CHAPTER 6
DIAMOND LAKE AND LAKE CREEK AQUATIC WEEDS, DISSOLVED OXYGEN AND pH TMDL

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Table 6.1 Diamond Lake pH TMDL Components	
Waterbodies **OAR 340-042-0040(4)(a)**	Diamond Lake, HUC (Hydrologic Unit Code) 1710030101, within the 4th field HUC 17100301 (North Umpqua Subbasin).
Pollutant Identification **OAR 340-042-0040(4)(b)**	Excess nutrients from internal recycling and excessive algal growth
Target Criteria Identification (Applicable Water Quality Standards) **OAR 340-042-0040(4)(c)** **OAR 340-041-0016** **OAR 340-041-0009(1)(a)(B)** ***CWA §303(d)(1)***	**pH:** OAR 340-041-0326(1) The target is the applicable pH criterion of 8.5 Standard Units (S.U.).
Existing Sources **OAR 340-042-0040(4)(f)** ***CWA §303(d)(1)***	Tui chub have eliminated most of the larger, herbivorous zooplankton, resulting in a zooplankton population that is comprised of over 90 percent rotifers. These organisms have a short life-span and have poor grazing efficiency resulting in excessive phytoplankton growth. Internal load of nutrients and acceleration of nutrient cycling associated with loss of larger herbivorous zooplankton, loss of larger zoobenthos, persistent anoxia in the hypolimnion, excretion from fish, and nitrogen fixation by cyanobacteria.
Seasonal Variation **OAR 340-042-0040(4)(j)** ***CWA §303(d)(1)***	**pH:** Critical pH and aquatic weeds in Diamond Lake have occurred during the summer months. This is also the critical period for Lake Creek. Dissolved Oxygen: Critical dissolved oxygen levels in Diamond Lake have occurred during the summer months.
Total Maximum Daily Load ***CWA §303(d)(1)***	An incremental TMDL based on fish biomass in which the tui chub is eliminated and a conservative trout-stocking program is implemented.
Allocations ***40 CFR 130.2(f)*** ***40 CFR 130.2(g)*** ***40 CFR 130.2(h)***	Removal of a high percentage (~90 to 100 percent) of the tui chub from Diamond Lake.
Margins of Safety ***CWA §303(d)(1)***	The margin of safety is implicit in the conservative management of the system and close monitoring of the lake during changes in management.
Water Quality Standard Attainment Analysis ***CWA §303(d)(1)***	Even under a no-fish scenario, it is likely that water quality standards for pH will be exceeded periodically under favorable weather conditions, however the frequency of exceedence based on past climate history is expected to be less than under any scenario with fish present.
Water Quality Management Plan	The Water Quality Management Plan provides the framework of management strategies to attain and maintain water quality standards.

OVERVIEW

Reason for Action

Section 303(d) of the Federal Clean Water Act (1972) requires that waterbodies that violate water quality standards, thereby failing to fully protect beneficial uses, be identified and placed on the state's 303(d) list. Diamond Lake has been identified as impaired and was placed on DEQ's 1998 303(d) list for pH and aquatic weeds/algae. Diamond Lake is currently listed on the 2004-06 303(d) list for these same parameters, as well as dissolved oxygen. This TMDL will address these three listings. This TMDL will also address the pH listing on Lake Creek, which is the outlet from Diamond Lake and carries water from Diamond Lake to Lemolo Reservoir. It is anticipated that when the restoration of Diamond Lake is complete and pH, dissolved oxygen and aquatic weeds/algae meet water quality standards, that Lake Creek as well will meet water quality standards for pH.

Diamond Lake, Oregon is a 1,226 hectare lake in the central Cascades located at an elevation of 5,184 ft (1,580 m). Since 2001 the lake has been experiencing large blooms of the cyanobacteria, Anabaena flos-aquae. In addition, the cyanobacteria have been producing a toxin, anatoxin-a, at levels considered potentially injurious to humans. In 2002, the ODEQ issued a contract to JC Headwaters, Inc. (JCH) to analyze the existing conditions and develop a TMDL for Diamond Lake. Chapter four of the appendix has the complete text of the analytical approach and analysis performed by JC Headwaters for the development of the TMDL. The hydrologic budget and hydrodynamic modeling using CE-QUAL-W2 showed that inputs of nitrogen (N) and phosphorus (P) to Diamond Lake are largely natural. This is in agreement with a previous study of Diamond Lake from 1972-1977 by EPA. However, the changes to the fishery, particularly the recent expansion of tui chub population, have had profound changes on the biology of the lake that have had major consequences on nutrient cycling within the lake. Thus, this TMDL will largely focus on the biology (the fishery) of the lake.

Analytical Approach

Most TMDL analyses for eutrophication-related water quality problems in the United States have focused on total phosphorus (TP) and approaches for limiting TP export to the receiving water. This reflects the fact that the majority of lakes in the United States are P-limited. However, in the Cascades, the groundwater and surface waters come into extensive contact with the bedrock, which is comprised largely of basalt, andesite, and andesitic basalt. These rocks have an abundance of phosphorus, and the weathering reactions yield waters that are naturally high in phosphorus. In contrast to many waters in the United States where P-limitations permit the use of P-based models, many Cascade lakes require an analysis of both P and N to understand the eutrophication process.

