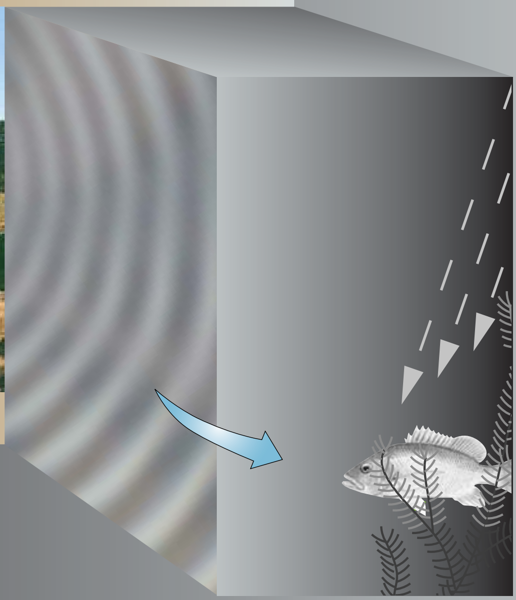
Luna Lake: Total Maximum Daily Load Study

Prepared for: ADEQ



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Luna Lake TMDL – ADEQ Abstract

The Arizona Department of Environmental Quality has identified Luna Lake as not supporting its designated uses due to observed exceedences of water quality standards for pH and narrative nutrients (excessive weeds). Historically, high external inputs of nutrients (nitrogen and phosphorus) to the lake, as well as in-lake nutrient cycling, have resulted in a highly productive (eutrophic) system. Because Luna Lake does not fully support its designated uses, ADEQ has developed a Total Maximum Daily Load (TMDL) for nitrogen and phosphorus. Based on nutrient load reductions and the projections for associated indicators, the standards for pH, ammonia toxicity, and narrative nutrients will be achieved pursuant to section 303(d) of the Clean Water Act.

The TMDL is the mechanism established in the Clean Water Act for situations in which water quality impairments cannot be mitigated by imposition of technology-based effluent limits on permitted point sources. As this TMDL explains, it appears that non-point sources of nutrients are the cause of eutrophic conditions in Luna Lake. The TMDL consists of allocation of the available loading capacity of the lake (the maximum rate of loading that would be consistent with achieving standards for designated uses) to point sources, non-point sources, and a margin of safety. Within the Luna Lake watershed there are no permitted point sources of nutrients. There are several non-point sources of nutrients in the watershed and within the lake itself including: septic systems, forest runoff, agricultural runoff, residential and commercial runoff, decomposition of aquatic plants, and groundwater.

TMDLs for nitrogen and phosphorus in Luna Lake can be expressed by the equation: Wasteload Allocation (WLA - point sources) + Load Allocation (LA - non-point sources) + Margin of Safety (MOS) = TMDL. (*The Margin of Safety for this TMDL has been built into conservative assumptions within the watershed loading and in-lake nutrient cycling models developed for this analysis, captured in Section 4 of this report.) TMDL for nitrogen equates to a 46 % reduction from historical levels, and for phosphorus, a 67 % reduction from historical levels. In addition, a projected 37 % reduction in Chlorophyll-a from historic levels will be used as an indicator for assessing TMDL success. This TMDL estimates the desired loading capacity of Luna Lake to be approximately 25,320 pounds per year of nitrogen (69.4 lbs/day) and 6954 pounds of phosphorus (19 lbs/day). Based on the modeled historic budget, the following load reductions from non-point sources are needed to achieve water quality standards (taken from "Scenario 2, non-dredging option", Table ES-2 for N & Table ES-3 for P):

Nitrogen TMDL:
LA1 (septic) + LA2 (residential) + LA3 (commercial) + LA4 (groundwater) + LA5 (ag-livestock) + LA6 (ag-elk) + LA7 (barren land) + LA8 (forest) + LA9 (range) + LA 10 (macrophyte decomp) + LA11 (sediment release) + MOS = 25,320 lbs/yr Total Nitrogen

or (all numbers represent lbs/day): 10.45+3.11+1.21+4.35+8.70+4.35+.42+6.76+ .36+27.54+2.12+MOS = **69.4 lbs/day N**

The categories of nonpoint sources in which reductions are required for nitrogen include: septic (50%), residential (50%), Ag-livestock (25%), Ag-elk (25%), and macrophyte decomposition (60%).

Phosphorus TMDL:

LA1 (septic) + LA2 (residential) + LA3 (commercial) + LA4 (groundwater) + LA5 (ag-livestock) + LA6 (ag-elk) + LA7 (barren land) + LA8 (forest) + LA9 (range) + LA 10 (macrophyte decomp) + LA11 (sediment release) + MOS = 6954 lbs/yr Total Phosphorus

or, (all numbers represent lbs/day): .33+.42+.12+.91+1.0+.50+4.83+.01+9.86+.72 + MOS = **19 lbs/day P**

The categories of nonpoint sources in which reductions are required for phosphorus include: septic (50%), residential (50%), Ag-livestock (25%), Ag-elk (25%), and macrophyte decomposition (60%).

Implementation:

Development of the TMDL Implementation Plan will establish the critical endpoint for macrophyte removal (biomass and/or percent cover) in accordance with the best professional judgement of the Arizona Game and Fish Department and ADEQ. Factors will include maintaining the best balance between the ecological effects of submerged vegetation, emergent vegetation, and phytoplankton in relation to achieving designated use standards.

Improvements in DO and pH will be met through attainment of the specified load allocations. Reductions in nutrient loads, both external and internal, will reduce the biological demand (BOD) of decomposing macrophytes. Dissolved oxygen is expected to increase in accordance with reductions in BOD. Reduction in pH fluctuation is also expected due to reduction in plant biomass and BOD. There will be an added benefit in removal of macrophytes such that corridors are created for aeration.

In conjunction with these TMDLs, and in recognition of the limitations inherent in the modeling work used to simulate nutrient loading and cycling in the lake, ADEQ recommends, 1) a strong monitoring effort to gauge the success of implementing Best Management Practices (BMP’s) to reduce non-point source loading of nutrients, and 2) regular monitoring of tributary and in-lake water quality to assess the impacts of these nutrient load reductions. ADEQ is committed to work with local stakeholders, the community of Alpine, and the Arizona Game and Fish Department to develop an implementation and monitoring plan sufficient to meet these goals.

EXECUTIVE SUMMARY

Description of TMDL Process

High quality water is an extremely valuable commodity in Arizona. Water quality standards are established to protect the designated uses of Arizona's waters. When States and local communities identify problems in meeting water quality standards a total maximum daily load (TMDL) can be part of a plan to fix water quality problems. The purpose of this TMDL study is to provide the local community, ADEQ, and U.S. EPA Region 9 with technical information that can be used to develop a water quality plan.

Watershed Overview

Luna Lake, located in southeastern Apache County in the Apache-Sitgreaves National Forests, is a man-made impoundment on the San Francisco River, which flows 11 miles from it's headwater springs in the ponderosa/mixed conifer forests of Noble Mountain to Luna Lake. The lake, which is classified as eutrophic, is located east of Alpine, Arizona. The elevation in the watershed ranges from 9,576 ft at the San Francisco headwaters to 8,004 ft at the town of Alpine to 7882 ft at Luna Lake. The lake has a mean depth of 6.8 feet and a maximum depth of 27 feet. The lake has a residence time of approximately 38 days.

Luna Lake is designated for the following uses under Title 18, Chapter 11 of the Arizona Administrative Code:

A&Wc: Aquatic and wildlife uses, coldwater fishery;
FBC: Full body contact;
FC: Fish consumption;
AgI: Agricultural irrigation; and
AgL: Agricultural livestock watering

GIS coverages for land use, land ownership, and vegetation types were obtained from the Arizona Department of Environmental Quality (Ms. L. Jaress), and from BASINS2 (US EPA, 1998). Land usage is based on Anderson Level 2 land classification system.

Identification of Violated Water Quality Standards and Impaired Designated Uses

Water quality standards are commonly expressed as either numeric (a specific concentration which cannot be exceeded) or narrative (used to describe a condition that is not desired). Arizona uses both types of water quality standards for Luna Lake. Luna Lake is listed on Arizona's 1998 303(d) list as impaired due to violations of narrative nutrient standards, and numeric pH and dissolved oxygen standards.

The water quality standards for these parameters (Title 18, Chapter 11 Arizona Administrative Code) are as follows:

- pH shall be between 4.5 and 9.0 SUs; The critical low pH for Aquatic and Wildlife is 6.5 SU;
- Dissolved oxygen shall not be lower than 7.0 mg/L between the surface and one meter depth, and the minimum dissolved oxygen saturation is 90%; and
- Nutrient concentrations shall not cause growth of algae or aquatic plants or settling of bottom deposits that inhibit or prohibit the habitation, growth, or propagation of other aquatic life or that impair recreational uses. Nutrient concentrations shall not change the color of the surface water from natural background levels of color.

In addition to the water quality standards for Luna Lake, standards for the San Francisco River and tributaries upstream of Luna Lake state that total phosphates shall not exceed 1.0 mg/L as P. Based on these water quality standards, pH standards for Luna Lake were violated in 24 out of 154 samples (16%) between 1995 and 1997. Dissolved oxygen standards in the upper one meter water depth were violated in 4 out of 14 samples (29%) during the same time period. Narrative nutrient standards in Luna Lake have also been violated during this time period due to the presence of noxious aquatic weeds and phytoplankton.

Excess nutrients in Luna Lake sediments most likely account for excessive macrophyte growth and algal blooms in the Lake. Records from the Arizona Game and Fish Department (AGFD) for the period 1982 to 1997 (J. Novy, AGFD, personal communication) provide information for 9 annual harvests. Between 1982 and 1990, the annual harvest of macrophytes from Luna Lake ranged from between 81 and 999 tons (0.67 to 8.3 tons per acre). Between 1994 and 1997, the annual harvest of macrophytes from Luna Lake ranged between 246 and 527 tons (2.1 to 4.4 tons per acre).

pH and dissolved oxygen are easily measurable water quality parameters and numeric water quality standards aid in determining whether violations are occurring. Luna Lake has been listed as impaired because of high pH levels, low dissolved oxygen concentrations, and nutrient concentrations that stimulate the growth of noxious aquatic weeds and phytoplankton in the water column. All three of these measures are inter-related, with the presence of excessive aquatic plant biomass driving the elevated pH and depressed DO levels

Numeric Targets

Possible water quality targets to control the noxious weed growth in Luna Lake could be expressed in terms of nutrient concentrations (e.g., mg/L of phosphorus and/or nitrogen) or macrophyte/phytoplankton parameters (e.g., extent of growth, area of effect, biomass). The Water Quality Standards for these parameters in Title 18, Chapter 11 of the Arizona Administrative Code are as follows:

- pH, (A&Wc). The following water quality standards for pH, expressed in standard units (SUs) shall not be lower than 4.5 SU or greater than 9.0 SU (A.A.C. R18-11-109, paragraph D). The critical low pH for Aquatic and Wildlife is 6.5 SU;

- Dissolved oxygen, Aquatic and Wildlife, cold water fishery (A&Wc). The dissolved oxygen concentration in surface water shall not fall below 7.0 mg/L (A.A.C. r18-11-109, paragraph G). In the case of lakes, there is a further footnote in that: the dissolved oxygen water quality standard for a lake shall apply below the surface but not at a depth greater than 1 meter. The dissolved oxygen standard also includes a provision for a minimum saturation of 90%;

- Nutrients, (A.A.C. R18-11-109, paragraph A, Narrative Water quality Standards). This paragraph lists eight different impacts on surface waters that are considered the narrative standards for the state. The narrative water quality standards that are applicable to Luna Lake (R18-11-108-Narrative Water quality Standards) are listed below:

A surface water shall be free from pollution in amounts or combinations that:

- Cause the growth of algae or aquatic plants or the settling of bottom deposits that inhibit or prohibit the habitation, growth, or propagation of other aquatic life or that impair recreational uses;

- Change the color of the surface water from natural background levels of color.

The water quality standard for the San Francisco River and tributaries upstream of Luna Lake Dam state that the waters shall not exceed 1.0 mg/L total phosphates as P (A.A.C. R18-11-109, Section H, Numeric Water Quality Standards).

The numeric targets recommended for the Luna Lake TMDL are compared to existing conditions in Table ES-1.

Table ES-1
Comparison of Existing Conditions to TMDL Endpoints

Parameter	Existing Value (Mean and range)	TMDL Endpoint	Comments
pH (SU)	8.5 (7. 2 – 9.68)	Arizona Water Quality Standard: pH > 4.5 and < 9.0	This range ensures minimum concentrations of unionized ammonia and reduces toxicity to aquatic organisms caused by pH shock. Validated by monitoring
Dissolved Oxygen (mg/L)	6.2 (0.16 – 10.51)	Arizona Water Quality Standard: DO > 7.0 mg/L or 90% saturation in upper 1 meter water depth	This range ensures that water column concentrations of dissolved oxygen will be adequate to sustain aquatic life. Validated by monitoring
Phosphorus (mg/L)	0.18 (0.02 – 0.30)	Arizona Water Quality Standard: < 1.0 mg/L for Tributaries, Best Professional Judgment for Lake; phosphorus high in runoff	ADEQ (1999) total phosphorus between 0.01 – 0.02 mg/L or, ADEQ (2000): total phosphorus between 0.01 – 0.04 mg/L is classified “mesotrophic”; 0.04 – 0.07 is classified “eutrophic” Validated through Phased TMDL Monitoring.
Nitrogen (mg/L)	0.5 (<0.01 – 1.98)	Arizona Water Quality Standard: Best Professional Judgment for lake, which is limited b y nitrogen	ADEQ (2000): total nitrogen between 0.28 – 0.75 mg/L is classified “mesotrophic”; 0.75 – 1.2 is classified “eutrophic” Validated through Phased TMDL Monitoring.
Total Ammonia (mg/L)	Total Ammonia: 0.24 (0.08 – 0.57) Unionized Ammonia: 0.4 mg/L (using worst-case conditions)	Protection of sensitive coldwater fish species (i.e., salmonids): Arizona Acute Standard for Acute exposure: pH & temperature dependent* Federal Criteria: concentrations of unionized ammonia for: Acute Exposure (< 1 hr): =0.35 mg/L; Chronic (4-days): =0.02 mg/L	Unionized ammonia is a strongly toxic aquatic pollutant whose concentration is driven by water column pH and temperature. *Concentrations measured to date are protective of the coldwater fishery in Luna Lake, but acute threshold for extreme high pH and temperature is 0.67 mg/L Validated through Phased TMDL Monitoring.
Aquatic Plants	The presence of excessive quantities that are causing impairment to the beneficial uses of the lake	Reduce quantities of nuisance aquatic plants	Reduce the quantities of nuisance aquatic plant biomass to levels that would not drive water column pH and dissolved oxygen levels to extremes or result in increasing the concentrations of unionized ammonia to toxic levels. Validated through Phased TMDL Monitoring.

Technical Approach

The technical approach to the Luna Lake TMDL study included four primary elements: 1) conduct a source analysis for loadings, 2) develop a nutrient mass balance model for Luna Lake, 3) link the pollutant loads (stressors) to water quality endpoints, and 4) allocate loads to source categories that ensure water quality objectives are met. A watershed loading model (GWLF) and an in-lake processes model (BATHTUB) were used to perform the analysis for these elements of the TMDL.

Source Analysis of Loadings

Simulated loadings of total and dissolved nitrogen (Figure ES-1) and phosphorus (Figure ES-2) in Luna Lake from within the watershed varied with annual precipitation over the 12-year period. Nutrient loads during low flow years (e.g., 1989) were less than half of the loads during the high flow years (e.g., 1992).

The long-term average annual loading of total nitrogen and total phosphorus from the Luna Lake watershed source categories are illustrated in Figure E-3a & b. The following nutrient allocations and reductions are expected to reduce the frequency, duration, and magnitude of water quality standard violations and result in attainment of designated uses. Occasional exceedances of numeric pH standard may still occur in summer months at Luna Lake, exacerbated by the effects of high altitude. However, the lake will be managed as whole to provide refuge from pH impairment during these critical times. Luna Lake will remain eutrophic, but the degree of eutrophication will be controlled. The nutrient reduction objectives expressed in the allocations are targeted on nonpoint sources and in-lake sources of nutrients.

ADEQ has assigned Scenario 2 allocations for this TMDL, summarized in Table ES-2 (nitrogen) and ES-3 (phosphorus). Additional reductions through targeted allocations that would be necessary to completely reverse eutrophication would require unrealistic levels of control and/or infeasible expense on all source categories including background sources.

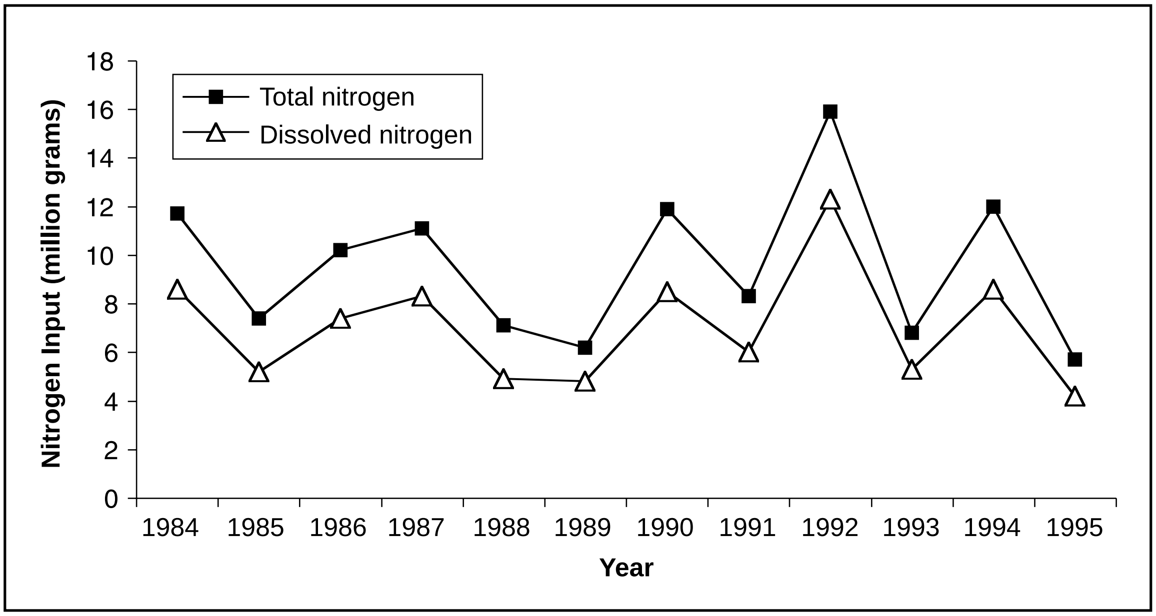


Figure ES-1. Annual total nitrogen and dissolved nitrogen inputs to Luna Lake.

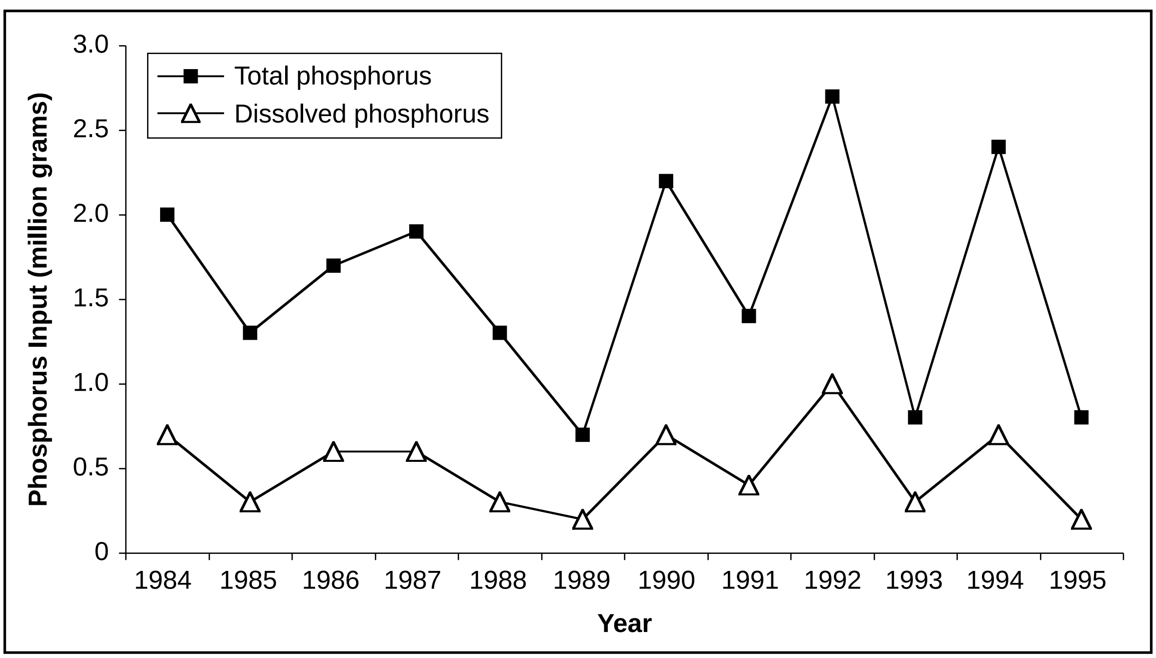
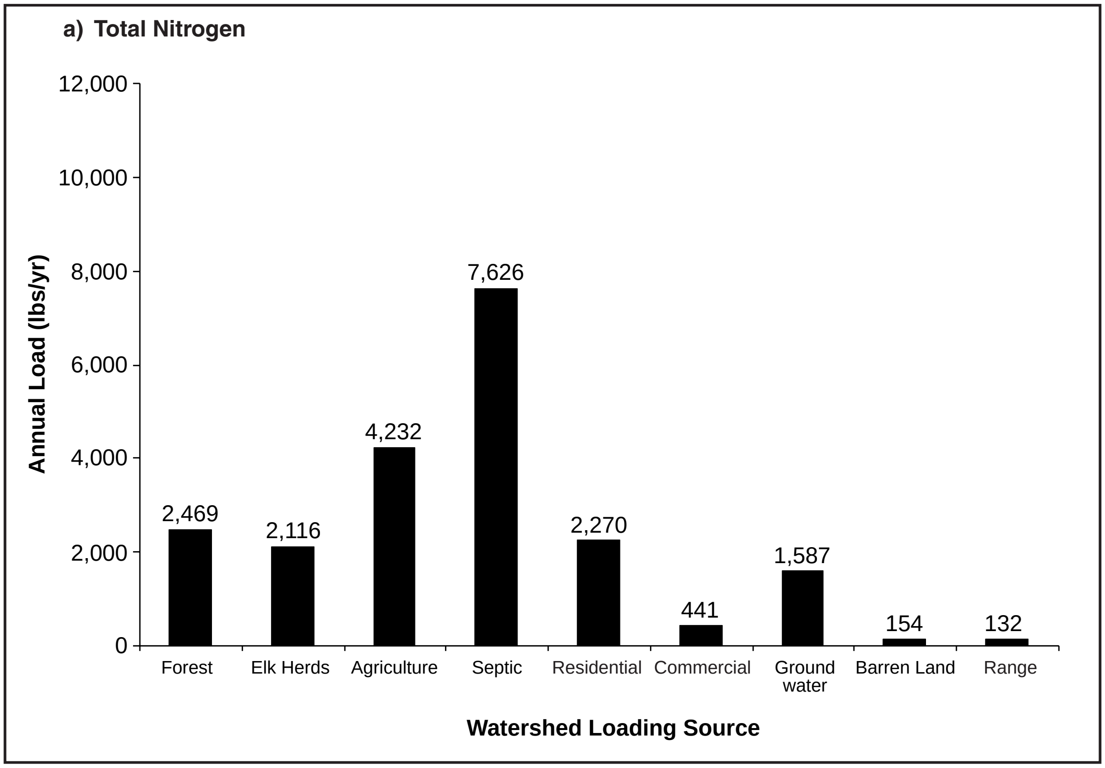


Figure ES-2. Annual total phosphorus and dissolved phosphorus inputs to Luna Lake.



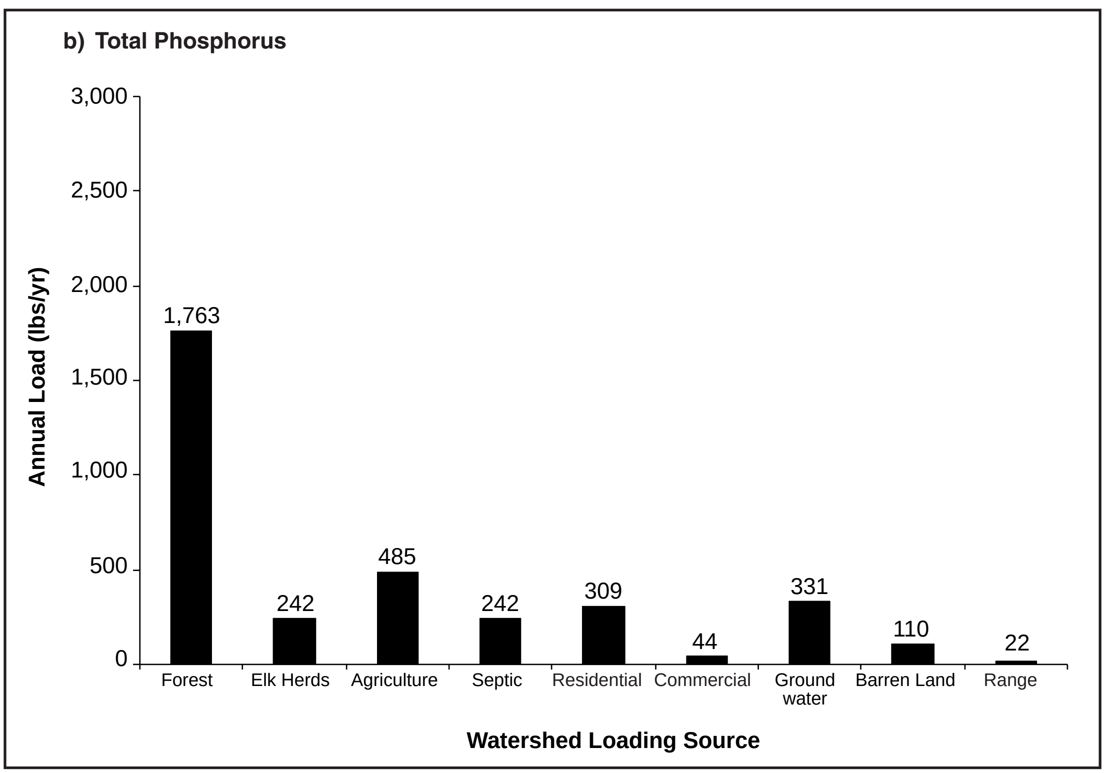


Figure ES3a & b. Long-term averages of annual (a) total nitrogen and (b) total phosphorus contributions to Luna Lake.

Table ES-2
Luna Lake Allocations for Nitrogen (Scenario 2)

Source Category	Existing Nitrogen Total Loading (TL) (Lbs/yr)	% Existing Total Watershed/ Lake Loading	% Targeted Reduction of Category	Amount Nitrogen Reduced (Lbs/yr)	Remaining Load (RL) (Lbs/yr)
Septic	7,628	16%	50%	3,814	3,814
Residential	2,271	5%	50%	1,135.5	1,135.5
Commercial	441	1%	0%	0	441
Groundwater	1,587	3%	0%	0	1,587
Agriculture	4,233	9%	25%	1,058	3,175
Elk Herds	2,116	5%	25%	529	1,587
Barren Land	154	0%	0%	0	154
Forest	2,469	5%	0%	0	2,469
Range	132	0%	0%	0	132
Macrophyte Decomposition	25,132	54%	60%	15,079	10,053
Sediment Release (Dredging)	772	2%	0% (50%)	0 (386)	772 (386)
Total (Dredging)	46,935	100%		21,615.5 (22,001.5)	25,319.5 (24,933.5)

% of total existing nitrogen load remaining = 54%
= (53%)

% total watershed loadings of nitrogen reduced = 46%
= (47%)

Note: Numbers in parentheses represent values associated with the dredging scenario.

Table ES-3
Luna Lake Allocations for Phosphorus (Scenario 2)

Source Category	Existing Phosphorus Total Loading (TL) (Lbs/yr)	% Existing Total Watershed/ Lake Loading	% Targeted Reduction of Category	Amount Phosphorus Reduced (Lbs/yr)	Remaining Load (RL) (Lbs/yr)
Septic	242	2%	50%	121	121
Residential	309	2%	50%	154.5	154.5
Commercial	44	0%	0%	0	44
Groundwater	331	3%	0%	0	331
Agriculture	485	4%	25%	60.5	181.5
Elk Herds	242	2%	33%	80	162
Barren Land	110	1%	0%	0	110
Forest	1,764	14%	0%	0	1,764
Range	22	0%	0%	0	22
Macrophyte Decomposition	8,995	70%	60%	5,397	3,598
Sediment Release (Dredging)	264	2%	0% (50%)	0 (132)	264 (132)
Total (Dredging)	12,808	100%		5,854 (5,986)	6,954 (6,822)

% of total existing phosphorus load remaining = 54%
= (53%)

% total watershed loadings of phosphorus reduced = 46%
= (47%)

Note: Numbers in parentheses represent values associated with the dredging scenario.

Linkage of Nutrient Loadings to In-Lake Water Quality Indicators

The BATHTUB model was used to predict the concentrations of total phosphorus, total nitrogen, and chlorophyll-*a* in Luna Lake in response to different nutrient loading scenarios. Three major sets of conditions were analyzed:

1. Effects of scaled reductions in watershed nutrient loads
2. Effects of scaled reductions in macrophytes
3. Effects of scaled reductions in watershed nutrient loads with all macrophytes removed from the lake (dredged).

The concentrations of total phosphorus, total nitrogen, and chlorophyll-*a* that were predicted under the different environmental conditions and scenarios are compared to the ADEQ trophic classifications that are used for the 305 (b) statewide water quality assessment process. For comparison, effects on trophic levels from TMDL scenarios are presented in Figures ES-4 to ES-6. The results focus on nutrient and phytoplankton (chlorophyll-*a*) concentrations and the resulting trophic status, rather than directly on water quality variables such as pH and dissolved oxygen. Macrophyte productivity was simulated in BATHTUB as aerial biomass (chlorophyll-*a*) and will be tracked both directly and through planktonic productivity. The TMDL makes the assumption that a significant reduction in trophic parameter (nutrients and chlorophyll-*a*) loading to the lake will result in incremental but also significant reductions in lake trophic status, with corresponding improvements in maintaining acceptable pH and DO levels.

