Management of Pine Lake Water Quality

Sammamish, WA

Final Report

May 2009

Prepared by:
Tetra Tech Inc.
1420 5th Avenue, Suite 550
Seattle, WA 98101

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Sammamish, WA

Final Report
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Prepared for: City of Sammamish
Public Works
801 228th Avenue SE
Sammamish, WA 98075

Prepared by: Tetra Tech, Inc.
1420 5th Avenue, Suite 550
Seattle, WA 98101
206.728.9655

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ACKNOWLEDGEMENTS

Tetra Tech. Inc. thanks the citizen volunteers that spent many cold and wet hours collecting valuable data on precipitation, stormwater runoff and lake level.

Doug and Christine Strohm
Harvey Miller
Ilene Stahl
Jason Wright
Kate Bradley
Leslie Dorsett
Rosemary and Jim Kahn

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EXECUTIVE SUMMARY

Pine Lake is a small shallow lake located within the City of Sammamish, Washington. The water quality and aesthetic appeal of the lake is directly related to the availability of phosphorus, an essential nutrient for algal growth. Algal growth is the result of photosynthesis or primary productivity that can occur in the lake. The more phosphorus supplied to the lake, the more algae the lake will support, thus the "greener" the lake will become. Excess phosphorus loading input in the last century resulted in superabundant algal growth leading to blooms, decline in water quality, and over-all beneficial uses of the lake. Steps were taken to restore the lake by diverting drainage from a subbasin, which passed through a wetland and into the lake. The drainage was routed around the lake to its outlet stream. Recently, there was concern that continued land use changes converting from forest to urban residential and commercial uses within the watershed would again result in increased phosphorus loading to the lake and thereby decrease the quality of the lake.

The objective of this investigation was to formulate a lake/watershed management plan that would address the phosphorus loading drivers in the lake's watershed. To formulate the plan, the following questions had to be answered: 1) to what extent has land use changed in the watershed; 2) has the hypolimnetic (bottom water) phosphorus concentration continued to increase; 3) to what extent has external phosphorus loading increased in association with land use changes; 4) are winter blooms still occurring; 5) has spring and summer water quality, in terms of phosphorus concentration and algae (chlorophyll *a*, green photosynthetic pigment), continued to improve following wetland diversion; and 6) how should the Pine Lake Watershed and the lake be managed to sustain its high quality?

Current lake condition was assessed through water column sample collections from the lake's deepest point on a monthly basis during winter and twice-monthly during spring and summer. Water and phosphorus budgets were constructed based on observed hydrologic and chemical data. From the phosphorus budget, a two-layer (epilimnion-surface water and hypolimnion-bottom water) phosphorus mass balance model was developed. This simple accounting approach of phosphorus in and out of the lake helped define the key characteristics that make the lake function. Using this model, the lake's sensitivity to changing land use was assessed to assist in development of a lake management plan.

This study documents that the quality of Pine Lake has improved greatly since diversion of the wetland inflow in 1988. The historic spring cyanobacteria, blue-green bacteria (algae), blooms have all but disappeared. However, post destratification fall and winter blooms still occur, as was the case in 2005. While diversion of phosphorus input from the wetland was the cause for the spring bloom elimination, fall-winter blooms result largely from high phosphorus content in the anoxic hypolimnion (deep cold water zone) that becomes distributed throughout the whole lake following fall mixing.

While these fall-winter blooms can be aesthetically offensive, they do not affect recreation or other beneficial uses during summer. Lake quality during the summer has generally been relatively good, and has even improved in the past 15 years such that mean summer surface chlorophyll *a* (used as a measure of algal production) and total phosphorus are now about 3 μg/L and 10 μg/L, respectively and are indicators of very good water quality conditions in the lake. The reason for the good summer lake conditions is in part due to thermal stratification that serves to trap most of the phosphorus recycled from bottom sediments into the cold lower water layer as well as the typical dry northwest summers with little stormwater runoff. If mixing of the epilimnion by wind were sufficient to erode the metalimnion (thermocline or mid layer of water where there is a transition from surface warm water to bottom colder water) during summer the result would be increased epilimnetic phosphorus and algal blooms would probably occur. However, Pine Lake has a relatively small area and is mostly surrounded by large trees that protect it from wind. Tree removal around the lake may pose a risk to the lake's summer stability.

Preservation of the lake's ability to remain in a healthy condition requires best management practices (BMPs) to be implemented. The following management recommendations are focused in five key areas: 1) stormwater runoff controls, 2) in-lake controls, 3) nearshore controls, 4) administrative policy, 5) continuation of monitoring. In order to provide a measure for assessing the lake's overall health and condition, a benchmark water quality goal for total phosphorus and chlorophyll *a* is required. Based on review of monitoring data and water quality predictions, a minimum goal of 19 μg/L of winter whole lake and 10 μg/L summer epilimnetic phosphorus concentrations is proposed. A corresponding chlorophyll *a* goal of 19 μg/L and 2.8 μg/L for winter and summer concentrations is achievable by implementating management options.

Development within the lake's watershed has resulted in an increase in phosphorus loading to the lake over the last two decades. This phosphorus loading to the lake has continued to fuel cyanobacterial blooms in the winter. However, the City's and County's efforts to employ water quality BMPs like biofiltration and infiltration have reduced the potential phosphorus loading that could have been generated from the land use conversion. It is important that biobuffers and stormwater management for water quality controls continue to receive high priority within the City and that watershed residents become aware of their individual roles in maintaining the water quality of the lake.

It is recommended that all development and redevelopment within the Pine Lake Watershed be conducted in compliance with the revised Critical Areas Ordinance passed December 20, 2005, such that all new development must retain 80% of the total phosphorus in runoff on an annual basis (Ord. 21A.50.355, Sammamish, 2005) using all known, available and reasonable technology (AKART). This alone will not prevent degradation of the water quality of Pine Lake. Additional steps to reduce phosphorus generation within the watershed are encouraged, such as imposing a strict pet waste ordinance, a phosphorus ban on all fertilizers within the watershed, and irrigation reduction through landscape practices that reduce the need for plant watering.

As pressure to increase zoning density above the current plan increases, it is important to understand that it is the pervious area, which was and is currently covered with native vegetation that continues to control the character of Pine Lake. The loss of this watershed feature will reduce the functional ability of the watershed to prevent degradation of the lake's water quality. Hence, future planning decisions should take into account that changes in the nature of the watershed can have an immediate impact on lake water quality.

The phosphorus model was produced assuming that climatic precipitation patterns will not significantly change. Specifically, the summers will remain relatively dry and the majority of the stormwater runoff will come in the winter period. A shift in the wet season could transport additional P to the lake in the summer and that could stimulate summer algal blooms. For example, unusually high rainfall in September in the late 1990s produced a cyanobacteria bloom in Lake Sammamish. Also, changes in the vegetative cover of the watershed and particularly the height and density of the trees that influence wind induced mixing could also increase phosphorus availability during the summer. This would also lead to a potential increase in algal blooms.

In-lake activities to directly control phosphorus concentrations may be needed if the model predictions are shown to be correct with full build-out of the watershed. At this time, it is recommended that continued monitoring of the lake be conducted to provide data to verify the model and track if and when in-lake action may be necessary. The control of internal recycling of phosphorus would be through phosphorus-inactivation via the addition of aluminum to the lake sediment to reduce phosphorus release from the lake sediments.

Aquatic plant abundance is not considered excessive within the lake. However, monitoring of the aquatic plant community is recommended on a regular basis to track changes and specifically to identify non-native invasive species as a preventative measure. If non-native plants are found in the lake, immediate steps should be taken to eliminate that species from the lake.

The nearshore of the lake serves two vital purposes relative to the lake's water quality. One, the shoreline vegetation serves as a buffer that stabilizes the soil and uptakes phosphorus. Two, the taller trees surrounding the lake help prevent wind induced mixing of the lake's water column; low wind is critical for the maintenance of strong thermal stratification in the lake that minimizes phosphorus entrainment into the epilimnion from the hypolimnion through mixing.

Establishing a formal unit in the City is recommended, or a Lake Management District should be formed, to conduct formal reviews of all proposed development and oversee compliance of City ordinances relative to lake water quality protection. In addition, this entity would be responsible for conducting the monitoring program outlined below, storage of lake and watershed data, and formulating management activities to maintain the quality of the lake.

It is strongly recommended that a long-term monitoring program be conducted to continue to gather data on the lake's water quality and its inflowing waters. Only through a long-term monitoring program will the assumptions and uncertainties of the current phosphorus model be truly understood and a long-term adaptive model be formulated.

1. INTRODUCTION

1.1. PURPOSE

Water quality in Pine Lake, a 36 ha water body with a 5.9 mean depth, is determined largely by the amount of algae and the dominant taxa present. The lake is located on the Sammamish Plateau and has had a history of blue-green algal blooms, composed of primarily *Aphanizomenon*, which, because of its buoyancy, form mats on the lake surface during calm weather (Stamnes, 1972; Uchida, 1976). Algal abundance or concentration is, in turn, directly related to the concentration of phosphorus (P). The algal particles are the principal light scattering component resulting in marked reductions in transparency or clarity of the water. Thus, to maintain good water quality, P concentrations must remain relatively low.

An analysis of past data showed that in spite of improved water quality during spring and summer, due to diversion in 1988 of the high-P wetland input, winter algal blooms have continued to occur in the lake (Welch, 2002). A lakeshore resident (Harvey Miller) recorded a total of 923 days of “bloom conditions” between 1986 and 2004 (~ 9% of the time). Three fourths of those bloom days were during late fall or winter. These blooms, occurring since the 1988 wetland diversion, may have been due to increased hypolimnetic P and/or increased non-wetland P loading. Estimated non-wetland P loading had increased four fold between 1979-1980 and 1989-1990, with the mean total P (TP) concentration in runoff water increasing from 44 to 77 μg/L. That increase (18.5 kg) is analogous to an “adding back” of one half of the wetland input (36 kg) that had been diverted by the wetland project. That increase was associated with a decrease in undeveloped land (forest and grassland) from 65% to 26% between 1976 and 1989 and an increase in residential land use from 9% to 53% (Wigmosta, 1990; Anderson and Welch, 1991).

There was concern that continued changing land use from forest and grassland to residential/commercial use would increase the non-wetland P loading and threaten the lake’s recovery from its eutrophic state that existed prior to diversion of the wetland input. Increased P loading from non-wetland runoff could not only raise lake P concentration directly, but also indirectly by enriching lake bottom sediments that would increase internal P loading due to sediment P recycling. Thus, the purpose of this investigation was to define that risk in quantitative terms as much as possible.

1.2. APPROACH TO STUDY

The current lake condition was assessed through water column sample collections from the lake's deepest point on a monthly basis during winter and twice-monthly during spring and summer. Water and P budgets were constructed from lake level and precipitation records and determination of P runoff coefficients from sub watersheds in the basin. Phosphorus content of non-wetland runoff was determined from three intermittent streams when they were flowing during and following storms. From the P budget, a two-layer (epilimnion and hypolimnion) P mass balance model was developed, similar to that used for Beaver Lake (KCSW, 2001) and Lake Sammamish ((Perkins 1995; Perkins et. al., 1997). Using this model, the lake's sensitivity to changing land use was assessed to assist in development of a lake management plan.

1.3. OBJECTIVES

Allowing the lake's water quality to degrade from increased storm runoff loading could compromise the improvement in lake water quality realized from the wetland diversion. Therefore, the emphasis for this project was placed on protecting the lake from increasing developed land and the concomitant increased P runoff from the 240 ha watershed. To do that, the following questions needed answers: 1) to what extent has land use changed in the watershed; 2) has hypolimnetic P, which is much of the cause for late fall and winter blooms, continued to increase; 3) to what extent has external P loading from non-wetland sources increased and has it been associated with land use changes; 4) are winter blooms still occurring; 5) has spring and summer water quality, in terms of P and algae (chl *a*), continued to improve following wetland diversion; and 6) how should the lake be managed to sustain its high quality? Based on this information, a management plan for the lake was developed.

2. HISTORY OF PINE LAKE WATER QUALITY

2.1. LEGACY OF SPRING & SUMMER ALGAL BLOOMS AND CAUSE(S)

Pine Lake was considered to have the poorest water quality of Puget Sound low land lakes in the 1970s (Uchida, 1976). Total P concentrations during the spring (March-May) were consistently above 20 µg/L prior to 1989 (Stamnes, 1972; Jacoby et al., 1997). However, the principal source of nutrients was undetermined. Failing septic tank drain fields were thought responsible and there were proposals to sewer the lake. The work directed by Metro in 1979-1980 determined that a substantial fraction of the source of high TP concentrations was runoff from a wetland. That source contained TP up to 300 µg/L, 90% of which was soluble, and represented 49% of the total annual input in 1979-1980 (Pelletier and Welch, 1987). Diversion of that wetland input in the fall of 1988 represented 47% of the external load and has since resulted in relatively lower spring TP values (Jacoby et al., 1997). Spring algae abundance, as chl *a*, was also higher prior to the diversion; the maximum chl *a* in spring 1980 was 46 µg/L. Similar large blooms were probably missed in intervening years before the diversion, because sampling intensity by Metro and KCSW ranged from only 1 to 4 observations each spring (March-May) compared to 11 in 1980. Blooms were more pronounced in the spring than summer because wetland outflow with high TP was greatest at that time.

2.2. WETLAND DIVERSION AND RESPONSE

The restoration project for Pine Lake started in 1979-1980 with a Phase I study supported by USEPA, WDOE and METRO (Harper-Owes, 1981; Welch et. al., 1981). Although 42% of the TP loading was internal and only 20% came from the adjoining wetland, the effect of the wetland input was disproportionately high, due to its high soluble P fraction (90%) and high concentration. Internal loading from bottom sediments was mostly confined to the summer stratified period and was relatively unavailable to the lake surface lighted zone. Therefore, diversion of the wetland input was deemed the appropriate first step. Sewering the lake to divert seepage from septic tank drain fields was considered much less appropriate, because aerial infrared photographs and onside investigation revealed only two failing drain fields (Harper-Owes, 1981). Thus, a piping system was installed in the fall of 1988 to divert the wetland drainage to the lake’s outlet stream. See Anderson and Welch (1991) for more details on the structure and ensuing problems.

Prior to diversion summer (June-September) surface TP and chl *a* remained much lower than spring values. That is understandable, because during the stratified summer period, with normally low-rainfall and runoff, loss of TP from the epilimnion via sedimentation was greater than external input. Since diversion of the wetland, TP and chl *a* have tended to be similar during spring and summer. Moreover, there seems to have been a slight downward trend in spring TP and chl *a* over time with the lower values occurring since the early 1990s. These trends will be described later in the report. Nevertheless, some noticeably high values of TP and chl *a* have occurred in spring and summer since diversion.

There was marked improvement in water quality during the spring months once the high TP input from the wetland was diverted. The large blooms of *Aphanizomenon* no longer occurred and spring water quality in the epilimnion improved to a level similar to that during summer. Epilimnetic water quality during summer changed little from the 1970s through the 1990s with a few individual values of TP greater than 20 µg/L and chl *a* greater than 10 µg/L still occurring. Mean summer surface concentrations of TP and chl *a*, however, were all equal to or below those 20 and 10 µg/L levels, respectively.

A mean summer epilimnetic TP concentration of 20 µg/L in Puget Sound low-land lakes has been suggested by the Department of Ecology as an action value, or problem situation, requiring further assessment. That mean TP (20 µg/L) corresponds to a mean chl *a* of about 7 µg/L for Pine Lake. A mean epilimnetic chl *a* concentration of 2.8 µg/L is the water quality goal for Lake Sammamish established by King County. A TP concentration that produces chl *a* concentrations of 2.8 µg/L in Pine Lake is less than 10 µg/L (see Results). While mean summer epilimnetic TP values in Pine Lake remained below 20 µg/L, mean TP was usually over 10 and chl *a* often over 2.8 µg/L. If the water quality goal of 2.8 µg/L chl *a* is considered appropriate for Pine Lake, a summer TP goal closer to 10 µg/L is probably a more realistic limit to protect Pine Lake water quality than the State action value of 20 µg/L. That conclusion seems even more justified given the high quality of the lake observed in 2004-2005, which is described below.

3. METHODS

3.1. LAKE & STORM WATER SAMPLING

The lake water column was sampled monthly at the deepest point (12 m) from September 2004 through March 2005 and then twice monthly from April though September (Figure 1). This is the same site sampled historically. One additional site in shallower water was monitored concurrently with the deep station in 1979-1980 to assure that constituents observed at the deep station were representative of the whole lake.

Dissolved oxygen (DO), temperature, pH and conductivity were determined at 1–m intervals from surface to bottom (11 m) using a Hydrolab Minisonde 4A. The DO, conductivity, and pH probes were calibrated in the laboratory prior to each sampling and DO was verified in the field against air saturation.

Water samples were collected at the surface, 1, 3, 5, 7, 9 m and the bottom for SRP and TP and at 1 , 5 m and bottom (11 m) for chl *a*, phaeophytin (inactive chl *a*), and alkalinity. Constituents in water samples were analyzed by Aquatic Research Inc., using procedures outlined in Standard Methods (APHA, 2001). Historical TP data from 1998-2003, determined by King County, were corrected (increased) for problems of incomplete digestion with a factor of 1.26 (Personal communication Debra Bouchard, King County, December 2005). The apparent incomplete digestion occurred when King County changed analytical procedures for TP in 1998. Total P in this study were analyzed by the traditional standard method of heated per sulfate digestion.

Runoff from storms was sampled by a team of Pine Lake residents. Water samples for TP were collected from four storms in three streams draining to the lake (Figure 1). Flows were determined simultaneously from staff gauges. One of these streams from the north flows through a detention pond that removes particulate matter.

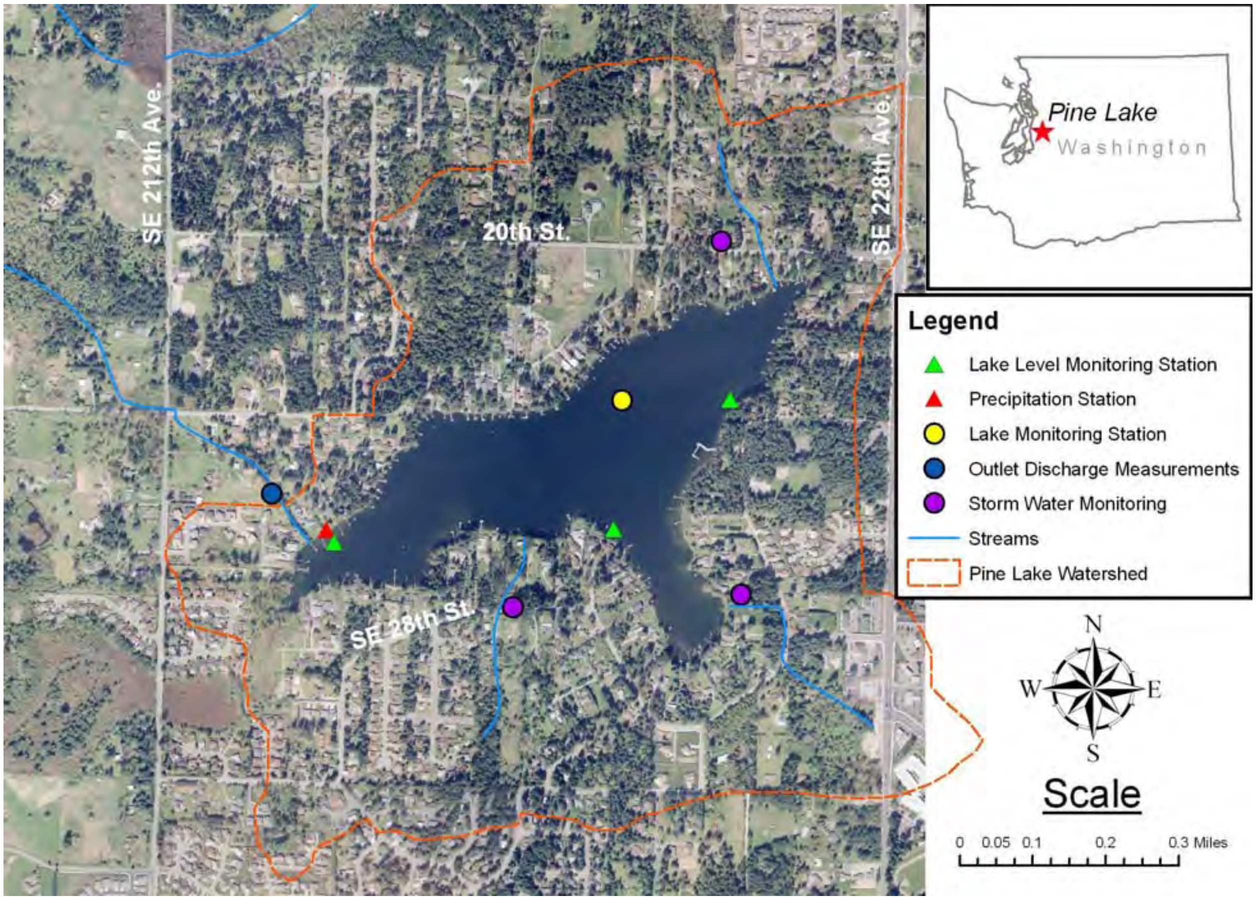

Figure 1. Pine Lake Location Map

There were six streams draining to the lake during the studies in 1979-1980 and 1988-1990 (Anderson and Welch, 1991). Only three of those streams remain. Water draining to the south side of the lake now enters detention ponds and runoff from 228th St. drains to the east away from the lake. Some of the drainage that used to flow in streams from the north is now thought to enter through pipes. Other drainage collection facilities are either in place or under construction to receive runoff from development on the south side. Thus, much of the free-flowing storm runoff that entered the lake in earlier years has been intercepted and is receiving treatment or is not exposed for sampling.

