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Final Report to Municipality of
Metro Seattle for Research
Contract: Management of Lake
Sammamish Quality

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INTRODUCTION

Historical Perspective

Lake Sammamish resulted from the recession of the Vashon glaciation about 14,000 years ago. It is 19.8 km^2 in area, 17.7 m in mean depth, with a drainage area of 253 km^2 and flushes at 0.55/yr. The lake has absorbed two periods of deterioration in the past 100 years. One was during deforestation of the watershed between 1880 and 1931. During that period the sedimentation rate increased from 1.2 to 2.1 mm/yr. The rate subsequently (1921-1944) increased to 6.7 mm/yr, probably due to road building and development in the denuded watershed. Since 1945 the sedimentation rate has been constant at 3.2 mm/yr, about one half the peak value (Birch, 1976).

The other period of deterioration occurred as a result of the increased population in Issaquah and the discharge of wastewater to Issaquah Creek, the principal inflow to the lake. The population of Issaquah was 4,314 in 1970, with over one-half the growth having occurred during the previous ten years. The watershed contained about 40,000 people at that time (Rock, 1974).

In 1968 the Issaquah sewage effluent (852 m^3/day), which included wastewater from the Dairygold dairy, was diverted by Metro from Issaquah Creek to the treatment plant at Renton. The capital cost of the diversion was \$4.5 x 10^6 (\$14 x 10^6 in 1983 dollars).

The diversion decreased the phosphorus loading to the lake by about one-third, and the lake was expected to respond rather quickly as had Lake Washington (Welch, 1977). Based on the flushing rate alone, the lake phosphorus concentration should have recovered to 90% of its equilibrium level within four years. However, it did not change significantly in phosphorus and chlorophyll <u>a</u> content or depth of visibility (Secchi disc) during 1970-1975

(Welch, 1977), compared to results from a prediversion study in 1964-1966 (Isaac et al., 1966). Average summer values for chl _a_ and Secchi disc and annual whole-lake values for phosphorus for the pre- and postdiversion periods were, respectively, 5 μg/L, 3.2 m and 33 μg/L for the prediversion period and 7 μg/L, 3.4 m and 28 μg/L for the postdiversion period. Although the whole lake P concentration indicated that the lake was eutrophic (>20 μg/L), this was largely due to the anaerobic nature of the hypolimnion, during summer stratification, and the associated release of phosphorus from reduced bottom sediments. Other indices, e.g. chl _a_ (<10 μg/L) visibility (>2m), the chronology of phosphorus content and diatoms in sediments (Rock, 1974), and chironomid remains in the sediment (Wiederholm, 1976), suggested that the lake had not exceeded the mesotrophic state during the two periods of deterioration and may have been mesotrophic for over 100 years.

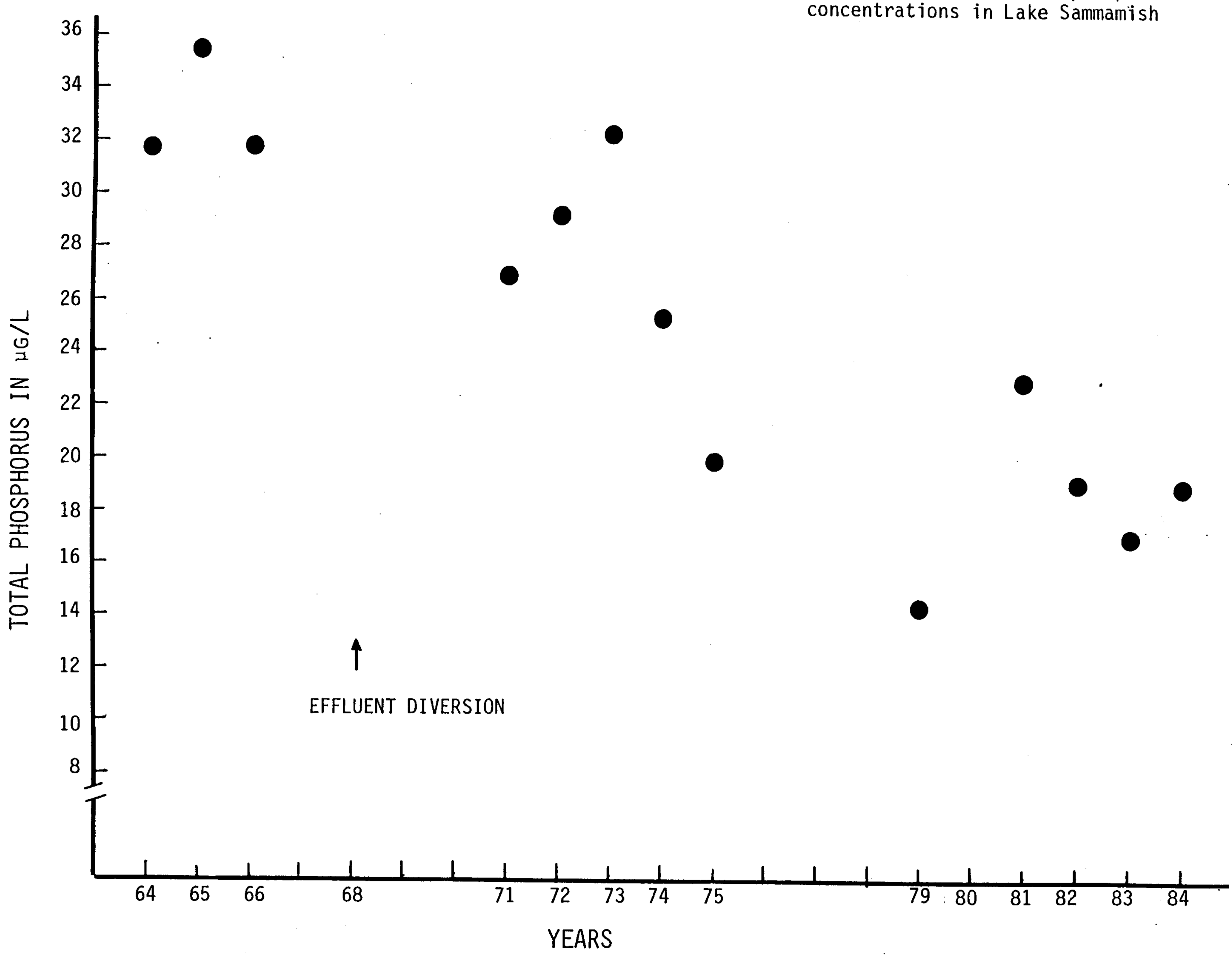
There was really no evidence that the trophic state of Lake Sammamish had dramatically worsened as a result of the 50% increase in phosphorus loading due to the increased growth of Issaquah and wastewater discharge. The most dramatic change in the lake had apparently resulted from the earlier deforestation. Some deterioration had no doubt occurred as a result of increased wastewater input, but there was no long-term record of water quality data, only the diatom and chironomid remains, which may not have been sensitive enough to detect changes within the mesotrophic state; e.g., the mean pennate/centrate diatom ratio over the past 100 years was 1.2 ± 0.2, ranging from 1.0 - 1.5. The range for mesotrophy is 1.0 - 2.0 (Stockner, 1972).

Recent Observations

The lake has definitely improved in quality during recent years, probably beginning in 1975 when the mean phosphorus content was 20 µg/L (Figure 1). Metro began monitoring the lake in 1979, with the first complete data base in 1981. Chl a was 2.5 µg/L in 1981-1984, one-third the earlier postdiversion mean, and Secchi depth averaged 4.9 m, 1.5 times the postdiversion value. Phosphorus remained at a 20 µg/L annual mean (Fig. 1). Thus, the lake had eventually improved markedly, but the improvement was delayed longer than expected. Presumably, the improvement was in response to phosphorus diversion, but the exact cause for the delay is uncertain.

The delay and eventual improvement are apparently due, in part at least, to the persistence of internal loading of P from reduced hypolimnetic sediments during summer stratification in the early 1970's and a subsequent decrease in that source of P. Figure 2 shows the trends in sediment P release (SPR) and oxygen deficit rate (ODR), both determined as daily rates of increase and decrease, respectively, per unit hypolimnetic area. Although there is considerable variability, the three periods, prediversion, postdiversion and since 1975, show, respectively, mean values of 6.1 ± 1.6, 5.6 ± 3.2 and 2.5 ± 2.1 $mg/m^2 \cdot day$. Pre- and postdiversion ODR was 483 ± 22 $mg/m^2/day$ (n = 6), while since 1974 it has averaged 312 ± 96 $mg/m^2/day$ (n = 7). Although not entirely clear, the decreases in lake P content appear to be related to the decreases in ODR and sediment P release. If total loading for the three periods is considered, the diversion decreased loading by about 19% and the recent decrease in sediment release, as well as a slight decrease in external loading, has decreased total loading by 30%. The changes largely account for the observed changes in lake P concentration (Figure 1).

Figure 1. Annual mean, whole lake phosphorus concentrations in Lake Sammamish



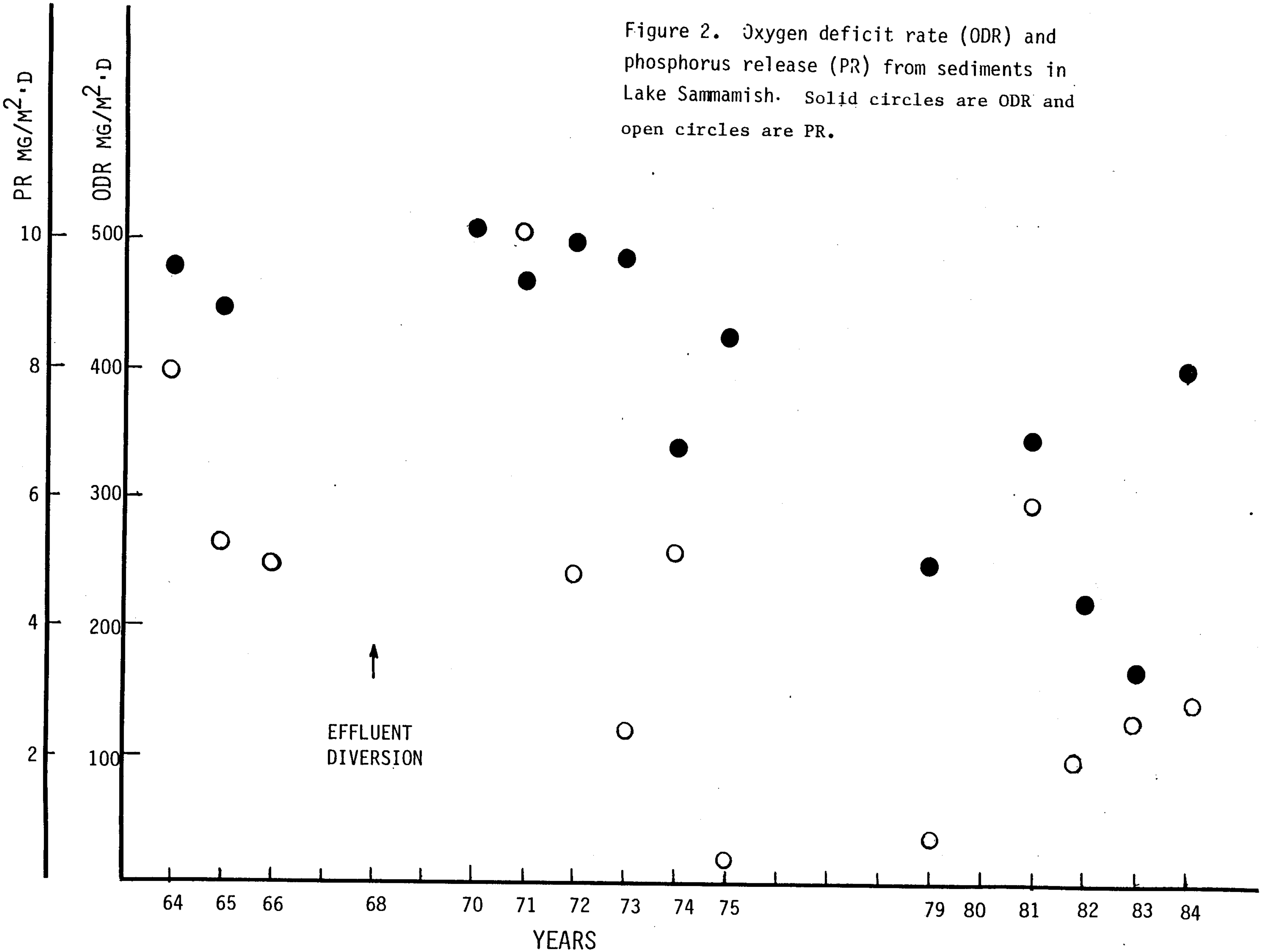


Figure 2. Oxygen deficit rate (ODR) and phosphorus release (PR) from sediments in Lake Sammamish. Solid circles are ODR and open circles are PR.

The Problem

Development of the East Sammamish Plateau and the Issaquah Creek watershed is expected to increase dramatically in the near future. Replacing a forested landscape with commercial development or single/multiple family dwellings will increase the phosphorus loss or yield from the area by about six-fold. Such an increase in P yield could potentially return Lake Sammamish toward its earlier mesotrophic-eutrophic water quality (trophic) state. Results from monitoring the inflow from three subbasins on the developed west side of the lake between 1976 and 1979 showed a mean annual P concentration of 100 µg/L, or approximately what the Issaquah Creek concentration was before diversion (Welch and Perkins, 1980). If the Eastside of the lake were developed to the level of the Westside, which is nearly completely developed, and assuming a comparable inflow P concentration, P loading would be expected to increase by 20% (Welch et al., 1980).

A careful examination of the expected land use changes and their projected effect on the lake's quality was needed. In order to project effects with confidence, a better understanding of why the lake responded to diversion so slowly and a more detailed P model to predict response were also considered important. Finally, alternatives to prevent water quality degradation, if it were expected to occur, and the probable costs involved were perceived to be needed information to develop a management scheme for the lake. These were essentially the goals of this project.

Objectives

The general objectives of the project were as follows:

1. Reassess the response of Lake Sammamish to wastewater diversion that includes the results of an analysis of sediment P content and release rate.

2. Evaluate the sensitivity of Lake Sammamish (P, chlorophyll a and transparency) to past, present and projected P loading (1990 and 2000), incorporating the understanding of internal P cycling from objective 1.

3. Determine the effectiveness and cost of various surface runoff control strategies to prevent lake water quality deterioration compared with that of restoration once the lake's quality has been degraded.

ASSESSMENT APPROACH

Sediment P Analysis

Three sediment cores were collected from the profundal basin of Lake Sammamish (METRO Station 612) on September 4, 1984, using a piston of clear polycarbonate tubing, 35 mm ID, 1.5 mm wall thickness and 1 m length. The cores were extruded and sliced at 1 cm intervals, weighed, dried at 103°C for 24 hours, reweighed, comminuted, and homogenized; 100-150 mg subsamples of the top ten 1 cm sections of two cores were acid digested (NHO_3-HF-HNO_3-$HClO_4$) by a procedure similar to that of Bortleson and Lee (1972), except that all these digestions were carried out in a single teflon crucible. The digestrate was passed through a prerinsed Whatman No. 4 filter and brought to a known volume with distilled-dionized water. This solution, or an aliquot therof, was analyzed for total P using the ascorbic acid-molybdenum blue method (APHA, 1975). All P determinations were carried out on two replicate aliquots of the digestate, and the mean of these values is given.

Sediment P Release

Phosphorus release rates from Lake Sammamish sediments were determined in the laboratory under anoxic conditions. Twenty-three short sediment cores were collected on September 4, 1984 from the profundal zone using a 7 kg gravity corer of a modified Phleger design. The coring chambers were made of clear tenite butyrate tubing of 9.57 cm^2 internal cross-sectional area and 30 cm length. After collection, the height of the water columns above the sediment was adjusted to 13 cm by allowing the sediment to slide out of the tube. The tubes were purged with N_2, sealed air tight and stored in an incubator at 10°C or 20°C in the dark.

Samples of overlying water were taken for total P analysis from two replicate cores each of incubation intervals of 0, 2, 4, 8, 16, 32 and 64 days after core collection. Two samples from each core were analyzed for total P by the ascorbic acid-molybdenum blue method (APHA, 1975). In this report, only the 10°C P release rates are given since they best simulate lake conditions.

The cores from the 32-day and 64-day sediment P release study, along with two similar short cores collected at the same time, were analyzed for sediment interstitial water total P concentrations (Reeburgh, 1967). The cores were placed in a glove box under a nitrogen atmosphere; the top cm was discarded and slices from 1-3, 5-7 and 9-11 cm were compressed in a pressure chamber at 90 PSI for 30 minutes. The interstitial water was passed through a 0.45 μm Millipore filter, acidified and analyzed for total P.

Model Development

A simple mass balance model was formulated after Vollenweider (1969) and Larsen et al. (1979) to simulate the seasonal change in whole-lake P concentration. A seasonal model was considered necessary to evaluate the relative effect of internal loading of P from sediments during summer versus P from external runoff occurring mainly during the winter. The model is as follows:

$$\frac{dP}{dt} = \frac{J_{ex}}{V} - \rho(TP) - \sigma\ (TP) + \frac{J_{int}}{V}$$

where,

TP is whole-lake mean total phosphorus concentration at the end of the last time step, mg/m^3

J_{ext} is external P load from all streams, stormwater runoff and atmospheric deposition, mg/week

V is lake volume, m^3

ρ is flushing rate, 1/week or $\frac{Q}{V}$, $m^3/m^3 \cdot week$

σ is sedimentation rate coefficient, 1/week

J_{int} is internal P load released from sediments, mg/week

Assumptions for developing and calibrating the model were as follows. The lake is treated as a completely stirred reactor with a constant volume. Therefore, the hydraulic inflow is equal to the outflow during the time step and the P concentration calculated is the volume-weighted mean of the whole lake.

The loss to sediments is a product of the time step P concentration and the sedimentation rate coefficient. The latter was considered to be a function of the flushing rate. That follows because with an increase in the rate of water flowing through the lake, there is simply less time for the P present to settle out. P concentration is also less because of dilution. Therefore, if a net loss of P is to occur, σ must increase, but at a slower rate than ρ. Similarly, if the sediments are to be a net sink for P, any increase in the time available for sedimentation must be larger than any increase in the water residence time ($1/\rho$). Thus, $\sigma = \rho^n$, where $0<n<1$.

The internal loading of P occurs during the period of anaerobiosis in the hypolimnetic waters and is the product of the lake bottom area below 15 m and a sediment release rate ($mg/m^2 \cdot week$). This rate is assumed to be constant from July 15 to October 31, to increase just before turnover (Nov. 1-21) and to be zero the remainder of the year.

The weekly time step is used for two reasons. First, due to the wide variation in both the hydraulic and nutrient loading, evident from two years of daily flow and P concentration data from Issaquah Creek, a larger time step would mask out possibly significant loading events. Secondly, the magnitude of the internal P release is not constant at all times and the weekly time step allows for more fine tuning of the model and, ultimately, a greater potential for treating this important mechanism.

To calibrate the model, daily data for flow and P concentration were available from Issaquah Creek for October 1972 to September 1973 and July 1974 to June 1975 (Rock, 1974; Birch, 1976). Based on a budget done by Moon (1972), the inflow from Issaquah Creek was found to be 70% of both the hydraulic and P loading to the lake.

The first step in calibration was to solve for the sedimentation rate (σ) in terms of the flushing rate (ρ). The 1974-75 data were used for calibration purposes. During the time when internal loading is assumed to be zero, σ was determined as a power function of ρ by minimizing the sum of squares of the deviations between the actual lake value and the calculated value. The result was $\sigma = \rho^{0.78}$.

The value for the sediment release rate was determined in the same manner. A value of 32 $mg/m^2 \cdot week$ fit the data best, with an increase of three-fold occurring just before turnover. The resulting average for the July 15 to November 21 period is 6.1 $mg/m^2 \cdot day$, which is similar to the mean value determined from the measured, hypolimnetic increase during the same period for 1970-1975, 5.6 ± 3.2 $mg/m^2 \cdot day$ (Figure 2).

For projection, the model was calibrated to the 1982, 1983 and 1984 data, and the mean of the resulting sediment release rates was 21 $mg/m^2 \cdot week$ (4.1 $mg/m^2 \cdot day$). The mean determined from the hypolimnetic P increase during that period was 2.5 ± 0.5 $mg/m^2 \cdot day$ (Figure 2).

Phosphorus Yield Coefficients

Increased P loading from development in 1990 and 2000 was determined by a product of land use P yield coefficients (kg/ha·yr) and the area of land for the following uses: forest (for), agriculture (agri), commercial (comm), single family residential (SFR) and multiple family residential (MFR). The resulting annual loading was distributed over the year in proportion to the normal rainfall pattern, which was different for high-and low-flow years. These yields were not varied with annual runoff, however, because information does not exist for such a relationship.

High and low yield coefficients were used to represent the degree of uncertainty involved. Further uncertainty was reflected with lake P model predictions for high and low flow years and, additionally, for any flow year based on a probability relationship of flow over the past 20 years of record. These considerations will be discussed later.

For the Issaquah Creek watershed, the high yield coefficients for the land uses in question were taken from Reckhow and Chapra (1983). Total loads were the sum of the products of these coefficients and areas under various uses taken from current U. S. Geological Survey land use and land cover maps

(USGS, 1975; Anderson et al., 1976). An x-load factor (1,100 kg/yr), which included estimates of loads from residential septic tanks, anadromous fish and the state salmon hatchery, was subtracted from the known load from Issaquah Creek during the early 1970's. The Reckhow and Chapra high yields were then adjusted for the Issaquah Creek watershed by the ratio of actual watershed load (total known load minus x factor) to the load derived from the products of land use areas and yield coefficients. The resulting yield coefficients in kg/ha·yr were: For 0.34, Agri 1.5, Comm 2.7, SFR 1.9 and MFR 2.2. These were all higher than Reckhow and Chapra's values.

The low yield coefficients were derived from Issaquah Creek loads determined from monthly measurements of P and continuous flow during 1980-1984, which were the lowest loads on record. The monthly loads were adjusted by a ratio of known monthly load to load estimated from randomly selected monthly P values using the complete data sets from the early 1970's. The purpose was to correct the 1980-1984 loads to more realistic values if complete (daily) P concentrations had been determined instead of only monthly measurements. These adjusted 1980-1984 P loads were about 1,200 kg/yr less than those in the 1970s. No supportable explanation can be offered for the apparent decrease. The same procedure was then employed as used to derive the high yield coefficients. The x-load factor was subtracted from the known 1980-1984 load, and the ratio of that value to the load estimated by the product of the Reckhow and Chapra high yield coefficients and 1980's land use areas was used to adjust the high yield coefficients. The resulting coefficients were: For 0.22, Agri 0.95, Comm 2.2, SFR 1.2 and MFR 1.4.

The East- and Westside yield coefficients were derived by assuming that 30% of the load comes from sources other than Issaquah Creek (Moon, 1971). The same approach was used as for Issaquah Creek; the high yield coefficients from Reckhow and Chapra were scaled in proportion to the actual loads determined by Welch and Perkins (1980) from three Westside subbasins. These high yield coefficients (in kg/ha·yr) were: For 0.12, Agri 0.70, Comm 0.91, SFR 0.70 and MFR 0.81. The low yield coefficients for the East-and Westside were taken directly from Reckhow and Chapra and are: For 0.09, Agri 0.51, Comm 0.68, SFR 0.50 and MFR 0.58.

Both high and low P yield coefficients for the Issaquah Creek watershed are about three-fold higher than for the East and Westside portions. This difference is considered justified, because the coefficients are based on rather extensive data bases. Specific sources of P to Issaquah Creek (x-factor loads) were assessed and subtracted from the total, but they were relatively insignificant (∿10%). One is left with the conclusion that the Issaquah Creek watershed simply yields more P per area to Lake Sammamish than do the East and Westside portions. This difference simply reflects the nature of the watershed portions and does not bias the predicted effects of development. That is, the yield coefficients for all four developed land uses increase about six-fold over that of forest whether for all watershed portions and for both the high and low yields.

