Phosphorus Balance Models for Eucha & Spavinaw Reservoirs

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Introduction

This report describes the development and application of models for simulating the water and phosphorus balances of Eucha and Spavinaw Reservoirs, Oklahoma (Figure 1). Algal growth resulting from excessive phosphorus concentrations is a factor contributing to taste-and-odor episodes in the Tulsa water supply system (OWRB, 2002).

The models are based upon fundamental mass-balance concepts commonly used in simulating water quality variations in lakes and reservoirs (Chapra & Reckhow, 1983). The models are calibrated to extensive data from Eucha and Spavinaw Reservoirs collected over the 1998-2001 period (Tables 1 & 2). The models are used to quantify the magnitudes and relative importance of external sources vs. internal recycling of phosphorus as factors driving algal productivity in the reservoirs. The potential benefits of management measures to reduce external sources and internal recycling are evaluated.

Model Development

Model structure & equations are illustrated in Figure 2. The water and phosphorus balances of each reservoir are simulated on a monthly basis. Five differential equations representing these balances are solved simultaneously in each month and reservoir. The reservoir linkage is represented (i.e. outflows from Eucha constitute a portion of the inflows to Spavinaw). This provides a means for evaluating effects of load reductions in the Eucha watershed on both reservoirs. For calibration purposes, the Spavinaw model uses measured Eucha outflow volumes and loads. Equations for simulating phosphorus cycling are derived partially from recent modeling studies of Lake Okeechobee, Florida (Walker, 2000), Upper Klamath Lake, Oregon (Walker, 2001), and Lake Istokpoga, Florida (Walker & Havens, 2002).

Simulations are driven by monthly time series of inflow volumes, inflow P loads, rainfall, evaporation, and thermocline depths determined from measured temperature profiles (Tables 1 & 2). Inflow volumes and loads are derived from watershed simulations using the SWAT model (Storm et al. ,2002). Storm et al. calibrated the watershed simulations to measured flows and loads in watersheds that represented a variety of land uses and accounted for ~90% of the total drainage area. Other measured inputs include sediment characteristics (P content, bulk density) and reservoir morphometry (area & volume vs. elevation profiles). Other measurements used for calibration and testing include outflow volumes, outflow loads, and phosphorus concentrations in the epilimnion and hypolimnion of each reservoir, as derived from hydrologic and water quality monitoring.

Two water compartments are represented in each reservoir: epilimnion (upper layer) and hypolimnion (bottom layer). Water balance terms include inflow, rainfall, evaporation, outflow, and change in storage. Outflow is computed by difference from the other terms, all of which are directly measured. The volume of the epilimnion and hypolimnion vary with time to reflect changes in reservoir surface elevation and thermocline migration. Monthly thermocline depths are determined from vertical temperature profiles (inflection point or depth of maximum temperature gradient). Vertical flows across the thermocline (generally from the epilimnion to the hypolimnion in the spring and from the hypolimnion to the epilimnion in the late summer and fall) are computed from changes in hypolimnion volume. Water balances are tested by comparing observed and predicted outflow volumes from each reservoir. These comparisons test the combined linkage of the SWAT watershed simulations and the reservoir water balance models.

Three storage compartments for phosphorus are represented: epilimnion, hypolimnion, and the active sediment layer (Figure 2). Water-column mass balance terms include inflow load, atmospheric deposition, settling, recycling from sediments (aerobic & anaerobic), transport across the thermocline (advective and diffusive), outflow, and changes in storage. The settling term reflects (a) sedimentation of particulate phosphorus entering from the watershed and (b) algal uptake of dissolved phosphorus and subsequent settling. Because it is out of the photosynthetic zone, phosphorus in the hypolimnion is assumed to be conservative (no net settling or other loss). Particulate phosphorus settling from the epilimnion is assumed to pass through hypolimnion and be deposited in the bottom sediments. Subsequent recycling from sediments back into the water column reflects microbial decomposition of settled algal biomass and chemical mechanisms discussed below.

The standard mass-transport equation is used to represent diffusion of phosphorus across the thermocline (Chapra & Reckhow, 1983). The diffusive transport coefficient (K_4, m/yr, Figure 2) is estimated independently for each reservoir based upon observed rates of temperature increase in the hypolimnion between June and August of each year, after the thermocline is well-developed. Transport coefficients in individual years range from 0.4 to 3 m/yr in Eucha and 1.2 to 2.5 m/yr for Spavinaw. Because diffusive transport is relatively unimportant (small compared with transport attributed to thermocline erosion), a constant value of 2 m/yr is assumed for each reservoir and year.

Phosphorus balance terms for the bottom sediment include sedimentation from the water column, releases to the water column (aerobic and anaerobic), and burial (Figure 2). The bottom sediment compartment represents a thin layer of sediment (5 cm) that interacts with the water column. Sediment below this depth is assumed to be “buried” and isolated from the water column as a consequence of chemical stability and the diffusion barrier provided by the overlying sediment. The assumed sediment thickness (typically ranging from 1 to 10 cm in other lake modeling studies, Chapra & Reckhow, 1983) influences the transient response of water-column phosphorus concentrations to variations in external nutrient loading, but does not influence on the long-term average concentrations resulting from a given loading regime.