Post runoff TP data related to land use from other areas on the plateau were included to augment the 2004-2005 storm data collected from the Pine Lake watershed. The purpose was to develop representative TP yields and runoff concentrations for the various land uses in the watershed.

3.2. ASSESSMENT OF WATERSHED LAND USE

Current land uses were delineated under seven categories based on City of Sammamish records. Future build-out land use was projected for these seven categories, plus two more that represent a zoning change to designate park and open space and light rural residential (1 dwelling/4 acres), which are not currently designated. The projected land use areas were furnished by the City of Sammamish.

3.3. DEVELOPMENT OF P MODEL

Prediction of water quality in the lake was based on a calibrated, two-layer, non-steady state mass balance model for TP (Figure 2). This type of model was used for Lake Sammamish (Perkins, 1995; Perkins et. al., 1997) and by Tetra Tech for Beaver Lake (KCSW, 2001). Predictions of P in two layers; epilimnion and hypolimnion, during the stratified period, is necessary because epilimnetic concentrations during summer determine the concentration of algae (chl *a*), and in turn transparency - the characteristics of water quality. Simulating the whole lake TP during the non-stratified period is also important in Pacific Northwest lakes, because winter is the period of high runoff and transport of TP from the watershed, with little runoff during summer. A two-layer model is also important to represent the behavior of hypolimnetic TP, which originates largely via internal loading from sediments. The water column in Pine Lake is strongly stratified in summer; that minimizes the availability of the high hypolimnetic TP to the epilimnion until fall turnover and that behavior is important in describing surface water quality in summer.

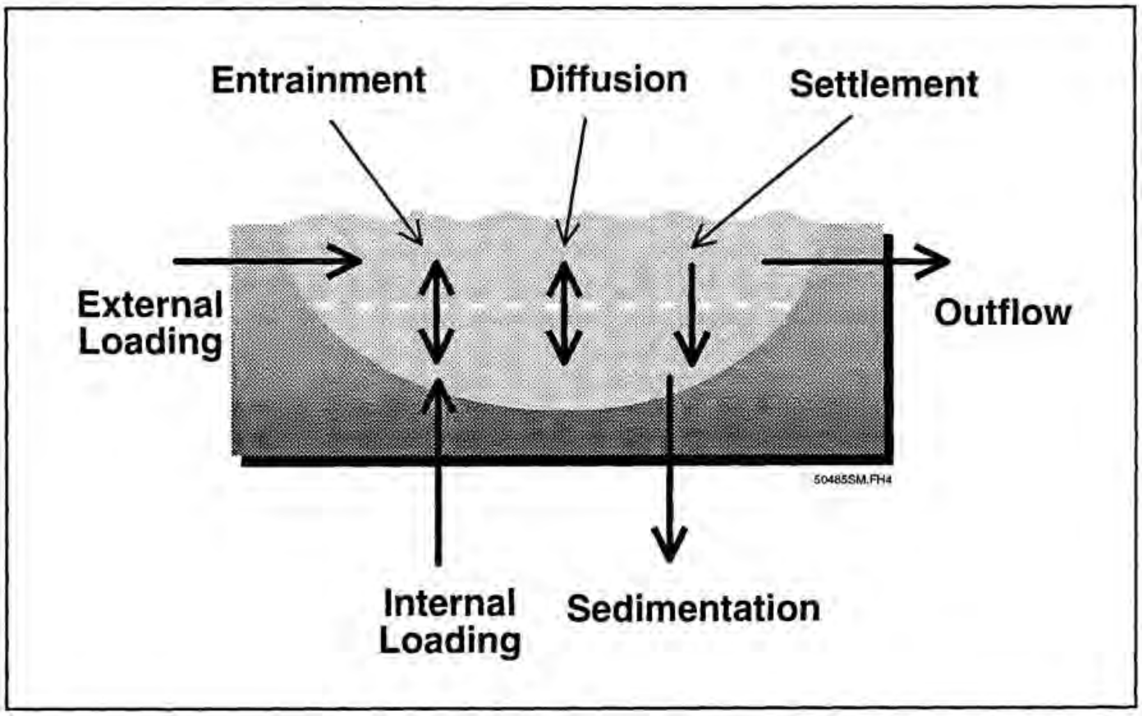

Figure 2. Fluxes included in a two-layer TP model (Perkins, 1995)

The mass balance model is formulated as follows:

$$\frac{\Delta TP}{dt} = J_{ext} + J_{int} - S - Q(TP) \quad (kg/wk) \qquad \text{Eq. 1}$$

Where ΔTP = change in lake TP per week

J_{ext} = external loading from runoff

J_{int} = internal loading from bottom sediments

S = sedimentation loss

Q = hydraulic outflow

TP = lake TP concentrations

Phosphorus inputs and outputs of the two layer model are illustrated in Figure 2. Besides the processes apparent in eq. 1, TP is transferred between the epilimnion and hypolimnion via diffusion and entrainment. Estimation of TP transferred from the hypolimnion's high concentration to the epilimnion with low concentration is based on heat exchange and calculated from the temperature gradient according to:

$V_t = (V_h/A_t t_s) \ln (T_{h,i} – T_e)/(T_{h,a} – T_e)$ Eq. 2

Where V_t = vertical exchange coefficient (m/wk)
V_h = volume of hypolimnion (m^3)
$T_{h,i}$ = minimum temperature of hypolimnion
$T_{h,a}$ = maximum temperature of hypolimnion
t_s = time between maximum and minimum temp (wk)
T_e = average temperature of epilimnion during stratification
A_t = average surface area of thermocline

With an estimate of the heat exchange coefficient V_t, diffusion of TP can be calculated as follows:

Diffusion (kg/wk) = $V_t A_t [(TP_e) – TP_h)]$ Eq. 3

Where V_t = vertical exchange coefficient
TP_e = concentration of epilmnetic TP
TP_h = concentration of hypolimnetic TP
A_t = area of thermocline

Entrainment is the process by which hypolimnetic water, and its TP, is captured into the epilimnion through the stratified period, according to:

Entrainment (kg/wk) = $(T_{d,f} – T_{d,i}) A_t [(TP_h) – (TP_e)]$ Eq. 4

Where $T_{d,f}$ = thermocline depth at end of time step
$T_{d,i}$ = thermocline depth at beginning of time step

Thermocline depths were determined from twice-monthly temperature profiles during the stratified period.

Sedimentation, or loss of TP from the water column to the bottom, was handled by estimating settling rate (V_a, m/wk) in the epilimnion and hypolimnion separately. For the epilimnion, the rate is as follows:

$$S(kg/wk) = V_a\, A_t\, (TP_e) \qquad \text{Eq. 5}$$

The settling velocity used for the Lake Sammamish TP model, derived from measured sedimentation, ranged from 0.5 to 3 m/wk (Perkins, 1995; Perkins et. al., 1997).

Sedimentation from the hypolimnion is less because most of the TP is soluble (TSP), having been released from bottom sediments and not assimilated by algae. Thus, settling velocity in the hypolimnion was assumed to be some fraction of V_a (see Perkins):

$$V_{a,\ hypo} = f\, V_a \qquad \text{Eq. 6}$$

Where $f = PP/(PP + TSP)$

Values for f should vary between 0 and 1. When sediment release is low, f will approach 1, and the fraction of PP (PP is particulate P) in the hypolimnion will equal that in the epilimnion, but when release is high, f will approach zero.

Hypolimnetic sedimentation was estimated by assuming the amount of TSP depends on the ratio of sediment release (SRR) to the vertical exchange co-efficient, SRR/V_t. Further, assuming epilimnetic TP is mostly PP, and TSP in equation 6 can be represented by SRR/V_a, the following estimates hypolimnetic settling:

$$V_{a,\ hypo} = V_a\, (TP_e) / [(TP_e) + SRR/V_t] \qquad \text{Eq. 7}$$

Summer mean surface or epilimnetic chl *a* was estimated from Pine Lake data along with the equation for a large lake data set (Jones and Bachmann, 1976). The same procedures were used for transparency, as dependent on chl *a*.

4. RESULTS

4.1. LAKE CONDITION-SEASONAL & HISTORIC

4.1.1. Trends in Lake Conditions

There is a relatively good long-term data set for Pine Lake, due to the small-lakes monitoring program of Metro and King County and two, in-depth studies by the University of Washington (1979-1980 and 1988-1990). These data show some interesting trends relative to the diversion of wetland input in 1988. Mean surface TP during spring was much higher prior to the diversion in 1988 and values were also much higher in spring than summer (Figure 3). While higher values in spring than summer is common for western Washington lakes, the wetland input to Pine Lake accentuated the difference more than in most lakes. Summer means after the diversion remained similar to those in earlier years until the late 1990s, but have generally declined since then, as have spring values. The much higher spring values, prior to diversion, were usually well above the eutrophic boundary of 25µg/L and always above 20 µg/L (Figure 3). Summer means, which are usually the criterion for trophic state and suitable water quality, have never been above the eutrophic boundary. Since the late 1990s, mean surface TP in both spring and summer has decreased to around 10 µg/L. Data from 2005 are consistent with that trend. The spring value in 2004 was slightly higher than other years since 1997, due to one exceptionally high value. The 20 µg/L line represents the State action level for Puget Sound lakes and 10 µg/L is the suggested goal for summer mean TP in Pine Lake, as discussed above.

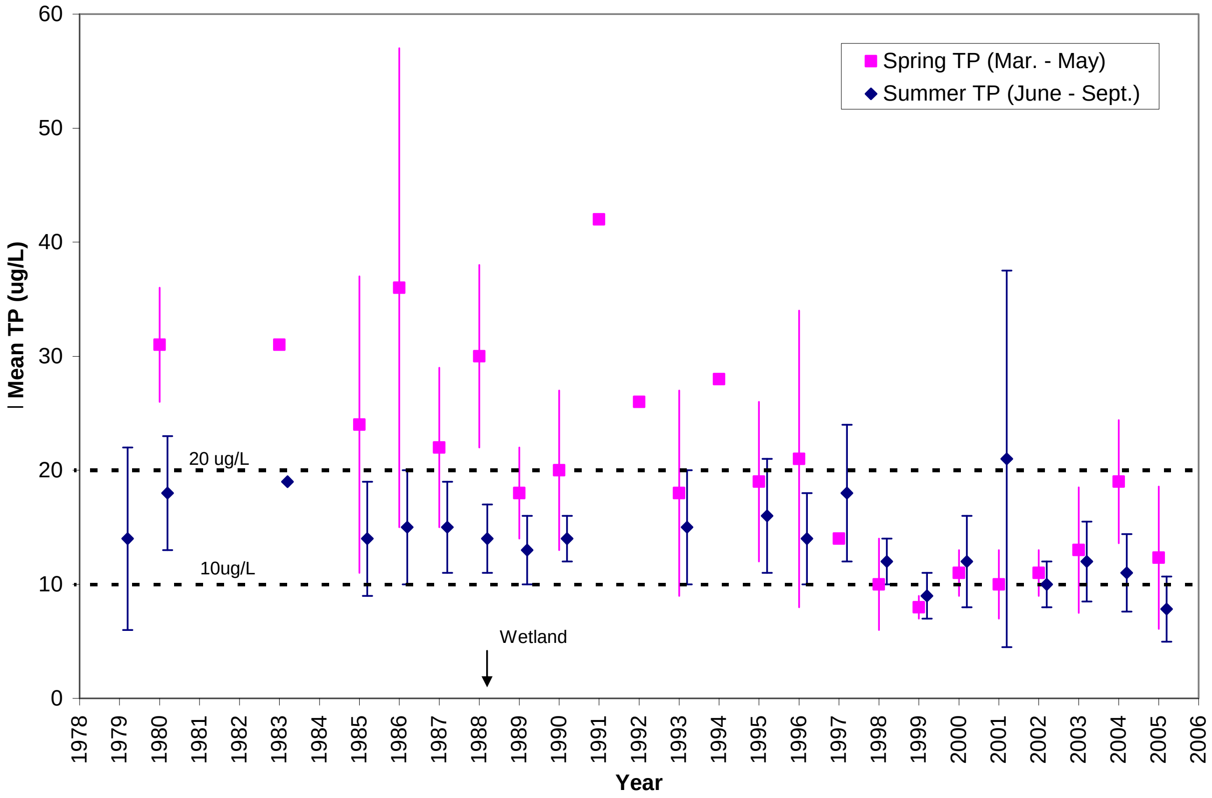

Figure 3. Mean (+/- SD) spring and summer surface (1m) TP concentrations. The 20 and 10ug/L lines represent the State action value and suggested goal for summer in Pine Lake. TPs for 1998-2004 corrected for analytical change by 1.26

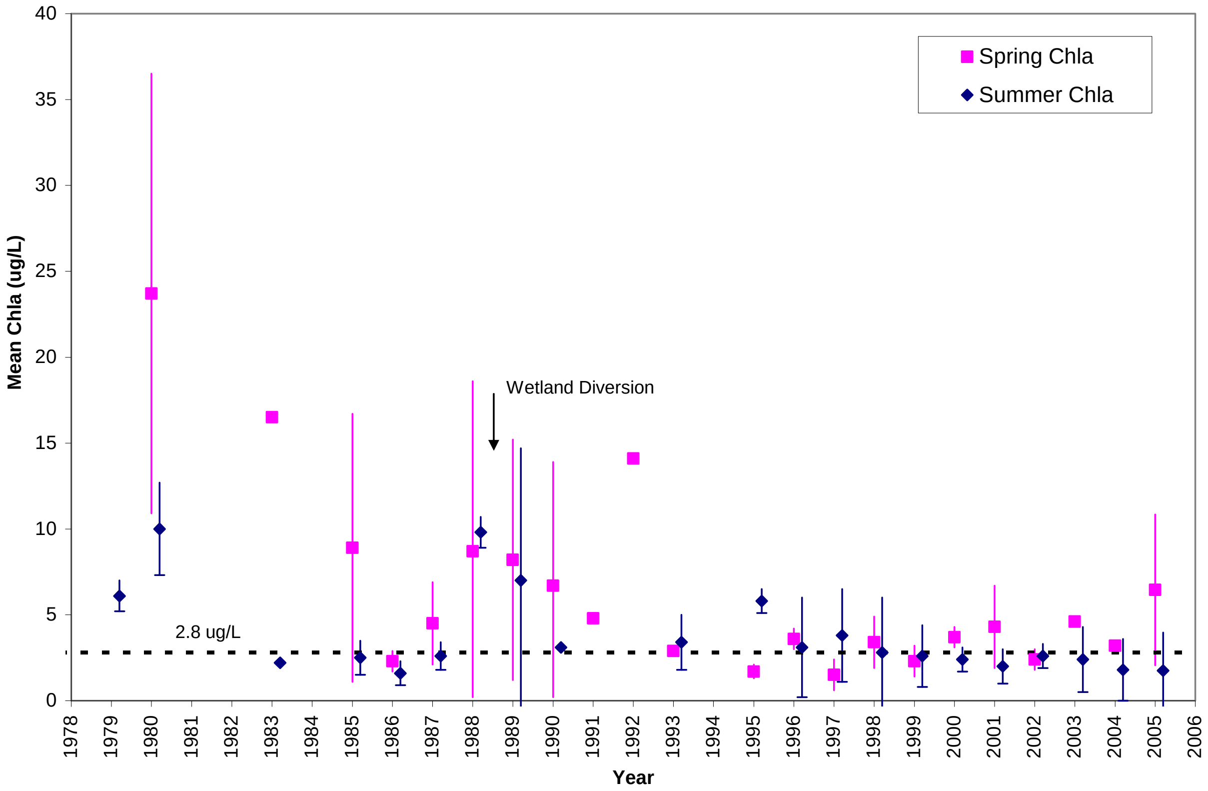

Figure 4. Mean (+/- SD) spring and summer surface (1m) chl *a* concentrations. The 2.8 µg/L line represents the water quality goal for Lake Sammamish.

A similar pattern exists for chl *a* relative to the wetland diversion. That is not surprising, because P is limiting and chl *a* correlates well with TP in most lakes. Thus, mean surface summer chl *a* was usually less than spring values in the past before diversion, but since the diversion they have been similar and lower, usually around the 2.8 µg/L level (Figure 4). That is consistent with the trends in TP. The wetland previously delivered a large fraction of the TP input to the lake, usually concentrated to the winter and spring, producing the large spring blooms. Those blooms would strip the surface water of P when the lake stratified in late spring and the algal cells sank, usually leaving the surface water low in P, and hence, low in chl *a* as the summer, low runoff period approached. The chl *a* values from spring 2005 (Figure 4) were slightly higher than other years since 1997, although TP was not consistently higher (Figure 3). As discussed above, the 2.8µg/L line is the King County summer goal for Lake Sammamish. That level is near the oligotrophic - mesotrophic boundary of 3 µg/L; 9 µg/L represents the mesotrophic – eutrophic boundary.

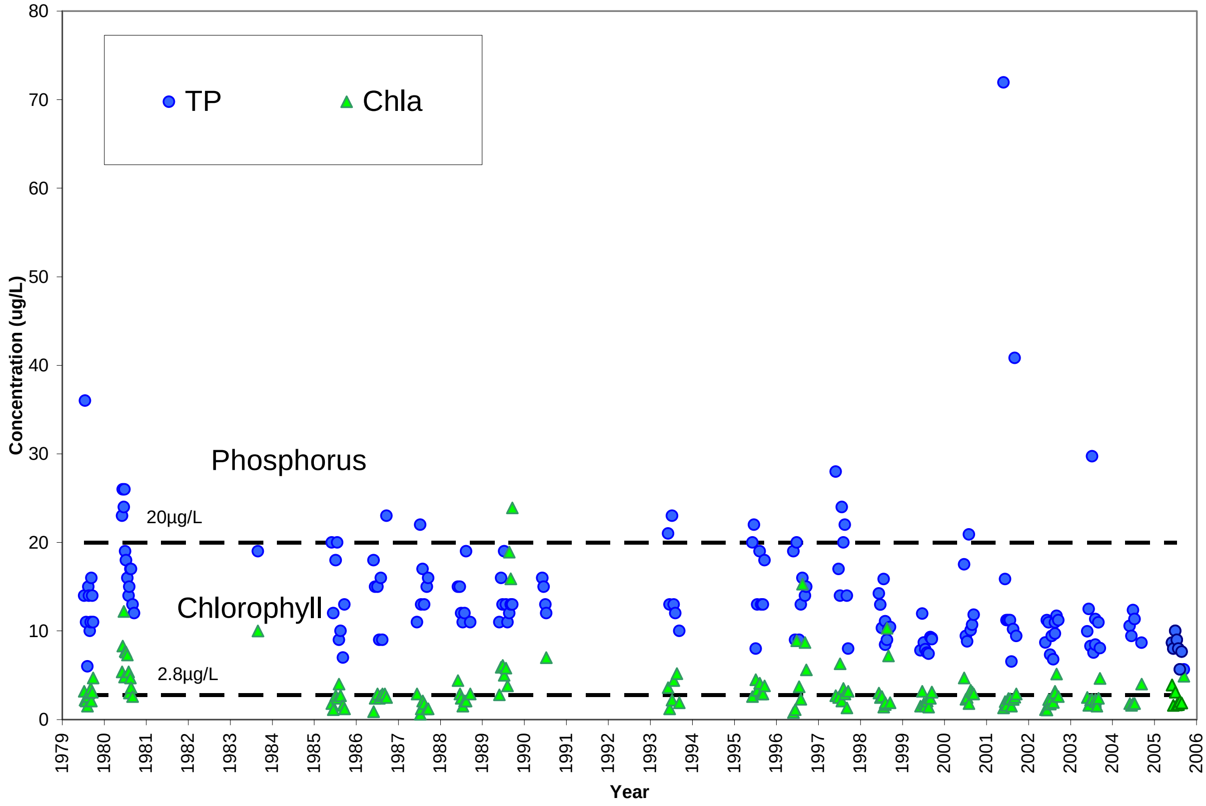

Figure 5. Summer Surface (1m) TP and Chl *a* concentration for individual dates. TPs from 1998-2004 corrected for analytical change by 1.26

To illustrate the range in conditions, surface values for TP and chl *a* on individual dates during summer are shown in Figure 5. These data show the high TP concentrations in 2001, exceeding 70 µg/L, although chl *a* did not respond to the high TP and remained low. There have been a few summer concentrations for TP over 20 µg/L and chl *a* over 10 µg/L since diversion. However, values for both TP and chl *a* were consistently low during summer 2005, and chl *a* has been at or near the 2.8 µg/L level since 2000.

4.1.2. Stratification and Winter Algal Blooms

During summer, thermal stratification persists due to warmer, less dense water overlying colder, denser water. This results in hypolimnetic water that is essentially devoid of DO. With that anoxic condition, iron in sediments reduces and allows P to diffuse from bottom sediments into overlying water resulting in a buildup of P in the hypolimnion (Figure 6). However, that high P is locked in bottom water and largely unavailable for algae in the epilimnetic lighted zone during summer. Hence, concentrations of TP and chl *a* in the epilimnion (1-3 m) are low (Figures 3-5). If wind mixing increased substantially at anytime during summer, bottom water P could diffuse and/or entrain up into the surface water and produce a summer bloom. That happens in lakes with a large wind fetch, but has not occurred in Pine Lake to any noticeable extent. A more likely cause for higher algal (chl *a*) concentrations during the summer in the past (e.g., 1989, 1996; Figure 5) would have been high surface runoff with high TP concentrations. The high epilimnetic TPs in 2001 may have been due to high runoff (Figure 5).

