WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

Cottage Lake
Total Phosphorus
Total Maximum Daily Load Analysis

Submittal Report

June 2004
Publication Number 03-10-085

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Water Quality Program

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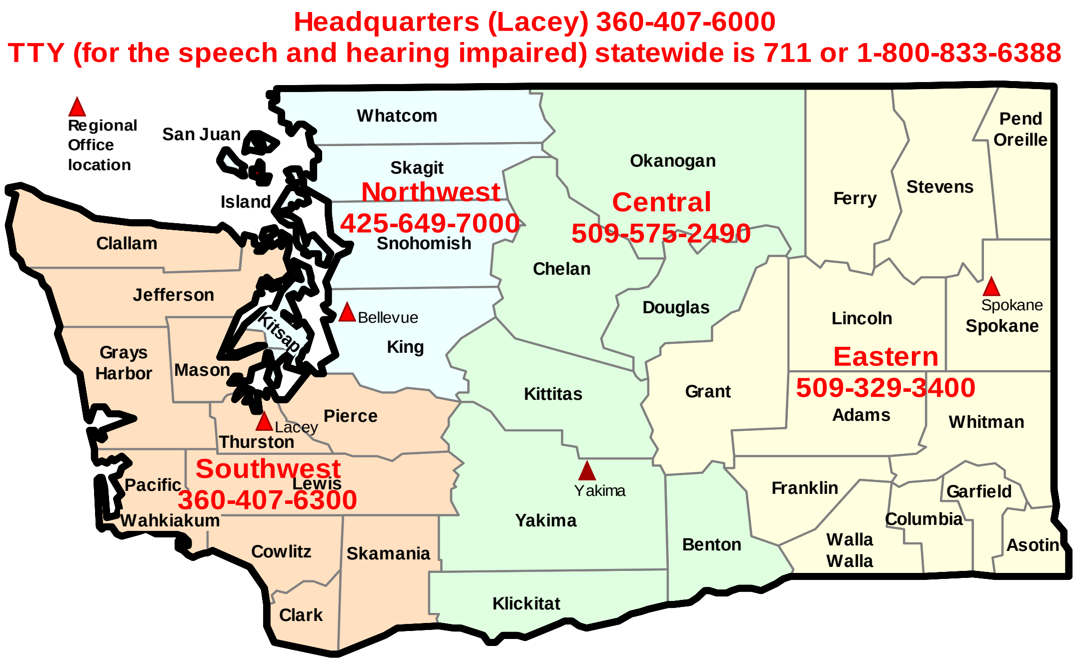

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Executive Summary

Elevated total phosphorus (TP) concentrations observed in Cottage Lake, located in King County, resulted in its inclusion on Washington State's 1996 and 1998 303(d) lists. Section 303, part d of the Clean Water Act requires that states compile a list of waters that are not achieving water quality standards. Once a water body is included on the list, a total maximum daily load (TMDL) study is required to address the water quality problem. The primary objectives of the TMDL study are to examine pollutant sources and determine the reductions (allocations) necessary to achieve the water quality standard.

For a number of years Cottage Lake has experienced chronically elevated phosphorus concentrations that have led to increased growth of algae (blooms) during the summer months. Excessive algae growth reduces water clarity, increases oxygen demand in the bottom sediments severely impacting coldwater aquatic habitat, and can, depending on the dominant algae present, pose a human health risk. These conditions have undermined the beneficial uses of the lake for activities such as fishing and swimming while importantly reduced Cottage Lake's overall aesthetic value and biological health.

Surface and ground water inflow associated with non-point pollution sources such as residential and commercial development and maintenance and animal husbandry are a few of the pathways present in the Cottage Lake drainage area that contribute phosphorus either directly to the lake or to inflowing surface waters ultimately resulting in the increase of the lake's productivity.

This TMDL analysis set a 20 microgram per liter (ug/L) TP target concentration for Cottage Lake. The target concentration is the maximum level expected, on average, within the upper water column during the summer period, June through August. The reason for a summer period target is that summer is when Cottage Lake receives the greatest recreational use coincident with high rates of algae growth. The target concentration applies to the epilimnion portion of the water column because this is the section of the lake where both recreational use is concentrated and peak algae growth occurs.

To meet the target TP concentration, reductions in phosphorus sources will be necessary. The TMDL analysis examined internal and external sources of phosphorus to Cottage Lake. The principal external source is the main surface water inflow, Daniels Creek, while phosphorus release from lake sediments is the primary internal source. Other sources of lesser influence on summer TP concentrations, though examined through this analysis, include Cottage Creek, nearshore surface and groundwater inflow. Modeling analysis determined that a 50 percent reduction in TP loading from all sources would be necessary to achieve a summer mean TP concentration of 20 ug/L.

Introduction

Overview of the Total Maximum Daily Load Study Process

The federal Clean Water Act (CWA) requires each state to establish water quality standards to protect, restore, and preserve water quality. These standards have been set to protect designated uses such as drinking water supplies or cold water habitat critical to the survival of certain organisms. Criteria, usually numeric, are used as a gauge to achieve those uses. When a lake, river, or stream fails to meet water quality standards after application of technology-based pollution controls, Section 303(d) of the CWA requires that states include it on a list of impaired water bodies and prepare an analysis called a **Total Maximum Daily Load** (TMDL). The United States Environmental Protection Agency (EPA) has established regulations (40 CFR 130) and developed guidance for establishing water clean up plans (EPA, 1991).

Through the TMDL process, a **loading capacity,** or the maximum amount of a given pollutant that can be discharged to a water body while still meeting water quality standards, is determined. That load capacity is allocated among the various sources responsible for the pollution problem. If the pollutant originates from a discrete source (point source) such as an industrial facility's discharge pipe, that facility's share of the loading capacity is called a **wasteload allocation**. If the pollutant originates from a diffuse source (nonpoint source) such as runoff from an agricultural operation, that facility's share is called a **load allocation**.

The TMDL analysis must also consider **seasonal variation** in pollutant concentrations and include a **margin of safety** that takes into account uncertainty about the causes of the water quality problem or a water body's specific loading capacity.

Cottage Lake's Inclusion on the 303(d) List

Cottage Lake, located in King County near the city of Woodinville, appears on Washington State Department of Ecology's 1996 and 1998 303(d) lists for total phosphorus (TP). (Total phosphorus is the concentration of phosphorus present in both organic and inorganic forms within the water column.) Cottage Lake (WA-08-9070 & 49ITVC) has also been included in the latest, though as yet unapproved, 2002/04, 303(d) list for TP as a Category 5 listing. Category 5 listings require that a TMDL study be conducted on the water body.

For a number of years, Cottage Lake has experienced chronically elevated phosphorus concentrations that have led to elevated algae levels (blooms) and associated depressed dissolved oxygen concentrations during the summer months. These conditions have undermined the beneficial uses of the lake for activities such as fishing and swimming while importantly reducing the lake's overall aesthetic value and biological health.

To address community concerns regarding the impaired use of Cottage Lake due to poor water quality, King County conducted a study of the lake in 1993. Major study objectives included the identification of the principal sources of TP to the lake and to determine appropriate source control methods. From April 1993 to March 1994, physical, chemical, and biological parameters were measured in the lake and its principal inflow sources. This analysis resulted in the Cottage Lake management plan (KCM, 1996). The Washington State Department of Ecology used the data collected during the management plan study and its principal findings, as the basis for including Cottage Lake on the 303(d) list. Because the data collection was extensive (having measured TP concentrations of the inflows, outflows, and within the lake on a regular basis during the study period) and relatively recent, the information contained within the management plan document provides the base from which this TMDL analysis and modeling was conducted.

Watershed Characteristics

The Cottage Lake drainage area is located in northeast King County and south Snohomish County approximately four miles east of the city of Woodinville (Figure 1). Its drainage area is situated within the upper Bear Creek basin, a tributary of the Sammamish River.

Cottage Lake has an approximately 17 square kilometer drainage area and receives surface water inflow from Daniels and Cottage Creeks (Figure 1). The Daniels Creek drainage area comprises 74 percent or 13 square kilometers of Cottage Lake's drainage area while Cottage Creek represents approximately 20 percent of the total area. The remainder to the drainage area (6 percent) is represented by land surfaces that drain directly to the lake.

An important feature of the Daniels Creek drainage is Crystal Lake and its associated wetlands. The Crystal Lake watershed comprises approximately 8 square kilometers or 47 percent of the entire Daniels Creek watershed. With the majority of Daniels Creek's watershed draining to this wetland system, Crystal Lake creates a divide in the hydraulics and, therefore, the water quality of this drainage.

The water surface elevation of Crystal Lake is maintained by a low-head earthen dam (three to five feet in height) constructed in 1931. A water right certificate (water right 3778, R1-*03116CWRIS) allowed for the storage of 2,500 acre-feet to increase habitat for fishing and hunting. The dam and associated water storage resulted in greatly expanding the original size of Crystal Lake.

There is no provision for maintaining the flows of Daniels Creek through the release of water from Crystal Lake during the summer months. It is not unusual that only minimal discharge from the dam structure occurs, resulting in only minor inflow to Cottage Lake during summer months. However, in the fall, sufficient discharge occurs allowing for its use as spawning and rearing habitat by coho (*Oncorhynchus kisutch*) salmon. For this reason, King County recognizes this section of Daniels Creek as a locally significant resource area (King County, 1989).

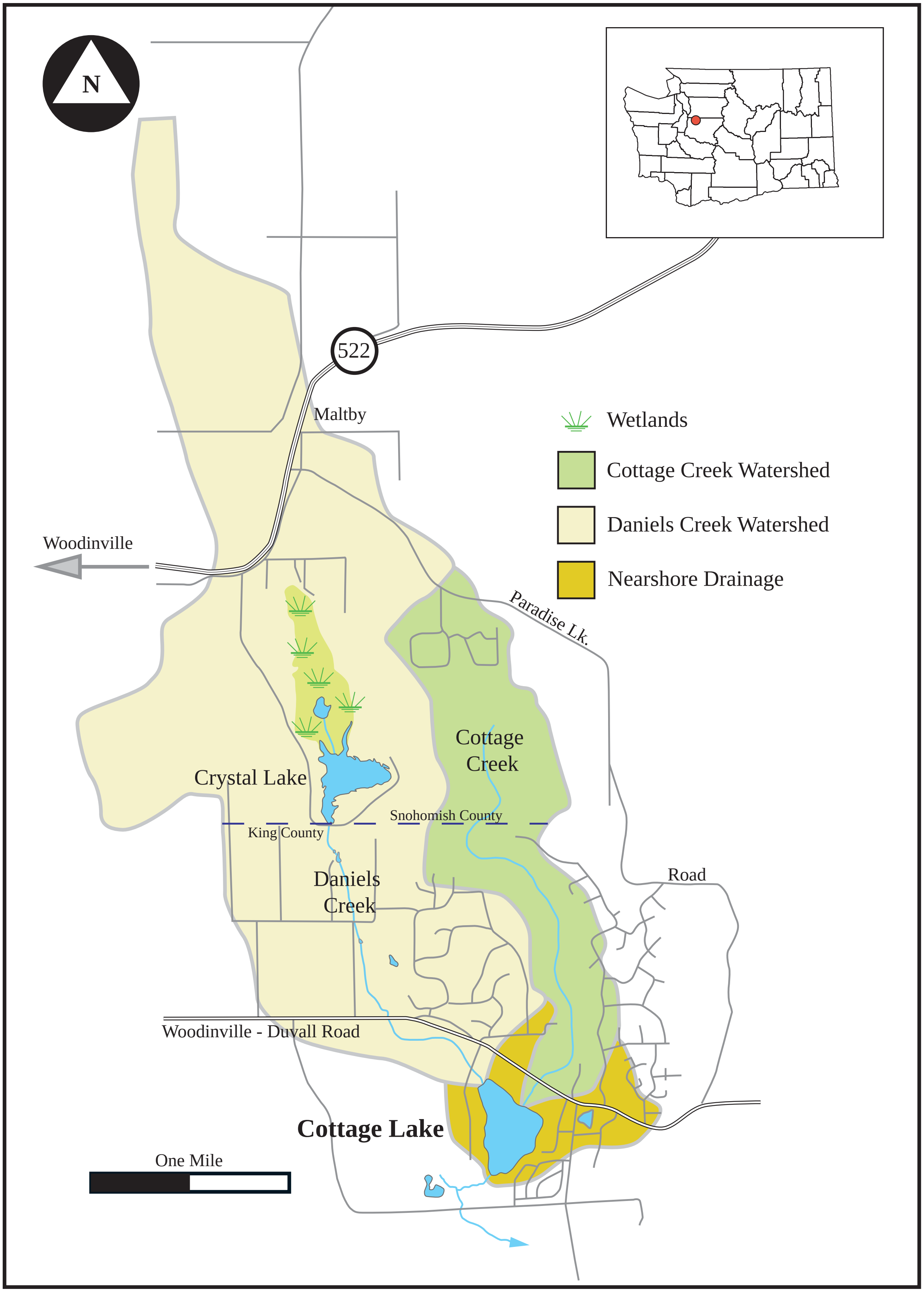

Figure 1. The Cottage Lake drainage area near Woodinville, Washington.

Lake Physical Characteristics

Cottage Lake has a surface area of 26 hectares (Table 1, Figure 2). The mean depth of the lake is approximately 4.6 meters with a maximum depth of 7.6 meters (Bortleson, 1976).