A STELLA® model of linked differential equations was developed to represent the major biological components of Diamond Lake, their interactions, and the nutrient fluxes associated with the biological responses to the fisheries. The model results indicate that the current conditions in the lake can be explained by the changes in the fisheries. Diamond Lake was naturally fishless. In the early 20th century the Oregon Department of Fish and Game began stocking the lake with trout. Tui chub were inadvertently introduced to the lake, probably as live bait for trout fishing. The tui chub have eliminated most of the larger herbivorous zooplankton, resulting in a zooplankton population that is comprised of over 90 percent rotifers. These organisms have a short life-span and have poor grazing efficiency on the phytoplankton. The reduction in grazing pressure reduces the constraints on the phytoplankton. The proliferation of the chub has also eliminated most of the larger zoobenthos such as the amphipods, resulting in a population that is comprised largely of dipterans (Chironomidae) and tubifex worms (Tubificidae). Again, the smaller zoobenthos have shorter life-spans than the pre-fish community and would be expected to increase the rate of cycling nutrients from the sediments.

The modeling scenarios indicate that it is necessary to remove the vast majority of tui chub from Diamond Lake to meet water quality standards. Partial removal of the chub results in compensatory growth of the remaining individuals and the high fecundity of the species in this environment results in rapid recovery to levels of maximum biomass supported by the lake. The evidence also indicates that the lake will not meet water quality standards at trout stocking densities employed since 1962. The model was used to estimate trout stocking densities that yielded water quality conditions similar to those experienced prior to stocking. Modeling and analysis (see Appendix 1) indicate that the natural nutrient loadings would lead to algal growths during certain climatic conditions and that these growths may result in the numeric pH criteria being exceeded. These exceedences would be experienced during climatic conditions consisting of above-average temperature and below-average wind velocities that persist for extended periods. Since natural conditions exceed the numeric criteria, the TMDL targets attainment of water quality conditions similar to that experienced under natural conditions.

DIAMOND LAKE TMDL

Pollutant Identification

The lake routinely exceeds pH values of 8.5 and experiences nuisance growths of cyanobacteria, primarily Anabaena flos-aquae the summer months (Eilers 2003b). Since 2001 the lake has been experiencing large blooms of the cyanobacteria, Anabaena flos-aquae. In addition, the cyanobacteria have been producing a toxin, anatoxin-a, at levels considered potentially injurious to humans. In 2002, the ODEQ issued a contract to JC Headwaters, Inc. (JCH) to analyze the existing conditions and develop a TMDL (Total Maximum Daily Load) for Diamond Lake. The hydrologic budget and hydrodynamic modeling using CE-QUAL-W2 showed that inputs of nitrogen (N) and phosphorus (P) to Diamond Lake are largely natural. This is in agreement with a previous study of Diamond Lake from 1972-1977 by EPA. However, the changes to the fishery, particularly the recent expansion of tui chub population, have had profound changes on the biology of the lake that have had major consequences on nutrient cycling within the lake.

Based on this analysis, it has been determined that both nitrogen and phosphorus are pollutants of concern. However, since it is the internal lake processes which have the greatest effect on conditions which lead to algae blooms, high pH values and reduced dissolved oxygen levels, the sources which will be addressed will include internal and external loading and alterations which have been caused by a modified fish population.

Sensitive Beneficial Use Identification

The primary benefit to achieving the water quality standards for dissolved oxygen, pH and aquatic weeds is to support a healthy and balanced distribution of resident fish and aquatic life and to protect salmonid spawning and rearing.

Oregon Administrative Rules specify the beneficial uses to be protected in the Umpqua Basin. OAR 340-041-0320 provides that water quality in the Umpqua Basin must be managed to protect the beneficial uses shown in Table 320(A). The uses which are designated for protection in Diamond Lake are shown in Table 6.2 below, which highlights those that are related to dissolved oxygen, pH and aquatic weeds.

Table 6.2 Beneficial uses designated in Diamond Lake

(From OAR 340-041-0320, Table 320A)
Beneficial uses related to pH are marked in ***gray***

Beneficial Use	***Designated***	***Beneficial Use***	***Designated***
Public Domestic Water Supply	√	Salmonid Fish Spawning	√
Private Domestic Water Supply	√	Salmonid Fish Rearing	√
Industrial Water Supply	√	Resident Fish and Aquatic Life	√
Irrigation	√	Anadromous Fish Passage	√
Livestock Watering	√	Wildlife and Hunting	√
Boating	√	Fishing	√
Hydro Power	√	Water Contact Recreation	√
Aesthetic Quality	√	Commercial Navigation & Transportation	

While designated for all the uses noted in Table 6.2, current uses in Diamond Lake do not include domestic or industrial water supply, hydro power, salmonid fish spawning or anadromous fish passage.

For dissolved oxygen, pH and aquatic weeds, resident fish and aquatic life are the most sensitive beneficial uses which occur in Diamond Lake.

The Water Quality Standards rule also designates fish uses to be protected in the Umpqua Basin as shown in Figures 320A and 320B of the rule. Figure 320A is a map of the waters of the Umpqua Basin with designations as to their use by salmonids; it is available on DEQ's web site at http://www.deq.state.or.us/wq/standards/FishUseMapsFinal/FFigure320A_Umpqua.pdf
The waters in and around Diamond Lake are designated as supporting "salmon and trout rearing and migration". This designation includes all salmon species, steelhead, rainbow and cutthroat trout. No salmon or steelhead spawning occurs in Diamond Lake.

Target Criteria Identification

pH, Algae and Aquatic Life Requirements
Algae production is the direct cause of wide pH fluctuations in Diamond Lake. The algae of concern are phytoplankton, algae that are suspended in the water column. As phytoplankton obtain carbon dioxide for cell growth, the bicarbonate present in the water is decreased. Removal of the bicarbonate from the water will generally increase the water's pH. High pH is stressful to fish.

