process, contains a detailed description of the calibration.

Step 4. Fine Sediment Load to Fine Sediment Particle Number

The modeled output for fine sediment load (mass) from the various land-uses was then multiplied by a particle number conversion factor to estimate the fine sediment particle numbers. A fine sediment-particle converter for each land-use was not developed. Rather, two converters were created, one to represent the urban land-uses and another to represent the non-urban (primarily forest) land-uses.

The notion of a converter is based on a set of assumptions: (1) total suspended sediment in flow is dominated by inorganic soils, (2) the fine sediment particles (< 63 µm) can be characterized by having a density of 2.56 g/cm^3, (3) the particles were spherical in shape, and (4) the distributions of the seven particle size classes between 0.5 – 64 µm used in the Lake Clarity Model followed the distributions presented in Table 5-13. From this approach we can convert from either fine sediment particle number to mass (< 63 µm) or conversely from mass to particle number. The converters for urban load and non-urban load were calibrated by iteratively searching for those particle diameters that provided a match between the reported total mass and total particle numbers for the seven size classes (i.e. 0.5 – 1 µm ….32 – 64 µm) for both urban and non-urban loads as reported in Table 4-66 and Table 5-13.

Output from the fine sediment-particle number converter for urban load is shown in Table 5-15 for the basin-wide values from this generalized land-use category. This converter can also be used to estimate particle load from each of the urban land-uses. Calibration placed the particle diameter values for the last three size classes at the lower end of their range.

Table 5-15. Output from fine sediment mass (< 63 µm) to particle number converter for urban land-uses. The column labeled proportion represents the relative contribution based on mass or weight.

Size range (µm)	Diameter (µm)	Volume (µm^3)	Particles (#)	Weight (MT)	Proportion
0.5 – 1	0.75	0.2	2.71E+20	153	0.033
1 – 2	1.5	1.8	5.42E+19	245	0.053
2 – 4	3	14.1	1.40E+19	505	0.109
4 – 8	4	33.5	5.76E+18	494	0.106
8 – 16	8	268.1	2.79E+18	1913	0.412
16 – 32	16	2144.7	5.91E+16	325	0.070
32 – < 63	32	17157.3	2.30E+16	1010	0.217
		Total	**3.48E+20**	**4645**	**1**

Similarly, output from the fine sediment-particle number converter for non-urban load is shown in Table 5-16 for the basin-wide values from this generalized land-use category. The converter was also used to estimate particle flux from each of the land-uses. Calibration placed the particle diameter value for the last size class near the lower end of its range. For comparison, the ratio of urban fine sediment mass calculated by the converter (4645 metric tons) to that modeled (4430 metric tons; Table 4-66) was very similar at 1.05. For non-urban land-uses this ratio was 1.02 showing that the converter was applicable based on the necessary assumptions.

Table 5-16. Output from fine sediment mass (< 63 µm) to particle number converter for non-urban land-uses. The column labeled proportion represents the relative contribution based on mass or weight.

Size range (µm)	Diameter (µm)	Volume (µm^3)	Particles (#)	Weight (MT)	Proportion
0.5 – 1	0.75	0.2	3.17E+19	18	0.004
1 – 2	1.5	1.8	6.75E+18	31	0.006
2 – 4	3	14.1	1.67E+18	60	0.013
4 – 8	6	113.1	6.44E+17	186	0.039
8 – 16	12	904.8	2.96E+17	684	0.144
16 – 32	24	7238.2	8.01E+16	1484	0.312
32 – < 63	39	31059.4	2.89E+16	2300	0.483
		Total	**4.12E+19**	**4764**	**1**

The following example is provided to explain how the converter operates. A loading value is first portioned by weight into the respective size classes by multiplying the load by the values under the subheading “Proportion” as shown in Table 5-15 and Table 5-16. For instance, 500 metric tons of total urban fine sediment load (< 63 µm) is divided into seven classes based on the proportion, giving you the weight column in Table 5-17.

Table 5-17. Example to illustrate how the urban land-use converter is used if 500 metric tons of fine sediment was generated in a year.

Size range (μm)	Diameter (μm)	Volume (μm³)	Proportion	Weight (MT)
0.5 – 1	0.75	0.2	0.033	16.51
1 – 2	1.5	1.8	0.053	26.40
2 – 4	3	14.1	0.109	54.39
4 – 8	4	33.5	0.106	53.18
8 – 16	8	268.1	0.412	205.93
16 – 32	16	2144.7	0.070	34.93
32 – < 63	32	17157.3	0.217	108.67
		Total	**1**	**500**

The particle number associated with each size class is then calculated as:

$$Weight(MT) \times \frac{1000kg}{MT} \times \frac{1 \times 10^{18}\,\mu m^3}{m^3} \times \frac{m^3}{2560kg} \times \frac{1}{(volume)\mu m^3} = number\_of\_particles$$

Note that the specific density is inverted in the above equation, 2.56 g/cm^3 = 2560 kg/m^3 for inorganic soil (Troeh and Thompson 2005). The next step is then to convert the mass values per size class to the number of fine sediment particles (Table 5-18).

Table 5-18. Urban converter example showing the breakdown of number of fine sediment particles per size class based on a loading value of 500 metric tons.

Size range (μm)	Diameter (μm)	Volume (μm³)	Proportion	Weight (MT)	Particles (#)
0.5 – 1	0.75	0.2	0.033	16.51	2.92E+19
1 – 2	1.5	1.8	0.053	26.40	5.83E+18
2 – 4	3	14.1	0.109	54.39	1.50E+18
4 – 8	4	33.5	0.106	53.18	6.20E+17
8 – 16	8	268.1	0.412	205.93	3.00E+17
16 – 32	16	2144.7	0.070	34.93	6.36E+15
32 – < 63	32	17157.3	0.217	108.67	2.47E+15
		Total	**1**	**500**	**3.746E+19**

Estimated Land-use Specific Particle Loading - Applying the approach described above for particle size distribution as related to specific land-uses and employing the fine sediment to particle flux conversion, the following set of values was produced (Table 5-19). The importance particle loading from the urban regions is highlighted. The slight differences in particle numbers for the urban and non-urban land-uses (Comparison of Table 5-13 and Table 5-19) results from assumptions of the converter.

Table 5-19. Estimated loading of particle number for the combined particle sizes < 63 µm for each specific land-use contained in the Lake Tahoe Watershed Model. Values were determined using TSS output from the model along with the series of conversions described in Section 5.2. These represent basin-wide baseline values over the calibration/validation period of 1994-2004. Under specific land-use heading "P" denotes pervious cover and "I" denotes impervious cover.

Specific Land-use	Urban (U)	Non-Urban (NU)
Residential Single Family (P)	1.54E+19	
Residential Multiple Family (P)	1.34E+19	
Commercial, Industrial, Utility (P)	1.35E+19	
Residential Single Family (I)	1.81E+19	
Residential Multiple Family (I)	2.42E+19	
Commercial, Industrial, Utility (I)	5.07E+19	
Primary Roads	1.10E+20	
Secondary Roads	8.80E+19	
Ski Runs (P)		1.86E+18
Vegetated EP 1		7.02E+16
Vegetated EP 2		2.38E+18
Vegetated EP 3		9.75E+18
Vegetated EP 4		1.85E+19
Vegetated EP 5		2.29E+18
Vegetated Recreational		1.29E+17
Vegetated Burned		NA
Vegetated Timber Harvested		NA
Vegetated Turfgrass		2.52E+16
Unpaved Roads		8.86E+17
TOTAL	**3.33E+20**	**3.59E+19**
GRAND TOTAL (U + NU)	**3.69E+20**	

5.2.2 Comparison of Land-use Based and Lake Clarity Model Fine Sediment Particle Loading

While both the land-used based and Lake Clarity Model particle loading approaches for estimating fine sediment particle loading from the various major pollutant sources share certain similar features, they are not identical and consequently, a comparison is in order. Figure 5-6, Figure 5-7, and Figure 5-8 present the results of this comparison accounting for general land-use categories (urban versus non-urban) and location, and are based on the data used to create Table 5-20. Location was based on the nine major sub-basins as depicted in Figure 5-1. Each sub-basin includes both the stream flow and intervening flow within its boundaries.

The results from the two approaches were similar for both total particle load from urban and non-urban land-uses at the watershed level, and for the sub-basins. The relative percent difference for total particle loading between the TSS + Converter and the Lake Clarity Model particle input approaches was minimal at 8.9 percent, 2.1 percent and 7.5 percent for urban, non-urban and total combined categories, respectively. When analyzed at the sub-basin level, sub-basin 3000 had the largest difference between the two approaches for urban and total combined. Sub-basin 4000 showed the widest variation for the non-urban category. Since particle loading from the urban land-uses dominated, the variation in the non-urban values was of minimal consequence.

In conclusion, the importance of fine sediment particles (< 16 µm) to water clarity conditions in Lake Tahoe comes from recent scientific findings. The pollutant budget developed for the loading of these particles from atmospheric deposition and a wide range of watershed sources is unique to the literature. The Lake Tahoe scientific community is at the early stages of developing a more detailed knowledge base on this subject. Using the criteria for defining levels of confidence for pollutant loading estimates, fine sediment particle loading fell primarily into the medium category (see Table 4-66).

A medium level of confidence is descibed as:

> *Estimates based on reliable field data or modeling supported by field data; however, the supporting database is either not extensive and/or comprehensive. Primarily non peer-reviewed studies exist for the Tahoe basin to support data. Weight of evidence provided by independent studies for Lake Tahoe is limited. Additional studies, conducted within an adaptive management framework, will likely improve our understanding but not likely change broad-based management strategy.*

This section presented how particle numbers were determined for each of the major sources and how they were developed for use in lake clarity and watershed modeling efforts. New research is in progress within the Tahoe basin to better understand specific source, transport and fate of fine sediment particles for the purpose of informing management decisions related to source control and water quality treatment.

Table 5-20. Comparison of particle loading based on the approach used for the Lake Clarity Model (LCM) (Section 5.1) and the approach using the TSS output from the Lake Tahoe Watershed Model in conjunction with the 'converter' (TSS plus Converter)(Section 5.2). Data expressed as number of fine sediment particles < 16 µm.

	TSS plus Converter	LCM Input	TSS plus Converter	LCM Input	TSS plus Converter	LCM Input
Sub-Basin	**Urban**	**Urban**	**Non-urban**	**Non-urban**	**Total**	**Total**
1000	7.4E+19	6.2E+19	2.3E+18	4.6E+18	7.6E+19	6.6E+19
2000	8.8E+18	5.2E+18	5.8E+17	2.0E+18	9.4E+18	7.2E+18
3000	2.0E+18	3.6E+19	3.7E+17	1.3E+18	2.3E+18	3.7E+19
4000	2.6E+19	5.2E+19	2.3E+16	7.1E+17	2.6E+19	5.3E+19
5000	7.5E+19	4.7E+19	5.9E+18	2.0E+19	8.1E+19	6.7E+19
6000	3.0E+19	2.3E+19	2.6E+18	1.0E+19	3.3E+19	3.3E+19

7000	2.8E+19	2.1E+19	1.7E+19	3.3E+18	4.5E+19	2.4E+19
8000	4.2E+19	2.0E+19	1.6E+19	2.9E+18	5.8E+19	2.3E+19
9000	4.5E+19	9.1E+19	4.0E+18	3.1E+18	4.9E+19	9.4E+19
TOTAL	**3.3E+20**	**3.6E+20**	**4.8E+19**	**4.9E+19**	**3.8E+20**	**4.1E+20**

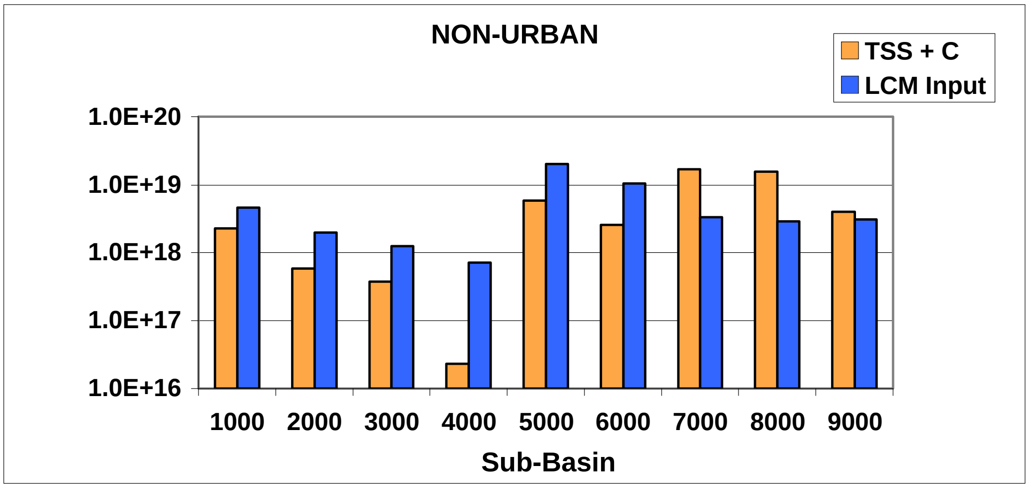

Figure 5-6. Comparison of fine particle estimations from land-use based (TSS + Converter (C)) and Lake Clarity Model (LCM) particle loading by sub-basin for the non-urban loads.

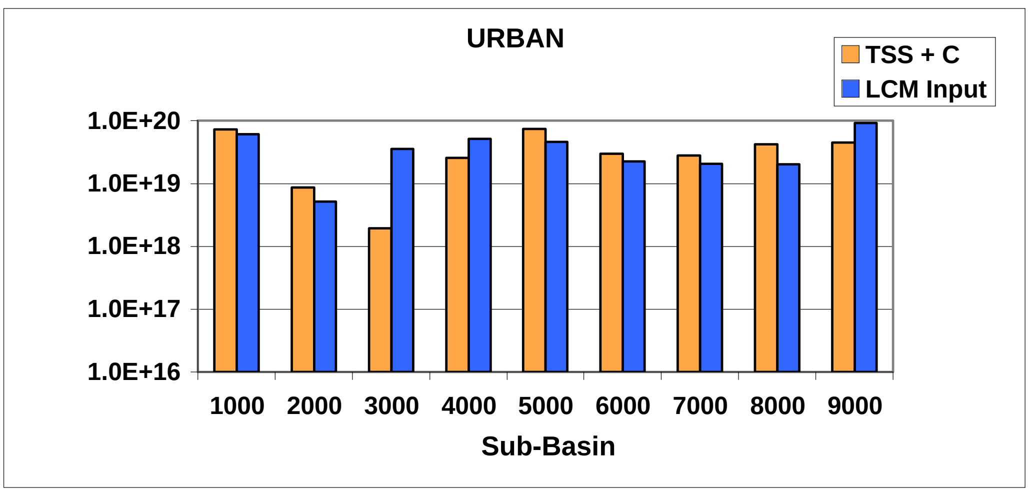

Figure 5-7. Comparison of fine particle estimations from land-use based (TSS + Converter (C)) and Lake Clarity Model (LCM) particle loading by sub-basin for the urban loads.

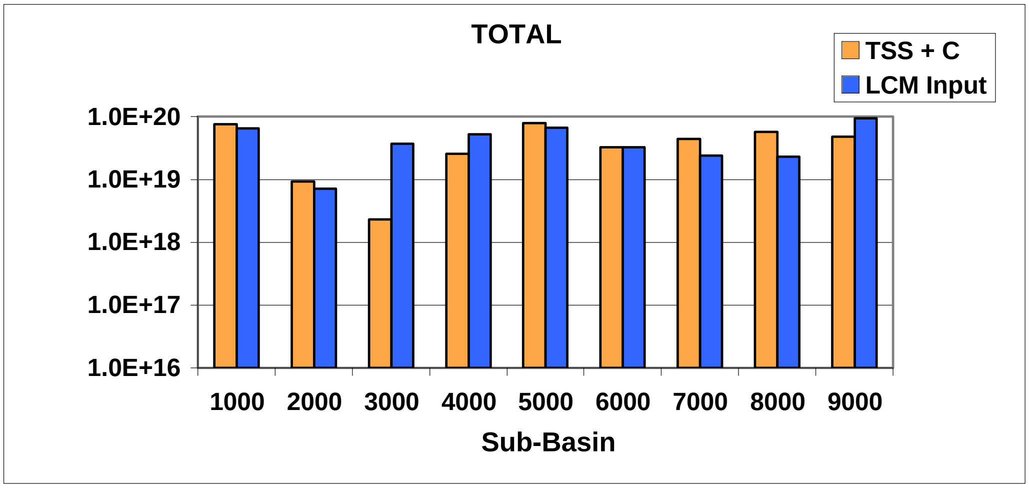

Figure 5-8. Comparison of fine particle estimations from land-use based (TSS + Converter (C)) and Lake Clarity Model (LCM) particle loading by sub-basin for the total loads.

6 Linkage of Pollutant Loading to In-Lake Effects

Detailed information on the amount of loading and the timing of delivery for nutrients and fine sediment particles entering the lake is needed to evaluate the effects of these pollutants on lake clarity. For this TMDL, two different types of models were necessary to simulate the cause and effect relationship between pollutant loadings and lake clarity in Lake Tahoe. The Lake Tahoe Watershed Model was used to address the generation of pollutant loads over the land surface and through groundwater contributions, as well as to predict the resulting impact on stream water quality (Tetra Tech 2007). A separate receiving water model (Lake Clarity Model) was necessary to simulate conditions in Lake Tahoe itself (Perez-Losada 2001, Swift 2004, Sahoo et al. 2007).

Similar to watershed models, receiving water models are composed of a series of algorithms used to simulate flow/currents and water quality in a waterbody. These models vary from simple 1-dimensional models to complex 3-dimensional models capable of simulating water movement, salinity, temperature, sediment transport, biology, and water quality. Many lake and watershed models have been developed for lake management purposes. These models often yield satisfactory results on one lake, but are not effective on others. The failure of particular models is believed to include insufficient understanding of the contributions of nutrients from internal and external sources, and the dynamics of physical, biological and chemical interactions in a lake (Riley and Stefan 1988). Given the unique features of Lake Tahoe and its oligotrophic nature, it was determined that a customized model that focused on Secchi depth was needed (Reuter et al. 1996).

To better understand and provide scientific guidance for the improvement of Lake Tahoe's clarity, the UC Davis Dynamic Lake Model (DLM) coupled with the Water Quality Model (DLM-WQ) was further developed and used to create the UC Davis Lake Clarity Model. The Lake Clarity Model is a complex system of sub-models including the hydrodynamic sub-model, ecological sub-model, water quality sub-model, particle sub-model and optical sub-model. The conceptual design of the Lake Clarity Model for Lake Tahoe is shown in Figure 6-1.

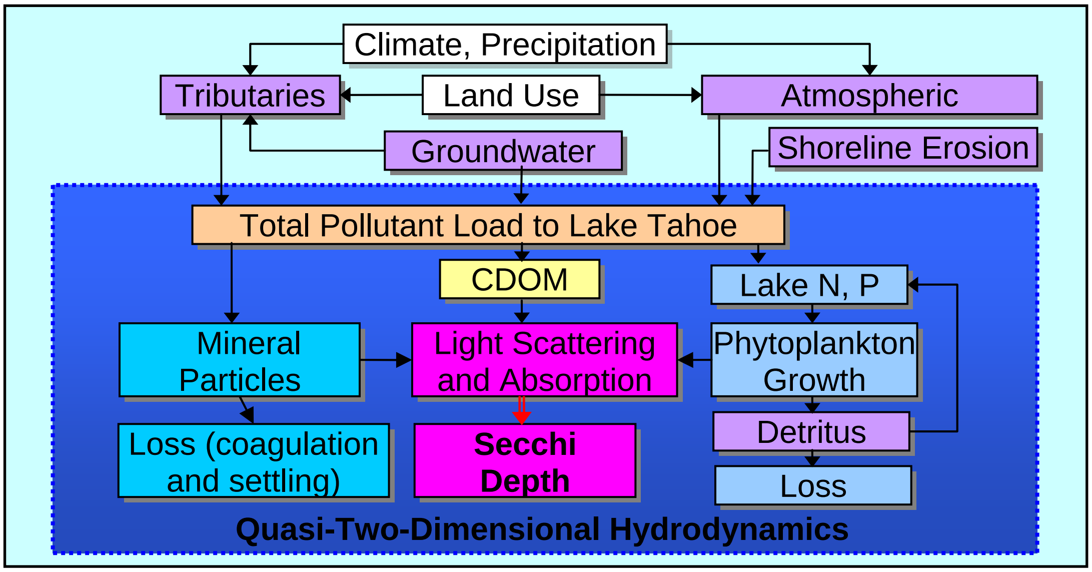

Figure 6-1. Schematic of Lake Clarity Model.

All the sub-models are shown inside the shaded box in the middle of Figure 6-1. The pollutant sources and amounts of inorganic particle and nutrient loading from atmospheric deposition, tributaries with various land-uses (urban and non-urban), shoreline erosion and groundwater (nutrients only) are shown on top as data inputs. The optical sub-model estimates Secchi depth based on scattering and absorption characteristics of particles, algae, colored dissolved organic matter (CDOM), and water itself.