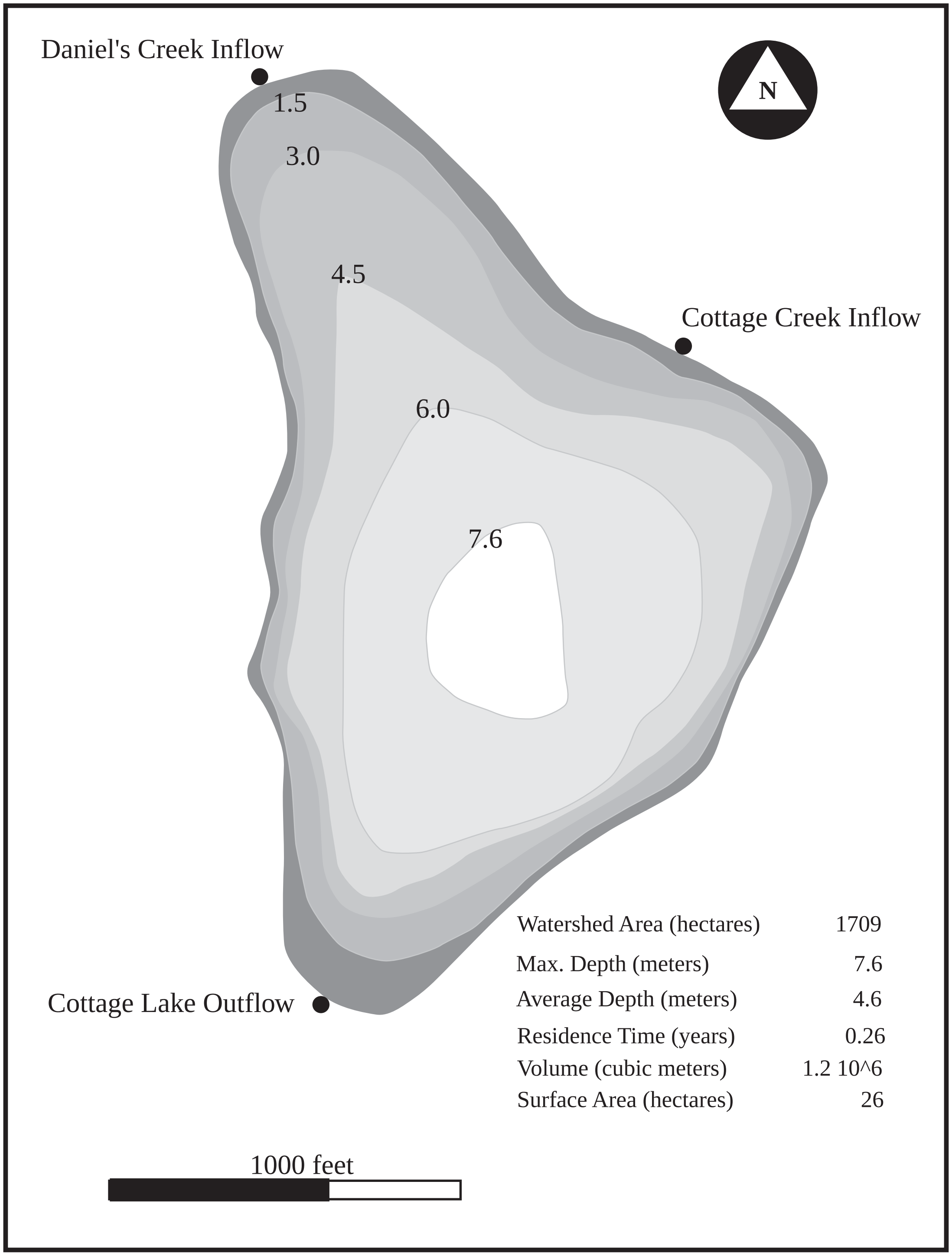

Figure 2. The bathymetry of Cottage Lake (depth contours in meters).

Table 1. Cottage Lake physical characteristics.

Surface Area (hectares)	25.5
Mean Depth (meters)	4.6
Maximum Depth (meters)	7.6
Lake Volume (cubic meters)	1,200,000
Epilimnion Volume (cubic meters)	685333 (surface to 2.5 meter depth)

Water Quality Characteristics

Cottage Lake is monomictic meaning the whole lake circulates freely from late-fall through early-spring but stratifies (or separates into distinct layers) with differing circulation patterns during the spring and summer months, the result of solar heating. Stratification has a major effect on the water quality of Cottage Lake, in particular the movement of phosphorus in the lake. Because internal sources are an important component in the supply of phosphorus to the lake's water column, an understanding of these processes is important. For this reason, a discussion of stratification and how it affects Cottage Lake's water quality is presented below. In addition, this information provides a foundation for understanding the phosphorus transport mechanisms used in the model that will be described later in this report.

Water Temperature

Each spring, typically in early April, the water column of Cottage Lake begins to stratify or separate into distinct volumes based on differing rates of heating. The density of water, or its weight per volume, is temperature dependent with density increasing as temperatures decrease (within the temperature range observed during the summer period). For this reason, surface warming, the result of absorption of solar radiation, leads to the formation of a density gradient within the lake.

From the surface to approximately 2.5 meters, depth (the upper water column) is known as the epilimnon. During the stratified period, this layer of the lake is uniform in temperature (isothermal) and circulates freely (Figure 3). Water temperatures within the epilimnion display greater variation than found at lower depths due to heating and cooling processes, influences that the lower depths are largely buffered from.

At depths below the epilimnion, water temperatures decline rapidly. The section of the water column that has the greatest change in temperature with depth, extending from approximately 2.5 meters to 4.5 meters, is known as the metalimnion. The coldest water (therefore having the greatest density) is situated below 4.5 meters and is known as the hypolimnion. This volume has little variation in temperature during the summer months changing from approximately 8^{o}C in April to 10^{o}C in October (Figure 3).

During the period the lake is stratified, while the epilimnion freely circulates, the metalimnion and hypolimnion remain relatively stagnant. Depending on meteorological conditions (wind speed, cold fronts, etc.) the epilimnion can mix with the upper metalimnion, though this occurs infrequently. With limited mixing, the gain in heat to the metalimnion and hypolimnion is due primarily through convection or the passage of heat from the epilimnion. Because of this heating process, the water temperatures of the metalimnion and hypolimnion display little variation in heating and cooling during stratification. Rather, they display a steady though gradual increase in temperature. The passage of heat from the epilimnion to the metaliminion and hypolimnion occurs through convection. For this reason, water temperatures of the epilimnion peak in mid-August, while temperatures observed in the metalimnion and hypolimnion are at their maximum just prior to lake turn-over in November.

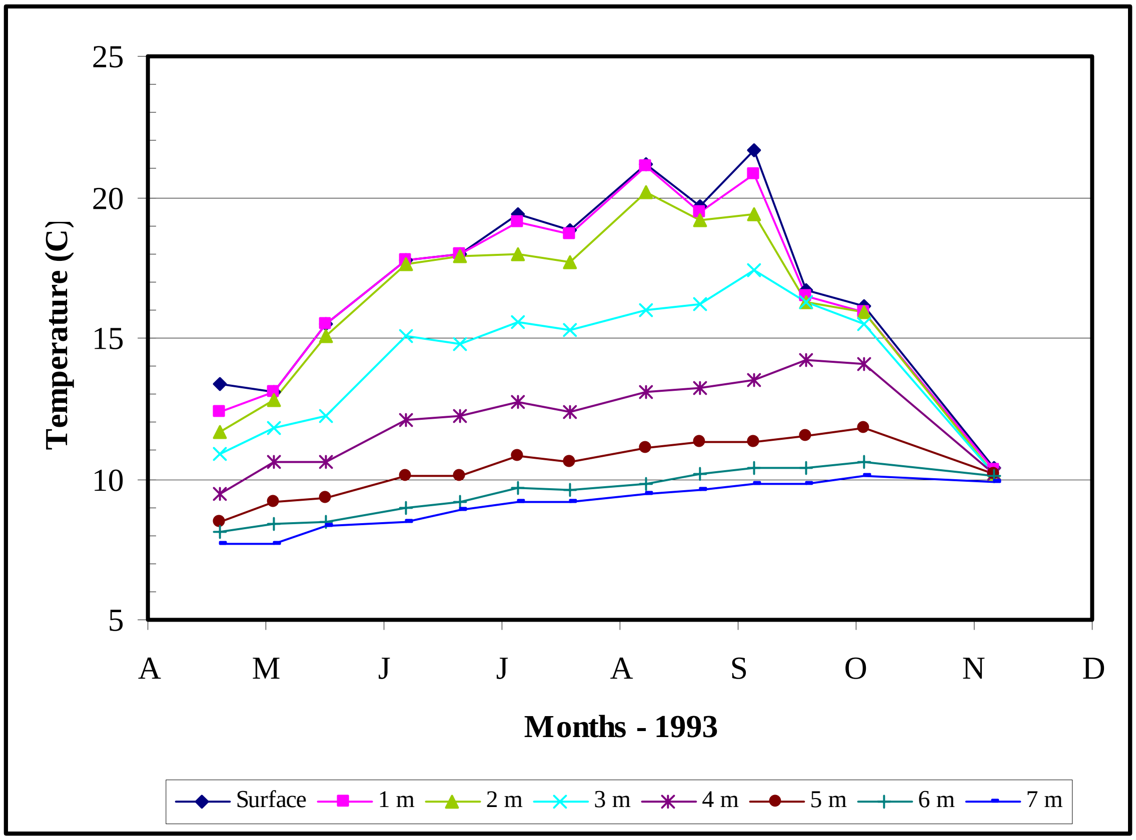

Figure 3. Temperature levels (C) observed by depth during the study period.

Dissolved Oxygen

Following the onset of stratification in spring and the relative isolation of the hypolimnion within the water column, biological decomposition of organic matter present in the bottom sediments of Cottage Lake rapidly assimilates all available oxygen (Figure 4). Without a source for oxygen, the hypolimnion (below 4.5 meters) remains anaerobic for the majority of the period between May and October. In 1993, anaerobic conditions extended from the bottom up to a depth of 3 meters for much of the summer encompassing approximately 46 percent of the volume of the lake. This level of oxygen demand is indicative of a highly productive lake system with elevated sediment organic content.

Within the upper sediment layers, when dissolved oxygen concentrations of overlying water are above approximately 2 milligrams per liter (mg/L), phosphorus is typically bound to iron in its ferric state (Fe^{+3}). However, with further decreases in dissolved oxygen levels, iron is reduced from ferric to ferrous (Fe^{+2}) iron and, in the process, phosphorus becomes soluble within the sediments. Once soluble, phosphorus then diffuses into the overlying water column.

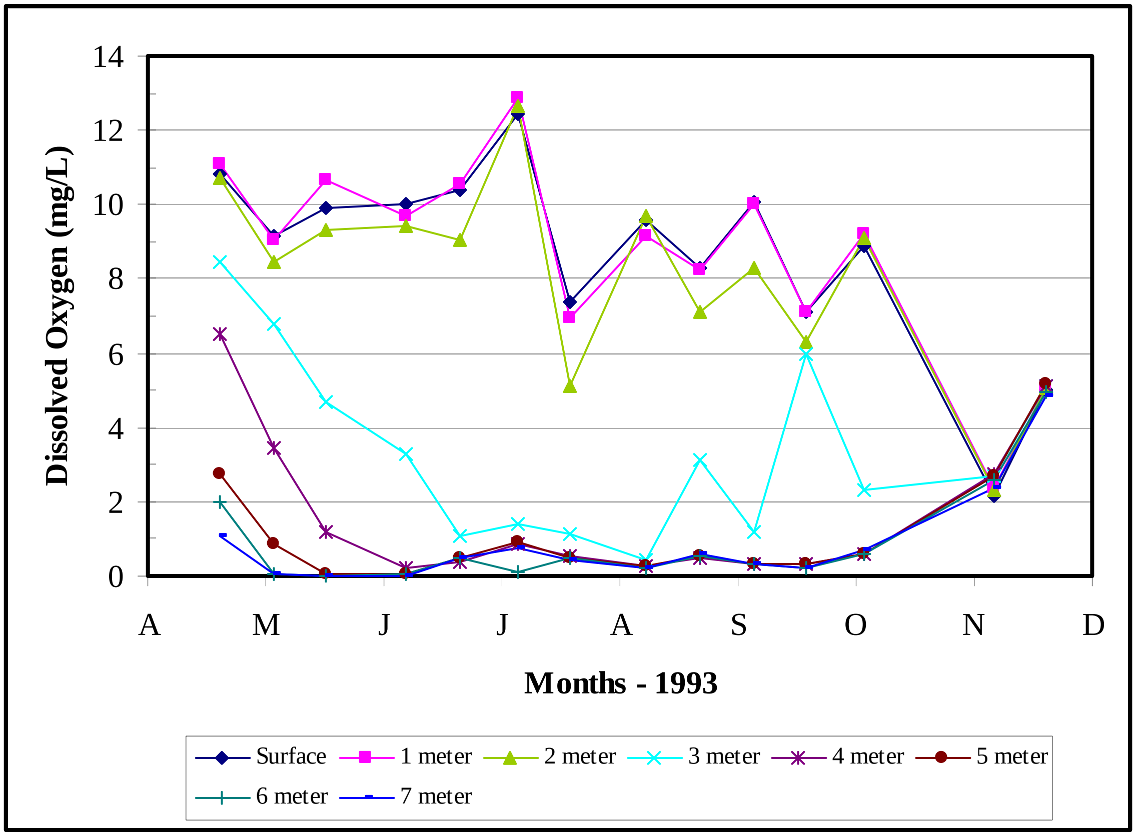

Figure 4. Dissolved oxygen concentrations (mg/L) observed by depth during the study period.

Hypolimnetic Total Phosphorus

Following stratification and the onset of anoxic conditions in the hypolimnion, phosphorus is released into the water column from the sediments. With the in-lake source being the sediments, phosphorus concentrations are greatest at the sediment-water interface. The rate that phosphorus is released from sediments can be significant, particularly in productive lakes with highly organic sediments such as those found in Cottage Lake. For this reason, hypolimnetic TP concentrations, represented by the 6 and 7 meter depths, increase linearly during the stratification period (Figure 5, note log scale).