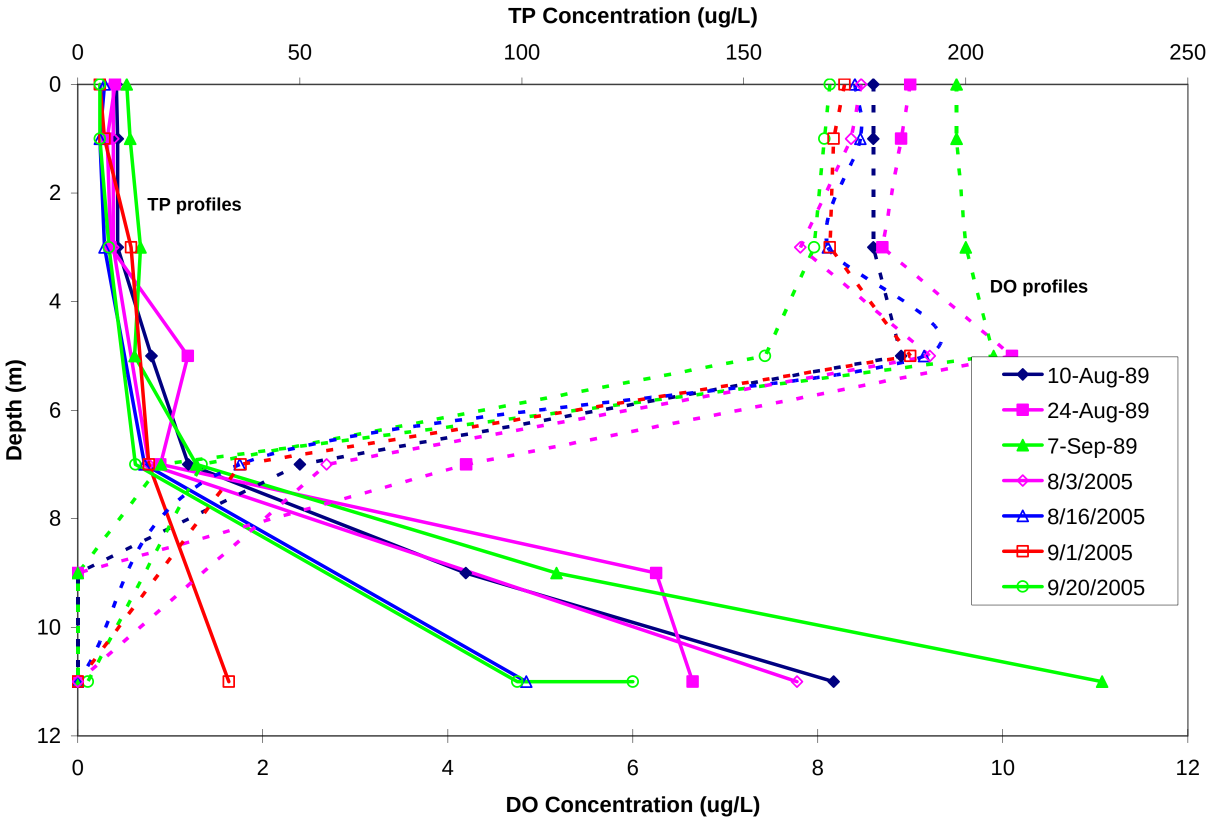

Figure 6. Profile of DO and TP during late summer in 1989 and 2005

Chlorophyll *a* was observed to accumulate during summer stratification at mid depth in 1989, with lower values near the bottom (Figure 7). The mid-depth maximums were thought to be forerunners for later winter blooms (Anderson and Welch, 1991; Jacoby et al., 1997). A mid-depth maximum probably did not occur in 2005, although the 7 and 9 m depths were not sampled for chl *a* (Figure 7). Instead, the highest chl *a* concentrations were found at the bottom – and they were higher at that depth than in 1989. Phaeophytin (dead cells) concentrations were also very high in samples from 11 m in 2005; in many instances higher than chl *a* itself. Nevertheless, the plotted chl *a* values were corrected for phaeophytin, so there were in fact high levels of bottom water chl *a* that were technically active, according to analytical procedures. These high concentrations may partly represent recruitment of vegetative cells from bottom sediment and have either contributed directly or served as an inoculum for the subsequent fall and/or winter bloom.

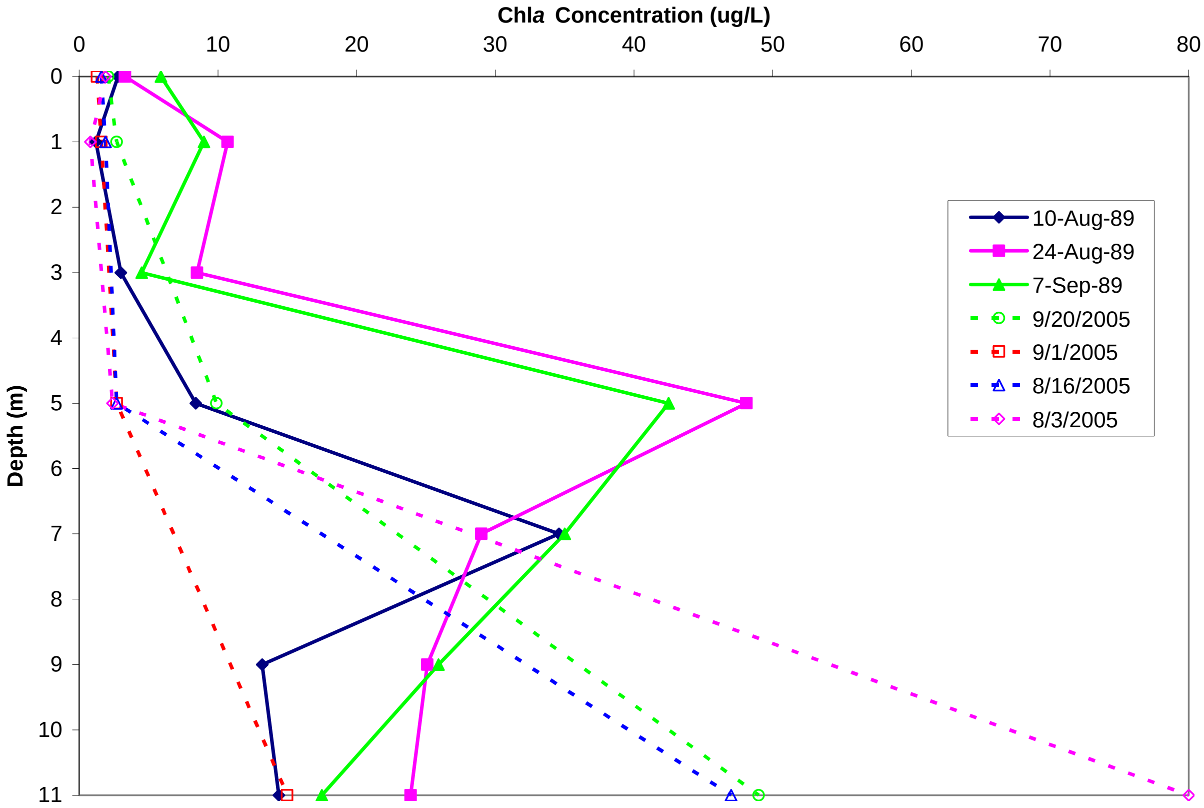

Figure 7. Profile of chla during late summer of 1989 and 2005

Thermal stratification breaks up in autumn once surface water has cooled sufficiently so that the vertical density difference is minimal. This condition results in mixing of high-P (and chl *a*) bottom with low-P surface waters. This means that hypolimnetic P is available in the lighted zone for algal growth. The January 20 profiles show higher TP and chl *a* concentrations in surface (20 µg/L) than bottom water, and much higher than in summer (Figure 8). The water column TP was partly a result of mixing high-TP bottom water throughout the lake; volume weighted, water column TP on 9/17/04 was 16 µg/L. Higher concentrations near the surface probably resulted from blue-green algae, and their cellular P, rising in the water column under quiescent conditions to maximize light availability.

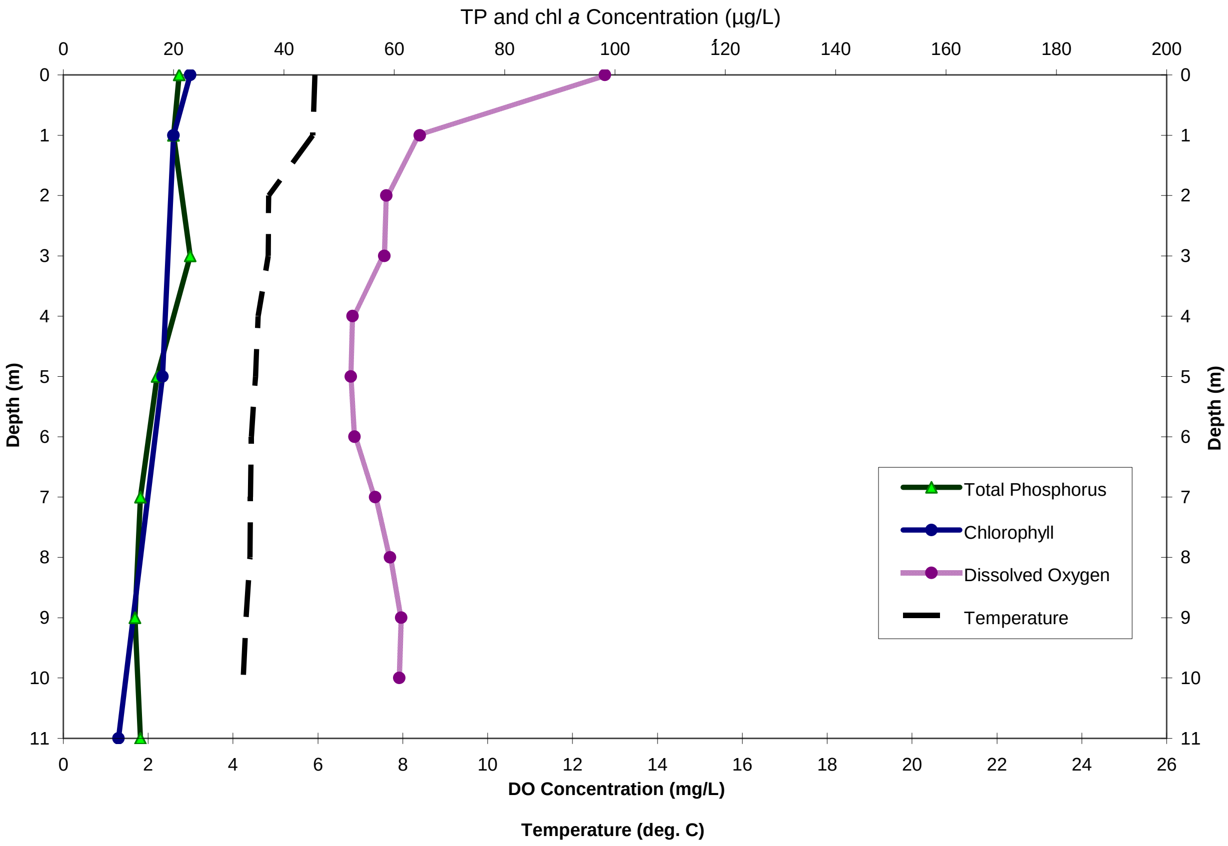

Figure 8. The profile of DO, temperature, TP and chl *a* for 1/20/05

Although incident light intensity is low in winter, blooms nevertheless occur in relatively shallow lakes. Although light in the mixed water column is usually suboptimal, there is still enough for some growth. Deep, well-mixed lakes, like Lakes Washington and Sammamish, do not have winter blooms due to light limitation, i.e., mixed algal cells spend too much time out of the photic zone under the low incident light conditions for net production to occur (gross production – respiration). The slightly warmer water at the surface and under saturated DO (~ 55%) at 1 m and below indicates a rather stable condition. However, there was mixing and reaeration, because the column-weighted DO prior to turnover was only 5 µg/L. The higher, saturated DO level at the surface was probably due to a combination of atmospheric reaeration and photosynthesis. That the water column had not mixed sufficiently three months after turnover and the under saturated condition persisted until spring is noteworthy. Blue-green algae can be buoyant and under relatively calm conditions, will rise to the surface as a highly visible bloom. The poorly mixed conditions in Pine Lake, throughout the winter, allowing blue-greens to concentrate near the surface at maximum light intensity, may account for the frequently occurring winter blooms in this lake. In contrast to Pine Lake, Lakes Sammamish and Washington, with long wind fetches, are well mixed all winter and such blooms do not occur.

Blue-green algal blooms can be initiated through recruitment of vegetative cells from the bottom sediment. *Aphanizomenon*, the bloom former in Pine Lake, was recruited from bottom sediments in Upper Klamath Lake at 650 – 1,070 mm^3/m^2 per day. These cells contained very high P concentrations (2 $\mu g/mm^3$), so this represented an internal P loading source of 1.3 – 2.1 mg/m^2 per day of TP (Barbiero and Kann, 1994). Similar P translocation rates through sediment-to-water recruitment of this taxon occurred in Green Lake, Seattle (Barbiero and Welch, 1992). Although these recruitment rates (P transport rates) occurred during summer in these lakes, the process may be occurring at other times in Pine Lake and partly account for the high hypolimnetic chl *a*.

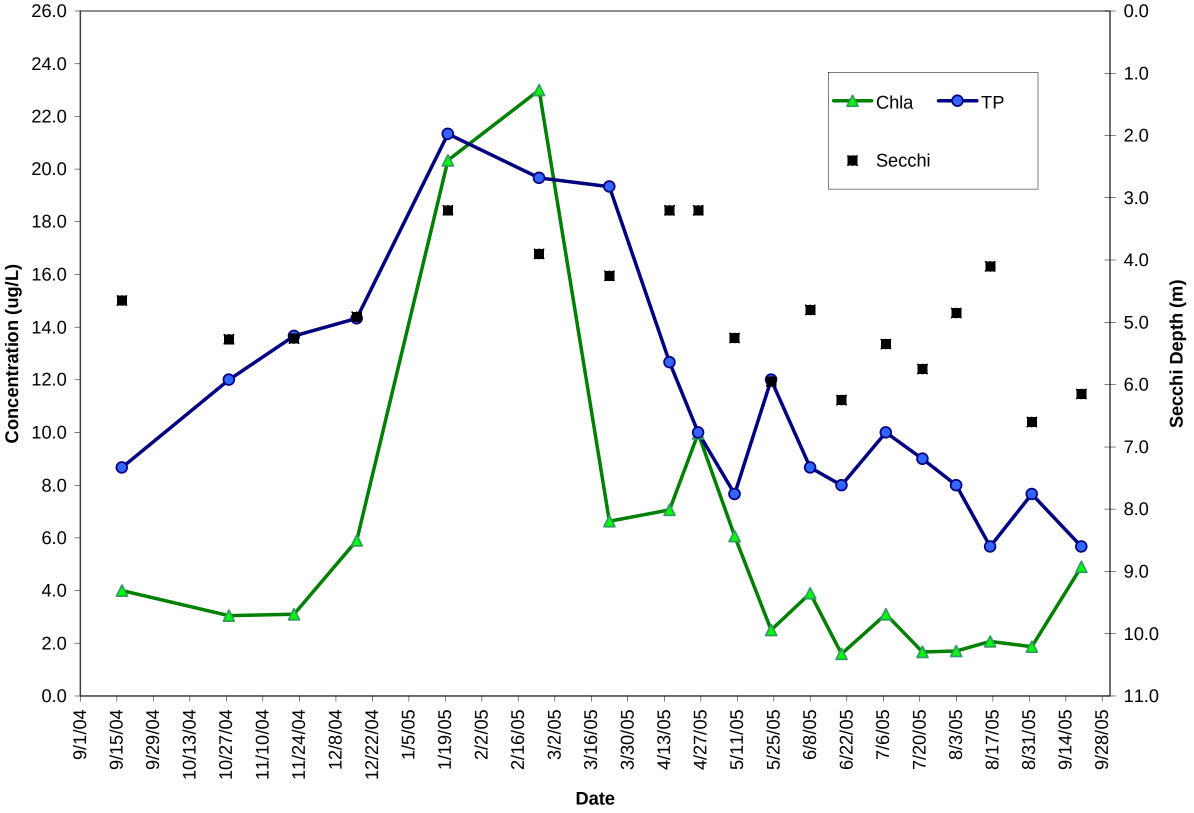

Figure 9. Surface (1m) TP, chl *a* and transparency (Secchi depth) during 2004-2005.

The winter algal bloom in 2005 had chl *a* concentrations in surface water exceeding 20 µg/L in January and February with a winter mean of 11.7 µg/L – four times the summer mean (2.9 µg/L). Figure 9 shows this bloom condition associated with an increase in TP following fall destratification, although, as noted above, the water column was rather stable. Some of that increased TP could have resulted from runoff with autumn rains, but most probably originated from mixing the hypolimnion (TP > 100 µg/L) throughout the lake as noted above.

Transparency was lowest during the winter (~ 3 m) and highest during summer ranging from 4 to 6.5 m (Figure 9). The lower winter values are due largely to the higher chl *a* concentrations but some non-algal matter may have entered the surface water via runoff. Nevertheless, the predicted depth of visibility (10% of incident light) during the bloom, given a light extinction coefficient due to algae of 0.55/m (0.025 m^2/chl x 22 mg/m^3 chl), is 4.2 m – slightly greater than was observed. While other light scattering particles besides algae were probably present to lower transparency, chl accounts for most if not all of the light scattering to produce the observed transparency.

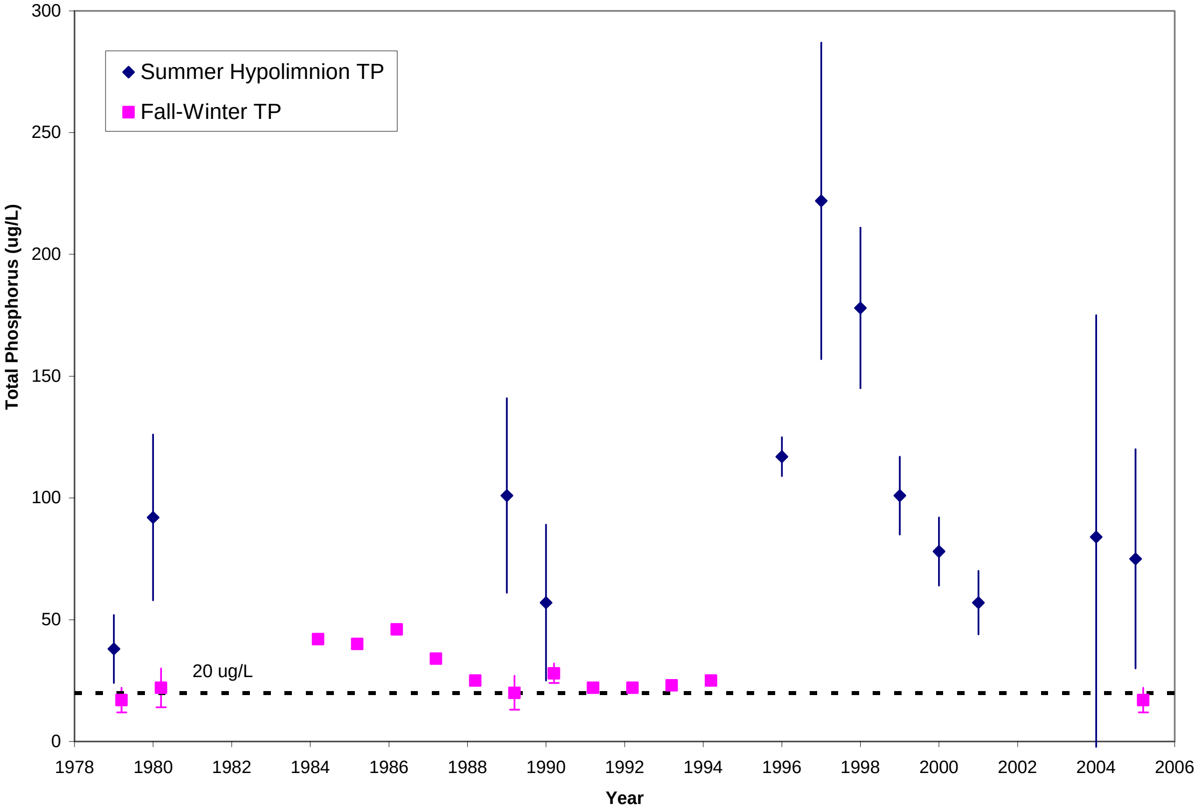

Figure 10. Hypolimnetic meanTP (9 and/or 11m) and winter surface (1-5m) TP. TPs from 1998-2003 corrected for analytical change by 1.26.

While hypolimnetic TP data are too sparse to determine if a trend in P internal loading exists with time, due to incomplete profile sampling in most years, there was no discernible difference in summer means of

9-11 m values between 1979-1980 and 1989-1990 when a considerable increase in watershed development occurred (Figure 10). While the highest means occurred in 1997-1998, much lower values followed. Values in 2004-2005 were similar to those in the 1980s. Therefore, the data do not suggest either a reduction in hypolimnetic TP (and internal P loading) due to diversion of wetland TP input or an increase due to increasing watershed development. A decline in internal loading can be expected following a reduction in input P, but several decades may be necessary. Hypolimnetic TP content and calculated rates of internal P loading declined in Lake Sammamish after several years following sewage diversion (Perkins et al., 1997).