Readings of pH are generally at a daily minimum in the early morning and increase over the course of the day. This daily increase in pH is associated with algal photosynthesis, which is at its maximum during the mid-day light and warmth.

Applicable Water Quality Criteria

Diamond Lake is listed for exceedences of the dissolved oxygen, pH and aquatic weeds/algae criteria. Since this TMDL analysis has found that these criteria are naturally exceeded during certain climatic conditions (i.e., above-average temperatures and below-average wind velocities that persist for extended periods), the natural conditions provision will also be utilized in this TMDL.

Water Quality Criteria for Dissolved Oxygen
Oregon Administrative Rule 340-041-0016 provides, in part as follows:

340-041-0016
Dissolved Oxygen

(1) Dissolved oxygen (DO): No wastes may be discharged and no activities must be conducted that either alonge or in combination with other wastes or activities will cause violation of the following standards:
. . .
(b) For water bodies identified by the Department as providing cold-water aquatic life, the dissolved oxygen may not be less than 8.0 mg/l as an absolute minimum. Where conditions of barometric pressure, altitude, and temperature preclude attainment of the 8.0 mg/l, dissolved oxygen may not be less than 90 percent of saturation. At the discretion of the Department, when the Department determines that adequate information exists, the dissolved oxygen may not fall below 8.0 mg/l as a 30-day mean minimum, 6.5 mg/l as a seven-day minimum mean, and may not fall below 6.0 mg/l as an absolute minimum . . . .

Water Quality Criteria for pH

Oregon Administrative Rule **340-041-0326(1)** provides as follows, with the provisions applicable to Diamond Lake and Lake Creek highlighted in bold.

340-041-0326
Water Quality Standards and Policies for [the Umpqua] Basin:
(1) pH (hydrogen ion concentration). pH values may not fall outside the following ranges:
(a) Marine waters: 7.0 – 8.5;
(b) Estuarine and fresh waters (except Cascade lakes): 6.5 – 8.5;
(c) **Cascade lakes above 3,000 feet altitude: pH values may not fall outside the range of 6.0 to 8.5.**

Since Diamond Lake is a Cascade lake at an altitude of 5,184 feet, the pH criteria requires pH in these waters to be in the range of 6.0 to 8.5. Lake Creek requires pH in the 6.5 – 8.5 range.

Water Quality Criteria for Aquatic Weeds and Algae

The following is the Oregon standard applicable to aquatic weeds and/or algae (**OAR 340-041-0007**):

(11) The development of fungi or other growths having a deleterious effect on stream bottoms, fish or other aquatic life, or which are injurious to health, recreation, or industry, shall not be allowed.

Additionally, the values set forth in **OAR 340-041-0019** are utilized to identify waterbodies where phytoplankton may impair beneficial uses, thus triggering further studies and, as appropriate, the development of control strategies.

Nuisance Phytoplankton Growth

(1) The following values and implementation program must be applied to lakes, reservoirs, estuaries and streams, except for ponds and reservoirs less than ten acres in surface area, marshes and saline lakes:

(a) The following average Chlorophyll a values must be used to identify water bodies where phytoplankton may impair the recognized beneficial uses:

(A) Natural lakes that thermally stratify: 0.01 mg/1;

(B) Natural lakes that do not thermally stratify, reservoirs, rivers and estuaries: 0.015 mg/1;

(C) Average Chlorophyll a values may be based on the following methodology (or other methods approved by the Department…

Paragraph (2) of this Section of the rule describes the studies and implementation programs which may be initiated by DEQ.

It is important to note that the chlorophyll a values identified in this Section are not criteria which may not be exceeded but rather trigger values which are used to identify waters where phytoplankton may impair beneficial uses. If a waterbody exceeds the chlorophyll a values identified, the rule requires the development of a control strategy. The provision specifically provides that the control strategy may include the modification of the values in Section (1) when natural conditions are responsible for the exceedence.

Natural Conditions Criteria

The following provision applies to instances where the natural condition of a water body is less stringent than the numeric criteria.

OAR 340-041-0007
Where a less stringent natural condition of a water of the State exceeds the numeric criteria set out in this Division, the natural condition supersedes the numeric criteria and becomes the standard for that water body. However, there are special restrictions, described in OAR 340-041-0004(9)(a)(C)(iii), that may apply to discharges that affect dissolved oxygen. Since there are no discharges which affect dissolved oxygen addressed in this TMDL, these later restrictions are not applicable.

As will be discussed in this TMDL, natural exceedences of the pH and aquatic weed criteria are expected to occur during extended periods of above-average air temperature and below-average wind velocities. During these times, this provision applies.

Numerical Target

Based on the above criteria and the analysis discussed below, a target of 4,000 kg/year of cyanobacteria biomass has been established for this TMDL. This target provides for the attainment of the pH, dissolved oxygen and aquatic weed criteria during times when it would be naturally attained and addresses natural exceedences of the numeric criteria during extended periods of above-average air temperatures and below-average wind velocities.

Seasonal Variation

The TMDL analysis evaluates lake conditions year round, however the focus is on the summer months when algal growth and cyanobacteria outbreaks occur. This is also true for Lake Creek. Exceedences of the criteria only occur during the summer months. The variation in growth rates during summer and winter months is considered in the TMDL. Thus, the TMDL reflects the variation present between seasons.

Historical Data

Annual water quality monitoring by DEQ and others demonstrates that pH values exceeded 9.0 during the summer season every year from 1992-2002, with a maximum of 9.7 between 1992-2003. Similarly, annual monitoring data from this same period indicate that average chlorophyll a values exceeded 0.01 mg/l every summer. The maximum value recorded between 1992-2003 was 0.064 mg/l (USDA, Final Diamond Lake EIS, 2004).