Concentrations begin to decrease in late summer when the epilimnion begins to cool resulting in deeper mixing into the water column, diluting hypolimnetic TP concentrations. When this occurs, the higher phosphorus concentrations of the hypolimnion are assimilated into the expanding (sinking) epilimnion through entrainment. Peak water column phosphorus concentrations occur at the time when complete water column mixing occurs, typically by late-October, early-November as occurred in 1993.

Another process that supplies phosphorus to the epilimnion during the stratification period is diffusion. With sediments releasing phosphorus into the water column, concentrations within the hypolimnion are approximately 20 times greater than observed in the epilimnion (Figure 5). With this large concentration gradient present, phosphorus migrates through diffusion to the upper water column though at a lower rate than occurs by entrainment (fall turnover).

However, depending on the meteorological conditions (for instance, a strong low pressure system and associated winds, cold air and precipitation), mixing between the epilimnion and metalimnion can occur even during a period of strong stratification. Cottage Lake is most susceptible to the introduction of TP from the metalimnion to the epilimnion when stratification is weakest, in early spring or late fall; but it can occur, depending on the disturbance level, at any time.

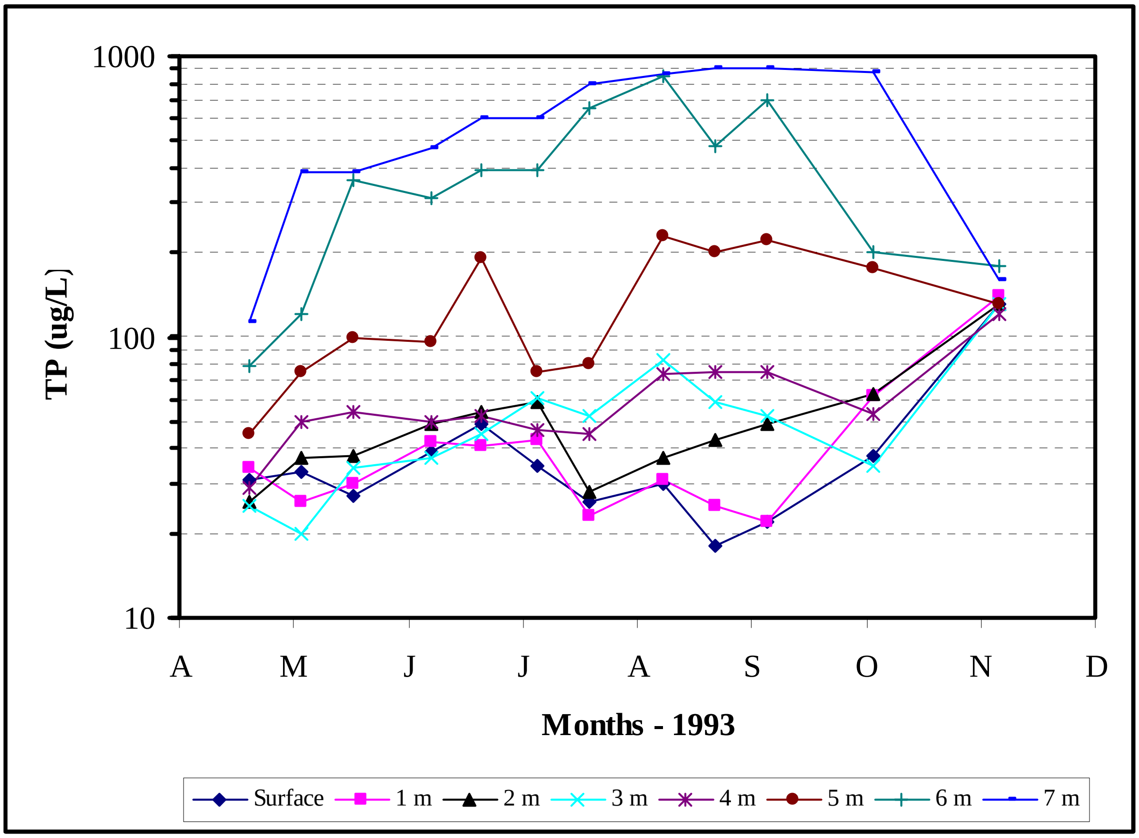

Figure 5. TP concentrations (ug/L) observed by depth (meters) during the study period (note log scale).

Hydrology

Surface water enters Cottage Lake via Daniels Creek, Cottage Creek, overland flow, direct precipitation, and ground water seepage. During the study period (April 1993 to March 1994), Daniels Creek provided approximately 73 percent of the surface water inflow to Cottage Lake with Cottage Creek the next largest source at 17 percent. This annual percent representation of the inflow remained consistent during the critical summer period (June to September) during the study. Additional sources of inflow include precipitation (4 percent) and near-shore surface water and groundwater inflow (6 percent).

During the study period, the average flow levels for Daniels and Cottage Creeks were 5.8 cubic feet per second (cfs) and 1.5 cfs, respectively. Average 1993 summer period (June through August) flows were 2.2 cfs and 0.6 cfs, respectively. However, because the spring and early summer of 1993 was an exceptional period for surface water runoff, these flow levels are not representative of average conditions. Average flow levels recorded at a nearby United States Geological Survey (USGS) station (Bear Creek near Redmond, WA, gauge no. 12122500) during the months of June and July 1993 were the highest recorded over its 23-year period of record (1945-49, 1979-96). The average August flow level was at the 90^{th} percentile, indicating that only approximately two years for the period of record have been greater. As mentioned previously, the flow in Daniels Creek is regulated by a low head dam located at the outlet of Crystal Lake and it is not unusual that during dryer years the summer period flows entering Cottage Lake are negligible.

The majority of the outflow from the lake (97 percent) occurs through surface water discharge to Cottage Lake Creek on the lake’s southern most point. The management plan study found ground water to be an insignificant component of the lake’s total outflow. The only other source of water loss from the lake is through evaporation, which represents approximately three percent of the total outflow occurring primarily during the summer months.

Land Use / Zoning

Cottage Lake receives drainage from areas within both Snohomish and King Counties (refer to figure 1) with the county border situated just south of the Crystal Lake outlet. A small area within the watershed, located at its western boundary, lies within the newly incorporated city of Woodinville.

Within King and Snohomish Counties, the current zoning for the Cottage Lake watershed is primarily designated low density residential development set at a level of one house per five acres. Commercial development is primarily located along the Woodinville-Duvall Road, in King County and Highway 522, in Snohomish County.

Table 2 presents the area (hectares) within the watershed represented by general land use types. Current land use within the watershed was determined by Arc-View analysis using two grids, a land use grid (25 m resolution) created for the Puget Sound Regional Council based on 1992 data, and a University of Washington Urban Design and Planning land use grid (29 m resolution) based on 1998 data. Future land use, assuming a build-out condition, was determined based on current zoning designations for both King and Snohomish Counties.

As observed from Table 2, primary changes in land use within the Cottage Lake watershed will be associated with losses in forestry and agricultural land use and increased low density residential development. Under the build-out condition, low density development will increase approximately 268 percent. The primary residential zoning throughout the watershed will remain one house per five acres. Future commercial development will continue to be restricted to lands adjoining the major highways and is expected to increase by 27 percent. It is assumed that wetlands within the Daniels Creek sub-drainage will remain undeveloped.

Table 2. Current and future land use within the Cottage Lake watershed.

Land Use Type	Area (hectares) Current (1/2)*	Area (hectares) Future
Low Density Residential	388	1429
High Density Residential / Commercial	105	133
Forest	987	0
Agricultural	89	0
Wetland	65	49
Open Water	46	50

* 1. Puget Sound Regional Council – Puget Sound Land Cover Inventory
2. University of Washington, Urban Design and Planning – Puget Sound Land Use / Land Cover 1998

Fisheries Resources

The Bear Creek sub-basin, within which Cottage Lake is located, represents the most important salmonid bearing system in the Sammamish River geographic area (Kerwin, 2001). Salmonids observed utilizing Cottage Lake, its upper tributaries, and outflow channel (Cottage Lake Creek) as spawning and rearing habitat include: Chinook, coho, sockeye, kokanee, steelhead, rainbow, and coastal cutthroat. In 1999, the National Marine Fisheries Service listed Puget Sound Chinook as threatened under the Endangered Species Act. Chinook within the Cottage Lake drainage are Puget Sound stocks and, therefore, fall under this designation. In fact, Cottage Lake Creek downstream of the lake is known as a primary Chinook spawning area.

Applicable Criteria

Water quality standards in Washington State are published pursuant to Chapter 90.48 of the Revised Code of Washington (RCW). Authority to adopt rules, regulations, and standards as necessary to protect the environment is vested with the Department of Ecology. Under the federal Clean Water Act, the EPA Regional Administrator must approve the water quality standards adopted by the state (Section 303(c)(3)). Through adoption of water quality standards, Washington designated certain characteristic uses to be protected and the criteria necessary to protect those uses [Washington Administrative Code (WAC), Chapter 173-201A). (For additional information on Washington State's water quality standards, refer to http://www.ecy.wa.gov/programs/wq/swqs/index.html.)

This TMDL addresses impairment of Cottage Lake's characteristic uses and aesthetic qualities caused by the nutrient phosphorus. Elevated phosphorus levels in lake systems can result in the onset of eutrophication, which is typically characterized by excessive algae growth within the upper water column. Eutrophic conditions in lakes ultimately lead to severe habitat impairment affecting the majority of aquatic organisms originally present under less adverse conditions while also leading to the loss of characteristic uses of the lake for activities such as swimming, fishing, and boating. Washington State laws relevant to the protection of water quality in Cottage Lake include:

Protection of Characteristic uses [WAC 173-201A-030(5)] Lake Class
Characteristic uses shall include, but not be limited to, the following:
1) Water supply (domestic, industrial, agricultural).
2) Stock watering.
3)***** Fish and shellfish:
- Salmonid migration, rearing, spawning, and harvesting.
- Other fish migration, rearing, spawning, and harvesting.
- Clam and mussel rearing, spawning, and harvesting.
- Crayfish rearing, spawning, and harvesting.

4)***** Wildlife habitat.
5)***** Recreation (primary contact recreation, sport fishing, boating, and esthetic enjoyment).
6) Commerce and navigation.

*** Characteristic uses applicable to Cottage Lake**

Target Total Phosphorus Concentration

One of the primary goals of this TMDL analysis is to establish a load capacity or the maximum amount of phosphorus that can be introduced to Cottage Lake from all identified sources while remaining at or below a target concentration. The target concentration provides the foundation from which the load capacity and wasteload (pollutant source) allocations are determined. However, there are not specific water quality standards that apply to TP for lakes in Washington. Rather, the Department of Ecology has suggested TP target concentrations based on an eco-regional framework. Table 3 provides an overview of the TP criteria for lakes located within the Pacific Coast range, Puget Sound lowlands, and Northern Rockies eco-regions. Cottage Lake lies within the Puget Sound Lowlands eco-region.

Cottage Lake, during the summer of 1993, had an average summer epilimnetic TP concentration of 41 ug/L, indicative of a mesotrophic-eutrophic level of productivity. For these cases, a lake specific study is recommended in order to establish the target concentration.

Table 3. Washington State's recommended total phosphorus lake criteria for the Pacific Coast range, Puget Sound lowlands and Northern Rockies eco-regions.

Trophic State	Ambient TP Range (ug/L)	TP Criteria
Ultra-Oligotrophic	0 – 4	4 or less
Oligotrophic	>4 – 10	10 or less
Lower Mesotrophic	>10 – 20	20 or less
Mesotrophic – Eutrophic	>20	Lake Specific Study

Chapter 173-201A-030, Section 5(c) recommends the following be established by the lake specific study:

> Section ii – Determine appropriate total phosphorus concentrations or other nutrient criteria to protect characteristic lake uses. If the existing total phosphorus concentration is protective of characteristics uses, then set criteria at the existing total phosphorus concentration. If the existing total phosphorus concentration is not protective of the existing characteristic lake uses, then set criteria at a protective concentration. Proposals to adopt appropriate total phosphorus criteria to protect characteristic uses must be developed by considering technical information and stakeholder input as part of a public involvement process equivalent to the Administrative Procedure Act (Chapter 34.05 RCW).
>
> Section iii – Determine if the proposed total phosphorus criteria necessary to protect characteristic uses is achievable. If the recommended criterion is not achievable and if the characteristic use the criterion is intended to protect is not an existing use, then a higher criterion may be proposed in conformance with 40 CFR part 131.10.

This TMDL analysis uses the information contained within the Cottage Lake management plan as the lake specific study. The results of that work indicated that a shift in the trophic status from eutrophic to mesotrophic will result in the achievement of the lake's beneficial uses. A lower in-lake total phosphorus concentration (the result of source control) will shift the environmental conditions which currently favor excessive algae growth, the major factor sited as impairing characteristic uses of the lake.

A target TP concentration establishes a maximum level that should be observed, on average, within the epilimnion (0 to 2.5 meter depths) during the summer period (June through August), while remaining protective of the lake's characteristic uses. The reason for a summer period target is that summer is when Cottage Lake receives the greatest recreational use coincident with high rates of algae growth. The target concentration applies to the epilimnion portion of the water column because this is the section of the lake where both recreational use is concentrated and peak algae growth occurs.

To achieve this trophic shift, a target summer period (June through August) total phosphorus concentration for the epilimnion of Cottage Lake is set at 20 micrograms per liter (ug/L).

Target Summer Period Total Phosphorus Concentration

- 20 micrograms per liter (ug/L)

In lake systems, among the most evident effects to water quality from the elevated introduction of phosphorus is increased growth of algae during the summer months. Excessive algae growth reduces water clarity, results in chronic increased oxygen demand in the bottom sediments severely impacting coldwater aquatic habitat, and can, depending on the dominant algae present, pose a human health risk.