Land Use Projections

Land use projections for 1990 and 2000 were taken from several sources. For Issaquah Creek watershed, land use data were obtained from City of Issaquah planning reports (COI, 1984). Ninety percent of Comm, SFR and MFR development is assumed to occur within the city limits of Issaquah. Percent changes in the Issaquah Forecast Analysis Zone (FAZ) were taken from population and employment forcasts in the Puget Sound Council of Governments reports (PSCOG, 1984).

For the Westside, percent changes from 1970 land use in East Bellevue, Newcastle and Eastgate divisions were taken from forecasts in the PSCOG and King County (KCPD, 1984) reports. Percent increases from 1975 land use in the East Sammamish zone were also taken from King County and PSCOG forecasts.

SEDIMENT AND MODELLING RESULTS

Sediment P

The total sediment P profiles shown in Table 1 suggest that no discernible changes in P sedimentation have occurred the last 10 years. Assuming that the total sedimentation rate reported by Birch (1976) remained relatively constant over the last 10 years, one would expect a decreased total flux of P to sediments to be reflected in the sediment P profile. However, the sediments remain strongly anoxic, and under these conditions any decreased P fluxes from the water column are overshadowed by P diffusion from the deeper sediments to the surface.

Results of P release during the 64-day incubation study are shown in Figure 3. The release rates were calculated as a linear regression of the means of the total P (unfiltered) values. TP was used because in past studies identical release rates were measured for soluble P and total P, indicating that P release is controlled by diffusion. Table 2 summarizes past and present P release data from laboratory incubation studies, hypolimnetic P buildup, and calculated rates based on diffusion of interstitial P. The P release rate observed in the 1973 incubation study is significantly higher than that measured in this study. These results indicate that the intensity of the anoxic condition in the sediments, which is

Table 1. Total P content, as percent of oven-dried sediments, of Lake Sammamish Cores collected at station 612 during fall of the indicated years.

Depth (cm)	1984a	1977b	1973c
1	.361	.241	.36
2	.296	.282	.28
3	.243	.185	.30
4	.259	.166	.26
5	.203	.192	.16
6	.222	.260	.21
7	.228	.197	.21
8	.208	.195	.23
9	.191	.195	.25
10	.198	.159	.22

a. this study
b. Lazoff (1980)
c. Birch (1976)

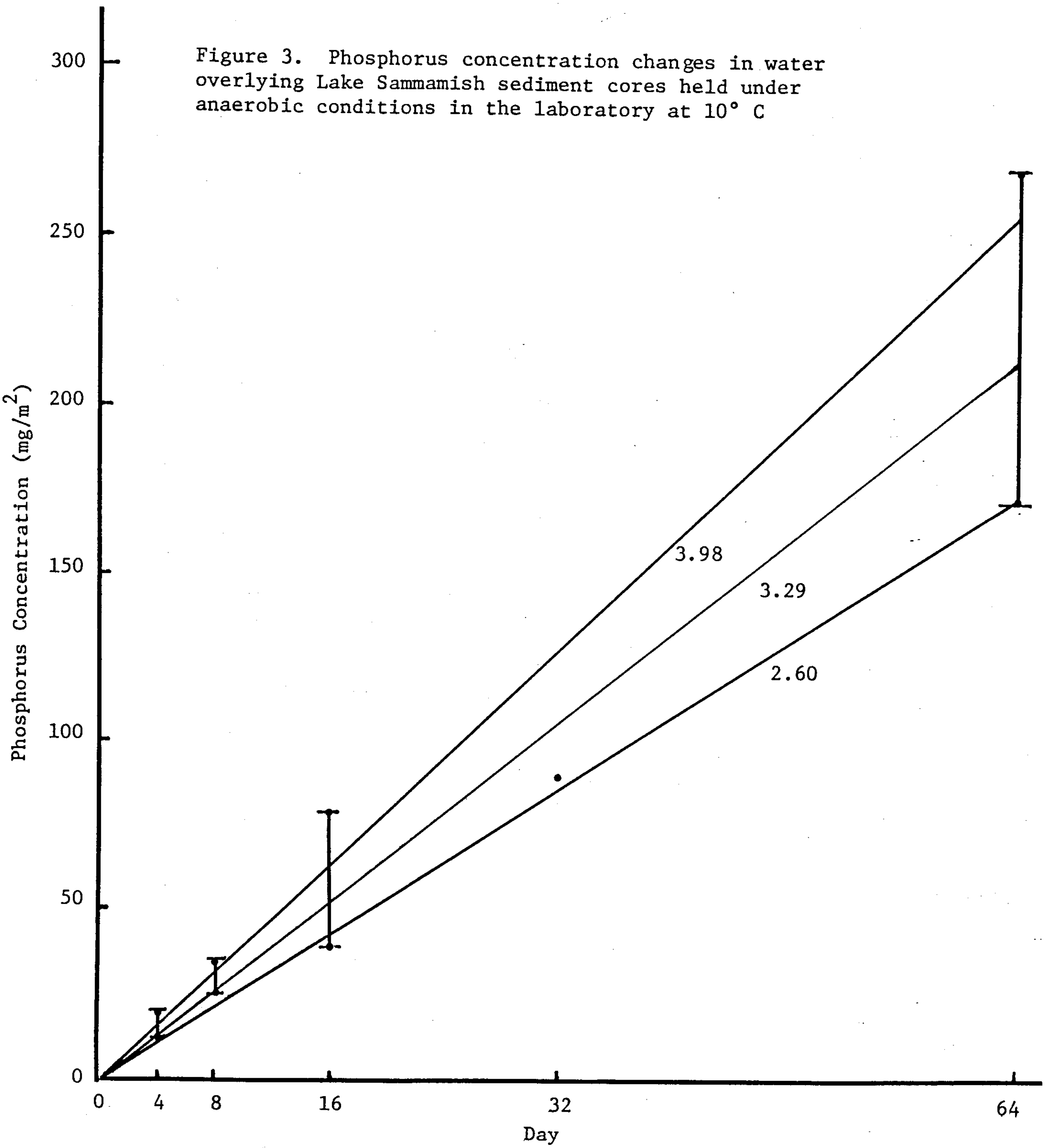


Figure 3. Phosphorus concentration changes in water overlying Lake Sammamish sediment cores held under anaerobic conditions in the laboratory at 10° C
Phosphorus Concentration (mg/m2)
300
250
200
150
100
50
0
3.98
3.29
2.60
0
4
8
16
32
64
Day

Table 2. Phosphorus release in mg P/m^2.day; calculated from laboratory incubation studies, hypolimnetic (area > 15 m, 11.6 x 10 m^2) P build up and interstitial P diffusion).

Year	Release Rate
A. Laboratory Incubation	
1984 (at 10°C)	3.29 (3.98-2.60)
1973 (at 13°C)	7.13
B. Hypolimnetic P Build Up (July - November)	
1984	3.01
1983	2.58
1982	2.03
1981	6.32
1979	0.76
1975	0.41
1974	5.15
1973	2.42
1972	4.84
1971	10.14
1966	4.99
1965	5.30
1964	7.96
C. Interstitial P Diffusion	
1984	1.60
1973	2.32

responsible for the buildup of P in the interstitial water and subsequent diffusion to overlying water, apparently has declined over the last ten years. Also, interstitial P concentrations measured at the outset and end of the 64-day incubation in 1973 were appreciably higher than those measured in the present study, suggesting that the biochemical oxygen demand of the present day sediments has decreased (Table 3). This fact is further substantiated by the measured decrease in the oxygen deficit shown in Figure 2.

Examination of interstitial P from the 1-3 and 5-7 cm sections of the sediment cores reveals significant concentration gradients between the sediment and overlying water (Table 3). Characteristically, the concentration of P increases with increasing anaerobic conditions, indicating the iron-dependent P release. A theoretical P flux was calculated by applying a diffusion equation, presented by Berner (1975), to P concentration gradients measured in cores collected in 1973 and 1984 (Table 2). In these calculations the P concentration gradient was assumed to be linear over a short distance (2 cm), and a measured porosity of 0.90 and a diffusion coefficient of 7.15 x 10^{-6} cm^2/sec for $H_2PO_4^-$ were used. The calculated diffusive fluxes of P in both 1973 and 1984 are significantly lower than the laboratory P release rates, indicating that the actual P concentration gradient, the driving force for diffusion, is higher than that measured at the outset of the incubation.

Apparent sediment P release rates are given for the years 1964-1965, 1979, and 1981-1985 (Table 2). These rates were calculated by linearly regressing hypolimnetic (15-32 m) mean P concentrations on a weekly to monthly basis, from mid-July to the peak of anaerobiosis, mid October or November. There appears to be a trend of decreasing sediment P release, as determined by hypolimnetic buildup, especially between the early 1970's and recent times.

Table 3. Concentration of total soluble P in the interstitial and overlying water of short sediment cores from station 612 of Lake Sammamish before and after 64-day incubation.

Collection Date	Depth in Core (cm)	P (µg/L) Before Incubation	After Incubation
9/4/84	overlying water	-	-
	- lake	32	-
	- coring tube	32	2727
	1-3	630	930
	5-7	626	883
	9-11	-	2284
9/22/78[1]	overlying water (lake)	18	
	5-7	544	
10/3/73	overlying water		
	- lake	21	-
	- coring tube	21	3742
	1-3	860	3960
	5-7	1240	1990
	9-11	-	3400

[1]Incubation temperatures for 1985 and 1973 were 10° and 13°C, respectively.

[2]Felmy (1981)

Even so, there is also extensive year-to-year variation in apparent release rates, especially in recent years. Variation is less during the three years before diversion. Explanations for these variations could be consistent with the overall, long-term trend. First of all, P hypolimnetic buildup is a net result of sediment release, oxygen intrusion due to wind mixing, and sedimentation. Therefore, during years that are relatively dry with lesswind, stratification will be stronger and oxygen depletion will be more intense. For such years, the buildup of P will be greater. Sedimentation as a result of iron complexation of P will be less, and the "apparent" sediment P release (hypolimnetic buildup) will be greater. During years of greater wind and oxygen entrainment, the opposite condition will result and sediment P release will be less.

Sampling error also contributes to this variability; data for some years were only available on a monthly basis, i.e., release rates were estimated from the slope of a line calculated from 4 or 5 data points. High winds and oxygen intrusion between two sampling dates, for example, will produce much larger errors than if twice monthly data were available. Nevertheless, the means of the three periods suggest that, on the average, release rates are less during recent years (Table 2).

In summary, these results indicate that the anoxic conditions in the hypolimnion of Lake Sammamish have become less severe following the decrease of external P loading as a result of wastewater diversion in 1968. This conclusion is based on the observed decreasing trends in interstitial P concentrations, and hypolimnetic P buildup from mid 1960 to present, and the _in situ_ incubation study. This reasoning is further substantiated by the measured decreasing trends in the hypolimnetic oxygen deficit and the water column P concentration immediately following destratification. The latter has decreased from the mid-80s (μg/L) in 1964-1965, to 30 μg/L in the mid 1970's to lows of 20 μg/L during 1981-1984. It is hypothesized that the response of lake productivity to decreased external P loadings was initially partially neutralized by continuing high internal P loading rates, resulting from the intensively anoxic lake sediments. In time, lake productivity responded to the decreased external P loading, which in turn modified, in a slow but steady fashion, the hypolimnetic anoxic conditions, resulting in decreased internal P loading leading to improved lake transparency.

Calibration/Verification

The model was calibrated to the 1974-1975 lake and Issaquah Creek data set in which twice weekly P concentrations were available from the lake and continuous flow and daily P determinations from the creek. The total load was computed assuming that 70% of the total was from Issaquah Creek. Figure 4 shows the model-calculated P values (solid line) and the observed discrete values. The sediment release rate (32 $mg/m^2 \cdot week$) was increased three fold to estimate better the typical peak in P content observed at turnover.

The lake P data were much more variable during 1972-1973. Wide fluctuations occurred in successive observations for reasons possibly associated with internal lake dynamics. The model, based on weekly time steps and completely mixed requirements, could not be expected to simulate such short-term fluctuations. Nevertheless, model predictions approximated the observed values reasonably well (Figure 5). At least the magnitude was similar and the seasonal high (overturn) and low (summer stratification) were approximated. Without the sedimentation rate coefficient (σ) being allowed to vary with flushing ($\rho^{0.78}$), there was marked disagreement between predicted and observed.

Figure 4. Model calibration (solid line) compared to observed whole lake TP (circles) during 1974-1975

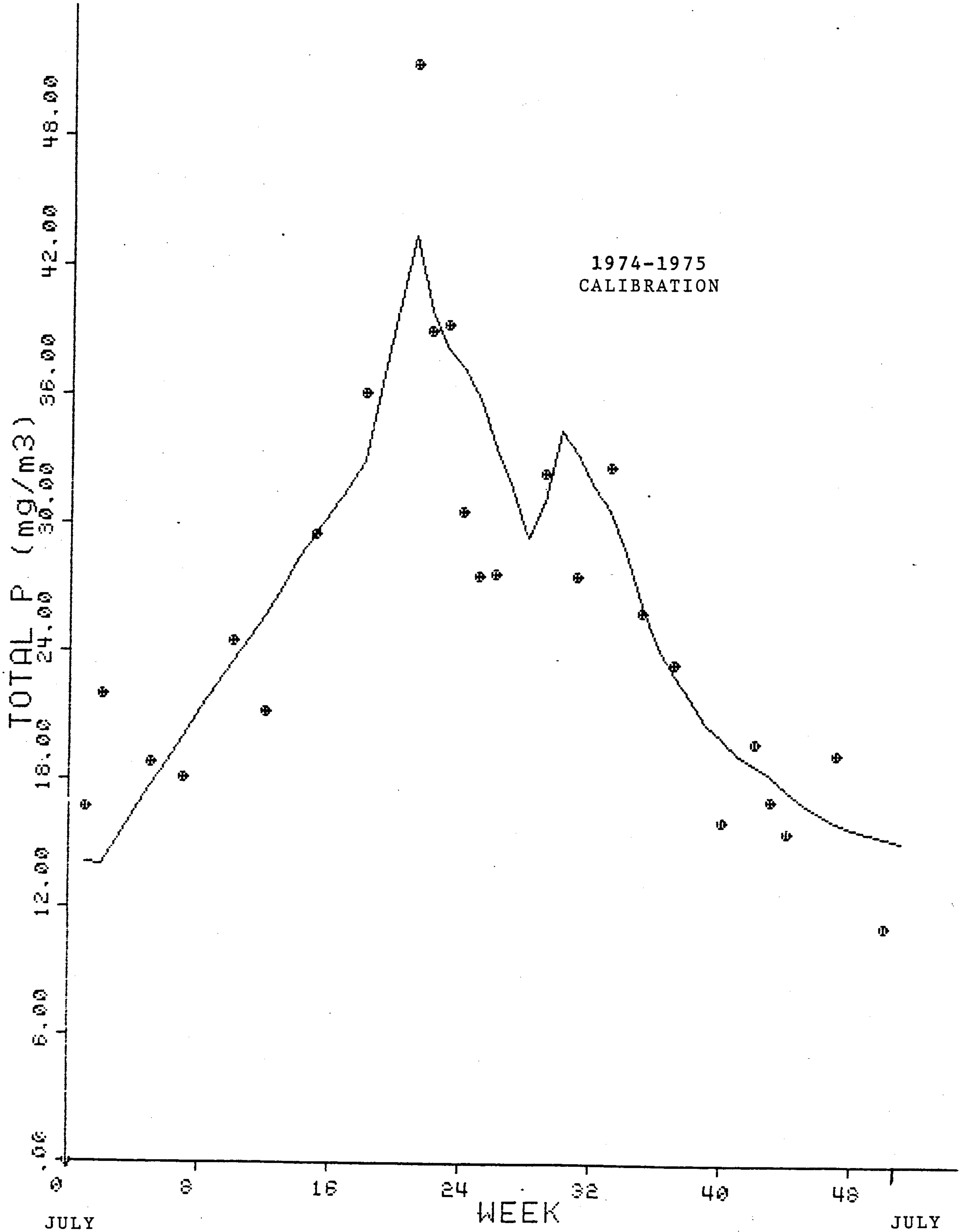


Figure 5. Model verification (solid line) compared to observed whole lake TP (circles) during 1972-1973

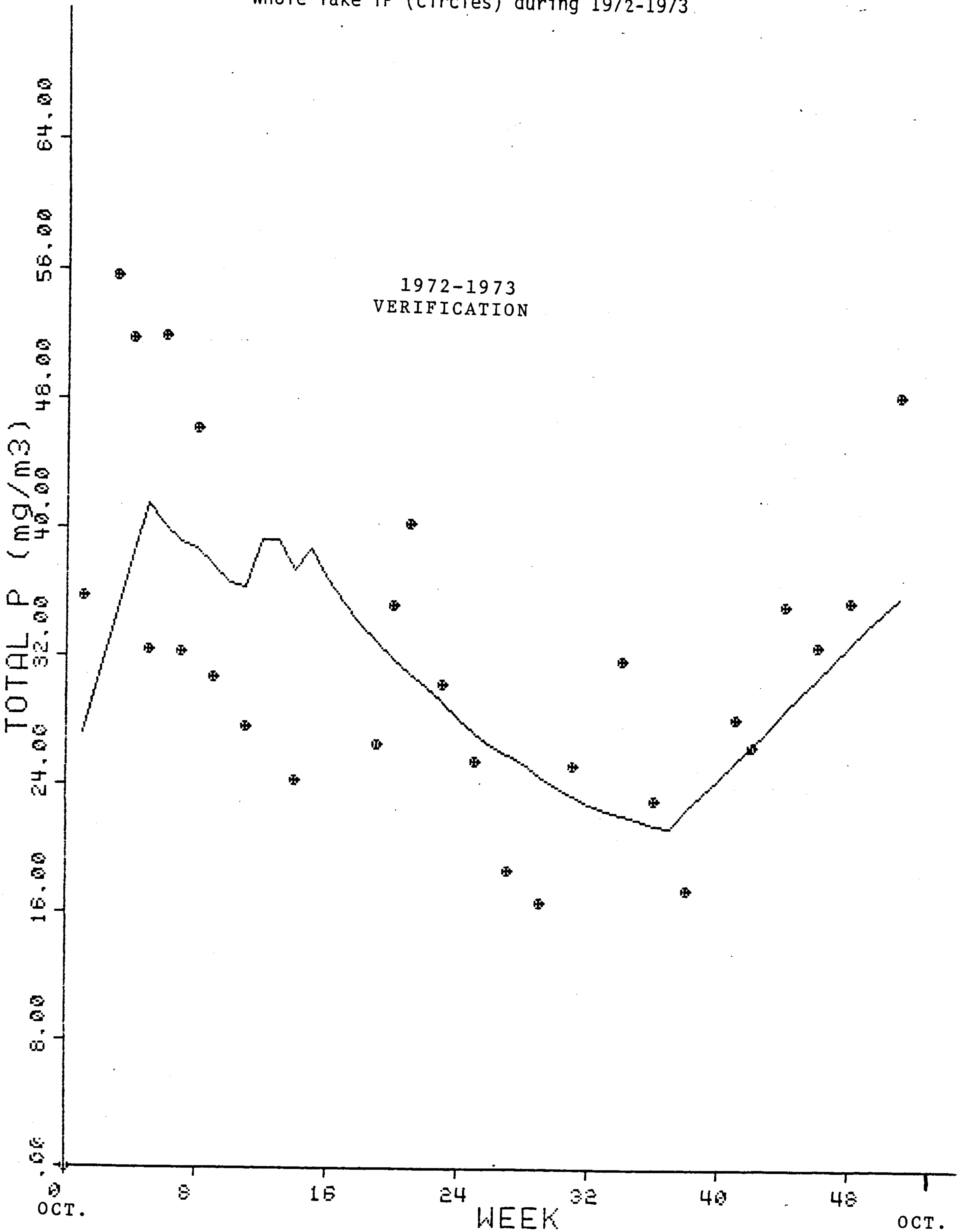
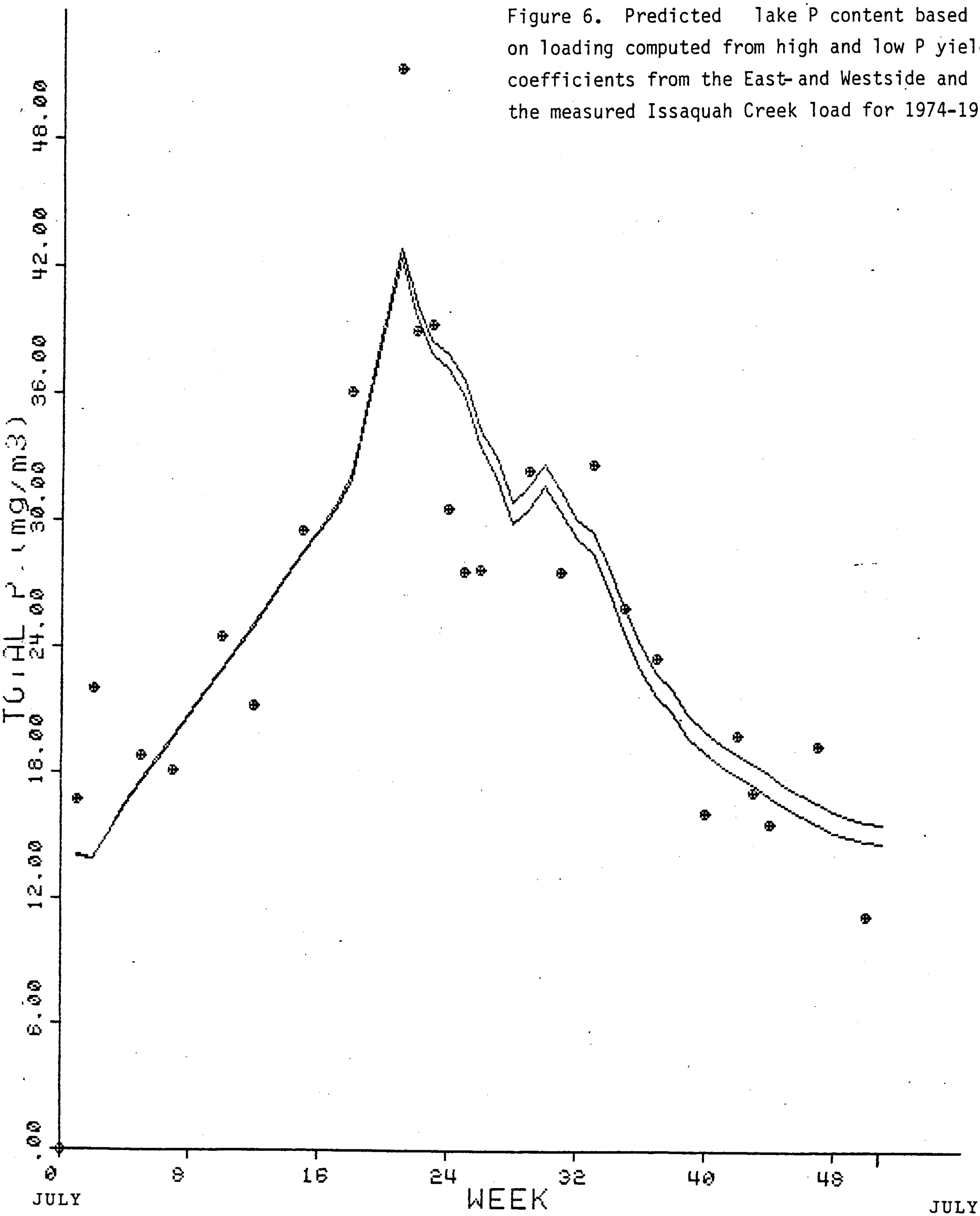


Figure 6. Predicted lake P content based on loading computed from high and low P yield coefficients from the East- and Westside and the measured Issaquah Creek load for 1974-1975



The validity of using high and low P yield coefficients is illustrated in Figure 6. Using the chosen high and low yield coefficients and 1975 land use, instead of the known Issaquah Creek loads used to calibrate the model, the majority of the observed values are near or within the predicted envelope.

Projected Land Use

The projected land use changes are shown in Table 4. The largest change is expected on the Eastside, where forest is projected to decrease by 2820 ha. Forest is expected to decrease by 1324 ha in the Issaquah Creek watershed, while the least change will occur on the nearly completely developed Westside (681 ha). In the past nine years there has been little change in the Issaquah Creek Watershed, while nearly 1000 ha were developed on the Eastside.