The hydrodynamic component of the Lake Clarity Model is based on the original Dynamic Reservoir Model (DYRESM) (Imberger and Patterson 1981). Lindenschmidt and Hamblin (1997) reported that DYRESM has already tested its widespread applicability to a range of lake sizes and types. Hamilton and Schladow (1997) combined the ecological sub-model and water quality sub-model that described the numerical description of phytoplankton production, nutrient cycling, the oxygen budget, and particle dynamics with the DYRESM model. Schladow and Hamilton (1997) also demonstrated the applicability of the DLM-WQ model for a mesotrophic reservoir of Australia. The model has further been modified by Fleenor (2001), Perez-Losada (2001), and Swift (2004). The optical sub-model (Swift 2004, Swift et al. 2006) is incorporated to estimate Secchi depth. The model has been further refined between 2005 and 2007 as part of the Lake Tahoe TMDL science effort.

Due to the inherent complexity of natural environmental systems, an exact agreement between simulated data points and observed data points is not expected (Spear 1997). The limited number of measurements that are available give a coarse representation of an ecosystem subject to strong spatial-temporal fluctuations, while the model simulates the evolution of representative variables under idealized conditions. As a consequence, the modeling task in this study was focused on reproducing the seasonal and longer-term patterns and trends of phytoplankton biomass (chlorophyll *a*), inorganic particle concentrations, nutrient concentrations, and Secchi depth.

The main objectives of this effort were to:

- calibrate and validate the seasonal physical and chemical changes in Lake Tahoe using the available input data,
- estimate the Secchi depth based on the input data,
- assess the particle and nutrient load reduction from various sources including atmospheric deposition, runoff erosion, bank erosion and shoreline erosion,
- examine the effects of input data on Secchi depth,
- examine the effects of input load reduction on Secchi depth, and
- generate guidelines for lake clarity management and improvement.

6.1 Required Inputs to the Lake Clarity Model

Input data to the Lake Clarity Model include daily weather data, daily stream inflow and lake outflow, lake morphometry, lake physical data, boundary conditions, initial conditions of the water column, physical model parameters, water quality boundary conditions and water quality parameters. Required weather data include daily total short wave radiation, incoming long wave radiation, precipitation, daily average wind speed, air temperature and humidity. The daily flow volumes and physical, chemical, and biological characteristics of inflows to the lake and daily outflow volumes are required. In addition, the Lake Clarity Model requires atmospheric deposition, shoreline erosion and groundwater flux as well as the in-lake profile data for the starting day of simulation is needed.

6.1.1 Meteorological Data

Meteorological activity is the driving force for lake internal heating, cooling, mixing, circulation, which in turn affect nutrient cycling, food-web characteristics and other important features of Lake Tahoe's limnology. Required daily meteorological data for the Lake Clarity Model include solar short wave radiation (KJ/m^2/day), incoming long wave radiation (KJ/m^2/day) or a surrogate such as fraction of cloud cover, air temperature (^{o}C), vapor pressure (mbar) or relative humidity (%), wind speed (m/s at 10 meters above the ground surface) and precipitation (mm, 24-hour total). Data from 1994 and 2004 were collected at the meteorological station near Tahoe City (SNOTEL gages maintained by the NRCS). The hourly recorded data were then further averaged or integrated as necessary to obtain daily values.

6.1.2 Stream Temperature Data

The Model also required additional calibration for water temperature in un-monitored streams so that depth of insertion for each river into Lake Tahoe could be estimated. The USGS measured stream water temperature as part of the LTIMP program. Data are available for four streams: Upper Truckee (09/18/1997-09/29/2002), Trout (09/18/1997–09/29/2002), Incline (04/08/1998 09/29/2002), Glenbrook (4/8/1998-9/29/2002) and Blackwood (5/30/2003–8/9/2003).

A sub-routine, Artificial Neural Network, was developed to estimate water temperature based solely on solar radiation and air temperature (Sahoo et al. 2007). The estimated and measured data demonstrated a very high degree of agreement with R^2-values ranging from 0.89–0.97. Based on these results, water temperature for the ungaged streams was modeled for the period 1994-2004 using solar radiation and air temperature data from the modeled streams based on physical proximity.

6.1.3 Lake Data

Numerous in-lake samples are taken at different depths on a regular basis by UC Davis-TERC (unpublished). These samples include measurements of: temperature, chlorophyll, dissolved oxygen, dissolved phosphorus, total reactive phosphorus, total hydrolysable phosphorus, total phsophorus, nitrate, ammonia, Kjeldahl nitrogen and concentrations of seven classes of particles are collected. These samples are taken at two lake stations: 1) the mid-lake station in the deeper part of the lake (460 meters deep) and 2) the index station along the west shore (150 meters deep). A comparison of the data from the index and mid-lake stations revealed that the water quality variables exhibit the same patterns of variation but with somewhat of a time lag (Jassby et al. 1999). Assuming horizontal homogeneity, water samples collected at the mid-lake station were used as representative of the average conditions of the lake.

6.1.4 Particle Loading

Refer to Chapter 5 for a full presentation of how particle size distribution was used as an input to the Lake Clarity Model.

6.1.5 Nutrient Loading

Streamflow

The Lake Tahoe basin contains 63 watersheds (Rowe et al. 2002). Mapping by the U.S. Geological Survey (Jorgensen et al. 1978) shows that in addition to the 63 identified watersheds, numerous intervening zones defined as areas between adjacent watersheds that would contribute runoff to the lake as both surface and subsurface flow but have no defined stream channel (Thodal 1997). The Truckee River is the lake’s only outflow draining north through the City of Reno on its way to its terminus in Pyramid lake. Flow and water quality of ten streams (e.g., Upper Truckee, Ward Creek, Trout Creek, Third Creek, Logan House Creek, Incline Creek, Glenbrook Creek, General Creek, Edgewood Creek and Blackwood Creek) are regularly monitored as part of the Lake Tahoe Interagency Monitoring Program (Boughton et al. 1997). These tributaries are estimated to account for up to 50-55 percent of the total stream input.

Records of continuous flow, temperature and water quality data from the LTIMP program exist on an event basis with sampling frequency on the order of 25-30 times per year (e.g. Rowe et al. 2002). The Lake Tahoe Watershed Model was used to generate the time series stream nutrient inputs required for Lake Clarity Model.

Tetra Tech (2007) calibrated the Lake Tahoe Watershed Model using measured nutrient data from the 10 LTIMP streams based on (1) the seasonal trends, (2) nutrient species distribution and loading patterns, (3) organic and inorganic nutrient quantities, and (4) nutrient mass associated with sediment/particulate matter. Land-use nutrient loading rates, based on characteristic EMCs, were used to estimate nutrient load from the unmonitored streams. Based on the available LTIMP data, the calibrated daily nutrients available to Lake Clarity Model from the Lake Tahoe Watershed Model include ammonia (NH_4^+), nitrate (NO_3^-), total nitrogen (TN), soluble reactive phosphorus (SRP), and total phosphorus (TP).

The Lake Clarity Model requires information on nutrient speciation instead of total nitrogen or phosphorus. According to the Coats and Goldman (2001) nutrient analysis on the 10 LTIMP streams, the discharge-weighted concentration of organic nitrogen was typically 10 times that of inorganic nitrogen. Particulate organic nitrogen (PON) ranged 22 to 81 percent of total organic nitrogen (TON) and the percentage of PON varied among streams. Analyzing the average DON fraction of TON of the 10 LTIMP streams, the average contribution of PON and DON was found to be 44 and 56 percent of TON, respectively. Similarly, Hatch et al. (2001) found that the average contribution of DOP and POP were 8 and 92 percent of the TOP, respectively. These percentage values were applied to total organic phosphorus or nitrogen to estimate particulate and dissolved phosphorus or nitrogen of each stream. The subdaily time step used in Lake Clarity Model estimate nitrogen or phosphorus loading at each time step as (daily nitrogen or phosphorus concentration) $\times$ (seconds of each time step)/86,400.

A focused research effort was conducted at Lake Tahoe to direct measure bioavailable phosphorus (BAP) (Ferguson 2005; Ferguson and Qualls 2005). For streams, the SRP, DOP and POP that contributed to BAP were set to 95, 15 and 36 percent, respectively. For intervening zones which include mostly urban areas the percentage of SRP, DOP and POP transformed to BAP were set to 95, 15, and 50, respectively. It was assumed that 100% of total dissolved inorganic nitrogen (NH_4 and NO_3) is bio-available. Bio-available nitrogen from PON and DON was determined by calibration. The value was found to be 75 percent. Few studies have directly measured bioavailable; however, the Lake Clarity Model calibrated value was similar to 59 percent value reported by Seitzinger et al. (2002) in urban/suburban runoff.

Urban Runoff

The land-uses considered as sources for urban upland loading are defined as part of the Lake Tahoe Watershed Model development. The urban land-use layer for the Lake Tahoe Watershed Model was based on two primary sources of spatial data: (1) an updated parcel boundaries layer from a number of agencies comprising the Tahoe basin GIS User's Group and (2) a detailed one-square-meter resolution Hard Impervious Cover (HIC) layer that was developed using remote sensing techniques from IKONOS satellite imagery (Minor and Cablk 2004). Values include both the pervious and impervious portions for each land-use. The specific land-uses considered under the urban classification (with percent distribution for entire Lake Tahoe basin) include, single family residential (4.9 percent), multiple family residences (1.3 percent), commercial/institutional/communications/utilities (1.3 percent), primary and secondary paved roads (1.6 percent). The upland runoff loads were separated into urban and non-urban source areas based on the percentage of flows coming from the respective areas. Flow percentage values were provided by Tetra Tech (2007). The distinction between urban and non-urban loading was possible since the Lake Tahoe Watershed Model was able to separate urban from non-urban flow.

Stream Channel Erosion

The total phosphorus content in stream channel material collected from the LTIMP streams (except Logan House) was directly measured by Ferguson 2005 and Ferguson and Qualls 2005. These results ranged from 0.075-0.199 mg total phosphorus/mg sediment with a mean of 0.153 µg total phosphorus/mg sediment and a 95 percent confidence interval of 0.096-0.197. This mean value was applied to all streams and was multiplied by sediment load from channel erosion to obtain phosphorus loading. For the purpose of this evaluation, it was assumed that nitrogen loading from stream channel erosion was negligible and that most of the nitrogen load occurred either via surface runoff or seepage through the stream channel. Additionally, the particulate forms of nitrogen associated with stream channel sediments are considered the least bioavailable.

In the present study 50 percent of total stream channel erosion is considered as urban.

Atmospheric Deposition

Annual estimates of wet and dry deposition directly to the surface of Lake Tahoe are provided in Section 4.5.4 for nitrogen and phosphorus. Table 6-1, Table 6-2, and Table 6-3 provide values for nutrient atmospheric deposition used in the Lake Clarity Model.

Table 6-1. Estimation of wet deposition of nutrients on Lake Tahoe. Total wet days in 2003 (Winter (Jan-Mar) = 18, Spring (April-June) = 13, Summer (July-Sep) = 7, Fall (Oct-Dec) = 18) is 56 (Source: Scott Hackley and John Reuter, UCD-TERC).

Nutrients[a]	Average annual load over lake (metric tons)	Number of Precipitation Days >0.1 inch	mg/m^2/precipitation day for Lake Clarity Model
NO_3	18	56	0.6898
NH_4	17	56	0.6515
DIN	35	56	
DON	22	56	0.8293
TON	24	56	
PON	2	56	0.0904
TN	59	56	2.2610
SRP	1.0	56	0.03832
TDP	1.8	56	
POP	1.0	56	0.03832
DOP	0.8	56	0.03066

TP	2.8	56	0.10730

[a]Species in bold are used in the Lake Clarity Model.

Table 6-2. Estimate for dry deposition of nitrogen directly to the surface of Lake Tahoe.

Nutrients[a]	Average seasonal/annual nutrient load on Lake Tahoe (metric tons)				
	Winter	Spring	Summer	Fall	Annual
NO_3	6	5	9	8	28
NH_4	18	15	21	23	77
DIN	24	20	28	33	105
DON	13	8	6	4	32
TON	15	10	8	6	38
PON	2	1	1	2	6
TN	39	30	36	39	143
Nutrients[a]	**Average seasonal/annual nutrient load on Lake Tahoe ($mg/m^2/day$)**				
	Winter	**Spring**	**Summer**	**Fall**	**Annual**
NO_3	0.17884	0.13757	0.22723	0.23201	0.19447
NH_4	0.53652	0.41270	0.53020	0.66702	0.53478
DON	0.40060	0.22891	0.15593	0.12041	0.22286
PON	0.04650	0.03247	0.03595	0.04489	0.03967
TN	1.16245	0.81165	0.89882	1.12233	0.99177

[a]Species in bold are used in the Lake Clarity Model.

Table 6-3. Estimate for dry deposition of phosphorus directly to the surface of Lake Tahoe.

Nutrients[a]	Average seasonal/annual nutrient load on Lake Tahoe (metric tons)		
	Winter	Summer	Annual
SRP	0.5	0.8	1.3
TDP	0.9	1.5	2.4
TP	2.1	3.2	5.4
Nutrients[a]	**Average seasonal/annual nutrient load on Lake Tahoe ($mg/m^2/day$)**		
	Winter	**Summer**	**Annual**
SRP	0.00593	0.01341	0.00903
POP	0.01423	0.02850	0.02100
DOP	0.00474	0.01174	0.00747
TP	0.02490	0.05365	0.03750

[a]Species in bold are used in the Lake Clarity Model.

5.1.4.5 Shoreline Erosion

Adams and Minor (2002) estimated that approximately 117 metric tons (approximately 2 metric tons/year) of phosphorous and 110 metric tons (approximately 2 metric tons/year) of nitrogen has been eroded into the lake from shorezone since 1938. Because the nutrient loading is very small compared to other sources, nutrient loadings from shorezone erosion were not considered in this study.

5.1.4.6 Groundwater

The values of groundwater discharge and nutrient loading to Lake Tahoe reported in USACE (2003) are used in this study. According to that study the seasonal variation of groundwater nutrient loading of all species of nitrogen and phosphorus is not significant. However, evaluation showed that nitrogen concentrations of shallow groundwater (less than 15 meters) were 2 to 5 times higher than those of deep groundwater (greater than

15 meters). The difference in nitrate concentrations from deep to shallow aquifers was the most apparent. It is expected that anthropogenic sources would have a more profound effect on the shallow aquifer. This is shown by the lower percentage concentration of nitrate coming from ambient sources. Phosphorus, on the other hand, showed no statistical difference in the shallow versus deep aquifer ($p > 0.5$).

In another study, Thodal (1997) estimated that the groundwater contribution is 11.4 percent of the annual stream and direct runoff. Also, Thodal (1997) estimated that the mean concentration of total nitrogen and total phosphorus are 1.0 mg/L and 0.074 mg/L, respectively. NO_3 (including nitrite) is the predominant form (85%), followed by dissolved organic nitrogen DON (10%) and ammonia NH4 (5%). On the other hand, phosphorus concentration is more balanced; orthophosphate form (assumed to go to the SRP pool) is 55 percent compared to the organic form (42%) that are assumed to be simulated POP. Thodal's estimates are found to be close to the values estimated by USACE (2003).

A summary of the ranges for groundwater discharge, nutrient loading to Lake Tahoe and average nutrient concentration by region are provided in Table 4-5 in Section 4.1 (USACE 2003). Nitrogen loading in the shallow aquifer is assumed to be three times higher than the deep aquifer. Moreover, because all estimated data are for aquifers of depth less than 110 meters depth, the values are applied only to lake layers 110 meters from the surface. The phosphorus input to the lake is assumed equal at all depths. However, the nitrogen input to the lake is 3 times higher at depth 0 to 15 meters than at depths 15 meters to 110 meters.

6.2 Calibration and Validation

6.2.1 Justification and Application to the Lake Clarity Model

In the purest sense and assuming a complete understanding of all processes involved, a physical model would not need calibration. However, measurement error associated with input data, and analysis and estimation uncertainty requires that a calibration be performed. Moreover, the underlying physical processes are very complex, and their mathematical descriptions are approximations. The error (direct or cumulative) produced in the model prediction is minimized by calibration. Using the calibrated values, the model is validated using an independent data set. Calibration is an ongoing process, since it is unrealistic to think that the error can be reduced to zero. Also, parameters calibrated to represent one process may no longer fit as well when combined with other calibrated processes. Therefore, models typically keep some parameters that have been tuned aggressively but within reasonable limits, while others are kept constant so that the number of parameters to be calibrated is reduced.

In the present study, the optical model parameters (Table 6-4) were calibrated by Swift et al. (2006). Those authors optimized the parameters of the optical sub-model using the measured lake profile data and comparing the measured Secchi depths with estimated Secchi depths. For the hydrodynamic sub-model, the temporal and spatial process descriptions are fundamentally correct and without error, therefore it is basically free from calibration (Hamilton and Schladow 1997). Moreover, the hydrodynamic model has been successfully applied to a large number of lakes and reservoirs (e.g. Schladow and Hamilton 1997, Lindenschmidt and Hamblin 1997). There are not sufficient zooplankton data to completely calibrate the zooplankton model parameters. Consequently, the zooplankton model parameters were chosen as described in the literature (Table A-1). Therefore, only the water quality and ecological sub-models needed to be calibrated as part of this study. All input values have some measurement error and estimation of inputs based on regression equations (e.g., stream particle estimation, stream nutrients estimation) results in some uncertainty in the input. Therefore calibration and validation is conducted to adjust the model parameters so that the predicted values will approximate measured values. In general, the calibration and validation process is the most significant tool for reducing uncertainty. According to Klemes (1986) and Jayatilaka et al. (1998), a model should be validated for need and the types of applications for which it is intended.

Table 6-4. Parameters of optical sub-model used in the Lake Clarity Model (Swift et al. 2006).

Symbols	Descriptions	Units	Value	Source
Γ	Coupling constant	-	8.7	Fixed (1)
a_w	Pure water absorption	m^{-1}	0.012	Fixed (2), Measured (8)
b_w	Pure water scattering	m^{-1}	0.0027	Fixed (4)
a^*_{chl}	Chlorophyll-specific absorption	$m^2\ mg^{-1}$	0.025	Measured (3)
b^*_{chl}	Chlorophyll-specific absorption	$m^2\ mg^{-0.62}$	0.105	Calibrate (7)
a_{CDOM}	CDOM absorption	m^{-1}	0.038	Measured (8)
μ_0	Sun angle effect on K_d	-	Variable	Estimated
b^*_{ip1}	Scattering for particle size (0.5 – 1.0 μm)	m^2 particle^{-1}	4.287×10^{-12}	Fixed (6)
b^*_{ip2}	"…" (1.0 – 2.0 μm)	m^2 particle^{-1}	3.015×10^{-11}	Fixed
b^*_{ip3}	"…" (2.0 – 4.0 μm)	m^2 particle^{-1}	9.939×10^{-11}	Fixed
b^*_{ip4}	"…" (4.0 – 8.0 μm)	m^2 particle^{-1}	3.757×10^{-10}	Fixed
b^*_{ip5}	"…" 8.0 – 16.0 μm)	m^2 particle^{-1}	1.459×10^{-9}	Fixed
b^*_{ip6}	"…" (16.0 – 32.0 μm)	m^2 particle^{-1}	5.831×10^{-9}	Fixed
b^*_{ip7}	"…" (32.0 – 63.0 μm)	m^2 particle^{-1}	0	Fixed
r	Conversion factor for Chlorophyll to particles	# mg^{-1}	5.6×10^{9}	Calibrated (8)

[1]Preisendorfer (1986), Gordon and Wouters (1978)
[2]Pope and Fry (1997)
[3]Particulate absorption measured following Mitchell (1990)
[4]Morel and Prieur (1977)
[5]Kirk (1994)

[6]Davies-Colley et al. (1993), Tassan and Ferrari (1995)
[7]Calibration guided by Morel (1987, 1994), Kirk (1994)
[8]Swift et al. (2006)

The optical sub-model estimates the Secchi depth from the concentration of phytoplankton, inert particles of seven arrays and dissolved colored organic matters present in the lake water. The water quality sub-model is largely focused on phytoplankton which is primarily controlled by is nutrients, light and zooplankton. To estimate the Secchi depth correctly, all inputs and parameters of sub-models should be optimized so that the estimated (modeled) output approximates the field measurements.

Table 6-5 summarizes the range of values taken as the limits for the model parameters; these are based on cited values in the literature. Whenever possible, the model parameters were calibrated within these ranges. However, the characteristics of every aquatic system are different. As discussed above, Lake Tahoe is a subalpine and oligotrophic lake that never freezes; therefore some of the parameters available in the literature may not be ideal. In cases where these types of model parameters do not contribute to a good match with the measured values (after many combinations with other parameters), a value higher or lower than the limits in Table 6-5 was assumed.

Table 6-5. Model parameters implemented in the Lake Clarity Model.