A gauge on significant water quality improvements and the achievement of beneficial uses can be indicated by the Trophic State Index (TSI) (Carlson, 1977). The TSI uses the level of three parameters including total phosphorus, Secchi depth, and chlorophyll(a) to evaluate the trophic state, or productivity, of a lake. Ranges in the values for these parameters, (typically applying for the summer months) as they relate to the trophic state, are provided in Table 4.

Table 4. The range in TSI parameters as they relate to lake trophic status.

Trophic State	Secchi Depth (m)	Chl(a) (ug/L)	TP (ug/L)	TSI
Oligotrophic	> 4	< 3	< 14	< 40
Mesotrophic	2 – 4	3 – 9	14 – 25	40 – 50
Eutrophic	< 2	> 9	> 25	> 50

For Cottage Lake, average values of Secchi depth, chlorophyll (a), and total phosphorus for the period June through August of 1993 were 1.7 meters, 34 ug/L, and 41 ug/L, respectively. The average TSI for Cottage Lake in 1993 was 58, a level indicative of an eutrophic state. In order to affect a shift to a lower trophic level, reductions in TP and chlorophyll (a) concentrations are necessary.

Figures 6 and 7 provide box plots depicting the relationship between total phosphorus, chlorophyll (a), and Secchi depth observed in Cottage Lake's upper 2 meters based on study data along with additional data collected by King County between 1995 and 2002. (In interpreting the box plots, the top and bottom of the vertical lines represent the maximum and minimum from the data set while the top and bottom of the box depict the 75^{th} and 25^{th} percentile of the data, respectively.) As observed from Figure 6, the average 1993 summer period epilimnetic TP concentration of 41 ug/L is within a range (41 to 45 ug/L) that serves as an inflection point where small increases in the TP concentration result in large increases the chlorophyll (a) concentration.

Based on these figures, with the achievement of the target TP concentration of 20 ug/L, a chlorophyll (a) concentration of between approximately 10 and 4 ug/L can be expected (represented by the 75^{th} and 25^{th} percentiles of the 16 to 20 ug/L range of TP) resulting in a Secchi depth of between 2 to 3 meters. The trophic state index, based on these parameter values, will bring Cottage Lake from its 1993 level of 58 (indicative of an eutrophic state) to 48 (indicative of a mesotrophic state).

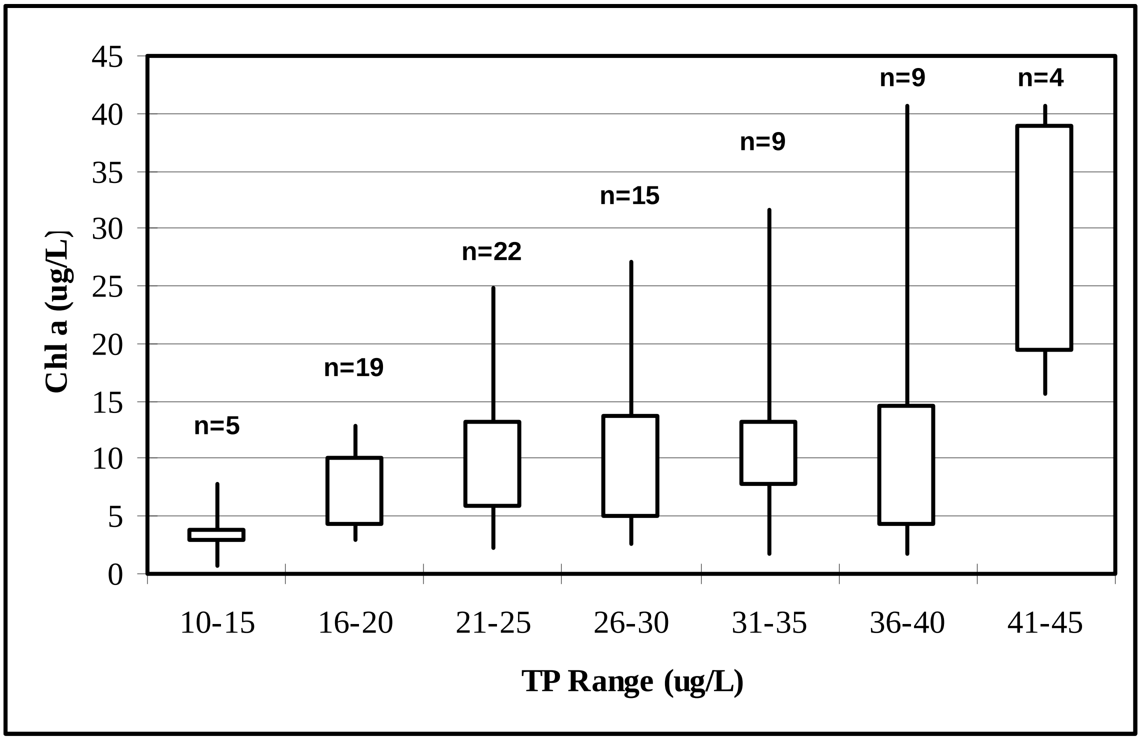

Figure 6. The relationship between TP and chlorophyll (a) observed in Cottage Lake.

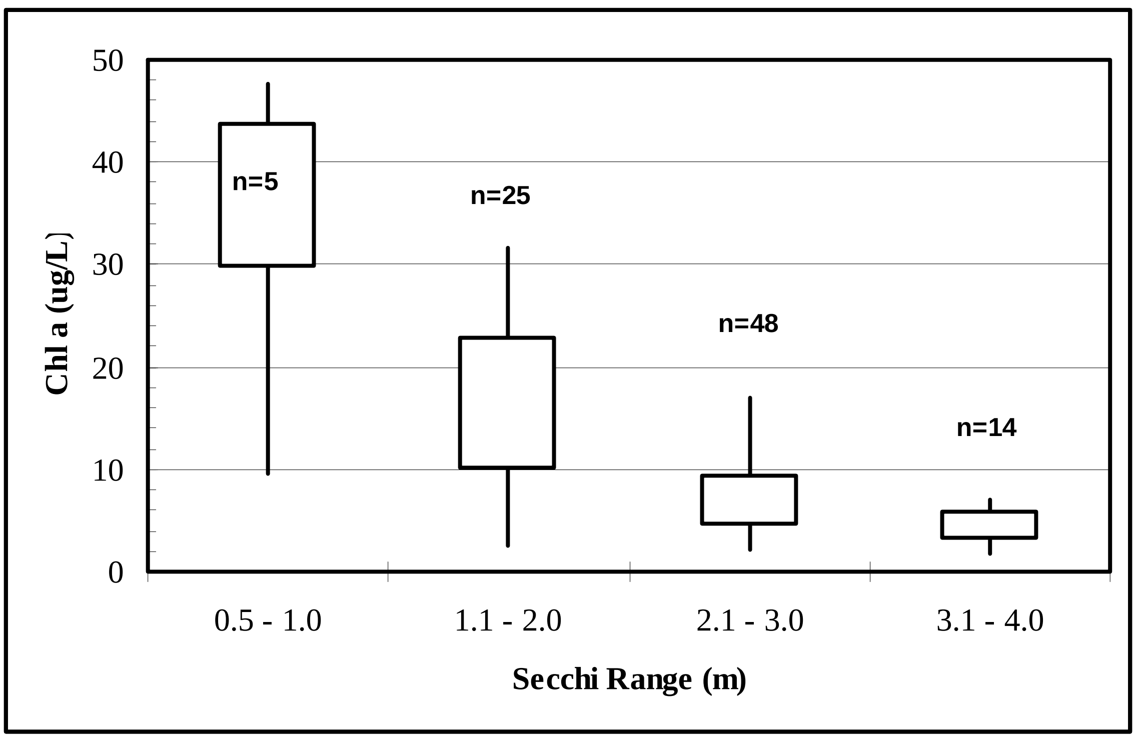

Figure 7. The relationship between Secchi depth and chlorophyll (a) observed in Cottage Lake.

Water Quality and Resource Impairments

Lakes can be characterized by their level of biological productivity, or trophic state. A lake's natural level of productivity is determined by factors such as its geology, watershed size, mean depth, climate, and the quantity and quality of the water entering and leaving the lake. Increases in a lake's productivity over time, known as eutrophication, is a natural process, although for many lakes such as Cottage Lake, this process has been accelerated by human-related activities. Surface and groundwater inflow associated with non-point pollution sources such as residential and commercial development and maintenance and animal husbandry are a few of the pathways present in the Cottage Lake drainage area that contribute phosphorus either directly to the lake or to inflowing surface waters ultimately increasing the lake's productivity.

Cottage Lake is a nutrient-rich lake characterized by frequent and intense algal blooms in the spring and fall that degrade the lake for recreational uses such as swimming, boating, and fishing. The aesthetic appeal normally associated with the lake decreases during the algae bloom periods. Public meeting discussions and written surveys of community residents, as part of the Cottage Lake management plan, indicated that existing water quality and associated primary productivity in Cottage Lake were unacceptable to many people who use the lake for recreation.

Existing water quality in Cottage Lake is classified as eutrophic based on concentrations of total phosphorus, chlorophyll (a), and water transparency (Secchi depth). During the summer of 1993 (June through August), the average total phosphorus concentration within the epilimnion (upper 2.5 meters of the water column) was 41 micro-grams per liter (ug/L), a chlorophyll (a) concentration of 34 ug/L, and a Secchi depth of 1.7 meters. In comparison, lakes in western Washington of similar size and setting (though with lower total phosphorus inflow or loading), typically have average epilimnetic summer period TP concentrations of approximately 20 ug/L, chlorophyll (a) concentrations of 10 ug/L, and Secchi depths of 2 meters.

Seasonal Variation

Both the epilimnion and hypolimnion display seasonal variation in TP concentrations (Figures 8 and 9) with stratification the primary force driving that variation.

During the study period (April 1993 to April 1994) within the upper water column (0 to 4 meters), concentrations ranged between 20 ug/L in the early spring to approximately 130 ug/L at the fall over-turn. Following the onset of stratification, discontinuity in TP concentrations occurs within the upper water column. The greatest change in TP concentrations with depth occurs during July and August. The lowest TP concentrations occur at the surface (0 to 1 meter depth) with gradually increasing concentrations with increasing depth. During peak stratification in August, concentrations at the surface were approximately 30 ug/L while at 3 meters depth, the concentration was 60 ug/L. TP concentrations within the upper water column peaked at the time of the complete lake turn-over in late October at 130 ug/L (this isopleth is not depicted in Figure 8 due to the extreme variation in comparison to prior observations). Following the turnover, and with the lake remaining completely mixed until April, TP concentrations display a gradual and steady decline, the result of decreased internal loading and increased flushing.

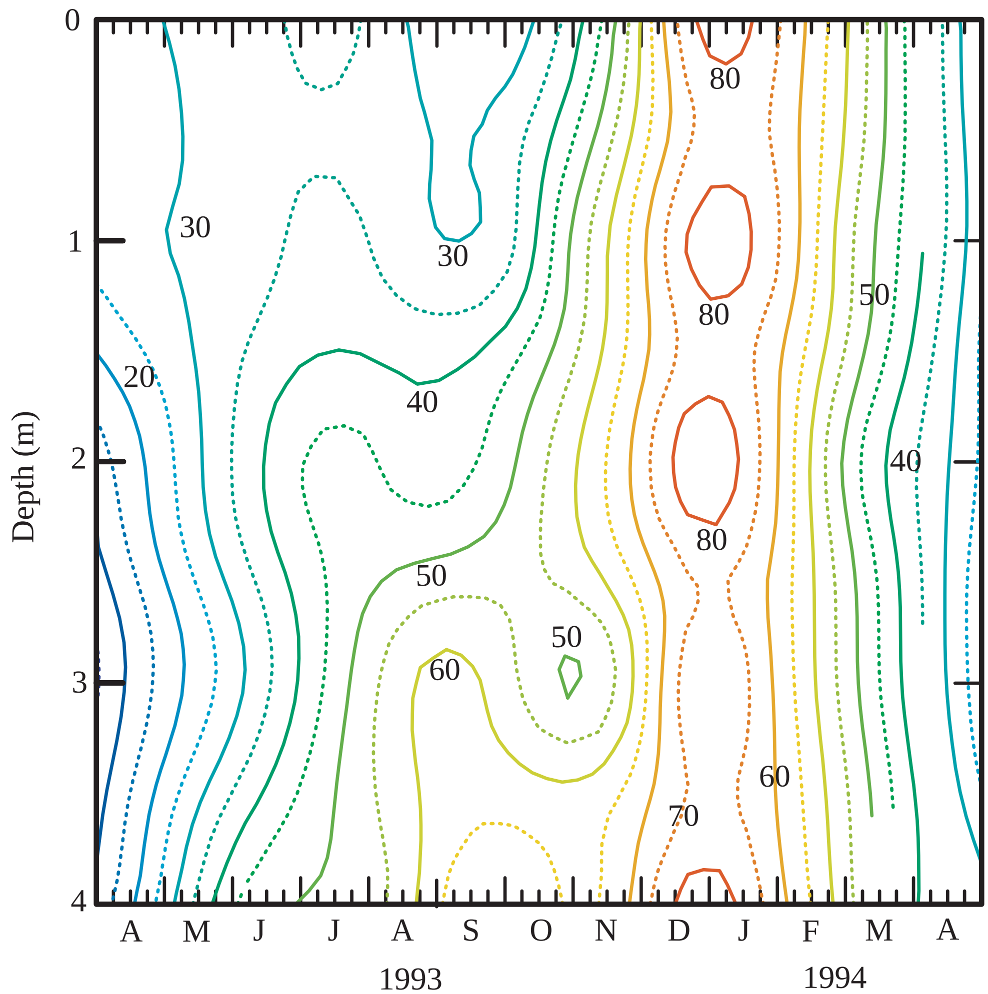

Figure 8. Total phosphorus isopleths (ug/L) through the upper water column of Cottage Lake from April, 1993 through April, 1994.