Projected Lake Response with Development

The predicted trophic state in Lake Sammamish by 1990 and 2000, if development occurs as expected and there are no controls, varies according to several factors and assumptions. An attempt has been made to account for the uncertainty of prediction by varying these factors and assumptions. High and low yield coefficients have been used to illustrate the uncertainty in that assumption, as described previously. In addition, predictions vary with flow, because increased flow tends to dilute P yield while reducing the sedimentation rate (although the coefficient is increased slightly). Decreased flow concentrates P yield, while increasing sedimentation rate. The overall effect of flow in the model is to produce higher lake P concentrations with decreased flow. In reality, P yield probably varies with year-to-year flow also, but

Table 4. Land use estimates for the Lake Sammamish drainage basin. All values are in ha.

	LANDUSE				
Year	For	Agri	Comm	SFR	MFR
		ISSAQUAH CREEK WATERSHED			
1975[1]	12964	473	101	611	51
1984[2]	12665	320	150	1100	65
1990	11908	128	250	1782	131
2000	9845	95	390	3620	250
		WESTSIDE SUBBASIN			
1975[3]	1966	140	122	2091	181
1984[2]	1191	90	360	2631	228
1990	901		416	2906	277
2000	510		530	3180	280
		EASTSIDE SUBBASIN			
1975[3]	5525	210	65	647	53
1984[4]	4586	291	183	1310	130
1990	3912	151	215	2045	177
2000	3262	50	351	2610	277

[1]PSCOG, 1984; Metro

[2]PSCOG, 1984

[3]USGS, 1975

[4]KCPD, 1984

that uncertainty was felt to be too complicated to incorporate in the model and little information on the relationship was available.

An additional uncertainty is the sediment release rate, which has been shown to be highly variable, at least as measured by hypolimnetic P increase (Figure 2). This factor was also varied by computing P concentrations for high and low sediment P release rates, taken as the calibrated rate ± the standard deviation for the 1979-1984 period. For the predictions, however, only the calibrated rate (21 $mg/m^2 \cdot week$) is used; the actual mean ± SD for 1979-1984 is 30.6 ± 14.5 $mg/m^2 \cdot week$. The sediment release uncertainty is nevertheless important because internal loading is large, representing 26 to 34% of the total for low and high yields. Also, it has apparently decreased in recent years, possibly because of the eventual flushing out of flocculent detritus in the hypolimnion, which resulted from the enrichment from wastewater input. Further increases in internal loading may restore higher release rates.

Because treating the uncertainty of P yield and flow produces four possibilities of four variables, sixteen numbers are generated for each year of projection. Sediment P release variability is omitted, because that would produce 48 numbers. To improve clarity, tables that include conditions and predictions are presented in Appendix A, while the predictions presented in the text are based on median values of the range in P yield. Also, the variation of predictions has been related to the probability of attaining a given flow based on the past twenty-year record of Issaquah Creek. Accordingly, the probabilities of observing flows and each of the four trophic state indices are plotted in Figures 7-11. From those plots, predictions for the median, or 50% probability flow, are summarized in Table 5. In addition to clarity, presentation of predictions based on 50% flow probability is

Figure 7. Probability of Issaquah Creek exceeding a given annual mean flow, based on past 20-year record

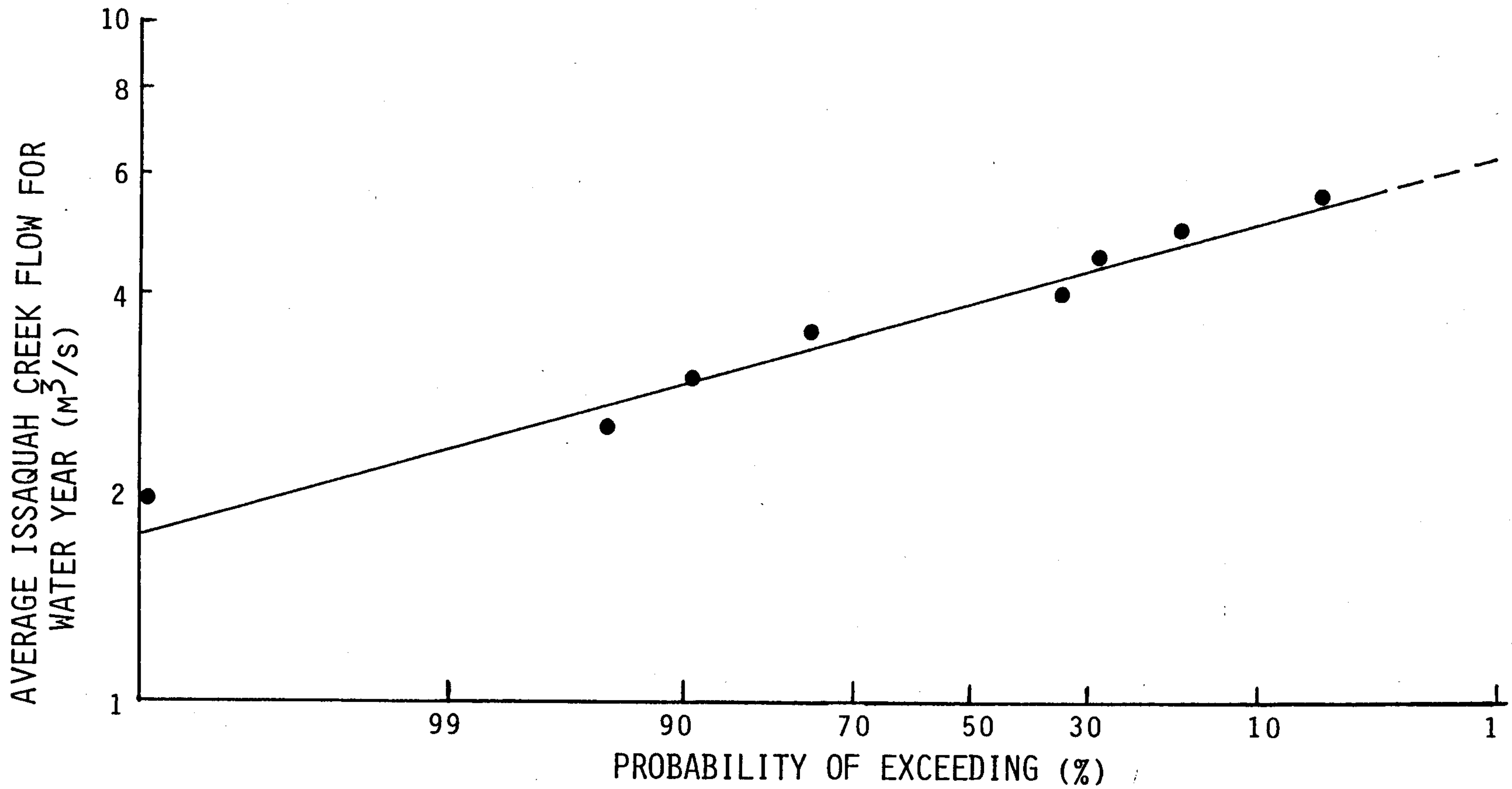


Figure 8. Predicted whole-lake, annual mean total P for 1990 and 2000 compared to 1984 levels, based on the probability of flow

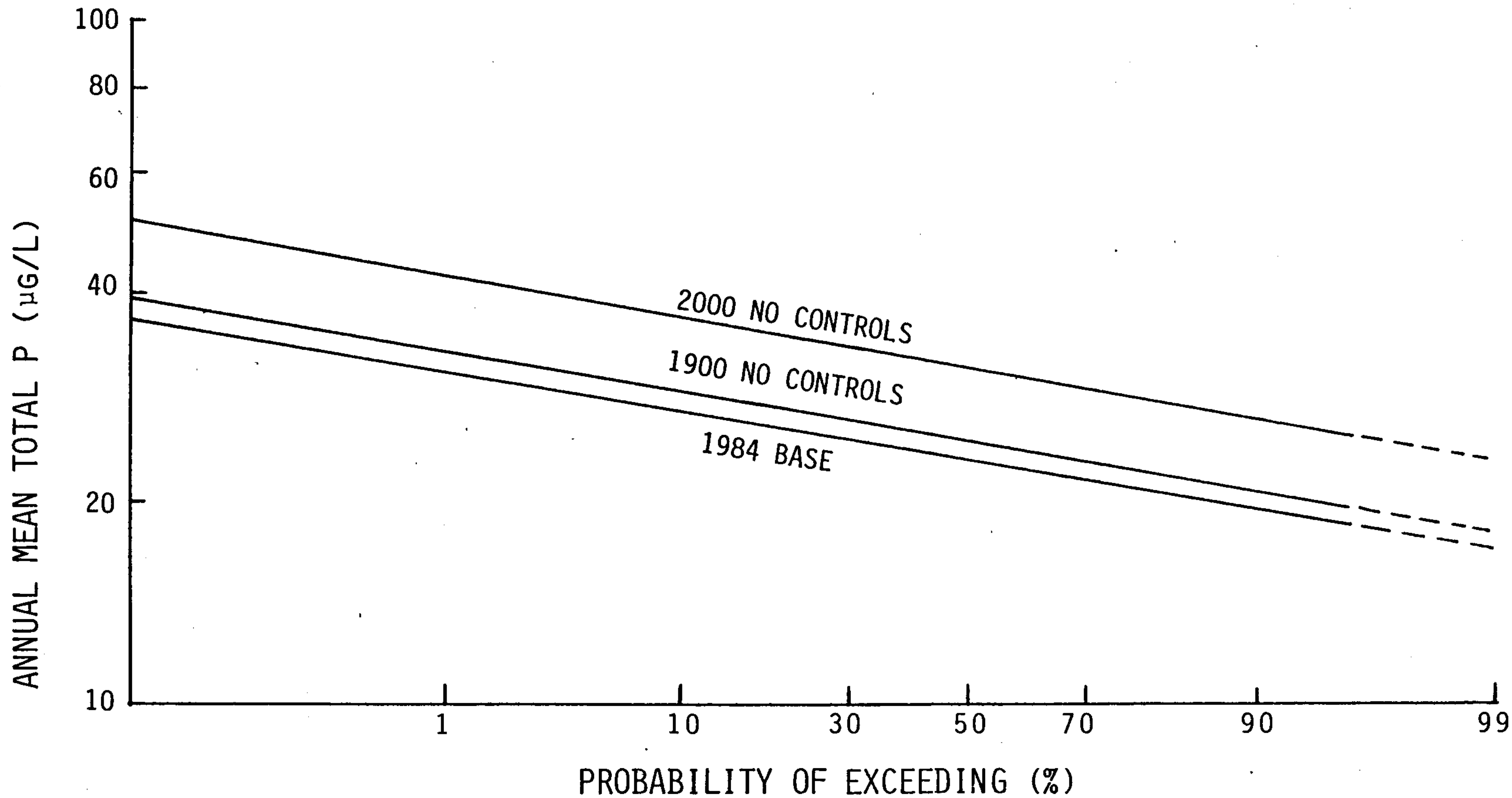


Figure 11. Predicted summer mean total P for 1990 and 2000 compared to 1984 levels, based on the probability of flow

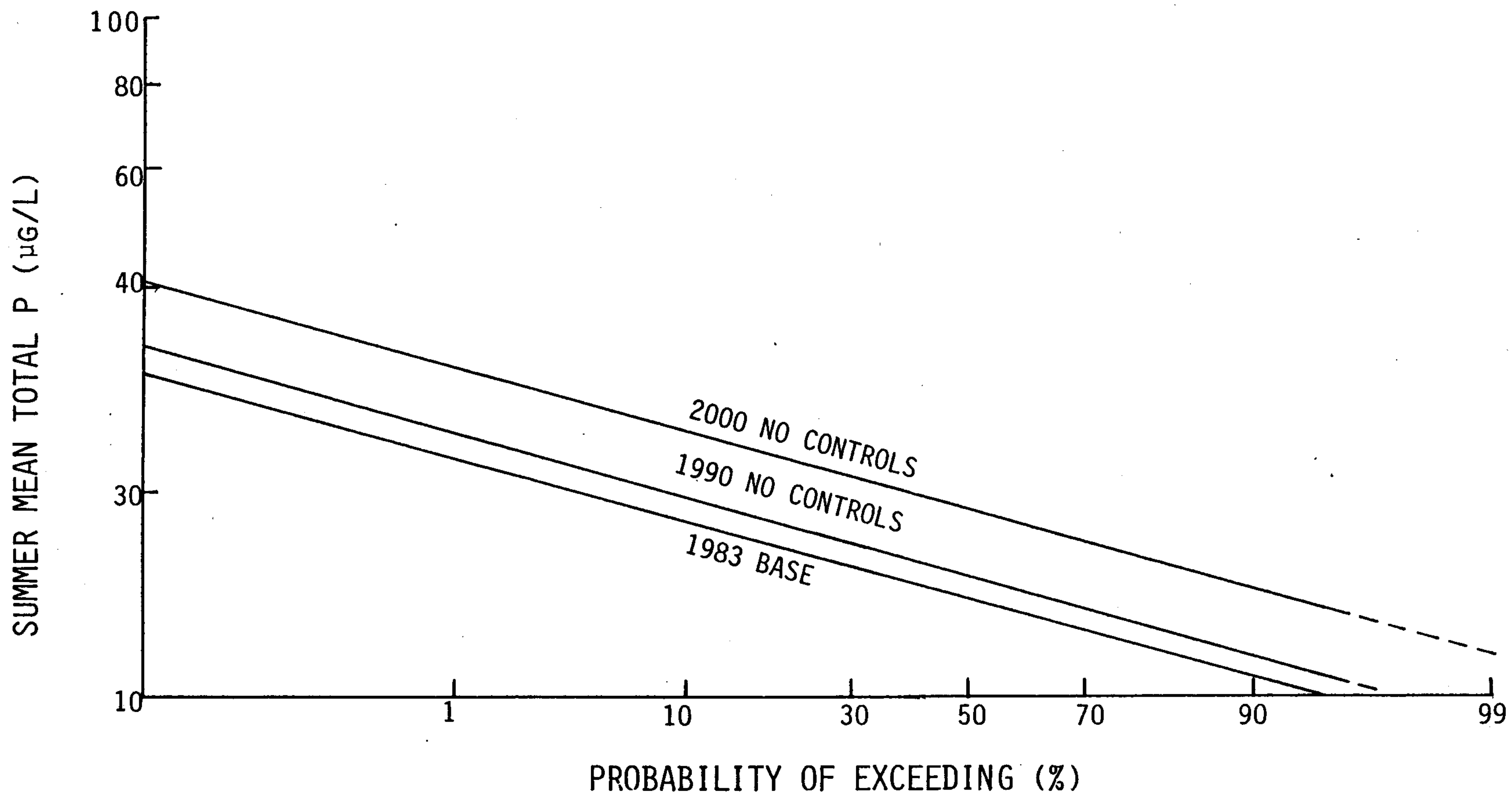


Figure 10. Predicted summer mean Chl a for 1990 and 2000 compared to 1984 levels, based on the probability of flow

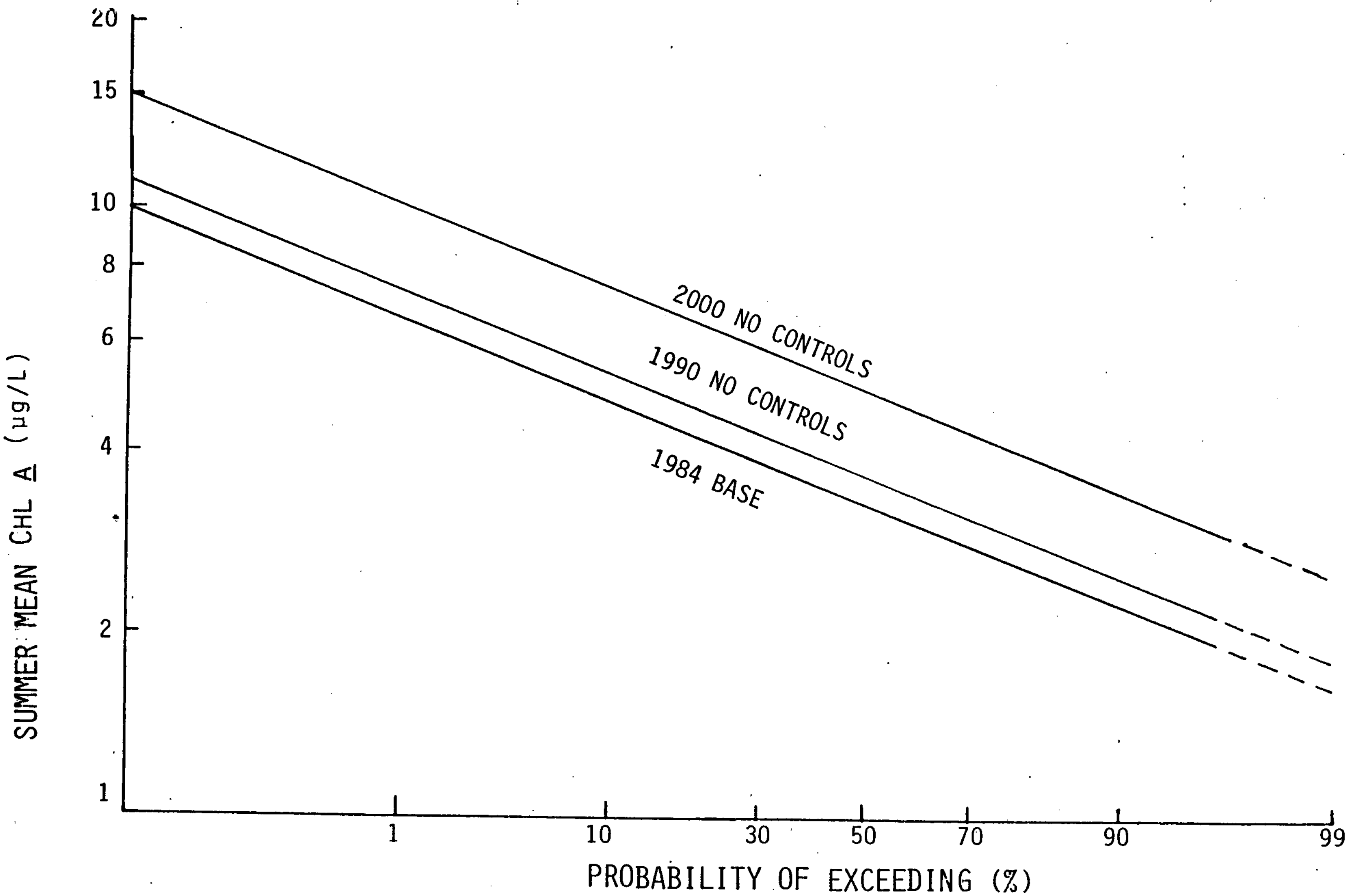
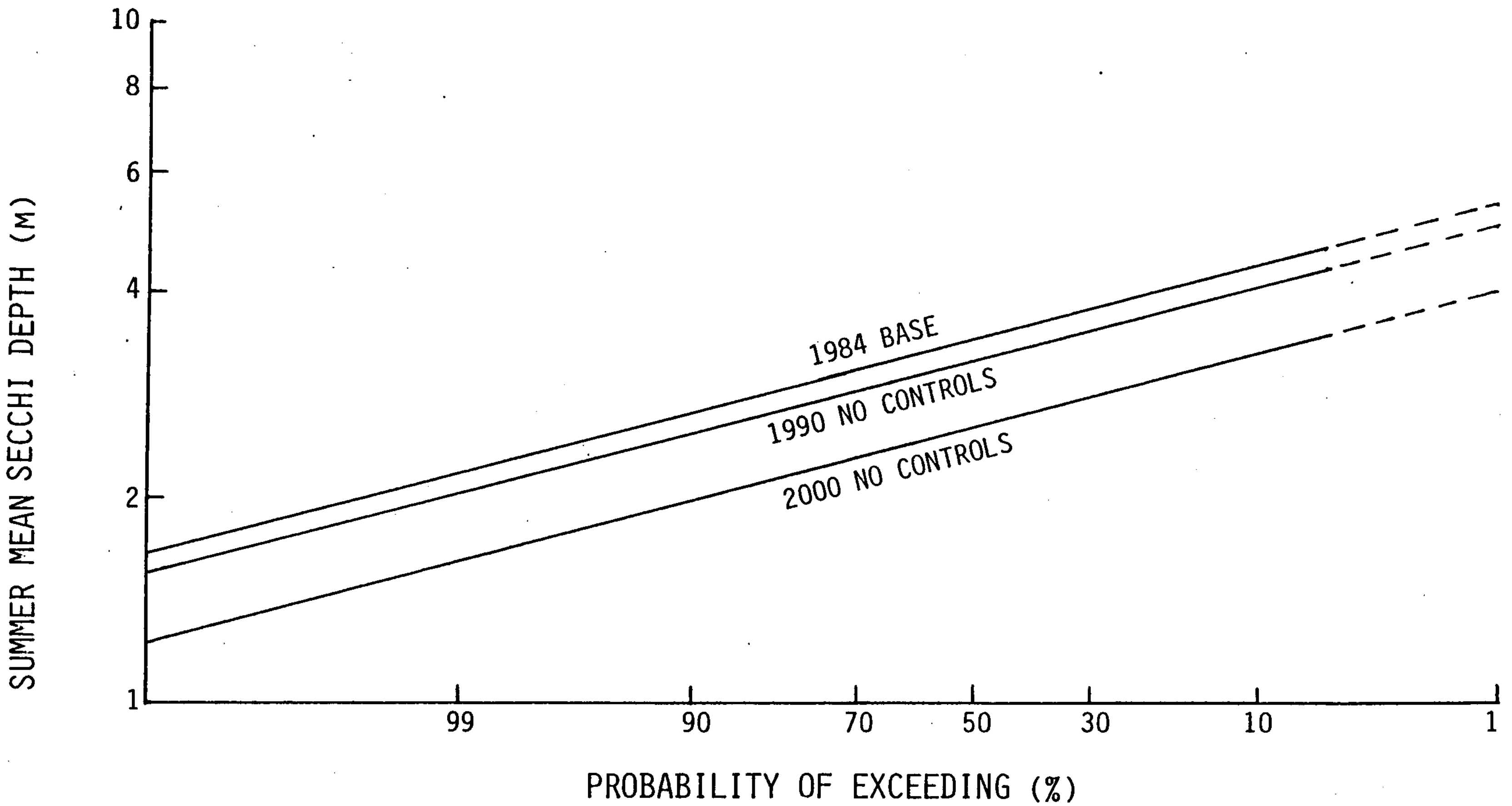


Figure 9. Predicted summer mean Secchi depth for 1990 and 2000 compared to 1984 levels, based on the probability of flow.



considered a reasonable basis for long-term management of the lake, recognizing that better and worse water quality years will result.

The model prediction for annual TP with the 1984 loading, based on mid-1980s land use and a median flow year, is 23 μg/L. The actual mean in 1982-1984 was 18 ± 1 μg/L. Some of the difference between model prediction and measurement may be the result of storm runoff water quality control measures already taken, but the uncertainty of prediction is too great to make this assertion with confidence. The values in 1990 and 2000, are 25 and 31 μg/L, respectively, if no runoff treatment controls are installed. These are median predictions, and the uncertainty expected for one year may be as high as ± 30% (Table 5). According to the model of Carlson (1977), chl a would be expected to increase proportionately and Secchi transparency would decrease (Table 5). The undertainty for these variables is even greater than that for TP.

Not included in the predictions of chl a and Secchi transparency are the uncertainties in the regression models (Carlson) for a single lake. This problem is evident for Lake Sammamish, in which the 11 years of data show higher ratios of Secchi transparency to chl a and TP to chl a than predicted by Carlson's models (Table 6). Levels in the lake during 1979-1984 were 10.4 μg/L TP, 2.5 μg/L chl a and 4.9 m Secchi depth, which are similar to those predicted by the Carlson models at that level of TP. However, the worst case, year 2000 low flow, would have 28 μg/L of TP, 9.4 μg/L chl a and 1.7 m Secchi predicted by the Carlson model, but according to past data from lake Sammamish, chl a is likely to increase to only 6 μg/L and Secchi to decrease to only 3.6 m (Table 6). Nevertheless, Carlson's models will be used to evaluate the relative change in trophic state with increased development and

Table 5. Predicted trophic state indices in Lake Sammamish as median probability values, or values that have a 50% chance of not being exceeded (TP and chl a in µg/L) or being exceeded (Secchi transparency in m), in 1900 and 2000 compared to the 1983 predicted state, based on the median probability for Issaquah Creek discharge for the past 20 years of 3.9 m^3/sec. Variation due to high and low P yield coefficients and the 5% and 95% probability flows in % of medians.