In the summers of 2001, 2002 and 2003, Diamond Lake experienced severe blooms of cyanobacteria (blue-green algae) Anabaena flos-aquae. This type of algae produces a neurotoxin, that in high concentrations, is harmful to humans and other animals. Another species of blue-green algae, Microcystis aeruginosa, was present in the 2003 bloom. This species produces hepatotoxins which are also a health risk. To protect public health and safety, the Umpqua National Forest, in cooperation with the Douglas County Health Department, closed Diamond Lake to some public uses (wading, swimming, water skiing and boating) during portions of all three summers.

Existing Sources

External Loading of Nutrients (Phosphorus and Nitrogen)

The flux of nutrients into and out of Diamond Lake is a function of the flows and the concentrations measured for each of the sources. The average nutrient concentrations measured for the Diamond Lake system are shown in Table 6.3 and the fluxes calculated from the flows and the concentrations are shown in Table 6.4.

The concentrations for the major sources show that natural sources from stream inputs have very high concentrations of phosphorus and extremely low concentrations of nitrogen. The estimates of nutrient flux derived from the flow and concentration data indicate that Diamond Lake retains about 50 percent of the total phosphorus inputs but exports over six times more nitrogen than it receives from the watershed and precipitation. The lake retains about 99 percent of the nitrate input and presumably assimilates this into the macrophytes and phytoplankton. However, the retention of the nitrate is insufficient to account for the generation of 26 metric tons of nitrogen; the difference is presumably attributed to nitrogen fixation by cyanobacteria.

Table 6.3 Concentrations of nitrogen and phosphorus inflows and outflows for the Diamond Lake system. Concentrations are expressed as micrograms per liter.

Source	Flow ($10^6 m^3$)	TP	PO_4	TN	Org N	NO_3	NH_3
Inflow							
Silent Creek	21.432	69	58	31.8	27	3.5	1.3
Short Creek	6.251	72	57	56.3	37	18.9	0.4
Groundwater	5.389	69	58	31.8	27	3.5	1.3
Precipitation	16.258	10	5	190	5	160	25
Other Tribs	1.57	69	58	31.8	27	3.5	1.3
Outflow							
Lake Creek	41.261	25	3	518.4	508	0.4	10
Evaporation	6.909	0	0	0	0	0	0
Groundwater	2.73	25	3	518.4	508	0.4	10

Table 6.4 Table 6.4. Annual fluxes of nutrients entering and leaving Diamond Lake. (Units are in kilograms per year)

Source	TP	PO_4	TN	Org N	NO_3	NH_3
Inflow						
Silent Creek	1478.8	1243.1	681.5	578.7	75.0	27.9
Short Creek	450.1	356.3	351.9	231.3	118.1	2.5
Groundwater	371.8	312.6	171.4	145.5	18.9	7.0
Precipitation	162.6	81.3	3089.0	81.3	2601.3	406.5
Other Tribs	108.3	91.1	49.9	42.4	5.5	2.0
	2571.6	**2084.3**	**4343.8**	**1079.1**	**2818.8**	**445.9**
Outflow						
Lake Creek	1281.5	153.8	26573.7	26040.6	20.5	512.6
Evaporation	0.0	0.0	0.0	0.0	0.0	0.0
Groundwater	68.3	8.2	1415.2	1386.8	1.1	27.3
	1349.8	**162.0**	**27988.9**	**27427.4**	**21.6**	**539.9**
Net	**-1221.9**	**-1922.3**	**23645.1**	**26348.3**	**-2797.2**	**94.1**
Net %	**-47.5**	**-92.2**	**544.3**	**2441.6**	**-99.2**	**21.1**

The loads to Diamond Lake presented in Table 6.4 do not reflect anthropogenic inputs from septic inputs from the Summer Home Tract, artificial bait used for trout fishing, and fish stocking. Estimates from these sources are addressed below. Inputs from waterfowl were not estimated because of the absence of data on waterfowl populations.

An estimate of nutrient contributions from the Summer Home Tract was prepared by J.C. Headwaters. The wide range of the estimate reflects the uncertainty over the proportion of the human wastes which may actually enter the lake. Sources of uncertainty include the range in sophistication of the types of septic treatments present, the direction of groundwater flow and the rate of infiltration. The nutrient flux from septic systems was estimated at 91 to 364 kg/year total nitrogen and 9 to 36 kg/year total phosphorus.

The use of artificial baits also results in an input of nutrients to the lake. Using conservative assumptions and the minimal information available, J.C. Headwaters estimated that 8.5 kg/year total phosphorus and 85 kg/hr total nitrogen was introduced through use of artificial baits.

The third anthropogenic source quantified by J.C. Headwaters was the mass balance associated with the nutrients contained in the fish released into Diamond Lake. Lauer et al. (1979) estimated that the contribution of fish to Diamond Lake averaged about 15 kg P/yr compared to a removal of 550 kg P (as fish) during 1973. Since the trout stocking program has changed radically in recent years in response to proliferation of tui chub, this estimate was updated by J.C Headwaters. The updated estimate for nutrient loading from fish stocking shows the nutrient fluxes associated with the current stocking program has a net input of 18 kg/year of phosphorus and 104 kg/year of nitrogen to the lake.

A comparison of the anthropogenic sources of nitrogen and phosphorus with the natural loads show that approximately 8.6 percent of the total nitrogen load to the lake and 1.9 percent of the total phosphorus load (Figure 6.1, Table 6.5) is derived from anthropogenic sources.