Within the lower water column (4 meters depth to the bottom), stratification has the dominant influence on TP concentrations. Following stratification, and the initiation of phosphorus release from anaerobic sediments, TP concentrations increase rapidly (Figure 9). TP concentrations were greatest at the sediment water interface, decreasing with shallower depth. At peak stratification, TP concentrations at the lake bottom were approximately 900 ug/L, at 4-meters depth, concentrations decreased to approximately 100 ug/L (Figure 9). During the stratification period, declining concentrations in the lower water column begin with increased mixing with the upper water column in September. With full water column mixing by November, concentrations continue to decline until the onset of stratification the following spring.

While the magnitude of the concentrations vary annually, the seasonal variation and the patterns observed in the upper and lower water column in 1993 are representative of a typical year.

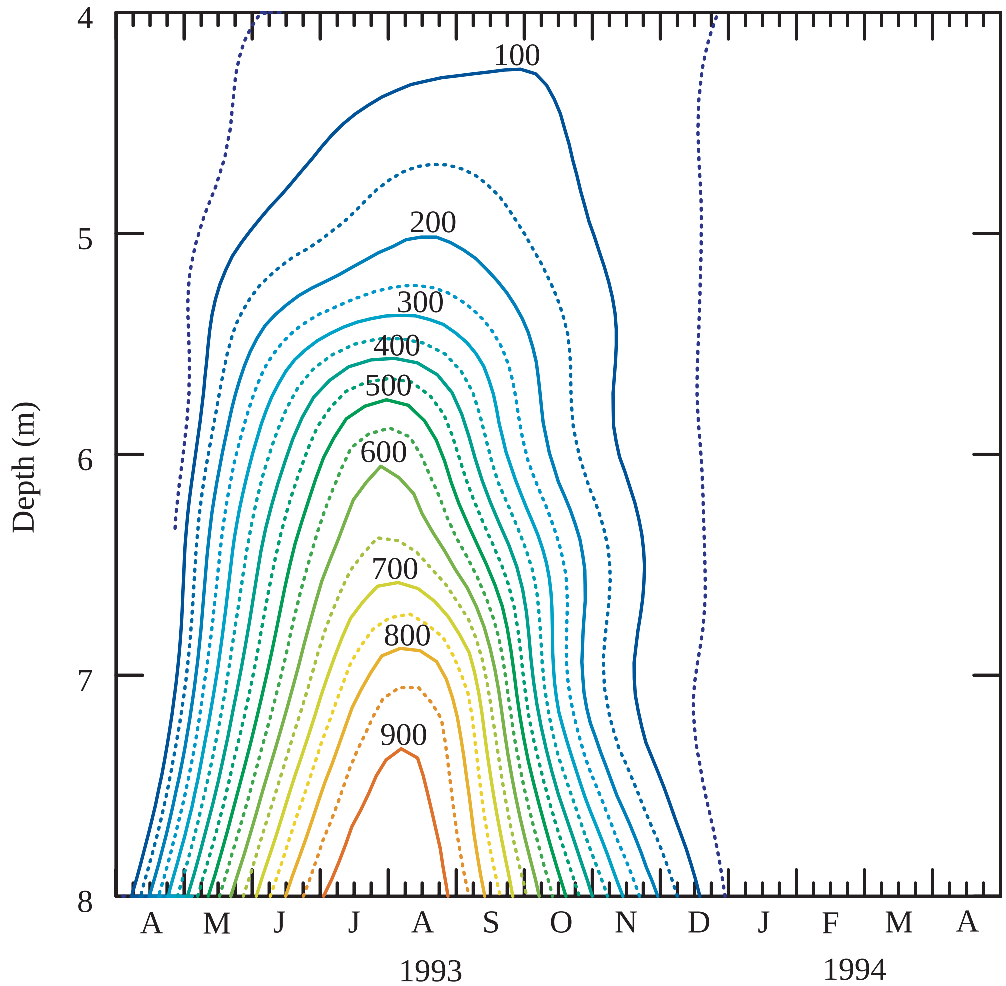

Figure 9. Total phosphorus isopleths (ug/L) through the lower water column of Cottage Lake from April, 1993 through April, 1994.

Technical Analysis

The establishment of Cottage Lake's load capacity and pollutant source allocations, the primary objectives of this TMDL, are based on data collected from May 1993 to April 1994 as part of the management plan study. The study determined TP concentrations in the lake and its principal inflows and outflows. This data served as input to a two-layer, mass-balance TP model. The primary utility of constructing a model is the ability to provide some quantification of the pathways TP is introduced and lost from Cottage Lake. Once the model was constructed, it was used to predict, for instance, how control of a particular phosphorus source affected lake concentrations.

The model, following its calibration, allowed the determination of the load capacity. The load capacity is the maximum amount (in kilograms) of total phosphorus that can be introduced to the epilimnion from June through August, while remaining at or below 20 ug/L, the target concentration. In addition, load allocations (or the portion of the load capacity assigned to specific pollutant sources) were determined. Through this process, a margin of safety was considered so that the load capacity and source allocations were set at a level that ensured that the target concentration is achievable. This section provides an overview of the analysis methods used to make these determinations.

Modeling Methods

Lake Bathymetry

Cottage Lake's bathymetry was determined by the United States Geological Survey (USGS) in 1974 (refer to Figure 2) (Bortleson, 1976). The USGS base map, with 1.5 meter incremental isopleths, was scanned and the area associated with each depth interval determined (Figure 10). The volume associated with each depth strata was then calculated (Wetzel, 1991). Once established, the volume to depth relationship was used to determine the volume associated with specific depth intervals within the lake. From this information, the volume of the epilimnion and hypolimnion was calculated along with the volume-weighted average TP concentrations for each strata, both critical information for the mass-balance model.

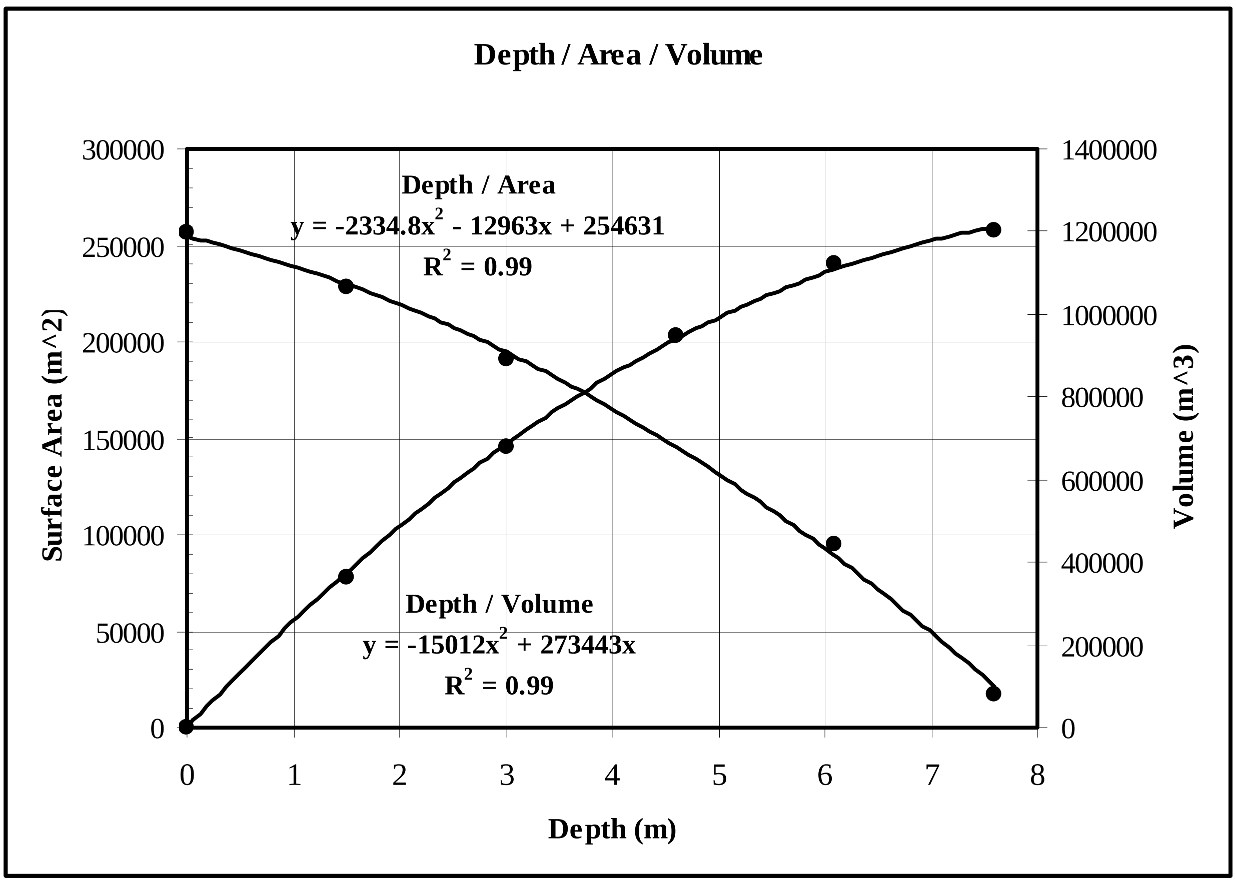

Figure 10. The relationship between depth, area, and volume for Cottage Lake.

Total Phosphorus Model – Terms and Assumptions

A mass-balance TP model was constructed to simulate Cottage Lake's epilimnion and hypolimnion concentrations during the study period (April 1993 – March 1994). The model used a daily time-step; all of the phosphorus inputs and outputs of the prior day determine the following day's lake concentration. Components of the model and its principal assumptions are provided below and depicted in Figure 11.

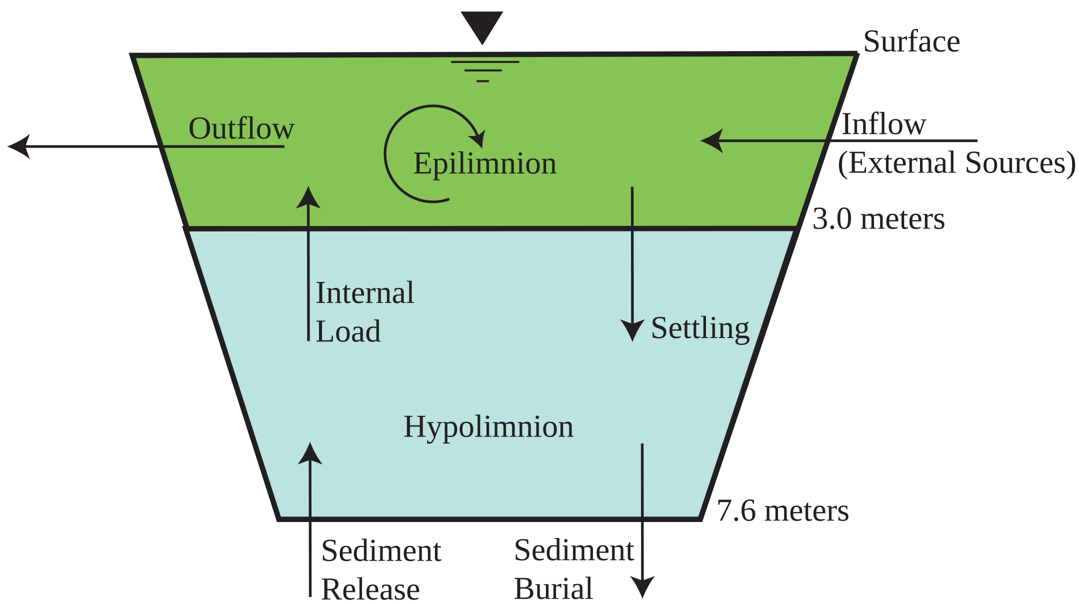

Figure 11. Components of the Cottage Lake total phosphorus mass-balance model.

Water Column Differentiation

During the period the lake was stratified (April through November), the epilimnion was assumed to extend from the surface to a depth of 3 meters. This portion of the water column had relatively uniform water temperatures and dissolved oxygen concentrations during the stratification period indicating complete mixing occurred to that depth. Based on this distinction, the epilimnion contained approximately 685,333 cubic meters (m^3) or 57 percent of the total lake volume.

For model simplicity, the hypolimnion was assumed to extend from 3 meters below the surface to the lake bottom (approximately 7.6 meters depth) containing approximately 515,741 cubic meters, or 43 percent of the total lake volume. In reality, the hypolimnion volume observed during the study period was situated below approximately 4.5 meters. However, the addition of another layer to the model that incorporated the metalimnion added a further level of complexity that extended beyond the data collected during the management plan study. This simplification of the lake does not affect the epilimnion, the zone of greatest interest for this analysis.

While the actual sections of the water column represented by the epilimnion and hypolimnion varied during the stratification period (particularly in the late spring and early fall) for the application of the model, it was assumed that the depths and volumes associated with this division remained constant through much of the analysis period. Beginning around mid-August, as the temperature of the epiliminion cooled and therefore, increased in density, it began to mix to greater depths. The expansion of the epilimnion culminated with the complete mixing of the lake in November. Following November, it remained completely mixed for the rest of the analysis period.

Epilimnion Layer

The epilimnion portion of the mass-balance model is represented by the equation below. The change in epilimnetic TP concentration with time is determined by the balance between the TP added from the lake's external and internal sources minus phosphorus associated with settling and outflow. All of these terms, which are in units of kilograms per day, are divided by the volume represented by the epilimnion (685,333 cubic meters). The resultant was multiplied by a factor of 10^6 to result in units of micrograms per liter per day (ug/L-d). A discussion of each of these terms is provided below.

$$dTP/dt = [(W_e + W_i - W_s - W_o) / (V_e)] * 10^6 \text{ (ug/L-d)}$$

W_e = external load (kg/d)
W_i = internal load (kg/d)
W_s = settling (kg/d)
W_o = outflow (kg/d)
V_e = epilimnion volume (m^3)

External Load (W_e)
The external load comprises the combined TP mass introduced to the lake from Daniels and Cottage Creeks, near shore surface runoff, near shore groundwater inflow, and precipitation. All external phosphorus sources to Cottage Lake were assumed to enter the lake's epilimnion.