In other words, implementation measures which decrease nutrient loading will lower productivity in the lake. Allocated reductions in external and internal nutrient loading are expected to result in substantial attainment of water quality standards. A focused monitoring plan will be developed to calibrate nutrient and chlorophyll concentrations to seasonal changes in plant biomass and diurnal fluctuations of DO and pH. This type of focused monitoring within the context of particular lake ecology, will allow development of a predictive model for minimizing pH and dissolved oxygen problems in Luna Lake, as well as developing a better understanding of actual vs. perceived impairments. Though periodic high pH and dissolved oxygen levels are typical in lakes that are highly productive, their quantitative impact of attainment of lake designated uses is not fully understood.

If, after the required load reductions are achieved, exceedances continue *and* specific impairments are demonstrated, there will be need to: 1) revisit load reduction, and 2) collect more extensive diurnal and temporal data, to 3) set up and calibrate a more complex predictive ecosystem model.

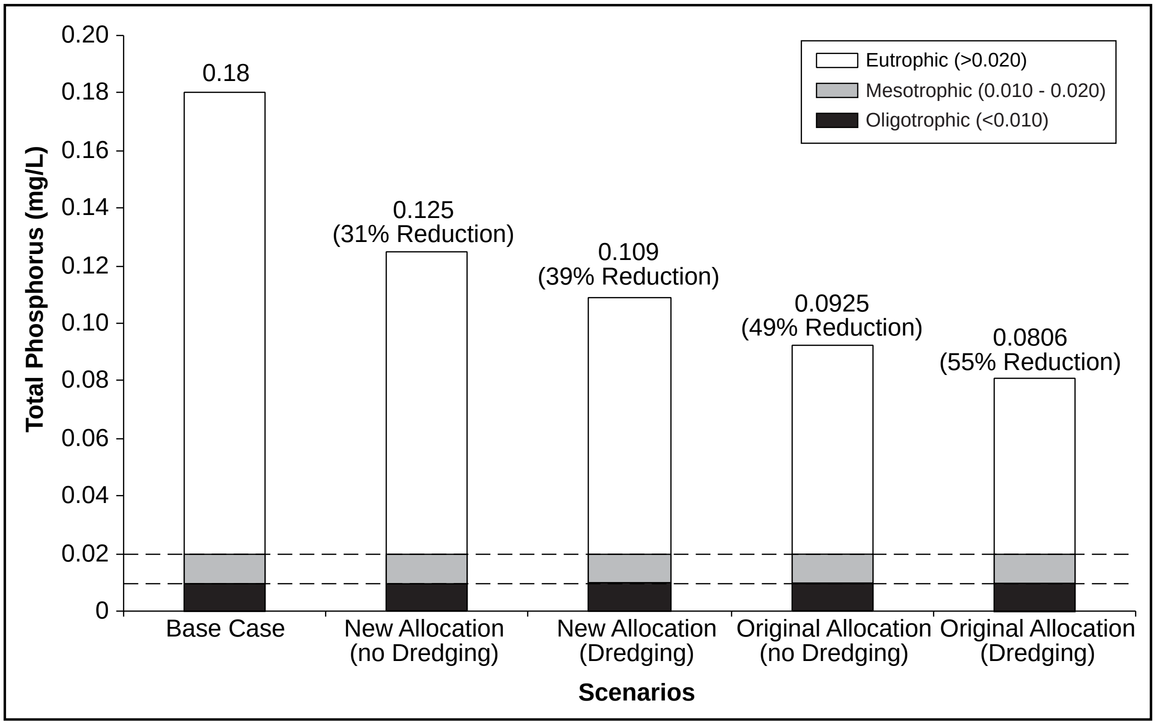


Figure ES-4. Effects scenarios of remedial actions on total phosphorus concentrations in Luna Lake.

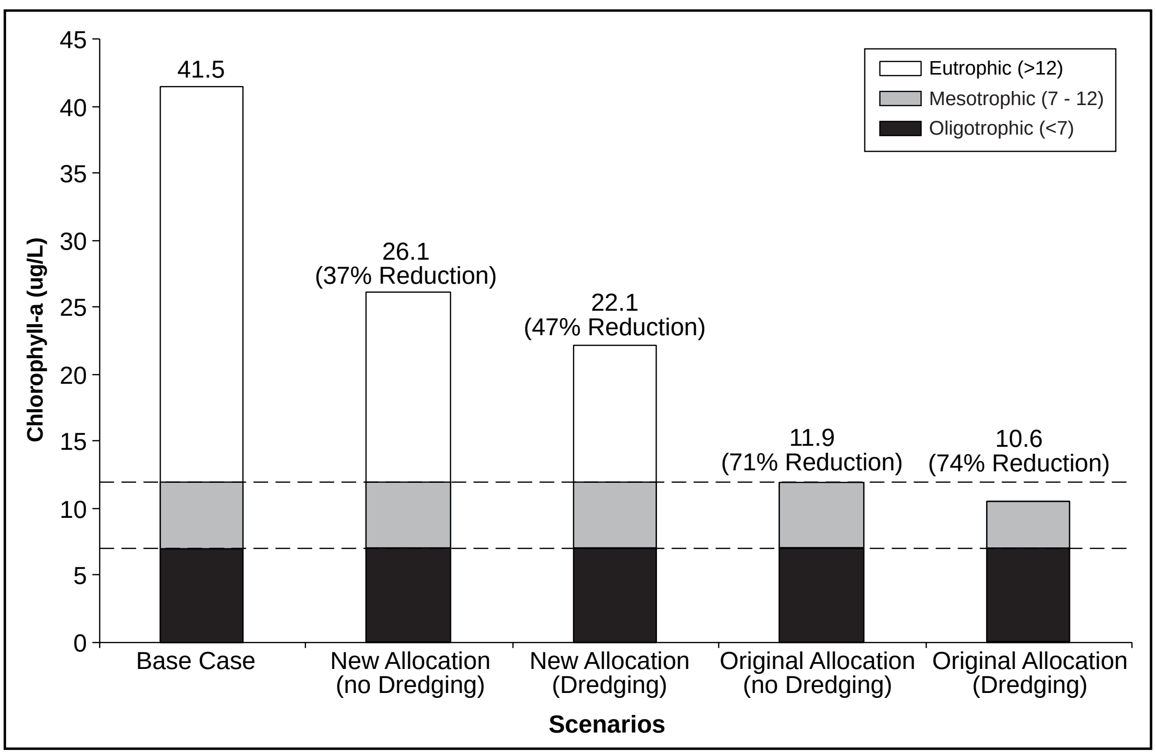


Figure ES-5. Existing scenarios of remedial actions on chlorophyll-*a* concentrations in Luna Lake.

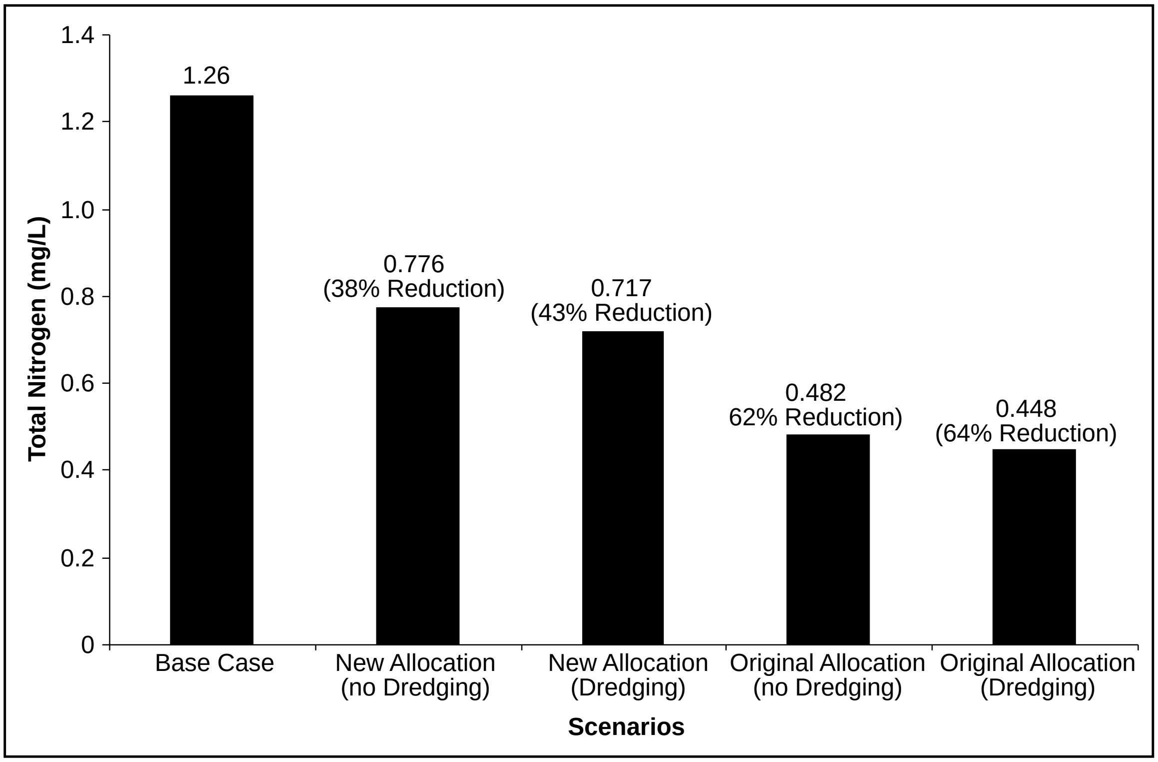


Figure ES-6. Effects scenarios of remedial actions on total nitrogen concentrations in Luna Lake.

The Trophic Classification Thresholds shown below are based on Brazonick, (1982), a multivariate TSI using Florida data. Because this scheme incorporates nitrogen, ADEQ plans to develop state-specific regression formulas to refine this index for Arizona lakes; many lakes exhibit seasonal variations or regional patterns in nutrient limitation.

*TSI	Trophic State	Chlor-a (ug/L)	SD (m)	Total P (ug/L)		Total N (mg/L)	
				P-lim	N&P-lim	N-lim	N&P-lim
<30	Oligotrophic	<5	>3	<10	<13	<.25	<.28
30-45	Mesotrophic	5-12	1.2-3	10-20	13-35	.25-.65	.28-.75
45-65	Eutrophic	12-20	.6-1.2	20-35	35-65	.65-1.1	.75-1.2
>65	Hypereutrophic	>20	<.6	>35	>65	>1.1	>1.2

*TSI stands for “Trophic State Index”

TMDL Margin of Safety

TMDLs must include a Margin of Safety that assures water quality standards will be met. The following list of factors that were included in the technical analysis comprise the Margin of Safety for the Luna Lake TMDL:

- The watershed loading model (GWLF) evaluated loadings over a long period of time that included a wide range of climatic, precipitation, and flow patterns. The analysis included extreme high and low flow events over the period of record, providing boundaries for the assessment.
- The in-lake process analyses (BATHTUB) did not include the effect of shading by macrophytes on algal production in the lake.
- In the nutrient budget calculations, high macrophyte densities were assumed for the nutrient release fluxes from macrophyte decomposition.

Implementation Options

Septic Systems: The septic system allocation is confounded by inconsistent information on the number of septic systems remaining in use in the Luna Lake area. Therefore, the first step for implementation for the septic allocation is to conduct a survey to determine the number of remaining systems that are in use and the extent to which unused systems are continuing to leach nutrients to Luna Lake. The community could then consider the benefits of mitigating unused systems and active systems that are not functioning properly. If there are a large number of active systems, the community could consider extending sewer lines to unserviced areas near the lake.

Agriculture and Elk Herds: Agriculture loading is largely attributed to grazing activities in the watershed. Elk herds produce similar loading effects. Animal waste is a rich source of nutrients, and soil compaction increases the rate of runoff during storm events. There are a series of voluntary grazing BMPs that could be used to reduce runoff and loading from pastures. These BMPs would also be effective in reducing elk loads. ADEQ's Nonpoint Source program can be consulted for specific techniques and potential sources of funding for BMP implementation. The 25% reductions targeted by the allocation scenario is not an unrealistic goal for a voluntary BMP program developed by local landowners and managers.

Residential: Residential nutrient loads are a result of increased impervious surface and soil amendments (e.g., fertilizers for lawns) used by residents, along with other materials associated with development. There are a series of voluntary BMPs that could be used to reduce runoff from residential areas and other developments. ADEQ's Nonpoint Source program can be consulted for specific techniques and potential sources of funding for BMP implementation. The 50% reduction targeted by this allocation is not an unrealistic goal for a well conceived program of BMPs for the Luna Lake watershed communities.

Dredging: Dredging addresses the sediment release source category by removing the nutrient rich layers of soil that have been deposited on the lake bottom. The dredging goal would remove the top meter of sediments that have accumulated most of the nutrients. This assumption is based on the findings of Baker and Farnworth (1995) in their report, "Feasibility of Management Options to Improve Water Quality in Rainbow Lake. The soils below the accumulated sediments also contain nutrients. Therefore, it is not possible to remove 100% of the nutrients released from the sediments. Dredging would also improve water quality conditions by increasing the depth of the lake, limiting the reemergence of macrophytes in certain portions of the lake. Dredging would also increase the storage capacity of the reservoir. Baker and Farnsworth (1995) also provide some preliminary cost estimates and recommendations for planning dredging operations.

Macrophyte Harvest: Macrophyte decomposition is addressed both through dredging and macrophyte harvesting. Macrophytes would be largely eliminated by any dredging operation, but only temporarily. Macrophytes are known to thrive even in oligotrophic conditions because they are limited by light more than by nutrients. Macrophytes will re-colonize Luna Lake within a short period time after dredging has been completed. The well-established macrophyte harvest program should address this allocation requirement. However, there are other management options that the local community may want to consider (e.g., biological control). Luna Lake is currently managed for both waterfowl habitat and sport fish, so some of the vegetation must remain in the lake because of its importance to waterfowl habitat.

Other Best Management Practices: This implementation option does not directly address any of the source category allocations. However, Best Management Practices that would help maintain higher levels of water in the lake could significantly contribute to improved water quality. These BMPs would be directed to improving the efficiency of use of irrigation water that is drawn from the lake, possibly reducing the total amount of water that would need to be taken from the lake. Another conservation option that should be evaluated is to assess the need for lining irrigation canals from the lake to reduce seepage losses. The increased volume would serve to dilute the remaining nutrients and increase water depth (decreasing light availability), thus reducing overall algal productivity and slowing the emergence of macrophytes on exposed lake bed.

Watershed Forum: Luna Lake provides different beneficial uses to a wide range of residents within the Alpine community and surrounding areas. Many of the implementation recommendations will require local support and initiative. The local community may want to consider forming a watershed forum to build support for the nonpoint source BMPs that will be necessary to improve water quality in Luna Lake. A watershed forum would provide residents with a mechanism for coordinating activities to design, pursue funding for, and apply solutions to water quality problems within the Luna Lake watershed. ADEQ has a watershed approach program that could provide general assistance to the forum upon request from the local community.

Monitoring Recommendations

ADEQ, the local community, and other cooperating agencies will initiate a monitoring program for Luna Lake to assess whether the overall objectives of this TMDL are being met (i.e., no violations of narrative nutrient and numeric pH and DO standards within acceptable ranges for assessment).

Currently, Luna Lake is classified as a eutrophic waterbody. Modeling as shown that reversing the trophic status of Luna Lake is infeasible. From both a technical and economic perspective, Luna Lake will probably remain eutrophic. The goal of this TMDL is to incrementally improve lake health and introduce controls sufficient to substantially meet water quality standards. This improvement can be achieved via the various management procedures that have been discussed in section 4.2. With this in mind, the specific objective of the monitoring program is to assess whether the management procedures are achieving their stated objectives and improving the water quality of Luna Lake. ADEQ and AGFD will take the lead in developing a monitoring program in cooperation with the local community.

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1.1 Description of TMDL Process

High quality water is an extremely valuable commodity in Arizona. Water quality standards are established to protect the designated uses of Arizona's waters. When States and local communities identify problems in meeting water quality standards a total maximum daily load (TMDL) can be part of a plan to fix water quality problems. The purpose of this TMDL study is to provide the local community, ADEQ, and U.S. EPA Region 9 with technical information that can be used to develop a water quality plan.

Section 303(d) of the Clean Water Act (CWA) requires states to identify the waters for which the effluent limitations required under the National Permit Discharge Elimination System (NPDES) or any other enforceable limits are not stringent enough to meet any water quality standard adopted for such waters. The states must also rank these impaired water bodies by priority, taking into account the severity of the pollution and the uses to be made of the waters. Lists of prioritized impaired water bodies are known as the "303(d) lists" and must be submitted to EPA every two years.

A TMDL represents the total load of a pollutant that can be discharged to a water body on a daily basis and still meet the applicable water quality standard. The TMDL can be expressed as the total mass or quantity that can enter the water body within a unit of time. In most cases, the TMDL determines the allowable pounds per day of a constituent and divides it among the various contributors in the watershed as waste load (i.e., point source discharge) and load (i.e., nonpoint source) allocations. The TMDL also accounts for natural background sources and provides a margin of safety. For nonpoint sources such as accelerated erosion it may not be feasible or useful to derive a pounds per day figure. In such cases, a percent reduction in pollutant discharge may be proposed.

TMDLs must include specific information to be approved by U.S. EPA Region 9. This information can be summarized in the following 8 elements:

1. **Plan to meet State Water Quality Standards:** TMDL includes a study and a plan for the specific water and pollutants that must be addressed to ensure that applicable water quality standards are attained.

2. **Describe quantified water quality goals, targets, or endpoints:** The TMDL must establish numeric endpoints for the water quality standards, including beneficial uses to be protected, as a result of implementing the TMDL. This often requires an interpretation that clearly describes the linkage(s) between factors impacting water quality standards.

3. **Analyze/account for all sources of pollutants.** All significant pollutant sources are described, including the magnitude and location of sources.

4. **Identify pollution reduction goals.** The TMDL plan includes pollutant reduction targets for all point and nonpoint sources of pollution.

5. **Describe the linkage between water quality endpoints and pollutants of concern.** The TMDL must explain the relationship between the numeric targets and the pollutants of concern. That is, do the recommended pollutant load allocations exceed the loading capacity of the receiving water?

6. **Develop margin of safety that considers uncertainties, seasonal variations, and critical conditions.** The TMDL must describe how any uncertainties regarding the ability of the plan to meet water quality standards that have been addressed. The plan must consider these issues in its recommended pollution reduction targets.

7. **Provide implementation recommendations for pollutant reduction actions and a monitoring plan.** The TMDL should provide a specific process and schedule for achieving pollutant reduction targets. A monitoring plan should also be included, especially where management actions will be phased in over time and to assess the validity of the pollutant reduction goals.

8. **Include an appropriate level of public involvement in the TMDL process.** This is usually met by publishing public notice of the TMDL, circulating the TMDL for public comment, and holding public meetings in local communities. Public involvement must be documented in the state's TMDL submittal to EPA Region 9.

1.2 Arizona's 303(d) Process

ADEQ has recently developed a four-step approach to eliminating water quality impairment through its 303(d) Process. After a waterbody is listed, further monitoring is initiated to validate the original listing and determine probable sources of the stressors causing the listing. This monitoring step was added because waters have been listed based on nominal data and information. ADEQ has very limited resources for surface water monitoring, assessments, and completing TMDLs; therefore, every year two watersheds will be focused on in a cycle, so that within five years all 10 watersheds will have been included.

Steps in Arizona's Revised 303(d) Process

1. List waterbodies based on listing criteria.
2. If the waterbody is in an active watershed management unit, validate stressor.
3. If valid stressor:
    - Complete a TMDL (loading capacity model); or
    - Bring the waterbody into compliance with standards (i.e., utilize permit process; utilize enforcement/compliance process; utilize remediation process; change standards or designated uses).
4. Delist waters when waters are in compliance with standards or approved TMDL is completed.

If additional data or closer examinations of existing data show that the water quality is impaired, then the most appropriate action to bring this waterbody back into compliance with its standard is pursued. Normally, this action would include completing a Total Maximum Daily Load analysis for the drainage basin.

Changes in standards or the establishment of site-specific standards are the result of ongoing science-based investigations or changes in toxicity criteria from EPA. Changes in designated uses and standards are part of the surface water standards triennial review process and are subject to public review. Standards are not changed simply to bring the waterbody into compliance, but are based on existing uses and natural conditions.

Luna Lake is included on Arizona's 1998 Water Quality Limited Waters List (303(d) List) for three stressors: narrative nutrient standards, numeric pH, and numeric dissolved oxygen standards. The listing is based on data collected by the ADEQ Clean Lakes Program between 1995 and 1997.

1.3 Watershed

1.3.1 Overview

Luna Lake, located in southeastern Apache County in the Apache-Sitgreaves National Forests, is a man-made impoundment on the San Francisco River, which flows 11 miles from it's headwater springs in the ponderosa/mixed conifer forests of Noble Mountain to Luna Lake. The lake, which is classified as eutrophic, is located east of Alpine, Arizona. The elevation in the watershed ranges from 9,576 ft at the San Francisco headwaters to 8,004 ft at the town of Alpine to 7882 ft at Luna Lake. The Luna Lake Watershed has an area of 23,030 acres (Figure 1-1). The surface elevation of Luna Lake fluctuates due to seasonal variations in inflows, irrigation withdrawals, and evaporation. When full, Luna Lake has a surface area of 154.5 acres (62.5 hectares) and a storage volume of 1390 acre-feet (1.71 x 10^6 cubic meters) (Novy and Jones, 1988). However, at maximum drawdown of 6.2 feet, the surface area is 47% and the volume is 40% of the full pool values (Novy and Jones, 1988). Since the lake fluctuates over this range several times a year, average values of the lake area and volume were estimated for use in the analyses. The average surface area was estimated using the average of the surface areas at full pool and maximum drawdown. The average volume was estimated using this area and the reported value of the mean depth. Therefore, the average surface area of Luna Lake is 114 acres (46 hectares) and the average volume is 932 acre-feet (1.15 x 10^6 cubic meters). The lake has a mean depth of 8.2 feet (2.5 meters), a maximum depth of 20.7 feet (6.3 meters), and a residence time of approximately 39 days (based on hydrologic analyses described in Section 3.1.2 below).

Luna Lake is designated for the following uses under Title 18, Chapter 11 of the Arizona Administrative Code:

A&Wc: Aquatic and wildlife uses, coldwater fishery;
FBC: Full body contact;
FC: Fish consumption;
AgI: Agricultural irrigation; and
AgL: Agricultural livestock watering

As mentioned, Luna Lake is listed on Arizona's 1998 303(d) List as impaired due to violation of numeric pH and dissolved oxygen standards and narrative nutrient standards, relating primarily to the aquatic and wildlife designated use.

GIS coverage for land usage, land ownership, and vegetation types were obtained from the Arizona Department of Environmental Quality (Ms. L. Jaress), and from BASINS2 (US EPA, 1998). Land usage is based on Anderson Level 2 land classification system. Topographic information was obtained from BASINS2 (1:250,000 scale DEM) and from USGS 1:24,000 scale topographic maps and DEMs for the area.

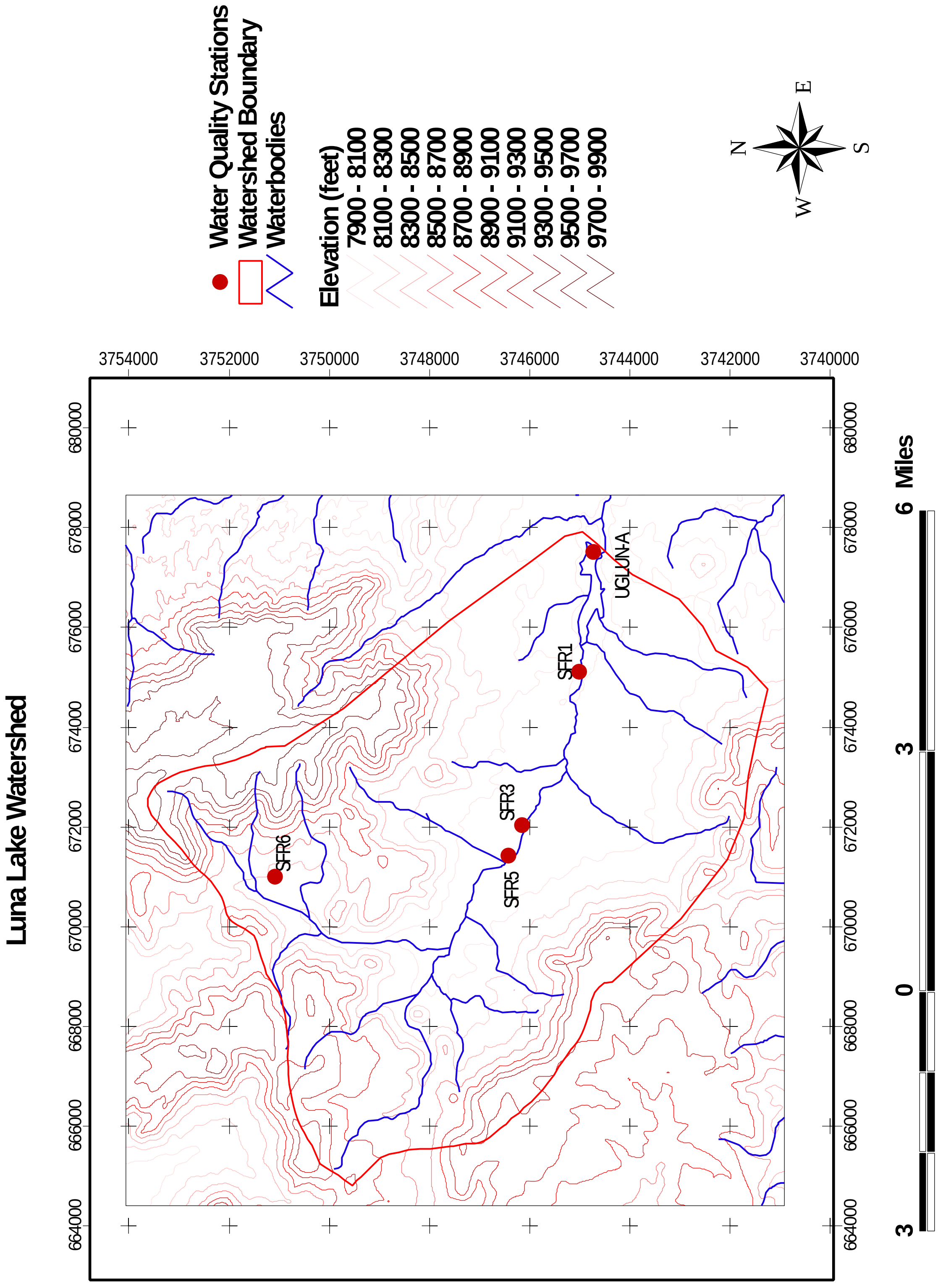


Figure 1-1. Luna Lake watershed.

1.3.2 Hydrology

Luna Lake is part of the San Francisco River Watershed (Hydrologic Unit Code 15040004), which is a sub-basin of the Upper Gila Watershed. The watershed is bounded by relatively steep mountains on the north, west, and south sides. A predominant source of water for Luna Lake is snowmelt from the adjoining mountains. Many springs also occur in the watershed.

Precipitation in the vicinity of Luna Lake averages 20.86 inches per year, ranging from a low of 11.23 inches observed in 1956 to a high of 37.56 inches measured in 1905 (WRCC 1999). The highest precipitation occurs from July through October, while the driest months are April through June. Total annual evaporation at Luna Lake is approximately 43 inches (NOAA 1982).

The average annual temperature is 43.8 ^{o}F (21.2 ^{o}C), varying from an average monthly temperature of 28.2 ^{o}F (-6.8 ^{o}C) in January to an average of 61.0 ^{o}F (52.2 ^{o}C) in July (WRCC 1999). The climate is cool because of the high elevation. Minimum daily temperatures reach freezing an average of 234 days per year, and the maximum daily temperature is below 32 ^{o}F (0 ^{o}C) an average of 6.5 days per year (WRCC 1999).

A comprehensive survey of the hydrology of Luna Lake has not been performed, however, there have been studies performed on the San Francisco River which is the major source of water into Luna Lake. The San Francisco River flows for approximately 75 miles, north to south, from Arizona through New Mexico and back into Arizona. It provides drainage for the western upper half of the Gila National Forest and the eastern part of the Apache National Forest. The river traverses a series of steep sided canyons alternating with wider meadowed valleys which are predominantly used for farming, cattle grazing, mining, and recreation (hunting, fishing, hiking, camping, and site-seeing) (Smolka 1987).

1.3.3 Physiographic Characteristics

Elevations in the watershed range from 9,576 feet at the San Francisco River headwaters to 8,004 feet at the town of Alpine to 7882 feet at Luna Lake. Luna Lake lies within the Arizona/New Mexico mountains ecoregion (Figure 1-2 Omernick 1987, 1995).

The Alpine-Nutrioso area in Apache County, Arizona, adjacent to New Mexico lies in a region that is generally called the White Mountain Region. For the most part, this region is not rugged, though it has one of the highest points in the Southwest (Baldy Peak, 11,590 feet). Much of the region is at altitudes greater than 8,000 feet and mountains above 9,000 feet are numerous. The area comprises part of a geologically little known mountain range that separates the Colorado Plateaus from the Basin and Range province across most of Arizona (Wrucke 1961).