Based on these estimates of anthropogenic loading to Diamond Lake, it appears that the source of the lake's water quality problems are a result of changes in the internal loading of N and P, not external nutrient loading. These are also the sources of the water quality problems in Lake Creek.

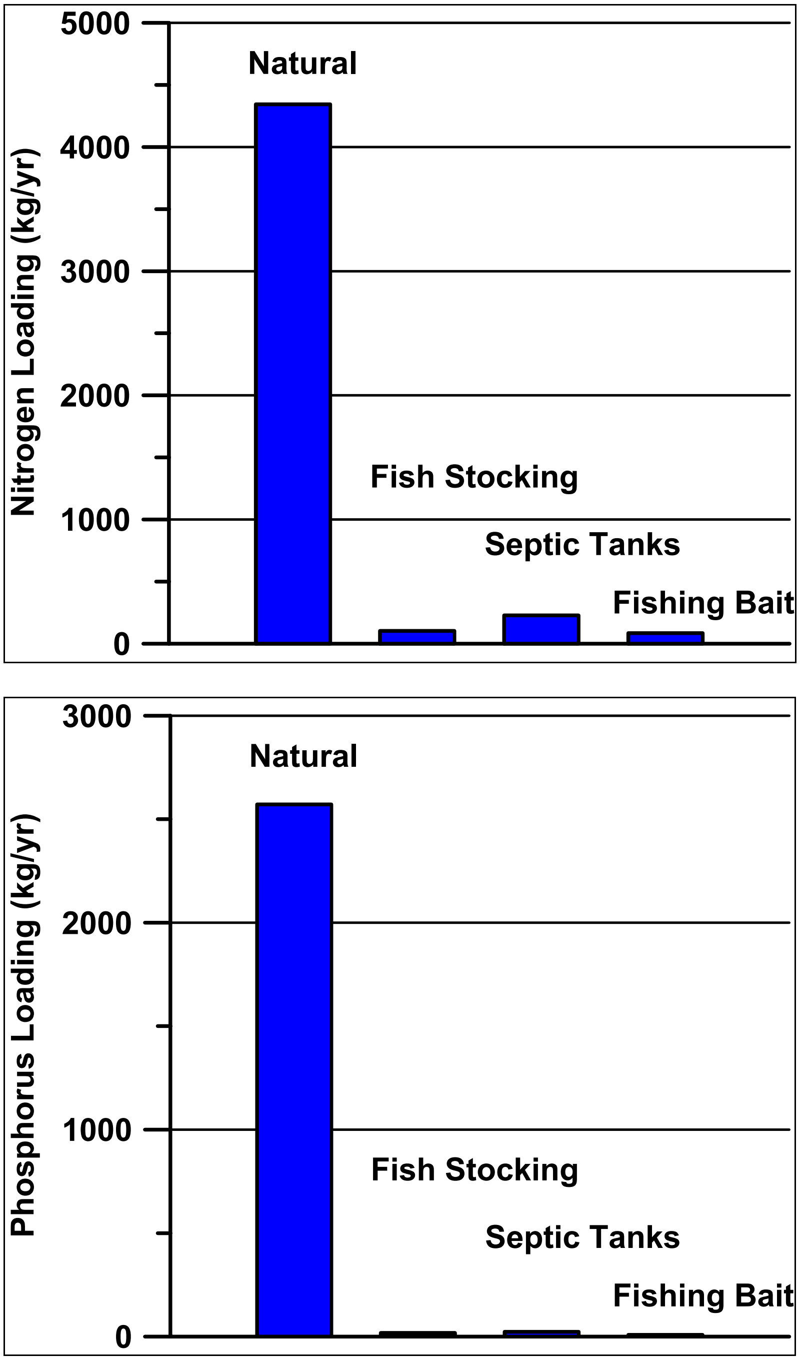

Figure 6.1 **Annual loads of nitrogen and phosphorus to Diamond Lake for 2002-2003.**

Table 6.5 Comparison of natural and anthropogenic sources of nitrogen and phosphorus annual loads.

Source	N (kg/Yr)	N (%)	P (kg/yr)	P (%)
Natural	4,344	91.4	2,572	98.1
ANTHROPOGENIC				
Fish Stocking	104	2.2	18	0.7
Septic Systems	228	4.8	22.5	0.9
Fish Bait	85	1.8	8.5	0.3
Subtotal	417	8.6	49	1.9
TOTAL	4,751		2,621	

Internal Loading

Internal loading represents nutrients that are recycled within the lake. Cycling of nutrients in a lake can be strongly affected by the biota. By manipulating the composition of top predators (zooplankton and/or benthos), the nutrient cycles are altered, thus affecting the composition of the primary producers. Analysis of internal loading requires studies of lake hydrodynamics, external nutrient fluxes and lake biology and the interactions between each of these within a particular lake. Biological components which need consideration are fisheries, zooplankton, macrophytes and zoobenthos. The interaction of these components was evaluated in the Diamond Lake study. Findings indicate that a significant source leading to excessive algae growths in Diamond Lake is the modification of the biological community, thus modifying internal loading of nutrients.

Internal nutrient loads were estimated via modeling. In 2002, an estimated 3,202 kg of total phosphorus and 24,588 kg of total nitrogen were generated from internal loading. This represents 55% of the total phosphorus loading and 87% of the total nitrogen loading to the lake.