Indices	1984	1990	2000	Yield ± %	Flow ± %
TP annual	23	25	31	10	20
TP summer, epi	14	15	19	13	34
Chl a	3.3	3.6	5.0	19	55
Secchi	3.5	3.2	2.6	13	28

Table 6. Comparison of relationships among summer TP, chl a and Secchi transparency, from 11 years of Lake Sammamish data with that predicted by models of Carlson (1977). TP and chl a in µg/L and Secchi (SD) in m.

	Lake Sammamish		Carlson	
TP	chl a	SD	chl a	SD
10	2.9	4.1	2.1	4.7
20	4.3	3.8	5.6	2.4
30	6.2	3.5	10.1	1.6

watershed controls because the Lake Sammamish data do not cover a sufficient range to develop reliable models.

A principal reason for using the seasonal transient model instead of an annual steady state model was to represent realistically the effect of increased P yield, which was partitioned in proportion to rainfall, on lake P. This was especially pertinent for summer values, which are most important to algal growth. There was some reason to believe that increased inputs in the winter w ould have little effect on summer values. Figures 12 and 13 show that the predicted P content for 2000, at high and low flows and high and low yield coefficients, is proportionately greater than the 1982-1983 level in summer as well as in winter. Therefore, increased P yield from development can be expected to affect summer algal biomass and water transparency.

CONTROL OF PHOSPHORUS IN STORMWATER RUNOFF

Techniques

Stormwater runoff controls may be classified broadly as temporary (construction phase) and permanent. Some temporary measures can be converted to permanent service with or without modification. Each category may be subdivided into best management practices (BMPs) and structural measures. BMPs are nonstructural or have a minimal structural component; e.g., natural land features may be exploited with little modification (Finnemore and Lynard, 1982). Their purpose is to reduce pollutants in runoff at or near the source; thus, they are generally applied at multiple locations throughout the catchment. Included are both institutional and technical procedures. Structural measures tend to be less broad in application and to serve larger areas. Fewer BMPs are available to control urban runoff than agricultural or

Figure 12. Predicted lake TP for year 2000 at high flow based on high and low P yield coefficients compared to observed 1982 values

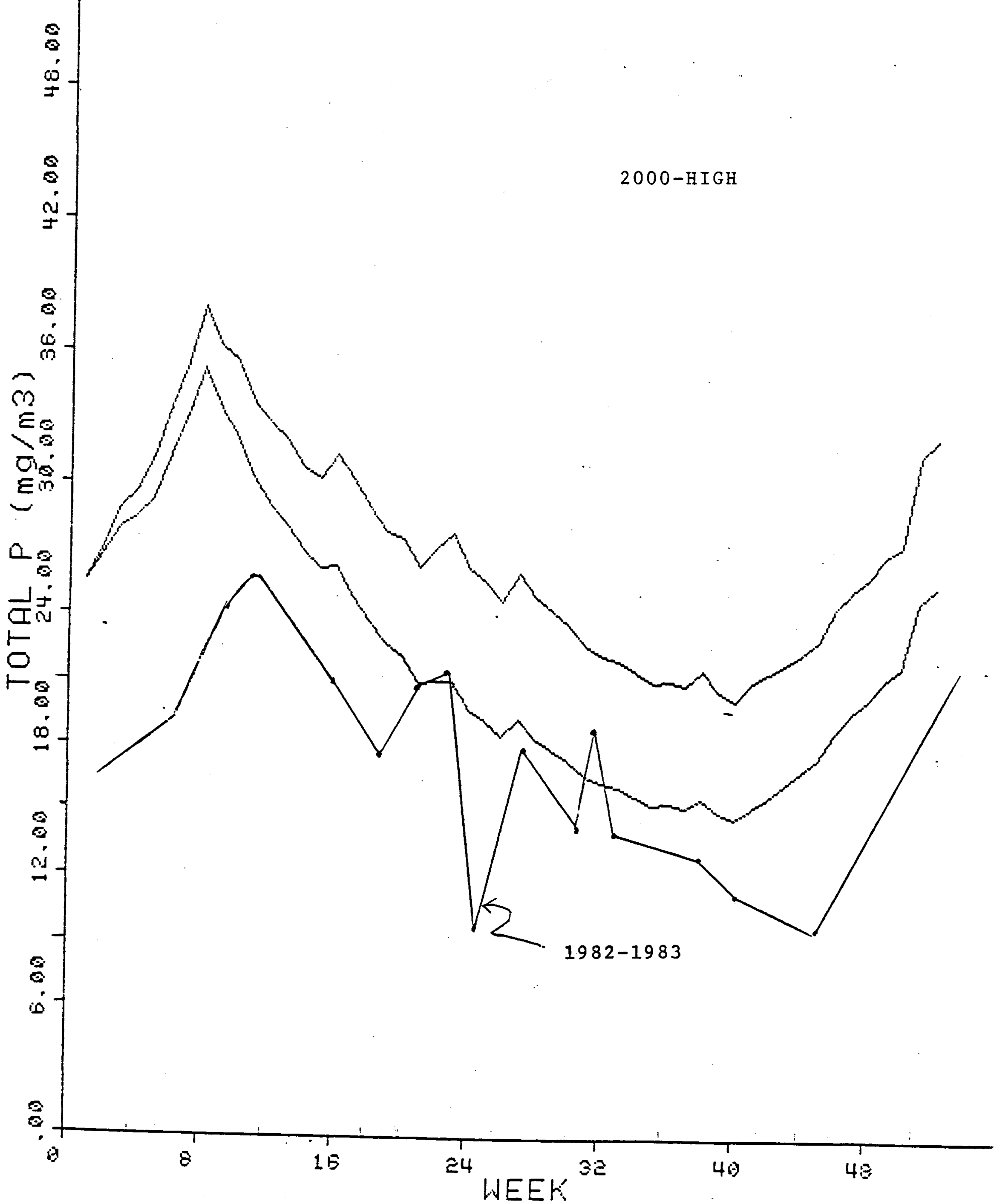
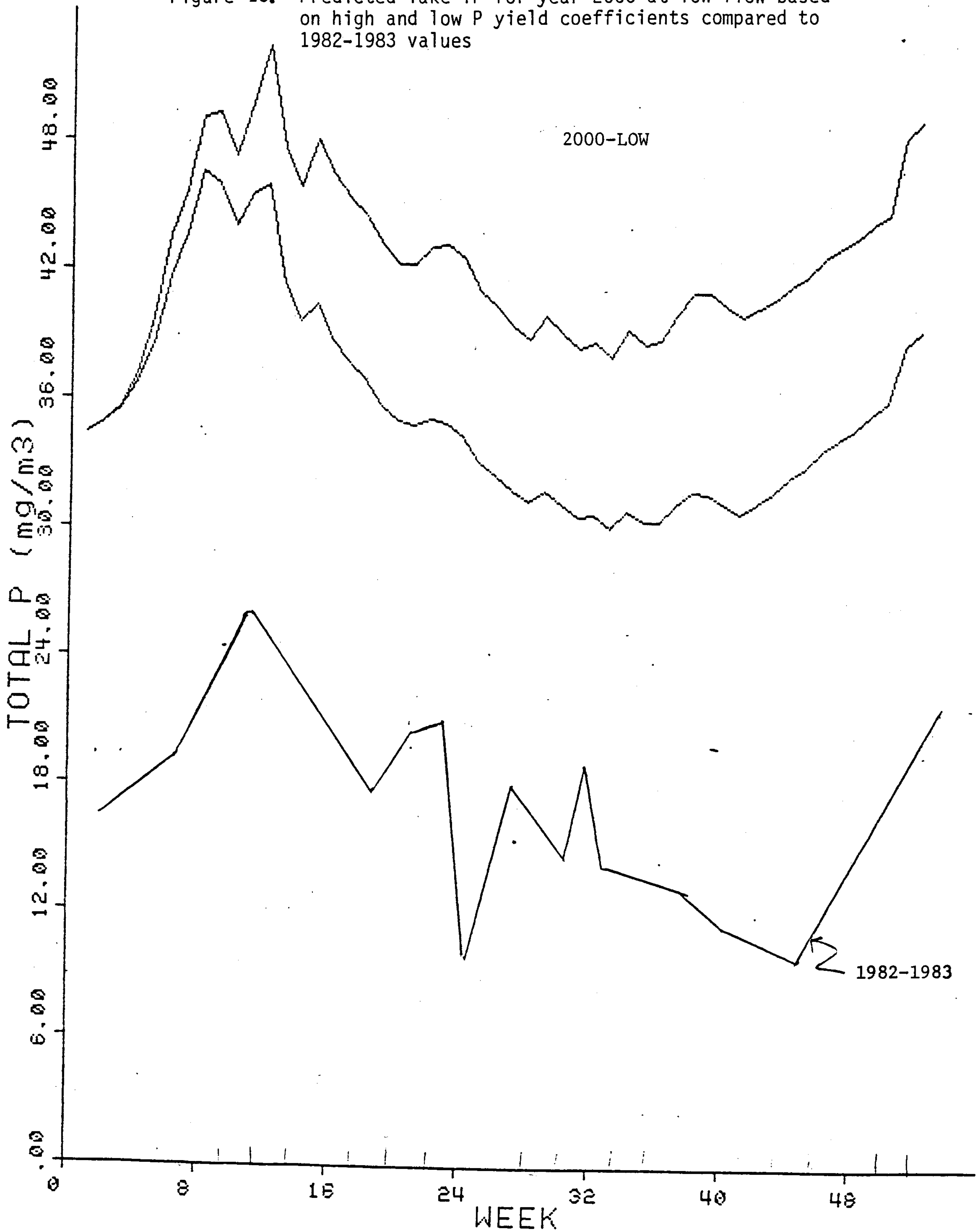


Figure 13. Predicted lake TP for year 2000 at low flow based on high and low P yield coefficients compared to 1982-1983 values



silvicultural runoff, for instance, and urban runoff control relies more on structural measures. The following discussion will identify the major BMPs and structural measures applicable to temporary and permanent control of runoff from urbanized areas. The discussion will then proceed to the application of selected techniques in the Lake Sammamish watershed.

Temporary water pollution control serves to reduce pollutants in construction site stormwater runoff. Following are common BMPs for which applicability and cost have been documented for this purpose:

Institutional (land use regulation, regulation of construction activity)
Fabric filters
Gravel filters
Mats
Gabions
Hydroseeding
Coverage of exposed earth by sheeting
Chemical soil stabilization
Sod

Useful guides have been prepared by the Municipality of Metropolitan Seattle (1981) and the Virginia Soil and Water Conservation Commission (1979).

The leading structural, temporary water pollution control device is the sedimentation pond. Some recent work has improved the scientific basis for design of construction site sedimentation basins (National Cooperative Highway Research Program, 1980). These ponds may be converted to permanent usage following construction with consideration of the long-term service requirements in initial design or with modification. Another structural measure is the paving grid, designed to stabilize slopes and promote infiltration. Gravel filters and gabions also may be regarded as structural when permanently installed.

With respect to construction activity in the Lake Sammamish watershed over the next 15 years, it is generally recommended that BMPs be specified in accordance with the Metro guide and existing regulations. Extensive use of state-of-the-art BMPs is particularly important when development occurs in relatively steeply sloped portions of the Issaquah Creek catchment. Careful consideration should be given to the use of sedimentation ponds on a case-by-case basis. They should be specified in any case when it is doubtful that BMPs will prevent transport of eroded materials into water bodies under the hydrologic conditions that may occur during the period of construction. Sedimentation ponds are likely to be advisable particularly in relatively steeply sloped areas, when the construction site is near a water body, and when the site is relatively large and/or construction will occur over a relatively long period of time. Because retention or detention of runoff from finished sites is expected to be a major permanent control technique in the watershed, it is recommended that developers be encouraged to design sedimentation ponds for conversion to permanent service whenever possible.

The effectiveness of the recommended temporary water pollution control measures in reducing Lake Sammamish phosphorus input during construction was not evaluated quantitatively. The basis does not exist in the litarature at present for performing that evaluation. Furthermore, various construction activities that are projected to occur in the next 15 years could not be pinpointed very exactly in space or time. Also, it was not considered necessary to perform a quantitative analysis of temporary water pollution control, because Lake Sammamish flushes relatively rapidly and a scattered series of short-term effects is considered to be much less consequential than more widespread persisting events. The strategy instead was to establish ranges of phosphorus export from various land uses to the lake in future years. It is assumed that these ranges encompass yields from whatever construction activity is occurring and represent a spectrum of temporary water pollution strategies that might be applied.

A limited number of BMPs are available for application to permanent urban stormwater runoff control, including the following:

Institutional (public education or regulation in such areas as litter control, fertilizer application, dumping, and control of domestic animals)

Street sweeping

Catch basin cleaning and other drainage system maintenance strategies

Only minimal effectiveness in phosphorus control has been demonstrated by street sweeping (U. S. Environmental Protection Agency, 1982) and catch basins (Aronson et al., 1983). Therefore, these alternatives were removed from further consideration. Institutional measures offer some potential to make a marginal reduction in phosphorus inputs to Lake Sammamish from both existing and new residential areas. It is recommended particularly that Metro conduct a program of high visibility to educate homeowners in the Lake Sammamish watershed about lawn fertilizer application and storm drain disposal of waste materials. There was no basis on which to estimate the cost or effect of such a program on phosphorus loading, but it was assumed that any result would be encompassed within the phosphorus export ranges used in the loading analysis.

Structural measures for treating urban runoff are more numerous than BMPs and offer much greater potential for significant phosphorus control. Table 7 lists the principal alternatives. These techniques operate either by sedimentation prior to surface discharge, soil removal of pollutants in infiltrating water, or pollutant reduction by surface soils and terrestrial or aquatic plants. Some of these measures, especially retention/detention (R/D) facilities, overland flow, and wetland treatment, have been the subjects of substantial research. The performance of others has been investigated more sporadically. Generally speaking, no research results are adequate to support comprehensive and broadly applicable design criteria. However, at least for the well-studied measures, they are sufficiently complete to evaluate the applicability of the given technique in a specific situation.

Table 7. Permanent Structural Measures for Phosphorus Control in Urban Stormwater Runoff Water

Technique	Variations
Retention/detention pond	Wet pond Dry pond--Exclusively for stormwater Multiple use (e.g., parking lot, recreation area, road right-of-way)
Retention/detention tank	
Chemically-assisted coagulation/sedimentation/precipitation	
Overland flow	
Wetland treatment	Natural Constructed
Soil infiltration	Perforated pipe Tile drainfield

The terms retention and detention are often used interchangeably. Technically, detention basins are small impoundments having short holdup times and ungated outlets. It is often the intention in designing these basins that the influent percolate into the ground or evaporate, rather than exit as surface runoff. Retention basins, on the other hand, store water longer under the control of outlet structures (Dally et al., 1983). Except where these distinctions matter in the discussion or where a reference has reported one or the other, the general term R/D facilities will be used here.

R/D ponds are excavated facilities, whereas R/D tanks are concrete or metal boxes generally installed below grade. The latter devices usually serve impervious areas somewhat limited in size, while ponds may serve any land use for which the necessary land is available. Wet ponds are designed to retain water at some level at all times. Since they drain completely, dry ponds may serve in other intermittent uses if these uses are not deterred by periodic flooding.

Most application of R/D facilities has been for flow attenuation, rather than for water quality benefits, and much of the research record involves the hydrology only. Primary concerns relative to water quality have been treatment efficiency, design, and operating strategy. Performance investigations have been carried out both in the laboratory (Whipple and Hunter, 1981; Randall et al., 1982) and in the field (Davis et al., 1978; Curtis and McCuen, 1977; McCuen, 1980; USEPA, 1981; and Dally et al., 1983). The studies agree, in general, that R/D devices are capable of removing the majority of the influent total suspended solids but frequently capture only a minority of pollutants such as metals and nutrients. As pointed out by Kathuria et al. (1976), Kamedulski and McCuen (1979), and Ellis (1985), performance can be improved by certain design and operating modifications and maintenance actions.

The current consensus is that the best R/D configuration from the water quality standpoint is a wet pond designed according to the following provisions (Ellis, 1985):

Ratio of length/width $\geq$ 3 (5 optimum).

Place the inlet and outlet on opposite sides and install baffles to prevent short-circuiting of flow.

Consider a series arrangement of more than one pond, instead of a single large pond.

A state-of-the-art device of this type served as the basis for analysis of the retention/detention alternative in the Lake Sammamish watershed. The available reports indicated that, properly maintained, the device is capable of total phosphorus removal ranging from 25 to 45 percent of the influent mass (Hartigan et al., 1981; U. S. Environmental Protection Agency, 1981).

Recent experience has indicated that large, regional retention facilities have advantages over smaller scale onsite ponds (Carlson, 1985). These advantages include greater pollutant removal effectiveness, more efficiency in maintenance, greater flexibility in operation, and lower costs of construction and operations and maintenance per unit area served. It is likely that the future trend will be toward more use of regional rather than onsite ponds. Still, the onsite alternative probably will continue to to be used where large-scale facilities are not feasible. The analyses of effectiveness and cost presented in the following two sections are based on a range of application from all onsite to all regional retention structures. An actual application is likely will fall somewhere between the extremes, probably toward the regional side.

Chemical treatment of stormwater would require a retention facility to provide the necessary water residence time. For phosphorus reduction, one or more chemicals would be added to the retained water to promote the flocculation of small particles and their subsequent settlement, together with the sorption and precipitation of dissolved and particulate P. As a basis for the analysis of this alternative in the Lake Sammamish watershed, a state-of-the-art retention pond was assumed. Automatic chemical feed also was assumed, since the device normally would have to operate unattended. The expected P removal efficiency of such a system (including the contributions of retention time and chemical treatment) is 40-80 percent (Lynard and Field, 1980).

Overland flow is a process in which treatment occurs through interaction of the waste stream with surface soils and vegetation, either while passing through a vegetated channel or in sheet flow over a broad surface area. Most previous applications of overland flow have been in the area of polishing pretreated municipal sewage, where the sheet flow configuration has been used. A substantial amount of research on these systems has documented various aspects of the process. Because urban runoff typically has pollutant concentrations of the same order of magnitude as treated sewage, some of the conclusions of this research are relevant to urban runoff control. Our research team has investigated the use of vegetated channels to remove pollutants from highway runoff (Wang et al., 1982; Little et al., 1982), which is more directly applicable to the problem under consideration here.

The extensive previous work on overland flow treatment of municipal wastewater has documented various aspects of system design and operation, mechanisms responsible for pollutant removal, and performance characteristics. One conclusion of particular importance in the present context is that performance often declines in the winter months and that nutrient removal efficiencies, in particular, frequently suffer at this time (Honachefsky, 1978; Jenkins and Martel, 1979).

In our study of the performance of grass-lined channels in highway drainage service (Wang et al., 1982), we consistently observed by an 80 percent reduction of total suspended solids and lead over a distance of 55 m (180 ft). More soluble metals, such as copper and zinc, were reduced by approximately 60 percent in this distance. Little et al. (1983) collected limited data on nutrient and oil and grease removals in one of these channels and observed the following:

	Removal Range (%)	No. Storms
Total Phosphorus	5-85	9
Soluble Reactive P	<0-73	6
Nitrate+Nitrite-Nitrogen	40-85	5
Oil and Grease	67-93	3

In two late fall storms, soluble reactive P at the channel outlet exceeded that at the inlet, probably because of release from dead plant material. These observations reemphasize the advisability of treating overland flow differently in evaluating water quality benefits during the winter, especially where the nutrients are concerned, at least until compensating operating procedures have been developed.

For application in the Lake Sammamish watershed, overland flow was considered to be a means of improving the quality of retention basin effluents in residential areas. Preliminary retention is advisable to limit the amount of coarse solids that can reduce the life of overload flow systems. The technique was not considered for commercial zones because of possible land limitations in these areas. Based on the available performance information, the total P removal efficiency of a state-of-the-art retention basin and vegetated channel in series is expected to be in the range of 35-95 percent, with seasonal variability being prominent.

Like overland flow, wetlands also have been investigated primarily as polishing facilities for treated municipal sewage. A fairly extensive research record exists, both for natural wetlands and wetlands constructed specifically to serve a waste treatment function. Hammer and Kadlec (1983) have reviewed operating data from wetland systems, mechanisms, design, operational techniques, and economics. Chan et al. (1982) summarized the nationwide experience in using wetlands for urban stormwater runoff treatment. Performance data from Reed et al. (1981) and Pope (1981) demonstrated that wetlands can be expected to remove the majority of influent solids. Nitrogen and phosphorus removals have been more variable, however, ranging from very little to nearly complete reduction. Little opportunity to use either natural or constructed wetlands for stormwater runoff treatment appears to exist in areas expected to be developed in the Lake Sammamish watershed. This alternative was not given further attention.

Promoting soil infiltration of stormwater runoff is an alternative to direct discharge into surface waters. Groundwater recharge from detention ponds is one form of this alternative. Stormwater can also be piped underground to a permeable catch basin, perforated pipe, or tile drainfield for infiltration. Wanielista et al. (1981) have reported on these techniques. The analysis for the Lake Sammamish case was not concerned with details of the hardware but used the reported performance data to evaluate use of the technique following retention in certain commercial areas in the watershed. Areas where it may be feasible were identified by assessing the suitability of soils on sites projected for commercial development. Sites having soils of limited permeability or seasonal high water tables were eliminated. The new commercial areas where the technique could be used are in the eastern I-90 corridor in the City of Issaquah, in the vicinity of N. E. 8th Street and 228 th Avenue N. E. on the Eastside of the lake, and in the undeveloped portion of Redmond within the watershed. It was not considered to be feasible in residential areas. P removal in a retention/infiltration system is expected to range from 60 to 100 percent, depending on whether any overflow and surface release occurs (Wanielista et al., 1981).

Predicted Lake Response

The Lake Sammamish model was used to predict the lake response to phosphorus loading changes over the next 15 years with selected controls on the quality of stormwater runoff from newly developed areas and with no controls. The cases considered in this assessment were:

1. No controls
2. Retention facilities serving all new developed areas
3. Retention facilities and chemical treatment serving all new developed areas
4. Retention facilities serving all new developed areas, overland flow serving all new residential areas, and soil infiltration serving all new commercial areas where soils permit

No control cases were applied to areas with existing development, because retrofitting of stormwater quality controls does not appear to be feasible. There is no legal framework for regulating such controls, and the needed land is unavailable in many locations. Moreover, lake water quality is relatively high with the current level of development.

Because of uncertainties existing in phosphorus yields and control device performance, as reported earlier, ranges of both were treated using the lake response model. Table 8 summarizes the resulting ranges of model predictions of lake response with no runoff controls and with the three control strategies. Predicted response is presented for the 1984 base year, 1990, and 2000 and for years of high and low Issaquah Creek flow in each case.