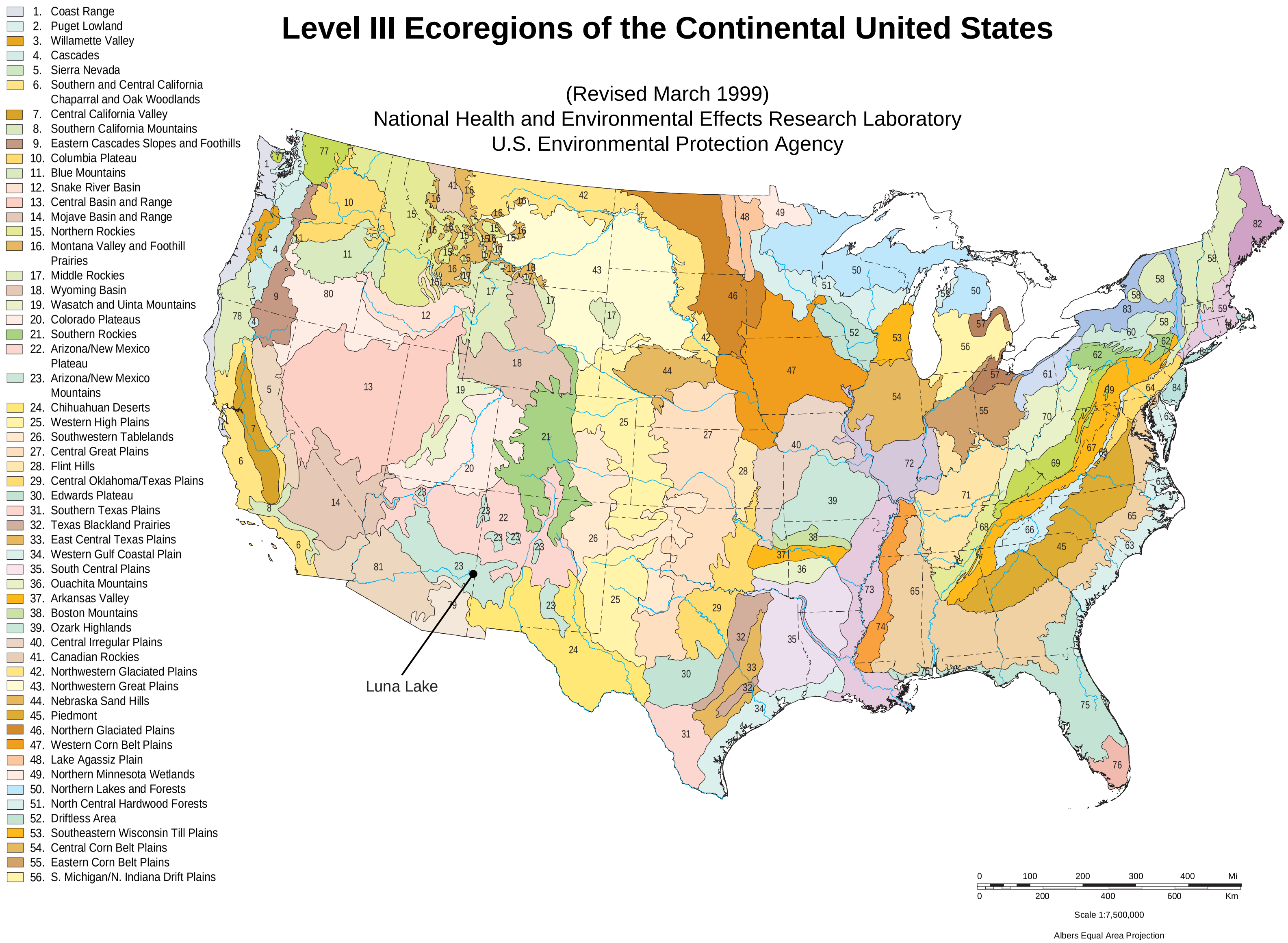


Figure 1-2. Level III Ecoregions of the Continental United States.

ECOREGIONS

The ecoregions shown here have been derived from Omernik (1987) and from refinements of Omernik's framework that have been made for other projects. These ongoing or recently completed projects, conducted in collaboration with the U.S. EPA regional offices, state resource management agencies, and with other federal agencies, involve refining ecoregions, defining subregions, and locating sets of reference sites. Designed to serve as a spatial framework for environmental resource management, ecoregions denote areas within which ecosystems (and the type, quality, and quantity of environmental resources) are generally similar. The most immediate needs are to develop regional biological criteria and water quality standards and to set management goals for nonpoint source pollution.

The approach used to compile this map is based on the premise that ecological regions can be identified through the analysis of the patterns and the composition of biotic and abiotic phenomena that affect or reflect differences in ecosystem quality and integrity (Wiken 1986; Omernik 1987, 1995). These phenomena include geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology. The relative importance of each characteristic varies from one ecological region to another regardless of the hierarchical level. Because of possible confusion with other meanings of terms for different levels of ecological regions, a Roman numeral classification scheme has been adopted for this effort. Level I is the coarsest level, dividing North America into 15 ecological regions, whereas at Level II the continent is subdivided into 52 classes (CEC 1997). Level III is the hierarchical level shown on this map. For portions of the United States (see map inset) the ecoregions have been further subdivided to Level IV. The applications of the ecoregions are explained in Gallant et al. (1989) and in reports and publications from the state and regional projects. For additional information, contact James M. Omernik, U.S. EPA National Health and Environmental Effects Laboratory (NHEERL), 200 SW 35th Street, Corvallis, OR 97333 (phone: 541-754-4458).

The geology of this region is characterized by flat-lying to gently dipping formations of Cenozoic age (consisting of sedimentary and volcanic rocks) that probably cover structurally simple Paleozoic and Mesozoic rocks like those on the Plateaus (Wrucke 1961).

The permeability of the soils in the Luna Lake area is mixed. The permeability is reported to have a mean value of 4.08 inches per hour, and range from a low of 0.72 inches per hour in the northeastern area to a high of 10.1 inches per hour in the southwestern area.

1.3.4 Vegetation

The vegetation of the area is a combination of ponderosa/mixed conifer forests interrupted by meadows and grassy valleys. Forested lands comprise approximately 82 percent of the land cover on the Luna Lake watershed (Figure 1-3, Table 1-1). The forests are predominantly evergreen, deciduous, and mixed evergreen/deciduous forests. Agricultural lands comprise approximately 11 percent of the watershed area and rangeland comprise less than one percent (BASINS2, U.S. EPA 1998).

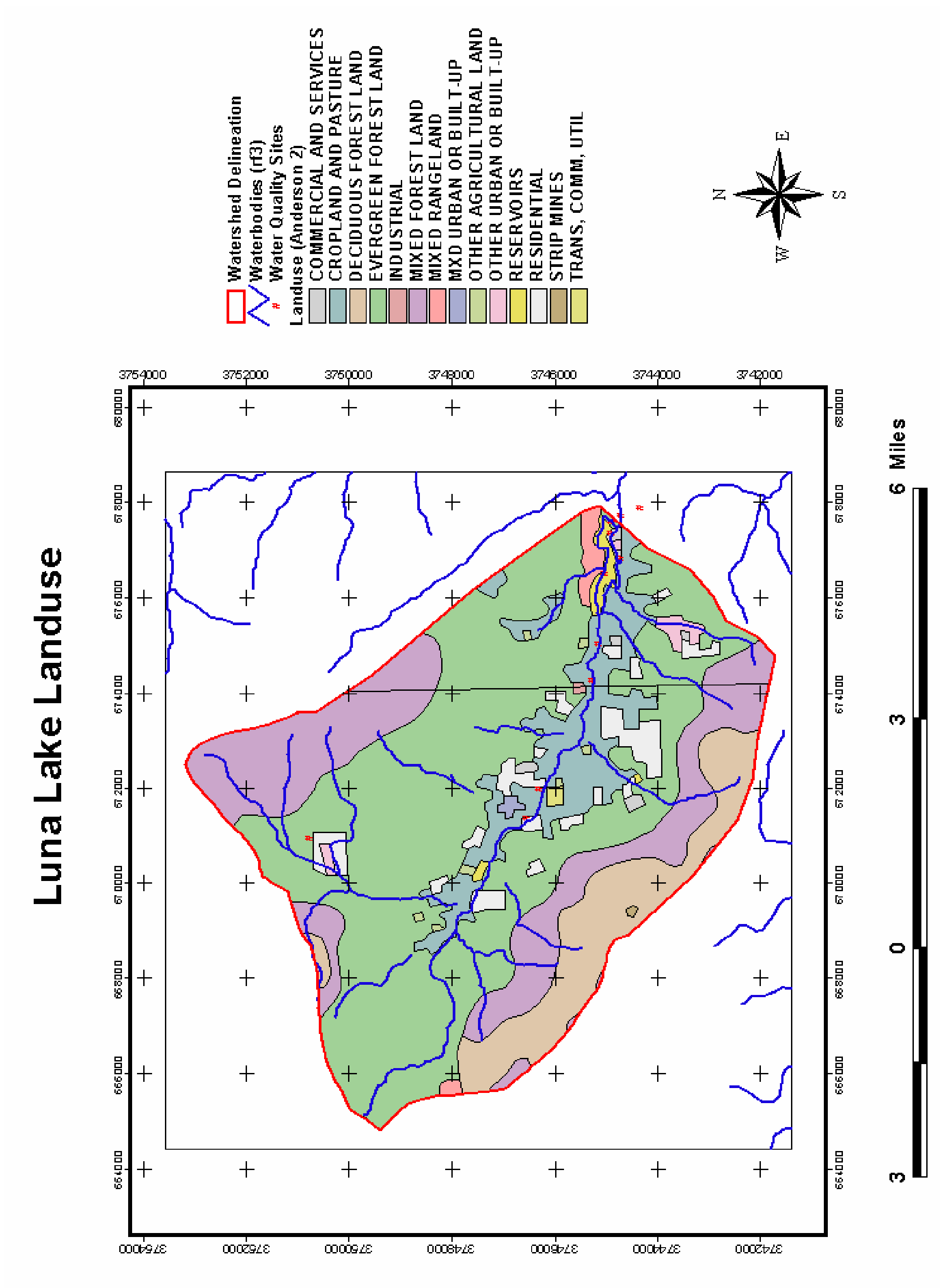


Figure 1-3. Luna Lake landuse.

Table 1-1
Luna Lake Detailed Land Use Distribution

Land Use Name and Code	Area (acres)	Percent
Urban or Built-Up Land		
Residential	1,040	4.5%
Commercial and Services	144	0.63%
Subtotal	1,184	5.1%
Agricultural Land		
Subtotal	2,326	10.1%
Forest Land		
Deciduous Forest Land	2,328	10.1%
Evergreen Forest Land	16,987	73.8%
Subtotal	19,315	83.8%
Range Land		
Subtotal	207	0.91%
Barren Land		
Subtotal	10	0.004%
Total	23,030	100%

1.3.5 Land Use

Land uses in the watershed include recreation, grazing and small plots of irrigated agriculture (ADEQ, 1997). Grazing, residential areas, septic systems, and irrigated agricultural lands are possible sources of nutrients. In terms of their significance, a lack of specific information on land uses resulted in the need to model land use with nationally-accepted default values. Determinations of the impact of specific land uses will need to be determined in the future through TMDL implementation.

1.4 Existing Conditions and Summary of Monitoring Data

Data from water quality sampling stations (Figure 1-1) within the Luna Lake watershed were obtained from various sources including, previously published reports (U.S. EPA, 1977); unpublished data from the Arizona Department of Environmental Quality and the Arizona Department of Game and Fish; and from BASINS2 (U.S. EPA, 1998). These data are summarized in Tables 1-2, 1-3, 1-4.

These data indicate that all sites within the Luna Lake watershed had measurable concentrations of nutrients (nitrogen and phosphorus). Chlorophyll-*a* concentrations are only available for Luna Lake and not for the San Francisco River sites. General water quality parameters are presented for selected constituents. These data are discussed in the following sections.

Table 1-2
Nutrient Concentrations in the Luna Lake Watershed

Site	NH_3-N (mg/L)	$NO_3 + NO_2$ (mg-N/L)	Total Kjeldahl N (mg-N/L)	Total Phosphorus (mg-P/L)
San Francisco River (SFR1)	0.14 (0.1 – 0.19)	0.08 (0.01 – 0.16)	0.62 (0.36 – 0.85)	0.16 (0.071 – 0.29)
San Francisco River (SFR3)	0.15 (0.1 – 0.28)	0.09 (0.01 – 0.26)	0.86 (0.35 – 1.58)	0.15 (0.056 – 0.244)
San Francisco River (SFR5)	0.25 (0.1 – 0.38)	0.14 (0.04 – 0.33)	0.99 (0.56 – 1.38)	0.15 (0.059 – 0.38)
San Francisco River (SFR6)	0.22 (0.12 – 0.28)	0.04 (0.02 – 0.06)	1.3 (1.3 – 1.4)	0.12 (0.041 – 0.229)
Luna Lake (UGLUN-A)	0.24 (0.08 – 0.57)	0.06 (<0.01 – 0.18)	1.2 (0.68 – 1.98)	0.18 (0.023 – 0.297)

Table 1-3
Chlorophyll-*a* Concentrations in the Luna Lake Watershed

Site	Secchi Depth (m) (Mean and Range)	Chlorophyll-*a* (μg/L) (Mean and Range)
San Francisco River (SFR1)	N/A	N/A
San Francisco River (SFR3)	N/A	N/A
San Francisco River (SFR5)	N/A	N/A
San Francisco River (SFR6)	N/A	N/A
Luna Lake (UGLUN-A)	1.8 (1 – 2.4)	7.8 (4.78 – 10.8)

N/A = Data not available.

Table 1-4
General Water Quality Parameters for the Luna Lake Watershed

Site	Temp (^oC)	DO (mg/L)	DO (% Sat)	Turbidity (NTU)	Total Alkalinity (mg $CaCO_3$/L)	pH (SU)	TDS (mg/L)

San Francisco River (SFR1)	4.2 (0.23 – 5.92)	7.7 (6.63 – 8.22)	75 (53.3 – 88)	16.1 (6.49 – 28.1)	168 (n = 1)	8.0 (7.86 – 8.11)	190 (160 – 219)	4 (n = 1)	N/A	N/A
San Francisco River (SFR3)	10.4 (2.5 – 21.5)	8.1 (5.67 – 10.4)	88 (49 – 105.8)	20 (6.69 – 38.5)	147 (79.7 – 253)	8.5 (7.61 – 9.75)	190 (135 – 292)	43 (6 – 76)	<2.5 (<2 – 4.1)	166 (97.2 – 294)
San Francisco River (SFR5)	13.2 (5.37 – 18.73	7.9 (7.15 – 8.79)	89 (75.8 – 103.7)	6.4 (3.93 – 9.89)	146 (111 – 235)	8.6 (8.11 – 9.69)	180 (132 – 278)	13 (5 – 28)	N/A	N/A
San Francisco River (SFR6)	16.7 (11.42 – 21.91)	7.1 (6.92 – 7.28)	98 (84.3 – 111.7)	6 (1.84 – 12)	110 (110)	9.6 (8.76 – 10.05)	146 (134 – 158)	7 (n = 1)	N/A	N/A
Luna Lake (UGLUN-A)	14.2 (8.59 – 22.2)	6.2 (0.16 – 10.51)	79 (28.9 – 147.3)	N/A	117 (105 – 130)	8.5 (7.2 – 9.68)	193 (170 – 230)	6 (<5 – 9)	25 (20 – 29)	119 (88 – 138)

N/A = No available data.

Nutrients - All of the sites within the Luna Lake watershed had measurable concentrations of nutrients (nitrogen and phosphorus). Nutrients are of particular concern in this and all watersheds because although they are important to the overall health of a waterbody, excessive levels can cause water quality problems (e.g., noxious algal and macrophyte blooms, odor, pH, dissolved oxygen concentrations, and fish kills).

Water column concentrations of nitrogen and phosphorus measured in the watershed between 1992 and 1997 tended to be generally higher in the Luna Lake and SFR6 sites, intermediate at the SFR3 and SFR5 sites, and lowest at the SFR1 site (Table 1-2). Total ammonia, nitrate/nitrite, Kjeldahl nitrogen, and total phosphorus concentrations ranged from 0.08 to 0.57, <0.01 to 0.33, 0.35 to 1.98, and 0.02 to 0.38 mg/L, respectively. No sediment data has been collected to date at Luna Lake.

Ammonia - The reported concentrations of ammonia could potentially be problematic if the corresponding water pH values were elevated. Elevated pH results in a larger percentage of unionized ammonia to be present in the water column. Unionized ammonia is very toxic to aquatic fish and invertebrates, especially salmonid fish (e.g., rainbow trout, brown trout, cutthroat trout, and golden trout). These fish have been reported in the literature to be acutely sensitive to unionized ammonia concentrations as low as 0.35 mg/L and chronically sensitive to concentrations of unionized ammonia as low as 0.02 mg/L (U.S. EPA, 1985 Ammonia Criteria Document EPA 440/5-85/001). Baker and Farnsworth (1995) also report that trout are sensitive to ammonia concentrations as low as 0.2 mg/L. Based on the maximum reported concentrations of ammonia, and maximum values for temperature and pH that have been observed in the available data, the unionized ammonia concentrations would range from a low of approximately 0.1 mg/L (SFR1 site) to a high of approximately 0.4 mg/L (UGLUN-A site). This would indicate that concentrations of ammonia toxic to salmonid fish can potentially be present in the Luna Lake watershed.

Chlorophyll-*a* - Chlorophyll-*a* is a direct measure of the concentration of algae in the water column. The algal concentration is directly affected by two primary water quality parameters (turbidity (water clarity) and nutrient concentration). The data collected between 1992 and 1997 (Table 1-3) indicate that these parameters were present in sufficient quantity and quality to allow for measurable concentrations of chlorophyll-*a* to be present in the Luna Lake site (UGLUN-A). During this time period, this site averaged a chlorophyll-*a* concentration of 7.8 μg/L, with a range spanning a low value of 4.8 μg/L to a high value of 10.8 μg/L. The secchi-depth, which measures water clarity, and thus the amount of sunlight that can penetrate the water, averaged 1.8 meters and ranged from 1 to 2.4 meters. Based on the chlorophyll-*a* concentrations and the secchi-depth values, Luna Lake would be classified as a mesotrophic – eutrophic lake (ADEQ).

General Water Quality Parameters - The general water quality parameters provide a measure of the overall water quality. These parameters include pH, dissolved oxygen

(DO), turbidity, alkalinity, total dissolved solids (TDS), total suspended solids (TSS), carbonate and bicarbonate. Many of these parameters are affected by the presence or absence of other water quality parameters (e.g., pH and DO are affected by the presence of algae). The data collected from the Luna Lake watershed between 1992 and 1997 (Table 1-4) indicate that the pH and dissolved oxygen concentrations have been problematic (i.e., pH values >9.0 SU and DO values < 7.0 mg/L).

1.5 Identification of Violated Water Quality Standards and Impaired Designated Uses

Water quality standards are commonly expressed as either numeric (a specific concentration which cannot be exceeded) or narrative (used to describe a condition that is not desired). Arizona uses both types of water quality standards for Luna Lake. Luna Lake is listed on Arizona's 1998 303(d) list as impaired due to violations of narrative nutrient standards, and numeric pH and dissolved oxygen standards.

The water quality standards for these parameters (Title 18, Chapter 11 Arizona Administrative Code) are as follows:

- pH shall be between 4.5 and 9.0 SUs; The critical low pH for Aquatic and Wildlife is 6.5 SU;

- Dissolved oxygen shall not be lower than 7.0 mg/L between the surface and one meter depth, and the minimum dissolved oxygen saturation is 90%; and

- Nutrient concentrations shall not cause growth of algae or aquatic plants or settling of bottom deposits that inhibit or prohibit the habitation, growth, or propagation of other aquatic life or that impair recreational uses. Nutrient concentrations shall not change the color of the surface water from natural background levels of color.

In addition to the water quality standards for Luna Lake, standards for the San Francisco River and tributaries upstream of Luna Lake state that total phosphates shall not exceed 1.0 mg/L as P. Based on these water quality standards, pH standards for Luna Lake were violated in 24 out of 154 samples (16%) between 1995 and 1997. Dissolved oxygen standards in the upper one meter water depth were violated in 4 out of 14 samples (29%) during the same time period. Narrative nutrient standards in Luna Lake have also been violated during this time period due to the presence of noxious aquatic weeds and phytoplankton.

Excess nutrients in Luna Lake sediments most likely account for excessive macrophyte growth and algal blooms in the Lake. Records from the Arizona Game and Fish Department (AGFD) for the period 1982 to 1997 (J. Novy, AGFD, personal communication) provide information for 9 annual harvests. Between 1982 and 1990, the annual harvest of macrophytes from Luna Lake ranged from between 81 and 999 tons (0.67 to 8.3 tons per acre). Between 1994 and 1997, the annual harvest of macrophytes from Luna Lake ranged between 246 and 527 tons (2.1 to 4.4 tons per acre).

pH and dissolved oxygen are easily measurable water quality parameters and numeric water quality standards aid in determining whether violations are occurring. Luna Lake has been listed as impaired because of high pH levels, low dissolved oxygen concentrations, and nutrient concentrations that stimulate the growth of noxious aquatic weeds and phytoplankton in the water column. All three of these measures are inter-related, with the presence of excessive aquatic plant biomass driving the elevated pH and depressed DO levels.

A conceptual model showing the relationships between aquatic plants (macrophytes and phytoplankton), pH, and dissolved oxygen is presented in Figure 1-4. This figure breaks the process down into 8 steps:

1. Nutrients (nitrogen and phosphorus) are added to the system and made available to the aquatic plants via point sources, non-point sources, and/or in-lake processes;

2. Excess nutrient concentrations and light stimulate growth;

3. Plant growth consumes CO_2 from the water. This causes the pH to rise. The slope and magnitude of the pH rise is dependant on the plant biomass;

4. Once maximum growth has occurred, the plants begin to fragment or die:

   - Phytoplankton are either consumed by zooplankton or die and settle to the lake bottom where they decompose and produce ammonia, carbon dioxide, and phosphorus or do not decompose and become part of the refractory fraction and slowly release nitrogen and phosphorus. Zooplankton eventually die and produce ammonia, carbon dioxide, and phosphorus.

   - Macrophytes begin to fragment and die back. Decomposition produces ammonia, carbon dioxide, and phosphorus. The portion of macrophytes that decompose slowly accumulate as organic material in the sediments.

   - Decomposition is oxygen consumptive and can deplete dissolved oxygen from the water column.

5. Ammonia undergoes nitrification to yield nitrate. This nitrate is recycled into the nutrient budget of the water column;

6. Some ammonia diffuses into the atmosphere;

7. Ammonia can become toxic if the pH and ammonia concentrations are high enough. As the pH increases, the concentration of toxic (unionized) ammonia increases logarithmically (Figure 1-5). Therefore, as the pH level rises, less total ammonia is required to produce the same amount of toxic unionized ammonia;

8. High concentrations of ammonia can kill fish and invertebrates. Their decomposition adds ammonia, phosphorus, and carbon dioxide into the system and depletes dissolved oxygen concentrations.

This process can lead to impairment of beneficial uses by:

- Allowing for unrestricted algal and macrophyte growth;
- Increasing water column pH;
- Decreasing water column DO concentrations can result in fish and invertebrate kills;
- Elevated pH concentrations can result in fish and invertebrate kills either directly, or indirectly by causing a higher percentage of total ammonia to become unionized; and
- Producing foul odors.

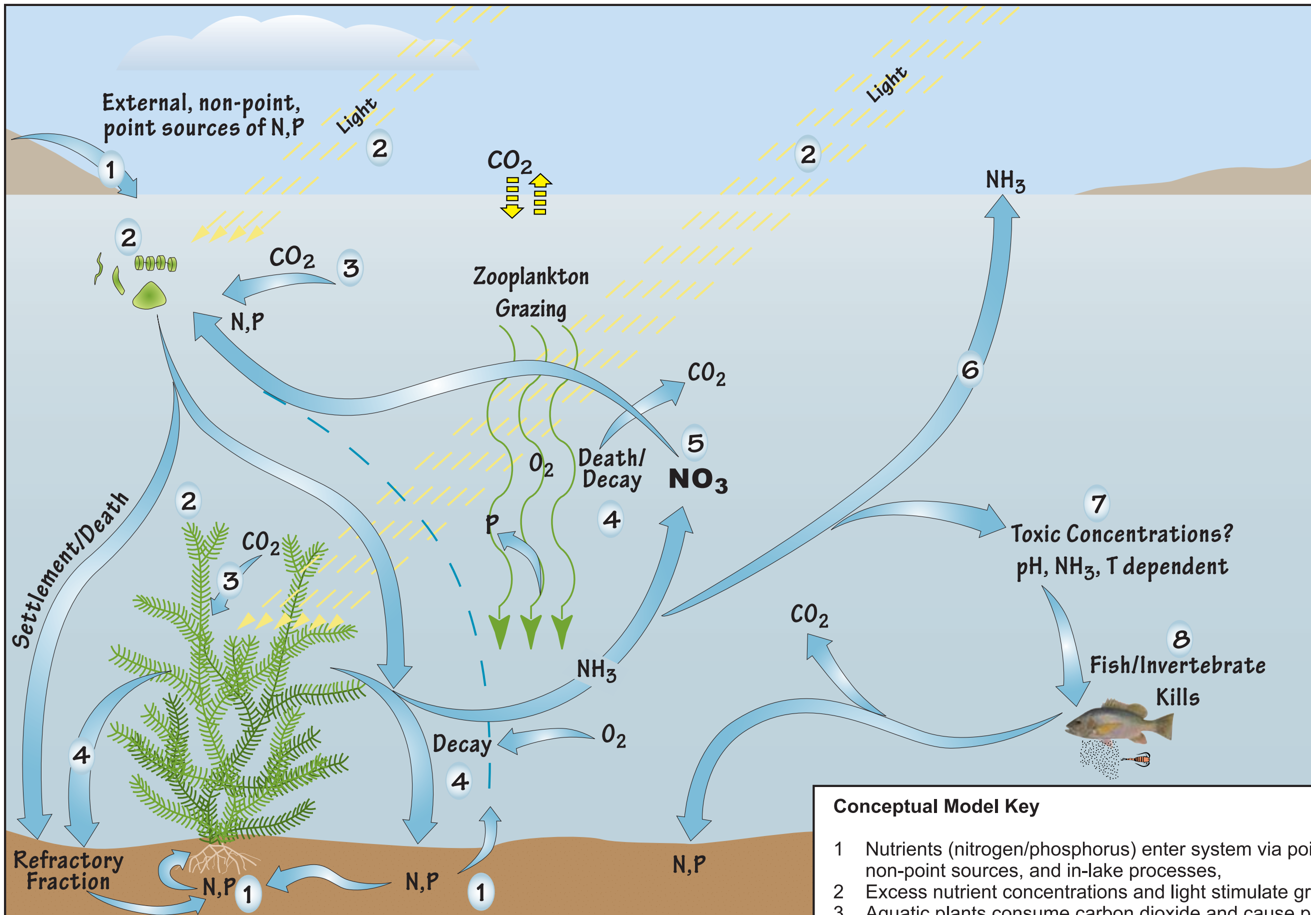


Figure 1-4. Conceptual model of the relationship between Macrophytes/Algae and nutrients, pH, and dissolved oxygen.

Conceptual Model Key

1 Nutrients (nitrogen/phosphorus) enter system via point sources, non-point sources, and in-lake processes,
2 Excess nutrient concentrations and light stimulate growth,
3 Aquatic plants consume carbon dioxide and cause pH to rise,
4 Aquatic plants fragment or die releasing ammonia, phosphorus, carbon dioxide, and consume oxygen into water column or sediments,
5 Ammonia undergoes nitrification to yield nitrate. Nitrate is recycled back into system,
6 Ammonia diffuses into atmosphere,
7 Ammonia can become toxic if pH and ammonia concentrations are high enough, and
8 High concentrations of unionized ammonia can cause fish and invertebrate kills and release ammonia into the water column and consume additional dissolved oxygen.

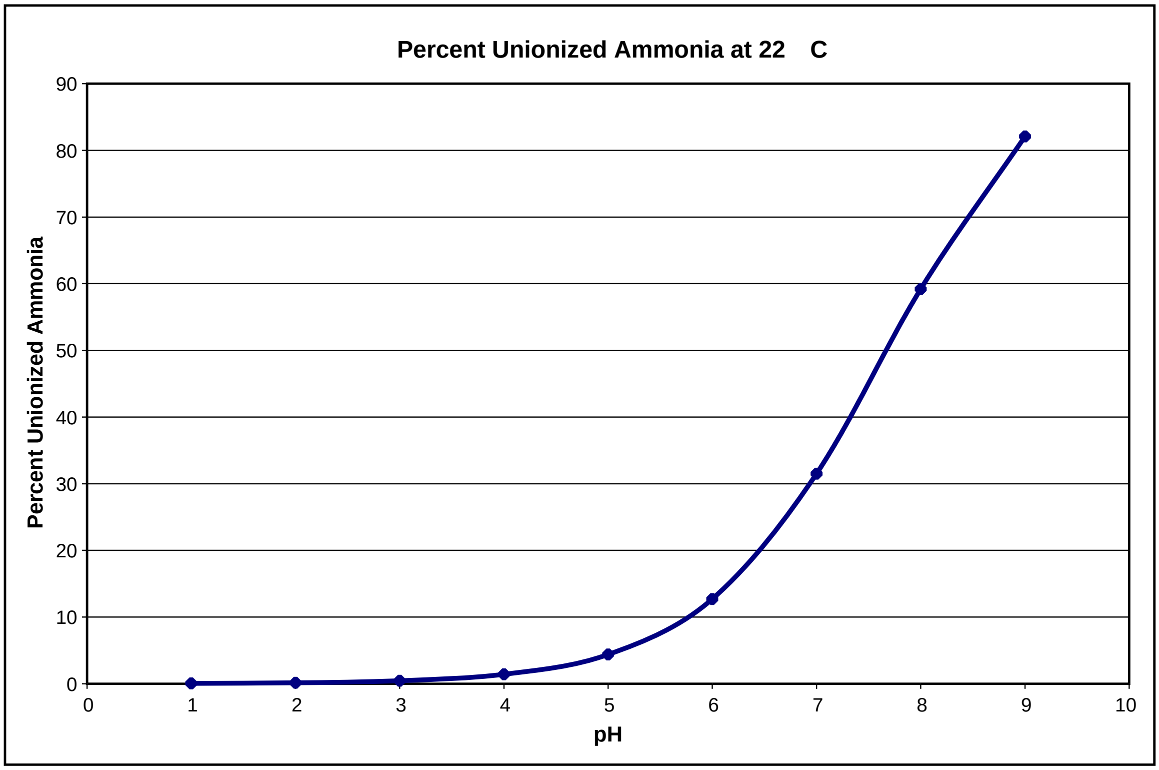


Figure 1-5. Relationship between percent unionized ammonia and pH at the maximum temperatures observed in Luna Lake.

1.6 Identification of Pollutants being Addressed and Why

This TMDL addresses the nutrients phosphorus and nitrogen. Although nutrients are required for plant growth and a healthy ecosystem, excess nutrients can cause eutrophication, which is characterized by excessive plant growth (algal blooms), and in shallow lakes can result in the development of extensive macrophyte beds. This produces other water quality problems such as low dissolved oxygen, high turbidity, high pH values, and high concentrations of toxic unionized ammonia.