Parameter	Symbol	Range Min/Max[a]	Model Value	Units	Ref.
Phytoplankton					
Maximum growth rate	G_{max}	0.58-2.5	1.5	d^{-1}	1
Maximum respiratory rate	k_r	0.005-0.20	0.007	d^{-1}	2
Maximum mortality rate	k_m	0.003-0.17	0.003	d^{-1}	3
Temperature multiplier for growth/respiration/death	θ	1.0-1.14	1.13	n. d.	4
Light saturation	I_s	50-500	51.0	$\mu E\ m^{-2}\ s^{-1}$	5,12
Temperature for optimum growth	T_{opt}		5.6	^oC	
Affect of temperature below T_{opt}	CT_1	0.004± 50%	0.002	$^oC^{-2}$	21,22
Affect of temperature above T_{opt}	CT_2	0.004± 50%	0.002	$^oC^{-2}$	21,22
Reference temperature for phytoplankton metabolism	T_{ref}		20	^oC	21
Effect of temperature on phytoplankton metabolism	CT_m	0.046-0.069	0.069	$^oC^{-1}$	21,22
Light Extinction					
Light attenuation of pure water		Optical Model		m^{-1}	19
Specific extinction coefficient of Chlorophyll *a* (mg/L)		Optical Model		m^{-1}	19
Specific extinction coefficient Particles (#/m^3)		Optical Model		m^{-1}	19
Nutrient Utilization					
Phosphorus to chlorophyll mass ratio	a_p	0.27-1.0	0.55	$\mu g\ \mu gChla^{-1}$	6
Nitrogen to chlorophyll mass ratio	a_n	5.0-15.0	10.0	$\mu g\ \mu gChla^{-1}$	6
Settling					
Setting velocity for phytoplankton	v_s	0.01-1.0	0.08	$m\ d^{-1}$	7,8,23
Setting velocity for detritus POP & PON	v_{det}	0.028-0.062	0.045	$m\ d^{-1}$	20

Parameter	Symbol	Range Min/Max[a]	Model Value	Units	Ref.
Phytoplankton transfer function	T_{phy}	$5.6\times10^9 \pm 50\%$	5.6×10^9	# $mgChla^{-1}$	19
Bio-Chemical Reactions					
Biological oxygen demand of sub-euphotic sediments	k_{bio}	0.02-15.0	0.02	$mg\ m^{-2}\ d^{-1}$	12
Decomposition rate of BOD	k_{bod}	0.005-0.05	0.005	d^{-1}	12
Half saturation constant efficiency of DO on de-nitrification	k_{den}	0.01± 50%	0.01	$mg\ m^{-3}$	13
Half saturation constant for N nutrient limitation	$k_{(NO3+NH4)}$	20-400	20	$\mu g l^{-1}$	16
Half saturation constant for P nutrient limitation	k_{SRP}	1 - 5	1.5	$\mu g l^{-1}$	15
Half saturation constant for Ammonia preferential uptake factor	k_{NH4}	20.0 - 120.0	20.0	$\mu g l^{-1}$	17
Half saturation constant for limitation of reactions by DO for nitrification	k_{nit}	0.5 or 2	0.5	$ml_{O2}\ l^{-1}$	12
Half saturation constant for limitation of reactions by DO for biochemical oxygen demand	k_{do}	0.5 ± 50%	0.5	$ml_{O2}\ l^{-1}$	12
Half saturation constant for limitation of reactions by DO for sediment processes	k_{sdo}	3.0 ± 50%	3.0	$ml_{O2}\ l^{-1}$	12
Density of BOD for settling	ρ_{BOD}	1040 ± 25%	1025	Kgm^{-3}	12
Nutrient Temperature Multipliers					
Nitrification	θ_{NO}	1.02-1.14	1.13	n. d.	18
Organic decomposition	θ_o	1.02-1.14	1.13	n. d.	18
Biological and chemical sediment oxygen demand	θ_{BOD}	1.02-1.14	1.13	n. d.	12
Sediment Fluxes					
Release rate of phosphorus SRP	r_{SRP}	0.0-0.05 0.005± 50%	0.000	$\mu g\ m^{-2}\ d^{-1}$	12
Release rate of nitrogen NH4	r_{NH4}	0.0-0.05 0.05± 50%	0.000	$\mu g\ m^{-2}\ d^{-1}$	12
Temperature multiplier for sediment nutrient release	θ_S	1.02-1.14	1.13	n. d.	12
Zooplankton Parameters					
Table A-1					
Particles					
Density of 7 particle size groups	ρ	2650± 25%	2600, 2100**	Kgm^{-3}	
Coagulation rate	*coag*	0.001 – 0.1	0.015	-	24, 25

[a] The ranges are estimates for composite phytoplankton ensembles.

** 2600 kg/m^3 for particle sizes 0.5μm to 4 μm and 2100 kg/m^3 for particle sizes > 4 μm

References: [1] Bowie et al. (1985) Table 6-5, [2] Bowie et al. (1985) Table 6-18, [3] Bowie et al. (1985) Table 6-20, [4] Chapra (1997) Fig-2.11, [5] Chapra (1997), [6] Bowie et al. (1985) Table 6-4, [7] Marjanovic (1989) Table-16, pg. 326, [8] Jassby personal communication (2003), [9] Bowie et al. (1985) Table 6-19, [10] Hunter et al. (1990), [11] Hunter personal communication (2003), [12] Schladow & Hamilton (1997), [13] Bowie et al. (1985) Table 5-3, [14] Bowie et al. (1985) Table 5-4, [15] Eppley et al. (1969), [16] Chapra (1997) Table 33.1, [17] Bowie et al. (1985) Table 5-5, [18] Chapra (1997) p 40, [19] Swift et al. (2006), [20] Reuter and Miller (2000) [21] Arhonditsis and Brett (2005) [22] Omlin et al. (2001a,b), [23] Romero et al. (2004), [24] O'Melia and Bowman (1984), [25] Casamitjana and Schladow (1993)

6.2.2 Calibration and Validation Results

Water Temperature

There is a three-year measured data set (2000-2002) from Lake Tahoe for water temperature, chlorophyll *a*, NO_3^-, NH_4^+, Secchi depth and particle size distribution and concentration. Therefore, the model was calibrated and validated using the data from 2000 to 2002. The available Lake Tahoe Watershed Model estimated stream inputs and directly measured weather data are distributed over time; however, atmospheric load, groundwater load and shoreline erosion data are the same for all the years. The LTADS atmospheric deposition study only collected a complete dataset for one year, while the shoreline erosion study reported an annual average value over a 60-year period of record. Omlin et al. (2001b) reported that the ecology in reality is more complex; however, the ecological model is simplified by necessity. For these reasons, there may not be an excellent match with the measured data for all cases.

A time series of vertical temperature profiles for the year 2000 are shown in Figure 6-2 and shows that simulated temperatures closely matched measured temperature records.

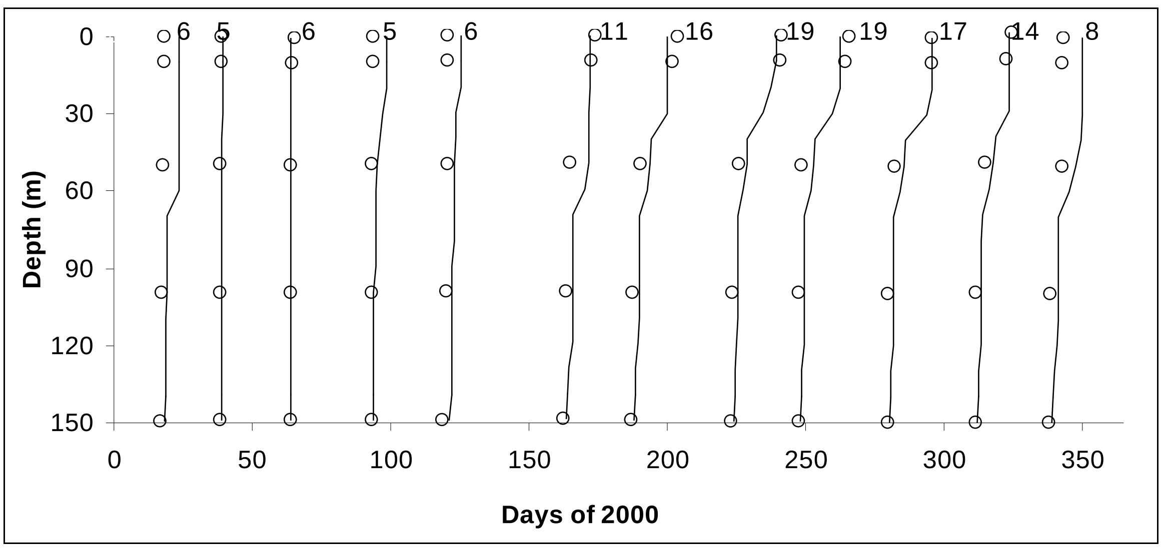

Figure 6-2. Temporal vertical variations of thermal structure for year 2000. Numbers associated with each vertical profile denote the measured surface temperature. Temperature at 150 meter deep from surface is around 5 ^{o}C. The hollow circles are the measured data points at 0 meter, 10 meters, 50 meters, 100 meters and 150 meters deep from the surface and the line represents the simulated.

Using the same input dataset and calibrated parameters used for the year 2000, the simulation was carried out for 2001 to 2002 for validation, again with simulated temperature compared with measured records. The time series-depth profiles (Figure 6-3) show that the simulated temperature values were again close to measured values. This indicates that the Lake Clarity Model simulates lake dynamics.

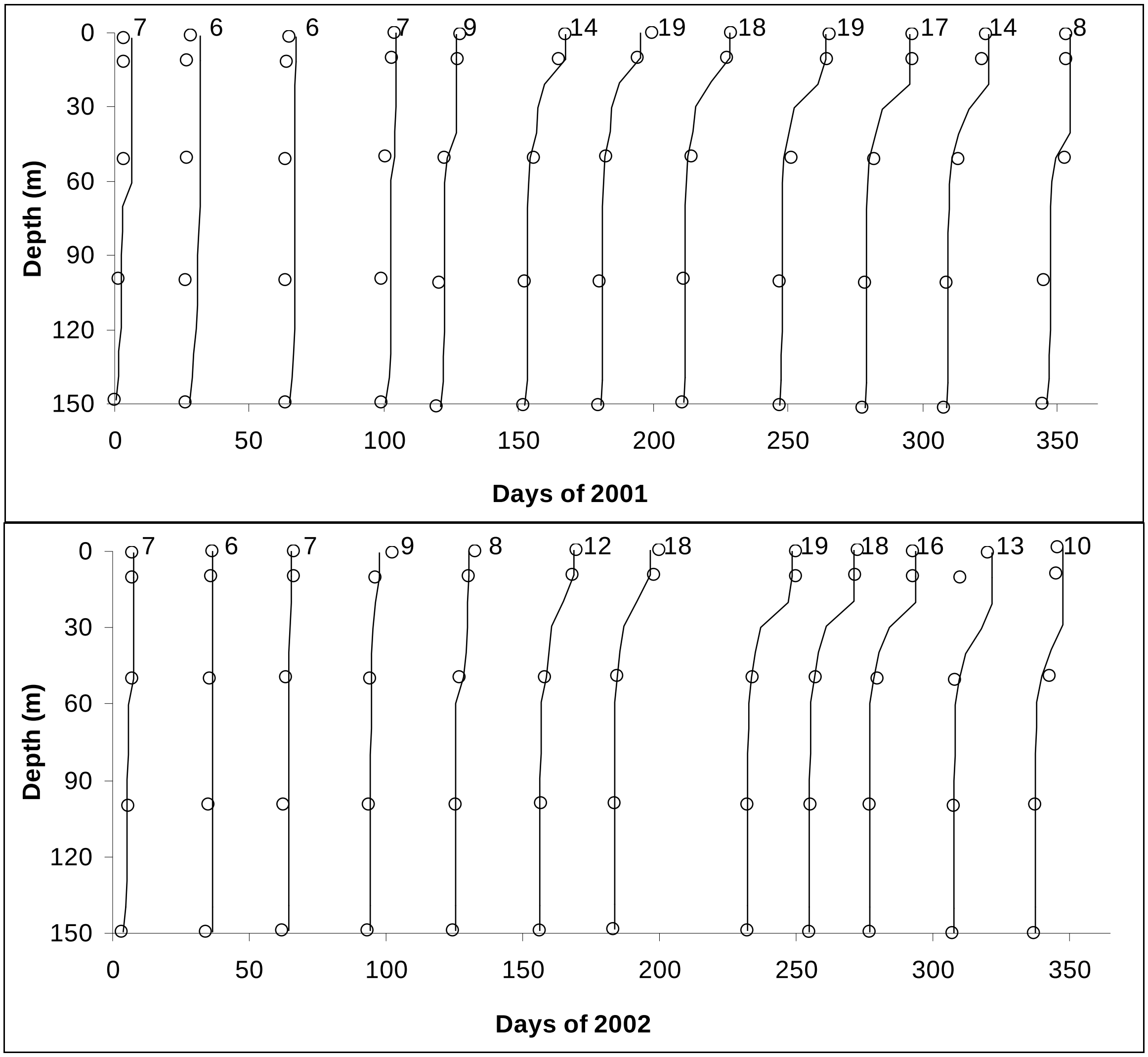

Figure 6-3. Temporal variations of thermal structure over two years (2001-2002). Numbers denote the measured surface temperature. Temperature at 150 meters deep from surface is around 5 ^{o}C. The hollow circles are the measured data points at 0 meter, 10 meters, 50 meters, 100 meters and 150 meters deep from the surface and the line represents the simulated temperature.

Chlorophyll *a*, Nitrogen, and Phosphorus

The simulated concentrations of chlorophyll *a*, nitrate and an estimate of biologically available phosphorus are shown in Figure 6-4 to Figure 6-6. Further details appear in Sahoo et al. (2007). It is evident that the Lake Clarity Model captures the trend of chlorophyll *a* and nitrate concentrations. It is a distinguishing feature in Lake Tahoe that the chlorophyll maximum concentration is seen at approximately 50 meters below the water surface. Moreover, the maximum chlorophyll *a* concentration is found to be bimodal within a year; i.e., summer maximum (approximately 50 meters below the surface) and winter maximum (0 to 30 meters from the surface). The development of deep chlorophyll *a* maximum generally occur in deep, well illuminated lakes and are a function of higher nutrient availability in the hypolimnion and the ability of the represented algal populations to achieve maximum growth under low light conditions

(Wetzel 2001). This supports the use of a lower saturated light intensity as a modeling parameter. Moreover, it is seen that the chlorophyll *a* concentration exists longer in the lake suggesting that the mortality rate is low. Taken together, these results suggest that the Lake Clarity Model simulates algal growth and phytoplankton biomass accrual (Figure 6-4).

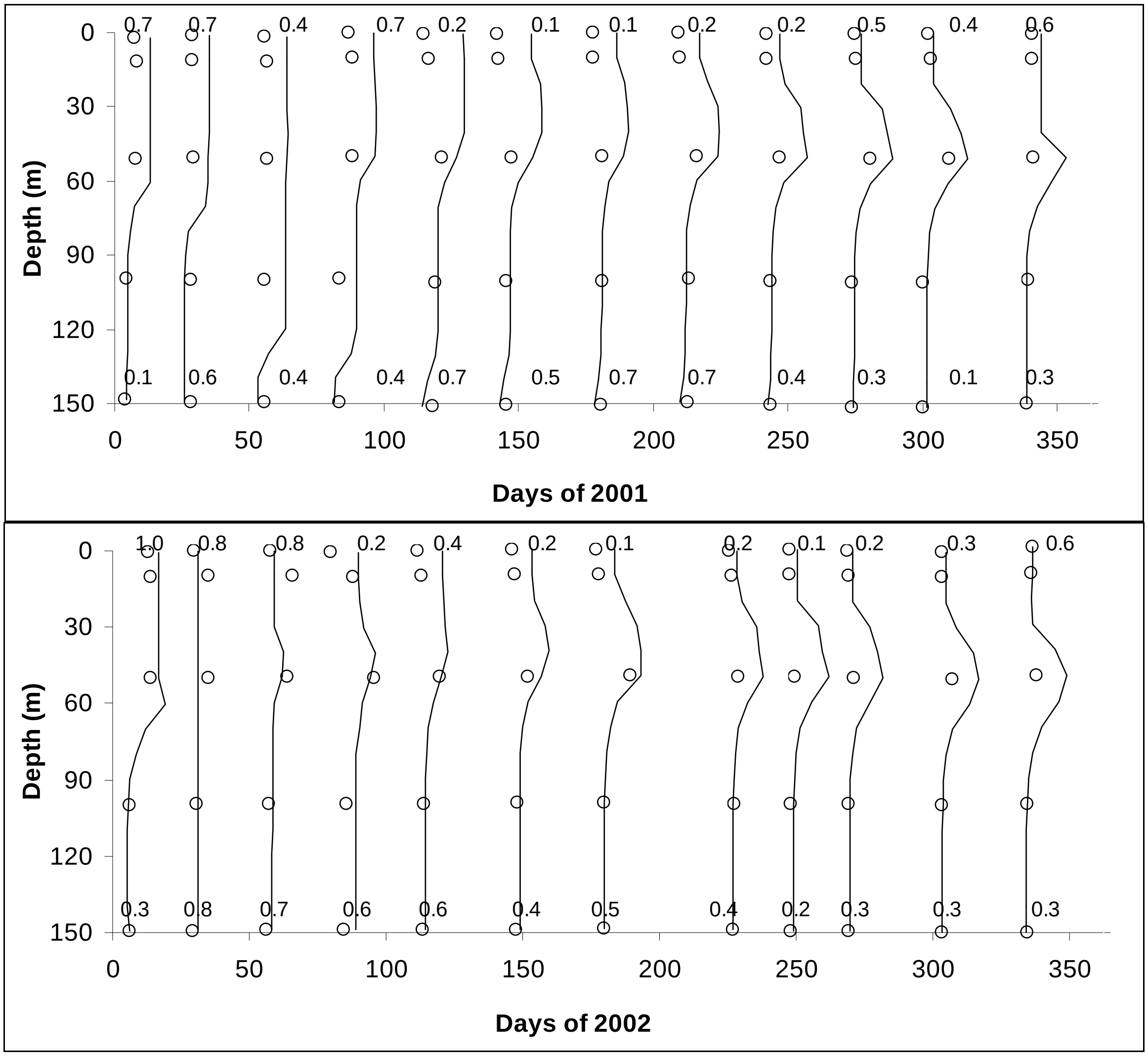

Figure 6-4. Temporal variations of chlorophyll *a* concentration over two years (2001-2002) (validation). Numbers denote the measured chlorophyll *a* concentration at surface and at depth 150 meters from surface. The hollow circles are the measured data points at 0 meter, 10 meters, 50 meters, 100 meters and 150 meters deep from the surface and the line represents the simulated chlorophyll *a* concentration.

Measured concentrations of nitrate in the upper waters during the summer are typically lower than in the deep-water (> 100 meters). This is because phytoplankton uptake of nitrate reduces the concentrations in this zone of algal growth. However, nitrate concentrations during winter are higher as a result of deep mixing, which returns waters of higher concentrations to the surface. During lake stratification in the late spring – early winter, nitrate builds up in the deeper hypolimnetic waters due to microbial cycling of dead organic nitrogen that settles in the water column. The depth of mixing can be determined by the dynamics of the 'nitracline', which is a well established seasonal pattern in Lake Tahoe (Paerl et al. 1975). Figure 6-5 demonstrates the ability of the Lake Clarity Model to simulate nitrate concentrations and seasonal dynamics.