It was apparent that lake conditions have depended and will continue to depend heavily on the major tributary flow and the resulting flushing rate. Therefore, the probability distribution of average annual Issaquah Creek flow was determined to be log-normal and was plotted in Figure 7. From this plot it was determined that there is a high probability in any given year of having

Table 8. Predicted Lake Sammmish Response to Increased Phosphorus Loading Resulting from Development, With and Without Storm Runoff Controls

Year	Case	Annual Mean TP (μg ℓ^{-1}) HW[a]	Annual Mean TP (μg ℓ^{-1}) LW[a]	Summer Mean TP (μg ℓ^{-1}) HW	Summer Mean TP (μg ℓ^{-1}) LW	Summer Mean Chl *a* (μg ℓ^{-1}) HW	Summer Mean Chl *a* (μg ℓ^{-1}) LW	Summer Mean Secchi Depth (m) HW	Summer Mean Secchi Depth (m) LW
1984	Existing	17.4-20.4	24.9-29.0	8.9-11.3	16.2-20.0	1.7-2.4	4.0-5.5	4.3-5.4	2.4-3.0
1990	No controls	18.4-21.7	26.2-30.9	9.7-12.4	17.4-21.7	1.9-2.7	4.5-6.2	3.9-5.0	2.2-2.8
	Retention only	17.7-21.2	25.4-30.2	9.2-11.9	16.6-21.0	1.8-2.6	4.2-5.9	4.0-5.3	2.3-2.9
	Retention and chemical	17.3-20.9	24.7-29.8	8.8-11.4	16.0-20.7	1.7-2.5	4.0-5.8	4.1-5.5	2.3-3.0
	Retention and overland flow/ infiltration	17.2-21.0	24.6-29.9	8.8-11.8	15.9-20.8	1.6-2.5	3.9-5.8	4.1-5.5	2.3-3.0
2000	No controls	21.6-25.9	35.8-42.0	11.5-15.1	22.5-28.2	2.5-3.6	6.6-9.1	3.2-4.2	1.7-2.1
	Retention only	19.6-24.6	33.0-40.1	10.1-14.0	20.2-26.5	2.0-3.3	5.6-8.3	3.5-4.8	1.8-2.4
	Retention and chemical	18.2-23.1	30.6-28.0	9.0-13.0	18.2-24.8	1.7-2.9	4.8-7.6	3.7-5.4	1.9-2.7
	Retention and overland flow/ infiltration	17.7-23.7	29.9-38.8	8.8-13.4	17.8-25.5	1.7-3.1	4.7-7.9	3.6-5.5	1.9-2.7

[a] HW-- high Issaquah Creek average flow (5.5 $m^3 s^{-1}$) during water year (10/1-9/30).

LW-- low Issaquah Creek average flow (3.0 $m^3 s^{-1}$) during water year (10/1-9/30).

a rather low average annual flow (e.g., a 50 percent probability that average flow will not exceed 3.9 m^3/s). Most of the observational years have been during higher flows, which, according to the model, would result in higher water quality.

Because of this observation, and since high and low water years were rather arbitrarily selected, it was decided to place the model predictions on a probabilistic basis. The assumptions of this analysis were that the flow distribution existing in the past would continue and that, because of the mathematical relationships in the model, the output parameters (TP, chl a and SD) would have the same probability distributions as Issaquah Creek average annual flow. This latter assumption proved to hold when the model-generated data were plotted.

Figures 14-21 present the probability distributions of predicted annual and summer mean TP and summer mean chl a and SD for 1990 and 2000, with and without controls. These plots were developed using the midpoints of the ranges reported in Table 8. The use of extreme values would shift curves slightly but would not substantially affect conclusions. The predicted results of retention plus chemical treatment did not differ noticeably from those of retention plus overland flow for residential areas and soil infiltration for certain commercial areas. Therefore, these cases were represented by a single curve labeled retention plus polishing. The right-hand portion of the curves is dashed to indicate that the available Issaquah Creek flow record on which the analysis is based does not extend into that region.

Table 9 summarizes predictions for the base and two future years at three probability levels. The model output for the base year demonstrates that the relatively high transparency and other good water quality conditions existing

Figure 14. Predicted whole-lake, annual mean total P for 1990 with and without stormwater controls

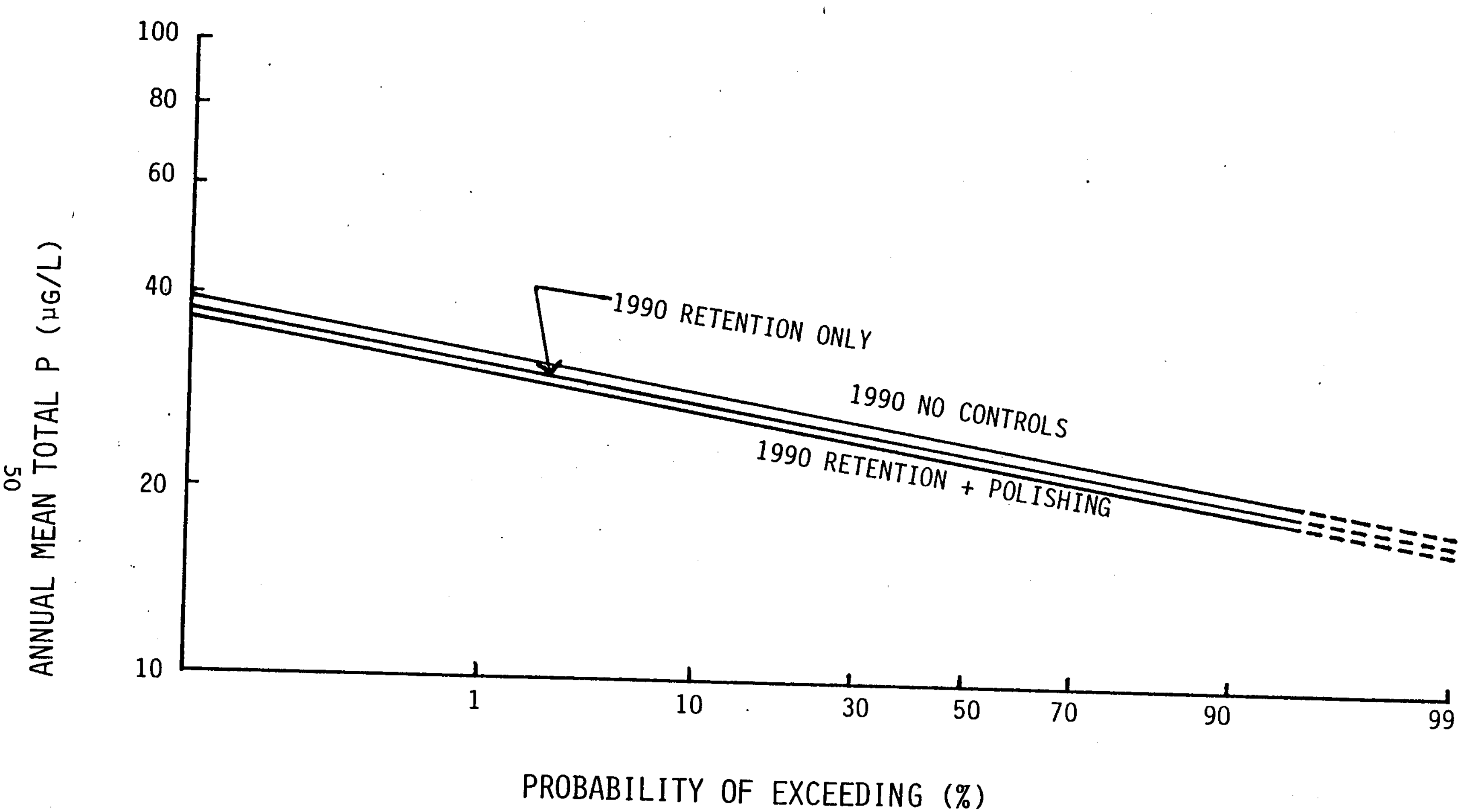


Figure 15. Predicted whole-lake, annual mean total P for 2000 with and without stormwater controls

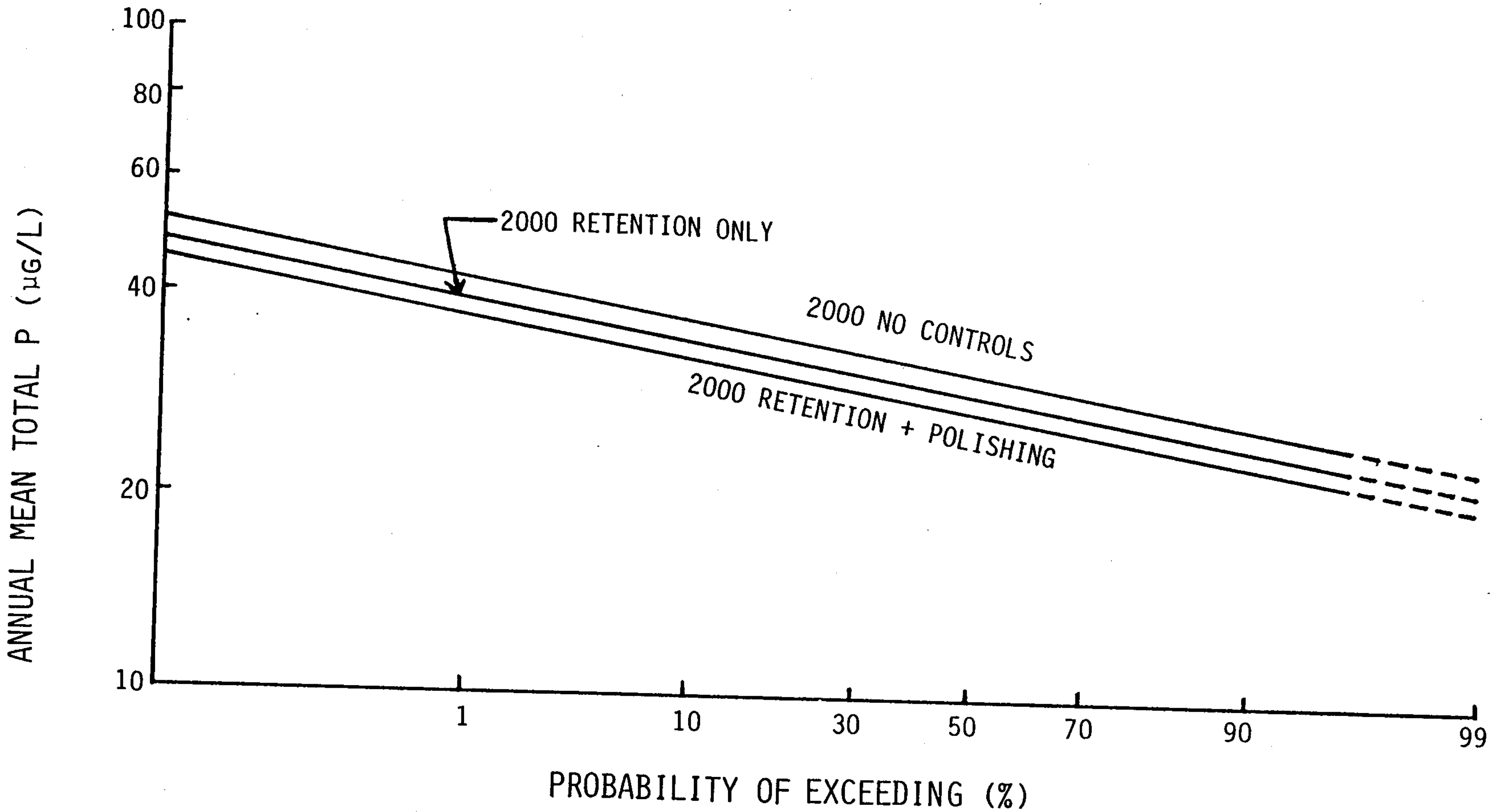


Figure 16. Predicted summer mean total P for 1990 with and without stormwater controls

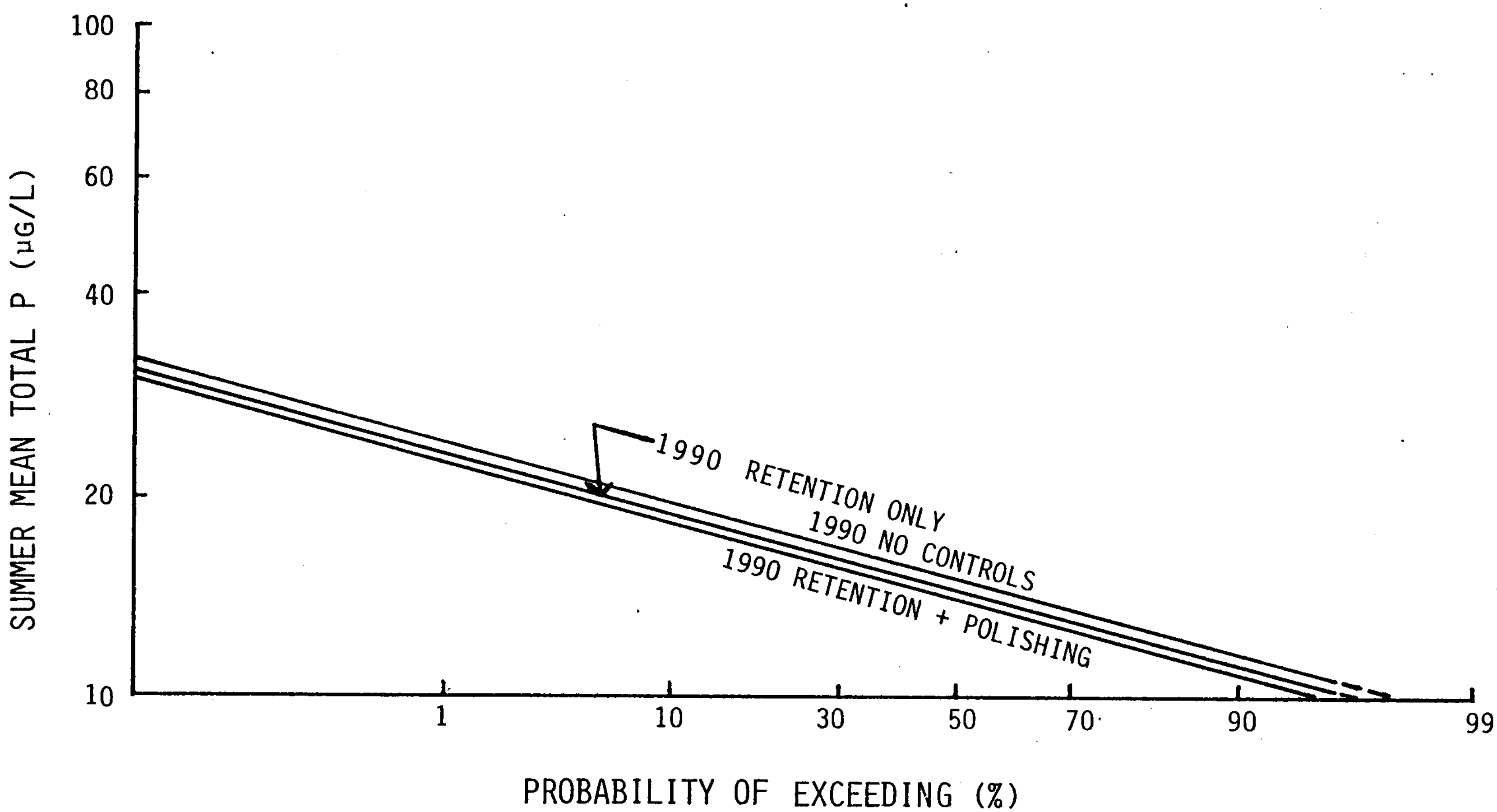


Figure 17. Predicted summer mean total P for 2000 with and without stormwater controls

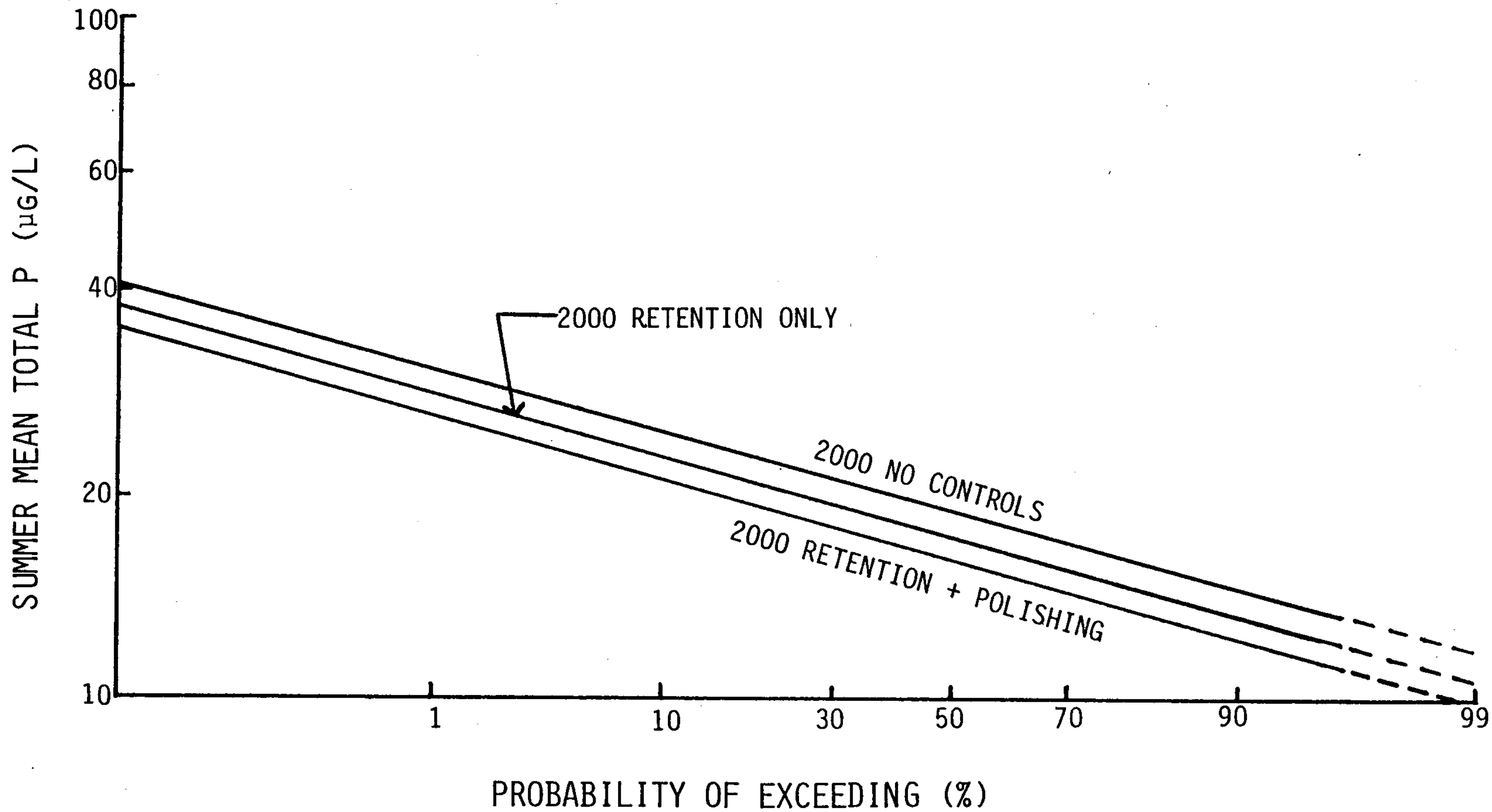


Figure 18. Predicted summer mean Chl a for 1990 with and without stormwater controls

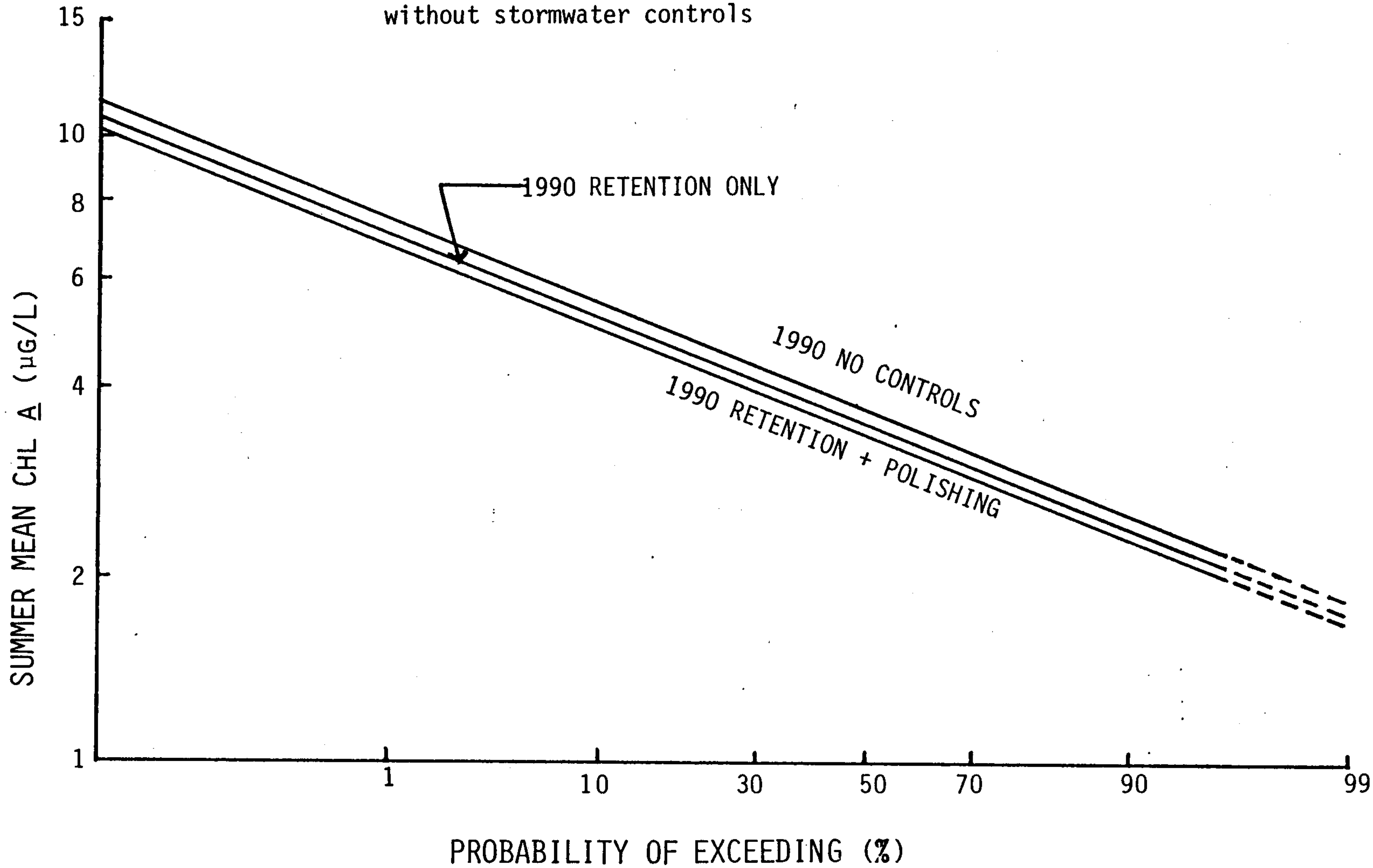


Figure 19. Predicted summer mean Chl a for 2000 with and without stormwater controls