Excess nutrients in Luna Lake most likely account for the excessive growth of noxious weeds and phytoplankton in the lake. High plant biomass in the lake and the in-lake effects thay have on water chemistry may also contribute heavily to the adverse pH and dissolved oxygen conditions which occur (USFWS, 1982). Fish kills have occurred in Luna Lake in recent decades, probably due more to the presence of toxic concentrations of ammonia than to low dissolved oxygen (Baker and Farnsworth, 1995; Jim Novy (AGFD), personal communication). The high pH and abundance of ammonia from decaying plant matter result in concentrations of unionized ammonia that are toxic to fish and invertebrates.

Studies in nearby Rainbow Lake (Baker and Farnsworth, 1995) indicate that lake sediments and decomposition of macrophytes are major sources of nutrients, and are probably more important than external loadings in that system. These internal sources may also be important for Luna Lake. However, the watershed is much larger for Luna Lake, and the valley containing the San Francisco River upstream of the lake is heavily grazed by livestock and elk. Therefore, this TMDL evaluates both nutrient inputs from sources within the watershed, and nutrient cycling within Luna Lake. Because macrophytes perpetuate the cycling of nutrients in the system, removal of plants to reach some target amount (e.g., biomass of plants) would directly reduce the impairment as well as remove nutrients from the system. Because the higher pH values occur during periods of macrophyte and phytoplankton growth (when they remove CO_2 from the water), and low dissolved oxygen concentrations occur during the decay of these plants, controlling the growth of both macrophytes and phytoplankton would result in lower pH levels and higher dissolved oxygen concentrations in the Lake.

2.0 NUMERIC TARGETS AND IN-LAKE INDICATORS

Previous sections have discussed the combined effects of the individual water quality parameters. This section will discuss the need to determine numeric targets and in-lake indicators that can be used to protect the beneficial uses of Luna Lake.

2.1 Numeric Targets

Possible water quality targets to control the noxious weed growth in Luna Lake could be expressed in terms of nutrient concentrations (e.g., mg/L of phosphorus and/or nitrogen) or macrophyte/phytoplankton parameters (e.g., extent of growth, area of effect, biomass). The Water Quality Standards for these parameters in Title 18, Chapter 11 of the Arizona Administrative Code are as follows:

- pH, (A&Wc). The following water quality standards for pH, expressed in standard units (SUs) shall not be lower than 4.5 SU or greater than 9.0 SU (A.A.C. R18-11-109, paragraph D). The critical low pH for Aquatic and Wildlife is 6.5 SU;

- Dissolved oxygen, Aquatic and Wildlife, cold water fishery (A&Wc). The dissolved oxygen concentration in surface water shall not fall below 7.0 mg/L (A.A.C. r18-11-109, paragraph G); the dissolved oxygen standard also includes a provision for a minimum saturation of 90%. In the case of lakes, the current dissolved oxygen water quality standard applies below the surface to a depth of 1 meter;

- Nutrients, (A.A.C. R18-11-109, paragraph A, Narrative Water quality Standards). This paragraph lists eight different impacts on surface waters that are considered the narrative standards for the state. The narrative water quality standards that are applicable to Luna Lake (R18-11-108-Narrative Water quality Standards) are listed below:

A surface water shall be free from pollution in amounts or combinations that:

- Cause the growth of algae or aquatic plants or the settling of bottom deposits that inhibit or prohibit the habitation, growth, or propagation of other aquatic life or that impair recreational uses;

- Change the color of the surface water from natural background levels of color.

The water quality standard for the San Francisco River and tributaries upstream of Luna Lake Dam state that the waters shall not exceed 1.0 mg/L total phosphates as P (A.A.C. R18-11-109, Section H, Numeric Water Quality Standards).

2.2 Identification of In-lake Indicators

Indicators are parameters that can be easily measured and understood and that can be applied to a complex system to assess whether impairment is occurring. This section describes seven in-lake indicators that will be used to assess whether the beneficial uses of Luna Lake are being impaired. These indicators measure chemical, biological, and physical water quality parameters, each of which are described below.

pH: pH levels in Luna Lake have exceeded the stated water quality standards in 16% of the samples measured in Luna Lake between 1995 and 1997. Elevated pH concentration is an indicator of eutrophic conditions with excessive plant growth. In addition, high pH levels increase the concentrations of toxic levels of ammonia in the water column causing toxic concentrations of ammonia to occur and lead to fish and invertebrate kills.

The high elevation of Luna Lake (7900 ft) predisposes the lake to high pH events. High elevations result in low atmospheric partial pressure for carbon dioxide which leads to low pCO_2 in the water column. Carbon dioxide is a key component of the carbonate/bicarbonate buffering system that controls the rate and magnitude of changes in aquatic pH. A ‘normal’ level of plant photosynthesis (e.g., uptake of carbon dioxide) may overwhelm the pH buffering capacity of such a lake under these conditions.

Lake pH can be measured in the field using a standardized pH meter. This indicator will be used to assess whether the control measures have accomplished their stated goal of no pH exceedances of the water quality standard for Luna Lake.

Dissolved Oxygen: Dissolved oxygen concentrations have violated the stated water quality standards in 29% of the samples measured in Luna Lake between 1995 and 1997. Dissolved oxygen concentrations in Luna Lake provide an indicator that assesses whether the decomposition of plant matter is exceeding the oxygen capacity of the lake. Low dissolved oxygen can lead to anoxic conditions and subsequent fish and invertebrate kills.

Lake dissolved oxygen concentrations can be measured in the field using a standardized DO meter. This indicator will be used to assess whether the control measures have accomplished their stated goal of no DO violations of the water quality standard for Luna Lake.

Nutrient Concentrations: Concentrations of nitrogen and phosphorus are most likely causing the excessive macrophyte and phytoplankton biomass in Luna Lake. These are, in turn, the controlling factors of the in-lake processes that drive the pH exceedances and potential dissolved oxygen violations in Luna Lake. Elevated nutrient concentrations lead to excessive macrophyte and algal growth that result in increased pH and decreased dissolved oxygen.

A combination of direct nutrient concentration measurement and indirect macrophyte biomass estimation within Luna Lake will be used as indicators of the stated water quality standards for nutrients (i.e., no nutrients in concentrations that would excessively stimulate the growth of aquatic plants, impair the beneficial uses of the lake, or change the color of the lake waters).

Macrophytes: The presence of excessive amounts of macrophytes in Luna Lake have historically contributed to water quality impairment and interference with the designated beneficial uses of Luna Lake, and because they play an integral part of the process of recycling nutrients in the system, the water quality target for the TMDL could then be some appropriate measure of macrophyte and phytoplankton growth (biomass, percent coverage, or another measure) to assess whether the narrative nutrient water quality standards are being met by the control measures.

Phytoplankton (Free Floating Micro-algae): Macrophytes are not the only plant life that exists in Luna Lake. There are also free floating micro-algae (phytoplankton) present. Eutrophic conditions can lead to an overabundance of non-desirable phytoplankton species (cyanobacteria, or blue-green algae) that can cause foul odors and, in some cases, release substances in the water that are toxic to both aquatic life and humans. Phytoplankton can bloom uncontrollably resulting in elevated pH and ammonia levels, and decreased dissolved oxygen concentrations.

This indicator, like the macrophyte indicator, would provide information that would allow us to assess whether the narrative nutrient water quality standards are being met by the control measures. The measure of this indicator could be as simple as measuring the chlorophyll-*a* concentration in the water column and comparing the result to the standard used by ADEQ to assess the trophic level of the lake.

Ammonia Concentration: As mentioned previously, ammonia is produced during the decomposition of plant or organic matter. The concentration of unionized ammonia is pH and temperature sensitive and extremely toxic to aquatic organisms, especially the unionized form. Two by-products of unrestricted macrophyte and algal growth are increased pH and ammonia concentrations. These two conditions, when co-occurring, can be deadly to fish and aquatic invertebrates.

The sensitivity of aquatic organisms to unionized ammonia has been well covered in the toxicological literature. Concentrations of unionized ammonia that are measured in Luna Lake can be compared against the concentrations of unionized ammonia that are known to impair aquatic life.

Lake Depth: Lake depth plays an integral part in determining the quantity and quality of sunlight that reaches the lake bottom (where the macrophytes are growing). Light attenuates fairly rapidly in water and decreases in quality with depth. This indicator can be used to determine whether the lake is sufficiently deep to prohibit light from reaching the lake bottom and stimulating macrophyte growth.

Measurement of light attenuation may be necessary to a sufficient understanding of optimum growth conditions for rooted plants and algae.

2.3 Identification of Target Levels to be Protective of Beneficial Uses

The system's response to nutrient inputs is especially variable because of the concentration of nutrients stored in the lake sediments. Ecoregional characteristics for reservoirs of similar type are unknown, eliminating the ability to establish reference conditions.

The generic relationship of pH, temperature, and dissolved oxygen to unionized ammonia for protection of aquatic and wildlife uses, have been identified in the Arizona Surface Water Standards, Title 18, Chapter 11 of the Arizona Administrative Code. Although conservatively protective, aquatic organisms residing within a high mountain lake, such as Luna Lake, may have adapted to a broader range of values. This consideration will be addressed in an ongoing monitoring plan.

The lake's response to nutrient reductions, subsequent phytoplankton and macrophyte levels, and the effects on water quality will need to be monitored more closely than they have in previous monitoring efforts.

The TMDL study results indicate that nutrient concentrations in the water column and bedded sediments will have to be reduced to control phytoplankton and macrophyte growth. The target range for nutrients and possible strategies for attaining the desired levels of nutrients are provided in Sections 3.0 *Watershed and Lake Modeling: Source Analysis for Loadings, Nutrient Mass Balance, and Linkage of Stressors to Water Quality Endpoints* and 4.0 *Recommendations for Allocations, Implementation and Monitoring* of this report.

2.4 Comparison of Numeric Targets and Existing Conditions

This section assesses how far the water quality parameters of concern for Luna Lake have to go in order to be in compliance with the stated water quality standards for the lake.

Table 2-1 illustrates the existing water quality conditions, the desired TMDL Endpoints, and commentary.

Table 2-2 (ADEQ 305(b) website 1999) provides the water quality parameters that the state of Arizona uses to determine the trophic level of a waterbody. This classification system uses three water quality parameters to assess trophic level (1) chlorophyll-*a*, (2) total phosphorus, and (3) Secchi-depth. Using this classification system, Luna Lake ranges from mesotrophic (based on chlorophyll-*a* concentrations) and eutrophic (based on Secchi depth and total phosphorus). ADEQ has included a revised trophic classification system for the upcoming 305(b) Water Quality Assessment. ADEQ will develop regional regression relationships using Brezonick's (1982) classification to refine this index (Table 2-2a).

Table 2-1
Arizona Trophic Classifications*
ADEQ Website 305(b) 1999

Trophic State	Chl-a (μg/L)	Total P mg/L	Secchi Depth (m)
Oligotrophic	<7	<0.010	>3.7
Mesotrophic	7 – 12	0.010 – 0.020	2.0 – 3.7
Eutrophic	>12	>0.020	<2.0

* ADEQ may apply other indices (e.g., nitrogen) depending on site-specific or limiting conditions; the index below is a refinement that includes nitrogen. Though it needs to be reworked to reflect Southwest conditions, ADEQ has included use of this index in the year 2000 Water Quality Assessment Report

*TSI	Trophic State	Chlor-a (ug/L)	SD (m)	Total P (ug/L)		Total N (mg/L)	
				P-lim	N&P-lim	N-lim	N&P-lim
<30	Oligotrophic	<5	>3	<10	<13	<.25	<.28
30-45	Mesotrophic	5-12	1.2-3	10-20	13-35	.25-.65	.28-.75
45-65	Eutrophic	12-20	.6-1.2	20-35	35-65	.65-1.1	.75-1.2
>65	Hypereutrophic	>20	<.6	>35	>65	>1.1	>1.2

*TSI stands for "Trophic State Index"

Table 2-2
Comparison of Existing Conditions to TMDL Endpoints

Parameter	Existing Value (Mean and range)	TMDL Endpoint	Comments
pH (SU)	8.5 (7. 2 – 9.68)	Arizona Water Quality Standard: pH > 4.5 and < 9.0	This range ensures minimum concentrations of unionized ammonia and reduces toxicity to aquatic organisms caused by pH shock. Validated by monitoring
Dissolved Oxygen (mg/L)	6.2 (0.16 – 10.51)	Arizona Water Quality Standard: DO > 7.0 mg/L or 90% saturation in upper 1 meter water depth	This range ensures that water column concentrations of dissolved oxygen will be adequate to sustain aquatic life. Validated by monitoring
Phosphorus (mg/L)	0.18 (0.02 – 0.30)	Arizona Water Quality Standard: < 1.0 mg/L for Tributaries, Best Professional Judgment for Lake; phosphorus high in runoff	ADEQ (1999) total phosphorus between 0.01 – 0.02 mg/L or, ADEQ (2000): total phosphorus between 0.01 – 0.04 mg/L is classified “mesotrophic”; 0.04 – 0.07 is classified “eutrophic” Validated through Phased TMDL Monitoring.
Nitrogen (mg/L)	0.5 (<0.01 – 1.98)	Arizona Water Quality Standard: Best Professional Judgment for lake, which is limited b y nitrogen	ADEQ (2000): total nitrogen between 0.28 – 0.75 mg/L is classified “mesotrophic”; 0.75 – 1.2 is classified “eutrophic” Validated through Phased TMDL Monitoring.
Total Ammonia (mg/L)	Total Ammonia: 0.24 (0.08 – 0.57) Unionized Ammonia: 0.4 mg/L (using worst-case conditions)	Protection of sensitive coldwater fish species (i.e., salmonids): Arizona Acute Standard for Acute exposure: pH & temperature dependent* Federal Criteria: concentrations of unionized ammonia for: Acute Exposure (< 1 hr): =0.35 mg/L; Chronic (4-days): =0.02 mg/L	Unionized ammonia is a strongly toxic aquatic pollutant whose concentration is driven by water column pH and temperature. *Concentrations measured to date are protective of the coldwater fishery in Luna Lake, but acute threshold for extreme high pH and temperature is 0.67 mg/L Validated through Phased TMDL Monitoring.
Aquatic Plants	The presence of excessive quantities that are causing impairment to the beneficial uses of the lake	Reduce quantities of nuisance aquatic plants	Reduce the quantities of nuisance aquatic plant biomass to levels that would not drive water column pH and dissolved oxygen levels to extremes or result in increasing the concentrations of unionized ammonia to toxic levels. Validated through Phased TMDL Monitoring.

3.0 WATERSHED AND LAKE MODELING: SOURCE ANALYSIS FOR LOADINGS, NUTRIENT MASS BALANCE, LINKAGE OF STRESSORS TO WATER QUALITY ENDPOINTS

3.1 Technical Approach

This section addresses four of the primary elements of this TMDL study: 1) conduct a source analysis for loadings, 2) develop a nutrient mass balance model for Luna Lake, 3) link the pollutant loads (stressors) to water quality endpoints, and 4) allocate loads to source categories that ensure water quality objectives are met. A watershed loading model (GWLF) and an in-lake processes model (BATHTUB) were used to perform the analysis for these elements of the TMDL. The purpose of this section is to describe how existing data were used to characterize watershed source inputs and resulting water quality effects in Luna Lake. It is important to designate nutrient inputs by category because control strategies will vary depending on the relative contributions from categories to total nutrient loading.

The loading estimates were developed and analyzed using the GWLF (Generalized Watershed Loading Functions) watershed model (Haith et al., 1992). The loading analysis for the watershed is subdivided into point source and several non-point source categories. No significant point sources were identified in the watershed. The non-point source watershed loading categories assessed included septic systems, agriculture (grazing), elk herds, forest, residential, commercial, barren land, and range. The GWLF model predicts water flows and loads of nitrogen, phosphorus, and sediments from the watershed. The flows and loads are calculated from watershed characteristics (land use type, soil characteristics, area, slope, vegetation cover, etc.) and precipitation data. The predicted flows and loads are then used as input to the lake model BATHTUB during the linkage analysis.

The nutrient mass balance quantifies the fluxes of nutrients into Luna Lake from watershed and atmospheric loadings; the fluxes out of the lake from outflows and macrophyte harvest; and internal cycling within the lake from nutrient sedimentation, sediment regeneration and release, and nutrient regeneration during plant decay. Nutrient loads from the watershed were estimated using flow and nutrient concentration data from the San Francisco River inflow to Luna Lake. Outflow fluxes of nutrients were calculated using outflow rates and nutrient concentrations in the lake. Macrophyte harvest removal fluxes were calculated from harvest rates and nutrient concentrations in the plants. Internal lake nutrient pools associated with sediments and macrophytes are important sources of concern for the TMDL, since the sediment pools of nitrogen and phosphorus in eutrophic lakes are typically large, and since sediment release could potentially support high macrophyte and algal densities even if external loads from the watershed are reduced to minimal levels.

The lake model BATHTUB was used for the linkage analysis. This model calculates water quality variables such as nutrient concentrations, chlorophyll-*a* concentrations (or algal densities), and turbidity based on the loadings, hydrology, lake geometry, and internal nutrient cycling processes within the lake. The watershed model provides the loads that drive the system, and the lake model calculates the lake response in terms of the water quality endpoints (N, P, chlorophyll-*a*, secchi depth), which can in turn be compared with the water quality targets.

3.1.1 Source Analysis of Loadings

Nutrient loadings were calculated for the different source categories within the Luna Lake watershed using the GWLF Model Version 2.0 (Haith et al., 1992). The following sources were evaluated:

- Agriculture (livestock grazing)
- Forest
- Range
- Elk herds
- Barren land
- Residential areas
- Commercial areas
- Groundwater
- Septic systems

Land use categories and corresponding coverage areas in the watershed were taken from the BASINS GIS database. The areas in each category are listed in Table 1-1. Agriculture in the watershed consists predominantly of livestock grazing in the valley along both sides of the San Francisco River. Range land includes a small region along the north shore of Luna Lake which is grazed less intensely than the main valley. Elk nutrient loads were evaluated separately from livestock grazing loads.

The analyses were conducted using daily meteorological data (e.g., precipitation and temperature) from the Alpine meteorological station for the12-year period from 1984 to 1995. This period was selected because the meteorological records were complete, the average conditions over the period were similar to the long-term average for the station, and representative high and low rainfall years occurred during the period. The following results were calculated from the model simulations:

- Annual inputs of nitrogen and phosphorus to Luna Lake for each of the 12 years
- Annual inputs of nitrogen and phosphorus to Luna Lake averaged over the 12-year period
- Annual inputs of nitrogen and phosphorus to Luna Lake during the years with the lowest precipitation (low flow year) and highest precipitation (high flow year) during the 12-year period. Precipitation during the low flow year (1989) was 38% less than the 12-year average precipitation, and precipitation during the high flow year (1992) was 38% greater than the average precipitation.

The GWLF model calculates flows and nutrient loads at the downstream boundary of the watershed where the San Francisco River enters Luna Lake. It does not calculate conditions along the length of the stream, or at different locations within the watershed. However, contributions from different locations and land uses within the watershed are calculated and added to give the total downstream loads, and these individual source contributions are itemized in the model output. The GWLF model simulates both hydrological processes in the watershed and nutrient loads from different sources. The nutrient loads depend on both the types and intensities of land uses and on the hydrologic processes that transport the nutrients through the watershed and into the stream. The hydrological and nutrient loading processes are each described separately below.

3.1.1.1 Watershed Hydrology and Transport Processes

The GWLF model calculates both flows and nutrient loads on a daily basis using daily meteorological data (precipitation and temperature) to drive the model. Precipitation is assumed to occur as rain when the air temperature is above freezing (0°C), and as snow fall otherwise. Smowmelt is calculated by a degree-day relationship when a snow pack is present and air temperatures are above freezing. The precipitation data are used to calculate a daily hydrologic budget for the watershed that includes runoff processes at the surface, ground water flows below the surface, evapotranspiration losses, and stream flows at the bottom of the watershed where the San Francisco River enters Luna Lake. The stream flows equal the sum of the surface runoff and the shallow groundwater flows that feed the stream.

Runoff from each land use category in the watershed is calculated from the daily precipitation data using the U.S. Soil Conservation Service (SCS) Curve Number approach. The curve numbers vary with land use type, vegetation type, percent vegetation coverage, soil type, extent of impervious areas, agricultural practices, growing versus dormant season, and antecedent moisture conditions. Precipitation in excess of runoff is assumed to infiltrate into the soil (or to contribute to snow pack if the temperature is below freezing). The infiltrated water contributes to the groundwater flows below the surface. The subsurface soil region is divided vertically into three zones: 1) the upper unsaturated zone, 2) the shallow saturated (groundwater) zone that feeds the stream, and 3) the deep saturated (groundwater) zone that is below the level of the stream bed and therefore does not contribute to the stream flow. Water that enters the deep saturated zone is assumed to leave the system, since it does not contribute to the stream flows and nutrient loads entering the lake.

The shallow groundwater flows that feed the stream are calculated from daily water balances of the unsaturated and shallow saturated zones. The water balance for the upper unsaturated zone includes the processes of rainfall, snowmelt, and surface runoff that determine how much water infiltrates into the soil, as well as losses from evapotranspiration and percolation into the next lower zone. The water balance for the shallow saturated zone includes percolation into this zone from the above zone, groundwater discharge to the stream, and seepage into the deep saturated zone that is below the stream. Changes in soil moisture are calculated daily for both of these zones based upon the above process fluxes. Percolation between the top two zones occurs when the soil moisture in the upper unsaturated zone exceeds the soil moisture capacity. Groundwater discharge to the stream and seepage to the deep lower layer are modeled as linear functions of the soil moisture in the shallow saturated groundwater layer.

3.1.1.2 Watershed Nutrient Loads

Nutrient loads are calculated differently for each source category using the flow information described above. Each of the major approaches for calculating nutrient loads are described below.

Rural Land Use Loads

For rural land uses such as agriculture (grazing), range, forest, and barren land, nutrient loads are calculated for both dissolved and particulate forms of nitrogen and phosphorus. Dissolved loads are calculated as the product of the daily runoff flows and representative nutrient concentrations in runoff for each land use type. These concentrations are compiled from the literature from several studies and are summarized in the GWLF User's Manual (Haith *et al*., 1992). The dissolved nitrogen concentrations in runoff were set at 0.07 mg/l for forests, 2.8 mg/l for range, 3.0 mg/l for grazed agricultural areas, and 2.6 mg/l for barren land. The dissolved phosphorus concentrations in runoff were set at 0.012 mg/l for forests, 0.15 mg/l for range, 0.25 mg/l for grazed agricultural areas, and 0.10 mg/l for barren land.

Particulate nutrient loads are calculated as the product of the sediment yields eroded from each land use type and the corresponding nutrient concentrations in the soils. The erosion model is based on the Universal Soil Loss Equation (Wischmeier and Smith, 1978)
approach. Erosion and sediment transport into the stream depend on the surface runoff rates, topography, soil characteristics, vegetation type and coverage, agricultural practices, and watershed size. A portion of the erosion loads are assumed to be deposited or filtered within the watershed before reaching the stream. This is represented by the

sediment delivery ratio, which is a function of watershed size. Erosion loads are distributed to the stream throughout the year based on monthly transport capacities. These are calculated as a power function of the daily runoff values. Nutrient concentrations in the soils were compiled from the literature for different regions and summarized in the GWLF User's Manual (Haith *et al*., 1992). The soil nitrogen and phosphorus concentrations were set at 3000 and 2200 mg/kg, respectively. These represent moderate nitrogen concentrations and relatively high phosphorus concentrations in the soils.

Elk Loads

The GWLF model does not explicitly account for nutrient loadings associated with elk herds that inhabit the large forested portion of the watershed. These loads were estimated from the calculated livestock grazing loads using information from local watershed and wildlife experts at the U.S. Forest Service and Arizona Game and Fish Department.

The model calculates livestock nutrient loads based on typical nutrient concentrations in pasture runoff, as described above, rather than directly from the number of livestock. The nutrient concentrations are based on typical livestock densities in pastures. Estimates of livestock numbers in the valley range from about 130 to about 300 or more. Assuming a value of 200 livestock, the animal density is about 55 animals per square mile. Estimates of elk numbers in the watershed vary from about 200-300 to about 600-800. Assuming a value of 600 elk distributed throughout the forest area, the animal density is about 20 animals per square mile. The elk density is therefore estimated to be about 1/3 of the livestock density. Although the total elk herds in the watershed may exceed the livestock numbers in the valley, they spend most of their time in the forested areas away from the stream. Small herds are observed near the San Francisco River only for short periods during the early mornings and evenings. The elk herds are also transient in that many of them migrate to lower elevations below the Luna Lake watershed during the winter months.

Runoff flows and nutrient release (per unit area) are much lower from the forested areas (where the elk spend most of their time) than from the grazed areas in the valley due to the larger water and nutrient uptake by trees. For example, using the default values of nutrient concentrations in runoff from the GWLF User's Manual (Haith *et al*., 1992), runoff from forests in the western U.S. have only about 2.3% of the nitrogen and 4.8% of the phosphorus of typical pasture runoff. The runoff flows from forests are also much lower. Based on the GWLF predictions for the Luna Lake watershed, the runoff flows from the forested areas are only about 11% of the runoff from the grazed areas in the valley on a per unit area basis. The total runoff flows are similar from both areas since the forested areas are much larger than the grazed areas in the valley.

Since the elk areal densities are less than the livestock densities, since nutrient release from forests is much less than from pastures, and since total runoff flows from the forests and pastures are about the same, the nutrient loads from elk herds were estimated to be less than the livestock loads. Local wildlife and watershed experts (U.S. Forest Service) estimated that the elk could contribute about 1/3 of the total ungulate nutrient loads.

Therefore, elk loads were assumed to be about 50 percent of the predicted livestock loads. The elk loads were also varied during model calibration (described below in Section 3.1.1.4), and this loading value gave good predictions of the measured nutrient concentrations in the San Francisco River. If the elk loads are assumed to come from the forests, this is equivalent to increasing the normal forest runoff loads of dissolved nutrients by a factor of 20 for nitrogen and a factor of 10 for phosphorus to account for elk. The elk load estimates have some uncertainty since there is not enough information available to make accurate direct estimates. Limited information is available in the literature on nutrient loading from elk, so additional studies would be required to refine these estimates.

Residential and Commercial Loads

Nutrient loads from residential and commercial areas are assumed to occur as particulate forms which occur only during storm runoff events. The nutrients are assumed to build up on land surfaces between storms due to various activities. Nutrient build-up (i.e., accumulation) rates are input to the model and vary with land use type, lot size, and the relative amounts of pervious and impervious areas. Both nutrient build-up and runoff are higher on the impervious areas. Residential and commercial areas were assumed to consist of 20% and 50% impervious surfaces, respectively. Commercial areas included all developed areas that were not residential, for example businesses, public buildings, and schools in the town of Alpine.

Nutrient build-up rates were taken from default values in the GWLF User's Manual (Haith et al., 1992) for the appropriate land use category and lot size. Nitrogen build-up rates in residential areas were set at 0.090 kg/ha-day in impervious areas and 0.022 kg/ha-day in pervious areas. The corresponding phosphorus build-up rates were 0.0112 kg/ha-day and 0.0039 kg/ha-day in the impervious and pervious areas, respectively. Nitrogen build-up rates in commercial areas were set at 0.056 kg/ha-day in impervious areas and 0.012 kg/ha-day in pervious areas. The corresponding phosphorus build-up rates were 0.0067 kg/ha-day and 0.0019 kg/ha-day in the impervious and pervious areas, respectively.

Nutrient accumulation is modeled using the above build-up rates along with an exponential depletion function, so that nutrient concentrations build up to maximum levels in a few weeks without rain. The accumulated nutrients begin to wash off during storms. The wash off rates increase with runoff rates according to an exponential function. Runoff rates are calculated from precipitation data using the SCS Curve Number approach.

Groundwater Loads

Nutrient loads from shallow groundwater flows occur as dissolved forms. These loads are calculated as the product of the groundwater flow rate and the dissolved nutrient concentrations in groundwater. These concentrations were taken from the default values in the GWLF User's Manual (Haith et al., 1992), and were set at 0.070 mg/l for nitrogen and 0.015 mg/l for phosphorus. These values represent areas in the western U.S. that are 75-90% forest.

Groundwater flows were calculated from the daily precipitation data using the water balance approach described above for the shallow saturated zone that feeds the stream. The portion of the groundwater flow that enters the stream was determined through model calibration, as described below in Section 3.1.1.4.

Septic System Loads

Nutrient contributions from septic system sources were calculated based on estimates of the number of people using septic systems in the watershed. Information from the Alpine Chamber of Commerce and other county and state agencies with census information indicated that the population in the watershed is about 2500 during the summer (June through August) and about 600 during the rest of the year. The population served by direct sewer connections was estimated to be 500, assuming about 250 connections and an average of 2 people per connection (based on information from the local sanitation department). The proportion of people served by the sewer system was assumed to be the same year round. Therefore, about 20 percent of the population is on the sewer system and 80 percent is on septic systems. This results in about 2000 people using septic systems during the summer and about 480 during the rest of the year.

It was assumed that 85% of the septic systems operate optimally according to design procedures recommended by the EPA, while the other 15% do not function optimally. These latter systems represent older septic systems, systems that have not been properly maintained, systems that are close to waterways, and old cesspools that are still present in the watershed. Septic system surveys in other areas have shown that 15 percent is a reasonable estimate of systems that don't conform to standards. The difference between the two septic system categories was assumed to influence only phosphorus loadings. In properly functioning septic systems, phosphorus in effluent is absorbed and retained by the soil, so no phosphorus loads enter the stream. In the other septic systems, phosphorus adsorption is assumed to be minimal, so phosphorus loads are contributed to the stream.

Septic system loads occur as dissolved nutrients and are transported to the stream through shallow groundwater discharge. The loads are calculated using per capita daily nutrient loading rates and plant uptake rates. Plants are assumed to remove a fraction of the per capita nutrient loads before they enter the stream. Plant uptake occurs only during the growing season, which was assumed to be June through September. Per capita nutrient loads in septic effluent and plant uptake rates were based on the default values in the GWLF User's Manual (Haith et al., 1992). The per capita effluent loading rates were 12.0 g/day for nitrogen and 2.5 g/day for phosphorus. The per capita plant uptake rates during the growing season were 1.6 g/day for nitrogen and 0.4 g/day for phosphorus, and zero during the rest of the year. Plants were therefore assumed to remove about 13 percent of the nitrogen and about 16 percent of the phosphorus during the growing season. The total septic system loads were calculated by multiplying the per capita loading rates by the corresponding populations on each type of septic system, and then subtracting the plant uptake fluxes.

3.1.1.3 Hydrology and Transport Model Parameters

The runoff, erosion, and groundwater flow calculations used to predict the above nutrient loads require several model input parameters. These are described below.