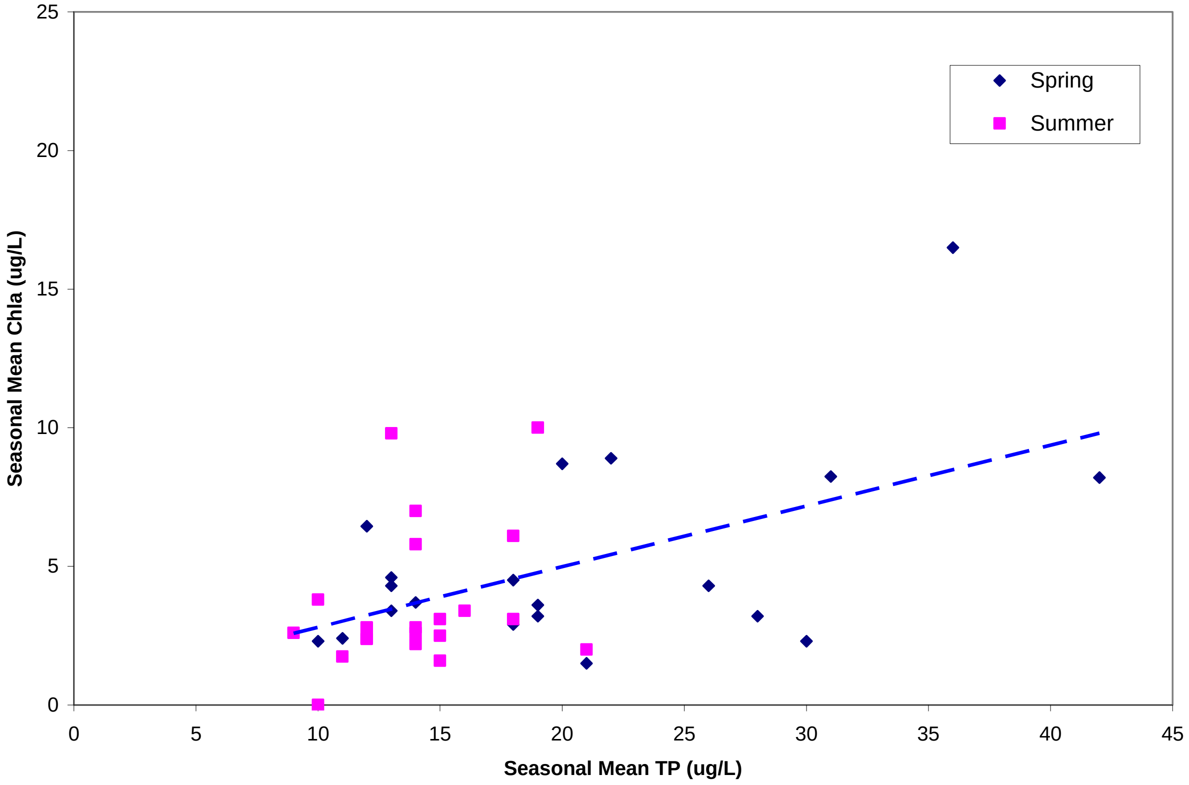

Figure 11. Relationship between mean TP and Chl *a* in surface (1m) sampled in spring and summer during 1979-2005. TPs for 1998-2004 corrected for analytical change by 1.26

The relationship between TP and chl *a* in Pine Lake is quite variable (Figure 11). The chl:TP ratio, or slope of the line in Figure 11, is 0.29. The summer means for chl *a* and TP are usually used in such relationships to predict the result of management options, because summer is the recreational period and algal growth potential is highest in summer. So if nuisance levels of algae were to develop from available nutrients, summer would be the likely seasonal period. Spring values are included in Figure 10 to utilize the higher, pre-diversion levels.

According to Figure 11, a summer mean of 20 µg/L TP should produce on average about 5.8 µg/L chl *a* in Pine Lake and 10 µg/L TP, about 2.9 µg/L chl *a*. A commonly used relationship developed from 143 North American lakes gives 6.5 and 2.3 µg/L chl *a* from those TP levels, which are similar to those predicted from Figure 11.

4.2. TREND IN WATERSHED LAND USE

The current land use in the 203 ha Pine Lake watershed is primarily light urban residential (93 ha, 45.5%) with the next largest component (49 ha) being open space (Figure 12; Table 1). Much of this light urban residential area (4 dwellings/acre) is not entirely built out (20%), as well as some medium and heavy urban residential (3%), and could be subject to redevelopment in future years. There is relatively undisturbed, lightly forested open space land that represents about 24% of the watershed. That area is definitely subject to development and is represented by the more vegetated portions of the watershed (Figure 12).

Table 1. Current and future land use in the Pine Lake watershed

	Current Area			Proposed (Future) Area		
Land-use Type	**(ha)**	**(ac)**	**% of Watershed**	**(ha)**	**(ac)**	**% of Watershed**
Open Water	35	87	17%	35	87	17%
Office	1	2	1%	1	2	1%
Commercial	3	7	2%	3	7	1%
Open Space (undeveloped)*	49	121	24%	0	0	0%
Park	0	0	0%	8	19	4%
Light Rural Residential (1 Dwelling/4 Ac)	0	0	0%	3	8	1%
Light Urban Residential (4 Dwelling/Ac)	93	231	45%	123	305	61%
Medium Urban Residential (6 Dwellings/Ac)	4	9	2%	10	24	5%
Heavy Urban Residential (8-18 Dwellings/Ac)	2	4	1%	4	10	2%
Streets / ROW	16	40	8%	16	40	8%
Total Area	**203**	**502**	**100**	**203**	**502**	**100%**

*Note: Open space denotes area currently not developed

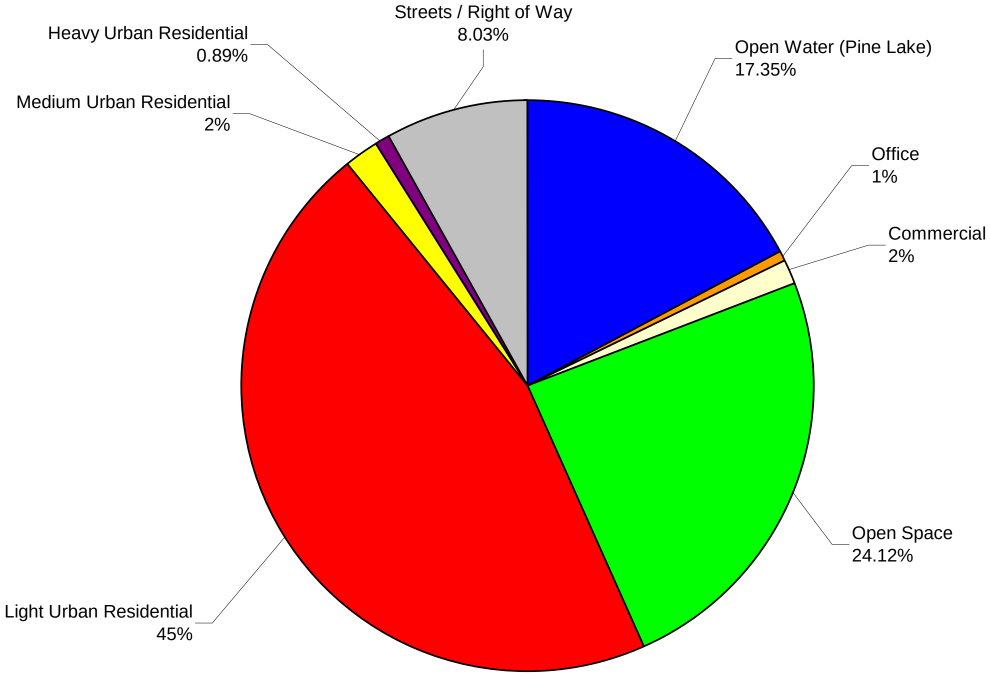

Figure 12. Pine Lake Current Land Use

Future land use projections suggest that the current open space, primarily light forest, will be developed at various levels of density depending on the zoning (Figure 13; Table 1). Park will be the only open space as shown in Figure 13. Commercial and office use will not change. The transition of undeveloped to fully developed will result in 30 ha more of light urban residential (4 dwellings/acre), 6 ha more of medium residential (6 dwellings/acre), and 2 ha more of heavy residential (8-18 dwellings/acre). Land designated for 1 dwelling/4 acres (light rural) will be a new category at 3.3 ha however is represented as the existing wetland near the south west corner of the lake. Thus, runoff from more developed land at greater density will increase as well as phosphorus loading.

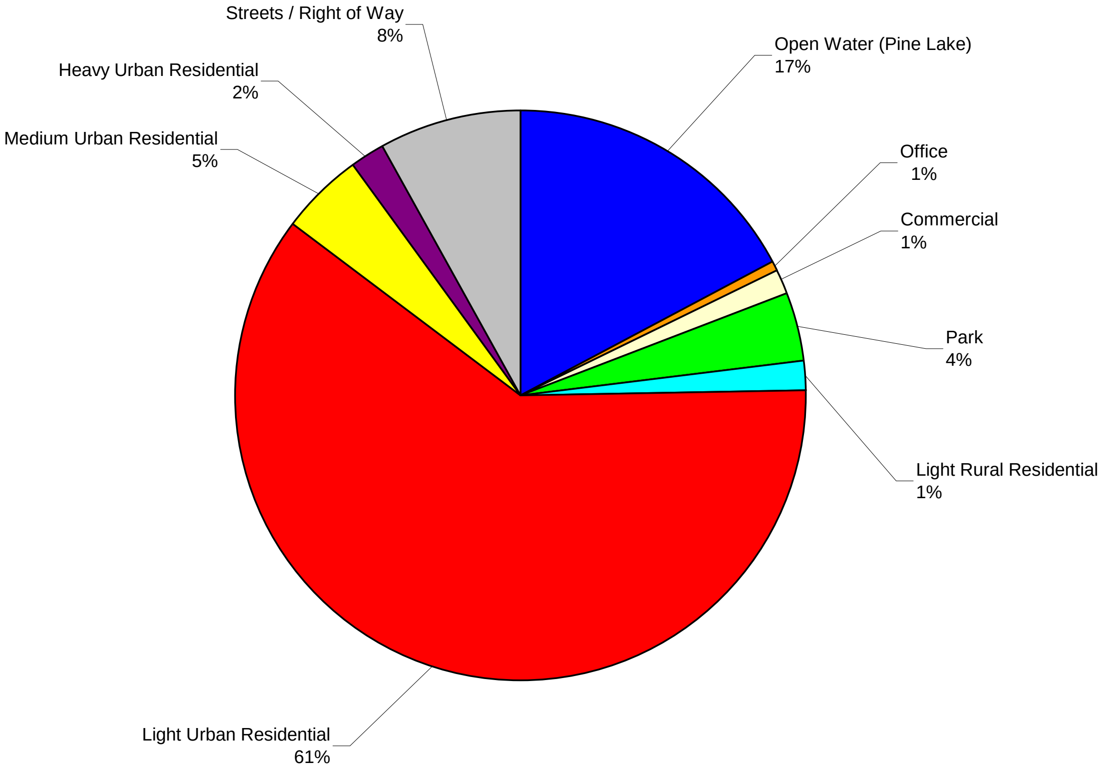

Figure 13. Pine Lake Proposed Future Land Use

4.3. WATER BUDGET

Quantification of external and internal nutrient loading is necessary to manage lake water quality. From that analysis, a nutrient prediction model for TP can be developed to predict the response of the lake's water quality. The first step in that process was to construct a water budget to quantify the loading from external sources. The water budget coincided with water quality sampling conducted by Tetra Tech (Tt) beginning in September 2004 continuing through October 2005 (2005 Water Year). The assumptions, methodology, and results for the water budget follow.

4.3.1. Physical Characteristics

The lake's watershed is primarily urban residential with all of the inflow tributaries ephemeral in flow characteristics (Figure 1, 12). Outflows from the lake are via a single outlet creek controlled by a weir that eventually discharges into Lake Sammamish.

Inflow from much of the sub-basin is conveyed through surface overland flow via roadside ditches and underground stormwater drainage pipes. Previous studies identified 6 primary inflow tributaries to the lake (Anderson et al., 1991). The 3 sub-basins that contributed the majority of flow in this study were monitored for TP concentration and discharge during the water year. Physical modification of the original 6 sub-basins has significantly changed the hydrologic characteristics. For example, 2 of the 3 basins sampled had a decrease in inflow volume, relative to the previous studies while the remaining one had increased. Figure 1 shows the inflow drainage network into Pine Lake as well as monitoring locations.

Soils within the Pine Lake watershed are composed of Alderwood gravelly sandy loam (USDA, 1973). Beneath these soils is a cemented layer of till left from glaciation. Alderwood soils range from 0.6-1.2 m with a hardpan layer beneath. All basin soils were assumed to fit the Soil Conservation Service (SCS) soil type “C”, which is typically characterized by moderate runoff rates and mild permeability.

Pine Lake has a surface area of 35 ha at an elevation of 115 m. Average depth is 5.9 m with a maximum of 11.9 m. Estimated storage is 2,100,000 m^3. Using bathymetry data from previous studies, a stage-storage rating curve was developed (Bortelson et al., 1976, Anderson et al., 1991). A surface area of 352,886 m^2 was calculated within ArcGIS and a digitized shoreline was delineated from the aerial photograph. This surface area will be used for the water budget. The Pine Lake stage-storage relationship is shown in Table 2 and Figure 14.

Table 2. Pine Lake Stage-Area-Storage Table

Depth (m)	**Surface Area (m^2)**	**Volume (m^3)**
0.0	352,886	2,096,833
1.0	323,921	1,789,833
2.0	294,841	1,482,833
3.0	265,647	1,181,351
4.0	236,338	937,544
5.0	206,916	720,084
6.0	177,378	531,265
7.0	147,726	371,085
8.0	117,960	239,546
9.0	88,079	136,647
10.0	58,084	62,387
11.0	27,975	16,768
11.9	0	0

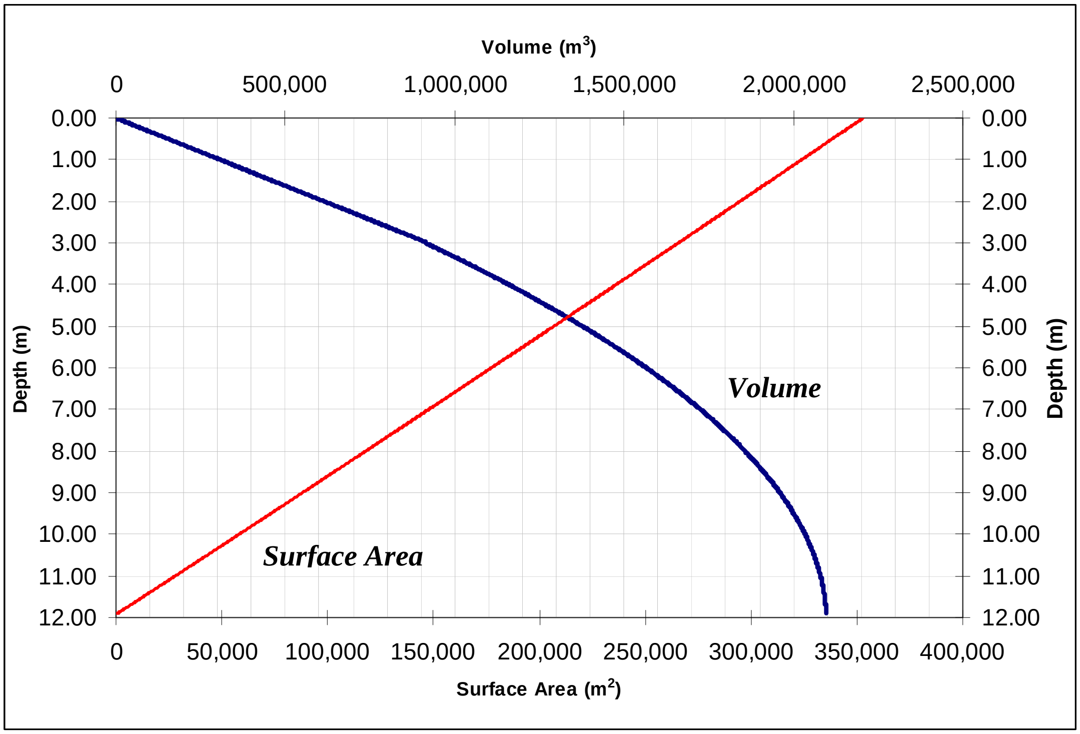

Figure 14. Lake Surface area and volume related to depth for Pine Lake (Derived from Bortelson et al., 1976)

4.3.2. Model development

A bi-weekly time-step water budget was determined for the water year. The budget is based on the conservation of mass (Equation 8). Inflow components included direct precipitation on the lake surface, stormwater runoff derived from a rainfall-runoff relationship, and a seasonal groundwater contribution. Outflow components include evaporation, outlet discharge, and a seasonal groundwater loss (Equation 9).

$$I(t) - O(t) = \frac{\Delta S}{dt} \qquad \text{Eq. 8}$$

Where:

I(t) – Inflow contribution (m^3/time)

O(t) – Outflow contribution (m^3/time)

$\frac{\Delta S}{dt}$ - Change in lake storage (m^3/time)

$$\frac{\Delta S}{dt} = (I_{\Pr ecip} + I_{Runoff} + I_{GW}) - (O_{Evap} + O_{Disch\arg e} + O_{GW}) \qquad \text{Eq. 9}$$

Where:

I_{Precip} – Inflow contribution from direct precipitation on the lake surface
I_{Runoff} – Inflow contribution from direct runoff from the drainage basin
O_{GW} – Inflow contribution from groundwater
O_{Evap} – Outflow contribution from evaporation
$O_{Discharge}$ – Outflow contribution from outlet discharge
O_{GW} – Outflow from groundwater

The rationale for determining each quantity follows. These data will be used in the TP budget as well as the non-steady state TP model. A bi-weekly time-step was chosen to coincide with the monitoring results.

4.3.3. Inflow Components

Inflow components into the lake consist of three parts; direct precipitation on the surface, runoff, and groundwater. Precipitation on the lake surface and its drainage basin was based on daily measurements recorded by the Sammamish Sewer and Water District (SSWD) and measurements collected by citizen volunteers. The SSWD site was used in the budget due to its daily frequency and its close proximity to the watershed. However, lake citizen readings were strongly correlated with SSWD data. Precipitation during the 2005 WY was 92.6 cm (36.5 in), approximately 8 percent below normal. A maximum 1-day total of 4.78 cm (1.88 inches) was recorded on March 28, 2005.

The volume of precipitation falling directly on the lake was calculated on a daily basis using a constant lake surface area of 352,886 m^2 and summarized into bi-weekly totals (Table 3). The 2005 WY total for direct precipitation was 326,892 m^3.

Table 3. Direct Precipitation on Pine Lake for the 2005WY

Bi-Week Number	**Date Range**		**Rainfall Total**		**Precipitation Volume**
	From	**To**	**(cm)**	**(in)**	**(m^3)**
1	**10/1/2004**	**10/9/2004**	**0.74**	**0.29**	**2,599**
2	**10/10/2004**	**10/23/2004**	**5.36**	**2.11**	**18,913**
3	**10/24/2004**	**11/6/2004**	**5.05**	**1.99**	**17,837**
4	**11/7/2004**	**11/20/2004**	**2.64**	**1.04**	**9,322**
5	**11/21/2004**	**12/4/2004**	**4.62**	**1.82**	**16,313**
6	**12/5/2004**	**12/18/2004**	**11.51**	**4.53**	**40,604**
7	**12/19/2004**	**1/1/2005**	**3.86**	**1.52**	**13,624**
8	**1/2/2005**	**1/15/2005**	**1.50**	**0.59**	**5,288**
9	**1/16/2005**	**1/29/2005**	**7.34**	**2.89**	**25,904**
10	**1/30/2005**	**2/12/2005**	**1.73**	**0.68**	**6,095**
11	**2/13/2005**	**2/26/2005**	**0.20**	**0.08**	**717**
12	**2/27/2005**	**3/12/2005**	**0.69**	**0.27**	**2,420**
13	**3/13/2005**	**3/26/2005**	**3.05**	**1.20**	**10,756**
14	**3/27/2005**	**4/9/2005**	**10.46**	**4.12**	**36,929**
15	**4/10/2005**	**4/23/2005**	**4.83**	**1.90**	**17,030**
16	**4/24/2005**	**5/7/2005**	**2.34**	**0.92**	**8,246**
17	**5/8/2005**	**5/21/2005**	**6.68**	**2.63**	**23,573**
18	**5/22/2005**	**6/4/2005**	**3.18**	**1.25**	**11,204**
19	**6/5/2005**	**6/18/2005**	**4.70**	**1.85**	**16,582**
20	**6/19/2005**	**7/2/2005**	**1.19**	**0.47**	**4,213**
21	**7/3/2005**	**7/16/2005**	**3.15**	**1.24**	**11,114**
22	**7/17/2005**	**7/30/2005**	**1.09**	**0.43**	**3,854**
23	**7/31/2005**	**8/13/2005**	**0.00**	**0.00**	**0**
24	**8/14/2005**	**8/27/2005**	**0.38**	**0.15**	**1,344**
25	**8/28/2005**	**9/10/2005**	**1.70**	**0.67**	**6,005**
26	**9/11/2005**	**9/24/2005**	**3.53**	**1.39**	**12,459**
27	**9/25/2005**	**9/30/2005**	**1.12**	**0.44**	**3,944**
		2005 WY	**92.6**	**36.5**	**326,892**

As previously mentioned, the majority of stormwater runoff is conveyed through roadside ditches (Figure 1). The whole watershed area of 1,680,538 m^2 was used to estimate a total inflow. Several small stormwater storage areas exist within the watershed, however, their detention time was estimated to be within the two-week time step for the budget.