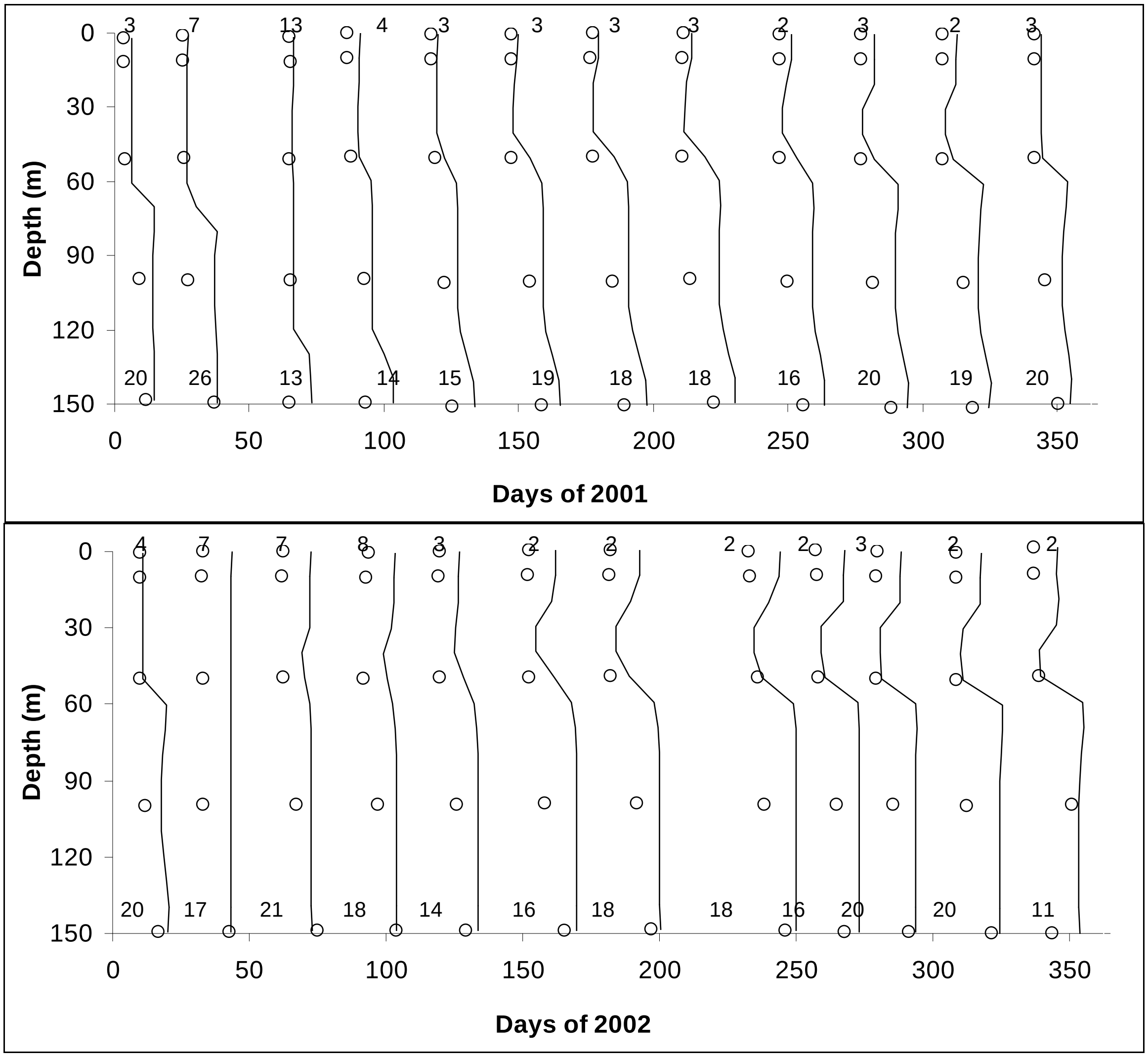

Figure 6-5. Temporal variations of nitrate concentration over two years (2001-2002) (validation). Numbers denote the measured nitrate concentration at surface and at depth 150 meters from surface. The hollow circles are the measured data points at 0 meter, 10 meters, 50 meters, 100 meters and 150 meters deep from the surface and the line represents the simulated nitrate concentration.

While the simulated nitrate concentration is found to be close to the measured values, the simulated BAP deviated somewhat from the measured values during the validation runs (Figure 6-6). However, it was found that the simulated BAP was low where the chlorophyll concentration is high, supporting the importance of algal uptake in nutrient distribution. When considering the degree of similarity between measured and simulated values for BAP it is critical to note the following points. First, the total range of measured BAP in the water column typically occurred within the very narrow boundary of < 1 – 2.7 µg/L. The range of simulated concentrations was in a very similar range of <

1 – < 2 µg/L. This is at the analytical limit of detection (Janik et al. 1990). It has long been recognized that in nutrient-poor water bodies, the residence time of orthophosphate (BAP) can be as low as minutes (i.e., very rapid biological utilization) (Lean 1973). Consequently, in a system with such low orthophosphate, it may be asking too much of this type of model to accurately simulate the very small and rapid changes in concentration. Given that changes in orthophosphate concentrations are in the < 1 µg/L scale, the 1 µg/L analytical limit of detection limits us from detecting subtle levels of variation in the water column. It is encouraging that the measured and modeled concentrations overlap. Measurement of orthophosphate at < 1 µg/L concentrations calls for initiation of a state-of-the-art, research level analytical chemistry program. Also note that the initial experimental algorithms developed for bioavailable phosphorus by Ferguson (2005) are used in this study. A comprehensive research effort on phosphorus cycling in Lake Tahoe would be required to significantly reduce uncertainty.

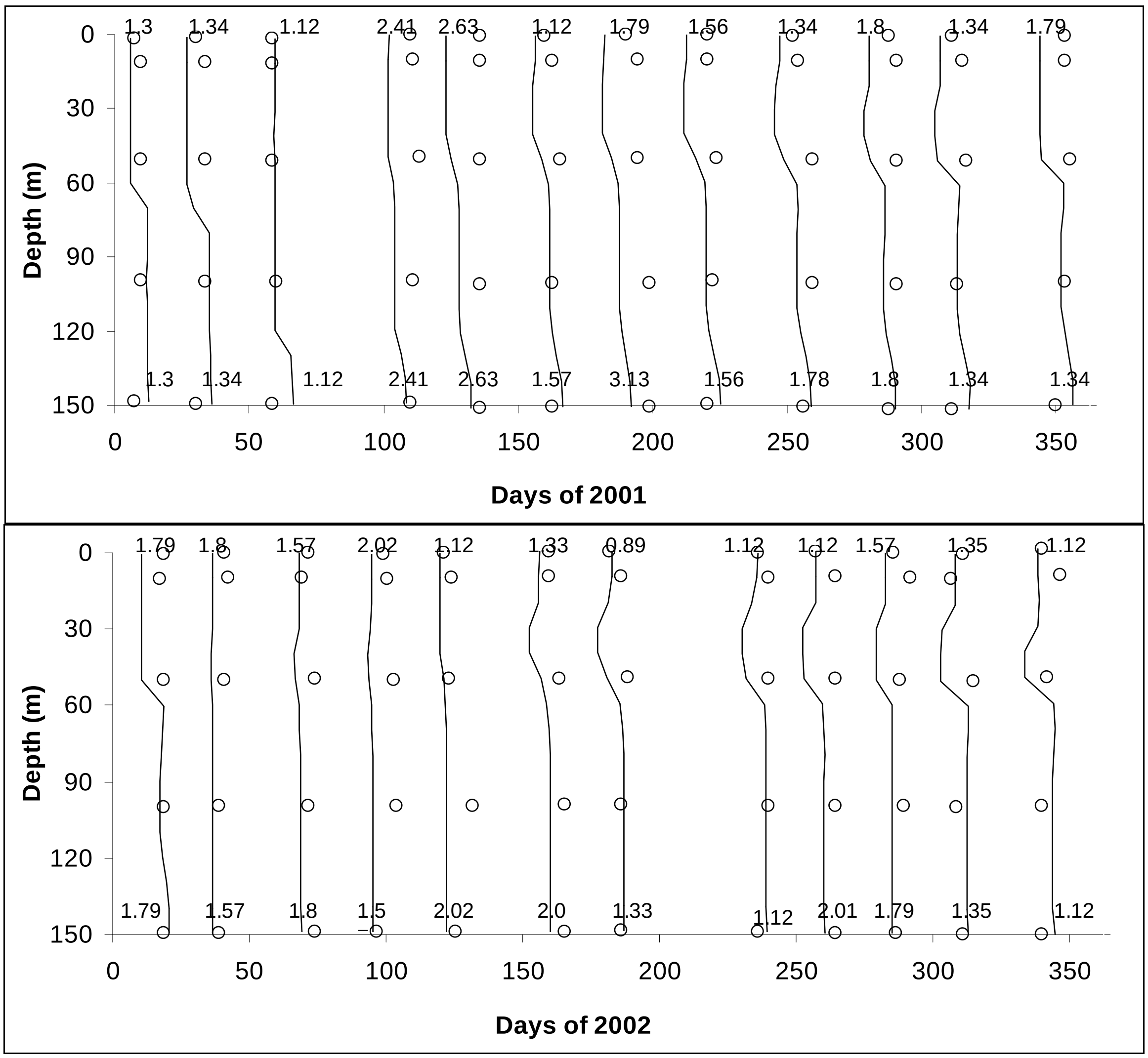

Figure 6-6. Temporal variations of bioavailable phosphorus concentration (expressed as orthophosphate or PO_4^{-3}) over two years (2001-2002) (validation). Numbers denote the measured orthophosphate concentration at surface and at a depth of 150 meters from the surface. The

hollow circles are the measured data points at 0 meter, 10 meters, 50 meters, 100 meters and 150 meters deep from the surface and the line represents the simulated nitrate concentration.

Secchi Depth

Finally, the simulated Secchi depths are compared with each of the measured Secchi depth values in Figure 6-7. In total, 157 field measurements were made in the five-year period (2000 to 2004). The annual average Secchi depths are compared in Table 6-6. These results show that the simulated Secchi depth very closely follow the trend of measured Secchi depths. The error in annual average Secchi depth was typically less than 8 percent except in 2000. Data on phytoplankton primary productivity showed that in 2000, an unusually shallow (15 to 20 meters) maximum occurred during March and April (UC Davis - TERC unpublished). In addition, major upwelling events during January and February 2000 brought up nutrients and possible fine particles from the deeper waters and contributed to the lower Secchi depth record during March, April, and May of 2000. The monthly average Secchi depth of March and April for 2000 rank as the shallowest on record compared to the March/April monthly averages for all other years (1968-2006). For this reason, simulated Secchi depth of year 2000 was found to be higher than measured Secchi depth. As stated earlier, it is not possible to simulate each individual measurement with absolute accuracy because of the complexity of the system and the time averaged inputs. Moreover atmospheric and groundwater loads are assumed to be the same for all years. With all these limitations, the Lake Clarity Model was able to simulate most of the seasonal trends over the five-year period. Since regulatory decisions are based on the annual average, it was particularly gratifying to see the high level of agreement between simulated and measured observations at this scale.

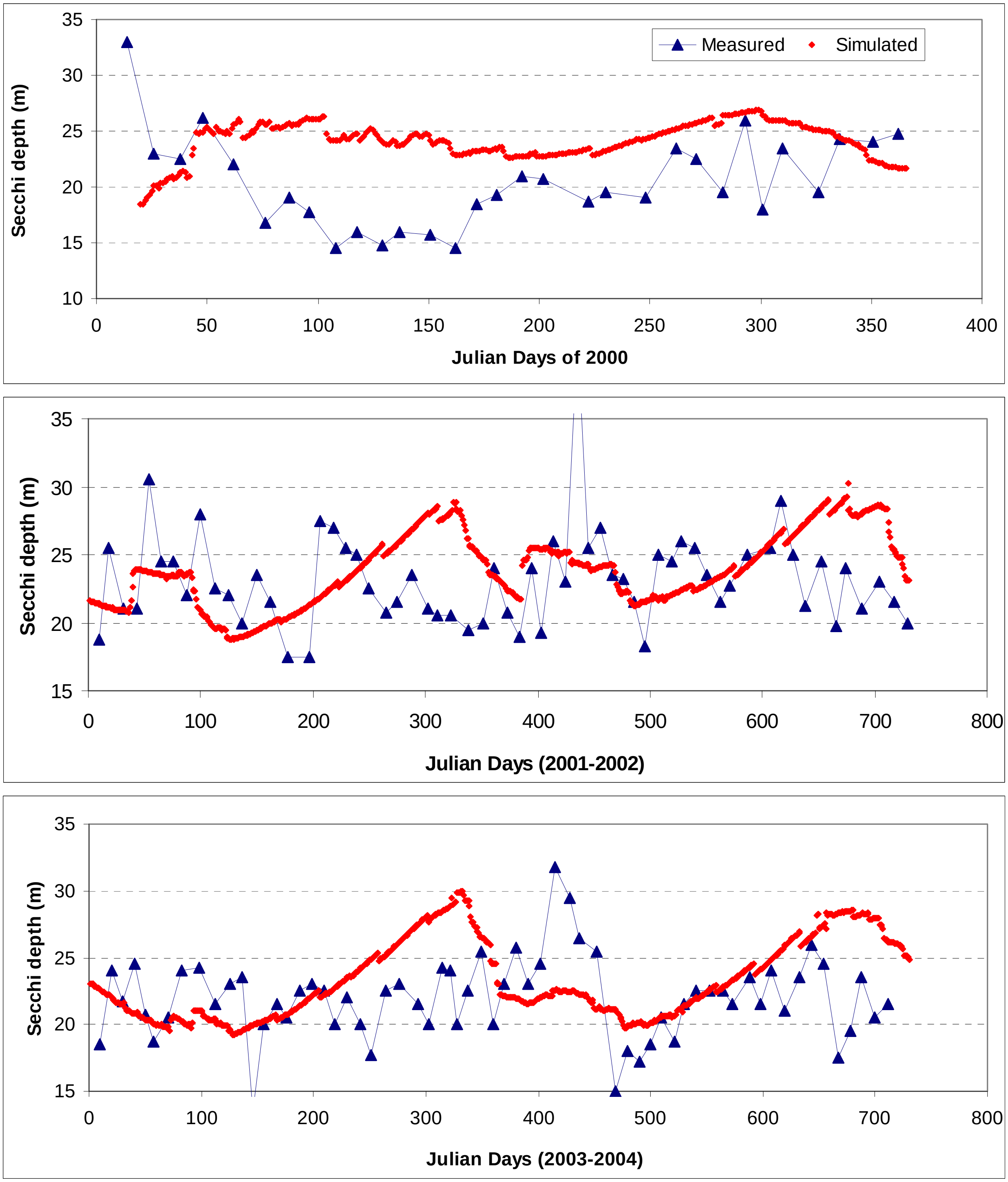

Figure 6-7. Comparison of measured and simulated Secchi depth for 2000-2004.

Table 6-6. Comparison of annual average Secchi depths.

Year	Measured Secchi Depth (meters)	Simulated Secchi Depth (meters)	Difference (meters)	Difference (%)
2000	20.452	23.785	-3.250	-15.827
2001	22.633	23.130	-0.689	-3.072
2002	23.758	23.885	-0.103	-0.432
2003	21.561	23.263	-1.638	-7.574
2004	22.403	23.942	-1.519	-6.776

6.3 Sensitivity and Uncertainty Analysis

To ensure that the model parameters and inputs values have been optimized, a sensitivity analysis was conducted by increasing and decreasing the input values/model parameters and observing the model results.

6.3.1 Model Parameters

Global sensitivity analysis identifies which of the model parameters/inputs has the largest effect on the model and, therefore, predicted Secchi depth. Representative parameters were selected in this analysis. In the current analysis, model parameters are changed to be 50 percent higher or lower than the calibrated values. This value was selected for sensitivity analysis so that changes in model output could be more easily detected if changes occurred.

Effect of Particle Settling Rate

The settling velocity of the particle is assumed to follow Stokes' equation:

$$w_k = \frac{g(\rho_p - \rho)}{18\mu} d_k^2 \qquad \textbf{Equation 4}$$

Where:

The subscript k (k = 1, 2, …, 7) = the particle size class
w_k = the settling velocity of particles of size k
μ = the absolute viscosity
ρ_p = the density of the particle
ρ = the density of water
d_k = the projected diameter of particle after coagulations

The 50 percent higher or lower particle settling rate of diameter d_k, is the $1.5 \times w_k$ or $0.5 \times w_k$, respectively. Since the projected particle diameter of each particle is different, the settling rate is also different. Therefore, the multiplication factor (1.5 or 0.5) is applied to each settling rate and the Lake Clarity Model predicted Secchi depth is shown in Figure 6-8. As expected, the predicted Secchi depth increased when the particle settling rate increases to 1.5 times more. Figure 6-8 also demonstrates that the

Secchi depth decreases continuously if the particle settling rate is reduced by half. However, it can be seen that there is a larger change in Secchi depth when the settling rate is 50 percent lower than when the settling rate is made 50 percent higher. In the case of a lower settling rate, light attenuation values of surface layers increase and higher temperatures in the photic zone produce more algae. This resulted with a higher rate of change of Secchi depth in the case of a lower particle settling rate.

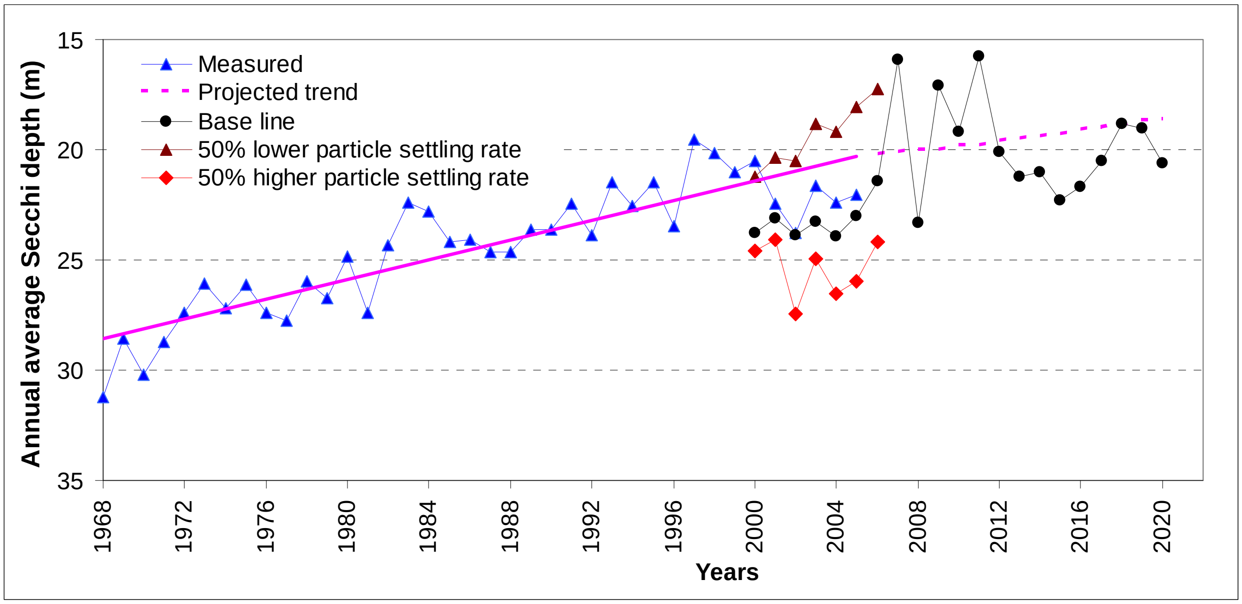

Figure 6-8. Estimated Secchi depths for ± 50 percent change of particle settling rate.

Effect of Phytoplankton Growth Rate

The concentration of phytoplankton is a function of growth rate, concentration of nutrients, light intensity, mortality rate and grazing rate. The growth rate was varied to determine the affect on simulated Secchi depth.

The phytoplankton concentration changes as the maximum growth rate changes. The change of estimated Secchi depth based on the change in ± 50 percent change of growth rate is presented in Figure 6-9. It shows that the rate of change of Secchi depth at a 50 percent lower growth rate is higher than the rate of change of Secchi depth at a 50 percent higher growth rate. The phytoplankton concentration measured in terms of chlorophyll *a* decreases to minimum level (i.e. 0.2 μg/L) after 6 years when the growth rate is decreased 50 percent. On the other hand, the phytoplankton concentration does not significantly increase for 50 percent higher growth rate because the overall phytoplankton growth depends on other factors such as nutrient concentration, light intensity, mortality rate and grazing rate. Mortality and grazing rate is higher for higher phytoplankton concentration. In addition, when the concentration of phytoplankton increases, more nutrients are consumed. Therefore, the available nutrients for growth in the next time step are reduced. This reduction of nutrients restricts phytoplankton growth. Consequently, simply increasing the growth rate does not significantly increase the phytoplankton concentration.

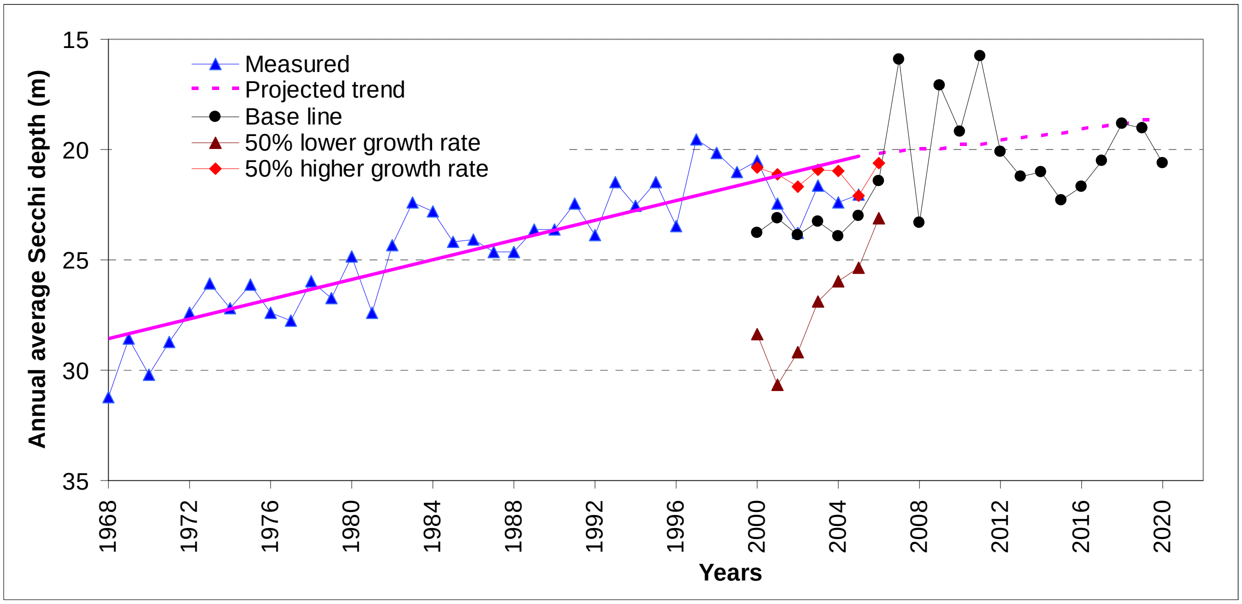

Figure 6-9. Estimated Secchi depths for ± 50 percent change of phytoplankton maximum growth rate.