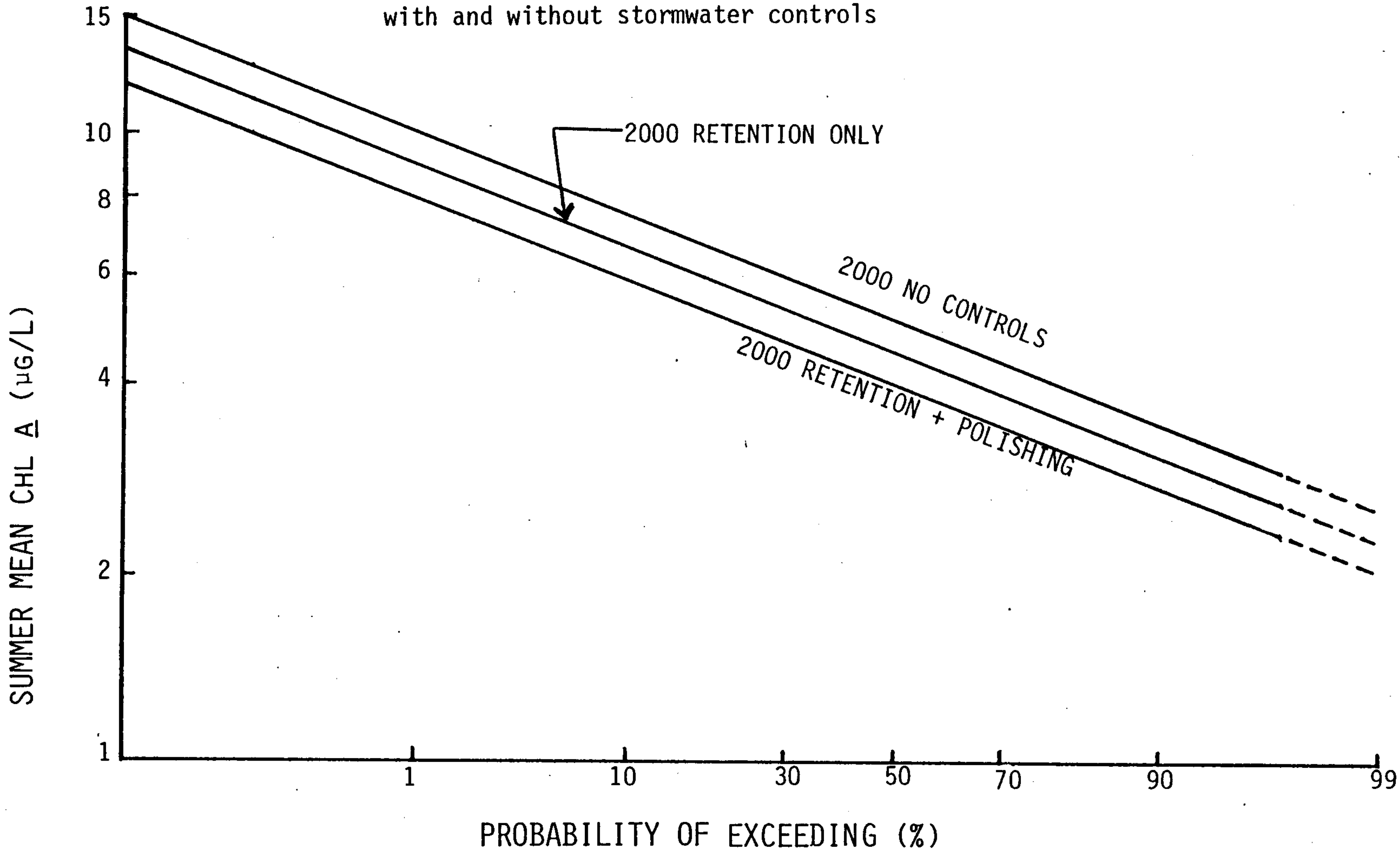


Figure 20. Predicted summer mean Secchi depth for 1990 with and without stormwater controls

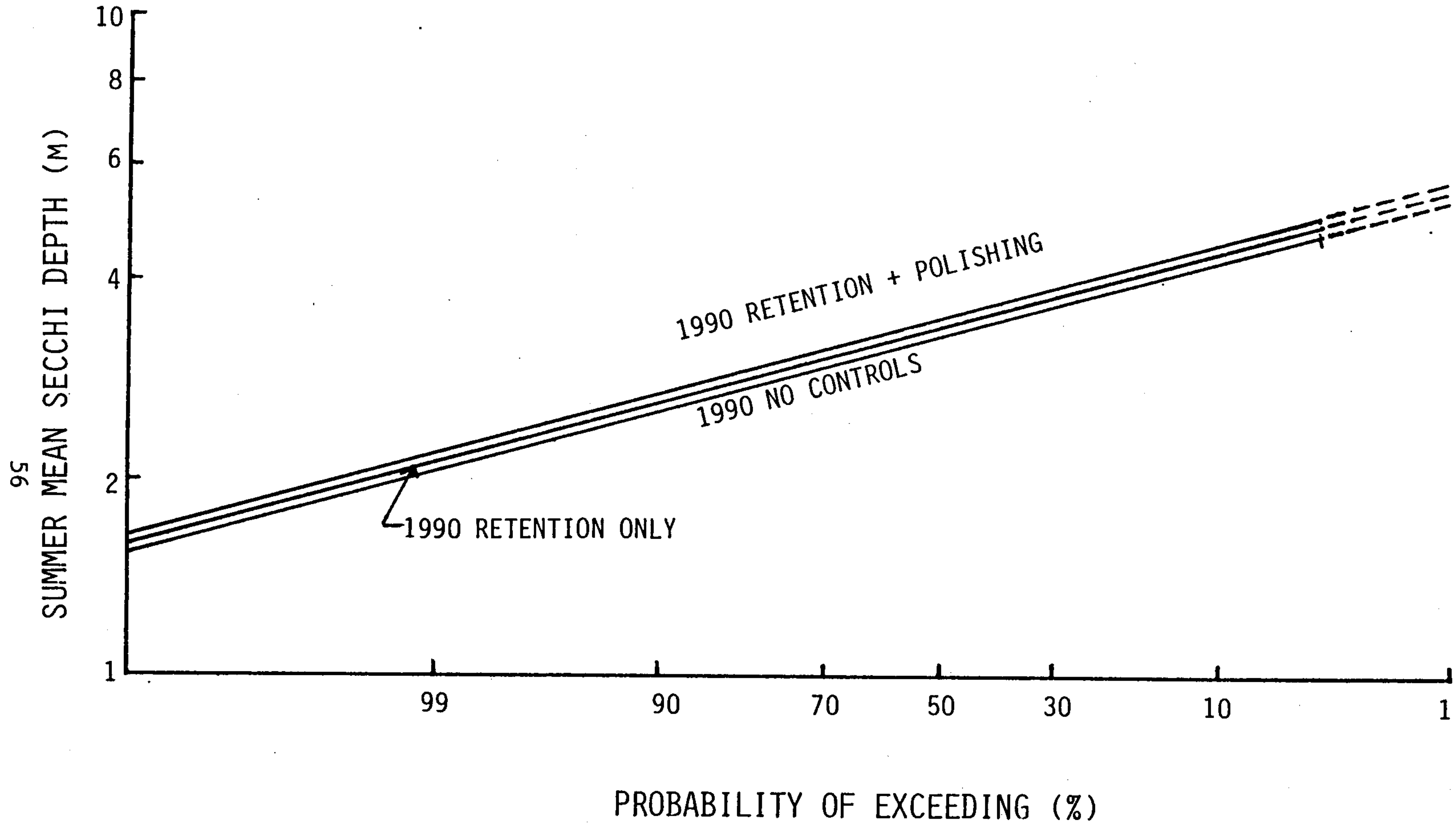


Figure 21. Predicted summer mean Secchi depth for 2000 with and without stormwater controls

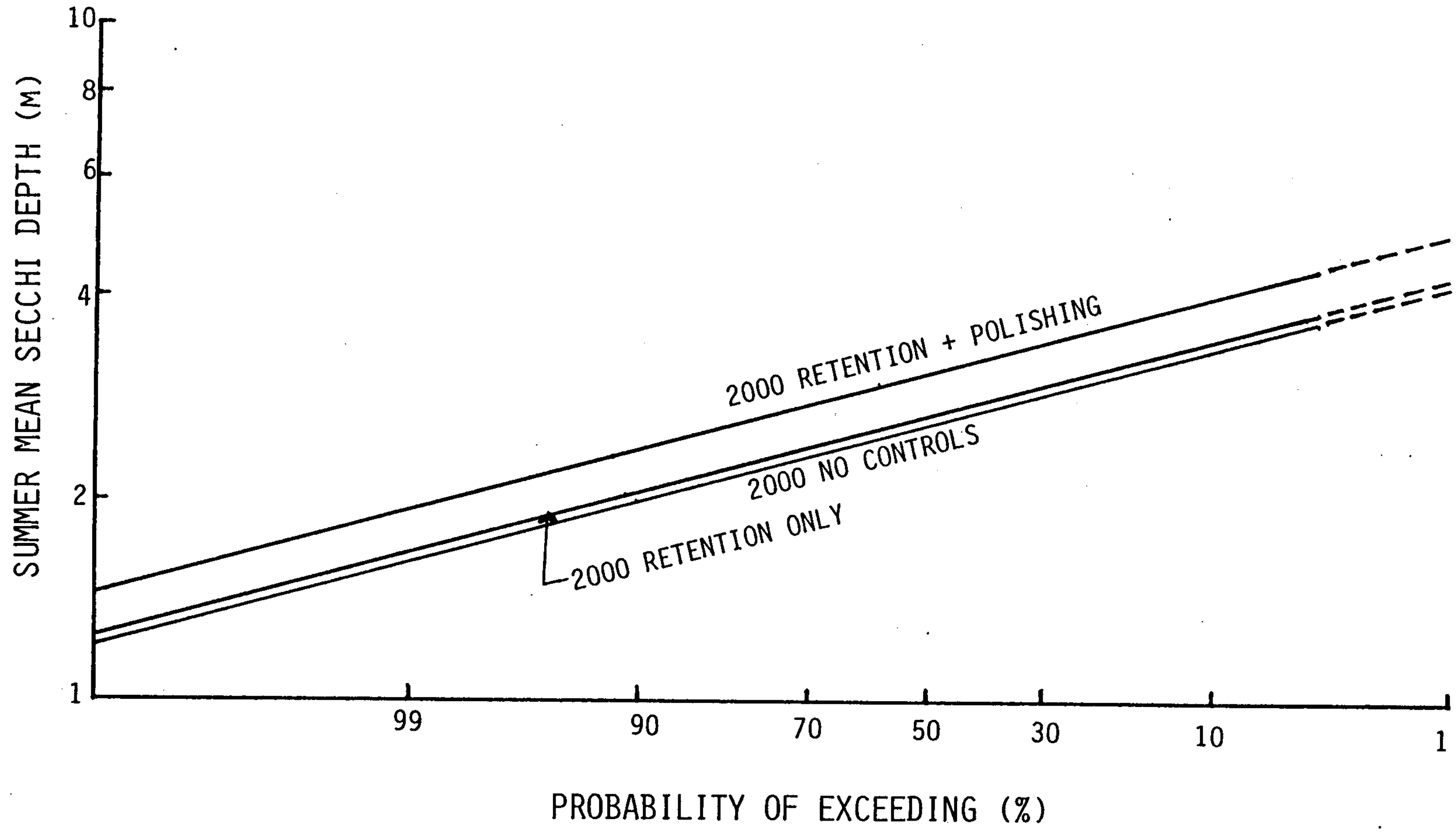


Table 9. Predicted Lake Sammamish Response to Increased Phosphorus Loading Resulting from Development, With and Without Storm Runoff Controls, for Three Probability Levels.

Year	Case	Probability (%)	Annual Mean TP ($\mu g\ \ell^{-1}$) will Exceed	Summer Mean TP ($\mu g\ \ell^{-1}$) will Exceed	Summer Mean Chl a ($\mu g\ \ell^{-1}$) will Exceed	Summer Mean S.D. (m) will not Exceed
1984	Existing	5	28.2	19.6	5.4	2.5
		50	23.0	14.0	3.3	3.5
		95	18.7	10.0	2.0	4.8
1990	No controls	5	30.1	21.2	6.0	2.3
		50	24.5	15.2	3.6	3.2
		95	19.9	10.9	2.2	4.5
	Retention only	5	28.9	20.4	5.7	2.4
		50	23.5	14.6	3.5	3.3
		95	19.0	10.4	2.1	4.6
	Retention and polishing	5	28.2	19.9	5.4	2.5
		50	23.0	14.2	3.3	3.4
		95	18.6	10.2	2.0	4.8
2000	No controls	5	39.0	26.9	8.3	1.8
		50	31.1	19.1	5.0	2.6
		95	25.0	13.6	3.1	3.6
	Retention only	5	36.1	24.8	7.3	1.9
		50	29.0	17.4	4.5	2.7
		95	23.1	12.3	2.8	3.7
	Retention and polishing	5	34.0	22.9	6.4	2.2
		50	27.1	16.1	4.0	3.1
		95	21.8	11.3	2.5	4.3

in Lake Sammamish recently are probably a consequence of favorable tributary flow, as well as the reduction in internal P loading discussed earlier. Exceeding a mean Secchi depth of 3.5 m has only a 50 percent probability under existing loading rates. With projected levels of development, the model predicts that 3.5 m mean Secchi depth will be reached in only about one year in every three by 1990 and one in 20 years by 2000, without runoff controls. Recall that the chl a and SD do not respond to TP as sharply in Lake Sammamish as indicated by Carlson's (1977) models, and the 3.5 m value should be considered as a relative rather than an absolute value.

It may be seen in Table 9 that full use of state-of-the-art retention facilities is anticipated to maintain lake trophic state fairly close to the present in 1990. Because development is proceeding rapidly, installation of high quality retention devices must begin immediately to gain this benefit. By 2000, only retention supplemented by polishing techniques can maintain lake conditions approaching the present, according to the model forecasts. Even with this high level of treatment, approximately 20 percent increases in mean TP and chl a concentrations and a 12 percent decrease in mean transparency are anticipated by 2000. A mean Secchi depth of 3.5 m is expected to be reached or exceeded under those conditions only about half as often as at present (27 versus 50 percent probability). Continuing to base runoff control strategy on retention alone, the predicted result is an increase in mean TP and chl a of as much as 40 percent and mean transparency decline exceeding 20 percent by the turn of the century. Mean Secchi depth of 3.5 m or greater then would be expected less than one year in ten.

Reference to Figures 20 and 21 indicates that a very low probability (less than one percent) exists under any circumstances for mean summer Secchi depth to drop below 2 m by 1990. A Secchi depth less than 2 m is a common criterion for defining a lake as eutrophic. By 2000 the model predicts that this transparency might not be maintained once every ten years, if there were no controls or retention only. The addition of polishing reduces the predicted probability for a 2 m SD to two percent. However, this analysis neglects any increase in sediment P release that might accompany slowly progressing eutrophication over the 15 year period. The increased internal loading could accelerate the rate of eutrophication and result in finite probabilities of reaching a eutrophic state well before 2000, although the evidence for that is lacking.

Costs of Stormwater Runoff Controls

Capital and annual operation and maintenance costs were estimated for the three control strategies defined in the previous section. Estimates in 1985 dollars were produced for the costs that would be incurred in applying each strategy by 1990 and 2000. It was assumed that the respective control strategies would be applied uniformly on all land areas projected for development in the watershed. Also assumed was thorough enforcement of all existing stormwater management regulations and any regulations adopted to implement this program. Changes in zoning could decrease costs; e.g. limiting development on areas having a slope greater than a particular amount would save the proportionately higher costs of controlling the quality of runoff from an easily eroded location. As discussed earlier, restricting development on forested areas would save the approximate six-fold increase in P yield associated with conversion of forest to a developed land use.

Cost estimates were based on published ranges for the respective control strategies as follows: (1) detention--Finnemore and Lynard (1982); (2) chemical treatment--Hartigan (1981); overland flow--land cost from Franklin (personal communication), site preparation cost from Kerr Associates, Inc. (1984), and annual operational cost from Hartigan (1981); (4) infiltration--Wanielista et al. (1981). All of these data, except the cost of land for overland flow, were collected in the late 1970's. Therefore, it was necessary to estimate inflation to the present (1985). A ten percent per annum inflation rate was used for this purpose. Escalation from 1985 to a future year was based on an annual inflation rate of eight percent. Finally, present value of the future cost estimates was estimated using a six percent discount rate.

Table 10 presents the distribution of estimated costs in areas assumed to receive stormwater control in the Lake Sammamish watershed. New development subject to control in the Issaquah Creek catchment is projected to occur both within the present City of Issaquah boundaries and in portions of the catchment under King County jurisdiction. Annexation of land from the county would transfer some or all of the area expected to be newly developed to city jurisdiction. All development east of Lake Sammamish will be in unincorporated King County. The subwatershed west of the lake is already heavily developed, and new developed areas subject to control will be relatively small. These areas occur in several plots in Redmond and Bellevue.

Table 11 summarizes the cost estimates by case and catchment. The capital cost estimates reflect total spending in 1985 dollars for installation of facilities by 1990 and 2000, respectively. The annual costs are an estimate (in 1985 dollars) of the average yearly expenses for operation and maintenance of the facilities between the present and 1990 or 2000, respectively. Because fewer facilities will be installed near the beginning of these periods, the actual annual costs would be less than the average early in the period and greater than the average later. Ranges are relatively wide

Table 10. Distribution of Areas Subject to Stormwater Runoff Control in the Lake Sammamish Watershed

Catchment	Land Use	1990 Area[a] (ha)	2000 Area[a] (ha)
Issaquah Creek	Commercial	100 (33)[b]	240 (79)
	Residential	749	2705
	Subtotal	849	2845
Eastside	Commercial	32 (16)	168 (84)
	Residential	782	1403
	Subtotal	814	1571
Westside	Commercial	56 (42)	170 (128)
	Residential	324	600
	Subtotal	380	770
	TOTAL	2043	5186

[a] Area expected to receive new development between 1985 and either 1990 or 2000.

[b] Number in parentheses represents area suitable for control by soil infiltration. The balance would be controlled by retention only in the retention/overland flow/infiltration case.

Table 11. Summary of Estimated Capital and Annual Costs[a] of Stormwater Runoff Controls Under Three Strategies by 1990 and 2000.

Case	Catchment	1990 Capital Cost (Million $)	1990 Average Annual Cost (Million $)	2000 Capital Cost (Million $)	2000 Average Annual Cost (Million $)
Retention only	Issaquah Creek	3.9-14.8	0.4-2.3	14.3-54.4	1.4-8.6
	Eastside	3.7-14.2	0.4-2.2	7.9-30.0	0.8-4.8
	Westside	1.8-6.6	0.2-1.0	3.8-14.8	0.2-1.2
	TOTAL	9.4-35.6	1.0-5.5	26.0-99.2	2.4-14.6
Retention and Chemical	Issaquah Creek	12.4-27.0	43-153	45.5-99.5	157-563
	Eastside	11.9-25.9	41-147	25.1-54.9	87-311
	Westside	5.6-12.0	19.2-68	12.4-27.0	21-76
	TOTAL	29.9-64.9	103-368	83.0-181	265-950
Retention, overland flow (residential) and infiltration (appropriate commercial)	Issaquah Creek	4.4-23.3 (4.2-16.3)[b]	0.4-2.6	15.7-87.4 (15.1-59.7)	1.5-9.6
	Eastside	4.0-22.8 (3.8-15.4)	0.4-2.5	9.1-47.8 (8.8-33.4)	0.8-5.3
	Westside	2.3-10.7 (2.3-7.5)	0.2-1.2	5.2-23.8	0.2-1.3
	TOTAL	10.7-56.8 (10.3-39.2)	1.0-6.3	30.0-159 (28.9-112)	2.5-16.2

[a] Estimates are in 1985 dollars.

[b] Numbers in parentheses represent costs excluding the cost of land for overland flow, assuming space that would be left open in any event would be dedicated to that purpose.

because they represent retention facilities ranging from small onsite ponds serving 4 ha to large regional ponds serving 200 ha. Full use of regional ponds would yield the lowest costs and complete use of small onsite ponds the highest. It was assumed that one vegetated swale would serve each retention pond in a residential overland flow system. Therefore, the use of fewer, larger ponds would yield economies in the overland flow area also. Overland flow costs were estimated both including and excluding the cost of land. Utilizing land planned to be left in open space for vegetated swales would save any extra costs of specifically dedicating land to this purpose. Some planned open space could also be devoted to retention ponds, although the estimates reflect the full land costs for these facilities.

The very high operating costs of chemical treatment render that alternative infeasible for this service. It was shown in the preceding section that overland flow in residential areas and soil infiltration in suitable commercial areas can achieve performance approximately equal to chemical treatment. In addition to much lower costs, they also have no mechanical parts and should give more reliable service.

The most highly recommended alternative is the third one. This alternative can be employed most economically by emphasizing regional retention ponds and dedicating some planned open space to overland flow treatment. With that plan, the total installation cost in 2000 could be as low as approximately $30 million (in 1985 dollars). Most likely, some small onsite retention ponds would have to be constructed. To allow for that possibility, a total installation cost of $50 million may be more realistic. Average annual operating expenses would be at least $2.5 million, with $5 million perhaps being a more realistic estimate. These costs would be distributed among the three subwatersheds as shown in Table 12. The

Table 12. Distribution of Capital and Operating Costs[a] for a Retention/Overland Flow/Soil Infiltration System in the Lake Sammamish Watershed.

Jurisdiction	Installation Cost (Million $)	Average Annual (Million $)	Area Developed (1ha)	$/ha Installation	$/ha Annual
Issaquah Creek	26	2.6	2,845	9,140	915
Eastside	15	1.5	1,571	9,550	955
Westside	9	0.9	770	11,675	1,170
Overall	50	5.0	5,186	9,640	965

[a] Total installation cost by 2000 and average annual cost of operation and maintenance between 1985 and 2000 (in 1985 dollars).

installation cost per hectare developed overall would be approximately $10,000, and the average annual cost per hectare would be slightly under $1,000 (1985 dollars). The present cost of land for single-family residential development in Redmond is approximately $40,000 for 1/4 acre (or nearly $400,000/ha), and commercial land is much higher (Franklin, personal communication). Improvements would add very substantially to the value. Therefore, the cost of stormwater runoff controls would represent a small fraction of the improved land value.

All jurisdictions in the Lake Sammamish watershed already have stormwater management policies and regulations. These provisions are based on prevention of peak stream flow increases, rather than specific water quality criteria. R/D facilities developed under them would not have the specific features needed for maximum phosphorus removal from runoff and would have to be designed differently and receive better maintenance to perform as needed to reduce P input to the lake. Under these modified design and operating guidelines, they still could serve the hydrologic objective set forth in the policies and regulations. Therefore, the costs of facilities that would be constructed under the existing regulations represent a portion of the costs estimated here.

Generally speaking, installation costs would be borne by private developers and would be reflected in the price of homes or commercial establishments. Rather than requiring developers to build onsite control facilities, governmental units may construct regional facilities and assess builders whose developments they serve. As noted previously, regional facilities generally have both cost and effectiveness advantages over onsite devices. Onsite stormwater control facilities are often deeded to the governmental jurisdiction after construction and then become a public responsibility and expense for operation, along with regional facilities. Therefore, the installation expenses in the tables above may be regarded as largely a private responsibility and the annual operating costs a public expense financed from general revenues or a stormwater utility fee assessed to property owners. This breakdown is only approximate for general guidance; the exact division of responsibility and funding arrangements would be determined by each local governmental unit.

RESTORATION IN LIEU OF WATERSHED CONTROLS

Restoration treatments were assessed assuming that watershed controls were not initiated as development proceeded. Of the 16 restoration techniques described in detail by Cooke et al. (1985), only five were considered reasonably feasible for Lake Sammamish. Of the five, two are less than 10% of the cost of the next cheapest treatment.

The two least expensive treatments would primarily affect the internal loading, which represents about 30% of the total load at present. Nutrient inactivation, through the application of alum (aluminum sulfate), results in a highly sorptive aluminum hydroxide floc layer on the sediment surface, which blocks the release of sediment P. The assumption is that virtually all of the previous sediment release would be curtailed by this treatment, which would minimize the effect of uncontrolled runoff. As can be seen in Table 13, lake quality following nutrient inactivation would be, by this comparison, nearly as effective as if the increased stormwater flow were diverted and at less than 5% of the cost.

Hypolimnetic aeration tends to curtail internal loading through oxidation of iron, but not nearly as effectively as nutrient inactivation. Therefore,

Table 13. Treatments and their 15-year costs (8% inflation discounted at 6%) to restore Lake Sammamish after 2000, assuming no runoff controls were instituted, along with lake response (summer values) for the median flow, median P yield condition.

Treatment	TP	Chl *a*	SD	$\$x10^6$
Stormwater diversion (10.5 mile pipe 9% and pond 91%)	14.0	3.3	3.5	56.6
Nutrient in activation (sediment release = 0.0 $mg/m^2 \cdot d$)[2]	15.3	3.8	3.2	1.94
Hypolimnetic aeration (sediment release = 8.4 $mg/m^2 \cdot d$)[2]	16.9	4.3	2.9	3.66
Sediment oxidation (sediment release = 4.2 $mg/m^2 \cdot d$)[2]	16.1	4.1	3.0	64.00
Dilution/Flushing	16.1	4.0	3.1	59.00[1]

[1]2.5 m^3/s water only; [2]equivalent to 80% removal of runoff P

the model predictions are for 40% of the calibrated rate, or 8.4 mg/m^2·week. The higher cost and poorer reputation for controlling sediment P release makes hypolimnetic aeration a less desirable alternative. However, aeration would expand the fisheries habitat, which could be an important consideration. The hypolimnetic oxygen content is raised without destratifying the lake. An appropriate number of units are placed in the hypolimnion to distribute water aerated by compressed air.