Surface Water Inflow - Water samples were collected from Daniels and Cottage Lake Creeks on a monthly to bi-monthly basis and analyzed for TP. These concentrations (in units of micrograms per liter) were multiplied by the flow level observed at the time of sample collection (in units of cubic meters per day). The resultant was divided by a factor of 10^6, resulting in a TP load level (in units of kilograms per day).

Near shore-surface and ground water – Based on median values from the study data set, the near shore runoff was assumed to have a TP concentration of 90 ug/L while ground water was assumed to have a median TP concentration of 80 ug/L.

Precipitation – A concentration of 33 ug/L was the assumed concentration of precipitation for the study period. This concentration is based on the median value of the total number of precipitation samples analyzed for TP during the study period.

Outflow (W_o)
The TP mass lost from Cottage Lake through the outflow was determined in the model by multiplying the measured outflow volume by the model-predicted lake TP concentration.

Settling (W_s)
A variable settling rate was calculated for Cottage Lake: one applying for when the lake was stratified and another for when the lake was completely mixed. For the majority of the stratified period (extending from April through October), a settling rate of 2.7 meters per month was used. From November 1993 through February 1994, when the lake remained completely mixed, a settling rate of 0.4 meters per month was applied. The settling rate was a primary calibration variable.

To determine the mass of TP lost from the epilimnion through settling, the settling rate (meters per day) was multiplied by the settling area (191,155 square meters - depicted by the 3-meter contour in Figure 2) and by the model-predicted TP concentration.

Internal Load (W_i)
The process whereby phosphorus is introduced to the epilimnion from the hypolimnion is known as internal loading. (The source is internal to the lake as opposed to external sources such as Daniels Creek inflow.) Internal loading is modeled using two different transport mechanisms. During the stratified period, the movement is through diffusion or the transport of TP from high concentrations present in the hypolimnion to the lower concentrations present in the epilimnion. The second process, entrainment, occurs in late-summer when the epilimnion begins to cool and mix to greater depths. As the epilimnion expands, it captures, or entrains, waters of higher phosphorus concentration. During the critical summer period, diffusion has the greatest influence on surface phosphorus concentrations.

Similar to the settling term, the internal load is difficult to accurately measure. To calculate the internal load associated with diffusion, a sub-model was used. The diffusion rate is based on a vertical heat exchange coefficient (Chapra, 1983). The vertical heat exchange coefficient is based on the sequential difference in temperature between the epilimnion and the hypolimnion during stratification. A vertical heat exchange coefficient was calculated for each sampling period from April through July and the average value of 0.019 meters per day (m/d) used for model application. From mid-July through August stratification was at its strongest level limiting internal loading. For this period, a vertical heat exchange coefficient of 0.006 m/d was applied. The hypolimnion and epilimnion TP concentrations, used to predict the load associated with diffusion, were based on model predicted values. Internal loading was represented by diffusion from April through mid-July while from September through November it was represented by entrainment.

$$U_t = (V_h / A_t * t_s) * \mathrm{Ln}\,(T_{h\text{-}initial} - T_{e\text{-}avg}) / (T_{h\text{-}final} - T_{e\text{-}avg})\ (m/d)$$

U_t = vertical heat exchange coefficient (m/d)
V_h = hypolimnion volume (m^3)
A_t = surface area of thermocline (m^2)
t_s = time following $T_{h\text{-}initial}$ (d)
$T_{h\text{-}initial}$ = thermocline temperature at onset of stratification (C)
$T_{e\text{-}avg}$ = average temperature of epilimnion over stratification period (C)
$T_{h\text{-}final}$ = thermocline temperature at time of analysis (C)

W_{i-d} =[U_t * A_t*(TP_h – TP_e)]*10^{-6} (kg/d)

W_{i-d} = internal load associated with diffusion (Kg/d)
U_t = vertical heat exchange coefficient (m/d)
A_t = surface area of thermocline (m^2)
TP_h = hypolimnion concentration (ug/L)
TP_e = epilimnion concentration (ug/L)

Entrainment was calculated by the rate in the expansion of the epilimnion (represented by isothemal conditions) multiplied by the average hypolimnetic TP concentration and the surface area of the thermocline. Temperature data indicated the epilimnion expanded by 0.7 m and 2.5 m in September and October. The lowest 1.2 m of the lake was entrained in November to complete the whole lake mixing. The expansion of the epilimnetic volume (and contraction of the hypolimnion) was accounted for when determining the change in TP concentration at each time step.

W_{i-e} =TP_h * (D_{t+dt} – D_t) * A_t * 10^{-6} (kg/d)

W_{i-e} = internal load associated with entrainment (kg/d)
TP_h = hypolimnion concentration (ug/L)
D_{t+dt} = epilimnion depth at time of evaluation (m)
D_t = initial epilimnion depth (m)
A_t = surface area of thermocline (m^2)

Hypolimnion Layer

The parameters used to calculate the change in the hypolimnetic TP concentration are presented in the equation below. The change in hypolimnetic TP levels are based on the balance between the additions of phosphorus associated with sediment release and settling (equivalent to the settling loss from the epilimnion) with losses through sediment burial and internal loading (diffusion and entrainment) to the epilimnion. Shared between the epilimnion and hypolimnion layers of the model are the diffusion/entrainment and settling pathways. A further explanation of each of the equation terms is provided below.

dTP/dt =[(W_{srr} + W_s – W_b – W_i) / (V_h)]*10^6 (ug/L-d)

W_{srr} = sediment release rate (kg/d)
W_s = settling (kg/d)
W_b = burial (kg/d)
W_i = internal load (kg/d)
V_h = hypolimnion volume (m^3)

Settling (W_s)
The TP settling term is shared between the epilimnion and hypolimnion layers of the model. For this reason, this term is equivalent for each of the model layers for each time-step. As TP settles and leaves the epilimnion, it enters the hypolimnion. So the loss of TP through settling in the epilmnion is a gain to the TP mass in the hypolimnion.

Burial (W_b)
A steady burial velocity rate of 5 meters per year (0.4 meters per month or 0.013 meters per day) was applied to calculate the rate of loss of TP from the water column and its active release from sediments. The amount of TP lost through burial was determined by multiplying the burial rate

by the active sediment depositional area (191,155 square meters - depicted by the 3-meter contour in figure 2) and the model predicted hypolimnetic TP concentration.

$$W_b = [V_b * A_t * TP_h] * 10^{-6} \text{ (kg/d)}$$

W_b = burial rate (kg/d)
V_b = burial velocity (m/d)
A_t = surface area of thermocline (m^2)
TP_h = hypolimnion concentration (ug/L)

The unknown in this calculation is the burial velocity or the rate of loss of hypolimnetic phosphorus. For model application, an initial rate was determined based on sediment core samples collected during the management plan study.

Sediment samples were collected from depositional areas within the lake (depths greater than 2-meters). On average, the sediment phosphorus content within the upper 12 centimeters of the sediment averaged 0.00145 kg TP/kg sediment (or approximately 0.14%). The water content of the cores was 93% water (7% solids). Assuming a depositional area of 191,155 square meters and the determination from the study of a sedimentation rate of 0.0045 meters per year, the annual burial, or retention of phosphorus, is approximately 87 kilograms per year. This long-term level of phosphorus retention served as a guide from which to base the burial velocity. The burial rate, initially 3.8 m/yr, was set to affect a similar phosphorus retention amount for the period April through November. The burial rate was increased during model calibration to 5.1 m/yr. It is recognized that this rate is a long-term average and that phosphorus migration within the surficial sediments does occur meaning retention does not preclude continued interaction with the water column.

Internal load (W_i)
The internal load, or loss associated with diffusion and entrainment, is the mass transfer of TP from the hypolimnion to the epilimnion. Similar to the epilimnetic settling term (W_s), this component is shared between the two layers and, therefore, is equivalent in magnitude for each time-step. For the hypolimnion, diffusion and entrainment is a loss while, as discussed earlier, for the epilimnion it is a gain in TP mass.

Sediment Release Rate (W_{srr})
The sediment release rate is based on differences in hypolimnetic TP levels between successive sampling events divided by the period (days) separating those events. Based on this method, an average sediment release rate of 7.5 mg/m^2-d was calculated. The limitation of this approach is that it incorporates the other sources and sinks for TP. For this reason, in model calibration, the sediment release rate was decreased to 4.5 mg/m^2-d resulting in a steady rate of approximately 1-kilogram per day from the onset of stratification in April until complete lake turnover in November.

$$W_{srr} = [(V_h) * (C_f - C_i) / dt] * 10^{-6} \text{(kg/d)}$$

W_{srr} = sediment release rate (kg/d)
V_h = hypolimnion volume (m^3)
C_f = hypolimnion TP concentration at time of evaluation (ug/L)
C_i = hypolimnion TP concentration of prior sampling (ug/L)
dt = number of days separating observations (d)

Calibration

The primary calibration parameters for the epilimnion layer was the settling rate while for the hypolimnion layer the burial velocity and sediment release rate were adjusted to provide the best overall fit to the model. The results of model calibration are presented graphically in Figure 12. The root mean square error (RMSE) between observed and predicted TP levels for the epilimnion was 11.2 ug/L. As observed in Figure 12, the greatest error in the model occurs at the time of the fall overturn. In particular, the concentration observed at complete lake turnover in November. In addition, the concentration observed on the sampling event on July 21 departs from the normal behavior of the model and the general trend in the lake concentrations around that period. For this reason, the model was not adjusted to try to fit this data point. However, over the critical summer period, there was a close fit between the observed and model predicted TP concentrations. During this period, the RMSE for the epilimnion was 1.6 ug/L. The RMSE for the hypolimnion layer for the calibration period (April through November) and summer was 28.8 ug/L and 33.2 ug/L, respectively.

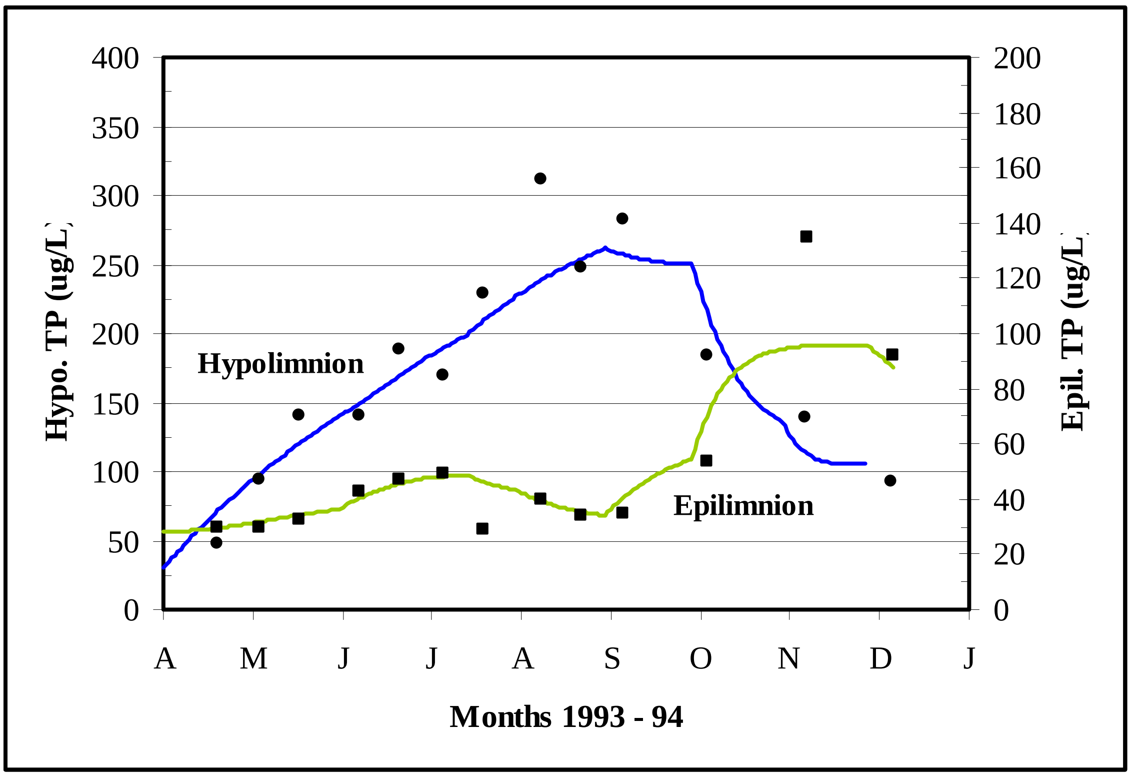

Figure 12. Results of model calibration for the epilimnion and hypolimnion layers of the mass-balance model. Model predictions are represented by lines and observed data represented by points (hypolimnion) and squares (epilimnion).

Model Results

From June through August of 1993, model results indicate that the lake received 112.3 kilograms of TP to the upper 3 meters of the water column from both internal and external sources (Table 5). Eighty-one kilograms, or approximately 72 percent of this total, comes from sources external to the lake. Of the external sources, the Daniels Creek drainage represented the greatest phosphorus source with 74 percent, or approximately 60 kilograms of the summer external load, with Cottage Creek contributing 15 percent of the total. Internal loading contributed 30.9 kilograms TP, June through August, or 28 percent of the total load.

Table 5. A monthly accounting of the model results for the epilimnion during the period, April to October 1993**.** (Units in kilograms TP per month.)