Effect of Saturated Light Intensity

As mentioned above, phytoplankton concentration is in part a function of light intensity. While the effect of a 50 percent increase and 50 percent decrease of saturated light intensity were not identical, the results were much more similar than those observed for phytoplankton growth rate (Figure 6-10).

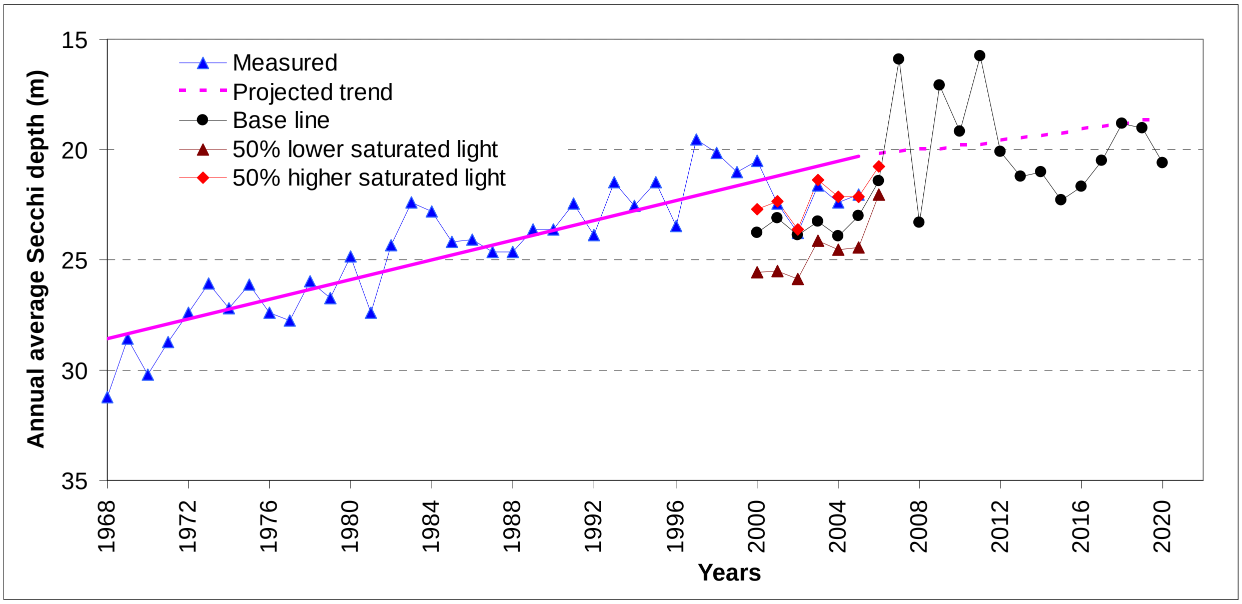

Figure 6-10. Estimated Secchi depth for ± 50 percent change of saturated light intensity.

Effect of Chlorophyll-Specific Absorption Parameter (a^*)

Swift et al. (2006) performed global sensitivity analysis that identified the parameters having the largest effect on the estimation of Secchi depth. Note that Swift et al. (2006) carried out the sensitivity analysis using the measured particle and phytoplankton concentrations. The a^* parameter, a coefficient that accounts for the absorption of light by phytoplankton, and used in the optical sub-model was varied ± 50 percent relative to the calibrated values. As expected, the estimated Secchi depth for the 50 percent higher a^* values decreases the clarity, on the other hand, the estimated Secchi depth for the 50 percent lower a^* values increases the lake clarity (Figure 6-11). However, in both cases, the rate of change in Secchi depth is only less than 1 – 3 meters, as reported by Swift et al. (2006).

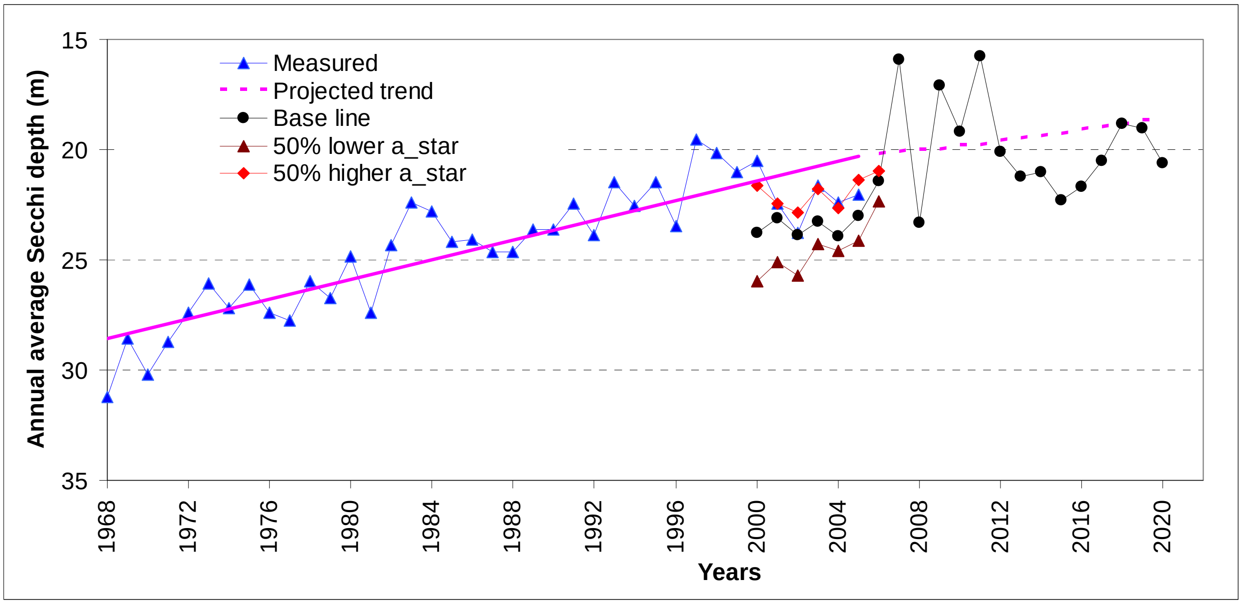

Figure 6-11. Estimated Secchi depths for ± 50 percent change of the a* (a_star) calibrated value.

6.3.2 Load Assumptions

While the Lake Tahoe Watershed Model was developed with LSPC based on varying hydrologic conditions each year, only single annual loading values were available for groundwater and atmospheric deposition, which were used in repetitive years (i.e., the same value for each modeled year). Sensitivity analysis was performed on those loads to determine the potential impacts of year-to-year differences in loading.

Effect of Fine Particle Loads

As discussed elsewhere in this report, fine particles, especially those in the 0.5 − 16 µm size range, have a significant affect on Lake Tahoe clarity. Consequently, a sensitivity analysis was conducted to evaluate how modeled Secchi depth would change if the particle loading estimates currently used as model input data were not accurate estimates of actual loading estimates. While a large effort was made to use values that indeed reflect actual loading, this analysis allows us to see the sensitivity of the Lake Clarity Model to hypothetical changes in particle loads.

The 1X category represents the loading currently used in the model; 0.1X and 0.5X hypothesize that the actual loading is less than estimated, while the 2X category hypothesizes that the current particle loading underestimates actual loading.

The results of this sensitivity analysis (Table 6-7) show that a change in estimated particle loading from the urban area produces the largest variation in modeled Secchi depth. This is because the vast majority of particles entering Lake Tahoe come from urban land-uses. If particle loading estimates were under-estimated or over-estimated by a factor of two, the modeled Secchi depth would change by approximately 3 meters. For the remaining major pollutant sources (i.e. atmospheric deposition, non-urban watershed, stream channel erosion and shoreline erosion) the corresponding change in modeled Secchi depth, for the same variability in loading estimates, would be less than 1 meter.

Table 6-7. Sensitivity of Lake Clarity Model to changes in fine particle loading from the major source categories. The values associated with the 1X row represents the modeled Secchi depth for baseline conditions using current estimates of particle loading. 0.1X and 0.5X represent conditions where the actual particle loading is assumed to be 90 percent and 50 percent lower than the current estimates, respectively. Similarly, the 2X category represents a condition where the actual particle loading is twice the current estimate.

Fine Particle Loading	Annual Average Secchi Depth (meters) over the 17 Years Simulation Runs				
	Atmosphere	Urban	Non-urban	Stream Channel erosion	Shoreline erosion
0.1X	22.5	26.0	21.5	20.8	20.9
0.5X	21.2	23.3	21.0	21.1	21.0
1X	20.5	20.5	20.5	20.5	20.5
2.X	20.1	17.2	20.2	20.6	20.4

Effect of Groundwater Loads

Groundwater contributes 12.8, 14.2 and 0 percent total nitrogen, total phosphorus and fine sediment loads, respectively, to Lake Tahoe. The estimated Secchi depth was examined assuming a ± 50 percent change in groundwater input conditions. Note that this is a large change but was done to clearly see an effect if one was indicated. Figure 6-12 shows that the Lake Clarity Model was largely insensitive to the variations of groundwater input. The main reasons of the model insensitivity to groundwater input is: (1) there is no fine sediment load from the groundwater, (2) the groundwater contribution is low and (3) the input load is distributed to the water column of 110 meters, thus, the groundwater load to the deep chlorophyll *a* maximum (40-60 meters) and phytoplankton biomass within the 0-30 meters Secchi depth is reduced.

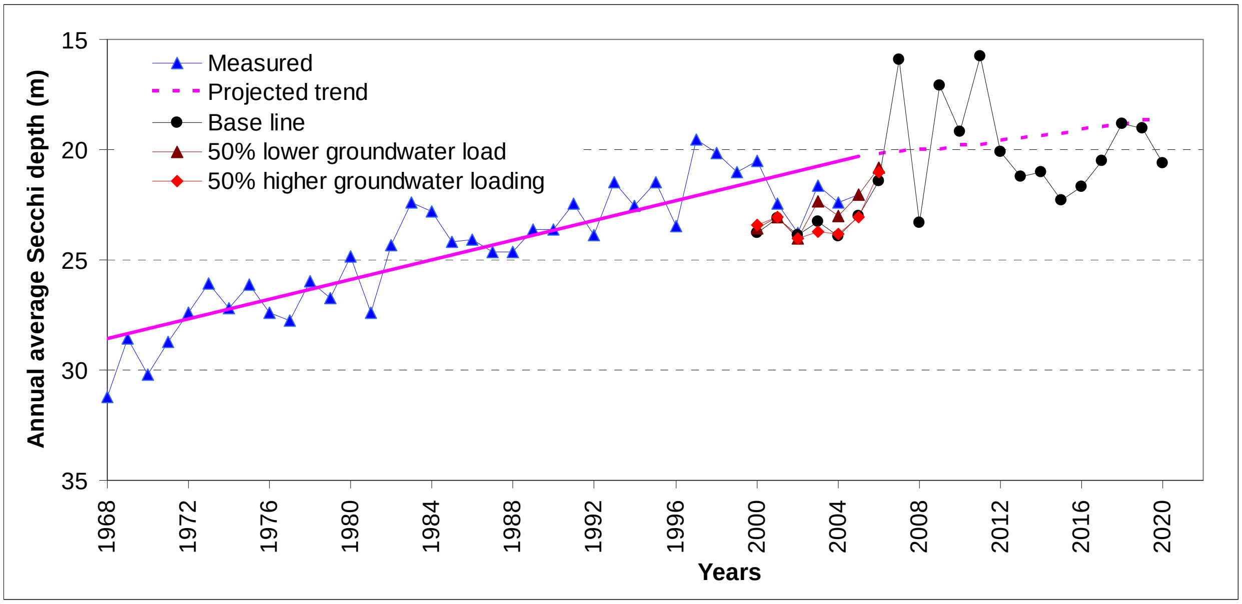

Figure 6-12. Estimated Secchi depths for ± 50 percent change of groundwater load.

Effect of Change in Atmospheric Loads

The effect of varying the atmospheric load of nutrients and fine particles into Lake Tahoe by ± 50 percent was also examined. The response of Secchi depth to the changes in atmospheric loads are shown in Figure 6-13. The estimated Secchi depth was sensitive to this degree of change in atmospheric load. There are two reasons for this: (1) atmospheric load adds all the inputs to the water surface, thus the effect of change in estimated Secchi depth is more immediate and pronounced and (2) atmospheric deposition is an important contributor of total nutrient and particle loading.

The Lake Clarity Model was also run without atmospheric inputs (i.e., a complete reduction). Figure 6-14 shows that the lake clarity increases approximately 7 to 8 meters in 6 years without atmospheric inputs. Though it is impossible to achieve this option, it does highlight the conclusion that atmospheric inputs have a direct impact on the lake clarity.

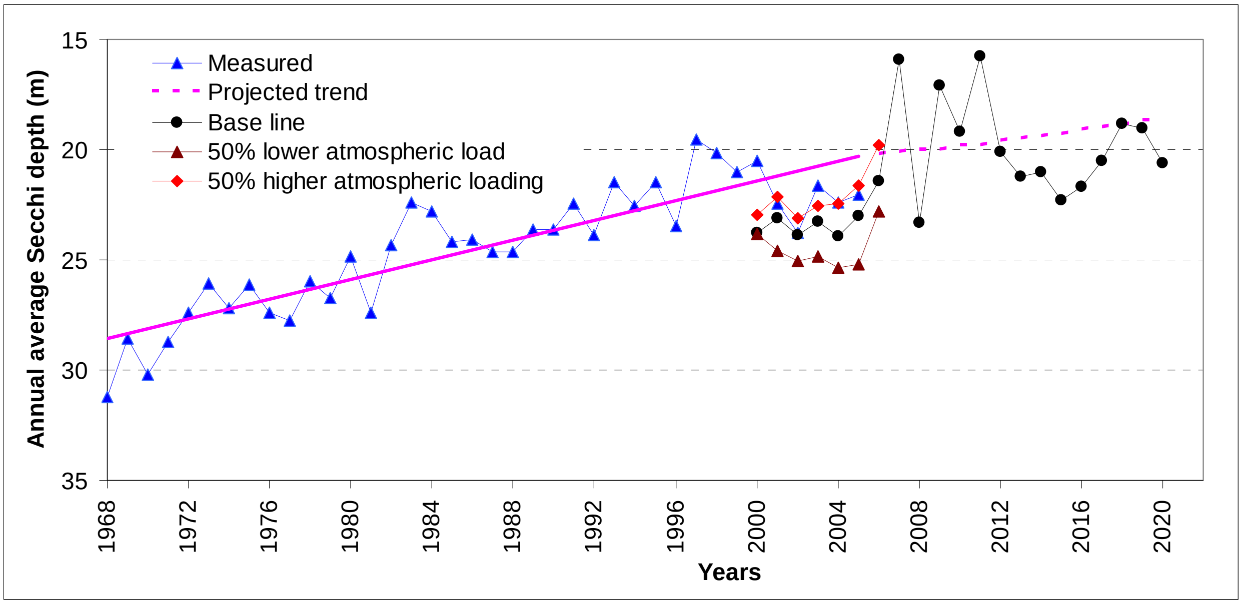

Figure 6-13. Estimated Secchi depths for ± 50 percent change of atmospheric load.

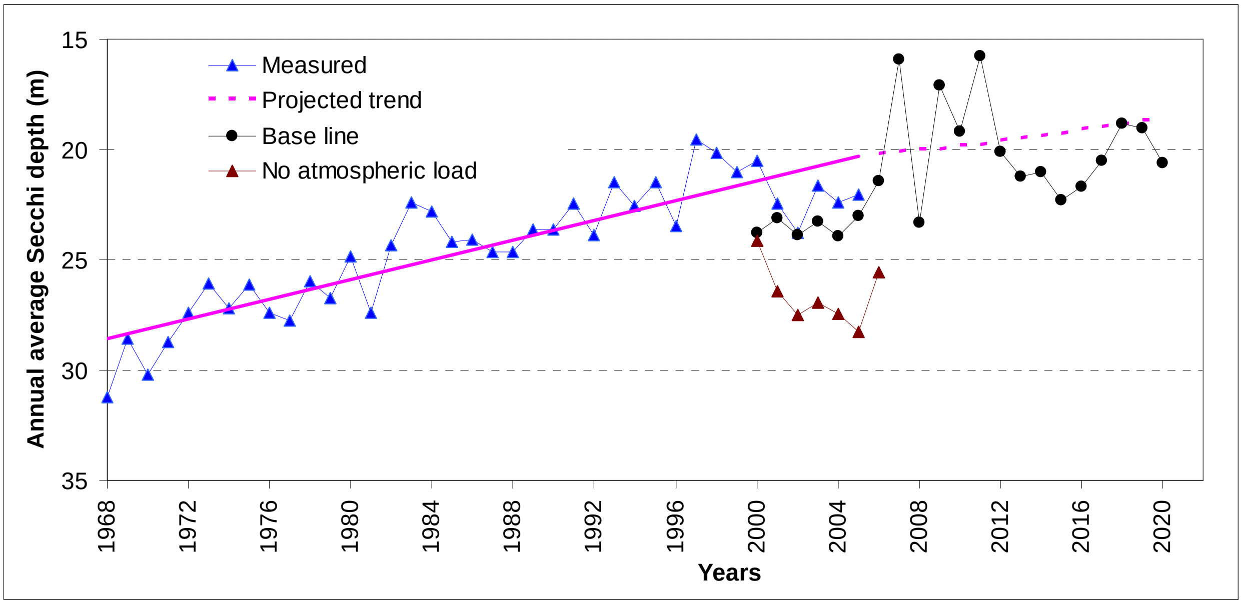

Figure 6-14. Estimated Secchi depths for no atmospheric load (100 percent reduced).

6.4 Model Results

Following model development, parameterization, development of input data, calibration/validation and an initial sensitivity analysis, the Lake Clarity Model was used to perform some preliminary runs based on pre-determined load reduction scenarios. It is important to highlight here that these runs are only examples and do not represent suggested management alternatives. Phase Two of the Lake Tahoe TMDL will be addressing load reduction opportunities and management alternatives. The Lake Clarity Model will be used to evaluate lake response to the various management/load reduction alternatives being considered. Therefore, the reader should not expect to see a full array of model results in this section; rather, the results presented are intended to demonstrate output and highlight the utility of this tool.

6.4.1 Pollutant Loading Input Dataset for Model Simulation Runs

To run the Lake Clarity Model, a series of simulation years into the future (20 year period of 2000-2020) was established. Please note that this period of time was selected for exemplary purposes only. It is not an endorsement of a 20-year implementation schedule – those issues will be considered as part of Phase Two of the Lake Tahoe TMDL. However, it does recognize that restoration will most likely be required on a decadal time scale. As part of Phase Two, the Lake Clarity Model will be used as a tool, along with annualized cost estimates, to develop a realistic set of implementation scenarios.

The baseline result in the analysis below (Figure 6-18) represents the future trend of Secchi depth if the lake continues to receive nutrient and fine sediment loads as it has in recent years. To the extent that the measured loading estimates included the effect of current and past BMPs, existing pollutant reduction efforts are also included in the baseline condition. Sections 4.3 and 4.4 highlighted that a significant fraction of the phosphorus and fine sediment particle loads are transported from the watershed along with hydrologic discharge. Since a principal driving force for watershed loading and lake clarity is annual precipitation (Jassby et al. 2003), the annual total precipitation for the period 1968 through 2005 was analyzed to establish a realistic scenario for future years, i.e. the Lake Clarity Model requires precipitation values for those years to be simulated (Figure 6-15). The minimum and maximum annual total precipitation during 1968-2005 was found to be 8.9 inches in 1977 and 69.1 inches in 1982, respectively. The precipitation frequency analysis was done on the basis of increments of five inches, (i.e. the number of years when annual precipitation was in the range 14 − 19 inches, 19 − 24 inches, etc.).

The Lake Tahoe Watershed Model provided detailed data on stream inputs for the period 1994 to 2004. Therefore, the precipitation information (and associated Lake Tahoe Watershed Model loading results) from these 11 years was used to populate the Lake Clarity Model runs for the period of 1999-2020. The precipitation distributions used for the Lake Clarity Model during 1999-2020 are shown in Figure 6-16 and Figure 6-17. Based on the availability of output from Lake Tahoe Watershed Model (1994-2004) the proposed water year precipitation for 1999-2020 (Figure 6-16) was selected to be as close to the water year precipitation analysis for 1968-2005 (Figure 6-15). Since precipitation in the future is unknown, the proposed values in Figure 6-17 are based on (1) the distribution of precipitation in past years (Figure 6-15) and (2) the expected Secchi depth during the future modeled years based on an extrapolation of the measured 1968-2005 Secchi depth data. Based on the past 39 years of data for annual average Secchi depth, a straight-line fit still provides the most reasonable fit (R^2=0.77; slope = -0.22 m/yr; p<0.001). For future runs of the Lake Clarity Model, more advanced statistical approaches can be taken to develop the proposed annual precipitation distribution for the period 1999-2020.