Algal Growth

The tui chub have eliminated most of the larger, herbivorous zooplankton, resulting in a zooplankton population that is comprised of over 90 percent rotifers. These organisms have a short life-span and have poor grazing efficiency on the phytoplankton. The reduction in grazing pressure reduces the constraints on the phytoplankton. The proliferation of the chub has also eliminated most of the larger zoobenthos such as the amphipods, resulting in a population that is comprised largely of dipterans (Chironomidae) and tubifex worms (Tubificidae). Again, the smaller zoobenthos have shorter life-spans than the pre-fish community and would be expected to increase the rate of cycling nutrients from the sediments.

Calibrated Model Analysis

Hydrodynamic Model

The CE-QUAL-W2 model (Version 3.1, Cole and Wells [2001]) was selected to simulate daily fluctuations in flows and water temperature during the period from April 22 through September 22, 2001. The lake was partitioned into a series of 21 longitudinal segments 250 m in width and vertical segmentation of 1 m depths using the bathymetry developed by Eilers and Gubala (2003). The temperature data were calibrated to profiles collected on eight days in 2001 resulting in a model that simulated observed temperature values generally within 1°C (Appendix 1). The model was run on a daily time-step. The key coefficients that were adjusted during the calibration process are presented in Table 6.6.

Table 6.6 Key coefficients that were adjusted during the hydrodynamic model calibration process.

Coefficient	Units	Value
Horizontal Eddy Viscosity	m^2/s	1.2
Horizontal Eddy Diffusivity	m^2/s	1.2
Sediment Heat Ex. Coefficient	$W/m^2/s$	2.00E-08
Sediment Temperature	C	5
Interfacial Friction	-	0.001
Fraction Solar at Surface To Water	0 - 1	1
Max. Vertical Eddy Viscosity	m^2/s	1.2
Wind Sheltering	0 - 1	0.15 - 0.2
Water Extinction Coefficient	0 - 1	0.27
Fraction of Solar Radiation Absorbed @ Water Surface	0 - 1	0.18 - 0.60

Biological Model

A number of investigators are now recognizing the need for incorporating biological processes in mathematical models for predicting water quality in lakes. Review of data on nutrient fluxes in Diamond Lake indicates that accurate forecasting of water quality conditions in Diamond Lake would require evaluating biological interactions at the species level.

To more accurately assess conditions in Diamond Lake, a custom application using the STELLA® framework (Ver. 8.0; High Performance Systems [2003]) was utilized. The model represents nine groups of organisms (trout, chub, rotifers, cladocerans + copepods, chironomids, amphipods, macrophytes, cyanobacteria, diatoms) and simulates both nitrogen and phosphorus transfers among the groups. The model in its present form is a series of linked differential equations to solve for the nutrient fluxes. The chub was represented by a population with a maximum life-span of seven years that was initialized by a “seed” population. The rate of chub increase was affected by the percentage of egg survival and food limitation factors. The food base was represented by phytoplankton (cyanobacteria and diatoms), zooplankton (rotifers and cladocerans/copepods), and benthos (amphipods and chironomids). The trout population was represented by stocked trout that also was connected to benthos and zooplankton for food sources. Trout abundance was determined by stocking rates, fishing pressure, and out-migration. The nutrients (TN & TP) were connected to the fish and food cycles to compute inputs or losses from the water. A sediment compartment is not included in this version of the model as it was not thought to have a significant impact on water quality conditions in the lake. The complete model representation, linkages, and code are shown in Appendix 1.

Model Simulation

The models noted above were used to assess current, past, and possible future ecological and water quality conditions in Diamond Lake. The principal findings from these inquiries are discussed in more detail in chapter four of the appendix (TMDL Modeling and Analysis of Diamond Lake, Oregon) and are summarized below.

- The development of the hydrologic model is in general agreement with previous investigations. The calculated hydraulic residence time for the 2003 water year is 1.65 years. Groundwater is a relatively small component of the inflows and outflows. The single largest hydraulic input is from Silent Creek.
- Diamond Lake is a major sink for phosphorus (with 92 percent retention for PO_4) and silicon (59 percent retention), but is a major exporter of nitrogen (6.4 fold increase), most of which is in organic form. The lake exports a large amount of nitrogen despite retaining 99 percent of the nitrate inputs.
- The phosphorus inputs to the lake are largely from natural sources; anthropogenic sources from the watershed represent less than 2 percent of the total phosphorus load to the lake. Nitrogen inputs to Diamond Lake from the watershed are only slightly greater than the phosphorus inputs, resulting in a system that would appear to be N-limited for periods of the year.
- Watershed inputs of N and P are currently much less than the internal load of nutrients and acceleration of nutrient cycling associated with loss of larger herbivorous zooplankton, loss of larger zoobenthos, persistent anoxia in the hypolimnion, excretion from fish, and nitrogen fixation by cyanobacteria.
- Most of the changes in the ecology and nutrient cycling of Diamond Lake appear to be the direct result of the large biomass of tui chub.
- The 2 pathways by which the tui chub enhance algal blooms are by reducing the number of larger sized zooplankton that can filter algal cess from the water column and by increasing the water column nutrient concentration through excretion of nitrogen and phosphorus in forms available for algal growth.
- Sensitivity analyses showed that, even if the survival of tui chub eggs was four times greater than that reported for East Lake, it is possible that some tui chub survived the rotenone treatment in 1954 and only reached a population size in excess of a million fish in the 1990's. If the birth rates and mortality rates are more favorable than reported for East Lake, the tui chub population currently in the lake can be explained by re-introduction of the chub circa 1990.
- The models show that the current biomass of tui chub can largely explain the frequency of the cyanobacterial blooms, although the intensity of the blooms appears to be strongly influenced by weather conditions associated with extended periods of high temperature, low average wind speed, and abundant solar radiation.
- To meet water quality goals, it appears necessary to remove a high percentage (~90 to 100 percent) of the tui chub from Diamond Lake. This will allow the internal nutrient cycling to return to natural rates, thus keeping the cyanobacteria blooms to natural frequency and intensity.
- The uncertainty analysis of the nutrient fluxes is considerable, largely because of the unknowns associated with the precise role of the biological communities in nutrient cycling.
- Even under natural conditions (a no-fish scenario), it is likely that water quality standards for pH will be exceeded periodically under favorable weather conditions, however the frequency of exceedence based on past climate history is expected to be less than under any scenario with fish present.