Month	External	Internal	Settling	Outflow
April	33.9	3.6	14.7	20.9
May	35.7	9.4	17.6	24.0
June	41.2	13.0	21.6	24.7
July	26.7	10.6	24.4	16.1
August	13.4	7.4	19.7	7.5
September	11.4	34.0	23.1	7.3
October	9.7	85.5	42.6	16.7

As discussed earlier, surface water flow levels throughout western Washington in the spring and early-summer of 1993 were at historically high levels. High inflow levels result in a disproportionate influence of external loading on summer period TP levels resulting in underestimating the influence of internal loading. To reduce this bias, average flow levels were calculated that then served as input to the model.

To adjust flow levels, a linear relationship was established between the average monthly flow observed in Daniels and Cottage Creeks, June through October of 1993, and those observed concurrently at a nearby USGS gauging station (Bear Creek near Redmond, No. 12122500) (Figure 13). Cottage Lake Creek, the outflow of Cottage Lake, flows for approximately 3.5 miles prior to its confluence with Bear Creek. Gauging Station 12122500 is located approximately one mile above the confluence. Flow levels had been recorded at station 12122500 from 1945 to 1949 and again from 1979 to 1996, a 22-year period of record.

Average monthly flow levels were determined for the Bear Creek gauging station from its 22-year flow record. Based on the flow relationship presented in Figure 13, corresponding average flow levels were determined for Daniels and Cottage Creeks. The results of this analysis resulted in decreasing April, May, June, July, and August combined inflows by 14 percent, 46 percent, 47 percent, 41 percent, and 11 percent, respectively.

Because a significant relationship could not be determined between flow levels and observed TP concentrations for either Cottage or Daniels Creeks, concentrations observed during the study period were retained as input to the model.

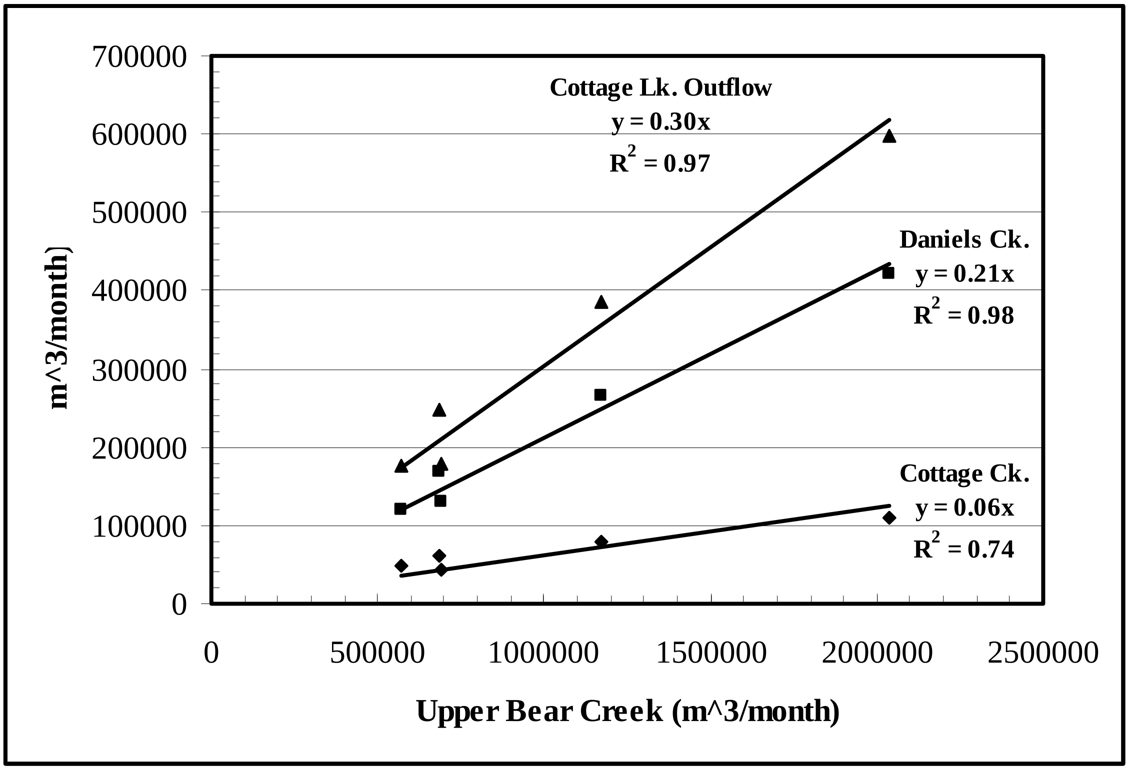

Figure 13. The relationship between the average monthly flow levels observed at Cottage Lake's major surface water inflows and outflow and those observed at the USGS Bear Creek gauging station, June through October 1993.

Model Adjustments

Based on average flow conditions, the external TP load during the summer period was reduced to 51.4 kilograms, a 37 percent reduction in comparison to the level observed in 1993. The total summer period TP load, including both internal and external sources, decreased to 81.7 kilograms from the model calibrated 112.3 kilograms. This change resulted in the predicted average summer TP concentration decreasing to 36.6 ug/L from 42.5 ug/L. (The observed summer average volume-weighted concentration in 1993 was 42.7 ug/L.)

Prior to the flow adjustment, during the summer period of 1993, internal loading represented 28 percent of the TP load to the epilimnion, however, with the adjustments, this percentage increased to 37 percent.

Loading Capacity

The load capacity determines the maximum amount of TP that the upper water column (epilimnion) of Cottage Lake can receive from June through August while remaining at, or below, 20 ug/L. This level is set regardless of what the pollutant sources are or their magnitude. The setting of the load allocations is that component of the TMDL that apportions the load capacity among the identified sources.

Model results indicate that the target concentration of 20 ug/L can be achieved through a 48 percent reduction in TP loading to the epilimnion during the summer period (June through August). The flow adjusted TP load of 82 kilograms must be reduced to 43 kilograms to reach the target concentration.

In determining the load capacity, it was assumed that internal loading would be reduced equivalently to reductions in the external load. This assumption is based on a long-term perspective that over time (decades) with reductions in the external load, the reservoir of phosphorus in the hypolimnion (the source of the internal load) will be reduced to an equivalent level through flushing.

Total Phosphorus Epilimnion Load Capacity (June – August)

- 43 kilograms (kg)

Load and Wasteload Allocations

The Cottage Lake management plan identified five sources that contribute TP to the lake. They include the major surface water inflows, Daniels and Cottage Creeks, nearshore surface and groundwater inflow, and internal recycling. Each was examined for its influence on the summer period lake TP concentration.

Table 6 provides the predicted effect on average lake TP concentrations from reductions in source loading. As observed from Table 6, the target concentration cannot be achieved through the reduction of a single source, instead broad reductions are required. Figure 14 is an interpretation of this information showing the relative influence each source has on epilimnetic TP concentrations. The greatest reduction in the average summer TP concentration will occur through source reduction in the Daniels Creek drainage and internal loading. For each 10 percent reduction in the summer period load of Daniels Creek and internal sources, model results indicate a 1.7 and 1.3 ug/L reduction in the summer period average lake TP concentration.

To determine a reasonable level of reduction that can be achieved for both Daniels and Cottage Creeks, the Washington State Department of Ecology's ambient monitoring database was consulted. A median TP concentration of 22 ug/L was observed at Ecology's ambient monitoring stations located in western Washington (total monitoring observations, n=667) during June through August (http://www.ecy.wa.gov/programs/eap/fw_riv/rv_main.html). The 75th and 25th percentiles for these waters are 38 ug/L and 13 ug/L, respectively. In comparison, the average June through August TP concentration observed in 1993 for Daniels and Cottage Creeks were 75 ug/L and 70 ug/L. This indicates the concentrations observed in these streams are approximately twice the 75th percentile level observed at the ambient monitoring stations. For this reason, the load allocations for these creeks are based on achieving summer period TP concentrations that are more representative of streams less impacted by non-point source pollution. A 55 percent reduction in TP concentrations results in stream concentrations of approximately 33 ug/L (Table 6). This level of reduction results in June through August loads for Daniels and Cottage Creeks of 16 and 4 kilograms, respectively.

Based on model results, achieving a 50 percent reduction in the loading from the surface water inflow will lower the summer TP concentration by 11 ug/L, from 38 ug/L to 26 ug/L. However, to achieve the target concentration other reductions are necessary.

Internal loading was among the largest sources of TP to the epilimnion during 1993. The magnitude of internal loading is highly variable year to year and is difficult to measure and control. The assumption in setting an allocation for internal loading is that with external source control, an equivalent reduction will eventually be realized with internal sources. For this reason, the internal load allocation has been set at 15 kilograms, a 50 percent reduction from the level predicted by the mass-balance model.

Near-shore surface and groundwater inflow were found to have a relatively small influence on summer lake TP concentrations. This is because the summer period is dry and the majority of the loading from these sources is during the fall and winter when runoff is greater. Recognizing that winter period loading influences both spring-time lake TP concentrations and, importantly, the phosphorus reservoir of the hypolimnion, a 50 percent reduction in loading was allocated to these sources. The setting of near-shore allocations also results in a broader scale participation in best management practice implementation further ensuring improvements in water quality.

Total Phosphorus Source	**Load Allocation (kg/ June –August)**
Daniels Creek	16
Cottage Lake Creek	4
Near shore Surface water Runoff	1
Near shore Groundwater Inflow	3
Internal Recycling	15

These allocations reduce each source, including internal recycling, by approximately 50 percent from the loads observed in 1993 (based on average inflow levels). A ten percent margin of safety was used in setting these source allocations. This level of reduction results in an average, June through August TP concentration, within the epilimnion (surface to 2.5 meters depth), of 18 ug/L with a standard deviation of 2 ug/L. The across-the-board 50 percent reduction in loading sources achieves the target concentration, and associated beneficial uses, while bringing inflow TP concentrations down to a level more reflective of the expected range for this region.

There is no known direct stormwater discharge to Cottage Lake. For this reason, the wasteload allocation is xero.

Table 6. Expected summer TP concentrations following source reductions. (The standard deviation of the summer period TP concentrations is within brackets.)

Source	Inflow TP (ug/L)	Percent Reduction in Load (%)	June-August TP (ug/L)	June-August TP (ug/L) *
Daniels Creek	75	0	36.6 (3.4)	
	68	10	34.8 (3.3)	33.8 (3.2)
	60	20	33.1 (3.2)	31.0 (2.9)
	53	30	31.3 (3.0)	28.2 (2.6)
	45	40	29.6 (2.9)	25.3 (2.4)
	38	50	27.8 (2.8)	22.4 (2.1)
	30	60	26.0 (2.6)	19.4 (1.8)
	23	70	24.3 (2.5)	16.5 (1.4)
Cottage Creek	70	0	36.6 (3.4)	
	63	10	36.2 (3.4)	35.2 (3.3)
	56	20	35.9 (3.4)	33.8 (3.2)
	46	30	35.5 (3.4)	32.3 (3.0)
	42	40	35.1 (3.4)	30.7 (2.8)
	35	50	34.8 (3.4)	29.1 (2.7)
	28	60	34.4 (3.3)	27.5 (2.5)
	21	70	34.0 (3.3)	25.8 (2.3)
Nearshore (SW)	90	0	36.6 (3.4)	
(Surface Runoff)	81	10	36.5 (3.4)	
	72	20	36.4 (3.4)	
	63	30	36.4 (3.4)	
	54	40	36.3 (3.4)	
	45	50	36.2 (3.4)	
	36	60	36.1 (3.4)	
	27	70	36.1 (3.4)	
Nearshore (GW)	80	0	36.6 (3.4)	
(Groundwater)	72	10	36.4 (3.4)	
	64	20	36.1 (3.4)	
	56	30	35.9 (3.4)	
	48	40	35.7 (3.4)	
	40	50	35.5 (3.4)	
	32	60	35.2 (3.4)	
	24	70	35.0 (3.4)	
Internal Load	-	0	36.6 (3.4)	
	-	10	35.6 (3.3)	
	-	20	34.5 (3.2)	
	-	30	33.3 (3.0)	
	-	40	32.2 (2.9)	
	-	50	30.9 (2.7)	
	-	60	29.6 (2.6)	
	-	70	28.3 (2.4)	
All Sources	-	0	36.6 (3.4)	
	-	10	33.1 (3.1)	
	-	20	29.6 (2.8)	
	-	30	26.0 (2.5)	
	-	40	22.4 (2.2)	
	-	50	18.8 (1.9)	
	-	60	15.2 (1.5)	
	-	70	11.6 (1.2)	

*Assumes an equivalent percent reduction in internal loading

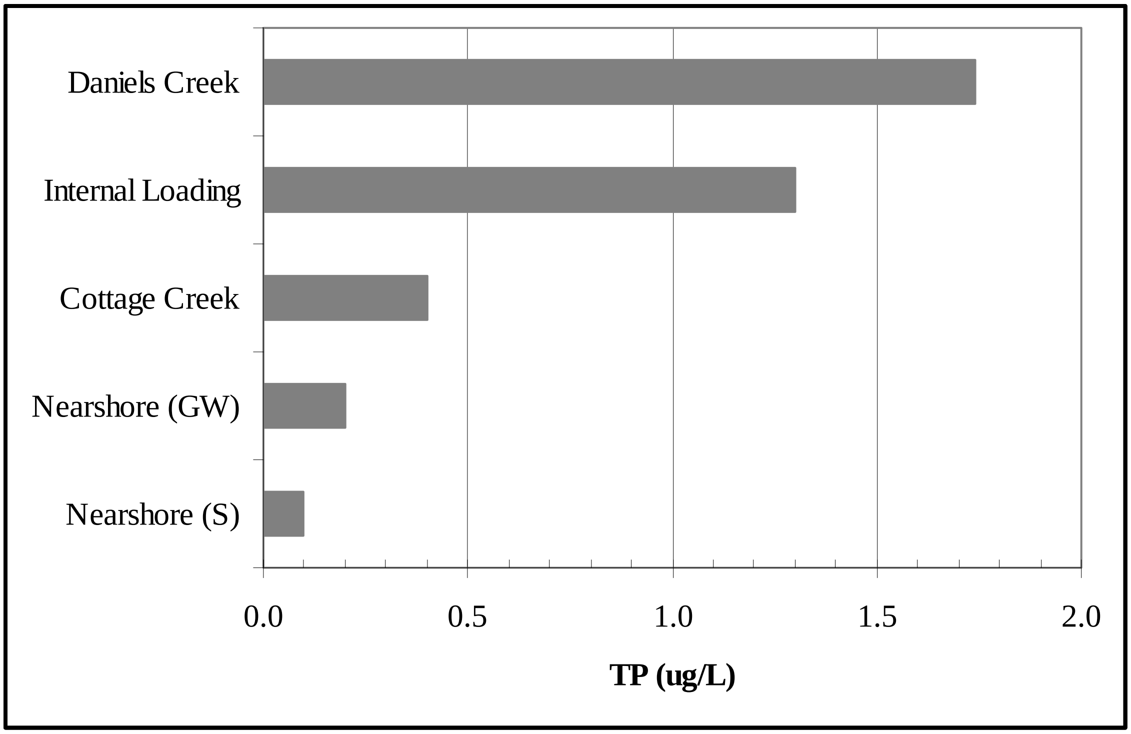

Figure 14. The reduction in the summer period TP epilimnion concentration (ug/L) per 10% reduction in source load.