A commonly employed technique for extrapolating future Secchi depth values from an existing long-term data set is to plot the inverse of the measured Secchi depth (m^{-1}) against time (Jassby et al. 2003, Swift 2004). A linear regression can then be applied and extrapolated over time. The results are then converted back to Secchi depths (m) and re-plotted. The projected trend line (dashed red line) of Secchi depth in the simulation plots that extend past 2005 were obtained in this fashion using measured data. Reuter and Miller (2000) reproduced a plot from T. Swift (UC Davis - TERC unpublished) that is based on the physics of lake optics and shows that the relationship between Secchi depth and the materials in the water that reduce light penetration (contrast attenuation) is not linear. Rather, as Secchi depth declines it require more material to be in the lake to see an additional unit change in clarity. This is the reason why the projected line of best fit through the plot of future Secchi depth predictions (2006-2020) does not increase at the same rate as the previously measured data. The years selected to represent future conditions for the model runs (red bars in Figure 6-17) were years that provided a good fit to the projected Secchi trend line (dashed red line).

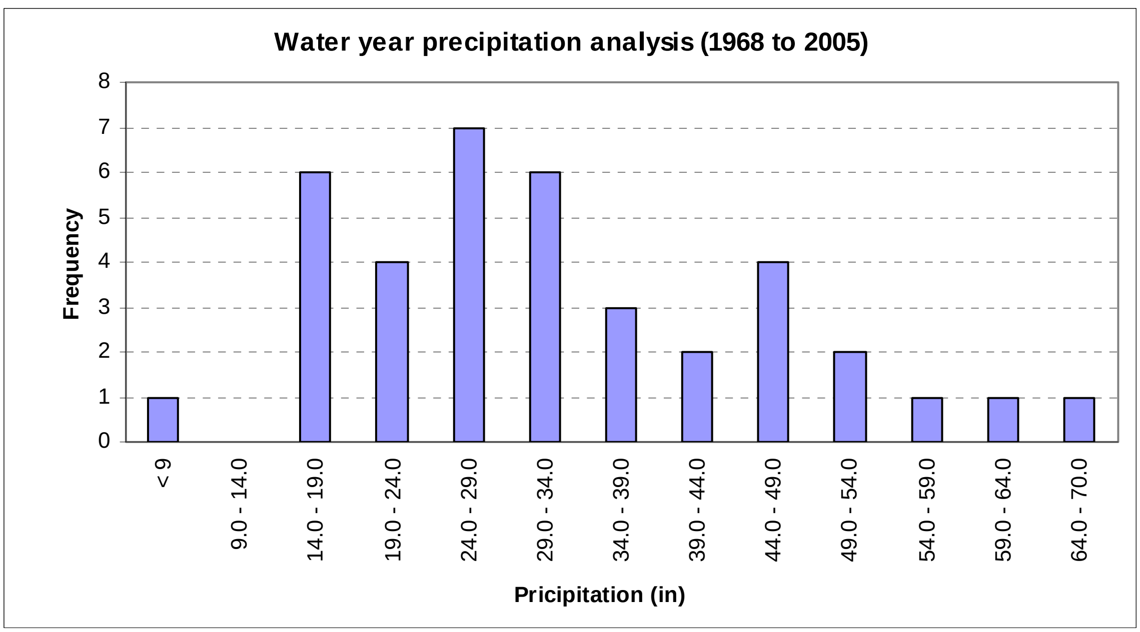

Figure 6-15. Frequency analysis of annual precipitation as measured at Tahoe City for 1968 to 2005.

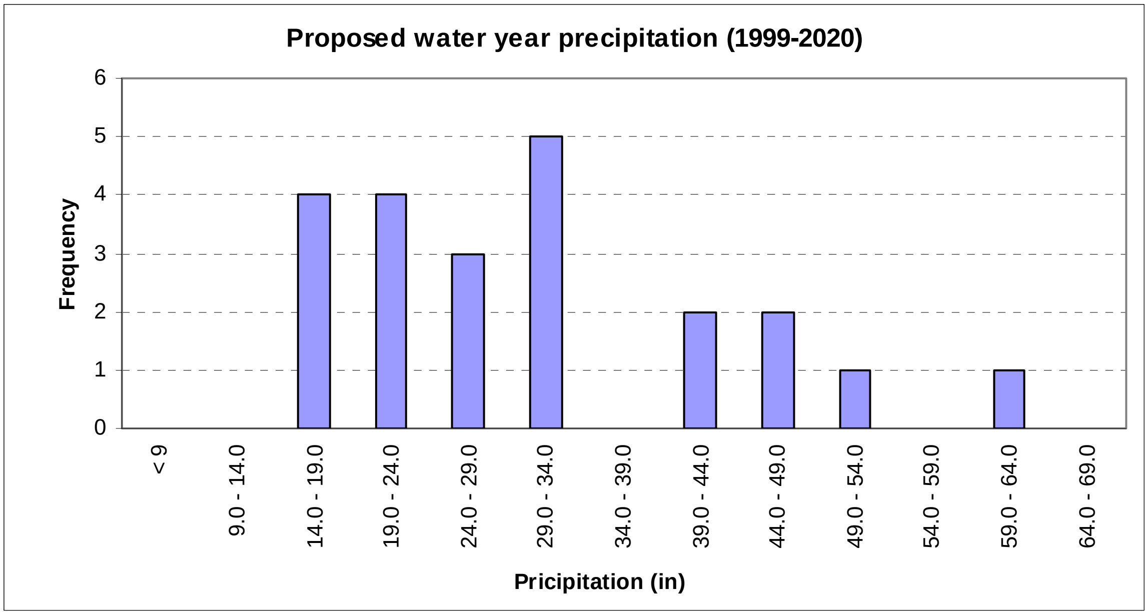

Figure 6-16. Proposed frequencies of annual precipitation occurrence based on the Tahoe City meteorological station for 1999 to 2020.

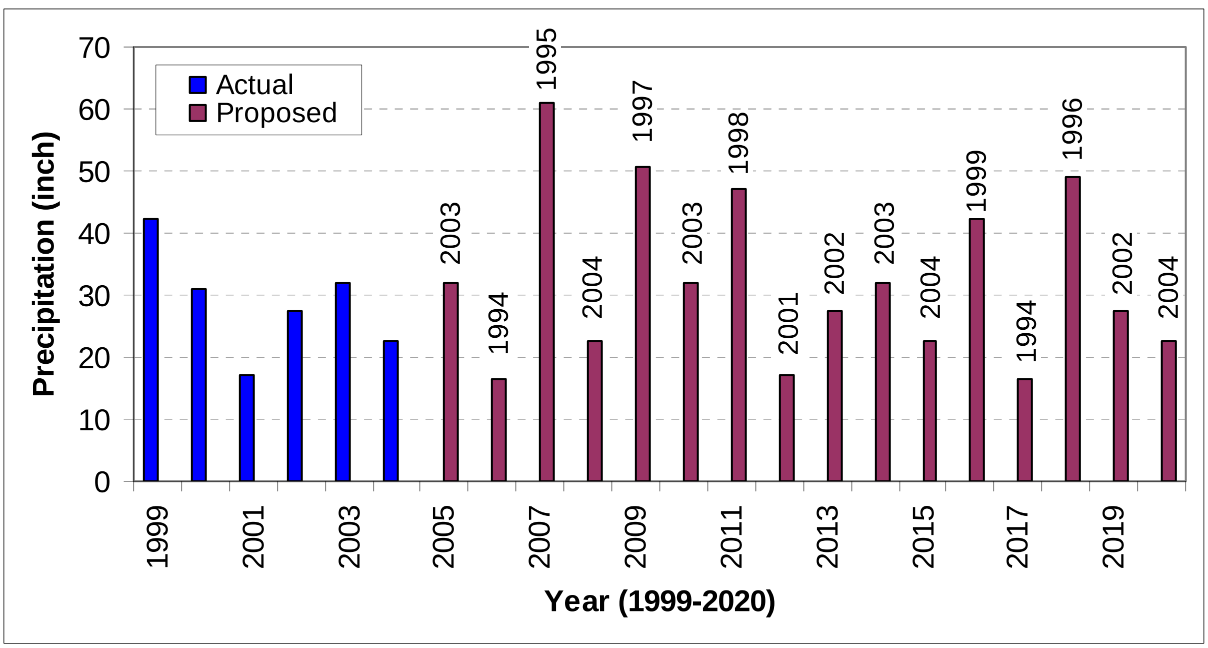

Figure 6-17. Proposed annual total precipitation distribution for 1999-2020 for the generation of baseline Secchi depth. The dates on top of each bar represent the year used to supply input data for runoff and pollutant.

The meteorological and stream pollutant load inputs to the Lake Clarity Model for the establishment of baseline estimates for years 2004 to 2020 are set to the same as proposed for precipitation years. For example, meteorological and stream pollutant load inputs for the year 2008 were taken to be the same as those of the year 2004 (Figure 6-17). Data on the long-term distribution of atmospheric, groundwater and shoreline erosion input data are not available. Thus, pollutant loads from groundwater and shoreline erosion are the same for all years. Atmospheric pollutant loads vary a little year-to-year because the number of wet days annually varies between years (Table 6-11).

Lake Tahoe Watershed Model output for total nutrient loads from intervening zones, streams, and atmosphere for years 1994 to 2004 are shown in Table 6-8 to Table 6-10. The 10 years (1994 to 2004) average nutrient loads are very close to the loads estimated for upland runoff and atmospheric deposition (Table 4-66).

Table 6-8. Annual intervening zone nutrient load model output from the Lake Tahoe Watershed Model (Tetra Tech 2007).

Year	SRP	POP	DOP	Total Phosphorus		NO_3+NO_2	NH_4	PON	DON	Total Nitrogen
	MT	MT	MT	MT		MT	MT	MT	MT	MT
1994	0.626	3.074	0.000	3.700		0.779	0.525	10.746	0.000	12.050
1995	2.286	11.241	0.000	13.527		2.696	1.761	37.932	0.000	42.389
1996	2.087	10.982	0.000	13.069		2.764	1.821	37.180	0.000	41.765
1997	1.984	9.379	0.000	11.363		2.005	1.247	28.052	0.000	31.303
1998	1.623	8.282	0.000	9.905		2.096	1.429	29.134	0.000	32.659
1999	1.070	5.222	0.000	6.292		1.333	0.923	19.292	0.000	21.548
2000	0.722	3.839	0.000	4.561		1.004	0.713	13.804	0.000	15.521
2001	0.316	1.815	0.000	2.132		0.500	0.365	6.629	0.000	7.494
2002	0.642	3.685	0.000	4.327		0.985	0.700	12.980	0.000	14.664
2003	0.596	3.292	0.000	3.888		0.852	0.615	11.622	0.000	13.089
2004	0.674	3.634	0.000	4.308		0.922	0.648	12.533	0.000	14.103
Ave.	**1.148**	**5.859**	**0.000**	**7.007**		**1.449**	**0.977**	**19.991**	**0.000**	**22.417**

Table 6-9. Annual stream nutrient load model output from the Lake Tahoe Watershed Model (Tetra Tech 2007).

Year	SRP	POP	DOP	Total Phosphoruss		NO_3+NO_2	NH_4	PON	DON	Total Nitrogen
	MT	MT	MT	MT		MT	MT	MT	MT	MT
1994	2.316	8.041	0.000	10.357		5.763	1.630	38.809	0.000	46.202
1995	9.856	32.013	0.000	41.869		14.485	5.719	155.989	0.000	176.193
1996	8.866	30.260	0.000	39.126		10.592	5.494	141.502	0.000	157.588
1997	7.712	24.889	0.000	32.601		8.312	4.177	115.657	0.000	128.145
1998	7.391	23.630	0.000	31.021		7.908	4.538	115.465	0.000	127.911
1999	6.180	19.223	0.000	25.404		5.655	3.635	94.209	0.000	103.500
2000	3.661	11.593	0.000	15.254		3.081	2.364	56.856	0.000	62.301
2001	1.591	5.202	0.000	6.793		1.413	1.174	26.428	0.000	29.016
2002	3.237	10.349	0.000	13.586		2.556	2.200	51.291	0.000	56.047
2003	3.552	10.991	0.000	14.544		2.637	2.241	54.280	0.000	59.158
2004	2.949	9.543	0.000	12.492		2.497	1.995	46.564	0.000	51.056
Ave.	**5.210**	**16.885**	**0.000**	**22.095**		**5.900**	**3.197**	**81.550**	**0.000**	**90.647**

Table 6-10. Annual stream and intervening nutrient load model output from the Lake Tahoe Watershed Model (Tetra Tech 2007) used in Lake Clarity Model.

Year	SRP	POP	DOP	Total Phosphorus.		NO_3+NO_2	NH_4	PON	DON	Total Nitrogen
	MT	MT	MT	MT		MT	MT	MT	MT	MT
1994	2.942	11.115	0.000	14.056		6.543	2.155	49.555	0.000	58.253
1995	12.142	43.254	0.000	55.396		17.181	7.480	193.921	0.000	218.582
1996	10.953	41.242	0.000	52.195		13.356	7.315	178.682	0.000	199.353
1997	9.696	34.268	0.000	43.964		10.316	5.424	143.709	0.000	159.448
1998	9.014	31.912	0.000	40.926		10.005	5.966	144.599	0.000	160.570
1999	7.250	24.446	0.000	31.696		6.988	4.559	113.501	0.000	125.048
2000	4.383	15.432	0.000	19.815		4.085	3.077	70.660	0.000	77.822
2001	1.907	7.018	0.000	8.925		1.913	1.539	33.058	0.000	36.509
2002	3.879	14.034	0.000	17.913		3.541	2.900	64.271	0.000	70.711
2003	4.148	14.283	0.000	18.431		3.489	2.856	65.902	0.000	72.247
2004	3.624	13.177	0.000	16.801		3.419	2.643	59.097	0.000	65.159
Ave.	**6.358**	**22.744**	**0.000**	**29.102**		**7.349**	**4.174**	**101.541**	**0.000**	**113.064**

The year-to-year distribution of atmospheric load as dry deposition was not reported by CARB (2006). Based on the available data the daily load from wet and dry deposition was considered to be the same for all the years. However, the number of wet and dry days varies from year-to-year and, therefore, each year is treated differently in the Lake Clarity Model runs. Note that a day is considered wet if total precipitation occurred in that day is greater than or equal to 0.1 inch (i.e. 2.54 mm). Table 6-11 presents the annual nutrient loads from atmospheric deposition.

Table 6-11. Annual atmospheric nutrient loads model output from the Lake Tahoe Watershed Model.

Year	SRP	POP	DOP	Total Phosphorus.		NO_3+NO_2	NH_4	PON	DON	Total Nitrogen
	MT	MT	MT	MT		MT	MT	MT	MT	MT
1994	2.839	4.313	2.332	9.484		54.022	94.872	8.812	63.291	220.997
1995	3.128	4.601	2.572	10.301		58.475	97.921	9.220	65.099	230.714
1996	3.316	4.681	2.716	10.713		61.539	97.265	9.531	70.459	238.794
1997	2.812	4.297	2.312	9.421		53.939	96.095	8.831	62.063	220.929
1998	3.267	4.603	2.672	10.542		61.517	98.052	9.544	69.556	238.669
1999	2.538	4.126	2.096	8.760		49.176	94.757	8.313	55.545	207.792
2000	2.644	4.189	2.179	9.012		51.138	95.296	8.519	58.205	213.158
2001	2.568	4.148	2.120	8.837		49.486	94.302	8.361	57.199	209.348
2002	2.537	4.141	2.097	8.775		48.793	94.278	8.286	55.935	207.291
2003	2.811	4.312	2.313	9.436		53.622	95.856	8.820	62.466	220.763
2004	2.410	4.023	1.992	8.424		47.248	94.269	8.177	54.883	204.577
Ave.	**2.806**	**4.312**	**2.309**	**9.428**		**53.541**	**95.724**	**8.765**	**61.337**	**219.367**

For the purpose of running the Lake Clarity Model, the mass or weight of sediment in each of the size classes is not directly used. This is because it is not the weight but number of fine particles that affect lake clarity. In development of the Lake Clarity Model, Perez-Losada (2001) divided fine particle loading (expressed as numbers of particles) into seven size classes as defined in Table 6-12. Table 6-13 and Table 6-14 provide annual estimates of particle loading from the watershed for each size class over the period 1994 through 2004. According to Swift et al. (2006) "for inorganic particles, approximately 75 percent of the scattering is due to particles between 0.5 and 5 μm and the seventh-size class does not contribute to the decrease in water clarity.” Since Rabidoux (2005) regression equations estimate the full seven particle size classes, the seventh-size class is shaded to distinguish it from classes that most affect lake clarity.

Table 6-12. Range of particle diameter associated with each of the seven particle size classes.

Particle class size	Diameter assumed for the class
1	0.5 μm – 1.0 μm
2	1.0 μm – 2.0 μm
3	2.0 μm – 4.0 μm
4	4.0 μm – 8.0 μm
5	8.0 μm – 16.0 μm
6	16.0 μm – 32.0 μm
7	32.0 μm – 64.0 μm

It has been mentioned that particles of the first six size classes are important for clarity and especially those in the 0.5 − 16 µm range. Thus, annual average particles from all sources (1994 to 2004 when data or reasonable estimates available) were presented in Chapter 5 (Figure 5-4). Once again, it is important to note that while sediment mass (kilograms) in the 16 − 32 and < 32 − 64 µm size classes may be significant, the number of particles in these classes are virtually zero as compared to the smaller classes and therefore have a negligible effect on clarity.

The average annual load of particles < 16 µm from all the major sources was on the order of 5 x 10^{20} particles. Table 5-13 and Figure 5-4 show the estimated break down of loading by source for each of the individual particle size classes in the < 16 µm range. Note that the sum of particle number for streams plus intervening zones (Table 6-13 and Table 6-14) is identical to the particle number for urban upland plus non-urban upland plus stream channel erosion since these are the only upland sources (**Error! Reference source not found.**). There is no load for the seventh particle size from both shoreline erosion and atmosphere. On the order of 85 percent of the particle load to Lake Tahoe is associated with surface runoff associated with urban and non-urban upland sources and stream channel erosion. By far the most significant contributor was urban upland runoff accounting for 72 percent of the total and supports the concept that the urban areas are critical with respect to pollutant control. The contribution of particles from atmospheric deposition was estimated at 15 percent of the total.

Table 6-13. Annual intervening zones total particle numbers per size class load calculations (refer to Table 6-12 for size class definitions).

Year	Yearly total stream particle number any size						
	1	2	3	4	5	6	7
	$\times 10^{19}$	$\times 10^{18}$	$\times 10^{18}$	$\times 10^{18}$	$\times 10^{17}$	$\times 10^{16}$	$\times 10^{15}$
1994	15.55	29.42	7.14	2.81	13.39	2.87	10.91
1995	56.60	115.72	30.74	13.18	65.04	15.26	60.58

1996	49.89	101.29	26.65	11.17	54.29	12.50	48.90
1997	43.37	90.37	25.31	11.79	61.16	15.08	61.93
1998	39.56	78.19	19.69	7.85	37.23	8.26	31.32
1999	28.37	55.81	13.88	5.45	25.49	5.62	21.14
2000	17.36	33.51	8.17	3.11	14.37	3.08	11.34
2001	7.30	13.66	3.14	1.10	4.85	0.98	3.41
2002	14.13	27.27	6.54	2.42	10.93	2.31	8.34
2003	13.22	25.42	6.02	2.14	9.40	1.95	6.82
2004	14.88	29.06	7.15	2.69	12.27	2.63	9.58
Ave.	**27.29**	**54.52**	**14.04**	**5.79**	**28.04**	**6.41**	**24.93**

Table 6-14. Annual stream total particle numbers per size class load calculations (refer to Table 6-12 for size class definitions).

Year	Annual total stream particle number any size						
	1	2	3	4	5	6	7
	$\times10^{19}$	$\times10^{18}$	$\times10^{18}$	$\times10^{18}$	$\times10^{17}$	$\times10^{16}$	$\times10^{15}$
1994	1.63	3.34	0.79	0.29	1.31	3.47	12.14
1995	9.49	20.35	5.08	2.00	9.43	25.17	97.29
1996	7.59	16.39	4.07	1.58	7.30	19.54	68.85
1997	7.02	15.25	3.87	1.55	7.34	20.28	74.05
1998	6.31	13.42	3.29	1.26	5.82	15.42	54.09
1999	5.13	11.01	2.70	1.03	4.66	12.43	43.35
2000	2.52	5.40	1.32	0.49	2.16	5.83	20.24
2001	0.95	1.99	0.47	0.17	0.68	1.81	6.07
2002	2.20	4.72	1.15	0.42	1.78	4.78	16.32
2003	2.42	5.20	1.27	0.46	1.94	5.20	17.61
2004	1.91	4.07	0.99	0.36	1.52	4.09	13.93
Ave.	**4.29**	**9.20**	**2.27**	**0.87**	**3.99**	**10.73**	**38.54**

Based on the above pollutant loads and weather inputs, the Lake Clarity Model simulated 20 years of Secchi depths. A plot showing previously measured data and modeled annual average Secchi values is presented in Figure 6-18. The solid red line in Figure 6-18 and subsequent versions of this plot represents a statistical line of best fit with an R^2-value of 0.77 and a p-value < 0.001, as described above. The dashed red line is the line of best fit based on the inverse Secchi plot over time with consideration of contrast attenuation and lake optics as described by Swift and presented in Reuter and Miller (2000). It is important to note that the Lake Clarity Model was calibrated and validated using data through 2005. Predicted values after that date are based on model simulation and not on actual data. Since the precipitation and loading data was not available for 2006 when this analysis was done, values based on historical observations (Figure 6-16 and Figure 6-17) were used. Likewise the measured Secchi depth for any of the simulated years into the future will differ from the modeled value to the extent that precipitation and meteorology for that particular year varied from the simulated values. Again, simulated values were based on historical observations.