Loading Capacity

As noted above, to meet water quality standards in Diamond Lake, it is necessary to address the internal loads of nutrients (phosphorus and nitrogen) and the factors which have increased those loads. While the loading capacity and allocations could be expressed in the form of nitrogen and/or phosphorus loads, these would not be the most efficient way to quantify needed reductions. Thus, for purposes of this TMDL, the target has been established as kg of cyanobacteria biomass produced each year. This measure provides a quantification of the algae of concern in the waterbody. Control of cyanobacteria to target levels will lead to water quality conditions necessary to attain water quality standards. Control of the internal nutrient loading cycles which lead to elevated cyanobacteria biomass will be done through control of the fisheries which currently are altering the internal nutrient cycles. Nutrient loads necessary to attain this target may also be predicted through modeling.

Modeling estimates that there is a current peak production of cyanobacteria biomass near 20,000 kg/yr. Based on this modeling a target production of 4,000 kg/yr cyanobacteria biomass has been established and could be attained by controlling the tui chub population. Attainment of this target would lead to attainment of the aquatic growth narrative, the pH criteria during periods which it would naturally be met and the natural conditions criteria during periods of naturally high algal growth.

Modeling and assumptions indicate that attaining this cyanobacteria biomass target (4,000 kg/yr) will require limiting external nutrient fluxes to current levels; nutrient inputs from fish bait, fish stocking and septic system to 1975 levels; and internal loading to one half of the nutrient loads noted in 1975 as estimated by Eilers TMDL modeling effort. After achieving a successful eradication of the tui chub the internal load of phosphorous would be reduced to approximately 778 kg/yr. This amounts to a 41% reduction in the current load. The contributing sources and total phosphorous load is 3,461 kg/yr (loading capacity) are noted in Table 6.7 below.

Assuming similar reductions in the internal loading of nitrogen there will be an internal load reduced to 5671 kg/yr approximately a 63 % reduction in the current load. The contributing sources and total nitrogen load is 10,524 kg/yr (loading capacity) are noted in Table 6.7 below.

Waste Load Allocations

There are no point sources which discharge to Diamond Lake. Therefore, a WLA of 0 has been established.

Load Allocations

As indicated above, the two main sources of nutrients to Diamond Lake are external fluxes and internal loads. Modeling indicates that attaining the cyanobacteria target will require limiting external nutrient fluxes to current levels; nutrient inputs from fish bait, fish stocking and septic system to 1975 levels and internal loading to one half of the loads estimated for 1975. Thus load allocations presented in Table 6.7 below have been established for Diamond Lake.

Table 6.7

Source	**Load Allocations**	
	N (kg/Yr)	**P (kg/yr)**
Natural	4,344	2,572
Fish Stocking	27	18
Septic Systems	228	23
Fish Bait	254	70
Internal Load	5,671	778
TOTAL (LOADING CAPACITY)	10,524	3,461

Loading values for nitrogen and phosphorous were selected from table 16 of the TMDL Modeling and Analysis of Diamond Lake, Oregon in Appendix 1 of this TMDL document. Natural load allocations are the 1900 estimated inputs that exclude any anthropogenic inputs of a fish-less unmanaged lake. Values used for contributions from Fish Stocking, Septic Systems and Fish Bait use 1975 estimates. As noted earlier, once the tui chub have been eradicated internal loads are estimated to be one half of the 1975 values.

The biological interactions within the lake have a major impact on how nutrient loading effects algal growth. Therefore, limiting internal loading alone, without some representation of the biological components affecting that load and the growth of cyanobacteria may not lead to attainment of water quality criteria. As such, this TMDL also includes an expression of the fisheries composition necessary to reduce internal nutrient loading to that expressed by the load allocations while also leading to the attainment of the cyanobacteria target. Modeling indicates that attainment of both of these targets will require elimination of 90 to 100% of the tui chub population and a reduction in the trout population.

Modeling indicates that it may be possible for the lake to support a population of 440,000 trout and attain water quality standards. However, due to the uncertainty with predictions related to the biological components in Diamond Lake, J.C Headwaters has recommended that a more conservative stocking strategy be employed and, as the lake recovers and internal cycling returns to more natural levels, gradual increases in trout stocking be implemented.

The Table 6.8 below (from table 17 of Appendix 1: Diamond Lake Modeling by Eilers) represents a conservative incremental trout stocking strategy as suggested in the TMDL modeling report. Prior to trout stocking various water quality parameters and lake water biometrics including zooplankton, phytoplankton and macroinvertebrates values will help determine lake health and thus determine appropriate stocking rates. This lake health or water quality indices determination will be part of the Oregon Department of Fish and Wildlife’s implementation plan.

Table 6.8 A possible trout stocking strategy for Diamond Lake that could be incrementally implemented.