In spite of the low cost of P inactivation and hypolimnetic aeration, stormwater diversion is the recommended alternative because it would remove most of the added P input. The other two techniques would not affect external P. However, the cost for a 16.8 km (10.5 mile) gravity feed pipe (42"), to carry the peak flows (1.48 m^3/s), and a large sedimentation pond (12.8 ha, 2 m deep) to remove P and sediment and protect the Sammamish River and Lake Washington, results in a relatively high cost (\$56.6 x 10^6, including 23% for O&M This cost does not include the collection system along the east side of the lake. However, pipe costs (material and installation) are only 9% of the total, and even doubling that for feeder pipes would raise the total cost only 8%. By contrast, the 1968 wastewater diversion would cost only \$19.3 x 10^6 in 2000 (\$14 x 10^6 in 1983 dollars, Cooke et al., 1985). This treatment is simple retention without the polishing included for watershed controls. A median of the ranges shown in Table 11 was used to estimate costs. There would be other problems and costs in obtaining the right-of-way to lay the main pipe and feeder pipes and construct the retention pond after development is complete that would not occur if installation were accomplished during development. Ultimately there may not be a great deal of difference in cost between watershed treatment and diversion.

The estimated water quality following diversion is the 1984 condition (Table 13) and assumes that nearly all of the increased P yield from the developed area would be removed. The effect on flushing would be a reduction from 0.5/yr to 0.45/yr. Because the decreased flushing rate would not change the inflow concentration (diversion would prevent inflow P from increasing), the sedimentation rate could be expected to increase, thereby reducing the lake concentration further. A reduced flushing rate should benefit lake quality.

Sediment oxidation and dilution/flushing are probably not practical, in addition to being the most costly alternatives. Oxidation of sediment is achieved through injection of $Ca(NO_3)_2$ to a depth of about 20 cm in the sediment. Through denitrification, the organic matter is digested and the sediments become aerobic, which results in complexation of P with oxidized iron and unavailable for release. While more expensive, the technique is considered to be a more permanent solution to sediment P release than alum addition. Nevertheless, the mechanics of injecting the sediments of such a deep and aerially large lake as Sammmamish seem logistically impractical.

Dilution/flushing also seems an impractical and infeasible alternative. The River Basins Coordinating Committee study (STR, 1974) recommended this treatment for Lake Sammamish at a cost of $7.2 x 10^6 ($19.9 x 10^6, 2000). However, the amount of water recommended was less than 10% of that suggested here. It would have required transport from the Cedar River, which would compete with needs for Cedar River salmon and the City of Seattle domestic supply. Although costs for transport of water from the Cedar River are not included in Table 13, their inclusion would certainly make this the least attractive alternative. Also, the required flow, if added to upper Issaquah Creek, would increase its summer low flow over 3.5 fold (0.9 to 3.4 m^3/s)

which may be detrimental to rearing salmon and steelhead. Theoretically, however, dilution would directly counteract the increased input from runoff, in contrast to P inactivation, and provide similar lake quality (Table 13). The quantity of water required was determined as that necessary to reduce the flow-weighted inflow P concentration from 85 mg/m^3 (median load at 2000) to 56 mg/m^3, which is the result of a median load at 2000 with 80% P removal by detention and chemical treatment. The effect of the increased flushing rate on P sedimentation was not considered in the Table 13 water quality values. The levels are those based on the 56 mg/m^3 inflow concentration resulting from 80% removal of P (Table 9). A concentration of 15 mg/m^3 was assumed for the Cedar River.

The results of this analysis suggest that it may be more cost-effective to wait until the lake degrades and then employ an in-lake treatment. That alternative includes a certain amount of risk to the quality of the lake. The lake P model assumes that a portion of sediment-released P is available for algae in the lighted epilimnion, in proportion to the ratio of observed summer epilimnetic P to whole lake P. If the whole lake P were reduced by curtailing sediment release, then the epilimnetic P would decrease accordingly, as suggested in Table 13. No doubt there is some entrainment of hypolimnetic P into the epilimnion, but it may be less than that suggested by the model. In that case, the summer epilimnetic P may be largely dependent on external sources and the improvement would be less than suggested in Table 13.

The results also suggest that stormwater diversion to restore the lake after degradation may be as or more cost-effective than watershed treatment included as development proceeds. However, there may be other hidden costs in the "wait-and-see" option. First, as has occurred in the past, watershed disturbance has increased P sedimentation in the lake. This could increase internal loading, the recent apparent decrease of which has been largely responsible for the lake's recovery to its present quality. Second, there should logically be more problems and costs to retrofit controls in the form of diversion facilities; e.g. obtaining right-of-way and space for the pipes and retention pond. Third, a polishing treatment may be required for the pond outflow to protect the Sammamish River and Lake Washington. Without space for grassy swale or wetland treatment of outflow, the more costly chemical treatment (Table 11) may be required. Lastly, responsibiltiy for the diversion facility would fall on the public and government, whereas stormwater controls should distribute costs more equitably.

SUMMARY AND CONCLUSIONS

1. Lake Sammamish has shown marked improvement in water quality in the past five to ten years. Annual total P concentrations have averaged less than 20 µg/L, and summer chl a and transparency have averaged 2.5 µg/L and 4.9 m, respectively, over the past five years. This is in contrast to prediversion levels of 33 µg/L, 5.0 µg/L and 3.3 m, for TP, chl a and transparency, respectively.

2. This dramatic improvement in recent years has apparently been due largely to a drop in the anaerobic, sediment release rate of phosphorus during summer and fall. The rate has declined from 5.8 ± 2.5 $mg/m^2 \cdot d$ before and after wastewater diversion (1964-1966 and 1971-1974) to 2.5 ± 2.1 $mg/m^2 \cdot d$ during more recent years. Associated with this decrease in release rate has been a 50% decline in hypolimnetic oxygen deficit rate.

3. Total loading, including internal loading, has decreased by 19% folowing the 1968 wastewater diversion, and 36% in recent years (since 1975), due to the decrease in sediment release, as well as a slight decrease in external loading. Causes for the latter could not be determined but may be partly due to improved detention of stormwater and BMPs instituted recently. These loading changes account for the observed changes in lake TP.

4. The observed decrease in sediment P release, as determined by the rate of hypolimnetic buildup of P, could not be substantiated by sediment profiles of interstitial P or total P. However, rates of release in anaerobic columns compared against similarly determined rates in 1970 and 1976 supported the observed decrease. The trend of a decreasing rate of hypolimnetic P buildup following diversion may have been due to a gradual removal of flocculent particulate material, and hence the decreased oxygen demand, at rates much less than the flushing rate.

5. Development by 1990 and 2000 is predicted to increase significantly TP in Lake Sammamish and to degrade the lake's quality. Using median P yield coefficients and the 50% probability flow levels, annual TP, summer TP, chl a and transparency are expected to change from model predicted values of 23 μg/l, 14 μg/L, 3.3 μg/L and 3.5 m, respectively, in 1984, to 31 μg/L, 19 μg/L, 5.0 μg/L and 2.6 m, respectively, by 2000. That is a 26% increase in annual TP and a 26% decrease in transparency. Although there is confidence in the predictions in absolute values of TP, there is some doubt about chl a and transparency, because Lake Sammamish does not seem

to respond as sharply to TP increase as most lakes on which the predictive model for those variables is based. Lake Sammamish tends to have greater transparency per unit chl a and TP. Nevertheless, the relative changes are considered valid.

6. Application of state-of-the-art stormwater retention technology is expected to be able to maintain the present Lake Sammamish water quality until 1990, but additional treatment will be necessary to avoid deterioration below present levels after that point.

7. The most appropriate additional treatment appears to be overland flow in residential areas and soil infiltration in commercial areas where soils are suitable. Chemical treatment is much more costly than these methods and is not significantly more effective.

8. The efficacy, feasibility and costs of alternative restoration treatments were considered in the event that preventive measures were not taken. Phosphorus inactivation by the addition of alum, and to a lesser extent hypolimnetic aeration, would be expected to restore lake quality (from the predicted degraded 2000 level) to near the level that could be achieved by diverting the increased runoff of stormwater around the lake to the Sammamish River or installing retention and land treatments, and at less than 10% of the cost. Dilution/flushing and sediment oxidation are considered infeasible. Although more costly, stormwater diversion or treatment are considered more appropriate alternatives because these measures would correct the cause for degradation. In the event that

sediment release worsened with increased P loading from runoff, P inactivation could be used as a followup step to complete restoration.

RECOMMENDATIONS

1. Apply BMPs to construction areas in accordance with the Municipality of Metropolitan Seattle (1981) guide and existing regulations, especially in the Issaquah Creek catchment.

2. Analyze the need for sedimentation ponds in construction areas on a case-by-case basis, giving particular attention to cases when BMPs are insufficient and the area is steep, near a water body, relatively large, and will have construction over a long period.

3. Conduct an educational program on proper use of lawn fertilizers and cautions against disposing of wastes in storm drains.

4. For treating stormwater runoff from new developed areas, install a system of state-of-the-art regional retention ponds, supplemented by overland flow treatment of the effluent in vegetated swales in residential areas and soil infiltration of the effluent in commercial areas suitable for that technique.

5. If preventive measures are not taken, stormwater diversion is considered the most appropriate treatment to restore water quality. However, land acquisition problems of locating a large retention facility and diversion pipes may lead to greater than anticipated costs, internal loading of P

may increase, chemical treatment may be needed to protect the Sammamish River and Lake Washington and costs would probably be disproportionately born by the public and government if restorative rather than preventive measures are chosen.

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APPENDIX A

Predictions of P loading and lake trophic state indices for 1990 and 2000

**********RESULTS FOR A HIGH WATER YEAR******** 1990

RELEASE RATES(mg/m2-WEEK)= 21.00 21.00

INITIAL KNOWN LAKE CONC(mg/m3)=20.00

LAND USE DATA (AREA IN ha, YIELDS IN kg/ha-yr)

ISSAQUAH CREEK SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	11908.	128.	250.	1783.	131.
HIGH	0.340	1.500	2.700	1.900	2.200
LOW	0.220	0.950	2.200	1.200	1.400

WESTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	901.	0.	416.	2906.	277.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

EASTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	3912.	151.	215.	2045.	177.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

PERCENT OF TOTAL LOADING

	ISS. CRK	WESTSIDE	EASTSIDE	INTERNAL
HIGH	41.79	13.35	11.41	33.45
LOW	34.72	12.23	10.52	42.53

AREAL LOADING (mg/m2-yr)

HIGH	433.92	138.65	118.47	347.35
LOW	283.55	99.88	85.83	347.35

HIGH AND LOW ANNUAL MEANS(mg/m3) 21.69 18.35

MEAN SUMMER VALUES(JUNE-AUGUST)

SURFACE

	TP(mg/m3)	Chla(mg/m3)	SECCHI DEPTH(m)
HIGH	12.36	2.72	3.90
LOW	9.67	1.89	4.99

********RESULTS FOR A LOW WATER YEAR******* 1990

RELEASE RATES(mg/m2-WEEK)= 21.00 21.00

INITIAL KNOWN LAKE CONC(mg/m3)=20.00

LAND USE DATA (AREA IN ha, YIELDS IN kg/ha-yr)

ISSAGUAH CREEK SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	11903.	128.	250.	1783.	131.
HIGH	0.340	1.500	2.700	1.900	2.200
LOW	0 220	0.950	2.200	1.200	1.400

WESTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	901.	0.	416.	2906.	277.
HIGH	0 120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

EASTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	3912.	151.	215.	2045.	177.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

PERCENT OF TOTAL LOADING

	ISS.CRK	WESTSIDE	EASTSIDE	INTERNAL
HIGH	41.79	13.35	11.41	33.45
LOW	34.72	12.23	10.52	42.53

AREAL LOADING (mg/m2-yr)

HIGH	433.92	138.65	118.47	347.35
LOW	283.55	99.88	85.83	347.35

HIGH AND LOW ANNUAL MEANS(mg/m3) 30.93 26.21

MEAN SUMMER VALUES(JUNE-AUGUST)

SURFACE

	TP(mg/m3)	Chla(mg/m3)	SECCHI DEPTH(m)
HIGH	21.69	6.21	2.22
LOW	17.37	4.48	2.77

**********RESULTS FOR A HIGH WATER YEAR******** 2000

RELEASE RATES(mg/m2 WEEK)= 21.00 21.00

INITIAL KNOWN LAKE CONC(mg/m3)=24.00

LAND USE DATA (AREA IN ha, YIELDS IN kg/ha-yr)

ISSAQUAH CREEK SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	9845.	95.	390.	3620.	250.
HIGH	0.340	1.500	2.700	1.900	2.200
LOW	0.220	0.950	2.200	1.200	1.400

WESTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	510.	0.	530.	3180.	280.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0 090	0.510	0.680	0.500	0.580

EASTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	3262.	50.	351.	2610.	227.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

PERCENT OF TOTAL LOADING

	ISS. CRK	WESTSIDE	EASTSIDE	INTERNAL
HIGH	48 66	12.18	11.21	27.96
LOW	41.45	11.46	10.59	36.51

AREAL LOADING (mg/m2-yr)

HIGH	604.59	151.33	139.23	347.35
LOW	394.35	109.03	100.73	347.35

HIGH AND LOW ANNUAL MEANS(mg/m3) 25.97 21.59

MEAN SUMMER VALUES(JUNE-AUGUST)

SURFACE

	TP(mg/m3)	Chla(mg/m3)	SECCHI DEPTH(m)
HIGH	15.05	3.63	3.20
LOW	11.52	2.45	4.18

*******<<RESULTS FOR A LOW WATER YEAR******* 2000

RELEASE RATES(mg/m2-WEEK)= 21.00 21.00

INITIAL KNOWN LAKE CONC(mg/m3)=35.00

LAND USE DATA (AREA IN ha, YIELDS IN kg/ha-yr)

ISSAQUAH CREEK SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	9845.	95.	390.	3620.	250.
HIGH	0.340	1.500	2.700	1.900	2.200
LOW	0.290	0.950	2.200	1.200	1.400

WESTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	510.	0.	530.	3180.	280.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

EASTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	3260.	50.	351.	2610.	227.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

PERCENT OF TOTAL LOADING

	ISS.CRK	WESTSIDE	EASTSIDE	INTERNAL
HIGH	48.66	12.18	11.20	27.96
LOW	41.45	11.46	10.59	36.51

AREAL LOADING (mg/m2-yr)

HIGH	604.59	151.33	139.22	347.35
LOW	394.35	109.03	100.72	347.35

HIGH AND LOW ANNUAL MEANS(mg/m3) 42.01 35.81

MEAN SUMMER VALUES(JUNE-AUGUST)

SURFACE

	TP(mg/m3)	Chla(mg/m3)	SECCHI DEPTH(m)
HIGH	28.19	9.13	1.71
LOW	22.52	6.56	2.14

APPENDIX B

Predictions of P loading and lake trophic state indices for 2000 and various restoration treatments

*********RESULTS FOR A HIGH WATER YEAR*******

RELEASE RATES(mg/m2-WEEK)= 0.00 0.00

INITIAL KNOWN LAKE CONC(mg/m3)=15.00

LAND USE DATA (AREA IN ha, YIELDS IN kg/ha-yr)

ISSAQUAH CREEK SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	9845.	95.	390.	3620.	250.
HIGH	0.340	1.500	2.700	1.900	2.200
LOW	0.220	0.950	2.200	1.200	1.400

WESTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	510.	0.	530.	3180.	280.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

EASTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	3262.	50.	351.	2610.	227.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

PERCENT OF TOTAL LOADING

	ISS. CRK	WESTSIDE	EASTSIDE	INTERNAL
HIGH	67.54	16.91	15.55	0.00
LOW	65.28	18.05	16.67	0.00

AREAL LOADING (mg/m2-yr)

HIGH	604.59	151.33	139.23	0.00
LOW	394.35	109.03	100.73	0.00

HIGH AND LOW ANNUAL MEANS(mg/m3) 19.16 14.77

MEAN SUMMER VALUES(JUNE-AUGUST)

	SURFACE TP(mg/m3)	Chla(mg/m3)	SECCHI DEPTH(m)
HIGH	12.59	2.79	3.83
LOW	9.06	1.72	5.32

*********RESULTS FOR A LOW WATER YEAR*******

RELEASE RATES(mg/m2-WEEK)= 0.00 0.00

INITIAL KNOWN LAKE CONC(mg/m3)=24.00

LAND USE DATA (AREA IN ha, YIELDS IN kg/ha-yr)

ISSAQUAH CREEK SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	9845.	95.	390.	3620.	250.
HIGH	0.340	1.500	2.700	1.900	2.200
LOW	0.220	0.950	2.200	1.200	1.400

WESTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	510.	0.	530.	3180.	280.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

EASTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	3262.	50.	351.	2610.	227.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

PERCENT OF TOTAL LOADING

	ISS. CRK	WESTSIDE	EASTSIDE	INTERNAL
HIGH	67.54	16.91	15.55	0.00
LOW	65.28	18.05	16.67	0.00

AREAL LOADING (mg/m2-yr)

HIGH	604.59	151.33	139.23	0.00
LOW	394.35	109.03	100.73	0.00

HIGH AND LOW ANNUAL MEANS(mg/m3) 31.44 25.24

MEAN SUMMER VALUES(JUNE-AUGUST)

	SURFACE TP(mg/m3)	Chla(mg/m3)	SECCHI DEPTH(m)
HIGH	22.97	6.76	2.10
LOW	17.30	4.45	2.78

*********RESULTS FOR A HIGH WATER YEAR*******

RELEASE RATES(mg/m2-WEEK)= 8.40 8.40

INITIAL KNOWN LAKE CONC(mg/m3)=18.50

LAND USE DATA (AREA IN ha, YIELDS IN kg/ha-yr)

ISSAGUAH CREEK SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	9845.	95.	390.	3620.	250.
HIGH	0.340	1.500	2.700	1.900	2.200
LOW	0.220	0.950	2.200	1.200	1.400

WESTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	510.	0.	530.	3180.	280.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

EASTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	3262.	50.	351.	2610.	227.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

PERCENT OF TOTAL LOADING

	ISS. CRK	WESTSIDE	EASTSIDE	INTERNAL
HIGH	58.47	14.63	13.46	13.44
LOW	53.07	14.67	13.56	18.70

AREAL LOADING (mg/m2-yr)

HIGH	604.59	151.33	139.23	138.94
LOW	394.35	109.03	100.73	138.94

HIGH AND LOW ANNUAL MEANS(mg/m3) 21.85 17.47

MEAN SUMMER VALUES(JUNE-AUGUST)

SURFACE

	TP(mg/m3)	Chla(mg/m3)	SECCHI DEPTH(m)
HIGH	13.57	3.12	3.55
LOW	10.04	2.00	4.80

*********RESULTS FOR A LOW WATER YEAR*******

RELEASE RATES(mg/m2-WEEK)= 8.40 8.40

INITIAL KNOWN LAKE CONC(mg/m3)=28.50

LAND USE DATA (AREA IN ha, YIELDS IN kg/ha-yr)

ISSAQUAH CREEK SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	9845.	95.	390.	3620.	250.
HIGH	0.340	1.500	2.700	1.900	2.200
LOW	0.220	0.950	2.200	1.200	1.400

WESTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	510.	0.	530.	3180.	280.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

EASTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	3262.	50.	351.	2610.	227.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

PERCENT OF TOTAL LOADING

	ISS. CRK	WESTSIDE	EASTSIDE	INTERNAL
HIGH	58.47	14.63	13.46	13.44
LOW	53.07	14.67	13.56	18.70

AREAL LOADING (mg/m2-yr)

HIGH	604.59	151.33	139.23	138.94
LOW	394.35	109.03	100.73	138.94

HIGH AND LOW ANNUAL MEANS(mg/m3) 35.71 29.52

MEAN SUMMER VALUES(JUNE-AUGUST)

SURFACE

	TP(mg/m3)	Chla(mg/m3)	SECCHI DEPTH(m)
HIGH	25.08	7.69	1.92
LOW	19.40	5.27	2.48

SEDIMENT OXIDATION - 2000

*********RESULTS FOR A HIGH WATER YEAR*******

RELEASE RATES(mg/m2-WEEK)= 4.20 4.20

INITIAL KNOWN LAKE CONC(mg/m3)=17.00

LAND USE DATA (AREA IN ha, YIELDS IN kg/ha-yr)

ISSAQUAH CREEK SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	9845.	95.	390.	3620.	250.
HIGH	0.340	1.500	2.700	1.900	2.200
LOW	0.220	0.950	2.200	1.200	1.400

WESTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	510.	0.	530.	3180.	280.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

EASTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	3262.	50.	351.	2610.	227.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

PERCENT OF TOTAL LOADING

	ISS. CRK	WESTSIDE	EASTSIDE	INTERNAL
HIGH	62.68	15.69	14.43	7.20
LOW	58.55	16.19	14.95	10.31

AREAL LOADING (mg/m2-yr)

HIGH	604.59	151.33	139.23	69.47
LOW	394.35	109.03	100.73	69.47

HIGH AND LOW ANNUAL MEANS(mg/m3) 20.58 16.20

MEAN SUMMER VALUES(JUNE-AUGUST)

SURFACE

	TP(mg/m3)	Chla(mg/m3)	SECCHI DEPTH(m)
HIGH	13.09	2.96	3.68
LOW	9.56	1.86	5.04

SEDIMENT OXIDATION - 2000

*********RESULTS FOR A LOW WATER YEAR*******

RELEASE RATES(mg/m2-WEEK)= 4.20 4.20

INITIAL KNOWN LAKE CONC(mg/m3)=26.50

LAND USE DATA (AREA IN ha, YIELDS IN kg/ha-yr)

ISSAQUAH CREEK SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	9845.	95.	390.	3620.	250.
HIGH	0.340	1.500	2.700	1.900	2.200
LOW	0.220	0.950	2.200	1.200	1.400

WESTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	510.	0.	530.	3180.	280.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

EASTSIDE SUB-BASIN

	FOR	AGRI	COMM	SFR	MFR
AREA	3262.	50.	351.	2610.	227.
HIGH	0.120	0.700	0.910	0.700	0.810
LOW	0.090	0.510	0.680	0.500	0.580

PERCENT OF TOTAL LOADING

	ISS. CRK	WESTSIDE	EASTSIDE	INTERNAL
HIGH	62.68	15.69	14.43	7.20
LOW	58.55	16.19	14.95	10.31

AREAL LOADING (mg/m2-yr)

HIGH	604.59	151.33	139.23	69.47
LOW	394.35	109.03	100.73	69.47

HIGH AND LOW ANNUAL MEANS(mg/m3) 33.68 27.49

MEAN SUMMER VALUES(JUNE-AUGUST)

SURFACE

	TP(mg/m3)	Chla(mg/m3)	SECCHI DEPTH(m)
HIGH	24.07	7.24	2.00
LOW	18.39	4.88	2.62

APPENDIX C

Data used for calibration and verification and to predict year 1990 and 2000 lake conditions

VERIFICATION DATA, 1972-1973

Issaquah Creek

Date	P mg/m^3	Q m^3/sec	J kg/day	ppt cm
100772		0.94	59.43	0.0
101472		0.91	33.51	0.03
102172		0.85	37.63	0.25
102872		1.21	46.82	1.37
110472		1.40	84.50	2.57
111172		2.28	88.55	2.62
111872		1.64	63.54	.38
112572		1.63	121.20	1.91
120272	73.00	4.43	200.41	3.43
120972	44.00	2.91	75.86	0.00
121672	125.00	1.94	171.23	3.81
122372	195.00	14.86	1766.57	9.66
123072	112.00	17.61	1386.36	2.72
10773	40.00	5.58	133.48	0.71
11473	162.00	9.58	1121.99	6.65
12173	57.00	8.06	305.51	1.93
12873	37.00	4.60	104.26	1.09
20473	36.00	4.15	92.15	1.17
21173	30.00	3.34	62.07	0.13
21873	25.00	2.99	46.90	0.58
22573	27.00	2.65	43.09	1.22
30473	60.00	4.18	163.16	2.82
31173	29.00	3.49	62.31	1.75
31873	28.00	3.88	66.19	1.17
32573	42.00	3.71	98.42	0.13
40173	23.00	2.83	40.81	0.58
40873	30.00	2.26	40.95	0.08
41573	28.00	1.82	31.74	0.18
42273	28.00	3.34	57.35	2.67
42973	23.00	2.65	39.47	0.38
50673	29.00	2.06	36.13	0.25
51373	37.00	2.41	54.80	1.42
52073	38.00	1.66	39.02	0.00
52773	48.00	2.02	61.73	2.39
60373	49.00	1.50	45.08	0.00
61073	38.00	1.45	33.61	0.86
61773	58.00	1.83	73.55	2.29
62473	85.00	2.17	112.96	2.16
70173	46.00	2.20	65.07	1.04
70873	40.00	1.43	34.91	0.15
71573	49.00	1.11	32.98	0.00
72273	47.00	0.92	26.37	0.05
72973	63.00	0.82	31.68	0.00
80573	70.00	0.73	30.67	0.18
81273	74.00	0.76	33.99	0.03
81973	59.00	0.77	27.51	0.48
82673	67.00	0.70	28.47	0.00
90273	70.00	0.71	30.38	0.00
90973	59.00	0.70	25.54	0.30
91673	61.00	0.68	25.11	0.10
92373	60.00	1.06	38.14	3.58
93073	60.00	1.03	37.05	0.61

Lake Sammamish Volume-weighted means

Date	P mg/m^3	week from t=0
100872	35.7	01
102272	55.6	03
110272	51.7	04.
111172	32.4	05.
111872	51.8	06.
112572	32.3	07.
120272	46.1	08.
120972	30.6	09.
121872	27.6	11.
011373	24.3	14.
021773	26.5	19.
0224	35.2	20.
0303	40.2	21.
0317	30.3	23.
0331	25.4	25.
0414	18.6	27.
0427	16.7	29.
0511	25.2	31.
0528	31.7	34.
0614	23.0	36.
0625	17.5	39.
0720	28.1	41.
0727	26.4	42.
0810	35.2	44.
0824	32.6	46.
0907	35.4	48.
0928	48.2	51.