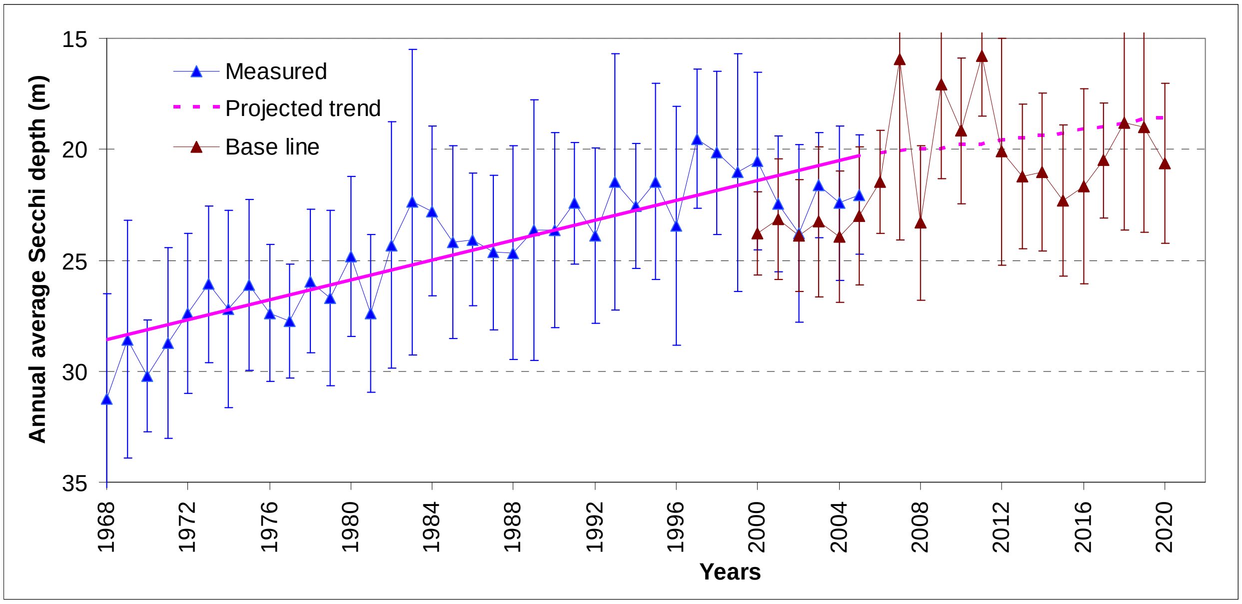

Figure 6-18. Measured and baseline Secchi depths for 2000-2020. The red line represents line of best fit while dashed red line represents to line of best fit for the simulated results. The vertical bars represent the natural seasonal variability in Secchi depth during a year. This is denoted as the standard deviation from the mean for the measured and modeled values used to calculate the annual averages.

6.4.2 Load Reduction Simulation Runs: Based on Basin-wide Loading

In this section, a limited number of example model runs are presented to demonstrate the utility of the lake clarity model as a tool to evaluate lake response to nutrient and fine sediment load reduction. As stated above, this was not intended to serve as a full alternatives analysis (that is part of Phase Two of the Lake Tahoe TMDL).

To begin, 0, 25, 50 and 75 percent load reduction assumptions were applied to nutrients and fine sediment particles individually, and in combination. For this discussion the load reductions are in relation to the entire, basin-wide pollutant loading estimates including all major sources and from urban and non-urban land-uses. Note that the values used for percent reduction in these model runs can be directly converted to absolute loads (metric tons) based on the nutrient and fine sediment budgets. It was assumed that the percent reduction was the same for each of the major pollutant categories.

The simulated average annual Secchi depths for the years 2011 to 2020 for the above load reduction combinations are shown in Table 6-15. These results suggest that the 30 meter target for Secchi requires reducing both nutrients and fine sediment loads. A higher percentage of load reduction for either nutrients or fine sediment could be examined; however, such scenarios would most likely be unrealistic to implement. The model results show a synergistic affect between nutrient and fine sediment reduction at the higher levels of load reduction. In concordance with the in-lake field studies by Swift (2004) and Swift et al. (2006), the Lake Clarity Model demonstrates greater effect of reducing fine sediment loading as compared to reducing nutrient loading. Between the 0 and 25 percent load reduction levels the model showed the same average Secchi depth improvement for fine sediment alone and fine sediment plus nutrients (i.e. 20.1 meters versus 23.2 meters; Table 6-15). Given, (1) the variability associated with these values; presented as the standard deviations in Table 6-15, (2) the observation that nutrient additions stimulate algal growth in Lake Tahoe (Goldman et al. 1993; Hackley et al. 2007), and (3) Swift et al. (2006) found that algae accounted for approximately 25 percent of the clarity conditions in the lake (Figure 3-12), it would be unwise to conclude that nutrient reduction has no affect on clarity at the 0-25 percent load reduction level.

The Lake Clarity Model results also suggest that there is little difference between nitrogen and phosphorus reduction when considering Secchi depth improvement. While algal growth bioassay experiments show that phosphorus added by itself is more likely to stimulate phytoplankton growth in Lake Tahoe as compared to additions of solely nitrogen, the combination of nitrogen + phosphorus additions results in significant increases in algal biomass at virtually all times of the year (Hackley et al. 2007).

Using the model output for Secchi depth at the 0, 25, 50 and 75 percent combined fine sediment and nutrient reduction in load (i.e. last column in Table 6-15), a linear regression line was plotted (Figure 6-19); this output also includes the variation associated with the model results. These results suggest that a combined load reduction from all sources, basin-wide on the order of 55 percent would be necessary to achieve the 30 meter lake clarity target. In practice, it would be impossible to immediately reduce the load equally from all sources. Therefore, to demonstrate the utility of the Lake Clarity Model, different time-course scenarios of load reductions were considered. Again, the time-course simulations presented below are simply examples and do not represent an endorsement.

Table 6-15. Average Secchi depth for the years 2011–2020 for different load reduction scenarios considering all major pollutant sources, basin-wide. The 0 percent reduction row includes continuation of water quality BMP/restoration at the same level as done during the period 1994-2004. The number within the parentheses represents the standard deviation over the modeled annual average Secchi depths for the years 2011 – 2020, i.e. that period after equilibrium conditions are first attained.

Reduction (%)	Average Secchi Depth (meters) for the Years 2011–2020				
	Nutrient (Nitrogen) Reduction	Nutrient (Phosphorus) Reduction	Nutrient (N+P) Reduction (meter)	Fine Sediment Reduction	Nutrient (N+P) and Fine Sediment Reduction
0	20.1 (2.06)	20.1 (2.06)	20.1 (2.06)	20.1 (2.06)	20.1 (2.06)
25	20.4 (2.06)	20.5 (1.83)	21.3 (2.18)	23.2 (2.46)	23.2 (2.16)
50	21.0 (2.28)	21.6 (2.07)	21.4 (2.40)	26.2 (2.30)	27.0 (2.17)
75	22.0 (2.46)	21.8 (2.41)	21.7 (2.29)	28.6 (2.55)	35.3 (2.82)

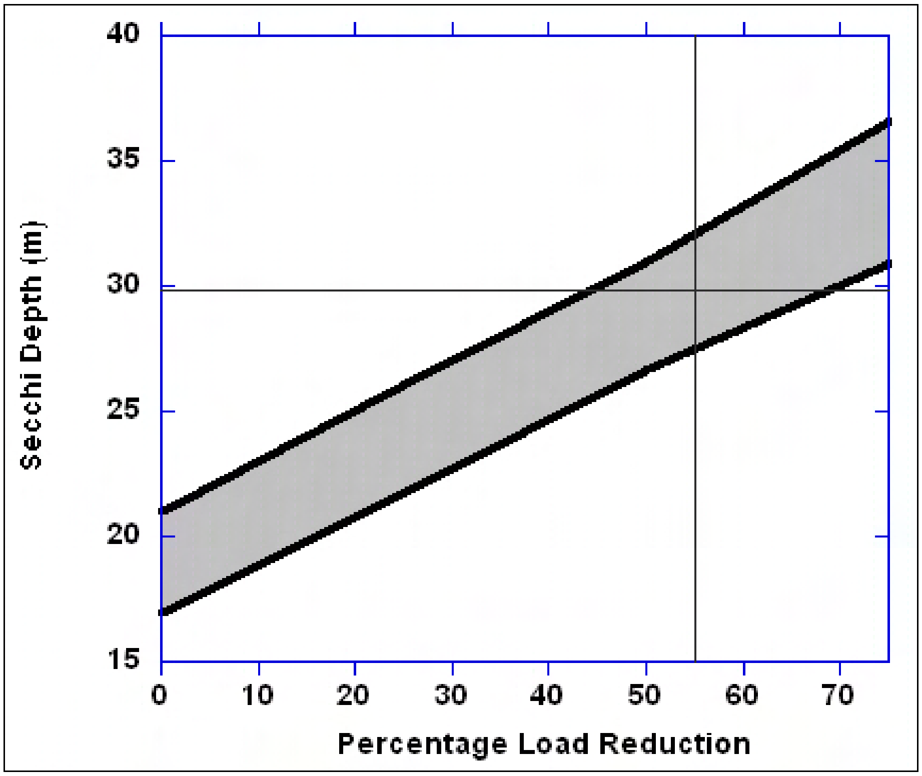

Figure 6-19. The variation of Secchi depth (meters) in response to percentage reductions of fine particles, nitrogen and phosphorus across all the major sources. Secchi depth is calculated as the average over 10 years after equilibrium conditions are first attained. The shaded area is the average Secchi depth ± 1 standard deviation, and therefore gives the expected range of variation in observed Secchi depth. The horizontal line is the clarity threshold value of 29.7 meters, and the vertical line represents a 55 percent reduction of fine particles, nitrogen and phosphorus across all sources. This case is illustrative and is not the recommended pollutant reduction target.

Since a stepwise reduction in loading would be the most realistic management scenario, the model was run to see how the lake would respond to such a practice. Two such scenarios: (1) a 75 percent load reduction from all sources at a uniform rate of 3.75 percent per year for 20 years and (2) a 55 percent load reduction from all sources at a uniform rate of 2.75 percent per year for 20 years were examined. In these two cases, the load reduction percentage increases every year. Thus, it is seen that after twenty years for the stepwise 75 percent reduction case, the 30 meter clarity was achieved in 14 years (Figure 6-20). In the case of a stepwise 55 percent reduction, clarity increased and approached the 30 meter target in 20 years (Figure 6-21). The reader is referred to Sahoo et al. (2007) who also conducted model runs based on varying percent load reductions of selected pollutant sources (e.g., stream loading and atmospheric deposition).

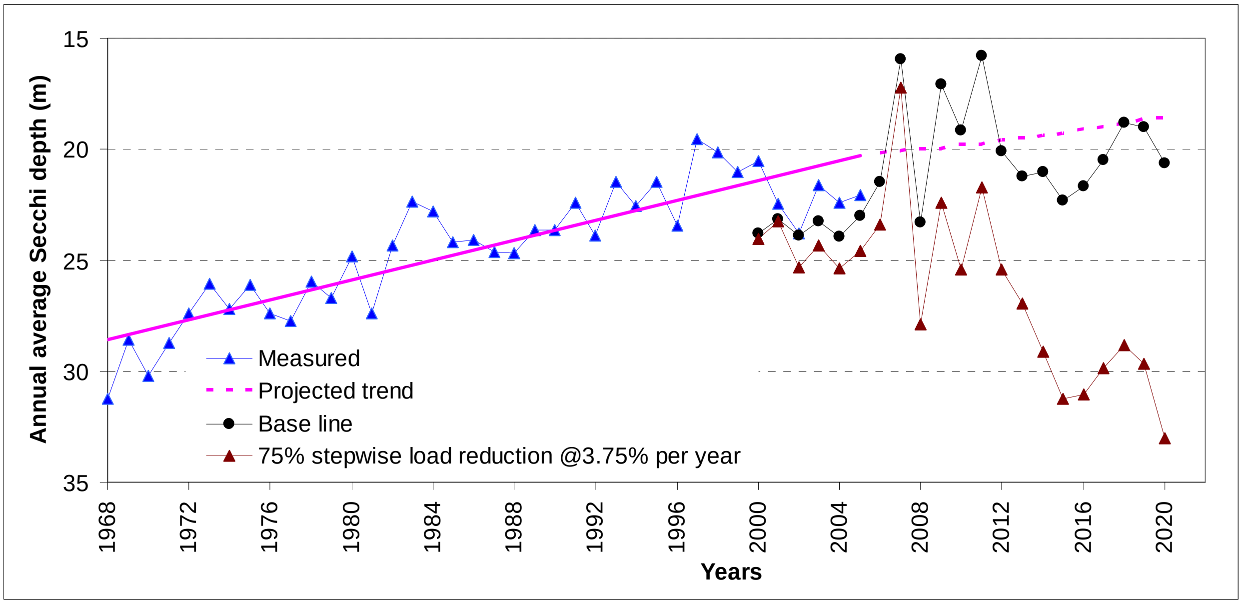

Figure 6-20. Simulated annual average Secchi depths for 75 percent load reduction from all sources at a rate of 3.75 percent per year for 20 years.

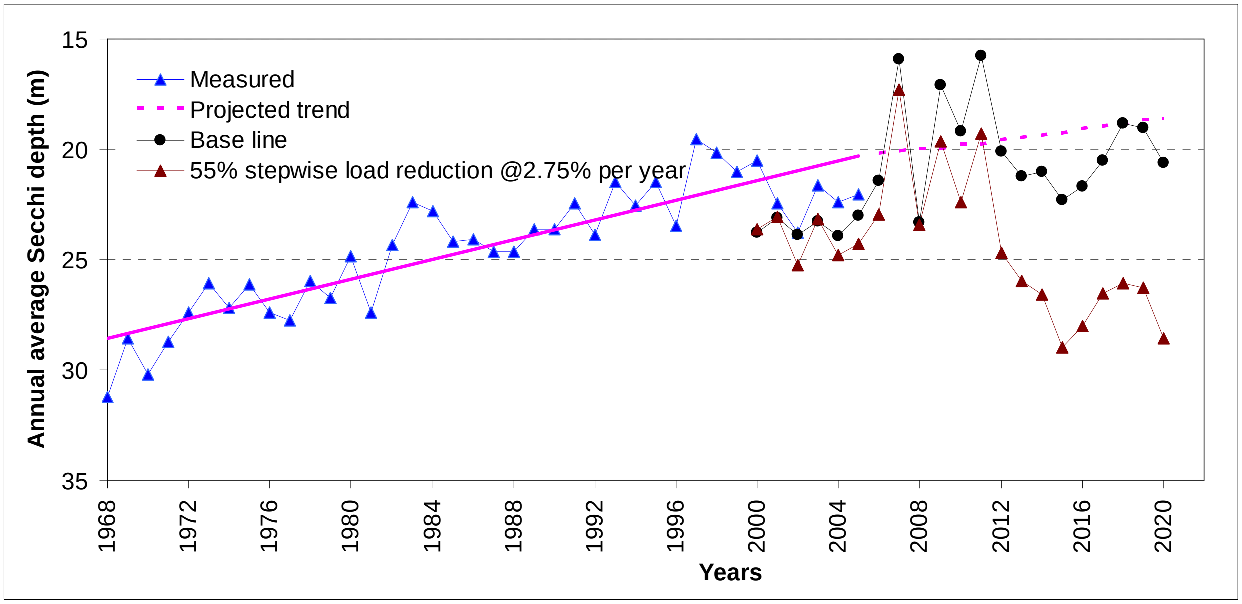

Figure 6-21. Simulated annual average Secchi depths for 55 percent load reduction from all sources at a rate of 2.75 percent per year for 20 years.

6.4.3 Load Reduction Simulation Runs: Based on Urban Loading

Pollutant loading from urban sources only was also considered as a potential option for clarity improvement. As specific scenarios are developed as part of the Lake Tahoe TMDL Phase Two, many other options can be tested.

Calculation of urban loads

Upland runoff and stream channel erosion

The land-uses considered as sources for urban upland loading are, in part, defined as part of the Lake Tahoe Watershed Model development. The urban land-use layer for the Lake Tahoe Watershed Model was based on two primary sources of spatial data: (1) an updated parcel boundaries layer from a number of agencies comprising the Tahoe basin GIS User's Group and (2) a detailed one-square-meter resolution Hard Impervious Cover (HIC) layer that was developed using remote sensing techniques from IKONOS^{TM} satellite imagery (Minor and Cablk 2004). Values include both the pervious and impervious portions for each land-use. The specific land-uses considered under the urban classification (with percent distribution for entire Lake Tahoe basin) include, single family residential (4.9 percent), multiple family residences (1.3 percent), commercial/institutional/communications/utilities (1.3 percent), primary and secondary paved roads (1.6 percent). The upland runoff loads were separated into urban and non-urban source areas based on the percentage of flows coming from the respective areas. Flow percentage values were provided by Tetra Tech (2007).

For stream channel erosion, an average approximately 30 percent of the total combined stream load (measured at the mouth) comes from stream channel erosion. In the present study 50 percent of total stream channel erosion is considered as urban.

Groundwater

The values reported in USACE (2003) are used for estimating the percentage of urban and non-urban nutrient loads (Table 6-16, Table 6-17, and Table 6-18). The ambient and non-ambient groundwater loads from the USACE analysis are considered for non-urban and urban loads respectively.

Table 6-16. Total groundwater load (USACE 2003).

Region	Total Groundwater Nitrogen Loading (kg/year)	Total Groundwater Phosphorous Loading (kg/year)
South Lake Tahoe/Stateline (South)	2400	430
East Shore (East)	6200	140
Incline Village (North)	4200	770
Tahoe Vista/Kings Beach (North)	9400	1100
Tahoe City/West Shore (West)	28000	4400
Total	50200	6840

Table 6-17. Total Non-urban groundwater load (USACE 2003).

Region	Ambient Total GW Nitrogen Loading (kg/year)	Ambient Total Groundwater Phosphorous Loading (kg/year)
South Lake Tahoe/Stateline (South)	1000	230

East Shore (East)	1300	140
Incline Village (North)	1800	330
Tahoe Vista/Kings Beach (North)	2600	480
Tahoe City/West Shore (West)	10000	1900
Total	16700	3080

Table 6-18. Total Urban groundwater load (USACE 2003).

Region	Non-Ambient Total GW Nitrogen Loading (kg/year)	Non-Ambient Total Groundwater Phosphorous Loading (kg/year)
South Lake Tahoe/Stateline (South)	1400	200
East Shore (East)	4900	0
Incline Village (North)	2400	440
Tahoe Vista/Kings Beach (North)	6800	620
Tahoe City/West Shore (West)	18000	2500
Total	33500	3760

In summary the USACE study concluded that 67 percent of total nitrogen load (33,500 kg) comes from urban sources as does 55 percent (3,760 kg) of total phosphorus.

Atmospheric deposition

CARB (2006) conducted the LTADS to quantify atmospheric deposition from nitrogen, phosphorus and particulate matter loading into Lake Tahoe. They provided estimates for total nitrogen and particle loads from four quadrants around the lake based on geographic location and denoted as N (north), E (east), S (south) and W (west) (refer to Figure 4-57 and Figure 4-58 in Section 4.5). The LTADS results show a very sharp contrast between deposition of nitrogen and inorganic particles (PM) in the east and west quadrates versus the north and south quadrates. The relative proportion of loading from the east and west quadrants was used as an indicator of non-urban sources and from the north and south quadrants as an indicator of urban sources and calculated the contribution of each relative to the total atmospheric load (Table 6-25). Phosphorus percentage was considered same as that for inorganic particles.

Table 6-19. Seasonal Urban Atmospheric Loads (see Section 4.5).

	Spring	Summer	Fall	Winter
Total Urban Nitrogen (metric tons)	17.4	24.9	28.9	22.3
Total Non-Urban Nitrogen (metric tons)	6.2	10.0	10.2	4.8
Total Nitrogen (metric tons)	23.6	34.9	39.1	27.2
% Nitrogen from Urban	74	71	74	82
Total Urban PM (metric tons)	139.1	173.2	141.3	177.0
Total Non-Urban PM (metric tons)	19.8	28.7	23.0	15.7
Total PM (metric tons)	158.9	201.9	164.3	192.8
% PM from Urban	88	86	86	92

Shoreline erosion

Since shoreline erosion is difficult to control, it is considered as non-urban and not included in the load reduction analysis relative to urban sources.