Runoff

Runoff is calculated on a daily basis for each land use category using the U.S. Soil Conservation Service (SCS) Curve Number approach. The curve numbers vary with land use type, vegetation type, percent vegetation coverage, soil type, extent of impervious areas, agricultural practices, growing versus dormant season, and antecedent moisture conditions. Since the soil types varied within a given land use category, runoff curve numbers were determined separately for each soil type, and then area-weighted composite values were calculated for each land use category. The areal distributions of soil types (soil hydrologic groups A through D) for each land use were taken from the STATSGO database in BASINS. Soil Conservation Service (SCS) runoff curve numbers were assigned for each soil type within a land use category based on a combination of land use type and soil hydrologic condition parameters. The curve numbers were taken from the tables in the GWLF User's Manual (Haith et al., 1992), which were originally obtained from the U.S. Soil Conservation Service (U.S. SCS, "Technical Release No. 25, 2nd Edition", 1986).

Runoff is calculated from the daily meteorological data, and is dependent on the current precipitation (and snow melt), and on the average moisture conditions during the previous 5 days. The model runs were initiated in May so it could be assumed that the snow pack and antecedent moisture conditions were zero. Runoff from residential and commercial areas were calculated separately for the pervious and impervious portions, since runoff rates and nutrient loads are substantially different over pervious and impervious areas.

Evapotranspiration

Daily evapotranspiration losses are calculated by multiplying the potential evapotranspiration by an evapotranspiration cover coefficient. The cover coefficient represents the fraction of the potential evapotranspiration that is actually attained for a given vegetation cover. The potential evapotranspiration is calculated as a function of the air temperature and the number of daylight hours. Evapotranspiration cover coefficients were calculated for each land use category based on land use and vegetation type. Area-weighted composite values were calculated for the entire watershed for different seasons. A value of 1.0 was assumed for all plants during the growing season, and a value of 0.3 was used for bare soils and deciduous trees during the dormant season. The growing
season was considered to consist of all months with monthly average air temperatures exceeding 10°C (June through September). For residential and commercial areas, the evapotranspiration cover coefficient was assumed to equal the pervious fraction of land.

Erosion

The soil erosion calculations are based on the Universal Soil Loss Equation, and require several model parameters. These include erosivity coefficients, sediment delivery ratio for the watershed, and the soil erodability values, slopes, lengths, cover and management factors, and supporting practice factors for each of the land use categories.

Rainfall erosivity coefficients describe the effects of rainfall intensity and precipitation patterns on soil erosion. These values vary with region and season. Rainfall erosivity coefficients were calculated separately for the warm season (April through September) and cool season (October through March). Since specific values were not available for Arizona, the average of all values tabulated in the GWLF User's Manual (for other regions of the United States) were used. These values were 0.28 for the warm season months and 0.15 for the cool season months.

The sediment delivery ratio accounts for the attenuation of sediment through deposition and filtering as it moves through the watershed. It represents the fraction of the erosion loads calculated from the Universal Soil Loss Equation that are ultimately transported to the stream at the downstream boundary of the watershed. The sediment delivery ratio decreases with watershed area. A value of 0.13 was selected based on the total watershed area and the empirical relationship (Vanoni, 1975) shown in the GWLF User's Manual (Haith et al., 1992).

Soil erodability factors (K) describe the erosion potential of a particular soil type, and depend on both the grain size distribution and the organic content of the soils. Soil erodability factors are available from soil surveys, and were taken from the STATSGO database in BASINS. Since the soil characteristics varied in the watershed, area-weighted averages of the soil erodability factors were calculated for each land use category.

Topographic information for each land use category (slopes and lengths) was taken from the Digital Elevation Model in BASINS and from USGS topographic maps. Topographic factors in the GWLF model were calculated with equations from Wischmeier and Smith (1978), which incorporate the slopes and lengths of each land use area. For larger forested areas with varying topography, the regions were broken into several sections of similar slope, and a composite factor was calculated using weighting factors as described in Wischmeier and Smith (1978).

Cover and management factors (C) in the Universal Soil Loss Equation represent the reduction in erosion potential due to vegetation cover or agricultural practices relative to the erosion that would occur if the soil were bare. These values depend on the vegetation type, percent canopy cover or ground cover, and the vegetation condition. Information on

vegetation characteristics were obtained from Laing *et al.* (1986) and from interviews with watershed experts at the local U.S. Forest Service District and Arizona Game and Fish Department. The appropriate cover and management factors were then selected for each land use category using the tables in the GWLF User's Manual (Haith et al., 1992).

Supporting practice factors (P) in the Universal Soil Loss Equation represent the reduction in erosion potential due to soil conservation practices (e.g., contouring, terracing). These values were set to 1.0 for all land use categories.

Groundwater Flow
The groundwater portion of the model requires three model parameters: the initial soil moisture capacity in the unsaturated zone, the groundwater recession coefficient, and the groundwater seepage coefficient.

The initial soil moisture capacity in the unsaturated zone was obtained from information in the BASINS database. An area-weighted average was calculated for the watershed, resulting in a value of 8.78 cm.

The groundwater recession coefficient describes the rate at which shallow groundwater flows to the stream change after surface runoff flows have stopped (i.e., during a receding hydrograph). It is normally determined by examining temporal changes in stream flow records. Since no stream flow records are available for the San Francisco River just above Luna Lake, a default value was selected from information in the GWLF User's Manual (Haith et al., 1992). Typical values range from 0.01 to 0.2 per day, so a midpoint value of 0.1 per day was selected.

The groundwater seepage coefficient represents transport of shallow groundwater to the deep groundwater zone below the stream bed. Since this parameter is difficult to measure directly, it is normally determined by model calibration, as described below.

3.1.1.4 GWLF Model Calibration

Calibration of the GWLF Model involved two steps. First, the hydrological portion of the model was calibrated so that the stream flow response to the precipitation data gave reasonable results. Then, the nutrient loading portion of the model was calibrated by adjusting certain parameters so that predicted concentrations of nitrogen and phosphorus in the San Francisco River just above Luna Lake matched the monitoring data in the stream. An attempt was made to use the default model parameters from the GWLF User's Manual (Haith et al., 1992) whenever possible, and to adjust only a few parameters that are site-specific or for which limited data were available. The default parameters were compiled from the literature from many studies conducted throughout the country. Many different values were tabulated that considered the effects of land use type, intensity of use, soil characteristics, topography, vegetation type, percent vegetation coverage, meteorological conditions, hydrologic conditions, and other site-specific factors. For parameters that vary with regions, the appropriate values for east central Arizona or for the western or southwestern U.S. were selected.

Since no reliable stream flow data were available from the San Francisco River to calibrate the watershed model, stream flows were estimated based on average long-term precipitation in the watershed. Stream flows were estimated assuming a 0.225 runoff ratio, which is approximately the same value observed for the nearby Rainbow Lake watershed, and is consistent with typical values of runoff from other forested watersheds (20 to 25% of precipitation). The model was calibrated by adjusting the groundwater seepage coefficient until the model flows matched the above estimated flows. The resulting value for the seepage coefficient was 0.06 per day.

Model calibration of the nutrient loads was accomplished by adjusting the sediment phosphorus concentration in the watershed using a value that is representative of areas with high phosphorus in sediments, and by adjusting the parameters representing nutrient loads from elk herds. This resulted in elk herd loading estimates that were 50 percent of the calculated loads from livestock grazing in the valley. This is consistent with estimates from the local wildlife experts (U.S. Forest Service), which estimated that elk could contribute about 1/3 of the total ungulate nutrient loads. Otherwise, all model parameters used in the analyses were taken from the default values listed in the GWLF User's Manual (Haith et al., 1992).

3.1.2 Nutrient Budget Analysis

Nutrient budgets were constructed for total nitrogen and total phosphorus in Luna Lake based on mass balances of watershed inputs, outflows, and internal fluxes in the system. The budgets were based on average hydrologic and nutrient conditions in the lake. A general description of the assumptions and sources of data is presented here. The results of the analyses are presented in Section 3.3.2 below.

Water Budget

A water budget was developed representing the long-term average conditions in the lake. The lake characteristics used in the analysis are summarized in Table 3-1. When full, Luna Lake has a surface area of 154.5 acres (62.5 hectares) and a storage volume of 1390 acre-feet (1.71 x 10^6 cubic meters) (Novy and Jones, 1988). However, at maximum drawdown of 6.2 feet, the surface area is 47% and the volume is 40% of the full pool values (Novy and Jones, 1988). Since the lake fluctuates over this range several times a year, average values of the lake area and volume were estimated for use in the analyses. The average surface area was estimated using the average of the surface areas at full pool and maximum drawdown. The average volume was estimated using this area and the reported value of the mean depth. Therefore, the average surface area of Luna Lake is 114 acres (46 hectares) and the average volume is 932 acre-feet (1.15 x 10^6 cubic meters). The lake has a mean depth of 8.2 feet (2.5 meters) and a maximum depth of 20.7 feet (6.3 meters).

The lake water budget includes stream inflow, precipitation, evaporation, outflow from the dam, and groundwater seepage. Data were directly available only for precipitation and evaporation. Since no reliable stream flow data were available for the San Francisco River in the vicinity of Luna Lake, inflows and outflows had to be estimated from the meteorological data. The average inflow from the San Francisco River to Luna Lake was

Table 3-1
Lake Characteristics of Luna Lake

Parameter	Value
Lake volume (acre-feet)	932.3
Lake surface area (acres)	113.7
Mean Depth (ft)	8.2
Max Depth (ft)	20.7
Precipitation rate (ft/yr)	1.7
Evaporation rate (ft/yr)	3.5
Watershed area (acres)	23,030

calculated from the long-term average precipitation in the watershed measured at the Alpine meteorological station using a stream flow-to-precipitation ratio of 0.225, the value measured for Rainbow Lake. Stream flow is typically 20% to 25% of precipitation in forested watersheds. Outflow and seepage were calculated by difference as stream inflow plus precipitation minus evaporation to get a mass balance of water. Outflow and seepage are treated as a single quantity since seepage is difficult to measure and since they are both the same in terms of nutrient removal from the lake. Precipitation into the lake was calculated as the product of the long-term average precipitation and lake surface area. Evaporation was calculated as the product of the evaporation rate (42.5 in/year) and lake surface area.

The water budget data used in the nutrient budget analysis are summarized in Table 3-2.

Nutrient Budget
The lake nutrient budget consists of atmospheric, hydrologic, sediment, and macrophyte components.

Atmospheric loadings were based on default deposition values from the BATHTUB model (10 kg/ha-year total nitrogen and 0.3 kg/ha-year total phosphorus), which are representative of general deposition rates of these nutrients. These rates were multiplied by lake surface area to estimate atmospheric loadings.

Inflow loads of nitrogen and phosphorus were calculated from the long-term average flow estimated for the San Francisco River multiplied by the average nutrient concentrations
measured in the river just above Luna Lake (0.84 mg/L total nitrogen and 0.16 mg/L total phosphorus). Outflows of nitrogen and phosphorus were calculated from the estimated outflow and seepage (calculated from the water budget) multiplied by the average nutrient concentrations measured in the lake (1.5 mg/L total nitrogen and 0.18 mg/L total

phosphorus). The nutrient concentrations in the San Francisco River and Luna Lake were averaged from the ADEQ monitoring data.

Table 3-2
Water Budget Summary for Luna Lake

Hydrologic Parameter	Value
Inflow (acre-feet/yr)	8,998.8
Precipitation (acre-feet/yr)	197.8
Evaporation (acre-feet/yr)	402.9
Outflow and seepage (acre-feet/yr)	8,796.1
Residence time (days)	38.7
Watershed runoff ratio	0.225

Since no sediment nutrient data were available for Luna Lake, sediment fluxes of nutrients were estimated from values measured at nearby Rainbow Lake, which has eutrophication problems similar to Luna Lake. Sediment nutrient release was estimated from phosphorus release rates measured in sediment cores from Rainbow Lake by Baker and Farnsworth (1995). The aerobic core value of 0.27 g/m^2-year was used for phosphorus. Nitrogen release was estimated from this value and the ratio of nitrogen to phosphorus in Rainbow Lake sediments (13.9), as measured by ADEQ during 1992-1993.

Deposition of nutrients in sediments was based on phosphorus accumulation rates in Rainbow Lake estimated by Baker and Farnsworth (1995) from sediment cores. Values from two sediment cores were averaged, resulting in a phosphorus deposition rate of 1.3 g/m^2-year. The nitrogen deposition rate was estimated using this value and the ratio of nitrogen to phosphorus in sediments (13.9) measured at Rainbow Lake by ADEQ during 1992-1993.

The sediment deep burial rate was estimated from sediment core profile dating for Rainbow Lake (Baker and Farnsworth 1995), yielding an estimate of the sediment deep burial rate of approximately 0.55 cm/year at a depth of about 20 to 30 cm. This depth was assumed to represent the lower, inactive sediment layer, which is below the typical macrophyte root depth. Deep burial rates were calculated using this sedimentation rate (0.55 cm/year) multiplied by average sediment nutrient concentrations (3,256 mg/L nitrogen and 235 mg/L phosphorus) measured in Rainbow Lake by ADEQ during 1992-1993.

Nutrient removal from macrophyte harvest was calculated from harvest rates by AGFD and nutrient concentrations in the plants. Harvest rates averaged 410 tons per year during 1992 to 1998. Macrophytes were assumed to contain 2.5% nitrogen dry weight, 0.5% phosphorus dry weight, and an 88% water content.

Nutrient release due to macrophyte decomposition was estimated using typical values of biomass turnover and the above nutrient concentrations in the plants. Nutrient release fluxes were calculated assuming a typical biomass turnover rate of 2.5 times the peak density. The peak density during the growing season was estimated at 500 g/m^2 dry weight based on information in the literature, and was the same value used by Baker and Farnsworth (1995) during their study of Rainbow Lake. Approximately two-thirds of the lake area was assumed to contain macrophytes, as observed during a survey by AGFD during 1982. During decomposition, 28 percent of the plant tissue was estimated to be refractory (Jewell 1971), and therefore to release nutrients at a lower rate than the remaining labile fraction. The labile fraction is assumed to release nutrients directly to the water, while the refractory portion may accumulate in the sediments. However, decomposition in sediments may also eventually release much of these nutrients back to the water, but at a slower rate.

Since macrophytes obtain nitrogen and phosphorus from the sediments, the nutrient pools in the sediments were estimated and compared with macrophyte harvest rates to determine if harvest could be considered an effective nutrient removal process and could eventually limit plant growth through sediment nutrient depletion. The nutrient pools to a depth of 25 cm, the typical root depth of the plants, were calculated using the sediment nutrient concentrations measured in Rainbow Lake by ADEQ during 1992-1993.

3.1.3 Linkage of Nutrient Loads to Water Quality Endpoints

The steady-state lake model BATHTUB (Walker, 1996) was used in the linkage analysis to determine the water quality response of Luna Lake to different loading scenarios. This model calculates water quality variables such as nutrient concentrations, chlorophyll-*a* concentrations (or algal densities), and turbidity. BATHTUB is a steady-state empirically based model. It calculates steady-state nutrient and water balances based on the loadings, hydrology, lake geometry, and internal nutrient cycling processes within the lake. The resulting nutrient levels are then used in a series of empirical relationships to calculate chlorophyll-*a* and turbidity. These relationships were derived from field data from many different lakes. The calculated values represent long-term values during the summer growing season that would result if loadings remain the same.

Average values of Luna Lake hydrologic characteristics (Tables 3-1 and 3-2) were used in the model simulations since they were most representative of long-term average conditions. The model was set up using the average flows estimated from the long-term precipitation data along with the average nutrient concentrations in the San Francisco River inflow from the ADEQ monitoring data. These values were consistent with the long-term average flows and nutrient loads predicted from the GWLF watershed model. Atmospheric loads were based on the default values in BATHTUB. The model was then calibrated by adjusting internal nutrient release fluxes for macrophyte decomposition and sediment release until predicted nutrient levels in the lake matched the average nutrient concentrations from the monitoring data.

Phosphorus was calibrated first, using the sediment release fluxes estimated from the nutrient budget (based on Rainbow Lake values from Baker and Farnsworth, 1995) and assuming any additional phosphorus releases were due to macrophyte decomposition. Nitrogen was calibrated next, dividing the calibrated release fluxes between sediments and macrophytes based on the relative proportions of phosphorus release calibrated previously. The total areal flux calibrated for nitrogen, which includes the sum of both macrophyte decomposition and sediment release, was within 5% of the corresponding total calculated in the nutrient budget. However, the total areal flux calibrated for phosphorus was twice as high as the corresponding total calculated in the nutrient budget.

The distribution of nitrogen and phosphorus releases between macrophyte decomposition and sediment release in BATHTUB was different than in the nutrient budget, since the same nitrogen:phosphorus (N:P) ratio was assumed for both sources in the BATHTUB calibrations. The nutrient budget used a high N:P ratio of 13.9 for the sediment release, and a lower N:P ratio of 5.0 for macrophyte decomposition. The sediment value was based on the nutrient ratio measured in the sediments at nearby Rainbow Lake (ADEQ, 1992-93), and the macrophyte value was based on typical values from the literature. The BATHTUB calibrated N:P ratio for both sources was much lower, about 2.8. This was due to the high phosphorus releases required to calibrate the model.

The high phosphorus releases required to calibrate BATHTUB to Luna Lake could be due to several factors. The soils in the large forested watershed surrounding Luna Lake contain high phosphorus concentrations, and are the major external source of phosphorus to the lake. Luna Lake has also been shown to be nitrogen limited through algal assay experiments (EPA, 1978) and through the low N:P ratios observed in the monitoring data. This indicates that excess phosphorus is available in Luna Lake. Excess phosphorus often results in luxury consumption of phosphorus by both phytoplankton and macrophytes, in which the plants store phosphorus in excess of their requirements for growth. This produces low N:P ratios, since more phosphorus is stored in the plants relative to the nitrogen stored. The high phosphorus from watershed sediment sources together with elevated phosphorus concentrations in phytoplankton and macrophytes, all of which ultimately contribute to the sediment nutrient pools, could produce much lower N:P ratios in Luna Lake sediments than the value measured at nearby Rainbow Lake. This in turn could produce lower N:P ratios in macrophytes, since they obtain most of their nutrients from the sediments. Measurements of the nutrient concentrations in both sediments and macrophyte tissues are necessary to confirm these hypotheses.

Other possible explanations for the high phosphorus releases required to calibrate BATHTUB to Luna Lake could be limitations in the amount of inflow and in-lake nutrient data available to calibrate the model, and limitations in the BATHTUB model itself. BATHTUB was originally developed for lakes in which phytoplankton, rather than macrophytes, were the major plant of concern. The model assumes nutrients are removed from the water column through phytoplankton settling. Macrophytes compete with phytoplankton for light, so as their density and canopy height increases during the summer, they inhibit phytoplankton growth. Since less phytoplankton would therefore be present in the water, less nutrient sedimentation would occur when macrophytes are abundant. Therefore, BATHTUB may overestimate the amount of nutrient sedimentation that would occur, which would in turn require that addition areal sources (i.e., sediment or macrophyte release) are specified to compensate for this effect during model calibration. Unfortunately, no other models are available that predict the combined effects of both macrophyte and phytoplankton interactions on nutrient cycles and water quality in lakes.

The BATHTUB model includes several different options and submodels. In general, the most recommended options (defaults) were selected. The phosphorus and nitrogen models used the second-order nutrient settling formulations. The chlorophyll-*a* model used the most comprehensive and general approach, which includes the effects of nitrogen, phosphorus, light, and flushing rate (rather than the default model, which does not consider nitrogen). Turbidity was calculated using the default model.

Nutrient availability in inflows was assumed to equal the total nutrient concentrations in the inflows. The default option for nutrient availability in inflows uses relationships that include the sums of both total nutrient concentrations and dissolved inorganic nutrient concentrations (phosphate or inorganic nitrogen), with weighting factors for each of these forms. This option was not used since internal release fluxes from sediments and macrophytes were modeled as inflows (as required by the BATHTUB model), and since phosphorus release from these sources was assumed to occur as phosphate. The default option would result in phosphorus availability much greater than the total amount of phosphorus released under these circumstances, since the weighting factor for phosphate availability is greater than 1 (the value is close to 2). The default relationships for nutrient availability in inflows in BATHTUB are based on empirical analyses of stream data, where phosphate is a small fraction of the total phosphorus (because much of the total phosphorus is associated with suspended particles). Therefore, it was not appropriate to use these relationships for macrophyte and sediment release of nutrients, which are major sources in Luna Lake. In addition, phosphate measurements were not available for the San Francisco River inflow, since only total phosphorus was measured, so it would not have been possible to use the default relationships even for this source.

The BATHTUB model was calibrated using the long-term average loading conditions and monitoring data, and then several analyses were performed using different loading scenarios:

- Loadings from the watershed were reduced incrementally to represent different watershed nonpoint source control options

- Under existing watershed loadings, different macrophyte densities in the lake were assumed to represent different macrophyte harvest options

- Assuming no macrophytes were present in the lake, successive reductions in watershed loading rates from current average conditions were applied to represent watershed source controls in conjunction with macrophyte elimination

These scenarios covered the whole range of available options, and indicate what levels of improvement can be expected and which types of loading categories (watershed loads vs. macrophytes) will be most effective in improving water quality in the lake. In addition to the above scenarios, which are based on long-term average conditions, two additional scenarios were analyzed to represent the effects of hydrologic extremes. These were for a high flow and a low flow year. The flow rates and nutrient concentrations in inflows were based on the results of the GWLF model analyses for the years with the highest and lowest precipitation in the meteorological records. However, these extreme conditions would not persist for very long, so the other scenarios above are more useful for the TMDL analyses.

3.2 Existing Sources and Effects

There are three potential sources of nutrients into Luna Lake. These are **point sources** (a discharge whose source is known and can be directly quantified); **non-point sources** (discharges that have no obvious single source (seepage, runoff) and are difficult to quantify); and **in-lake processes** (in-lake sources and processes that recycle nutrients). Each of these is discussed in the following sections.

3.2.1 Point Sources

Currently, there are no point-source discharges into Luna Lake. The single potential point source is the Alpine Sanitary District, located on the San Francisco River near the town of Alpine, Arizona. However, in-stream data available from stations on the river do not indicate any violations of the phosphorus water quality standard either upstream or downstream of Alpine. Therefore, it is assumed that point sources are not contributing significant nutrient loads to Luna Lake. Temporary leaks in the sewage treatment ponds have occurred a few times in the past, but they were quickly repaired. Because of their short duration, they are not considered significant sources of nutrients to the lake.

3.2.2 Non-Point Sources

Non-point sources include septic systems, pastures, runoff, and small plots of irrigated agriculture (ADEQ, 1997). These are all possible sources of nutrients into Luna Lake but insufficient information was available to make any determinations regarding their significance.

3.2.3 In-Lake Processes

Baker and Farnsworth (1995) calculated the nutrient budget for the nearby Rainbow Lake watershed and estimated that Rainbow Lake has a negative phosphorus retention rate (-10%) and is a source of phosphorus. Sediment cores taken from Rainbow Lake indicate that phosphorus concentrations have been and currently are elevated. Although no such study has been performed for Luna Lake, the same processes are most likely occurring.

Sediment nutrients are directly recycled to the water column via diffusion and indirectly recycled via uptake by macrophytes and release during senescence. The surplus of sediment nutrients stimulates algal and plant growth. As the algae and plants grow, they consume CO_2, which causes the lake pH to rise. When the algae and plants die, bacterial action promotes decay and nutrients are released either back into the water column or into the sediments. Nitrogen released during decomposition produces ammonia. The amount of ammonia that is converted to the toxic unionized form is directly related to pH and temperature (i.e., higher pH yields higher unionized ammonia concentrations). Thus, the process is as follows:

- Elevated nutrients cause plants to become stimulated and they grow;
- As they grow, they consume CO_2. This causes the water pH to rise;
- When the plants die or become fragmented, bacterial action begins the decomposition process;
- Decomposition releases the nutrients back into either the water column or the sediments, decreases dissolved oxygen concentrations, and produces ammonia;
- Nutrient concentrations are recycled;
- Low dissolved oxygen can lead to fish kills;
- High pH levels increase the concentration of unionized ammonia;
- Unionized ammonia is extremely toxic to aquatic organisms and can result in fish and invertebrate kills.

These processes appear to be the driving force behind the elevated nutrient concentrations in Luna Lake and resultant elevated pH values.

3.3 Loading Analysis and Nutrient Budget Results

The analysis of nutrient loading sources within the Luna Lake watershed and the results of the nutrient mass balance analysis in the lake are presented in this section.

3.3.1 Source Analysis of Loadings

Simulated loadings of total and dissolved nitrogen (Figure 3-1) and phosphorus (Figure 3-2) in Luna Lake from within the watershed varied with annual precipitation over the 12-year period. Nutrient loads during low flow years (e.g., 1989) were less than half of the loads during the high flow years (e.g., 1992).

On average over the 12-year period, agriculture (predominantly grazed land) and septic systems produced the highest levels of nitrogen input to the lake (Figure 3-3a). During a low flow year, septic input is the greatest source of nitrogen, while agriculture yields the highest levels during a high flow year (Figure 3-4). The combined loads from elk herds and forests are similar to the agricultural loads. Nitrogen contributions from range, barren land, and commercial areas were negligible due to their small areas (Figures 3-3a and 3-4).

The quantities of phosphorus within the watershed were substantially lower than those of nitrogen. Forests generated the highest levels of phosphorus input under all precipitation and flow scenarios due to the large areas and the high phosphorus concentrations in the soils (Figures 3-3b and 3-5). Agriculture (grazing) was the next largest source of phosphorus, but was not much greater than residential areas and groundwater sources. Septic systems produced lower loads of phosphorus than nitrogen relative to other sources since soils adsorb phosphorus unless the septic systems are not functioning properly (Figure 3-3b). As with nitrogen loading, septic system contributions of phosphorus were equivalent for average, low flow, and high flow scenarios since they depend more on the number of septic system users than on hydrologic conditions. Elk phosphorus loads were estimated to be half of the agricultural loads, and were comparable to the residential, groundwater, and septic loads. Phosphorus inputs from range and commercial areas were negligible (Figures 3-3b and 3-5).

3.3.2 Nutrient Mass Balance

The results of the nutrient mass balance analyses are presented in Table 3-3. The nitrogen and phosphorus budgets in Luna Lake include watershed inputs, outflows, and internal flux components. Nutrient inputs originate from atmospheric loading and inflows from the watershed. Nutrient losses occur through water outflows (dam releases and groundwater seepage) and macrophyte harvesting. Internal releases of nutrients occur within the lake from macrophyte decomposition and sediment exchange processes. Some of the nutrients eventually become buried below the active surface sediments which effectively sequesters them and makes them unavailable for cycling with the water column.

Inflows from the watershed are the major external loading source. Atmospheric loads are more than an order of magnitude lower. Internal loads such as macrophyte decomposition are also significant sources, and are about the same magnitude as the watershed loads. The outflow fluxes are larger than the external loads, which suggests that internal nutrient sources are important in Luna Lake.

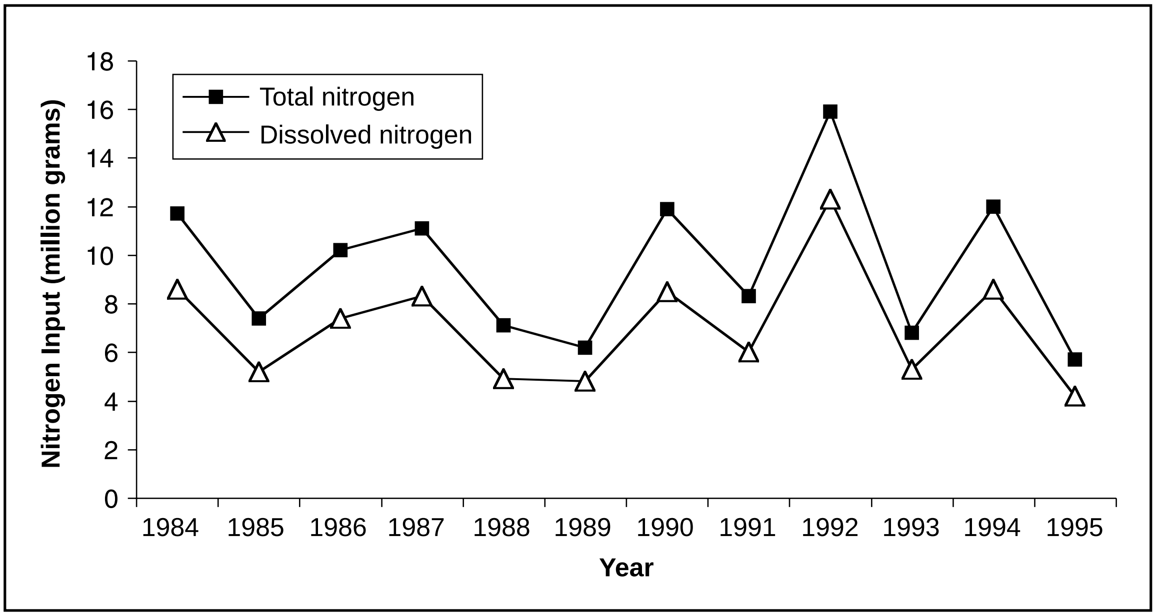


Figure 3-1. Annual total nitrogen and dissolved nitrogen inputs to Luna Lake.