CALIBRATION DATA, 1974-1975

ISSAQUAH CREEK

Date Ending	P mg/m^3	Q m^3/sec	J kg/wk	ppt(cm)
70174	69.00	1.94	80.51	0.432
70874	54.00	1.85	61.24	.203
71574	52.00	2.07	65.61	1.346
72274	64.00	2.42	94.45	2.286
72974	60.00	1.67	62.08	0.
80574	68.00	1.46	60.55	0.
81274	70.00	1.39	58.82	0.
81974	101.00	1.16	71.72	0.025
82674	66.00	0.93	36.63	0.
90274	37.00	0.84	18.94	0.
90974	72.00	0.82	35.60	0.533
91674	64.00	0.80	31.45	0.
92374	177.00	0.75	79.66	0.
93074	196.00	0.73	85.96	0.
100774	103.00	0.76	47.84	0.025
101474	102.00	0.72	44.50	0.102
102174	103.00	0.80	50.33	1.168
102874	115.00	0.82	58.90	3.124
110474	99.00	0.94	58.01	0.991
111174	74.00	1.35	60.83	2.946
111874	63.00	1.34	51.61	1.930
112574	28.00	5.86	80.64	7.620
120274	28.00	2.73	46.53	0.559
120974	39.00	2.25	54.65	2.794
121674	40.00	4.11	86.80	2.794
122374	36.00	9.52	239.54	3.073
123074	23.00	7.65	156.17	7.290
10775	22.00	9.21	131.50	3.810
11475	99.00	14.36	1283.28	6.960
12175	162.00	17.10	1825.90	1.981
12875	75.00	8.05	400.58	2.515
20475	22.00	4.23	56.62	0.127
21175	22.00	3.58	47.99	4.343
21875	29.00	8.52	149.20	3.531
22575	30.00	14.65	304.12	5.588
30475	25.00	10.86	168.24	3.937
31175	16.00	5.93	57.86	0.330
31875	21.00	5.57	74.43	2.667
32575	24.00	7.27	103.42	1.041
40175	24.00	3.98	59.86	0.438
40875	21.00	4.45	58.82	1.956
41575	37.00	3.04	68.35	0.533
42275	31.00	3.23	63.73	1.016
42975	29.00	6.50	122.90	2.794
50675	24.00	4.38	65.63	1.549
51375	27.00	3.17	52.43	0.762
52075	27.00	2.68	44.00	0.102
52775	26.00	2.38	37.00	0.457
60375	35.00	1.80	37.91	0.203
61075	49.00	1.51	44.33	0.
61775	42.00	1.32	34.99	0.762

LAKE SAMMAMISH
volume-weighted means

Date	P mg/m^3	Wk Since t=0
062674	16.7	01.
0708	22.0	02.
0724	18.8	05.
0807	18.1	07.
0827	24.5	10.
0910	21.2	12.
1002	29.5	15.
1022	36.1	18.
1113	51.3	21.
1119	39.	22.
1127	39.3	23.
1206	30.6	24.
1211	27.6	25.
1220	27.7	26.
010975	32.4	29.
0124	27.6	31.
0207	32.7	33.
0220	25.9	35.
0306	23.5	37.
0327	16.1	40.
0410	19.8	42.
0417	17.1	43.
0429	15.6	44.
0515	19.3	47.
0605	11.2	50.

	High Flow		Low Flow	
	Q x 10^{-6}		Q x 10^{-6}	ppt
wk	m^3/wk	in/wk	m^3/wk	in/wk
1.	0.61	0.05	0.57	0.00
2.	0.72	2.06	0.55	0.03
3.	1.67	3.61	0.51	0.25
4.	2.45	2.34	0.73	1.37
5.	4.04	5.21	0.85	2.57
6.	3.36	3.02	1.38	2.62
7.	2.53	1.78	0.99	0.38
8.	2.39	3.18	0.99	1.91
9.	3.35	1.73	2.68	3.43
10.	4.91	5.79	1.76	0.00
11.	4.98	1.44	1.17	3.81
12.	6.05	4.04	8.99	9.66
13.	4.62	3.05	10.65	2.72
14.	3.05	0.71	3.37	0.71
15.	3.96	2.64	5.79	6.65
16.	10.70	11.28	4.87	1.93
17.	9.04	5.51	2.78	1.09
18.	2.93	0.05	2.51	1.17
19.	5.20	2.24	2.02	0.13
20.	8.34	6.02	1.81	0.58
21.	5.63	1.80	1.60	1.22
22.	15.05	12.22	2.53	2.82
23.	12.68	10.49	2.11	1.75
24.	7.86	2.93	2.35	1.17
25.	4.01	1.93	2.24	0.13
26.	2.78	0.61	1.71	0.58
27.	3.62	5.51	1.37	0.08
28.	4.13	0.97	1.10	0.18
29.	4.02	1.91	2.02	2.67
30.	3.74	1.57	1.60	0.38
31.	2.51	0.00	1.25	0.25
32.	2.02	0.61	1.46	1.42
33.	1.76	0.86	1.00	0.00
34.	1.64	0.28	1.22	2.39
35.	1.23	0.00	0.91	0.00
36.	1.18	1.14	0.88	0.86
37.	1.17	0.46	1.11	2.29
38.	1.98	2.97	1.31	2.16
39.	2.81	0.03	1.33	1.04
40.	1.25	0.18	0.86	0.15
41.	2.09	3.23	0.67	0.00
42.	1.17	0.00	0.56	0.05
43.	0.88	0.00	0.50	0.00
44.	0.74	0.00	0.44	0.18
45.	0.62	0.00	0.46	0.03
46.	0.75	2.03	0.47	0.48
47.	0.71	0.84	0.42	0.00
48.	0.56	0.00	0.43	0.00
49.	0.56	1.09	0.42	0.30
50.	0.60	0.03	0.41	0.10
51.	1.43	8.26	0.64	3.58
52.	0.93	1.04	0.62	0.61

High and low-flow water years (Oct.-Sept.) observed during past 20 years used to predict 1990 and 2000 P loading

128.74 67.88 Total ppt (in) High, low flow

```
C**********************************************************************C
C                                                                      C
C              LAKE SAMMAMISH SEASONAL PHOSPHORUS MODEL                C
C                                                                      C
C                  dTP/dt=Jex/V-Q[TP]/V-SIG[TP]+Jint/V                 C
C                                                                      C
C**********************************************************************C

      PROGRAM SAMMIII
      DIMENSION DEF(15,3),FRAC(16:17,1:3),RLOAD(12,3),AREA(10,3)
      REAL LINH,LINL,LMEH,LMEL,LA,JINH,JINL,LNPH,LNPL
      INTEGER FA
      COMMON SM,TSI,CHA,SD
      CHARACTER*20 AQ
      OPEN(UNIT=5,NAME='INSAMM.DAT',STATUS='OLD')
      OPEN(UNIT=6,NAME='SAMMIII.OUT',STATUS='NEW')
      DATA TTPLH,TTPLL,TLINH,TLINL,TPLH,TPLL,WK,SMH,SML/
     +9*0./
      DATA DEF/.34,.22,1.5,.95,2.7,2.2,1.9,1.2,2.2,1.4,5*0.,
     +.12,.09,.70,.51,.91,.68,.70,.50,.81,.58,5*0.,
     +.12,.09,.70,.51,.91,.68,.70,.50,.81,.58,5*0./
      ASSIGN 205 TO FA
C
      QFAC=0.70
      RF=.78
      PHPPT=400+1100 !kg/yr ATMOSPHERIC INPUT+HATCHERY WASTE+SEPTIC TANKS
C
C LAKE VOLUME IN Mm3,SURFACE AREA AND HYPOLIMENTIC AREA IN Mm2
C
      V=330.            !m3E06 lake volume
      HA=13.1           !m2E06 surface area at 15m
      LA=19.8           !m2E06 area at surface
C
      PRINT*,' '
      PRINT*,'DO YOU WISH TO RUN THE MODEL FOR A HIGH OR LOW'
      PRINT*,'WATER YEAR? TYPE 1(HIGH) or 2(LOW).'
      READ*,C
      IF(C.EQ.2)ASSIGN 206 TO FA
      R=2.
C
      PRINT*,'ENTER INITIAL LAKE P CONC. FOR OCT 1 IN mg/m3.'
      READ*,TPLO
      TPLH=TPLO
      TPLL=TPLH

      PRINT*,'ENTER HIGH AND LOW SEDIMENT RELEASE RATES mg/m2-week.'
      PRINT*,'IF YOU WISH TO USE ONLY ONE VALUE, ENTER IT TWICE.'
      READ*,RRH,RRL
C
C CALL SUBROUTINE TO DETERMINE LOADINGS BASED UPON LAND USE
C
      CALL TLU(CHECK,DEF,AREA,RLOAD,TNPH,TNPL)
C
C READ IN TOTAL PPT WEEKLY FLOW AND FRACTIONAL PPT.
C ISSAQUAH CREEK IS ASSUMED TO BE 70% OF THE TOTAL FLOW.
C THIS ASSUMES NO INCREASE IN FLOW (OVER THE CREEK'S) FROM
C NON-POINT RUNOFF. QA=(Q/.7).
```

```
C THE FRACTION OF THE ANNUAL PRECIPITATION FALLING DURING
C EACH WEEK WILL BE USED TO PARTITION THE ANNUAL EXPORT
C COEFFICENTS IN DETERMINING THE LOADING FROM RUNOFF AND
C ATMOSPHERIC INPUT
C
  190 READ(5,195)TPPTH,TPPTL
  195 FORMAT(2(F6.2))
C
      IF(C.EQ.2)THEN
        TPPT=TPPTL
      ELSE
        TPPT=TPPTH
      END IF
C
      DO 350 I=1,52
       READ(5,FA)WK,Q,PPT
  205  FORMAT(1X,F3.0,2(F5.2))
  206  FORMAT(1X,F3.0,10X,2(F5.2))
C
       QA=Q/QFAC
       RO=QA/V
       FPPT=PPT/TPPT
C
C CALCULATE ATMOSPHERIC AND INTERNAL LOADINGS.
C INTERNAL LOADING IS RELEASE RATE*AREA OF LAKE
C BOTTOM THAT IS ANAEROBIC->15m DEPTH
C
      ATM=(PHPPT*FPPT)/V
      IF(WK.GE.42..OR.WK.LE.5.)THEN
       ARRH=RRH
       ARRL=RRL
      ELSE
       IF(WK.GT.5..AND.WK.LE.8.)THEN
         ARRH=3*RRH
         ARRL=3*RRL
       ELSE
         ARRH=0
         ARRL=0
       ENDIF
      ENDIF
C
      JINH=ARRH*HA
      JINL=ARRL*HA
      LINH=JINH/V
      LINL=JINL/V
C
C  CALCULATE HIGH AND LOW NON-POINT LOADINGS
C
      LNPH=(TNPH*FPPT)/V
      LNPL=(TNPL*FPPT)/V

C
C CALCULATE OUTFLOW CONC.
C
       OUTH=RO*TPLH
       OUTL=RO*TPLL
```

```
C
C DETERMINE LOSS VIA SEDIMENTATION
C
       SIG=RO**RF
       IF(WK.GT.8..AND.WK.LE.10.)SIG=1.5*SIG
       SEDH=SIG*TPLH
       SEDL=SIG*TPLL
C
C NEW CONC.
C
      DPH=ATM-OUTH-SEDH+LNPH+LINH
      DPL=ATM-OUTL-SEDL+LNPL+LINL
      TPLH=TPLH+DPH
      TPLL=TPLL+DPL
      TTPLH=TTPLH+TPLH
      TTPLL=TTPLL+TPLL
      TJINH=TJINH+JINH
      TJINL=TJINL+JINL
C
C FIND SUMMER MEAN
C
      IF(WK.GE.36.AND.WK.LE.48)THEN
        SMH=SMH+TPLH
        SML=SML+TPLL
      ENDIF
C
      WRITE(6,300)WK,TPLH,TPLL,LNPH,LNPL,LINH,LINL
  300 FORMAT(1X,F3.0,2(2X,F6.2),4(3X,F7.2))
  350 CONTINUE
C
C ANNUAL MEANS AND ABSOLUTE & FRACTIOAL VALUES OF THE AREAL LOADING.
C
      LMEH=TTPLH/52
      LMEL=TTPLL/52
      TLINH=TJINH/LA
      TLINL=TJINL/LA
      TLOH=TJINH+TNPH
      TLOL=TJINL+TNPL
      TFINH=(TJINH/TLOH)*100.
      TFINL=(TJINL/TLOL)*100.
C
      DO 465 J=1,3
        FRAC(16,J)=(RLOAD(11,J)*100)/TLOH
        FRAC(17,J)=(RLOAD(12,J)*100)/TLOL
  465 CONTINUE
C
      AQ='HIGH'
      IF(C.EQ.2)AQ='LOW '
      WRITE(6,375)AQ
  375 FORMAT('1','*********RESULTS FOR A ',A4 ,' WATER YEAR*******')
      WRITE(6,400)RRH,RRL
  400 FORMAT('0','RELEASE RATES(mg/m2-WEEK)=',F6.2,4X,F6.2)
      WRITE(6,410)TPLO
  410 FORMAT('0','INITIAL KNOWN LAKE CONC(mg/m3)=',F5.2)
      WRITE(6,415)
  415 FORMAT('0','LAND USE DATA (AREA IN ha,YIELDS IN kg/ha-yr)')
      WRITE(6,417)
  417 FORMAT('0',13X,'***ISSAQUAH CREEK SUB-BASIN***')
```

```
C
      DO 445 J=1,3
        WRITE(6,420)
  420   FORMAT('0',9X,'FOR',6X,'AGRI',6X,'COMM',6X,'SFR',7X,'MFR')
        WRITE(6,425)(DEF(I,J),I=11,15)
  425   FORMAT(1X,'AREA',2x,F7.0,4(3X,F7.0))
C
       WRITE(6,435)(DEF(I,J),I=1,9,2)
  435  FORMAT(1X,'HIGH',3X,F5.3,4(5X,F5.3))
       WRITE(6,437)(DEF(I,J),I=2,10,2)
  437  FORMAT(1X,'LOW',4X,F5.3,4(5X,F5.3))
C
        IF(J.EQ.2)GOTO 442
        IF(J.GT.2)GOTO 445
  440   WRITE(6,441)
  441   FORMAT('0',15X,'***WESTSIDE SUB-BASIN***')
        GOTO 445
  442   WRITE(6,443)
  443   FORMAT('0',15X,'***EASTSIDE SUB-BASIN***')
  445 CONTINUE
C
C DETERMINE TROPHIC STATE INDEX SUMMER Chla(mg/m3) AND SECCHI DEPH(m)
C
      SM=SMH*.70/13
      CALL TROPH
      SMH=SM
      CHAH=CHA
      SDH=SD
C
      SM=SML*.70/13
      CALL TROPH
      SML=SM
      CHAL=CHA
      SDL=SD
      WRITE(6,450)
  450 FORMAT('0'18X,'PERCENT OF TOTAL LOADING')
      WRITE(6,460)
  460 FORMAT(9X,'ISS.CRK',6X,'WESTSIDE',7X,'EASTSIDE',3X,'INTERNAL')
C
      WRITE(6,470)(FRAC(16,J),J=1,3),TFINH
  470 FORMAT(1X,'HIGH',5X,F5.2,8X,F5.2,9X,F5.2,8X,F5.2)
      WRITE(6,475)(FRAC(17,J),J=1,3),TFINL
  475 FORMAT(1X,'LOW',6X,F5.2,8X,F5.2,9X,F5.2,8X,F5.2)
      WRITE(6,480)
  480 FORMAT('0',17X,'AREAL LOADING (mg/m2-yr)')
C
      DO 483 J=1,3
         FRAC(16,J)=RLOAD(11,J)/LA
         FRAC(17,J)=RLOAD(12,J)/LA
  483 CONTINUE
C
      WRITE(6,485)(FRAC(16,J),J=1,3),TLINH
  485 FORMAT(1X,'HIGH',4X,F7.2,6X,F7.2,7X,F7.2,6X,F7.2)
      WRITE(6,490)(FRAC(17,J),J=1,3),TLINL
  490 FORMAT(1X,'LOW',5X,F7.2,6X,F7.2,7X,F7.2,6X,F7.2)
      WRITE(6,495)LMEH,LMEL
  495 FORMAT('0','HIGH AND LOW ANNUAL MEANS(mg/m3)',2(3X,F7.2))
      WRITE(6,500)
  500 FORMAT('0',13X,'MEAN SUMMER VALUES(JUNE-AUGUST)')
```

```
      WRITE(6,503)
  503 FORMAT('0',21X,'SURFACE')
      WRITE(6,505)
  505 FORMAT(14X,'TP(mg/m3)',5X,'Chla(mg/m3)',5X,'SECCHI DEPTH(m)')
      WRITE(6,510)SMH,CHAH,SDH
  510 FORMAT(1X,'HIGH',3(9X,F6.2))
      WRITE(6,515)SML,CHAL,SDL
  515 FORMAT(1X,'LOW',10X,F6.2,2(9X,F6.2))
C
      CLOSE(UNIT=5)
      CLOSE(UNIT=6)
C
      PRINT*, 'IF YOU WOULD LIKE A PLOT OF THIS RUN, TYPE 1.'
      PRINT*,'        IF NOT,TYPE 0'
      READ*,G
      IF(G.EQ.1)CALLPLOT
C
      STOP
      END
C
C***********************************************************************C
C
C LAND USED SUBROUTINE. AREAS AND RUNOFF COEFFICIENTS(Kg/ha-yr) are
C CONVERTED TO Kg/yr.
C
      SUBROUTINE TLU(CHECK,DEF,AREA,RLOAD,TNPH,TNPL)
      INTEGER B
      CHARACTER*10 ANS
      DIMENSION DEF(15,3),AREA(10,3),RLOAD(12,3)
      OPEN(UNIT=7, NAME='Y.DAT',STATUS='OLD')
C
      PRINT*,' '
      PRINT*,'THE WATERSHED IS DIVIDED UP INTO 3 SUB-BASINS, ISSAQUAH'
      PRINT*,'CREEK, WESTSIDE AND EASTSIDE. FOR EACH SUB-BASIN ENTER'
      PRINT*,'THE AREA (HECTARES) FOR EACH TYPE OF LAND USE AND HIGH'
      PRINT*,'AND LOW PHOSPHORUS YIELD COEFFICIENTS (kg/ha-yr)'
      PRINT*,'IF DESIRED.'
      PRINT*,' '
      PRINT*,'***ISSAQUAH CREEK SUB-BASIN, TOTAL AREA=14200ha***'
C
      DO 970 B=1,3
       PRINT*,' '
       PRINT*,'INPUT AREAS(ha) FOR EACH TYPE OF LAND USE IN THE'
       PRINT*,'FOLLOWING ORDER:  FOREST, AGRICULTURAL, COMMERCIAL,'
       PRINT*,'SINGLE-FAMILY RESIDENTIAL AND MULTI-FAMILY RESIDENTIAL.'
       PRINT*,'PLEASE PRESS "RETURN" AFTER EACH VALUE'
         READ(*,903)(DEF(I,B),I=11,15)
  903  FORMAT(F6.0)
C
      I=1
       DO 905 J=11,15
         AREA(I,B)=DEF(J,B)
         AREA(I+1,B)=DEF(J,B)
         I=I+2
  905 CONTINUE
```

```
C
      PRINT*,'DO YOU WISH TO USE EXISTING HIGH AND LOW YIELD'
      PRINT*,'COEFFICIENTS? (Y or N).  IF NO,THE MODEL WILL READ'
      PRINT*,'YIELDS FROM THE FILE Y.DAT'
      READ(*,907)ANS
  907 FORMAT(A1)
      IF(ANS.EQ.'Y'.OR.ANS.EQ.'y')GOTO 920
C
     READ(7,915)(DEF(I,B),I=1,10)
  915 FORMAT(F4.2)
C
C FIGURE LOADINGS FOR EACH LAND TYPE
C
  920 DO 925 I=1,10
        RLOAD(I,B)=DEF(I,B)*AREA(I,B)
  925 CONTINUE
C
C ADD UP HIGH AND LOW LOADINGS FOR EACH SUB-BASIN
C
      RLOAD(11,B)=0.
      DO 930 I=1,9,2
        RLOAD(11,B)=RLOAD(11,B)+RLOAD(I,B)
  930 CONTINUE
C
      RLOAD(12,B)=0.
      DO 935 I=2,10,2
       RLOAD(12,B)=RLOAD(12,B)+RLOAD(I,B)
  935 CONTINUE
C
      IF(B.EQ.2)GOTO 950
      IF(B.GT.2)GOTO 970
C
      PRINT*,' '
      PRINT*,'***WESTSIDE SUB-BASIN, TOTAL AREA=4600ha***'
      GOTO 970
C
  950 PRINT*,' '
      PRINT*,'***EASTSIDE SUB-BASIN, TOTAL AREA=6500ha***'
  970 CONTINUE
C
C CALCULATE HIGH AND LOW TOTAL NON-POINT LOADINGS
C
     TNPH=0.
     TNPL=0.
C
     DO 990 J=1,3
      TNPH=TNPH+RLOAD(11,J)
      TNPL=TNPL+RLOAD(12,J)
 990 CONTINUE
C
     RETURN
     END
C
C*******************************************************************C
C
     SUBROUTINE TROPH
C
     COMMON SM,TSI,CHA,SD
     TSI=(14.42*LOG(SM))+4.15
     CHA=EXP((TSI-30.6)/9.81)
     SD=EXP((60-TSI)/14.4)
     RETURN
     END
```

```
C
C***********************************************************************C
C
      SUBROUTINE PLOT
C
      DIMENSION WKM(52),TPLH(52),TPLL(52),WKS(2),PS(2)
      OPEN(UNIT=6,NAME='SAMMIII.OUT',STATUS='OLD')
      DATA WKS/0,52/,PS/0,50/
C
      DO 650 I=1,52
       READ(6,600)WKM(I),TPLH(I),TPLL(I)
  600  FORMAT(1X,F3.0,2(2X,F6.2))
  650 CONTINUE
C
      CALL SCAN(WKS,PS,-2,440)
      CALL AXES(4.0,'WEEK',15.2,'TOTAL P  (mg/m3)')
      CALL DRAW(WKM,TPLH,52,441)
      CALL DRAW(WKM,TPLL,52,441)
C
      CALL DRAW(0.,0.,1,9000)
      CALL DRAW(0,0,0,9999)
      CALL EXIT
      RETURN
      END
```