Urban load reduction scenarios

Based on the above assumptions, different load reduction scenarios are examined here as they pertain to the amount of urban pollutant reduction required to reach the approximately 30 meter water quality standard and TMDL target. As stated above, this exercise is intended to demonstrate the utility of the Lake Clarity Model and not recommend management actions.

Load reduction levels of 0, 25, 50, 75 and 90 percent were applied to nutrients and fine sediment particles individually, and in combination. It was assumed that the percent reduction was the same for each of the major categories. The simulated average annual Secchi depths for the years 2011 to 2020 for the above load reduction combinations are shown in Table 6-20 and Figure 6-22. These results suggest that the approximately 30 meter target for Secchi can be achieved with pollutant reductions from urban sources, but all urban sources need to be considered. As seen for the example of basin-wide reductions presented above, a combination of nutrient and fine sediment reduction provides a greater improvement in clarity. The modeling results suggest that a combined load reduction of greater than 75 percent from urban sources would be necessary to achieve the approximately 30 meter lake clarity target. As expected this is higher than the 55 percent reduction value based on all sources basin-wide (Figure 6-19). As presented above, and to demonstrate the utility of the Lake Clarity Model, different time-course scenarios of load reductions from urban areas exclusively were considered.

Table 6-20. Average Secchi depth for the years 2011–2020 for different load reduction scenarios considering all major pollutant sources, from the urban area. The 0 percent reduction row includes continuation of water quality BMP/restoration at the same level as done during the period 1994-2004. The number within the parentheses represents the standard deviation over the modeled annual average Secchi depths for the years 2011 – 2020, i.e. that period after equilibrium conditions are first attained.

Reduction (%)	Average Secchi Depth (meter) for the Years 2011–2020				
	Nutrient (Nitrogen) Reduction	Nutrient (Phosphorus) Reduction	Nutrient (N+P) Reduction (meters)	Fine Sediment Reduction	Nutrient (N+P) and Fine Sediment Reduction
0	20.3 (2.11)	20.3 (2.11)	20.3 (2.11)	20.3 (2.11)	20.3 (2.11)
25	20.8 (1.72)	20.8 (2.03)	21.6 (2.12)	21.4 (1.94)	22.9 (2.17)
50	21.4 (2.61)	20.5 (2.15)	22.0 (2.35)	24.4 (2.12)	26.1 (2.29)
75	21.6 (2.43)	20.7 (1.90)	21.1 (2.41)	27.6 (1.80)	29.4 (2.39)
90	22.2 (2.62)	22.6 (2.95)	20.8 (1.59)	29.9 (2.97)	32.9 (2.45)

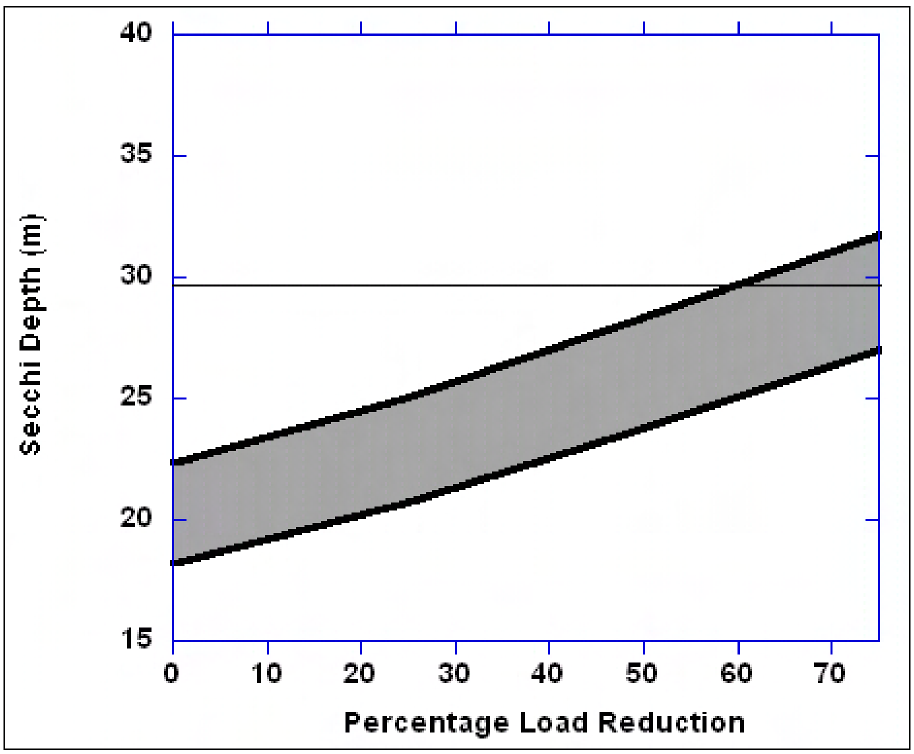

Figure 6-22. The variation of Secchi depth (meters) in response to percentage reductions of fine particles, nitrogen and phosphorus from urban sources only. Secchi depth is calculated as the average over 10 years after equilibrium conditions have been attained. The shaded area is the average Secchi depth ± 1 standard deviation, and therefore gives the expected range of variation in observed Secchi depth. The horizontal line is the clarity threshold value of 29.7 meters. This case is illustrative and is not the recommended pollutant reduction target.

Since a stepwise reduction in loading would be the most realistic management scenario, the model was run to see how the lake would respond to such a practice. Two such scenarios: (1) 75 percent urban load reduction from all urban sources at a uniform rate of 3.75 percent per year for 20 years and (2) 90 percent urban load reduction from all urban sources at a uniform rate of 4.5 percent per year for 20 years were examined. In these two cases, the load reduction percentage increases every year. Thus, it is seen that in the case of a stepwise 75 percent reduction, clarity increased and approached the 30 meter target in 20 years (Figure 6-23). For the stepwise 90 percent reduction case, the 30 meter clarity was achieved in 15 years (Figure 6-24).

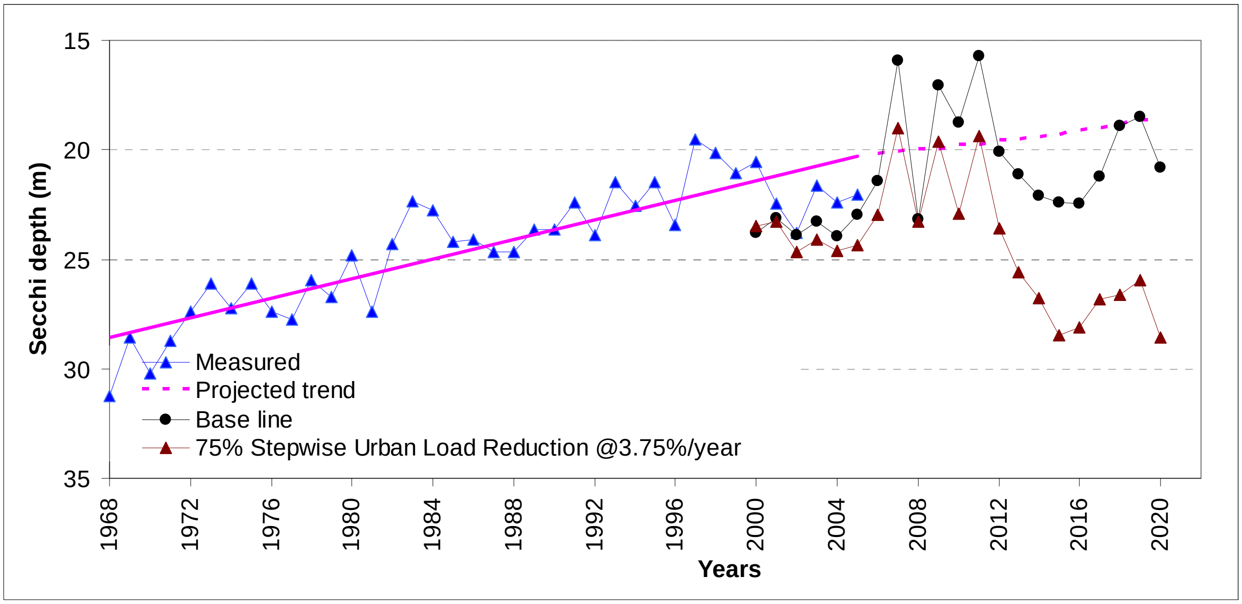

Figure 6-23. Simulated annual average Secchi depths for 75 percent urban load reduction from all sources at a rate of 3.75 percent per year for 20 years.

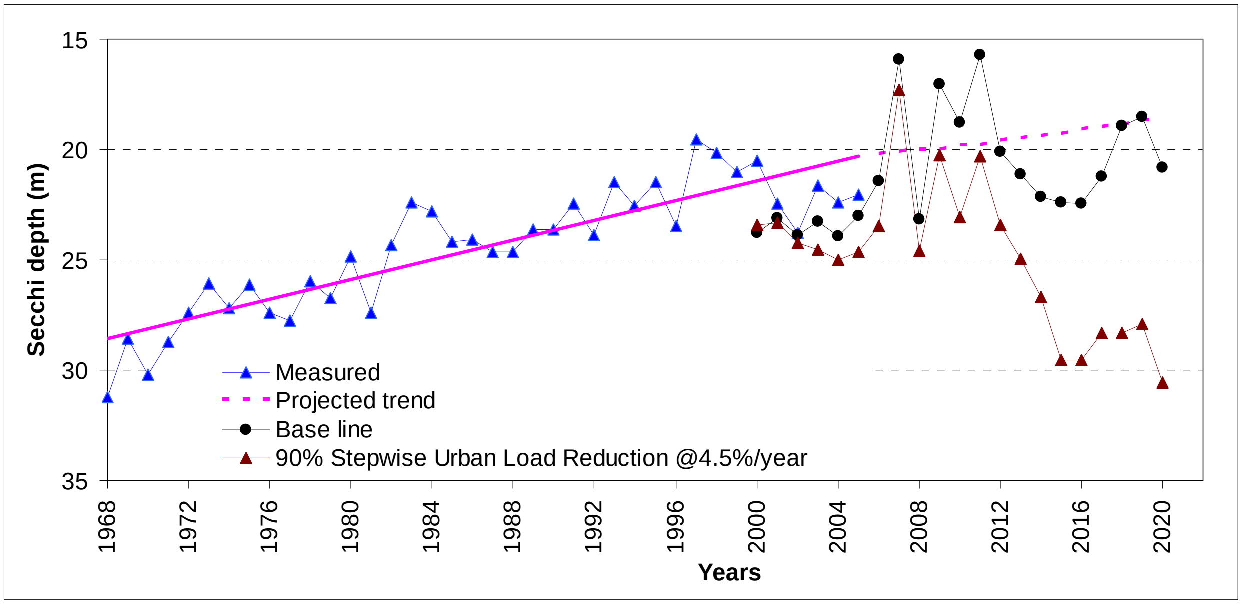

Figure 6-24. Simulated annual average Secchi depths for 90 percent load reduction from all sources at a rate of 4.5 percent per year for 20 years.

6.5 Discussion of Achievability

In conclusion, the results of the simulation runs conducted to date using the Lake Clarity Model suggest that is it possible to achieve the 30 meter TMDL target for Secchi depth in Lake Tahoe, provided that the required load reduction can be achieved. This is supported by the paleolimnological study by Heyvaert (1998) that found that lake water quality conditions were able to recover to historic levels in as short as 20-30 years following the Comstock era when about 60 percent of the basin was clear cut for timber use. In addition, the interannual variation in the modern Secchi record (since 1968) shows that during dry periods when pollutant loading is reduced, Secchi depth can increase by many meters over a period of just a few years. The Lake Clarity Model indicates that if pollutant loading were theoretically reduced to zero instantaneously, the lake could achieve the 30 meter target in 10 years.

It is also appropriate to comment on the reasonableness of the Lake Clarity Model results regarding the percent of load reduction estimated to meet the approximately 30 meter TMDL target. First, we acknowledge that either the 55 percent of the total load from all sources, basin-wide or the 75 percent reduction from urban sources are large numbers. In support of these findings, a recent GIS analysis conducted by Raumann and Cablk (2008) found that between 1969 and 2002 the total amount of developed land and impervious cover in the Upper Truckee and Trout watersheds (along the south shore) increased by 69 percent and 75 percent respectively. Given the large amount of urban development in the Lake Tahoe basin in the late 1960's these are conservative estimates to define the change in urban land-use over the period of record that has affected the long-term Secchi plot. These changes in urban land-use also do not account for the fact that increased impervious coverage has a double negative affect – more pollutant generation and less infiltration. Therefore, Raumann and Cablk's GIS analysis support the Lake Clarity Model findings that pollutant reduction on the order of 75 percent might be realistic for urban areas.

Swift (2004) developed a plot showing the relationship between particle number in Lake Tahoe proper and corresponding Secchi depth (Figure 6-25). This relationship was based on over 40 individual observations made in Lake Tahoe where Secchi depth and the number of particles found between the surface and the Secchi depth were measured at the same time. Based on these findings a reduction of particles in the lake of approximately 65 percent would be needed to achieve a Secchi depth of 30 meter. Again, this is on the same order of reduction as determined by the Lake Clarity Model and further supports the contention that the Lake Clarity Model can be used as a reliable management tool.

One final validation of (1) the Lake Clarity Model, (2) the contention that fine sediment particles drive Secchi depth, and (3) that the estimates of fine sediment particle loading to Lake Tahoe are reasonable comes from the Lake Clarity Model run in which urban particle loading from all the major sources (watershed, atmospheric deposition and stream channel) was set to non-urban (i.e. pre-development) conditions (refer to Table 5-8). The resulting Secchi depth at the end of the modeling period was 30.8 meters. As discussed below, this level of clarity is what the historical average in the absence of urban particle loading is believed to have been. This result further reinforces that the information on fine sediment particles and lake clarity that forms the foundation of the Lake Clarity Model is fundamentally sound.

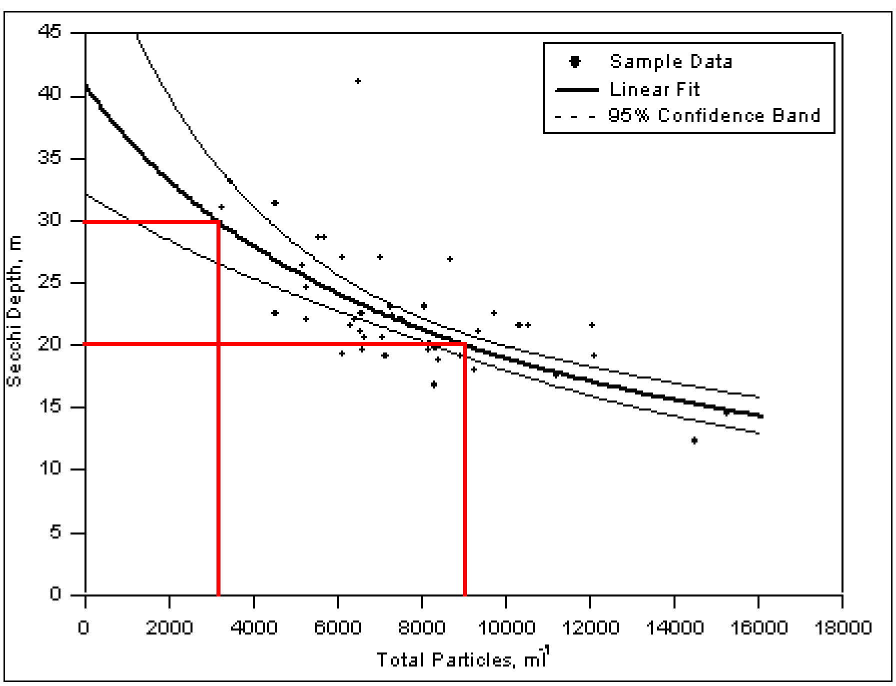

Figure 6-25. Direct measurements from Lake Tahoe that show the relationship between number of in-lake particles (not loads) and Secchi depth (Swift 2004). Figure was modified to highlight that a reduction of approximately 65 percent of the in-lake particles would

be needed to improve Secchi depth from its current value of nearly 20 meters to the TMDL target of nearly 30 meters.

Finally, it can be hypothesized that the approximately 30 meter Secchi depth standard for annual average conditions may not be that far removed from pre-1968 levels. University of California, Berkeley professor John LeConte was the first to measure the clarity of Lake Tahoe with a Secchi disk in September of 1873 (LeConte 1883). Using a 24 cm disk (one centimeter smaller than the 25 cm disk used today) he recorded a value of 33 meters, albeit a single measurement. In 1959 and 1960, University of California, Davis professor Charles R. Goldman (unpublished data) recorded individual Secchi measurements ranging from 24-36 meters (reported *In:* Reuter and Miller 2000). Therefore, if the approximately 30 meter TMDL target is close to the historical value it is not unreasonable to conclude that significant load reductions will be needed.

Taken together, these observations all indicate that recovery of the lake is possible and that the Lake Clarity Model now provides managers, for the first time, with a science-based tool that can be used for water quality planning.

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Appendix A

The zooplankton model is developed based on the equations described in Arhonditsis and Brett (2005). The jth zooplankton group (j = copepods or cladocerans) in ith layer over the time step is estimated as:

$$\frac{\partial ZOOP(i,j)}{\partial t} = growth\_rate(i,j) \times f(T_G) \times ZOOP(i,j) \times \left\{ \sum_{k=a\lg ae} grazing_{a\lg ae}(i,j,k) + grazing_{\det rius}(i,j) \right\} - mortality(i,j) \times f(T_m) \times ZOOP(i,j) - predation(i,j) - outflow(i) \times ZOOP(i,j)$$

Equation 5

Where:

growth_rate (*i,j*) = Growth rate of jth zooplankton in ith layer

ZOOP(*i,j*) = Concentration of the jth zooplankton group (j = cladocerans or copepods) in ith layer

$f(T_G)$ = temperature multiplier for growth of zooplankton

$grazing_{algae}$ (*i,j,k*) = Grazing rate of jth zooplankton group for kth

phytoplankton group (k = greens, diatoms, cyanobacteria) in ith layer

$grazing_{algae}$ (*i,j*) = Grazing rate of jth zooplankton group for detritus (i.e., particulate organic carbon (POC) in ith layer

mortality (*i,j*) = Metabolism rate (day^{-1})

$f(T_m)$ = temperature multiplier for mortality of zooplankton

predation (*i,j*) = Predation rate of j zooplankton group in ith layer

outflow (*i*) = Total outflow volume in ith layer

The growth rate of zooplankton as affected by the water temperature was also included in the model as was the competitive preferences of zooplankton for algae versus detritus as a food source, and loss due to predation.

For modeling purposes, we considered only one, composite group each for zooplankton and phytoplankton, i.e. activities of specific species were not incorporated. Parameters used in the zooplankton sub-model are given in Table A- 1.

Table A- 1. Parameters used in zooplankton sub-model along with references cited supporting the use of these values.

	Symbols	value	Units	Reference
1	growth_rate	1.0	day^{-1}	
2	CT_4	0.002	$^oC^{-2}$	2, 3, 5, 9, 10
3	CT_5	0.002	$^oC^{-2}$	2, 3, 5, 9, 10
4	CT_m	0.05	$^oC^{-1}$	
5	T_{opt}	18	^oC	2, 3, 5, 9, 10
6	T_{ref}	20	^oC	3, 4
7	KZ	100	$m\ C\ m^{-3}$	9, 10
8	$grazing_{max}$	0.45	dy^{-1}	2, 3, 5, 9, 10
9	pref	0.25	-	1
10	$pref_{det}$	0.25	-	1
11	$pred_1$	0.15	dy^{-1}	6, 7, 8
12	$pred_2$	40	$m\ C\ m^{-3}$	6, 7, 8

(1) Arhonditsis and Brett (2005), (2) Chen et al. (2002), (3) Wetzel (2001), (4) Omlin et al. (2001a,b), (5) Lampert and Sommer (1997), (6) Ross et al. (1994), (7) Malchow (1994), (8) Fasham (1993), (9) Jorgensen et al. (1991), (10) Sommer (1989), (11) Downing and Rigler (1984) and (12) Orcutt and Porter (1983).

Appendix B

Table B-1. Metric to English unit conversion chart

Conversions			
	To Convert From	**To**	**Multiply By**
Mass			
	metric tons (MT)	tons	1.1023
		pounds (lbs)	2,204.6
	kilogram (kg)	pounds (lbs)	2.2046
	gram (g)	ounce (oz)	0.0353
Volume			
	liter (L)	gallon	0.2642
Length			
	kilometers (km)	miles (mi)	0.6214
	meter (m)	feet (ft)	3.281
	centimeter (cm)	inch (in)	0.3937
Area			
	square kilometers (km^2)	square miles (mi^2)	0.3861
	square meter (m^2)	square foot (ft^2)	10.765
Temperature			
	degree Celcius (°C)	degree Farenheit (°F)	°F=(°C*1.8)+32

Note: The temperature conversion is in the form of an equation instead of a multiplier.