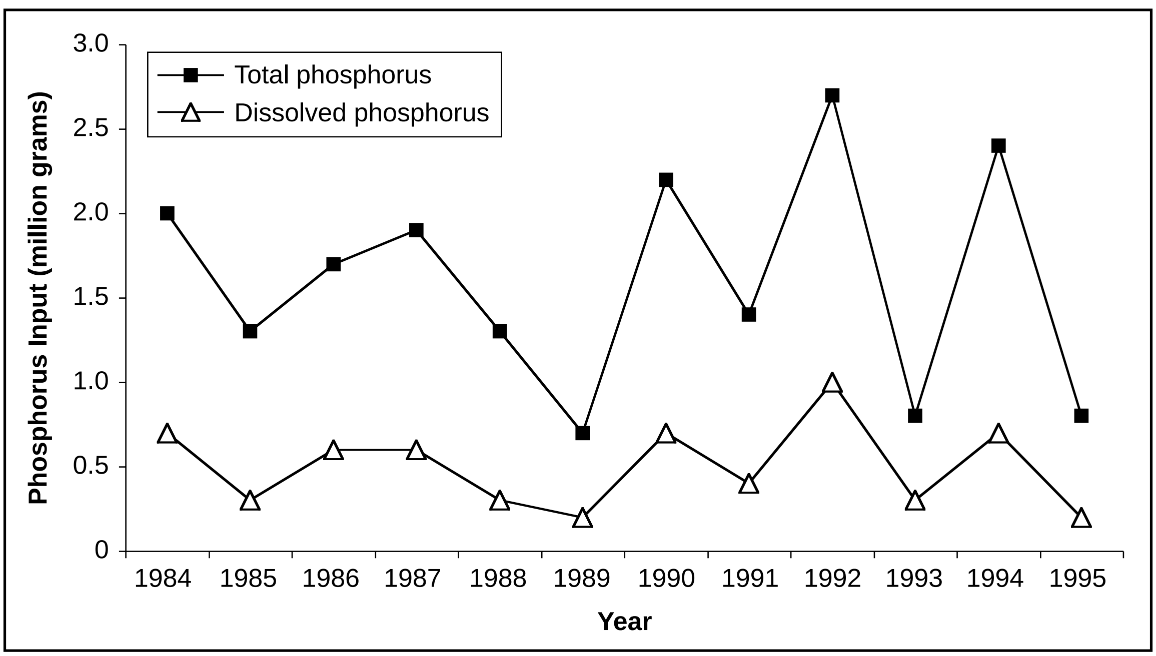
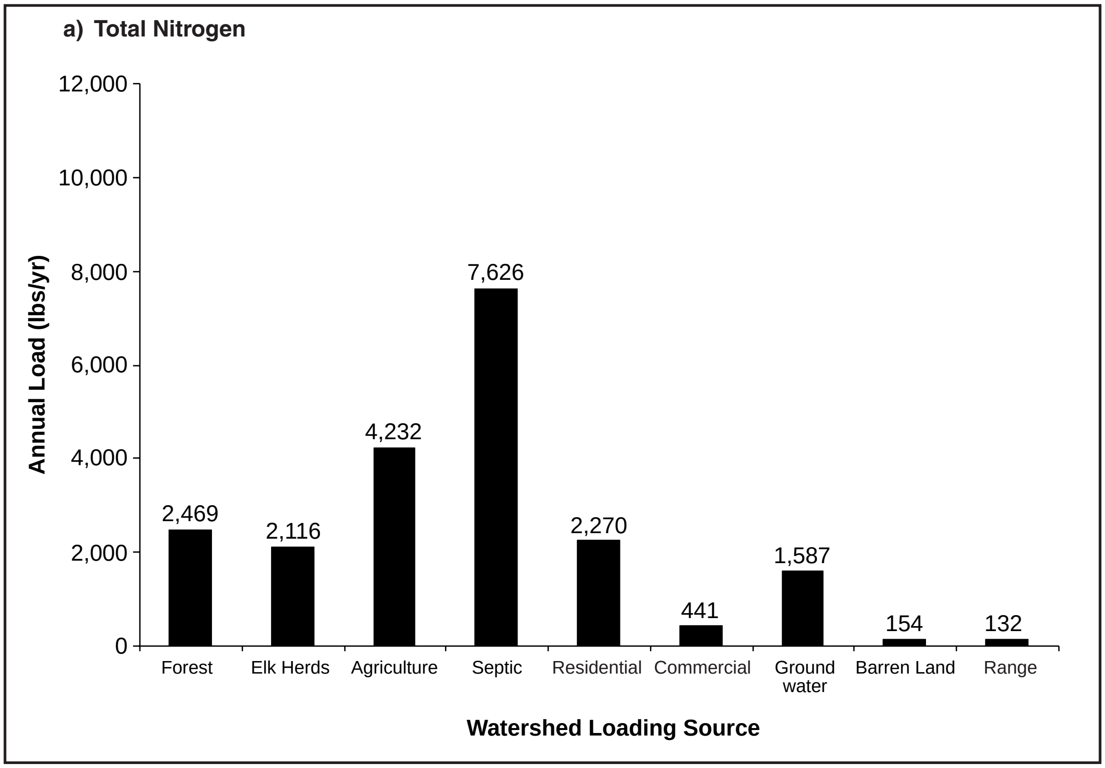


Figure 3-2. Annual total phosphorus and dissolved phosphorus inputs to Luna Lake.



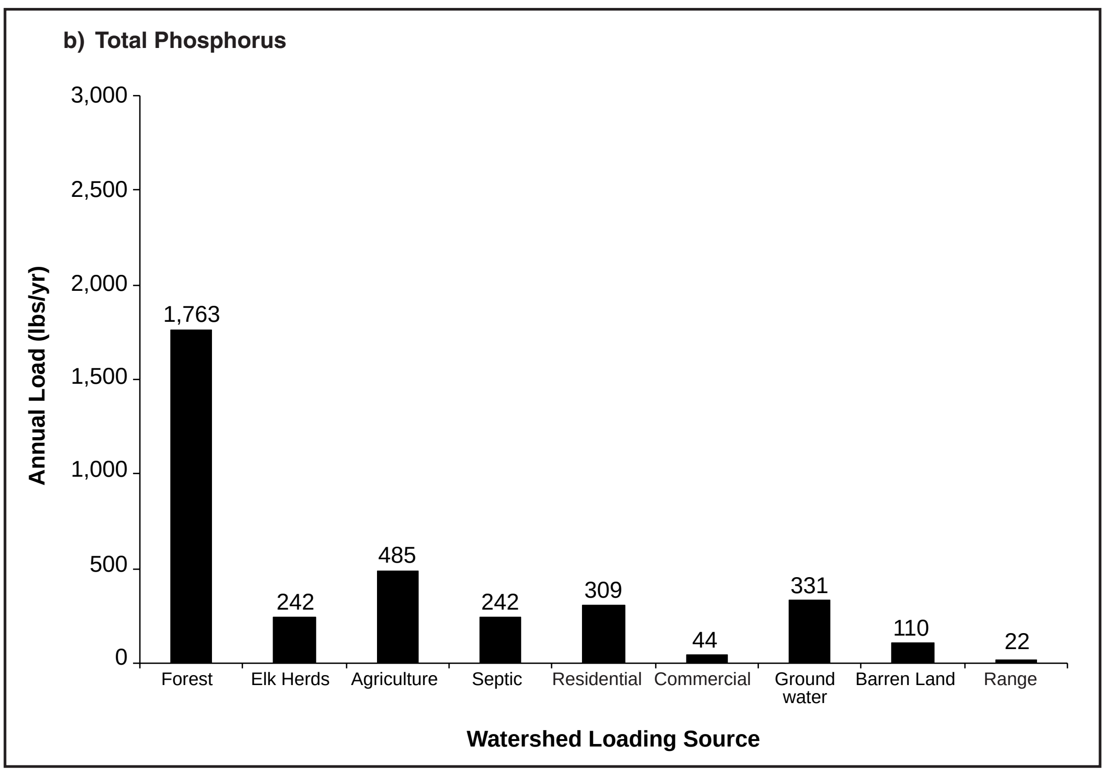
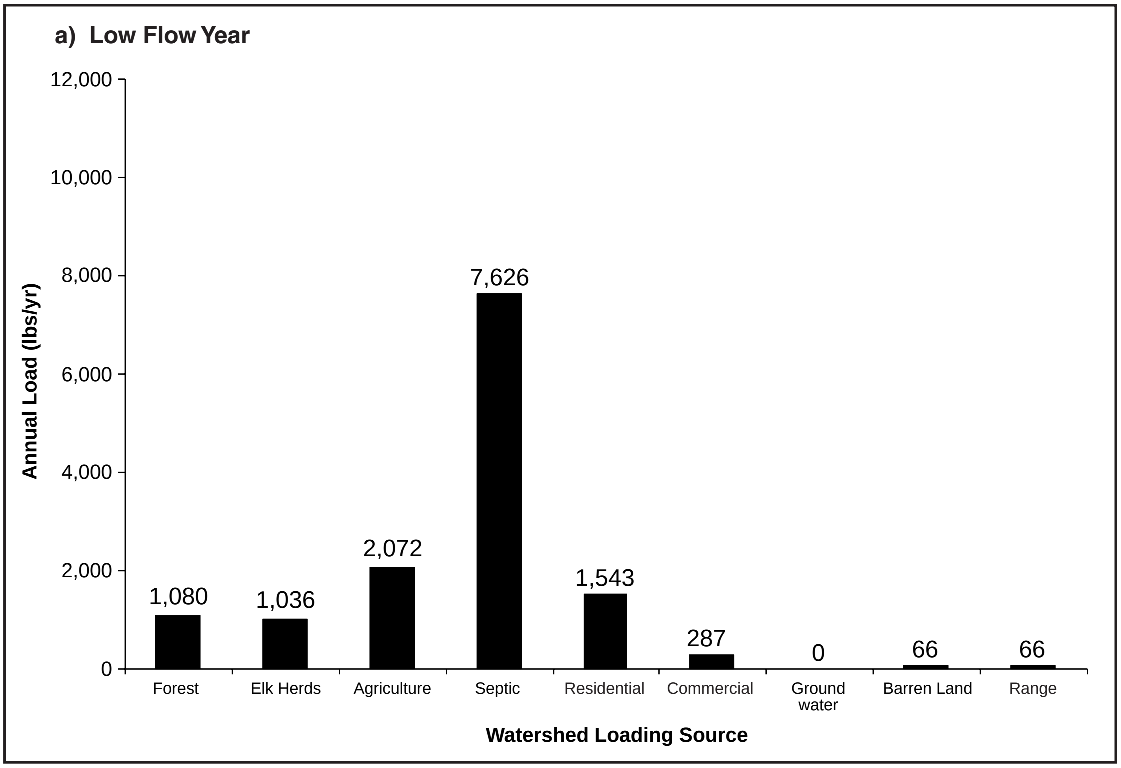


Figure 3-3. Long-term averages of annual (a) total nitrogen and (b) total phosphorus contributions to Luna Lake.



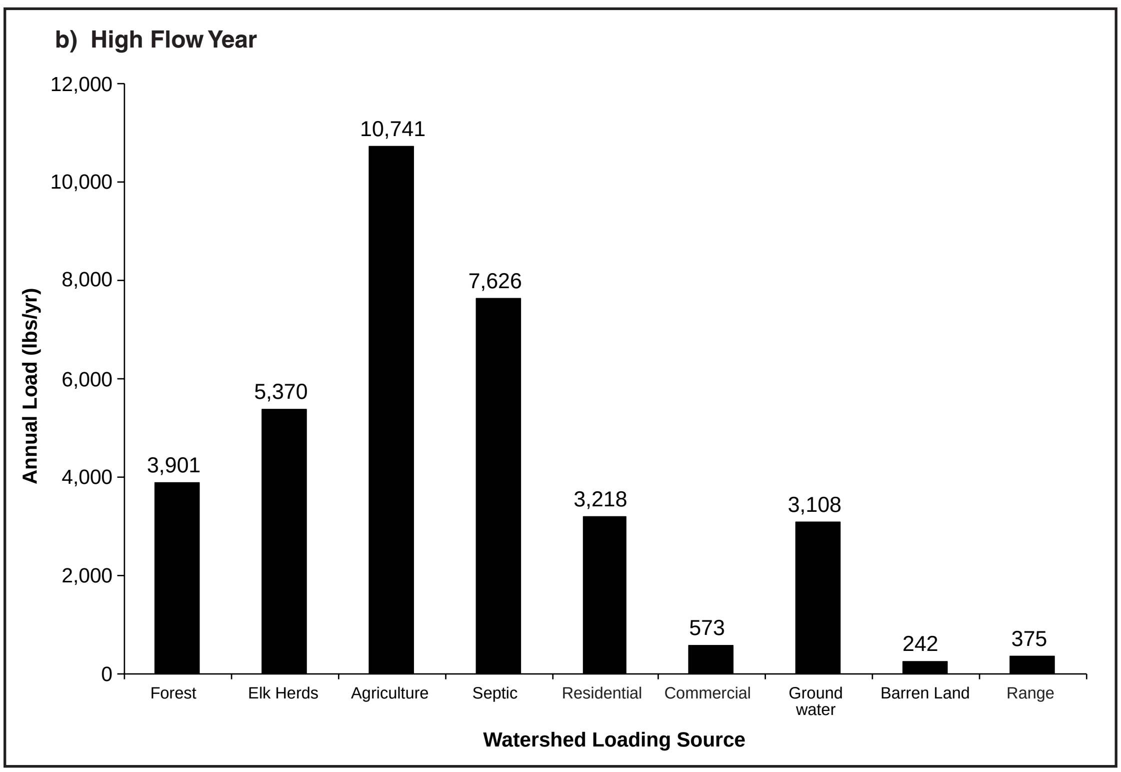
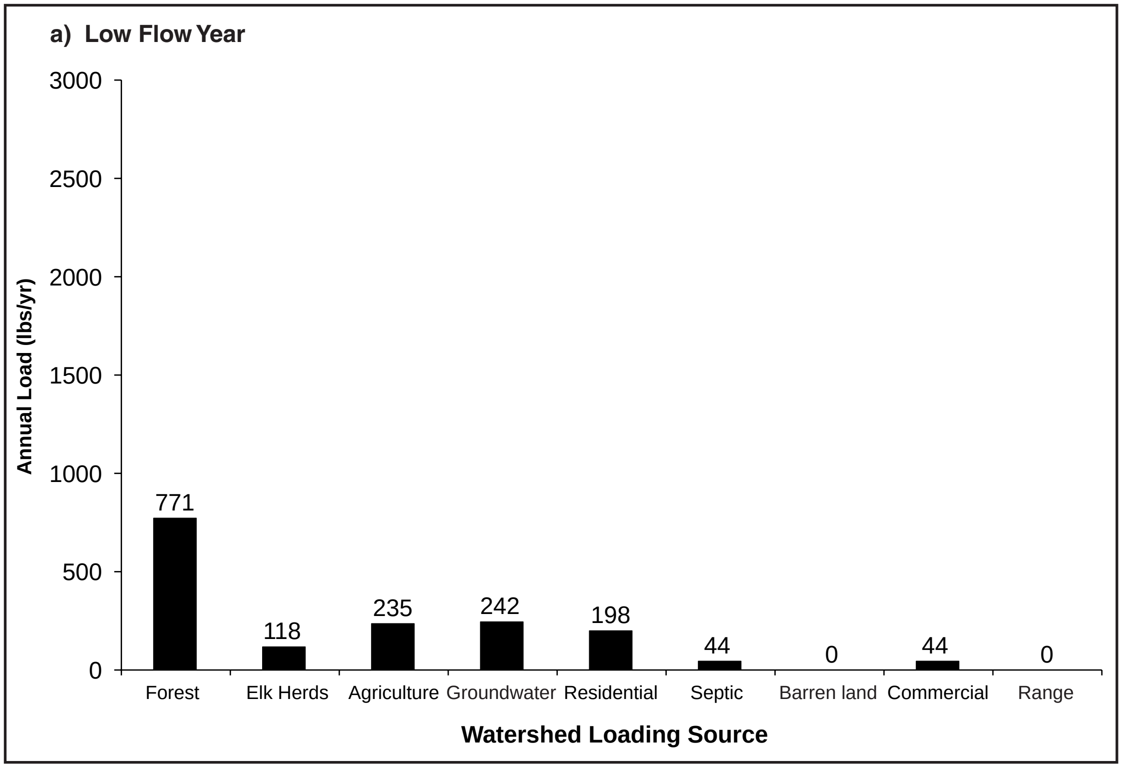


Figure 3-4. Annual total nitrogen contributions to Luna Lake during (a) low flow and (b) high flow years.



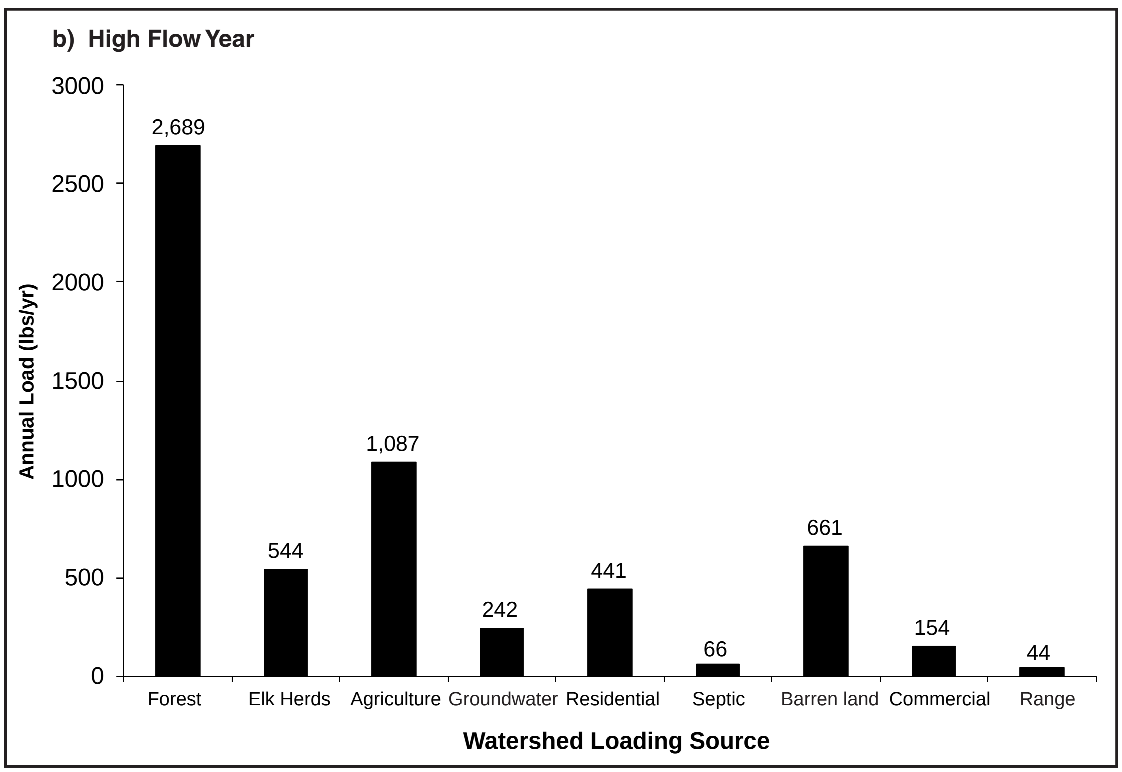


Figure 3-5. Annual total phosphorus contributions to Luna Lake during (a) low flow and (b) high flow years.

Table 3-3
Nutrient Budget For Luna Lake

	Total nitrogen (lbs/yr)	Total phosphorus (lbs/yr)
Atmospheric loading	1,014	30.4
Inflow (from watershed)	17,130	3,924
Outflow (includes seepage)	30,137	4,299
Potential macrophyte decomposition:		
Labile	15,057	3,020
Refractory	5,732	1,171
Total	20,789	4,191
Sediment release	3,792	273
Sediment deposition	18,364	1,318
Sediment deep burial	18,166	1,307
Macrophyte harvest	2,458	492

Sediment deposition fluxes for nitrogen are comparable to the watershed loading and macrophyte decomposition fluxes. Sediment deposition fluxes for phosphorus are about one-third of these corresponding values. The deposition fluxes were based on measurements from nearby Rainbow Lake by Baker and Farnsworth (1995) since no sediment data are available for Luna Lake. The deposition fluxes are associated with settling algae, senescing macrophytes, and suspended sediment inflows from the San Francisco River.

Sediment deposition and deep burial fluxes were approximately equal for both nutrients. This indicates that most of the nutrients deposited in the sediments eventually become buried in the deep sediment pool, where they are unavailable for cycling in the water. However, the continued cycling of nutrients in the upper active sediment layer will continue to be an important source of nutrients to the lake. Both nitrogen and phosphorus are released from the sediments at about 20% of the deep burial and deposition rates. The sediment release rates are much less than the nutrient release rates due to macrophyte decomposition.

Macrophyte harvest rates were compared to the sediment nutrient pools to determine if harvest could eventually reduce sediment nutrients to low levels that would inhibit further macrophyte growth. Based on sediment concentrations measured at Rainbow Lake by ADEQ and assuming a root depth of 25 cm, the sediment nutrient masses available to macrophytes are 374,000 kg of nitrogen and 27,000 kg of phosphorus. Comparison of the harvest removal fluxes to the sediment nutrient pools shows that it would take several hundred years to deplete the sediment nutrients. The actual times would be much longer since nutrients will continue to accumulate in sediments. Therefore, macrophyte harvest cannot reduce the potential for future macrophyte growth through significant nutrient depletion. However, harvest is effective for dealing with the immediate problems associated with high plant densities in the water.

3.4 Linkage of Nutrient Loadings to In-Lake Water Quality Indicators

The lake model BATHTUB (Walker, 1996) was used in conjunction with the ADEQ monitoring data, the GWLF watershed model results, and the nutrient mass balance results in the linkage analysis to predict the Luna Lake water quality response to different nutrient loading scenarios. Most of the analyses focused on the average loading conditions, which were based on the ADEQ monitoring data in the San Francisco River just above the entrance to Luna Lake. These were the same data that were used to calibrate the long-term average nutrient loads predicted by the GWLF watershed model.

External nutrient loads from the watershed were estimated with GWLF for three different meteorological conditions: the long-term average, the wettest year, and the driest year of the 12-year record. The long-term average loading conditions were used in most of the linkage analyses. Although the wetter periods produce higher flows and nutrient loads from the watershed, the resulting nutrient and phytoplankton concentrations in the lake are lower due to the higher flushing rates. The dry periods produce lower flows and lower nutrient loads, but result in higher nutrient and phytoplankton concentrations since there is much less flushing, and since there is less dilution of septic system loads, which are assumed to be the same regardless of precipitation. Although the dryer years are therefore more critical as far as water quality conditions in the lake, these hydrologic extremes cannot persist for very long and are therefore not representative of the long-term water quality conditions in the lake. As shown in the results presented below, it will be difficult to totally eliminate water quality problems in Luna Lake because of limitations in its natural setting (shallow depth, large watershed, and historical nutrient accumulation in sediments). Therefore, most of the analyses focused on changes to the long-term average loading conditions, rather than focusing on the driest year. However, the BATHTUB predictions for the driest and wettest years are included in the analyses.

The BATHTUB model was used to predict the concentrations of total phosphorus, total nitrogen, and chlorophyll-*a* in Luna Lake in response to different nutrient loading scenarios. Three major sets of conditions were analyzed:

4. Effects of scaled reductions in watershed nutrient loads
5. Effects of scaled reductions in macrophytes
6. Effects of scaled reductions in watershed nutrient loads with all macrophytes removed from the lake.

The concentrations of total phosphorus, total nitrogen, and chlorophyll-*a* that were predicted under the different environmental conditions and scenarios are compared to the ADEQ trophic classifications that are used for the 305 (b) statewide water quality assessment process. These comparisons are presented in Figures 3-6 to 3-14 and discussed in greater detail in the following sections. The results and discussions focus on nutrient and phytoplankton (chlorophyll-*a*) concentrations and the resulting trophic status, rather than directly on water quality variable such as pH and dissolved oxygen. pH and dissolved oxygen vary diurnally with photosynthesis and respiration rates in the lake. In order to predict the effects of different nutrient loads on these variables, a much more complex nutrient biogeochemical and ecosystem model would be required. In addition, much more extensive data, including some diurnal sampling and much more temporal coverage throughout the year, would be required to set up and calibrate such a model. This type of modeling was beyond the scope and data availability of this TMDL study. Therefore, nutrient and chlorophyll-*a* concentrations and their relationships to trophic status are used as indicators to estimate when pH and dissolved oxygen problems will occur in Luna Lake. High pH and low dissolved oxygen are typical in lakes that are characterized as eutrophic.

BATHTUB does not simulate macrophytes directly, but their effects on internal nutrient cycling can be modeled by specifying macrophyte decomposition as an areal nutrient source (similar to sediment release fluxes). Additional internal sources of nutrients were necessary to obtain good calibration of the model, which indicates the importance of these sources in Luna Lake. However, BATHTUB does not consider the effects of macrophyte shading on the predicted phytoplankton (chlorophyll-*a*) concentrations. This makes the predicted chlorophyll-*a* concentrations conservative, and explains why they appear higher than the monitoring data. Phytoplankton densities in Luna Lake are typically highest in the spring, before the macrophyte canopies have grown enough to block much of the light in the surface waters. As macrophyte densities are reduced through harvesting, increases in the available light can be expected to produces greater phytoplankton densities, similar to those calculated in the BATHTUB predictions. The predicted chlorophyll-*a* concentrations in Luna Lake under average loading conditions are about 50% greater than the values measured in nearby Rainbow Lake by Baker and Farnsworth (1995). This is consistent with the nutrient data for these two lakes. The average phosphorus concentration in Luna Lake is twice as high as in Rainbow Lake, and the average nitrogen concentration is 50% higher.

3.4.1 Effects of Scaled Reductions in Watershed Nutrient Loadings

Seven different scenarios were analyzed to predict the effects of scaled reductions in watershed nutrient loads to Luna Lake. These were (1) average watershed loads, (2) high precipitation watershed loads, (3) low precipitation watershed loads, (4) 80% of existing average loads, (5) 50% of existing average loads, (6) 30% of existing average loads, and (7) 10% of existing average loads. The effects of these scenarios on phosphorus, nitrogen, and chlorophyll-*a* concentrations in Luna Lake are discussed in the following sections. Refer to Tables 2.2a and 2.2b for trophic ranges.

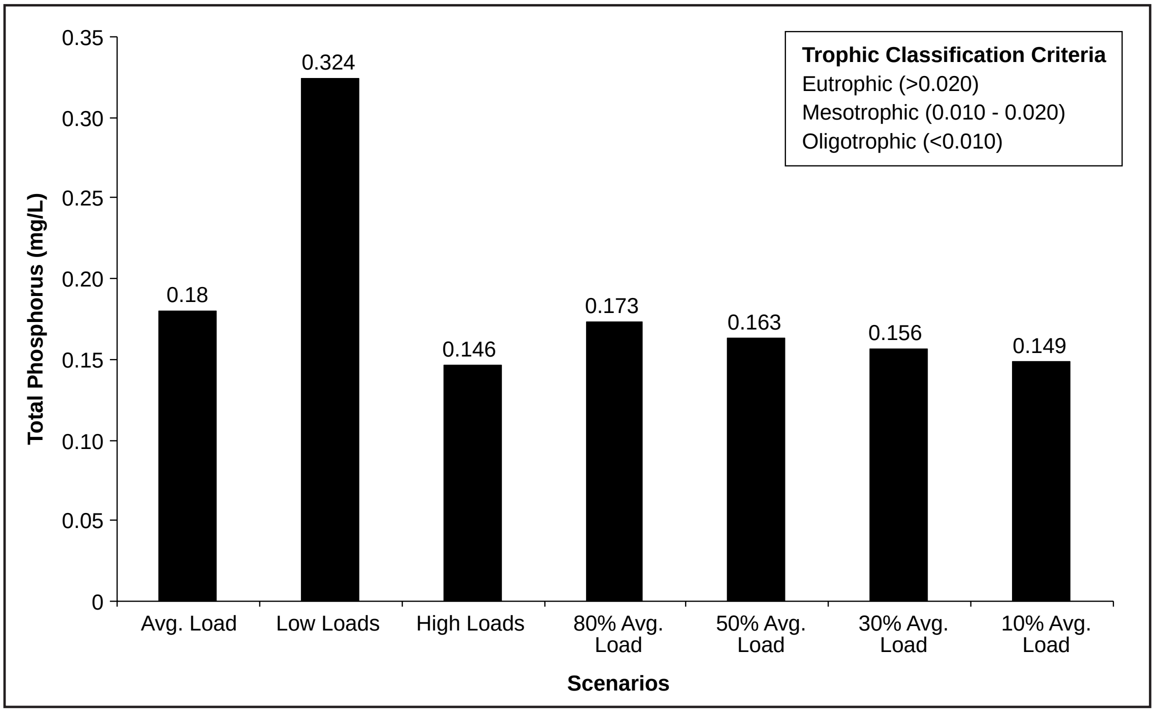


Figure 3-6. In-lake effects of scaled reductions in watershed nutrient loadings on total phosphorus concentrations in Luna Lake.

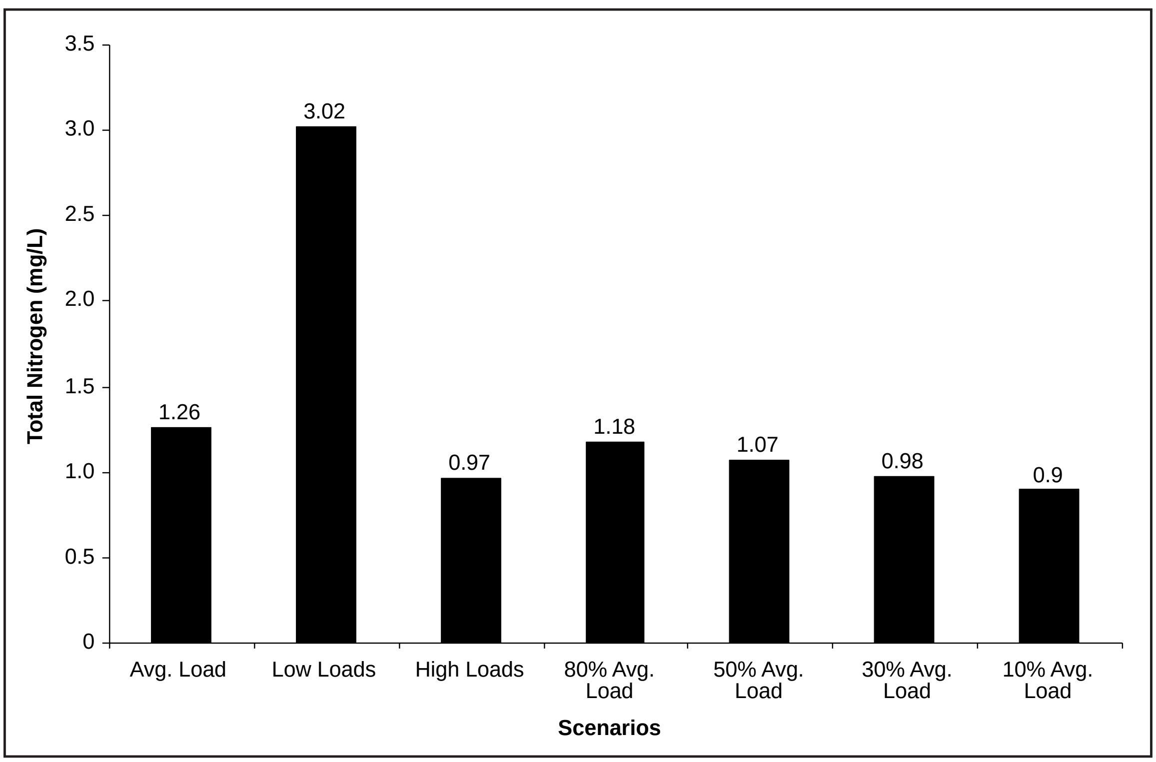


Figure 3-7. In-lake effects of scaled reductions in watershed nutrient loadings on total nitrogen concentrations in Luna Lake.