Using the SCS-Runoff method from guidelines established in Volume III of *Stormwater Water Management Manual for Western Washington*, a weighted curve number (CN) of 85.10 was calculated for the drainage basin based on the land use (Table 4 DOE, 2001). This method was used for previous water budgets (Welch et al, 1981; Dion et al, 1983; Anderson et al, 1991). Corrections to the pervious curve numbers (CNp) were made to account for impervious area (CNc) (NRCS, 1986). Impervious areas are likely to show a rainfall excess during periods of rainfall with rates greater than 0.25 cm/day (approximately 0.1 in/day) at daily totals less that 20 percent of the storage component (S). Runoff during these times was estimated only for impervious areas assuming a direct connection to the lake. Runoff depths were calculated on a daily basis using Equation 10 and multiplied by the basin area. Resulting daily runoff volumes were summarized into bi-weekly totals. No adjustments to the hydrograph shape were necessary, due to the short time interval and a bi-weekly time-step interval in the water budget. Monthly direct runoff volumes are shown in Table 5.

Table 4. Pine Lake Weighted Curve Number by Land Use Type

Land-use Type	Soil Type	Area (m^2)	Impervious %	CNp	CNc
Open Water	C	352886	-	-	
Open Space	C	490562	0	72	72
Office	C	8182	85%	93	97
Commercial	C	28668	85%	94	97
Light Urban Residential (4 Dwelling/Ac)	C	934847	38%	83	89
Medium Urban Residential (6 Dwellings/Ac)	C	36888	38%	90	93
Heavy Urban Residential (8-18 Dwellings/Ac)	C	18165	65%	94	97
Streets / ROW	-	163226	100%	98	98
			Weighted CN	**81.75**	**85.10**

$$Q_d = \frac{(P-0.2S)^2}{P+0.8S}, P \geq 0.2S$$

$$Q_d = 0, P < 0.2S \qquad \text{Eq. 10}$$

$$S = \frac{1000}{CN} - 10$$

Where:

Q_d - Runoff depth (inches)

P – Daily precipitation totals (inches)

CN – SCS curve number (dimensionless)

Table 5. Runoff Volumes into Pine Lake for the 2005WY

Bi-Week Number	Date Range		Runoff Volume	Mean Discharge
	From	To	(m^3)	(m^3/s)
1	10/1/2004	10/9/2004	389	0.001
2	10/10/2004	10/23/2004	14,262	0.012
3	10/24/2004	11/6/2004	13,274	0.011
4	11/7/2004	11/20/2004	1,565	0.001
5	11/21/2004	12/4/2004	9,072	0.007
6	12/5/2004	12/18/2004	24,675	0.020
7	12/19/2004	1/1/2005	2,274	0.002
8	1/2/2005	1/15/2005	972	0.001
9	1/16/2005	1/29/2005	21,801	0.018
10	1/30/2005	2/12/2005	1,397	0.001
11	2/13/2005	2/26/2005	389	0.000
12	2/27/2005	3/12/2005	778	0.001
13	3/13/2005	3/26/2005	3,032	0.003
14	3/27/2005	4/9/2005	35,666	0.029
15	4/10/2005	4/23/2005	12,378	0.010
16	4/24/2005	5/7/2005	1,556	0.001
17	5/8/2005	5/21/2005	8,607	0.007
18	5/22/2005	6/4/2005	2,076	0.002
19	6/5/2005	6/18/2005	7,654	0.006
20	6/19/2005	7/2/2005	972	0.001
21	7/3/2005	7/16/2005	2,254	0.002
22	7/17/2005	7/30/2005	799	0.001
23	7/31/2005	8/13/2005	0	0.000
24	8/14/2005	8/27/2005	389	0.000
25	8/28/2005	9/10/2005	892	0.001
26	9/11/2005	9/24/2005	12,592	0.010
27	9/25/2005	9/30/2005	576	0.001
		2005 WY Total	180,291	0.006

4.3.4. Outflow Components

The majority of the lake’s outflow was through the outlet discharge to the headwaters of Pine Lake Creek. The outlet from the lake is composed of a single trapezoidal channel that is controlled by a sharp crested weir installed in the early 1990s (Harvey Miller, 12/1/2005 Pers. Comm.; Anderson et al., 1991). The channel width varies from approximately 3 m at the widest point to 1 m near the outlet weir. The weir is constructed of multiple stop logs with a low flow notch (Figure 15). A composite rating curve was constructed to account for the influence of the low-flow notch and overflow spill way (Figure 16). Discrete measurements and corresponding stage measurements of direct outlet discharge were used to verify the rating curve for the outlet weir. The revised rating curve was based on depth above the low-flow invert. As shown in Figure 15, debris accumulation at the weir can substantially affect the rating curve especially in the water budget, for high flow events. Debris blockage was not taken into account except for known beaver activity described later on.

Figure 15. Pine Lake Outlet Weir

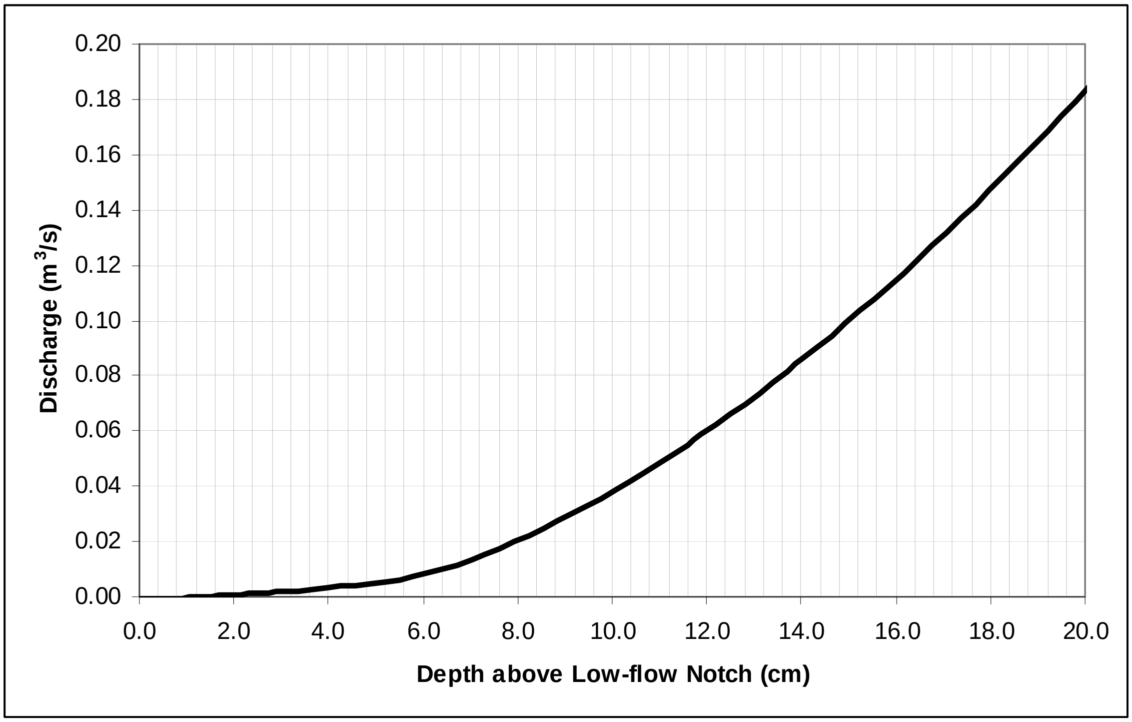

Figure 16. Pine Lake Outlet Weir Rating Curve

Daily stage measurements were recorded by lake residents (Miller, unpublished) and were adjusted to the project datum. Discharges for the corresponding stages were calculated using the rating curve displayed in Figure 16. During the 2005WY, outflow via the weir occurred only from mid-December through April. Resident beaver activity at the weir, from April 24th to May 8th, 2005, resulted in dam construction that blocked all outlet flow for the remainder of the monitoring period. Despite efforts to breakup the dam, the beaver quickly reconstructed it.

Table 6. Pine Lake Bi-weekly Outlet Discharge Volumes for 2005WY

Bi-Week Number	Date Range		Outflow Volume (m³)	Average Stage (cm)
	From	To		
1	10/1/2004	10/9/2004	0	-47.2
2	10/10/2004	10/23/2004	0	-45.3
3	10/24/2004	11/6/2004	0	-44.1
4	11/7/2004	11/20/2004	0	-41.1
5	11/21/2004	12/4/2004	0	-37.4
6	12/5/2004	12/18/2004	0	-15.2
7	12/19/2004	1/1/2005	1,018	1.4
8	1/2/2005	1/15/2005	965	1.5
9	1/16/2005	1/29/2005	32,966	8.4
10	1/30/2005	2/12/2005	11,827	6.3
11	2/13/2005	2/26/2005	3,545	3.2
12	2/27/2005	3/12/2005	185	0.3
13	3/13/2005	3/26/2005	435	0.2
14	3/27/2005	4/9/2005	24,087	7.1
15	4/10/2005	4/23/2005	10,202	5.6
16	4/24/2005	5/7/2005	1,906	4.5
17	5/8/2005	5/21/2005	0	7.2
18	5/22/2005	6/4/2005	0	9.0
19	6/5/2005	6/18/2005	0	6.6
20	6/19/2005	7/2/2005	0	1.4
21	7/3/2005	7/16/2005	0	-3.2
22	7/17/2005	7/30/2005	0	-8.9
23	7/31/2005	8/13/2005	0	-17.6
24	8/14/2005	8/27/2005	0	-24.8
25	8/28/2005	9/10/2005	0	-31.8
26	9/11/2005	9/24/2005	0	-33.5
27	9/25/2005	9/30/2005	0	-35.8
		2005 WY	87,135	-12.0

Evaporation depths were determined using the FAO Penman Equation (Doorenbos and Pruitt, 1977) on a monthly time step with Equation 11. Daily maximum and minimum temperature, wind speed, and albedo data recorded at Lake Sammamish were used to calculate evaporation rates adjusted to Pine Lake. Adjustments were made based on previous relationships from measurements at Seattle-Tacoma Airport (Ducken, 1990). Evaporation depths were summarized into bi-weekly totals and applied to the constant surface area of the lake (Table 7).

$$ET_o = C_P((W * R_n) + (1 - W)(0.27)(1 + U/100)(e_s - e_a)) \qquad \text{Eq. 11}$$

Where:

ET_o – Evapotranspiration, mm/day

R_n – Net radiation in equivalent evaporation in mm/day

W – Weighting factor dependent on temperature and altitude, mb/degrees C

U – 24 hour wind run at 2 meters in height, km/day

E_s – Saturation vapor pressure obtained at the mean temperature, mb

E_a – Mean actual vapor pressure at the daily average dewpoint, mb

C_p – Adjustment factor dependent on maximum relative humidity, solar radiation, daytime windspeed, and the ratio of daytime to nighttime windspeed

Table 7. Bi-weekly Evaporation Volumes from Pine Lake

Bi-Week Number	Date Range		Evaporation Rate	Evaporation Volume
	From	To	(cm/day)	(m^3)
1	10/1/2004	10/9/2004	0.09	2,952
2	10/10/2004	10/23/2004	0.12	5,902
3	10/24/2004	11/6/2004	0.10	5,163
4	11/7/2004	11/20/2004	0.07	3,567
5	11/21/2004	12/4/2004	0.07	3,444
6	12/5/2004	12/18/2004	0.06	2,952
7	12/19/2004	1/1/2005	0.04	1,968
8	1/2/2005	1/15/2005	0.05	2,460
9	1/16/2005	1/29/2005	0.06	3,198
10	1/30/2005	2/12/2005	0.08	4,182
11	2/13/2005	2/26/2005	0.14	6,883
12	2/27/2005	3/12/2005	0.18	8,724
13	3/13/2005	3/26/2005	0.19	9,215
14	3/27/2005	4/9/2005	0.32	15,975
15	4/10/2005	4/23/2005	0.25	12,534
16	4/24/2005	5/7/2005	0.43	21,135
17	5/8/2005	5/21/2005	0.28	14,010
18	5/22/2005	6/4/2005	0.28	14,006
19	6/5/2005	6/18/2005	0.49	24,208
20	6/19/2005	7/2/2005	0.38	18,922
21	7/3/2005	7/16/2005	0.62	30,843
22	7/17/2005	7/30/2005	0.44	21,873
23	7/31/2005	8/13/2005	0.48	23,592
24	8/14/2005	8/27/2005	0.52	25,560
25	8/28/2005	9/10/2005	0.30	14,991
26	9/11/2005	9/24/2005	0.26	13,025
27	9/25/2005	9/30/2005	0.42	7,373
		2005 WY	0.25	318,657

4.3.5. Groundwater

The inflow and outflow of groundwater was not determined directly. Instead, groundwater contributions were estimated from relationships determined in previous studies (Table 8; Dion et al., 1983). Groundwater movement was transversal through the lake, entering along the northeast and discharging via the southwest, which was assumed to be the current condition.

Table 8. Monthly Net Groundwater Contributions

Bi-Week Number	Date Range		Net Ground Water Contribution (m^3) (+inflow / -outflow)
	From	To	
1	10/1/2004	10/9/2004	112
2	10/10/2004	10/23/2004	813
3	10/24/2004	11/6/2004	69
4	11/7/2004	11/20/2004	19
5	11/21/2004	12/4/2004	39
6	12/5/2004	12/18/2004	690
7	12/19/2004	1/1/2005	232
8	1/2/2005	1/15/2005	386
9	1/16/2005	1/29/2005	1891
10	1/30/2005	2/12/2005	354
11	2/13/2005	2/26/2005	38
12	2/27/2005	3/12/2005	166
13	3/13/2005	3/26/2005	753
14	3/27/2005	4/9/2005	2654
15	4/10/2005	4/23/2005	1294
16	4/24/2005	5/7/2005	987
17	5/8/2005	5/21/2005	3371
18	5/22/2005	6/4/2005	1300
19	6/5/2005	6/18/2005	1526
20	6/19/2005	7/2/2005	388
21	7/3/2005	7/16/2005	3079
22	7/17/2005	7/30/2005	1068
23	7/31/2005	8/13/2005	0
24	8/14/2005	8/27/2005	246
25	8/28/2005	9/10/2005	929
26	9/11/2005	9/24/2005	1333
27	9/25/2005	9/30/2005	422
		2005 WY	24158

4.4. Water budget results

The previously described analyses resulted in a bi-weekly time-step water budget shown in Table 9 and summarized graphically on an annual basis in Figure 17. Total inflow contribution minus net contribution from groundwater resulted in 51% of the annual budget due to surface input. Outflow contributions were 42% of the budget with the remaining 7% represented by net change in lake storage and subsurface groundwater. A positive annual residual term of 87,000 m^3 indicates slightly more water entering the lake than measured (~13% of the total outflow budget). Comparisons with previous budgets show no direct indication of the source of error with inflows and outflows that were likely to be overestimated or underestimated, respectively.

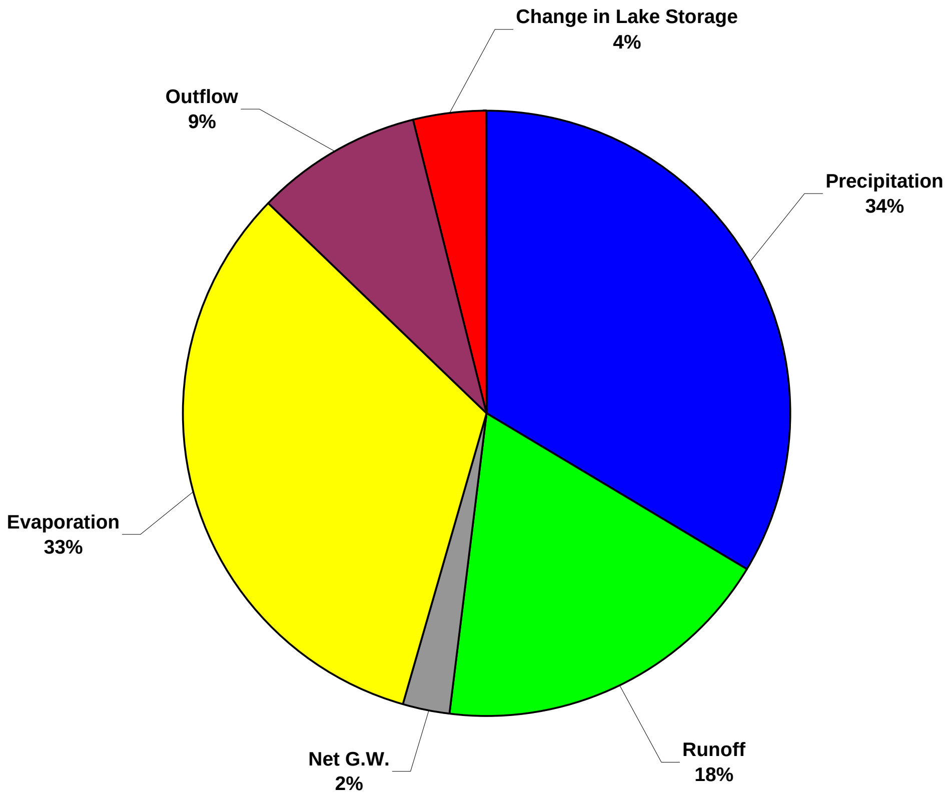

Figure 17. Water Budget for Pine Lake from December 2004 through October 2005 (precipitation 93.4 cm).

Table 9. Monthly Water Budget for Pine Lake from December 2004 through October 2005

All Measurements in m^3 x 10^{-3}

Bi-Week Number	Date Range		Inflows				Outflows				Change in Lake Storage		Residual
	From	To	Precipitation	Runoff	Deep G.W.	Total	Evaporation	Outflow	Deep G.W.	Total			
1	10/1/2004	10/9/2004	2.6	0.4	0.1	3.1	3.0	0.0	0.0	3.0	5.4		-5.2
2	10/10/2004	10/23/2004	18.9	14.3	0.9	34.0	5.9	0.0	0.1	6.0	-6.0		34.1
3	10/24/2004	11/6/2004	17.8	13.3	0.2	31.3	5.2	0.0	0.1	5.3	20.2		5.8
4	11/7/2004	11/20/2004	9.3	1.6	0.1	11.0	3.6	0.0	0.1	3.6	-1.1		8.5
5	11/21/2004	12/4/2004	16.3	9.1	0.2	25.6	3.4	0.0	0.1	3.6	19.1		2.9
6	12/5/2004	12/18/2004	40.6	24.7	0.8	66.1	3.0	0.0	0.1	3.0	114.8		-51.8
7	12/19/2004	1/1/2005	13.6	2.3	0.3	16.2	2.0	1.0	0.0	3.0	4.9		8.2
8	1/2/2005	1/15/2005	5.3	1.0	0.4	6.7	2.5	1.0	0.0	3.4	0.3		2.9
9	1/16/2005	1/29/2005	25.9	21.8	1.9	49.6	3.2	33.0	0.1	36.2	19.1		-5.7
10	1/30/2005	2/12/2005	6.1	1.4	0.4	7.9	4.2	11.8	0.0	16.0	-7.9		-0.3
11	2/13/2005	2/26/2005	0.7	0.4	0.0	1.1	6.9	3.5	0.0	10.4	-13.4		4.1
12	2/27/2005	3/12/2005	2.4	0.8	0.2	3.4	8.7	0.2	0.0	8.9	-6.3		0.7
13	3/13/2005	3/26/2005	10.8	3.0	0.8	14.6	9.2	0.4	0.0	9.7	13.6		-8.7
14	3/27/2005	4/9/2005	36.9	35.7	2.7	75.3	16.0	24.1	0.0	40.1	-2.5		37.7
15	4/10/2005	4/23/2005	17.0	12.4	1.3	30.7	12.5	10.2	0.0	22.8	13.5		-5.6
16	4/24/2005	5/7/2005	8.2	1.6	1.0	10.8	21.1	1.9	0.0	23.1	-7.5		-4.7
17	5/8/2005	5/21/2005	23.6	8.6	3.5	35.6	14.0	0.0	0.1	14.1	19.8		1.8
18	5/22/2005	6/4/2005	11.2	2.1	1.3	14.6	14.0	0.0	0.0	14.0	-7.4		8.0
19	6/5/2005	6/18/2005	16.6	7.7	1.6	25.8	24.2	0.0	0.0	24.3	-6.0		7.5
20	6/19/2005	7/2/2005	4.2	1.0	0.4	5.6	18.9	0.0	0.0	18.9	-24.5		11.2
21	7/3/2005	7/16/2005	11.1	2.3	3.2	16.6	30.8	0.0	0.1	31.0	-12.1		-2.3
22	7/17/2005	7/30/2005	3.9	0.8	1.1	5.8	21.9	0.0	0.0	21.9	-26.2		10.0
23	7/31/2005	8/13/2005	0.0	0.0	0.0	0.0	23.6	0.0	0.0	23.6	-29.8		6.2
24	8/14/2005	8/27/2005	1.3	0.4	0.3	2.0	25.6	0.0	0.0	25.6	-17.3		-6.3
25	8/28/2005	9/10/2005	6.0	0.9	1.0	7.9	15.0	0.0	0.0	15.0	-12.3		5.1
26	9/11/2005	9/24/2005	12.5	12.6	1.4	26.5	13.0	0.0	0.1	13.1	-16.8		30.1
27	9/25/2005	9/30/2005	3.9	0.6	0.4	5.0	7.4	0.0	0.0	7.4	4.7		-7.1
		Sub-Totals	***327***	***180***	***25***	***533***	***319***	***87***	***1***	***407***	***39***		***87***

4.4.1. Typical Wet / Dry Water Year Budget

Typical wet and dry water year budgets were constructed based on review of 57 years of precipitation measurements at SeaTac Airport. A wet year was classified as annual precipitation totals within the 80th percentile of records while a dry year was within the 20th percentile. A summary of these statistics is shown in Table 10.