Stocked Fingerlings	Number of Fish	Wet Wt (kg)	Wet Wt (g/fish)	Dry Wt (g/fish)	TP (%)	TN (%)	TP Load (kg)	TN Load (kg)
Stage 1	27,500	250	18	3.6	1.7	10	2	10
Stage 2	55,000	500	18	3.6	1.7	10	3	20
Stage 3	110,000	1,000	18	3.6	1.7	10	7	40
Stage 4	220,000	2,000	18	3.6	1.7	10	13	79
Stage 5	440,000	4,000	18	3.6	1.7	10	27	158

A multi-agency/entity work group has developed a Diamond Lake Restoration Strategy including a Final Environmental Impact Statement (FEIS) and Record of Decision (ROD) by the Umpqua National Forest, the designated land management agency for Diamond Lake area. The final FEIS includes pre- and post-lake treatment water quality monitoring in Diamond Lake and downstream waters to document effects on water quality. The final FEIS includes an implementation strategy to restore the water quality of the lake and thus the beneficial uses. The FEIS and ROD conclusions seek very similar management actions to those noted in this TMDL. The successful eradication and suppression of tui chub populations is necessary to restore lake water quality.

Based on these findings, a secondary load allocation of 0 tui chub and 440,000 trout per year is established. Attainment of these allocations should lead to cyanobacteria populations shown in Figure 6.2, and as a result, water quality standards for dissolved oxygen, pH, and aquatic weeds/algae in Diamond Lake, and pH in Lake Creek, will be attained.

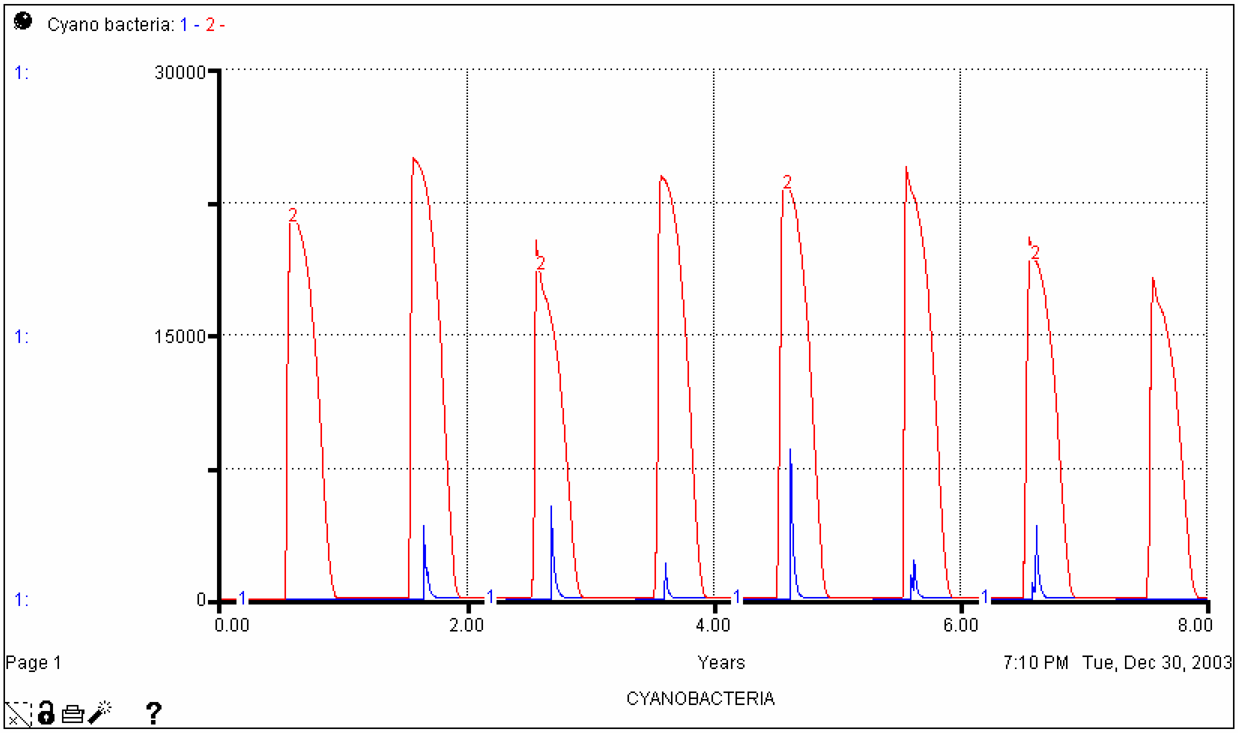

Figure 6.2 FIN-S model output displaying the biomass of cyanobacteria (kg) for the current population of tui chub (red) in Diamond Lake compared to a model simulation with no tui chub (blue).

Margins of Safety

The level of certainty within this TMDL is affected by availability of data and our understanding of the unique biological processes at work within Diamond Lake. While it is difficult to quantify uncertainty, factors leading to uncertainty and the manner in which they have been taken into account are presented throughout the technical report prepared by J.C. Headwaters (Eilers, 2005). Throughout model development, conservative measures were employed, thus leading to an implicit margin of safety.

References

Eilers, J.M., B.J. Eilers, and Jake Kann December 2003 and modified December 2005. TMDL Modeling and Analysis of Diamond Lake, Oregon. Prepared for the Oregon Department of Environmental Quality. 92 pp.

Eilers, J.M. November 6, 2005 e-mail to Paul Heberling of Department of Environmental Quality

USDA Umpqua National Forest November 2004. Diamond Lake Restoration Project Final Environmental Impact Statement 580 pp. plus appendixes

USDA Umpqua National Forest December 2004. Record of Decision Diamond Lake Restoration Project. 31 pp.