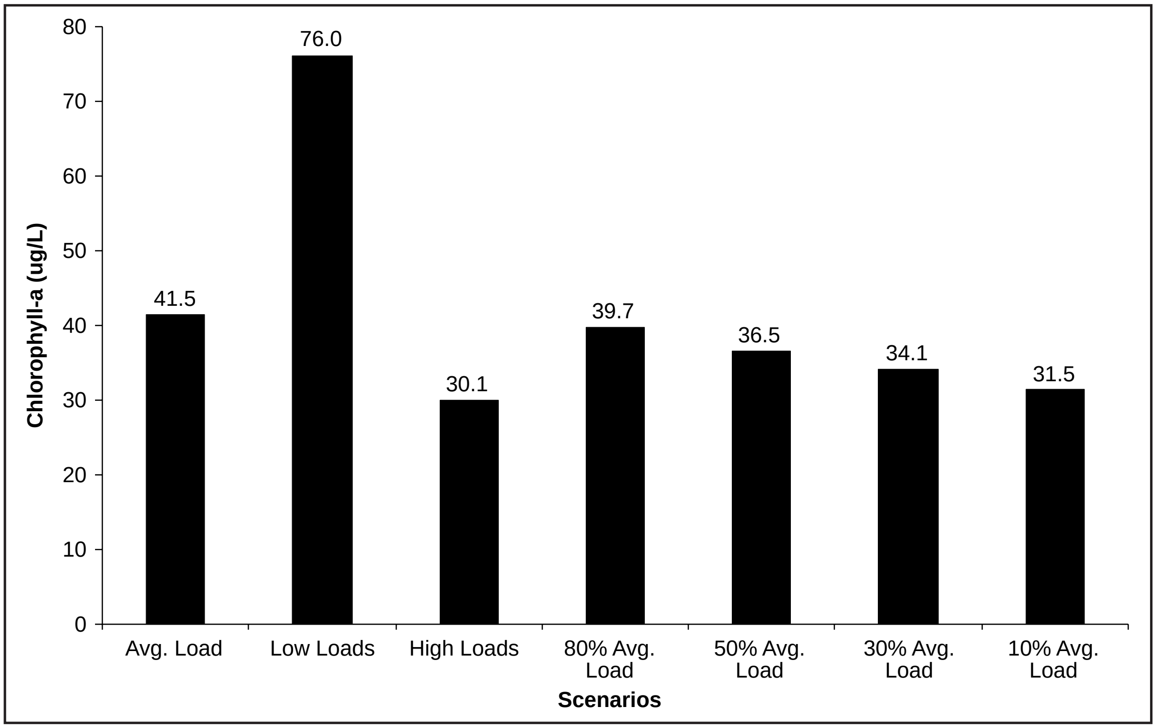


Figure 3-8. In-lake effects of scaled reductions in watershed nutrient loadings on chlorophyll-*a* concentrations in Luna Lake.

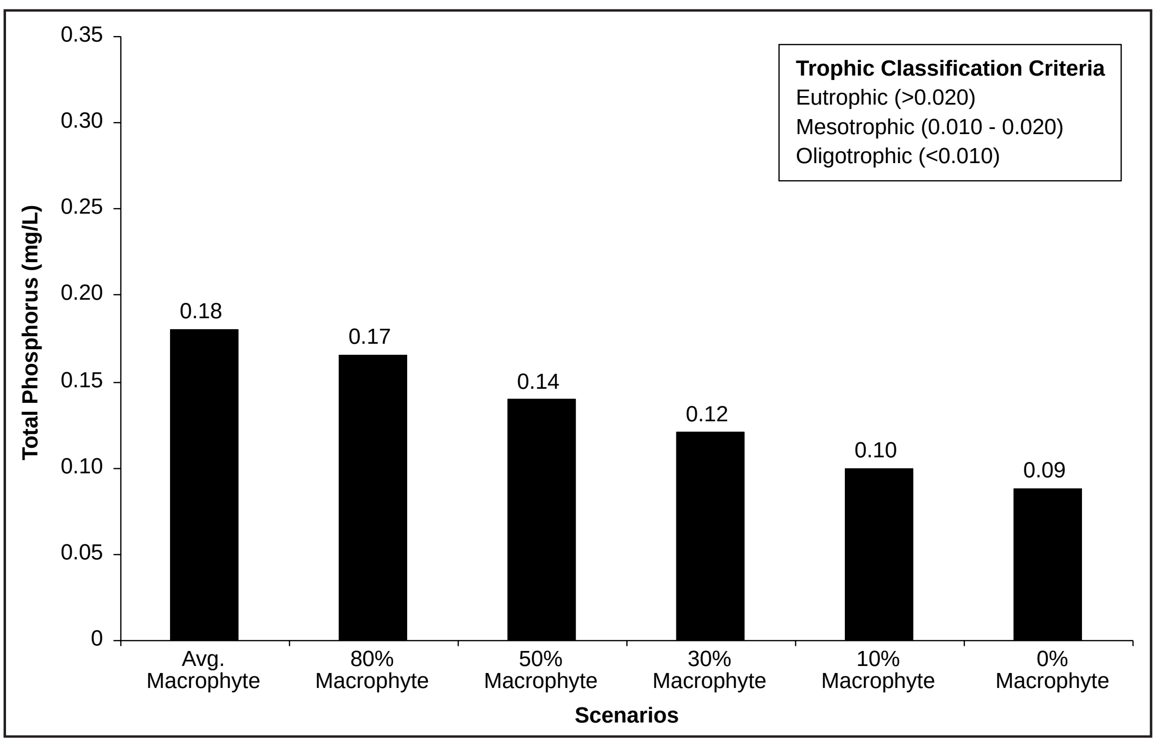


Figure 3-9. Effects of scaled reductions macrophyte biomass on total phosphorus concentrations in Luna Lake.

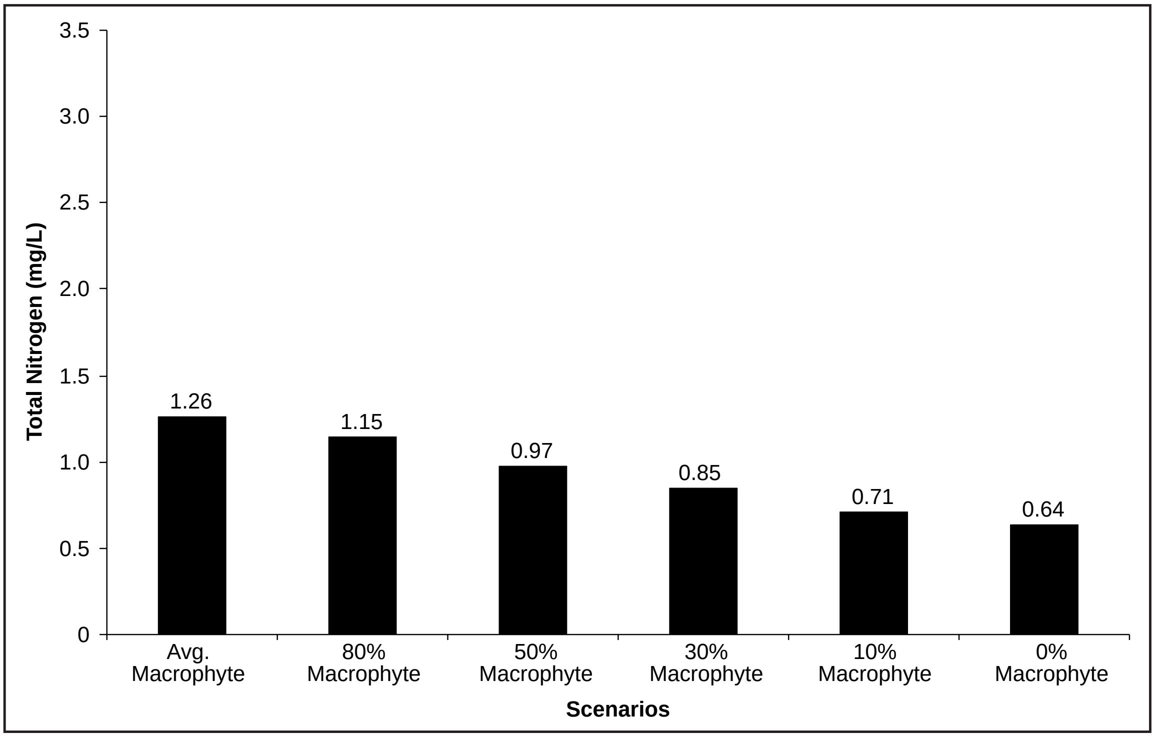


Figure 3-10. Effects of scaled reductions macrophyte biomass on total nitrogen concentrations in Luna Lake.

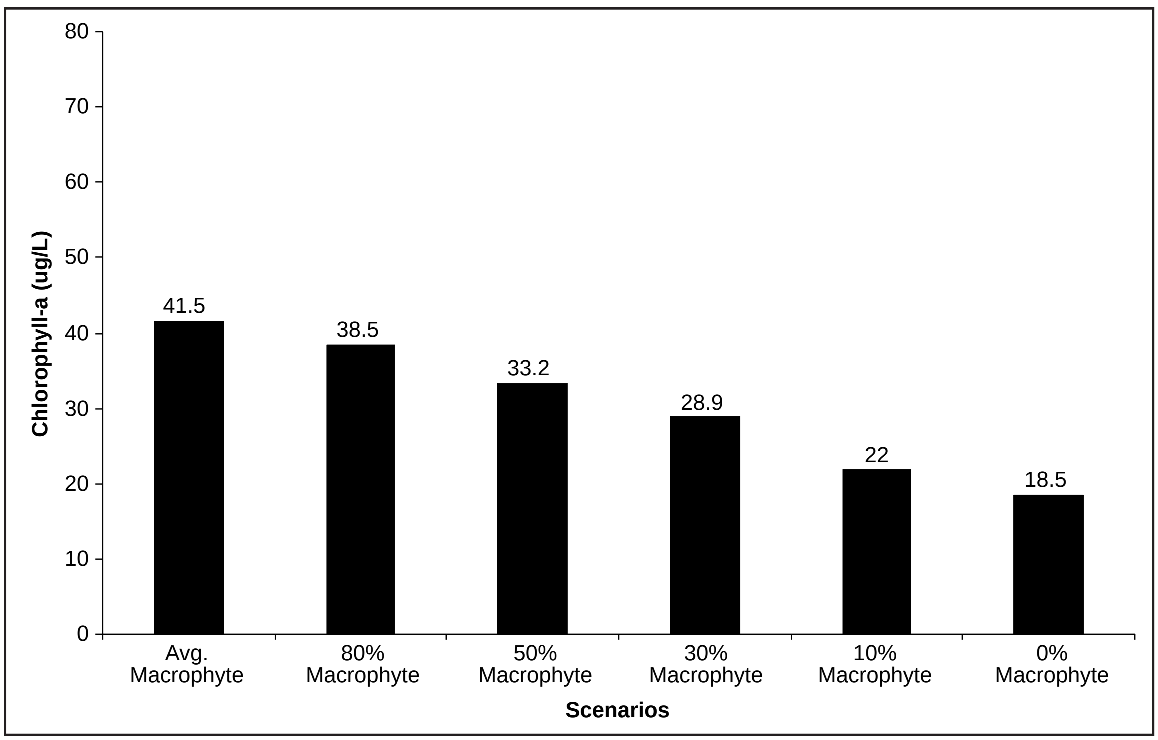


Figure 3-11. Effects of scaled reductions macrophyte biomass on chlorophyll-*a* concentrations in Luna Lake.

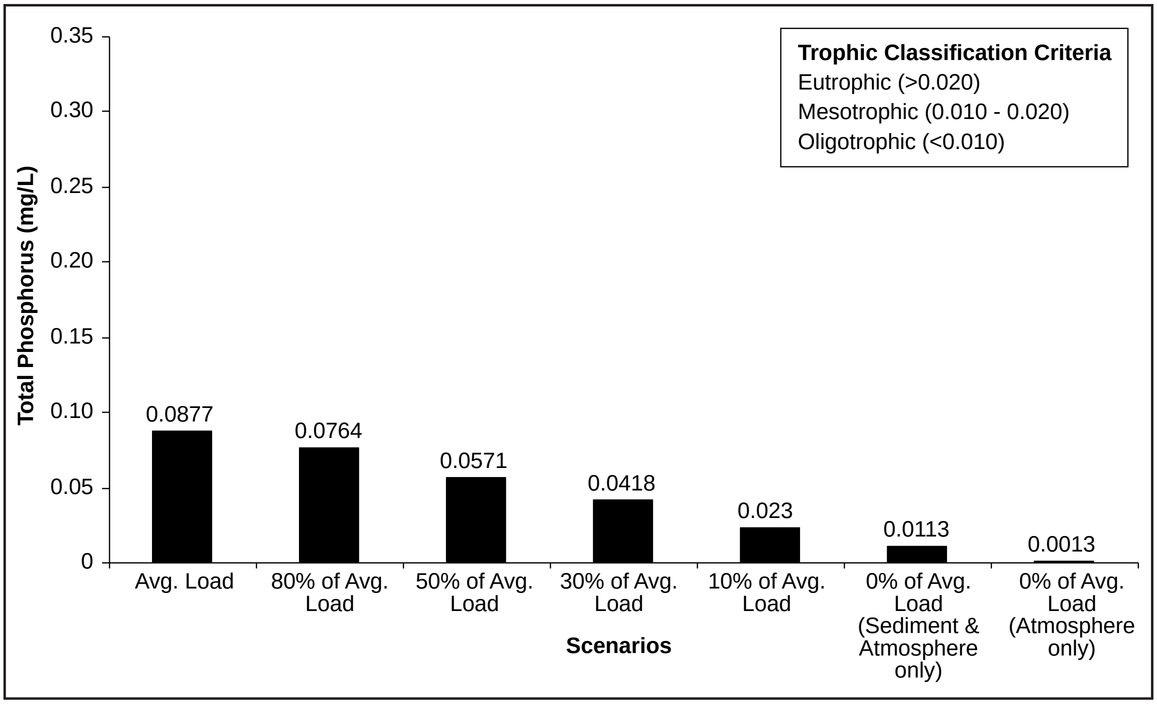


Figure 3-12. Effects of no macrophytes and scaled reductions in watershed nutrient loadings on total phosphorus concentrations in Luna Lake.

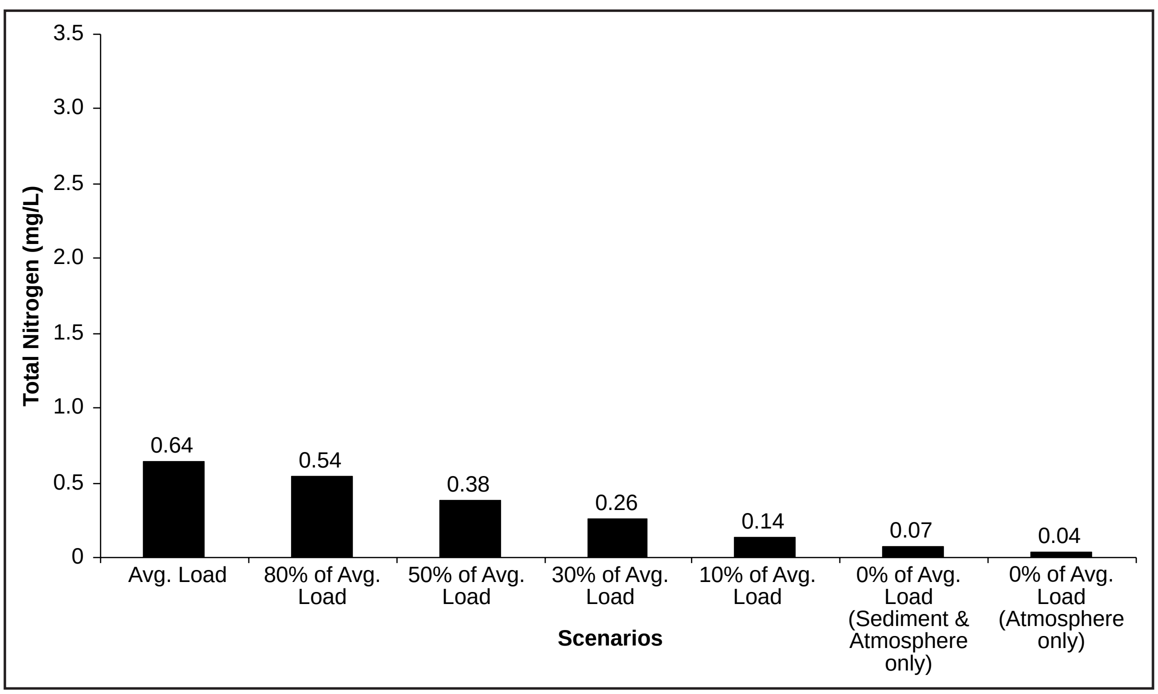


Figure 3-13. Effects of no macrophytes and scaled reductions in watershed nutrient loadings on total nitrogen concentrations in Luna Lake.

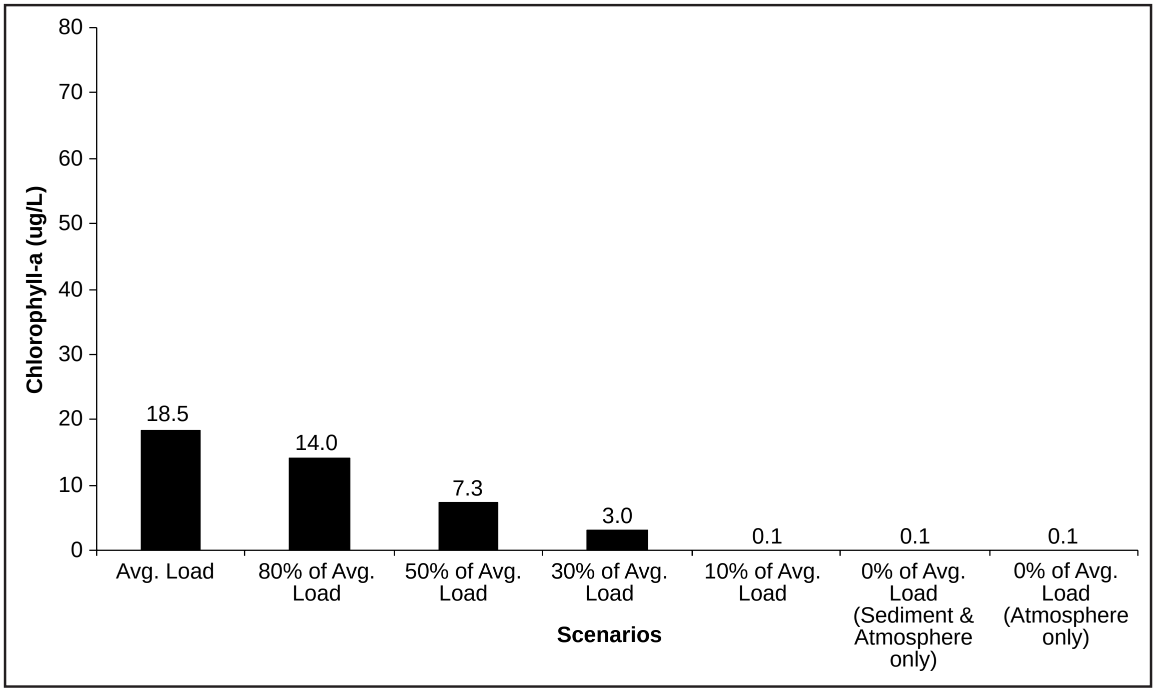


Figure 3-14. Effects of no macrophytes and scaled reductions in watershed nutrient loadings on chlorophyll-*a* concentrations in Luna Lake.

Total Phosphorus - The predicted total phosphorus concentration in the lake ranged from a low value of 0.15 mg/L for 10% of existing average load conditions to a high of 0.32 mg/L under low flow load conditions (Figure 3-6). The model predicted that total phosphorus concentrations in Luna Lake would decrease only slightly regardless of how much the external loadings were reduced. A 90% reduction in average watershed loads produced only a 17% reduction in phosphorus. This is due to the importance of internal nutrient sources such as macrophyte decomposition and sediment release. Load variations associated with differences in watershed precipitation (i.e., high versus low flow years) produced the biggest response due to flushing effects. Using the flows and corresponding nutrient loads from the GWLF model, in-lake phosphorus concentrations were highest for the low load scenario, which appears contradictory. This was because lake flushing was reduced due to the low inflows, increasing the impacts of internal nutrient releases on water column concentrations. In addition, the nutrient concentrations in inflow water predicted by GWLF were higher for the low flow scenario than the high flow scenario due to less dilution of some load types (e.g., septic systems) during transport through the watershed. The high flow scenario reduced the total phosphorus concentration in the lake by 19% from the average loads, while the low flow scenario increased the total phosphorus concentration by 80%.

Luna Lake remained in the eutrophic category regardless of how much external phosphorus loads were reduced. This indicates that external loadings of phosphorus are less important than internal cycling in the lake. This is further reinforced by the slight dilution of total phosphorus concentrations in the lake during periods of high watershed loads and flows and increased total phosphorus concentrations in the lake during periods of low flows and loadings.

Total Nitrogen - The predicted total nitrogen concentrations in the lake ranged from a low value of 0.90 mg/L for 10% of existing average load conditions to a high of 3.0 mg/L under low flow load conditions (Figure 3-7). The model predicted that total nitrogen concentrations in Luna Lake would decrease only slightly regardless of how much the external loadings were reduced. A 90% reduction in average watershed loads produced only a 29% reduction in nitrogen. As with phosphorus, the effects of hydrologic variations on reservoir flushing was more important than the external load variation. This indicates that in-lake processes are most likely driving the concentration of total nitrogen in Luna Lake. The high flow scenario reduced the total nitrogen concentration in the lake by 23% from the average loads, while the low flow scenario increased the total nitrogen concentration by 140%.

Chlorophyll-*a* - The predicted chlorophyll-*a* concentrations in the lake ranged from a low value of 30 ug/L under high flow load conditions to a high of 76 ug/L under low flow load conditions (Figure 3-8). The model predicted that chlorophyll-*a* concentrations in Luna Lake could be reduced by 24% if external nutrient loads were reduced by 90%. This value may seem significant, however achieving a 90% reduction in external watershed loads would be extremely difficult (if not impossible). A more realistic approach would be to expect a 50% reduction in external nutrient loads, which could be achieved by effectively controlling septic systems and implementing BMPs for the other sources. A 50% reduction in external nutrient loads would reduce the in-lake chlorophyll-*a* concentration by approximately 12%. Note that the chlorophyll-*a* concentrations predicted here are somewhat higher than the monitoring data. This is because the BATHTUB model does not include the effects of macrophyte shading on algal growth.

Luna Lake remained in the eutrophic category regardless of which of the external loadings scenarios were used.

3.4.2 Effects of Scaled Reductions in Macrophytes

Six different scenarios were analyzed to predict the effects scaled reductions in macrophyte biomass in Luna Lake. All scenarios assumed average watershed loading conditions, since these are more representative of long-term conditions in the lake. The scenarios were (1) existing macrophytes, (2) 80% of existing macrophytes, (3) 50% of existing macrophytes, (4) 30% of existing macrophytes, (5) 10% of existing macrophytes, and (6) no macrophytes. The effects of these scenarios on total phosphorus, total nitrogen, and chlorophyll-*a* concentrations in Luna Lake are discussed in the following sections.

Total Phosphorus – The predicted total phosphorus concentrations in the lake ranged from a low value of 0.088 mg/L under average load conditions with no macrophytes to a high of 0.18 mg/L under current average load and macrophyte conditions (Figure 3-9). Complete removal of lake macrophytes gained a reduction in total phosphorus of approximately 51%.

Although macrophyte removal was more effective than the corresponding percent reductions in watershed loads, Luna Lake remained in the eutrophic category regardless of how much of the macrophytes were removed from the lake.

Total Nitrogen - The predicted total nitrogen concentrations in the lake ranged from a low value of 0.64 mg/L assuming average load conditions with no macrophytes to a high of 1.3mg/L under current average loads and macrophyte densities (Figure 3-10). The model predicted that total nitrogen concentrations in Luna Lake could be reduced by approximately 49% if all of the macrophytes were removed from the lake. This indicates that the in-lake processes (e.g., macrophyte decomposition) are most likely playing a major role in the concentration of total nitrogen in Luna Lake.

Chlorophyll-*a* - The predicted chlorophyll-*a* concentrations in the lake ranged from a low value of 19 ug/L under average load conditions with no macrophytes to a high of 42 ug/L under current average loads with existing macrophyte densities (Figure 3-11). The model predicted that chlorophyll-*a* concentrations in Luna Lake would be reduced by approximately 55% if all of the macrophytes were removed from the lake. Even though this amount of reduction is significant, the model predicts that a fairly high concentration of chlorophyll-*a* will remain in the lake. The model predicted that Luna Lake would remain eutrophic regardless of whether macrophytes were present in the lake.

3.4.3 Effects of Having No Macrophytes and Scaled Reductions in Watershed Nutrient Loadings

Seven different scenarios were analyzed to predict the effects of scaled reductions in watershed nutrient loadings together with total macrophyte removal. These scenarios illustrate the levels of watershed controls that would be required to significantly improve the water quality of Luna Lake, even if all macrophytes were eliminated, for example by the application of herbicides. Even though total macrophyte removal is not realistic since macrphytes provide important waterfowl habitat in the upper portion of the lake, and since herbicides are not currently allowed in Luna Lake, these scenarios are useful to examine the lake response to external loads under optimal conditions of minimum internal loading. The scenarios evaluated were (1) average watershed loads, (2) 80% of average loads, (3) 50% of average loads, (4) 30% of average loads, (5) 10% of average loads, (6) no watershed loads (0%) (sediment and atmospheric sources only), and (7) atmospheric sources only. The effects of these scenarios on total phosphorus, total nitrogen, and chlorophyll-*a* concentrations in Luna Lake are discussed in the following sections.

Total Phosphorus - The predicted total phosphorus concentrations in the lake ranged from a low value of 0.023 mg/L under 10% of the existing average loading conditions without macrophytes to a high of 0.088 mg/L under existing average loading conditions with no macrophytes (Figure 3-12). The model predicted that total phosphorus concentrations in Luna Lake could be reduced by approximately 87% if external loads were reduced by 90% and macrophytes were eliminated. It is unreasonable to expect a 90% reduction of external nutrient loadings. A more realistic expectation is an external load reduction of 50% (achievable by reducing septic loads and implementing BMPs for other sources). This would reduce the in-lake total phosphorus concentration by approximately 68%. Two additional scenarios were predicted by the model. These scenarios reduced the nutrient inputs to sediment plus atmospheric sources only and atmospheric sources only. Based on these assumptions, total phosphorus concentrations in Luna Lake would be reduced to 0.010 and 0.001 mg/L, respectively.

Luna Lake remained in the eutrophic category for phosphorus even if the average watershed loadings were reduced by 90% and all macrophytes were eliminated

Total Nitrogen - The predicted total nitrogen concentrations in the lake ranged from a low value of 0.14 mg/L under 10% of the existing average loading conditions without macrophytes to a high of 0.64 mg/L under existing average loading conditions with no macrophytes (Figure 3-13). The model predicted that total nitrogen concentrations in Luna Lake could be reduced by approximately 89% if external loads were reduced by 90% and macrophytes were eliminated. It is unreasonable to expect a 90% reduction of external nutrient loads. A more realistic expectation is an external load reduction of 50% (achievable by reducing septic loads and implementing BMPs for other sources). This would reduce the in-lake total nitrogen concentration by approximately 70%. Two additional scenarios were predicted by the model. These scenarios reduced the nutrient inputs to sediment plus atmospheric sources only and atmospheric sources only. Based on these assumptions, total nitrogen concentrations in Luna Lake would be reduced to 0.073 and 0.042 mg/L, respectively.

Total nitrogen concentration was not used to determine trophic level since the ADEQ Trophic Level Classification system does not provide a trophic criterion for total nitrogen.

Chlorophyll-*a* - The predicted chlorophyll-*a* concentrations in the lake ranged from a low value of 0.1 ug/L under 10% of the existing average loading conditions without macrophytes to a high of 19 ug/L under existing average loading conditions with no macrophytes (Figure 3-14). The model predicted that chlorophyll-*a* concentrations in Luna Lake would be reduced by over 99% if all of the macrophytes were removed from the lake and external nutrient loads were reduced by 90%. Two additional scenarios were predicted by the model. These scenarios reduced the nutrient inputs to sediment plus atmospheric sources only and atmospheric sources only. Based on these assumptions, chlorophyll-*a* concentrations in Luna Lake would be reduced to minimal values of 0.1 ug/L or less for both cases.

The model predicted that Luna Lake would remain eutrophic with respect to chlorophyll-*a* until all of the macrophytes were removed and external nutrient loads were reduced by more than 20%.

The results of the model predictions indicated that, regardless of the different environmental conditions and scenarios that were modeled, Luna Lake would remain eutrophic according to the phosphorus criteria unless all macrophytes were eliminated and watershed loads were reduced by more than 90%. The chlorophyll-*a* results are less stringent, suggesting that the lake could be mesotrophic if all macrophytes were removed and watershed loads were reduced by 50%, or even oligotrophic if all macrophytes were removed and watershed loads were reduced by more than 50%. Although it may be possible to reduce watershed loads of nitrogen to close to 50% by eliminating all septic systems and implementing agricultural BMPs, a 50% reduction in phosphorus loads would be difficult since the forests contribute approximately half of the loads. Also, the shallow depths of Luna Lake make it impossible to eliminate all macrophytes without the intensive use of herbicides. Therefore, Luna Lake will probably remain eutrophic under any realistic loading scenarios. This is due to several factors:

- The shallow lake depth results in a large surface:volume ratio,
- A larger surface:volume ratio means that the relative contributions of sediment and atmospheric nutrients becomes greater,
- Shallow lake depth means that light can reach a large portion of the water column and stimulate phytoplankton and macrophyte growth, and
- Macrophyte growth enhances nutrient concentrations in the water through nutrient extraction from the abundant sediment pools and subsequent release to the water column during senescence.