Table 10. Summary Statistics of Rainfall Totals at SEATAC, Washington

	SEATAC Annual Totals	
Measure	**(cm)**	**(in)**
Average	**95.4**	**37.6**
Std. Dev	**19.6**	**7.7**
20th Percentile (Dry Year)	**78.3**	**30.8**
80th Percentile (Wet Year)	**114.4**	**45.0**
n	**57**	**57**

Annual precipitation totals recorded at the SSWD office were compared with those from SeaTac for the 1980, 1990, and 2005WY budgets. As an annual average, the lake has received between 20 to 25 percent more precipitation than was recorded at SeaTac during the past five years of record. Annual ranking of SeaTac data suggests that both the 1980WY and 1990WY budgets represented average precipitation totals, while the 2005WY water budget represented a typical dry year. Using a conversion factor of 1.23 times the typical wet year precipitation total at SeaTac resulted in an equivalent 140.7cm (55.4 in) falling on the Pine Lake watershed.

To provide a range of predictions of lake quality a typical wet year water budget was developed using the methods described earlier for 140.7 cm of precipitation. Using the relationship between precipitation-runoff developed above, the wet-year total was scaled to the temporal rainfall distribution observed in 2005WY. Additionally, groundwater (inflow and outflow) was adjusted to represent an equivalent wet year. Lake levels and discharge over the outlet weir were synthesized using volumetric inflow estimates and stage/storage/discharge relationships. The resulting typical wet year water budget is shown in Table 11 and Figure 18 and is based on the same temporal distribution experienced during 2005. Resulting volumes were used to estimate an upper limit of lakes response to increased inflows.

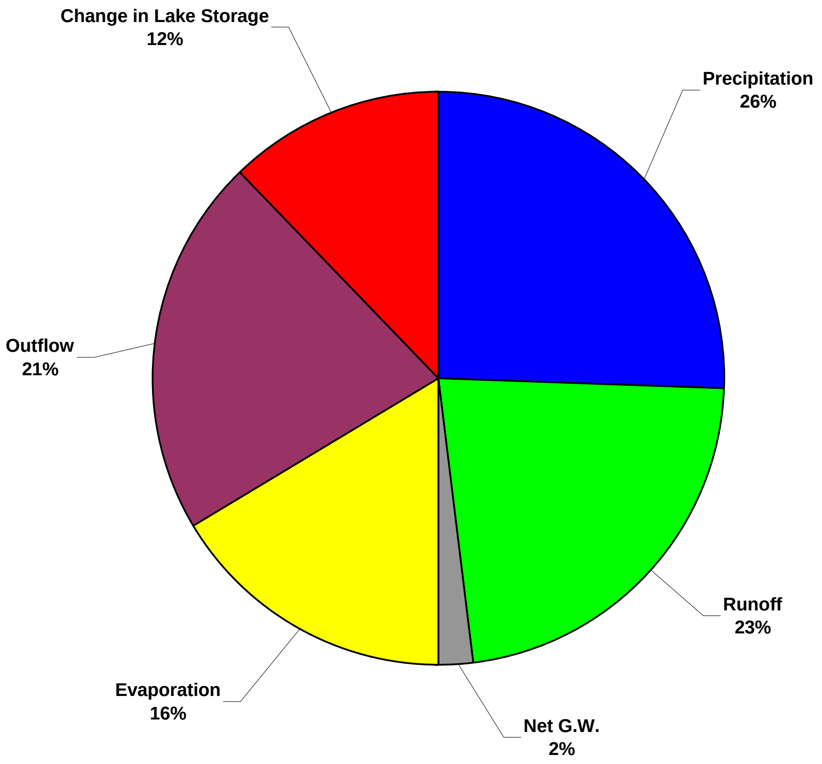

Figure 18. Typical Wet Year (Precipitation greater than 140.7cm) Water Budget at Pine Lake

Table 11. Typical Wet Year (Precipitation greater than 140.7cm) Water Budget at Pine Lake

All Measurements in $m^3 \times 10^{-3}$

Bi-Week Number	Date Range		Inflows				Outflows				Change in Lake Storage
	From	To	Precipitation	Runoff	Deep G.W.	Total	Evaporation	Outflow	Deep G.W.	Total	
1	10/1/2004	10/9/2004	3.9	0.4	0.2	4.5	3.0	0.0	0.0	3.0	1.6
2	10/10/2004	10/23/2004	28.7	36.8	1.3	66.9	5.9	0.0	0.1	6.0	60.9
3	10/24/2004	11/6/2004	27.1	33.5	0.3	60.9	5.2	0.0	0.2	5.4	55.5
4	11/7/2004	11/20/2004	14.2	2.8	0.1	17.1	3.6	0.0	0.1	3.7	13.4
5	11/21/2004	12/4/2004	24.8	24.1	0.3	49.2	3.4	1.0	0.2	4.6	44.5
6	12/5/2004	12/18/2004	61.7	63.0	1.2	125.8	3.0	79.7	0.1	82.8	43.0
7	12/19/2004	1/1/2005	20.7	8.0	0.4	29.1	2.0	42.9	0.0	44.9	-15.7
8	1/2/2005	1/15/2005	8.0	1.4	0.6	10.0	2.5	21.3	0.0	23.8	-13.8
9	1/16/2005	1/29/2005	39.3	49.1	3.0	91.4	3.2	81.9	0.1	85.2	6.2
10	1/30/2005	2/12/2005	9.3	3.2	0.5	13.1	4.2	15.7	0.0	19.9	-6.9
11	2/13/2005	2/26/2005	1.1	0.4	0.1	1.5	6.9	6.4	0.0	13.3	-11.8
12	2/27/2005	3/12/2005	3.7	0.8	0.3	4.7	8.7	2.6	0.0	11.4	-6.7
13	3/13/2005	3/26/2005	16.3	10.2	1.2	27.7	9.2	4.8	0.0	14.1	13.6
14	3/27/2005	4/9/2005	56.1	78.9	4.1	139.1	16.0	111.3	0.1	127.3	11.7
15	4/10/2005	4/23/2005	25.9	29.7	2.0	57.5	12.5	42.1	0.0	54.7	2.9
16	4/24/2005	5/7/2005	12.5	2.5	1.5	16.5	21.1	6.6	0.0	27.8	-11.3
17	5/8/2005	5/21/2005	35.8	24.3	5.3	65.4	14.0	0.0	0.1	14.2	51.2
18	5/22/2005	6/4/2005	17.0	6.5	2.0	25.5	14.0	0.0	0.1	14.1	11.4
19	6/5/2005	6/18/2005	25.2	20.8	2.4	48.4	24.2	0.0	0.1	24.3	24.1
20	6/19/2005	7/2/2005	6.4	1.4	0.6	8.4	18.9	0.0	0.0	18.9	-10.6
21	7/3/2005	7/16/2005	16.9	5.8	4.9	27.5	30.8	0.0	0.2	31.0	-3.5
22	7/17/2005	7/30/2005	5.9	1.9	1.7	9.4	21.9	0.0	0.1	21.9	-12.5
23	7/31/2005	8/13/2005	0.0	0.0	0.0	0.0	23.6	0.0	0.0	23.6	-23.6
24	8/14/2005	8/27/2005	2.0	0.4	0.4	2.8	25.6	0.0	0.0	25.6	-22.8
25	8/28/2005	9/10/2005	9.1	2.5	1.5	13.1	15.0	0.0	0.1	15.1	-1.9
26	9/11/2005	9/24/2005	18.9	29.2	2.2	50.3	13.0	0.0	0.1	13.2	37.2
27	9/25/2005	9/30/2005	6.0	2.5	0.7	9.2	7.4	0.0	0.0	7.4	1.7
		Sub-Totals	***497***	***440***	***39***	***975***	***319***	***417***	***2***	***737***	***238***

4.5. PHOSPHORUS BUDGET

A TP budget was constructed using the observed data during September 2004 through October 2005. The budget consists of the change in TP mass in the lake, as external loading, loss from the lake through the outlet and net internal loading less sedimentation (Table 12).

During the monitoring effort several stormwater samples were collected with flow weighted TP concentrations ranging from 28 µg/L to 136 µg/L. The majority of stormwater loading originates from an unnamed tributary along 28th Street. A value of 79 µg/L was used to represent low rainfall events and 136 µg/L for larger storm events when daily rainfall totals were greater than 2.54 cm (1 inch). Precipitation samples at Pine Lake showed an average atmospheric TP concentration of 17 µg/L, which was uniformly applied to monthly measured rainfall. Groundwater TP inflowing to the lake was assumed constant at 28 µg/L, which is similar to that used for the TP budget for Beaver Lake. Groundwater TP outflow was taken as the product of average whole lake SRP concentration and estimates of groundwater outflow. Loss of P to outflow (W_{OUT}) was the monthly surface (0-5 m) TP concentration multiplied by the discharge volume.

The 2005WY TP budget resulted in an annual net internal load (internal release less sedimentation) of approximately 47 kg, about half of which occurred during the summer stratified period. A total of 25.9 kg originated from external sources for the whole year with only 1.4 kg leaving via direct outflow. A total of 18 kg was retained within the water column (Table 12).

Compared with the budget in 1989-1990, there was an overall reduction in external loading, which may have been due to installation of stormwater BMPs and the low, water-year runoff. A significant reduction in TP exported from the system was related to the debris blockage at the outlet weir and would have been substantially greater with proper maintenance of the structure. Sedimentation and beaver activity at the weir had blocked all flow during March 2005. That raised water levels and prevented surface outflow, and transport to occur. On an annual basis, net sedimentation exceeded internal loading.

A TP budget typical of a wet year (140.7 cm) was constructed using the same assumptions and temporal distribution of precipitation as the 2005WY (dry year). For the wet year, a total of 39.3 kg would have originated from external sources and 6.3 kg exported via direct outflow. This represents a 152% increase of TP from external sources over the dry year. The net sedimentation (minus internal loading) was 11.2 kg, or 28% of the input. A total of 21.8 kg was retained in the water column equivalent to a 121% increase when compared with the dry year (2005).

Table 12. 2005 Phosphorus Budget

Bi-Week Number	Date Range		Inflow				Outflow				Change in Lake Mass	Residual
	From	To	Precipitation Load	Runoff Load	GW Load	Inflow Total	Evaporation Load	Outlet Load	GW Load	Outflow Total		
1	10/1/2004	10/9/2004	0.044	0.031	0.003	0.078	0	0.00	0.0000	0.00	0.00	0.1
2	10/10/2004	10/23/2004	0.322	1.120	0.024	1.465	0	0.00	0.0001	0.00	-1.60	3.1
3	10/24/2004	11/6/2004	0.303	1.042	0.006	1.351	0	0.00	0.0002	0.00	0.30	1.1
4	11/7/2004	11/20/2004	0.158	0.123	0.003	0.284	0	0.00	0.0001	0.00	1.58	-1.3
5	11/21/2004	12/4/2004	0.277	0.712	0.005	0.994	0	0.00	0.0001	0.00	0.98	0.0
6	12/5/2004	12/18/2004	0.690	3.356	0.022	4.068	0	0.00	0.0001	0.00	0.78	3.3
7	12/19/2004	1/1/2005	0.232	0.178	0.007	0.417	0	0.02	0.0000	0.02	4.69	-4.3
8	1/2/2005	1/15/2005	0.090	0.076	0.011	0.177	0	0.02	0.0000	0.02	6.09	-5.9
9	1/16/2005	1/29/2005	0.440	2.965	0.054	3.460	0	0.68	0.0001	0.68	4.92	-2.1
10	1/30/2005	2/12/2005	0.104	0.110	0.010	0.223	0	0.21	0.0000	0.21	1.16	-1.2
11	2/13/2005	2/26/2005	0.012	0.031	0.001	0.044	0	0.05	0.0000	0.05	1.71	-1.7
12	2/27/2005	3/12/2005	0.041	0.061	0.005	0.107	0	0.00	0.0000	0.00	2.52	-2.4
13	3/13/2005	3/26/2005	0.183	0.238	0.021	0.442	0	0.01	0.0000	0.01	3.50	-3.1
14	3/27/2005	4/9/2005	0.628	4.851	0.075	5.554	0	0.30	0.0000	0.30	-1.25	6.5
15	4/10/2005	4/23/2005	0.290	1.683	0.037	2.010	0	0.12	0.0000	0.12	-3.28	5.2
16	4/24/2005	5/7/2005	0.140	0.122	0.028	0.291	0	0.02	0.0000	0.02	-4.39	4.7
17	5/8/2005	5/21/2005	0.401	0.676	0.097	1.173	0	0.00	0.0001	0.00	5.31	-4.1
18	5/22/2005	6/4/2005	0.190	0.163	0.038	0.391	0	0.00	0.0000	0.00	-11.11	11.5
19	6/5/2005	6/18/2005	0.282	0.601	0.044	0.927	0	0.00	0.0001	0.00	-1.24	2.2
20	6/19/2005	7/2/2005	0.072	0.076	0.011	0.159	0	0.00	0.0000	0.00	2.13	-2.0
21	7/3/2005	7/16/2005	0.189	0.177	0.090	0.456	0	0.00	0.0001	0.00	1.62	-1.2
22	7/17/2005	7/30/2005	0.066	0.063	0.031	0.159	0	0.00	0.0000	0.00	-7.93	8.1
23	7/31/2005	8/13/2005	0.000	0.000	0.000	0.000	0	0.00	0.0000	0.00	-1.43	1.4
24	8/14/2005	8/27/2005	0.023	0.031	0.007	0.061	0	0.00	0.0000	0.00	0.46	-0.4
25	8/28/2005	9/10/2005	0.102	0.070	0.027	0.200	0	0.00	0.0001	0.00	2.18	-2.0
26	9/11/2005	9/24/2005	0.212	0.988	0.040	1.240	0	0.00	0.0001	0.00	-4.93	6.2
27	9/25/2005	9/30/2005	0.067	0.045	0.013	0.125	0	0.00	0.0000	0.00	15.14	-15.0
Annual Totals			***5.6***	***19.6***	***0.71***	***25.9***	***0***	***1.4***	***0.001***	***1.43***	***17.89***	***6.53***

4.6. MODEL PREDICTION OF TP RELATED TO LAND USE

A two-layer (epi and hypolimnion), non steady state mass balance model for TP was used as the basis for future management of Pine Lake (see 3.3). The model was originally developed for Lake Onondaga, NY and has been adapted to Lake Sammamish and Beaver Lake. The following section describes the calibration and results of the model.

4.6.1. Calibration of Predictive Model

Calibration of the mass balance P model with a two-week time step for the 2005WY resulted in predictions matching closely with observed data. Sensitivity analysis of initial estimates for V_T, V_A, and SRR allowed for final calibration of each parameter. Sensitivity was determined by an approach often used in hydrological modeling using a Nash-Sutcliff Efficiency (NSE) coefficient modified to evaluate each parameter in regard to the ability to reproduce the observed data (Nash and Sutcliffe, 1970). The NSE coefficient originally was intended to determine the predictive power of a specific hydrologic model in matching observed discharges. The coefficient increases to unity as simulated values match observed with equal weighting at each time step. Concentrations rather than discharge were substituted in the equation and used for comparison of whole lake and epilimnetic TP concentrations (Eq. 11). Predicted hypolimnetic TP concentrations were calibrated to historical data, as well as 2005 data, due to suspected inadequacy of 2005 data.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Qobs_i - Qsim_i \right)^2}{\sum_{i=1}^{n} \left(Qobs_i - \overline{Qobs} \right)^2} \right] \qquad \text{Eq. 11}$$

where $NSE =$ NSE coefficient for a specific model run

$[TP]obs_i =$ the value of the observed TP concentration at time step i (µg/L)

$[TP]sim_i =$ the value of the simulated TP concentration at time step i (µg/L)

$\overline{[TP]obs} =$ the mean concentration of the observed TP (µg/L)

Calibrated values for V_T (vertical exchange), V_A (settling), and SRR (sediment release rate) were specified to season to better characterize conditions that promote algal blooms in winter during the non-stratified period and during summer stratification. Initial values are shown in Table 13.

Internal P loading (SRR) occurs mostly from hypolimnetic anoxic sediment during the summer stratified period, and hypolimnetic P is transferred to the epilimnion via vertical exchange (V_T and entrainment) across the thermocline. V_T was calculated from observed temperature profiles. Therefore, the importance of internal loading to algae in the epilimnion can be evaluated by the two-layer nature of the model. Settling of TP was formulated and calibrated separately for the hypolimnion, epilimnion and whole lake (non stratified period). The final calibrated parameter set is shown in Table 14. Note that V_T and SRR occur during the stratified period only, although that period includes late spring and early fall.

Table 13. Initial Parameter Set of the Pine Lake Phosphorus Prediction Model (2005WY)

Parameter	Fall	Winter	Spring	Summer
	(10/1-11/20)	(11/21-3/26)	(3/27-4/23)	(4/24-9/30)
V_A (m/wk)	0.28	0.28	0.28	0.28
V_T (m/wk)	n/a	n/a	0.044	0.044
SRR (mg-m^2/day)	1.00	n/a	1.00	1.00

Table 14. Calibration Parameter Set of the Pine Lake Phosphorus Prediction Model (2005WY)

Parameter	Fall	Winter	Spring	Summer
	(10/1-11/20)	(11/21-3/26)	(3/27-5/7)	(5/7-9/30)
V_A (m/wk)	0.17	0.01	0.38	0.44
V_T (m/wk)	n/a	n/a	0.044	0.044
SRR (mg-m^2/day)	1.23	n/a	0.64	1.55

Final calibration of the model for 2005WY resulted in predictions of entire-year, whole-lake TP matching the observed 79% of the time, where 100% is a perfect fit. Additionally, predictions of TP in the epilimnion during stratification matched 61% of a perfect fit. Comparing the simulated TP concentration with observed shows the model's ability to simulate lake conditions reasonably well for each of the seasons (Figures 19-21). This calibrated model was then used to predict resulting seasonal TP concentrations extrapolated to a typical water year (117 cm), seasonally distributed as observed in 2005.