Future Condition

The effect of changing land use on external TP loading to Cottage Lake was examined. The representation of current land use types within the watershed was determined by Arc-View analysis using two grid covers: the Puget Sound Regional Council grid (25 m resolution) based on 1992 data, and a University of Washington Urban Design and Planning grid (29 m resolution) based on 1998 data. Future land use was determined, assuming a build-out condition, based on current zoning designations for both King and Snohomish Counties.

Land use was divided into six categories including: low density residential, high density residential/commercial, forest, agriculture, wetland, and open water. Table 7 presents the area (hectares) represented by each of these land use types, for the current and future condition, within each of the lake's major sub-drainages and for its entire watershed. Current land use is based on the average of the areas represented for each category, within each of the grids. In determining the future land use structure, it was assumed that the area currently represented by forest and farmland would eventually be replaced by low-density residential development, its zoning designation. Current wetland and open water areas within the watershed were assumed to remain unchanged.

Table 7. The current and future extent (hectares) of land use within the Cottage Lake watershed.

	Daniels Creek		**Crystal Lake**		**Cottage Creek**		**Nearshore**		**Watershed**	
	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Low Density	301	1044	176	661	54	307	33	84	388	1429
High Density / Commercial	80	111	63	109	15	17	10	6	105	133
Forest	694	0	485	0	247	0	47	0	987	0
Agriculture	74	0	46	0	10	0	5	0	89	0
Wetland	49	49	50	50	10	10	6	6	65	49
Open Water	25	25	17	17	2	2	20	25	46	50

For each land use type, a TP export loading coefficient was applied to determine an annual loading rate (Reckhow, 1980). The export loading coefficients for low density, high density/commercial, forest, and agricultural were 0.20 kilograms TP/hectare – year (kg/ha-yr), 0.71 kg/ha-yr, 0.13 kg/ha-yr, and 0.45 kg/ha-yr, respectively. These export coefficients fall into the mid-range of suggested levels for each land use type (Reckhow, 1983). Initially, the export coefficients were applied to the Daniels Creek drainage and small adjustments were made to them to more closely fit the TP load measured for this drainage during the study. Following these adjustments, the coefficients were applied to the Crystal Lake sub-drainage, Cottage Creek drainage, near shore drainage, and for the entire watershed. The results of this analysis are presented in Table 8. Differences between the predicted load, as determined by the export coefficients, and the study measured load, ranged between 40 percent for Cottage Creek to 2 percent for the watershed (Table 8).

The near-shore TP load associated with groundwater and surfacewater flow to Cottage Lake was combined because residences in proximity to the lake utilize on-site wastewater treatment, a primary source of elevating TP concentration in ground water. (Of the drainage areas to Cottage Lake, the near-shore drainage was the only one that provided a significant contribution of ground water.) The study and predicted annual TP load, for the near-shore drainage, differed by 19 percent.

Following calibration to the current land use structure, the export coefficients were then applied to the future condition. For the future, build-out condition, annual TP exports to Cottage Lake from its watershed will increase by approximately 61 kilograms, or 19 percent above current conditions. The percent increase in annual TP exports by drainage include: Daniels Creek (20 percent), Crystal Lake (27 percent), Cottage Creek (24 percent), with near shore drainage remaining relatively unchanged.

The effect that land use changes, and the associated increase in TP load, will have on Cottage Lake phosphorus concentrations were examined using the calibrated lake model. The current and future annual TP loads were each used as input to the model. In both cases, the annual load was divided into monthly load amounts set proportional to the monthly loads measured during the study.

For the current condition, the model determined an average summer period TP concentration of 44 ug/L based on an external load of 82.3 kilograms (kg) over the same period (June – August). In comparison, the original model run, based on the study data, determined a summer average TP concentration of 43 ug/L with an external load of 81.3 kg.

Table 8. Annual TP load (kg/yr) associated with each land use by drainage.

	Daniels Creek		**Crystal Lake**		**Cottage Creek**		**Near shore**		**Watershed**	
	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Low Density	60	209	35	132	11	61	7	17	78	286
High Density	57	79	45	77	11	12	7	4	75	95
Forest	90	0	63	0	32	0	6	0	128	0
Agricultural	33	0	21	0	5	0	2	0	40	0
Total Load	**240**	**288**	**164**	**209**	**59**	**73**	**22**	**21**	**321**	**382**
4/93 – 3/94 Load	**247**	**-**	**-**	**-**	**42**	**-**	**27**	**-**	**316**	**-**

The increased external load associated with the future condition resulted in an average summer period TP concentration of 50 ug/L. Both model runs assumed no change in internal loading from the original model calibration. However, increased external loading would likely lead to increased internal loading though, by how much, could not be determined given the scope of the original study's data collection effort.

As discussed earlier, in setting the load capacity for Cottage Lake, average inflow levels were used because during the study year above average precipitation and associated inflow levels occurred during the spring and early summer, inflating typical TP loading amounts. When average flow levels are considered, the increased external load associated with future development, will increase the average summer TP concentration by 4 ug/L to 42 ug/L. To meet the load capacity set for external sources (24 kilograms), the future condition external load of 61 kg (adjusted for average flow levels), will require a reduction of 60 percent, an additional 10 percent reduction above what is required by this TMDL.

Margin of Safety

A ten percent margin of safety was used when establishing the source load allocations. This margin of safety level resulted in an average model predicted summer TP concentration of 17.9 ug/L with a standard deviation of 2.0.

Summary Implementation Strategy

The primary objective of the TMDL analysis is the determination of a load capacity and source allocations. For this reason, the TMDL provides only a bare framework, a set of targets, to base restoration activities on. This section summarizes the strategy for implementing water quality corrective actions. Within one year following the approval of this analysis by the United States Environmental Protection Agency, a Detailed Implementation Plan (DIP) will be completed by Ecology that will clearly define the restoration activities required to meet the source allocation targets, incorporating community and local government input.

Initially, restoration will focus on controlling external TP sources. This is important for several reasons: analysis results indicate that major phosphorus sources are external to the lake, primarily in the Daniels Creek drainage. The reality that the success of any in-lake measures to control internal recycling will only be achieved once external sources are significantly reduced.

The long-term involvement of the lake and watershed community, in addition to state and local agencies, will be required to achieve the goal of reducing phosphorus sources throughout the watershed. External source control efforts, particularly in view of the expected increase in TP loading associated with future development, will require an extended and focused effort. External load allocations will be met by 2014. A longer timeline will be required to meet the internal recycling allocation. With reductions in external phosphorus loading to Cottage Lake over the next ten years, the internal recycling allocation should be met by 2024.

The following discussion presents an outline of the future water quality restoration work, identifying the principal parties and their anticipated roles, and the data needs that will be required to measure the success of those efforts.

Implementation Plan Development

Involved Parties and Regulatory Authorities

The following is a description of the key agencies and other groups that have influence, regulatory authority, information, or resources that will be included in the coordinated effort to implement this TMDL.

Department of Ecology

Ecology has been delegated authority under the federal Clean Water Act by the U.S. EPA to establish water quality standards, administer the NPDES wastewater permitting program and enforce water quality regulations under Chapter 90.48 RCW. Ecology responds to complaints, conducts inspections, and issues NPDES permits as part of its responsibilities under state and federal laws and regulations.

Washington State Department of Ecology will provide technical assistance and grant/loan opportunities based on the quality of local applications. Ecology will assist with developing a Detailed Implementation Plan within one year following the approval of this TMDL by the U.S. Environmental Protection Agency. The plan provides a detailed strategy for identifying and reducing pollutant sources within the watershed to achieve the TMDL allocations. The creation and implementation of the Detailed Implementation Plan is a coordinated effort involving lake and watershed residents, federal, state, and local agencies.

King County

King County has jurisdiction over Cottage Lake and has a long and continuing involvement in addressing water quality issues on the lake. King County continues to collect water quality data on the lake and has done so since the management plan study. Currently, the King County Department of Natural Resources is conducting a water quality investigation on Daniels Creek to identify phosphorus sources (Abella, personal communication). This information will be important to effectively apply best management practices.

Implementation Plan Activities

Expected management activities to improve Cottage Lake's water quality, encompass pollutant source control, further protection of critical wetlands, public education and involvement, and water quality monitoring. Effectively implemented and monitored, together these activities should ensure for significant reduction in TP loading providing for improvement in Cottage Lake's water quality and associated beneficial uses.

Reasonable Assurance

King County maintains the popular Cottage Lake Park, located at the mouth of Cottage Creek, and, therefore, has a vested interest in improving Cottage Lake's water quality.

Due to concerns of increased phosphorus export associated with new residential development, King County designated the Cottage Lake watershed a "sensitive lake treatment area" (King County, 1998). This designation requires that new development retain on-site a minimum of 50 percent of the TP associated with storm water runoff.

King County is under an Ecology administered National Pollution Discharge Elimination System Phase I storm water permit. Therefore, no future indiscriminate storm water discharge to the lake will occur.

Primarily driven by the 1999 listing of Chinook salmon as threatened under the Endangered Species Act, King County has taken a lead role in the planning effort to conserve salmon habitat within the Cedar-Sammamish basin (Water Resource Inventory Area (WRIA) 8). King and Snohomish Counties, along with a consortium cities and towns within WRIA 8, have outlined priority measures to protect and enhance salmonid habitat throughout the Cedar-Sammamish basin, with a number of projects identified for Cottage Lake Creek (WRIA 8 Steering

Committee, 2002). Cottage Lake Creek, situated below Cottage Lake, provides spawning and rearing habitat for a variety of salmonids including: Chinook, coho, sockeye, kokanee, and steelhead (Kerwin, 2001). Because Cottage Lake provides the majority of the flow to Cottage Lake Creek, its water quality is directly linked to the water quality of the lake. In order to realize fully the benefit of these restoration activities, the water quality of Cottage Lake will need to be addressed.

King County will continue to provide technical support to the Cottage Lake community and be instrumental with the implementation phase of this TMDL.

Adaptive Management

Effectiveness monitoring is a required component of each TMDL. This monitoring assesses whether (for instance) best management practices implemented to reduce phosphorus sources loads are successful or not. It requires a long-term effort in order to assess the pre and post implementation phases of restoration. However, this information can also be used to gauge progress towards meeting interim goals. It is expected that water quality monitoring of the lake and its major inflows will occur concurrent with, and follow, the implementation of best management practices.

Monitoring Strategy

Water quality monitoring of Daniels and Cottage Creeks will be essential as a pollutant source detection tool, for providing an assessment of whether source allocation targets are being met, and for determining the effectiveness of best management practices implemented to control phosphorus sources. In addition, summer-period lake monitoring will be needed to determine the effect of source controls on reducing lake phosphorus concentrations to the target level.

Potential Funding Sources

Funds to implement water quality improvements can be obtained through the Washington State Department of Ecology. Ecology's water quality program administers three major funding programs that provide low interest loans and grants for projects that protect and improve water quality in Washington State. They include: the Centennial Clean Water Fund, the State Revolving Loan Fund and the Section 319 Nonpoint Source Grants Program. (Cottage Lake's Phase I monitoring and planning was funded through the Centennial Clean Water Fund.) Examples of projects that have qualified in the past for this funding, relevant to Cottage Lake, include: water quality monitoring, watershed planning, lake restoration, and the acquisition of wetland habitat for preservation.

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Appendix A.

Cottage Lake TMDL Public Meeting

On Tuesday, January 27, 2004, Ecology co-sponsored a public meeting at the Woodinville Public Library for the proposed Water Cleanup Plan (TMDL) for Cottage Lake. Co-sponsors of the meeting included King County's Lake Stewardship Program and The Upper Bear Creek Unincorporated Area Council.

With approximately 25 people in attendance, Tony Whiley explained the Cottage Lake submittal report, detailing the data collected by King County and the information collected from the 1996 KCM Cottage Lake management plan. King County's Sally Abella provided insight into the water quality data that had recently been collected by King County and, more specifically, what the data revealed.

Tricia Shoblom discussed the Detailed Implementation Plan. Tricia explained that the DIP would specifically outline a strategy to help get the lake into compliance with the allocations set forth in the water clean up plan. A steering committee including Ecology, Fish and Wildlife, King County, King Conservation District, Snohomish County, and homeowners within the watershed will be meeting regularly to decide what type of implementation projects will be suitable for Cottage Lake.

A 30-day comment period ended on March 1, 2004. No comments were submitted for the Cottage Lake Water Cleanup Plan.