It is unreasonable to expect external nutrient loadings to be restricted to sediment and atmospheric sources only. However, the model does predict that even though the lake would remain eutrophic, the overall water quality could be improved by implementing certain management practices that would result in reducing the degree of lake eutrophication. It is possible to manage the lake to minimize the probability that the narrative and numeric water quality standards are violated, and therefore, be more protective of the beneficial uses of the lake. The model results also demonstrate that even though phosphorus concentrations in the San Francisco River are below the water quality standards for the river, they are not low enough to prevent eutrophication problems in Luna Lake.

4.0 ALLOCATIONS, IMPLEMENTATION, AND MONITORING

The TMDL management objectives for Luna Lake are to bring the reservoir into compliance with the water quality standards for narrative nutrient, and numeric pH and dissolved oxygen (DO). This section briefly reviews the TMDL calculations and provides considerations for residents within the Luna Lake watershed and the ADEQ for meeting the TMDL management objectives. The recommendations address four topics related to this TMDL study:

- How can nutrient loads within the watershed be apportioned to meet the TMDL management objective? The project team provides estimates for nutrient load allocations for nutrients by source categories that will be necessary to partially achieve the TMDL management objectives. The allocations are presented as percent reductions required within each load source category included in the analysis.

- What are some of the possible implementation alternatives available to the community, local management agencies, and ADEQ to achieve the nutrient load reductions that are required to meet water quality objectives? The community in consultation with ADEQ can best decide on the most acceptable and preferred mix of management options is for achieving the desired nutrient reductions. The recommendations include infrastructure upgrades (e.g., mitigation of unused septic systems, extending sewer service, lining irrigation canals), lake dredging and macrophyte harvesting, and Best Management Practices (e.g., grazing BMPs, residential BMPs, wildlife management BMPs and conservation irrigation practices).

- The TMDL will need to be a phased TMDL because of the uncertainty associated with the relationship between the stressor (nutrient loads) and response indicators (e.g., nitrogen and phosphorus concentrations, pH, chlorophyll-*a* – algae concentrations, unionized ammonia, DO, macrophyte densities). The phased TMDL will need to include a monitoring component to better characterize the effect of the management alternatives that are undertaken on in-lake nutrient concentrations and other in-lake processes (e.g., growth response of algae and macrophytes that drive extreme pH fluctuations and create low DO conditions). The ADEQ Clean Lakes Program will assist in designing a monitoring program to: a) test the validity of the percentage reduction scenario adopted in the allocation plan, and b) to track the success of TMDL implementation and designated sue attainment.

- This TMDL analysis identified the need for ADEQ, and U.S. EPA, and stakeholders to consider whether the current water quality standards for shallow, high-mountain lakes are appropriate. Management of lake eutrophication (productivity) is vital to lake health. However, due to atmospheric effects on buffering capacity of high elevation lakes, some degree of “natural background” higher pH is expected. ADEQ has prioritized the need to review the appropriateness of certain numeric standards and designated use criteria for shallow lake systems, as well as the interpretation of narrative nutrient standards. ADEQ will consult with experts to develop refined water quality standards for shallow alpine lakes where appropriate. In the meantime, ADEQ will work with the stakeholders of Luna Lake to develop a monitoring strategy that will capture seasonal and daily fluctuations.

4.1 Allocations

The following nutrient allocations and reductions may still result in occasional exceedances of in-lake pH, and dissolved oxygen standards. However, the prescribed allocations will reduce the frequency, duration, and magnitude of water quality standard violations and significantly enhance the capability of Luna Lake to fulfill its designated uses. That is, Luna Lake will remain eutrophic, but the degree of eutrophication would be reduced and maintained at a reduced level. The nutrient reduction objectives that are expressed in the allocations are realistically targeted on nonpoint sources and in-lake sources of nutrients.

There were eleven source categories identified in the source analysis and nutrient mass balance. These source categories included septic systems, residential landuse, commercial landuse, groundwater, agriculture (mostly livestock grazing), elk herds, barren land, forest land, range land, and two in-lake sources: macrophyte decomposition and sediment release. The Luna Lake TMDL allocations are expressed as percent reductions from the current annual loads to the lake. Five or six of the source categories were assigned allocations that would require reductions in source loadings from their existing levels. These include septic systems, agriculture (grazing), elk herds, residential areas, macrophyte decomposition, and sediment release. The remaining categories have not been targeted for reductions (i.e., 0 % allocation). Two different sets of allocation scenarios were analyzed. The first set represents a more extreme upper limit with 100% reduction in septic system loads, 33% reduction in agriculture and elk loads, and 90% removal of macrophytes. Two cases were considered: with and without lake dredging.

The lake dredging case was assumed to reduce sediment nutrient release by 50%. The second set of allocation scenarios represents a more realistic goal with 50% reduction in septic system loads, 25% reduction in agriculture and elk loads, 50% reduction in residential loads, and 60% removal of macrophytes. Residential load reductions were not considered in the first set of scenarios, since the focus there was on maximum reductions of the largest sources. Again, two cases were considered: with and without lake dredging. Tables 4-1 and 4-2 present the nitrogen loads and allocations for the two sets of allocation scenarios, and Tables 4-3 and 4-4 present the corresponding phosphorus loads and allocations. Both the existing loads from the different source categories and their allocations (targeted % reductions) are summarized in these tables. Information for three situations are included in each table, including estimates of existing loads, allocations with dredging, and allocations without dredging. The estimated ranges of total annual targeted reductions through the proposed allocations for the first set of scenarios are 32,342 to 32,728 pounds of nitrogen, and 8,578 to 8,710 pounds of phosphorus (Tables 4-1 and 4-3). The corresponding percent reductions in total nutrient loads are 69 to 70 percent for nitrogen and 67 to 68 percent for phosphorus. For the second set of scenarios, the estimated ranges of total annual targeted reductions through the proposed allocations are 21,615.5 to 22,001.5 pounds of nitrogen, and 5,854 to 5,986 pounds of phosphorus (Tables 4-2 and 4-4). The corresponding percent reductions in total nutrient loads are 46 to 47 percent for nitrogen and 46 to 47 percent for phosphorus.

The allocation scenarios were evaluated for their effect on in-lake water quality indicators using the BATHTUB model to simulate conditions within Luna Lake. Three water quality indicators were included in the analysis: total phosphorus, chlorophyll-*a*, and total nitrogen (Figure 4-1, 4-2, and 4-3).

The in-lake concentrations of total phosphorus were estimated to decrease from existing conditions by 49% for the first scenario and by 31% for the second scenario without using dredging. Dredging reduced phosphorus concentrations further by an additional 6% for the first scenario and 8% for the second scenario. The range of total phosphorus concentrations predicted by the model range from 0.18 milligrams per liter under existing conditions to 0.081 for the first scenario with dredging. ADEQ's trophic classifications for phosphorus predict that under the most stringent allocation scenario (i.e., first scenario with dredging), phosphorus concentrations are approximately 4 times greater than the upper limit for the mesotrophic boundary concentration of 0.020 milligrams per liter.

A similar pattern exists for total nitrogen and chlorophyll-*a*, with substantial reductions in water column concentrations for both parameters. However, the percent reductions for nitrogen and chlorophyll-*a* are higher than for phosphorus. The more stringent first allocation scenario results in estimated chlorophyll-*a* concentrations that are just under the boundary for mesotrophic waters (11.9 μg/l versus 12 μg/l). The second, more realistic, allocation scenario results in estimated chlorophyll-*a* concentrations that are

Table 4-1
Luna Lake Recommended Allocations for Nitrogen (Scenario 1)

Source Category	Existing Nitrogen Total Loading (TL) (Lbs/yr)	% Existing Total Watershed/ Lake Loading	% Targeted Reduction of Category	Amount Nitrogen Reduced (Lbs/yr)	Remaining Load (RL) (Lbs/yr)
Septic	7,628	16%	100%	7,628	0
Residential	2,271	5%	0%	0	2,271
Commercial	441	1%	0%	0	441
Groundwater	1,587	3%	0%	0	1,587
Agriculture	4,233	9%	33%	1397	2,836
Elk Herds	2,116	5%	33%	698	1,418
Barren Land	154	0%	0%	0	154
Forest	2,469	5%	0%	0	2,469
Range	132	0%	0%	0	132
Macrophyte Decomposition	25,132	54%	90%	22,619	2,513
Sediment Release (Dredging)	772	2%	0% (50%)	0 (386)	772 (386)
Total (Dredging)	46,935	100%		32,342 (32,728)	14,593 (14,207)

% of total existing nitrogen load remaining = 31%
= (30%)

% total watershed loadings of nitrogen reduced = 69%
= (70%)

Note: Numbers in parentheses represent values associated with the dredging scenario.

Table 4-2
Luna Lake Recommended Allocations for Nitrogen (Scenario 2)

Source Category	Existing Nitrogen Total Loading (TL) (Lbs/yr)	% Existing Total Watershed/ Lake Loading	% Targeted Reduction of Category	Amount Nitrogen Reduced (Lbs/yr)	Remaining Load (RL) (Lbs/yr)
Septic	7,628	16%	50%	3,814	3,814
Residential	2,271	5%	50%	1,135.5	1,135.5
Commercial	441	1%	0%	0	441
Groundwater	1,587	3%	0%	0	1,587
Agriculture	4,233	9%	25%	1,058	3,175
Elk Herds	2,116	5%	25%	529	1,587
Barren Land	154	0%	0%	0	154
Forest	2,469	5%	0%	0	2,469
Range	132	0%	0%	0	132
Macrophyte Decomposition	25,132	54%	60%	15,079	10,053
Sediment Release (Dredging)	772	2%	0% (50%)	0 (386)	772 (386)
Total (Dredging)	46,935	100%		21,615.5 (22,001.5)	25,319.5 (24,933.5)

% of total existing nitrogen load remaining = 54%
= (53%)

% total watershed loadings of nitrogen reduced = 46%
= (47%)

Note: Numbers in parentheses represent values associated with the dredging scenario.

Table 4-3
Luna Lake Recommended Allocations for Phosphorus (Scenario 1)

Source Category	Existing Phosphorus Total Loading (TL) (Lbs/yr)	% Existing Total Watershed/ Lake Loading	% Targeted Reduction of Category	Amount Phosphorus Reduced (Lbs/yr)	Remaining Load (RL) (Lbs/yr)
Septic	242	2%	100%	242	0
Residential	309	2%	0%	0	309
Commercial	44	0%	0%	0	44
Groundwater	331	3%	0%	0	331
Agriculture	485	4%	33%	160	325
Elk Herds	242	2%	33%	80	162
Barren Land	110	1%	0%	0	110
Forest	1,764	14%	0%	0	1,764
Range	22	0%	0%	0	22
Macrophyte Decomposition	8,995	70%	90%	8,096	899
Sediment Release (Dredging)	264	2%	0% (50%)	0 (132)	264 (132)
Total (Dredging)	12,808	100%		8,578 (8,710)	4,230 (4,098)

% of total existing phosphorus load remaining = 33%
= (32%)

% total watershed loadings of phosphorus reduced = 67%
= (68%)

Note: Numbers in parentheses represent values associated with the dredging scenario.

Table 4-4
Luna Lake Recommended Allocations for Phosphorus (Scenario 2)

Source Category	Existing Phosphorus Total Loading (TL) (Lbs/yr)	% Existing Total Watershed/ Lake Loading	% Targeted Reduction of Category	Amount Phosphorus Reduced (Lbs/yr)	Remaining Load (RL) (Lbs/yr)
Septic	242	2%	50%	121	121
Residential	309	2%	50%	154.5	154.5
Commercial	44	0%	0%	0	44
Groundwater	331	3%	0%	0	331
Agriculture	485	4%	25%	121	364
Elk Herds	242	2%	25%	60.5	181.5
Barren Land	110	1%	0%	0	110
Forest	1,764	14%	0%	0	1,764
Range	22	0%	0%	0	22
Macrophyte Decomposition	8,995	70%	60%	5,397	3,598
Sediment Release (Dredging)	264	2%	0% (50%)	0 (132)	264 (132)
Total (Dredging)	12,808	100%		5,854 (5,986)	6,954 (6,822)

% of total existing phosphorus load remaining = 54%
= (53%)

% total watershed loadings of phosphorus reduced = 46%
= (47%)

Note: Numbers in parentheses represent values associated with the dredging scenario.

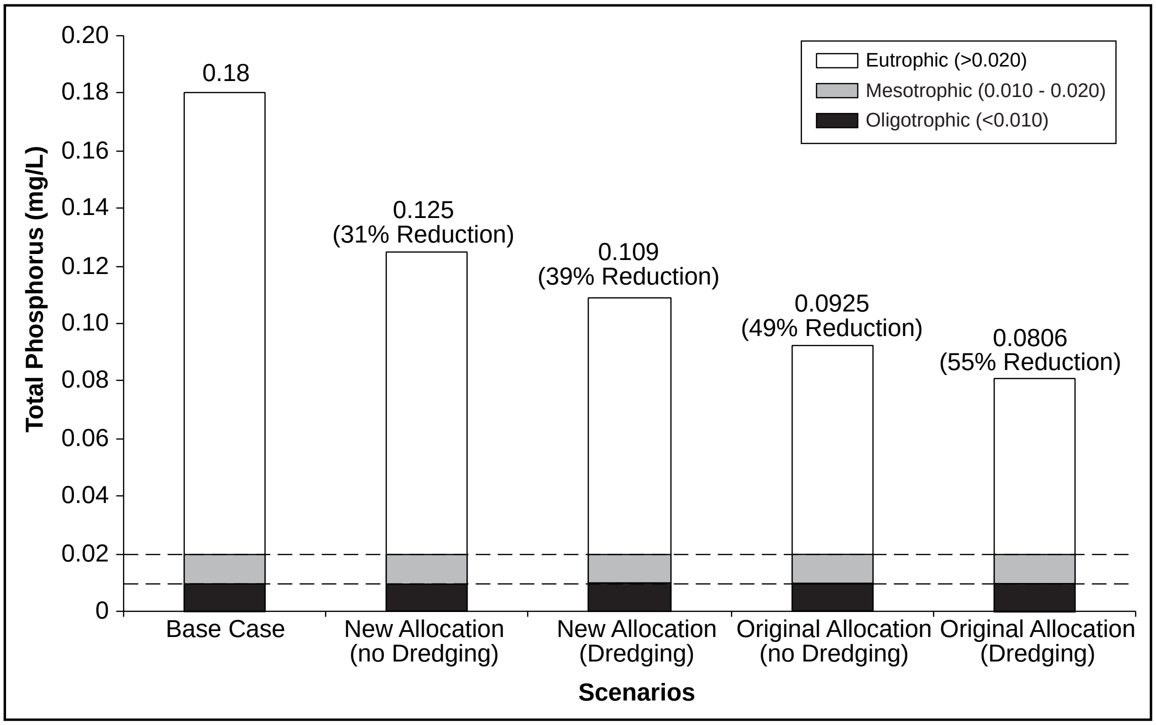


Figure 4-1. Effects scenarios of remedial actions on total phosphorus concentrations in Luna Lake.

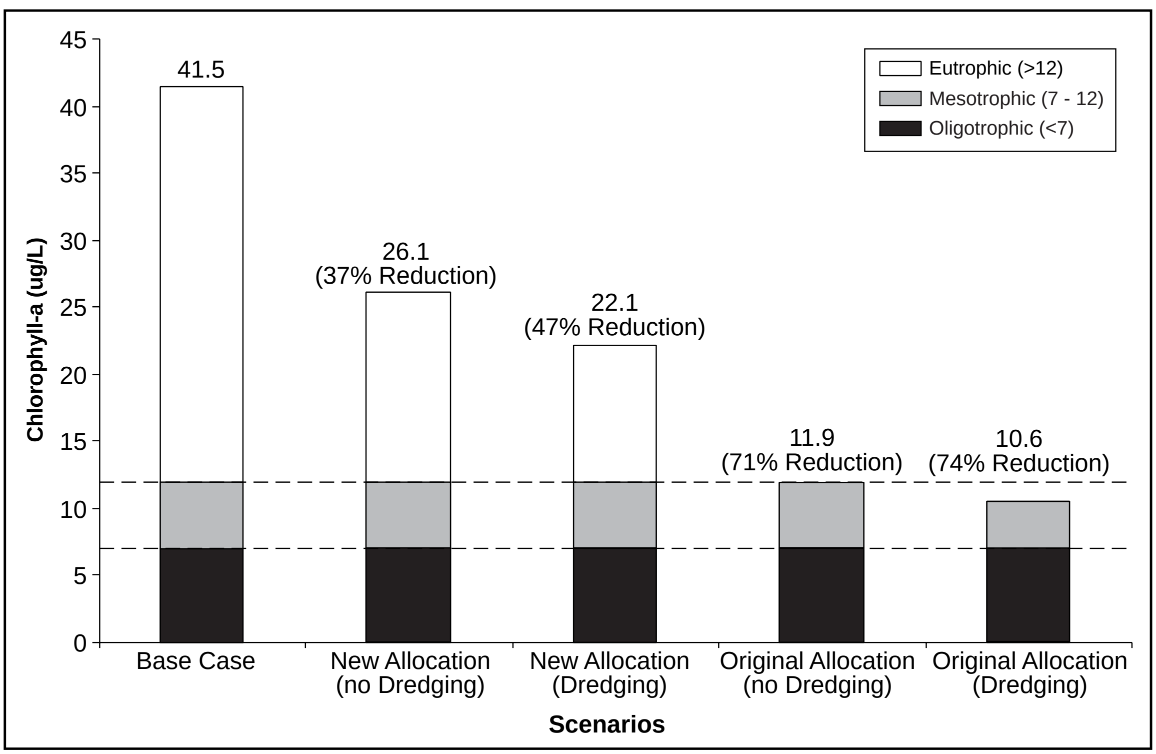


Figure 4-2. Existing scenarios of remedial actions on chlorophyll-*a* concentrations in Luna Lake.

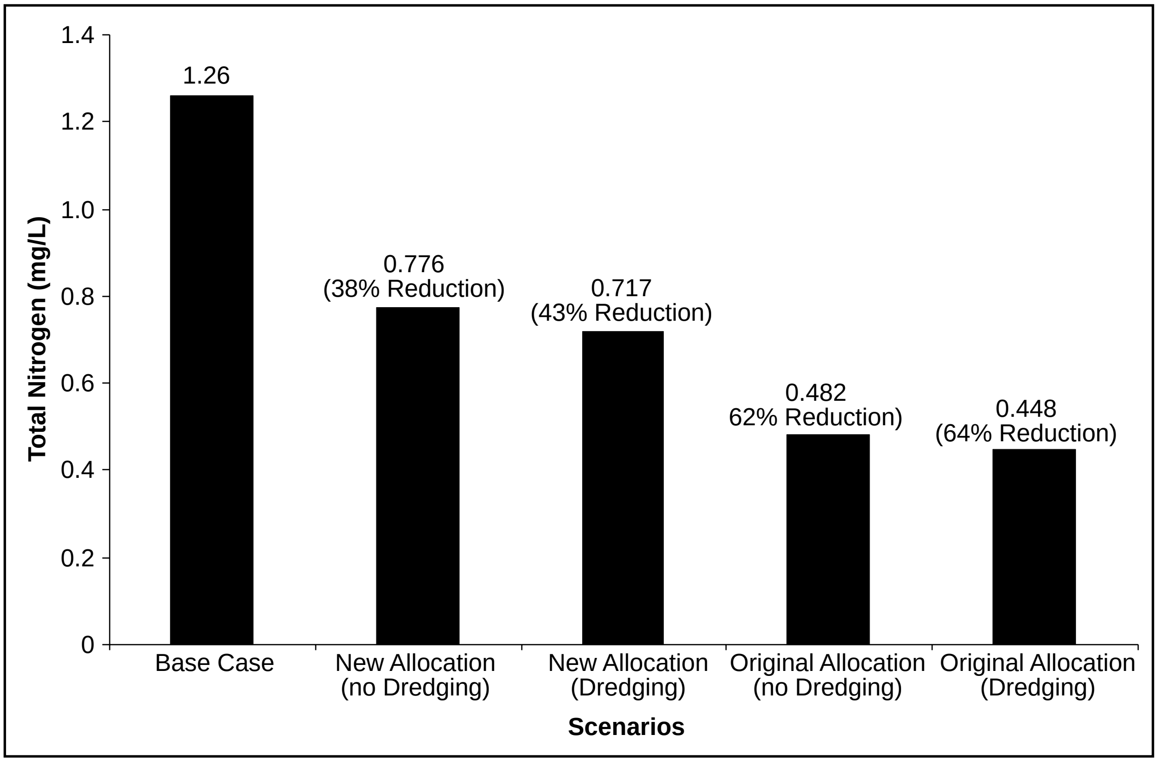


Figure 4-3. Effects scenarios of remedial actions on total nitrogen concentrations in Luna Lake.

approximately twice as high, and therefore still classified as eutrophic. ADEQ has proposed using total nitrogen in the 2000 trophic classification index, because it is an important water quality indicator during periods when algal growth in Luna Lake is nitrogen limited. The estimated concentrations for total nitrogen range from 0.45 mg/l for the first scenario with dredging to 0.78 mg/l for the second scenario without dredging. NOTE: these concentrations still range from mesotrophic to eutrophic.d

The allocations for individual source categories are discussed in greater detail below.

Septic Systems: Nutrient loading from septic systems is based on an estimated number of systems within the vicinity of the lake. This estimate was developed through discussions with officials from local agencies and model calibration adjustments. The estimated lake loading for phosphorus and nitrogen from septic tanks is 242 pounds per year for phosphorus and 7,628 pounds per year for nitrogen. The nitrogen allocation for septic is a 100% reduction of existing loads for the first allocation scenario and a 50% reduction of existing loads for the second allocation scenario. The higher allocation (100%) reduces the total nitrogen loading to the lake by approximately 16% (46,935 pounds to 39,307 pounds), while the lower allocation (50%) reduces the total nitrogen loading to the lake by approximately 8% (46,935 pounds to 42,121 pounds). Controlling nitrogen is a TMDL nutrient objective because nitrogen can be the limiting nutrient for algal growth. Also, reducing nitrogen will reduce ammonia concentrations. Algal growth contributes to extreme pH swings, which also contribute to ammonia toxicity. The phosphorus loads from septic systems are much lower than nitrogen, and could be eliminated by making sure that all septic systems are properly sited and operate according to current design standards.

Agriculture: Nutrient loading from agriculture is derived primarily from grazing near the lake. The existing nutrient loads from agriculture are 485 pounds of phosphorus (4% of total loading) and 4,233 pounds of nitrogen (9% of total loading) per year. The allocations for agriculture are targeted reductions of 33% for the first scenario and 25% for the second scenario. This reduces the nitrogen loading from this category to 2,836 pounds per year for the first scenario and 3,175 pounds per year for the second scenario. The phosphorus loading from this category will be reduced to 325 pounds per year for the first scenario and 364 pounds per year for the second scenario. The 25% to33% reductions are consistent with widely accepted values for grazing BMP effectiveness.

Elk Herds: Nutrient loading from elk herds is similar to the agricultural loads, except that elk spend most of their time in forests where runoff rates and nutrient release rates are lower. The existing nutrient loads from elk herds are 242 pounds of phosphorus (2% of total loading) and 2,116 pounds of nitrogen (5% of total loading) per year. The allocations for elk herds are targeted reductions of 33% for the first scenario and 25% for the second scenario. This reduces the nitrogen loading from this category to 1,418 pounds per year for the first scenario and 1,587 pounds per year for the second scenario. The phosphorus loading from this category will be reduced to 162 pounds per year for the first scenario and 181.5 pounds per year for the second scenario. The BMPs recommended for grazing should be effective in reducing the loads from elk herds. The 25% to33% reductions are consistent with widely accepted values for grazing BMP effectiveness.

Residential: The residential source category contributes nitrogen and phosphorus loads similar to the elk herds, but it may become more significant in the future as further development occurs. Residential source loadings are estimated to contribute 2,271 pounds of nitrogen and 309 pounds of phosphorus to Luna Lake each year. The allocation for phosphorus and nitrogen is a 50% reduction per year for the second scenario only, which corresponds to 1,135.5 pounds for nitrogen and 154.5 pounds for phosphorus. Residential load allocations were not included in the first scenario since the focus was on the largest sources.

Sediment Release: The allocation for sediment release will require that Luna Lake be dredged to remove the nutrient rich layer of deposited material on the bottom of the lake. The allocation for this category must account for some level of natural background release of nutrients that will continue to be released from the newly exposed soil following dredging. The estimated allocation of a 50% reduction is believed to be conservative and takes into consideration that sediments will begin accumulating immediately and serve as a new source of nutrients. Sediment release is estimated to contribute 772 pounds of nitrogen and 264 pounds of phosphorus each year. The allocation of 50% reduces this source to 386 pounds of nitrogen and 132 pounds of phosphorus.

Macrophyte Decomposition: Assigning macrophyte decomposition an allocation assumes that a regular macrophyte harvest program will be maintained. Macrophyte decomposition is the single largest source of phosphorus to Luna Lake, contributing 8,995 pounds per year, which is 70% of the total load. Macrophyte decomposition is estimated to contribute 54% of the annual nitrogen load (25,132 pounds). This allocation would require reducing existing macrophyte beds by 90% for the first allocation scenario and 60% for the second allocation scenario.

TMDL Margin of Safety

TMDLs must include a Margin of Safety that assures water quality standards will be met. The following list of factors that were included in the technical analysis comprise the Margin of Safety for the Luna Lake TMDL:

- The watershed loading model (GWLF) evaluated loadings over a long period of time that included a wide range of climatic, precipitation, and flow patterns. The analysis included extreme high and low flow events over the period of record, providing boundaries for the assessment.

- The in-lake process analyses (BATHTUB) did not include the effect of shading by macrophytes on algal production in the lake.

- In the nutrient budget calculations, high macrophyte densities were assumed for the nutrient release fluxes from macrophyte decomposition.

4.2 Implementation Options

Septic Systems: The septic system allocation is confounded by inconsistent information on the number of septic systems remaining in use in the Luna Lake area. Therefore, the first step for implementation for the septic allocation is to conduct a survey to determine the number of remaining systems that are in use and the extent to which unused systems are continuing to leach nutrients to Luna Lake. The community could then consider the benefits of mitigating unused systems and active systems that are not functioning properly. If there are a large number of active systems, the community could consider extending sewer lines to unserviced areas near the lake.

Agriculture and Elk Herds: Agriculture loading is largely attributed to grazing activities in the watershed. Elk herds produce similar loading effects. Animal waste is a rich source of nutrients, and soil compaction increases the rate of runoff during storm events. There are a series of voluntary grazing BMPs that could be used to reduce runoff and loading from pastures. These BMPs would also be effective in reducing elk loads. ADEQ's Nonpoint Source program can be consulted for specific techniques and potential sources of funding for BMP implementation. The 25% or 33% reductions targeted by the two allocation scenarios are not unrealistic goals for a voluntary BMP program developed by local landowners and managers.

Residential: Residential nutrient loads are a result of increased impervious surface and soil amendments (e.g., fertilizers for lawns) used by residents, along with other materials associated with development. There are a series of voluntary BMPs that could be used to reduce runoff from residential areas and other developments. ADEQ's Nonpoint Source program can be consulted for specific techniques and potential sources of funding for BMP implementation. The 50% reduction targeted by this allocation is not an unrealistic goal for a well conceived program of BMPs for the Luna Lake watershed communities.

Dredging: Dredging addresses the sediment release source category by removing the nutrient rich layers of soil that have been deposited on the lake bottom. The dredging goal would remove the top meter of sediments that have accumulated most of the nutrients. This assumption is based on the findings of Baker and Farnworth (1995) in their report, "Feasibility of Management Options to Improve Water Quality in Rainbow Lake. The soils below the accumulated sediments also contain nutrients. Therefore, it is not possible to remove 100% of the nutrients released from the sediments. Dredging would also improve water quality conditions by increasing the depth of the lake, limiting the reemergence of macrophytes in certain portions of the lake. Dredging would also increase the storage capacity of the reservoir. Baker and Farnsworth (1995) also provide some preliminary cost estimates and recommendations for planning dredging operations.

Macrophyte Harvest: Macrophyte decomposition is addressed both through dredging and macrophyte harvesting. Macrophytes would be largely eliminated by any dredging operation, but only temporarily. Macrophytes are known to thrive even in oligotrophic conditions. Macrophytes will re-colonize Luna Lake within a short period time after dredging has been completed. The well-established macrophyte harvest program should address this allocation requirement. However, there are other management options that the local community may want to consider (e.g., biological control). Luna Lake is currently managed for both waterfowl habitat and sport fish, so some of the vegetation must remain in the lake because of its importance to waterfowl habitat.

Other Best Management Practices: This implementation option does not directly address any of the source category allocations. However, Best Management Practices that would help maintain higher levels of water in the lake could significantly contribute to improved water quality. These BMPs would be directed to improving the efficiency of use of irrigation water that is drawn from the lake, possibly reducing the total amount of water that would need to be taken from the lake. Another conservation option that should be evaluated is to assess the need for lining irrigation canals from the lake to reduce seepage losses. The increased volume would serve to dilute the remaining nutrients, thus reducing overall algal productivity. The emergence of macrophytes on exposed lake bed would also be slowed.

Watershed Forum: Luna Lake provides different beneficial uses to a wide range of residents within the Alpine community and surrounding areas. Many of the implementation recommendations will require local support and initiative. The local community may want to consider forming a watershed forum to build support for the nonpoint source BMPs that will be necessary to improve water quality in Luna Lake. A watershed forum would provide residents with a mechanism for coordinating activities to design, pursue funding for, and apply solutions to water quality problems within the Luna Lake watershed. ADEQ has a watershed approach program that could provide general assistance to the forum upon request from the local community.

4.3 Monitoring

ADEQ will work with the local community and other cooperating agencies to develop a monitoring program for Luna Lake to assess whether the overall objectives of this TMDL study are being met (i.e., violations of narrative nutrients, numeric pH and ammonia toxicity water quality standards will occur within acceptable frequencies).

Currently, Luna Lake is classified as eutrophic. Ideally, this TMDL would recommend methodologies that would improve the trophic status of the lake and result in Luna Lake being reclassified as mesotrophic. However, model predictions indicate that this level of improvement is most likely unattainable. This does not mean, however, that the water quality of the lake cannot be improved by degrees. The goal of this TMDL is to incrementally improve the situation and to meet water quality standards. This improvement can be achieved via the various implementation options discussed in section 4.2. With this in mind, the specific objective of the monitoring program will be to assess whether the management actions are achieving their stated objectives and improving the water quality of Luna Lake. ADEQ will take the lead in developing a monitoring program in cooperation with the AGFD and local community.

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