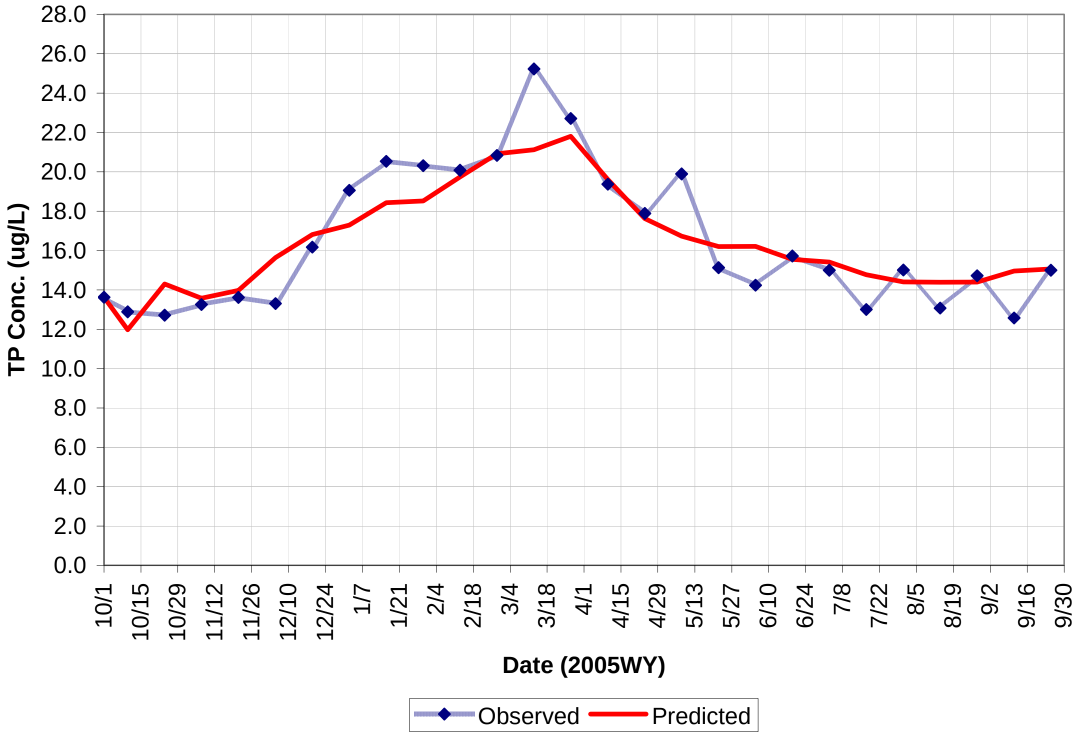

Figure 19. Whole Lake Predicted TP Concentrations Vs. Observed during 2005WY

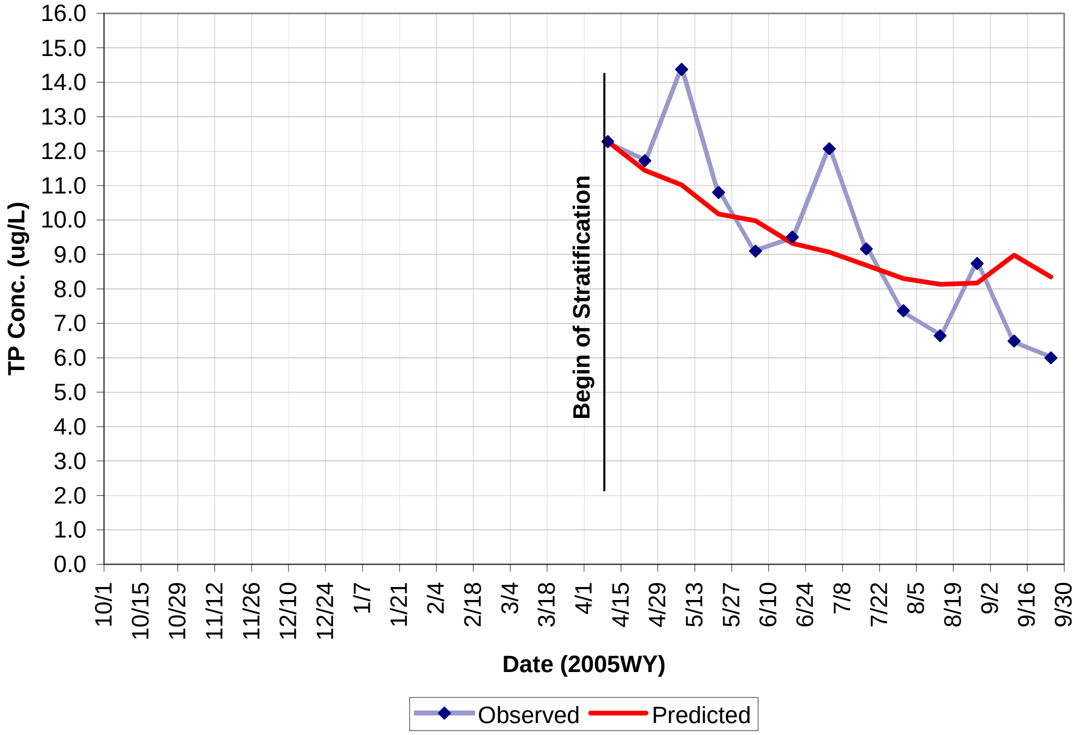

Figure 20. Epilimnetic Predicted TP Concentrations Vs. Observed during 2005WY

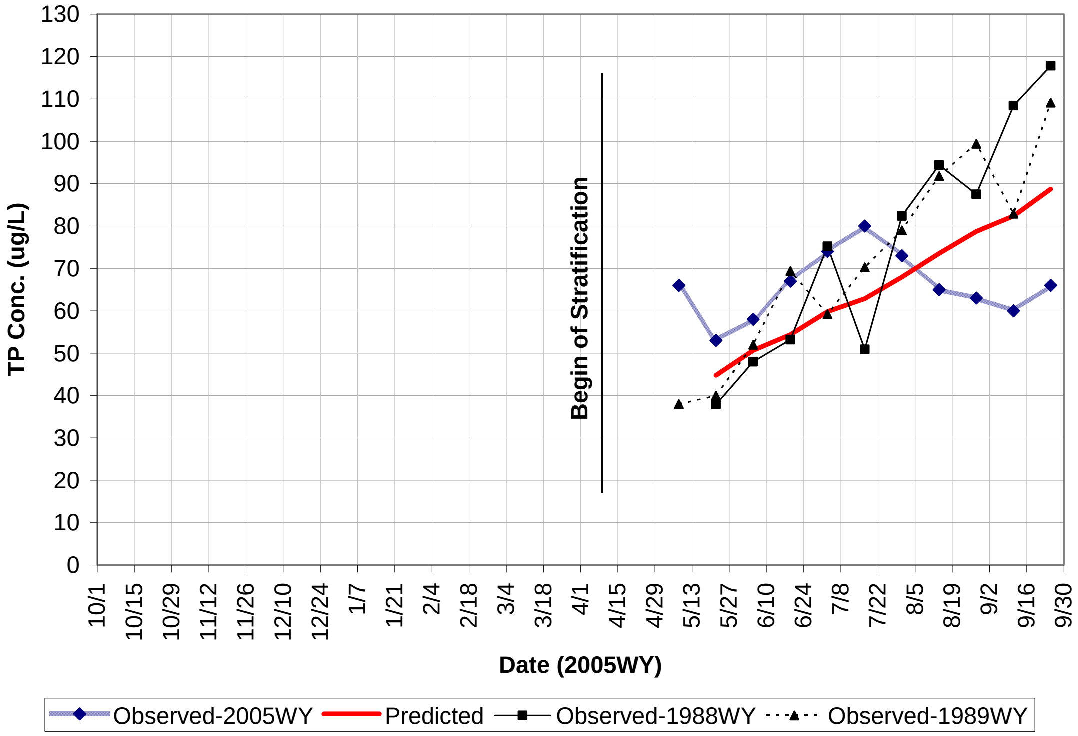

Figure 21. Hypolimnetic Predicted TP Concentrations Vs. Observed during 2005WY

Predictions of TP using initial parameter values substantially underestimated observed TP during the nonstratified period. To match observed TP, settling velocity during the winter period was reduced significantly due to presumed low density of P sorbed to humic material during winter runoff and the presence of a large, probably buoyant, Cyanobacteria biomass. An additional 0.6 to 1.2 kg/week was added during December and January during the presumed upward migration phase of the bloom forming cyanobacterium, *Aphanizomenon flos-aquae* (AFA) during that period. AFA has been observed to translocate P from sediments via recruitment of vegetated cells (see section 4.1.2).

Other possible sources to account for the post stratification TP increase in the lake are; 1) pre destratificaiton hypolimnetic TP, 2) stormwater runoff and 3) failing septic tank drain fields. Analyses from past years have shown that post-stratification, whole-lake TP concentration could be accounted for by mixing the high hypolimnetic TP throughout the lake (Anderson and Welch, 1991). That was not the case in 2004. Volume-weighted, whole-lake TP immediately prior to destratification (Oct.-Nov.) actually matched observed post-stratification (Dec.) observed TP (Figure 19). However, there was some uncertainty if the hypolimnetic data were representative.

Other possible souces for the “missing” TP during Jan.-Mar. were investigated. Stormwater runoff was not a likely source to account for the lake increase, because runoff events were not timed with the lake increase, nor was the stormwater TP concentration sufficient to reasonably match the lake concentration. Failure of drain fields was assumed to be negligible, as was the case in 1979-1980. Conditions may have changed, but the generally much lower lake TP since then suggests that drain fields still remain a minor contributor. Thus, a biological source, which was supported by observed high bottom water chl *a* prior to destratification, was used for the added TP needed to calibrate the model in winter, based on algal recruitment rates determined elsewhere.

An unexplained increase in TP following destratification is not uncommon in Pine Lake. In 1988, whole-lake TP increased from 28 to 47 µg/L between 10/14 and 11/11 prior to and after destratification (Anderson and Welch, 1991). A 100-day long bloom occurred after destratification between November and February 1988-1989, averaging 9.4 µg/L chl *a*. On the other hand, whole-lake TP did not exceed 31 µg/L prior to and after destratification in 1989, although chl *a* averaged 20 µg/L from September through November. In 2005, pre and post destratification TPs were similar and relatively low (~ 14 µg/L) and the increase did not begin until December (Fig. 19). While fall-winter blooms occur nearly every year in response to increased TP, factors accounting for the timing and magnitude of increased TP are poorly understood. Therefore, predictions of lake response from land use change are superimposed over a post-destratification pattern of TP similar to that observed in 2005.

Epilimnetic TP declined during the summer stratified period (Fig. 20) because surface runoff is low and increasing hypolimnetic P (Fig. 21) is largely unavailable to the epilimnion. Approximately 60% of epilimnetic P loading during summer came from the hypolimnion through vertical exchange.

The pattern of observed hypolimnetic TP in 2005 was atypical, based on previous studies. To err on the safe side, SRR was assumed to proceed through the stratified period based on the previously observed data, which are shown in Fig. 21. An average of the previously observed hypolimnetic TP was used for calibration.

4.6.2. Sensitivity Analysis

A sensitivity analysis was performed to illustrate lake TP response to varying the parameters in Tables 12 and 14 (Figs. 22-24). Whole-lake TP concentrations are highly sensitive to changes in SRR during the stratified period (Fig 22). However, epilimnetic TP is relatively insensitive to SRR change due to the highly stable nature of the stratified water column (Fig. 23). Both the whole-lake and epilimnetic TP are sensitive to changes in V_a, the settling rate during the stratified period. Varying V_a during winter has little effect because the calibrated V_a is so low to begin with (Table 14). Hypolimnetic TP, is of course, much more sensitive to SRR change than to V_a (Fig. 24).

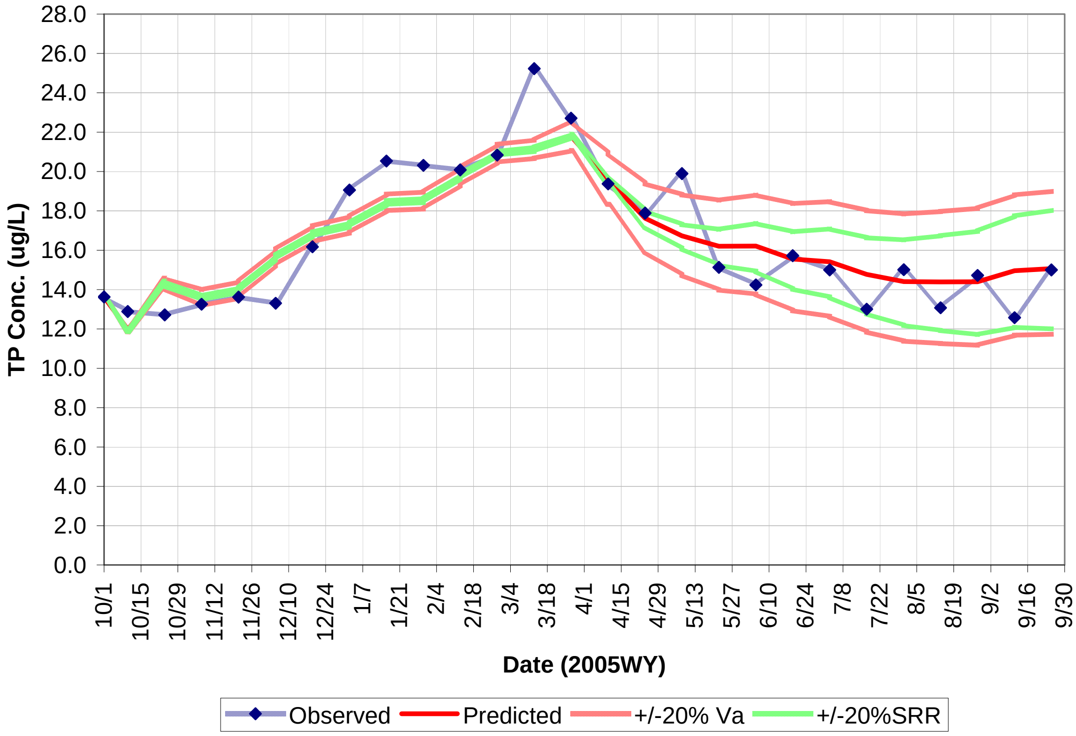

Figure 22. Sensitivity of Predicted Whole Lake TP Concentration varying V_a and SRR by +/- 20%

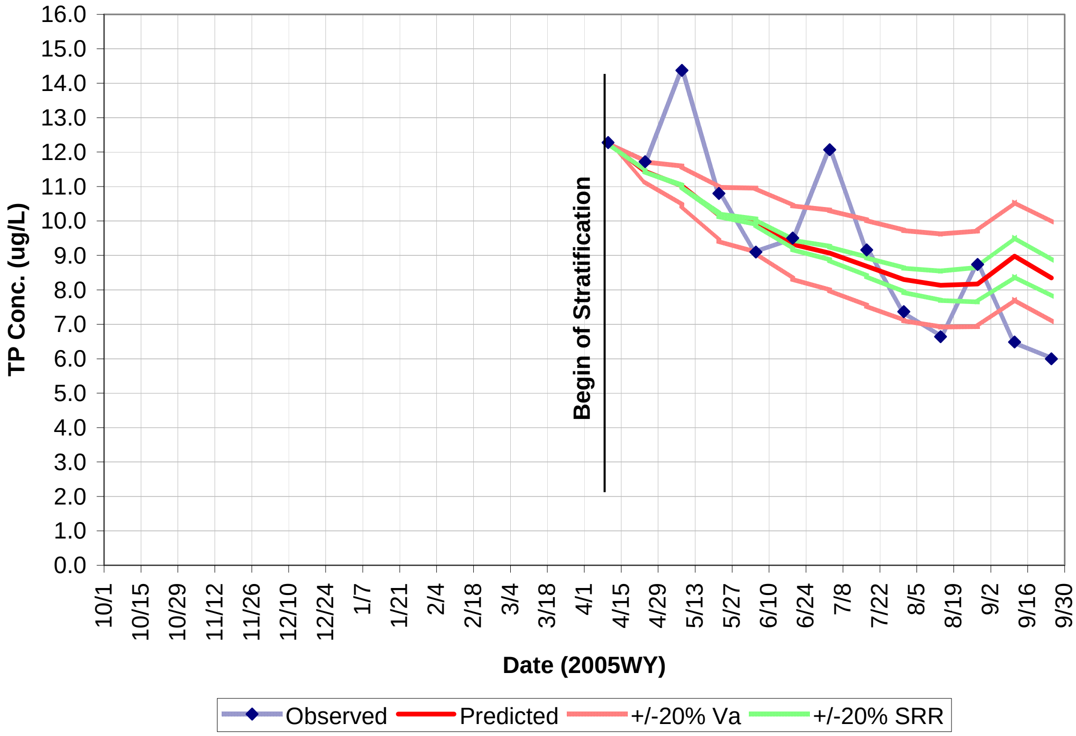

Figure 23. Sensitivity of Predicted Epilimnetic TP Concentration varying V_a and SRR by +/- 20%

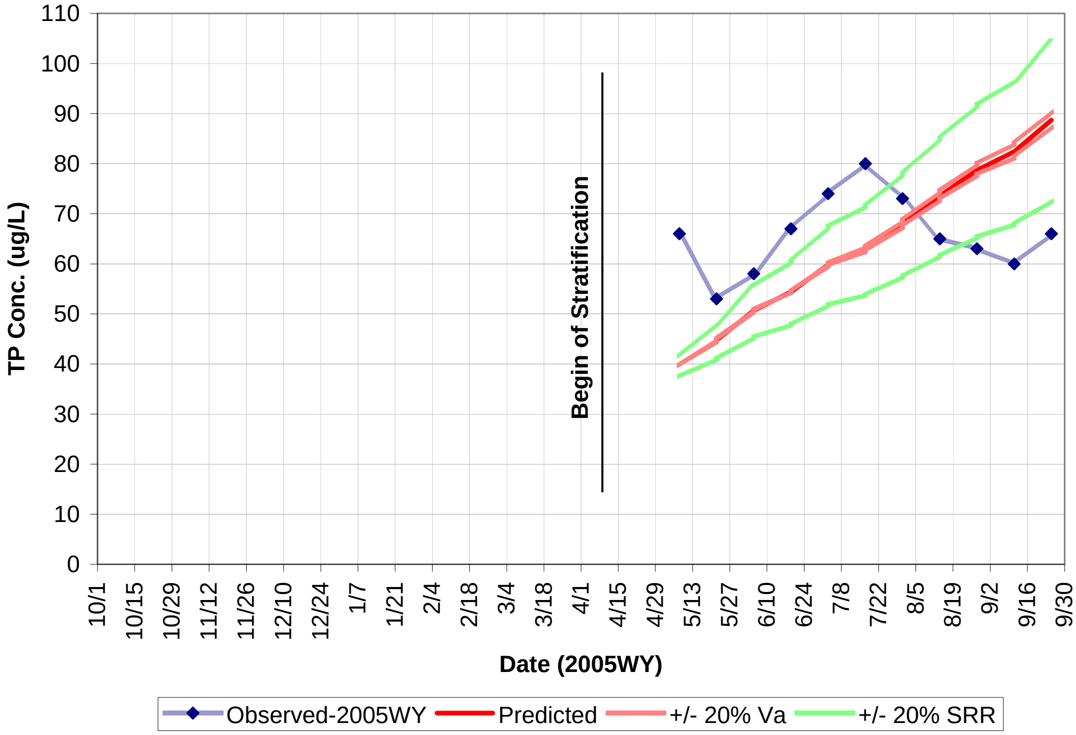

Figure 24. Sensitivity of Predicted Hypolimnetic TP Concentration varying V_a and SRR by +/- 20%

4.6.3. Future Loading Scenarios

Future loading scenarios were chosen to reflect possible land use changes within the watershed and to predict the lake's response to future build-out conditions, which are the complete development of the watershed based on future land-use shown in Figure 13 and Table 1. Management alternatives for treating external and internal TP loading resulting from increased development were evaluated by model output based on an average water year. These management alternatives are as follows:

- **No Action** – This alternative shows the effects of 1) complete development of the watershed, including redevelopment, as per future zoning designations, but without adequate BMP controls, and 2) importance of Critical Area Ordinances (CAOs).

- **80% Reduction of External Loading for New Development (Short Term)** – This alternative shows the effect of compliance with the revised CAOs passed December 20, 2005, such that all new development must retain 80% of the TP in runoff on an annual basis (Ord. 21A.50.355, Sammamish, 2005) using all known, available and reasonable technology (AKART). To predict the short-term effect (<10 years), only the remaining undeveloped areas were considered for an 80% reduction in runoff TP.

- **80% Reduction of External Loading for New Development (Long Term)** – This alternative shows the effect of complete redevelopment of the basin to full build-out conditions, assuming 80% TP reduction for 100% of the developed land.

- **In-Lake Management** – Lake response to the three above alternatives was predicted with and without in-lake control, which was assumed to be a one-time treatment of the hypolimnetic sediments with alum to inactivate sediment P reducing internal loading by 80%.

Description of the results of these alternatives follows.

4.6.4. Predictions Related to Land Use

Export (or yield) coefficients for TP were used to evaluate the effect of land use change on external TP loading to the lake. That was necessary, because runoff TP concentrations were unavailable for each specific land use around Pine Lake. Export coefficients have been used routinely to quantify loading on either an annual basis or distributed seasonally with changes in runoff volume (Perkins, 1995). The units of export coefficients are in mass per watershed (land use) area per year (kg/ha per yr).

Herrera (2006) assembled values for export coefficients determined in King County for this project and calibrated them to the observed 2005WY TP loading to Pine Lake (Table 15). Because the 2005WY was relatively dry, the calibrated coefficients in Table 15 were further corrected to a normal precipitation year by multiplying each coefficient by the ratio of normal annual precipitation: 2005WY precipitation (1.27). Coefficients were also corrected to a wet year by the same procedure.

The calibrated/corrected coefficients were then used to predict lake TP for scenarios of build out and each of the management alternatives. The annual external loads for each land use were distributed into twice weekly quantities over the normal precipitation based on the load distribution observed in the 2005WY. The varied annual external load for each alternative and resulting lake TP and chl *a* concentrations are shown in Tables 16 and 17. Internal loading was assumed to remain constant, although it may decline in the future as a result of the wetland diversion if further external inputs from future development are controlled.

Table 15. Annual TP Export Coefficients; Initial and Calibrated values.

Landuse Type	King County Published Export Coefficients (kg/ha per yr)	Calibrated Export Coefficients (kg/ ha per yr)
Open Water	-	-
Office	0.45	0.22
Commercial / Business	0.45	0.22
Park / Open Space	0.10	0.05
Light Rural Residential (1 Dwelling/4 Ac)	0.16	0.08
Light Urban Residential (4 Dwelling/Ac)	0.26	0.13
Medium Urban Residential (6 Dwellings/Ac)	0.43	0.21
Heavy Urban Residential (8-18 Dwellings/Ac)	1.03	0.56
Streets / ROW	0.34	0.17

Predictions of increased development and implementation of management alternatives to mitigate increased yields of TP to Pine Lake are shown in Tables 16 and 17. With no action, external loading will more than double over the 2005WY and increase nearly 50% over a normal year if the watershed is built out. This increase may be on the conservative side, because export coefficients were increased proportional to flow, which means that inflow TP concentration remains constant while runoff and load increase. Typically, TP concentration actually increases as storm flow increases, but there is no information on the flow-concentration relation for the Pine Lake watershed, so concentration was assumed to remain constant with increased flow. The increased load is due solely to land use change as per an increase in export coefficients. Nevertheless, doubling the external load is predicted to increase lake mean summer TP concentration by about 25-50% and chl *a* by 20-40%. This is assuming that internal loading remains constant and there is no evidence in the hypolimnetic data that TP is changing (Welch, 2002).

Table 16. TP Loading and Resulting Concentrations from Various Scenarios to Mitigate Land-Use Changes

Scenario	External Stormwater Loading (kg)	Total External Loading (kg)	Total Sedimentation (kg)	Total Internal Release (kg)	Hypolimnetic Diffusional Load (kg)	Mean Summer Epilimnetic Concentration (ug/L)	Mean Spring Epilimnetic Concentration (ug/L)	Mean Winter Whole Lake Concentration (ug/L)
Current Conditions - Observed 2005WY	19.6	25.9	36.0	29.6	7.5 (Epi)	8.8	11.2	18.9
Current Conditions - Average Annual Year	33.4	41.3	38.3	29.6	7.4 (Epi)	9.7	11.5	21.7
Current Conditions - Typical Wet Year	47.2	56.8	40.6	29.6	7.3 (Epi)	10.6	11.9	24.4
No Action	48.2	56.1	49.6	29.6	7.9 (Epi)	13.1	12.8	29.2
80% Retention on New Development - Short Term								
In-lake Treatment	28.4	36.2	44.5	6.0	1.7 (Epi)	9.1	12.0	23.6
w/out In-lake Treatment	28.4	36.2	55.2	29.6	8.2 (Epi)	11.2	12.2	24.1
80% Retention on New Development - Long Term								
In-lake Treatment	36.0	43.9	46.3	6.0	2.6 (Epi)	9.9	12.3	25.6
w/out In-lake Treatment	36.0	43.9	46.3	29.6	8.1 (Epi)	12.0	12.5	26.1

Table 17. Corresponding Predicted Chl *a* Concentrations Resulting from Land-Use Mitigation Scenarios

Scenario	Mean Summer Epilimnetic Concentration (ug/L)	Summer Chl*a* Concentration (ug/L)
Current Conditions - Observed 2005WY	8.8	2.5
Current Conditions - Average Annual Year	9.7	2.7
Current Conditions - Typical Wet Year	10.6	2.9
No Action	13.1	3.5
80% Retention on New Development - Short Term		
In-lake Treatment	9.1	2.6
w/out In-lake Treatment	11.2	3.1
80% Retention on New Development - Long Term		
In-lake Treatment	9.9	2.8
w/out In-lake Treatment	12.0	3.2

* Note: Regressional Equation [Chl*a*] = 0.2189[TP] + 0.611, $r^2 = 0.262$

5. DISCUSSION

5.1. LAKE CONDITION

The quality of Pine Lake has improved greatly since diversion of the wetland inflow in 1988. Large spring cyanobacteria (blue-green algae) blooms have largely disappeared, however post destratification fall and winter blooms still occur, as was the case in 2005. While diversion of P input from the wetland was the cause for the spring bloom elimination, fall-winter blooms result largely from high P content in the anoxic hypolimnion that becomes distributed throughout the lake following fall mixing. High cyanobacterial biomass can also accumulate at mid depth during the stratified period and contribute to fall-winter surface blooms (Anderson and Welch, 1991; Jacoby et al., 1997).

While these fall-winter blooms can be aesthetically offensive, they do not affect recreation during summer. Lake quality during the summer has always been relatively good, but has even improved in the past 15 years such that mean summer surface chl *a* and TP are now about 3 μg/L and 10 μg/L, respectively. The reason surface chl *a* and TP are low in summer is that stratification serves to trap most of the P, released from anoxic sediment, in the hypolimnion. While some P gradually diffuses across the thermocline into the epilimnion, most does not become available to the lighted epilimnion until near or during destratification in the fall. This condition is evidenced by the continual decrease in epilimnetic TP during the stratified period, while TP increases in the hypolimnion. These trends are predictable with the mass balance model due to low rates of diffusion and entrainment across the thermocline. If mixing of the epilimnion by wind were sufficient to erode the metalimnion (thermocline) during summer, increasing the epilimnetic P, algal blooms would probably occur. Pine Lake has a relatively small area and is mostly surrounded by large trees that protect it from wind that could otherwise deepen the mixed layer (epilimnion).

5.2. TP MODEL

The calibrated two-layer, mass balance model simulates seasonal changes in TP reasonably well. Diffusion and entrainment estimates of TP transport across the thermocline were calculated from observed temperature profiles, while settling rate was adjusted to match lake concentration, as was internal loading to a lesser extent. Past hypolimnetic TP data were incorporated to improve the reliability of the internal source, which was assumed to continue at the same rate in the future. In any event, P released form sediment to the hypolimnion during the anoxic, stratified period has a relatively small effect on epilimnetic TP in this highly, wind protected lake. Even with a doubling of external loading with build out, diffused hypolimnetic P to the epilimnion is expected to be only 15% of external load (Table 16).

One might expect internal loading to increase with increased external loading. While this is possible, and has certainly occurred in other lakes, the data for Pine Lake suggest that internal loading (hypolimnetic TP) has remained unchanged since the 1988 wetland diversion and, thus, appears to be rather unresponsive to change in external load. Nevertheless, long recovery times (to reduced internal loading) have been shown to be the rule rather than the exception following external load reduction in other lakes (Cooke et. al., 2005).

Calibrating the model to conditions in winter proved difficult and necessitated an additional source to match the winter increase in TP. That was supplied by an inferred recruitment of cyanobacteria from sediment at rates observed in Green Lake and Upper Klamath Lakes for the principal bloom taxon in Pine Lake. The other potential sources for that winter increase were not reasonable. The increase was not timed with storm events, it occurred well after lake mixing and failing septic tank drainfields were assumed unimportant, as was the case in 1979-1980. Inputs from failing drainfields would probably have been timed rather closely with storm events. Thus, the biological source was invoked for the 2005 WY. That may not explain the winter increase in other years, however the winter increase can occur with lake mixing and pre-mixing, whole-lake TP can fully explain the post mixing increase. So the timing of the winter pattern for TP may not precisely follow the pattern predicted by this model, although the magnitude may be reasonable close.

To improve the predictability the year-to-year pattern in winter TP requires more frequent sampling at more depths during the fall-winter period. Emphasis was placed on the spring-summer stratified period in this study, because that is the prime recreation period as well as the growing season when the largest algal biomass levels usually occur. Twice monthly sampling was conducted during April-September and only monthly during the remainder of the study period. To understand the P and algal patterns in full-winter, weekly sampling is recommended during October through December.

5.3. EFFECT OF DEVELOPMENT

The no action, build-out alternative should have the largest effect on winter lake TP, increasing it by 7-10 µg/L, depending on water year, to 29 µg/L (Table 16). That is because most of the stormwater enters the lake during the high precipitation winter. Summers are relatively dry in the Puget Sound region with low runoff. Therefore, summer algal problems in this area are usually more related to available internal rather than external loading (Welch and Jacoby, 2001). However, even with internal loading remaining constant, as well as diffusion across the thermocline (available internally loaded P), summer epilimnetic TP is expected to increase by 3-4 µg/L to 13 µg/L (Table 16).

Past data show that mean summer epilimnetic TP concentration in Pine Lake has been rather consistent at ~10 µg/L. Raising that mean by ~3 µg/L will add ~1 µg/L chl *a* (Table 17). While this is an effect of developing the remaining undeveloped 24% of the watershed, it is nonetheless an increase that can be mitigated. The reasons this average, normal precipitation, summer-period increase is modest are: 1) the stable nature of the lakes stratified water column, and 2) its relatively small area and the surrounding shoreline wind-shielding trees. Any unusual conditions, such as higher-than-normal summer precipitation and/or increased wind due to tree removal could result in more P entering the epilimnion from the watershed and hypolimnion, respectively. The mixing depth in Pine Lake is consistently about 5 m, because of its small area (34 ha) and, hence, small wind fetch. Mixing depth in Lake Sammamish (2,000 ha), on the other hand, is about 9-10 m, because of the much greater wind fetch. While area and fetch will not change in Pine Lake, wind strength could increase if significant reduction in shoreline trees occurred. The precise relationship between the lake’s exposure to wind and mixing depth is unknown, but would be a subject worth addressing before tree removal proceeds further.

5.4. MITIGATION OF DEVELOPMENT EFFECT

Instituting the CAP requirement of 80% retention of P for new development should theoretically mitigate some of the effect of increased development. That is, normal precipitation year epilimnetic TP is expected to rise by ~2 µg/L, or about 2/3 of that for no action (Table 16). Winter TP is still expected to increase by ~4 µg/L or about 20%, compared to 35% for no action (Table 16). The summer increase in mean epilimnetic TP represents about 0.5 µg/L chl *a*.

If sediment P were inactivated with an alum treatment to the hypolimnion, the summer increase in TP could be completely mitigated, but there would be little effect on the expected increase in winter (Table 16).

The graphical representation of these mitigation alternatives are shown in Figures 25-27. The bounds on TP for current, no new development scenarios illustrate the likely year-to-year variability to be expected. Those bounds may be smaller than will actually occur, because, as mentioned earlier (section 4.6.3), TP export coefficients were adjusted upward for normal and wet years, from the calibrated dry year, by the ratio of normal and wet year annual precipitation to the dry 2005/2004 precipitation. That means TP inflow concentrations remained the same. In reality, TP concentration usually increases as storm runoff increases, but the data for the Pine Lake watershed were inadequate to develop such a relationship. However, the assumption of constant inflow TP concentration may be valid; continuous daily monitoring of Issaquah Creek in the 1970s showed the same volume-weighted concentration (65 µg/L) for two years of markedly different flows.

There are other potentially effective mitigation alternatives that were not investigated, such as requiring only P-free fertilizer in the whole watershed. Recent results form Minnesota show that soluble P readily leaches from lawns that were over-fertilized with phosphate. P-free fertilizer use has been mandated for all lake watersheds in that State. A bill is currently under consideration in the Washington State Legislature to ban P in lawn fertilizer. The effect of P-free fertilizer would be expected to have more effect in the winter than summer in Pine Lake because of the seasonal pattern of precipitation.

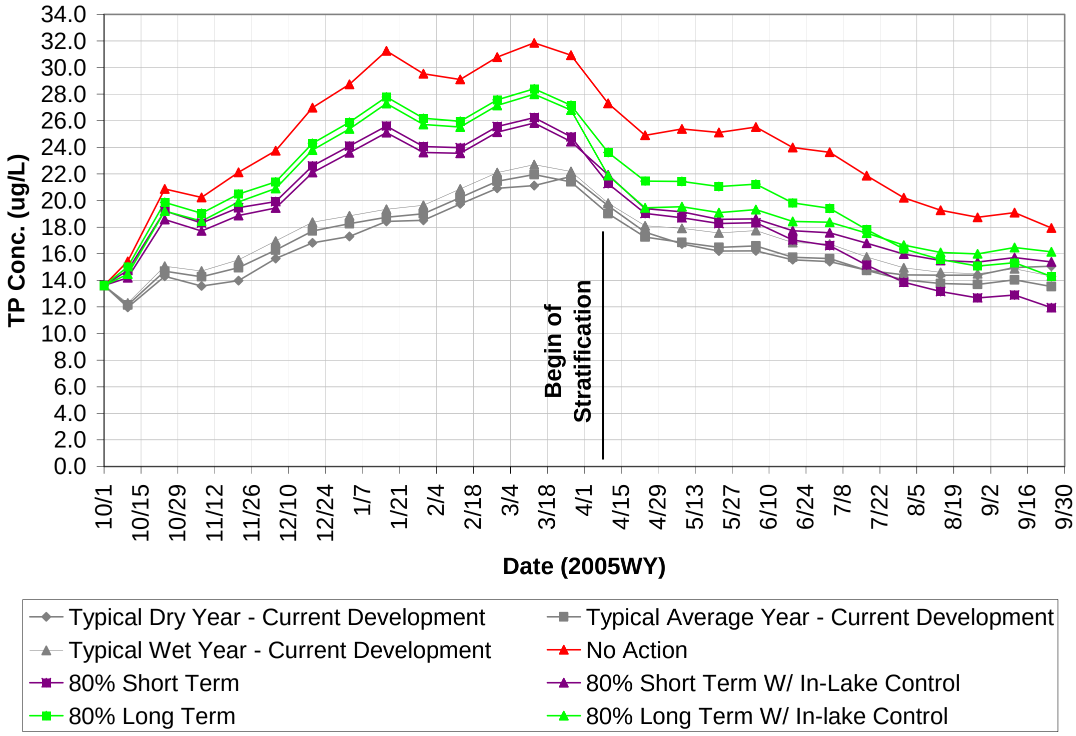

Figure 25. Predictions of Whole Lake TP for Various Mitigation Scenarios

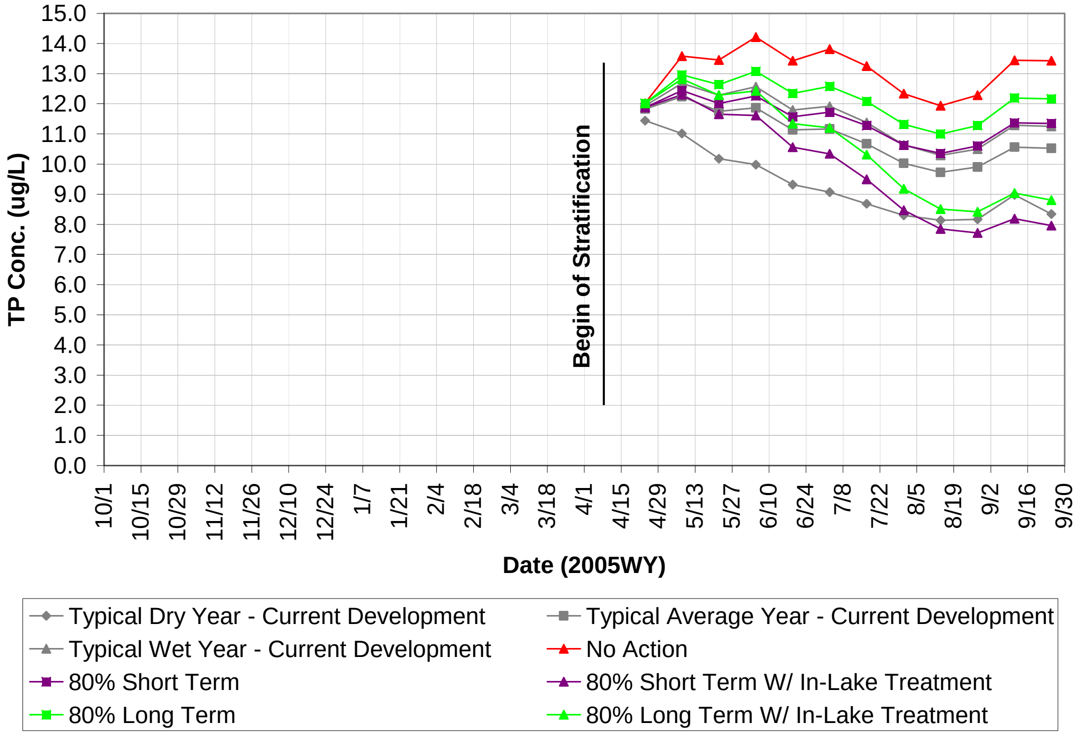

Figure 26. Predictions of Epilimnetic TP for Various Mitigation Scenarios

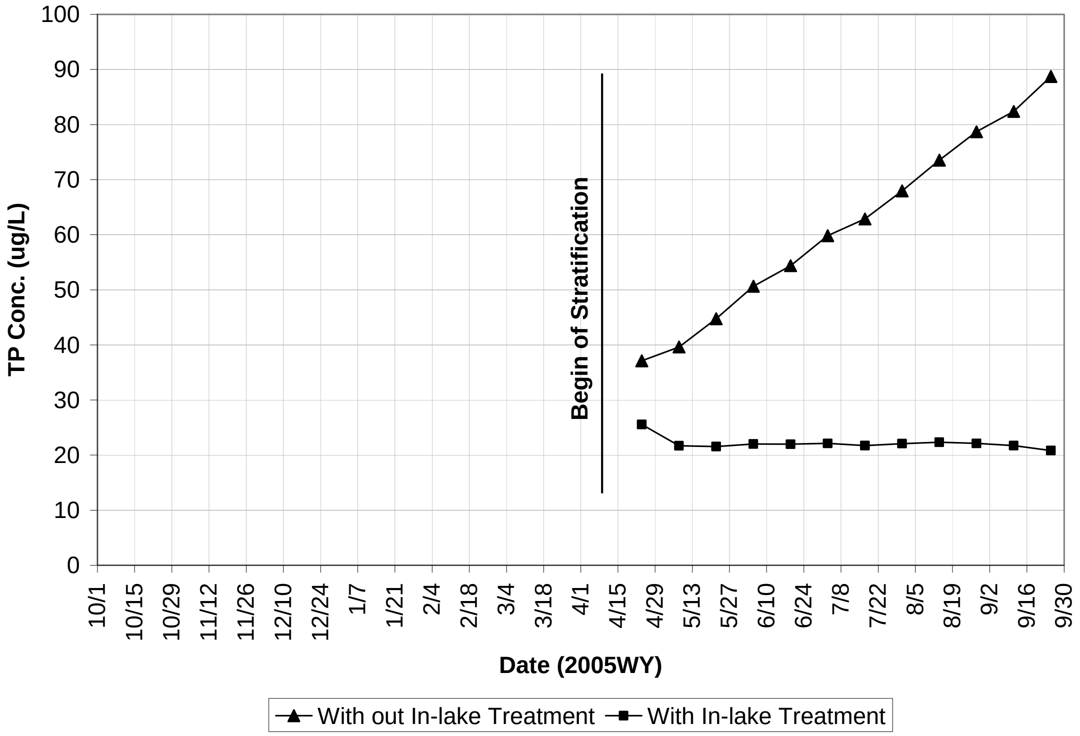

Figure 27. Predictions of Hypolimnetic TP With and Without P Inactivation of Sediment

6. MANAGEMENT PLAN

Similar to the recommendations identified in the Beaver Lake Management Plan, a combination of external and internal management recommendations are provided in the following sections (KCSM, 2001). Preservation of the lake’s ability to remain in a healthy condition requires a minimum level of best management practices (BMPs) to be implemented. The following recommendations are focused in five key areas: 1) stormwater runoff controls, 2) in-lake controls, 3) nearshore controls, 4) administrative policy, 5) continuation of monitoring.

6.1. MINIMUM WATER QUALITY GOAL FOR TP AND CHL *A*

In order to provide a measure for assessing the lake’s overall health and condition, a benchmark water quality goal for TP and Chl *a* is recommended. Based on review of monitoring data and water quality predictions, a minimum goal of 19.2 μg/L of winter whole lake and 10 μg/L summer epilimnetic TP concentrations was determined. A corresponding chl *a* goal of 19 μg/L and 2.8 μg/L for winter and summer concentrations is achievable by implementing management decisions.

6.2. EXTERNAL STORMWATER LOADING CONTROL

It is recommended that all development and redevelopment be conducted in compliance with the revised CAOs passed December 20, 2005, such that all new development must retain 80% of the TP in runoff on an annual basis (Ord. 21A.50.355, Sammamish, 2005) using all known, available and reasonable technology (AKART). This alone will not prevent degradation of the water quality of Pine Lake. Additional steps to reduce P generation within the watershed are encouraged, such as, imposing a strict pet waste ordinance, P ban on all fertilizers within the watershed, and irrigation reduction through landscape practices that reduce the need for plant watering.

6.2.1. Effectiveness of Recent Runoff Control

As stated in the background section of this report, the development within the lake’s watershed has resulted in an increase in the P loading to the lake over the last two decades. This P loading to the lake has continued to fuel cyanobacterial blooms in the winter. However, the City’s and County’s efforts to employ water quality BMPs like biofiltration and infiltration have reduced the potential P loading that could have been generated from the land use conversion. It is important that biobuffers and stormwater management for water quality controls continue to receive high priority within the City and that watershed residents become equally aware of their individual roles in maintaining the water quality of the lake.

6.2.2. Additional Measure to Achieve Protection

As pressure increases to increase zoning density above the current plan, it is important to understand that it is the pervious area that has and is currently covered with native vegetation that has and is controlling the character of Pine Lake. The lost of this watershed feature will reduce the functional ability of the watershed to prevent degradation of the lake’s water quality. Hence future planning decisions should take into account that changes in the nature of the watershed can have an immediate impact. The model was produced assuming that climatic precipitation patterns will not significantly change. Specifically, the summers will remain relatively dry and the majority of the stormwater runoff will come in the winter period. A shift in wet season could transport additional P to the lake in the summer and that could stimulate summer algal blooms. Also, changes in the vegetative cover of the watershed and particularly the height and density of the trees that influence wind induced mixing could also increase P availability during the summer. This would also lead to a potential increase in algal blooms.

6.3. IN-LAKE CONTROL

At this time in-lake activities to directly control P concentrations may be needed if the model predictions are shown to be correct with full build out of the watershed. At this time, it is recommended that continued monitoring at the lake be conducted to provide data to verify the model and track if and when in-lake action may be necessary. The control of internal P would be through P-inactivation with the addition of aluminum to the lake sediment to reduce P release from the lake sediments. However, this is not currently needed to maintain the current conditions, only if external loading increases and/or changes in P entrainment occur (summer mixing).

Aquatic plants are not excessive in the lake. It is recommended that monitoring of the aquatic plant community be conducted at the lake on a regular basis to track the community for changes and specifically to identify non-native invasives species as a preventative measure. If a non-native plant is found within the lake it is recommended that steps be taken immediately to eliminate that species from the lake.

6.4. NEARSHORE CONTROL

The nearshore of the lake serves two vital purposes relative to the water quality of the lake. One, the shoreline vegetation serves as a buffer that stabilizes the soil and uptakes P. Two, the taller trees surrounding the lake help prevent wind induced mixing; it is this function that is critical for the maintenance of strong thermal stratification in the lake and the minimization of P entrainment into the epilimnion from the hypolimnion through mixing.

6.4.1. Buffer Requirements

There are little direct data from the Pine Lake watershed that would definitively quantify how much native vegetative buffer is needed to protect the lake's water quality, or specifically control P loading to the lake. It is clear that the more buffer that can be maintained the less risk there will be for water quality degradation. Until there are data to support specific buffer widths and coverage it is recommended that native vegetative buffers be encouraged to the greatest extent allowable under current land use codes.

6.4.2. Open Space

Open space covered with native vegetation is Pine Lake's best friend. It is in the best interest of Pine Lake that open space within the watershed be preserved to prevent increase P loading that result from other land uses.

6.5. ADMINISTRATIVE POLICY

It is recommended that the City establish a formal unit within the City or a Lake Management District to conduct formal reviews of all proposed development and oversee compliance of City ordinances relative to water quality protection. In addition, this entity would be responsible for conducting the monitoring program outlined below, storage of lake and watershed data, and formulation of management activities to maintain the quality of Pine Lake.

6.6. CONTINUATION OF MONITORING

It is strongly recommended that a long-term monitoring program be conducted at the lake to continue to gather data on the lake's water quality and inflowing waters. Only through a long-term monitoring program will the assumptions and uncertainties of the model be truly understood and a long-term adaptive model formulated. This monitoring effort should at a minimum have the following elements:

- Monthly sampling 0.5, 5, 7, and 11 meters depths for TP, Temperature, DO and pH

- Monthly sampling of 0.5 M for chl *a* and algal identification and density
- Sampling of 8 stormwater runoff events from the three inlets for TP
- Daily record of wind direction and speed, lake level, and precipitation
- July aquatic plant survey

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