Recycling from the bottom sediment to the water column occurs at different rates to the epilimnion and hypolimnion, reflecting aerobic and anaerobic conditions, respectively. As typically observed in other lakes and reservoirs, sediment phosphorus release rates in Spavinaw & Eucha are higher under anaerobic than under aerobic conditions. Anaerobic release rates have been calibrated to measured hypolimnetic phosphorus concentration time series (5.2 mg/m^2-day for Eucha & 4.4 mg/m^2-day for Spavinaw), as described below. Based upon sediment core studies reported by Moore (2002), aerobic release rates are assumed to be 37% of the anaerobic rates. Aerobic releases reflect decomposition of settled algal biomass and other organic detritus, as well as wind-driven re-suspension of particulates. Anaerobic releases reflect decomposition processes and dissolution of iron phosphate compounds. Dissolved iron and phosphate ions would be stable in anaerobic bottom waters, but rapidly co-precipitate if they reach the aerobic surface layer as a result of diffusion or thermocline erosion. Because this co-precipitation mechanism is not reflected in the model, it is likely that simulations over-estimate the importance of anoxic recycling on surface phosphorus concentrations and resulting algal productivity.

The burial term reflects buildup of bottom sediment (movement of phosphorus below the active sediment layer). Because sediment accretion represents the only long-term sink for phosphorus, current accretion rates can be estimated independently based upon the external phosphorus budgets (inflow load – outflow load) and measured sediment properties (bulk density & total phosphorus content). This constraint is implicit in the solution of the phosphorus balance model for each reservoir. Model calibration results are consistent with accretion rates of 2.1 cm/yr in Eucha Reservoir and 0.2 cm/yr in Spavinaw Reservoir. Sediment properties and calibrated accretion rates influence the time scale of response to changes in external loadings, but do not influence the long-term-average predictions.

Historical sediment surveys provide a limited basis for comparison with sediment accretion rates calibrated from the phosphorus budgets. Based upon SCS surveys, OWRB (2002, p. 19) reports average accretion rates of 1.54 cm/yr (1935-1999) for Spavinaw and 1.13 cm/yr (1954-1999) for Eucha. These values do not necessarily reflect current rates because they span long time periods with changes in land use and reservoir construction. The calibrated Eucha rate (2.1 cm/yr) is roughly twice the average 1954-1999 rate (1.1 cm/yr). This would be consistent with increased eutrophication in recent years. The calibrated Spavinaw rate (0.2 cm/yr) is much lower than the 1935-1999 average (1.54 cm/yr). This is consistent with the relatively small direct drainage area. Most of the accretion in Spavinaw between 1935 and 1999 is likely to have occurred prior to 1954 (when Eucha dam was created) and when erosion rates in the local watershed may have been higher than current levels (OWRB, 2002).

When the entire system is considered (water column + active sediment layer, Figure 2), the burial term represents the only long-term sink for phosphorus. External loads from the watershed and atmospheric deposition represent the only long-term sources of phosphorus. Atmospheric deposition accounts for ~0.5 % of the external load to Eucha and ~2% of the load to Spavinaw. Releases from bottom sediments (frequently mislabeled “internal loads”) do not represent independent sources, but recycling of phosphorus that originally entered the reservoir from the watershed and atmosphere. Because of this coupling, reductions in sediment P releases would be expected to occur in response to reductions in external load, once the active sediment layer has equilibrated to the new loading regime.

The mass-balance model is coupled with an empirical chlorophyll-a/phosphorus relationship to simulate algal response to phosphorus during the May-September growing season. This is sufficient for predicting average May-September chlorophyll-a levels. Given the inherent variability of algal populations, accurate predictions are not expected on a monthly basis. Algal bloom frequency (percent of monthly-mean chlorophyll-a concentrations exceeding 20 ppb) is estimated from the predicted mean chlorophyll-a in each month of the growing season (May-September) and the frequency distribution of residuals (observed – predicted) concentrations derived from the model calibrations. Bloom frequency has been used as an indicator of impairment in lake/reservoir uses for water-supply and recreation (Walker,1985ab; Heiskary & Walker, 1988). This variable explicitly accounts for temporal variations simulated by the model and for random deviations from the predictions attributed to measurement variations and factors not represented in the model.

May-September average Chl-a/P ratios are 0.65 and 0.80 for Eucha & Spavinaw, respectively. Since the Chl-a/P ratio of algal cells is typically close to 1.0, the calibration indicates that ~65-80% of the phosphorus in the surface waters is tied up in algal cells. These percentages decrease later in the fall and winter, as factors other than phosphorus (e.g., temperature, light) become limiting to algal growth and, therefore, concentrations of dissolved phosphorus increase.

Model Calibration

Given the model structure and array of observed and predicted variables, there are essentially two degrees of freedom (i.e. two adjustable model coefficients) for calibrating the model to observed lake P concentrations. The parameter determining the sediment P release rate under anaerobic conditions (K_2, m/yr, Figure 2) is adjusted to match the observed buildup of phosphorus in the hypolimnion during the summer (Figure 3). The parameter determining the sedimentation of P from the epilimnion (K_1, m/yr) is adjusted to match observed May-September average P concentrations in the epilimnion (Figures 4-6).

The models are calibrated using monthly, volume-weighted-mean P concentrations in the epilimnion and hypolimnion of each reservoir measured over the 1998-2001 period (Tables 1 & 2). Volume-weighted means are computed as the area-weighted means of measured P concentrations at each depth within the epilimnion and hypolimnion. Data from the mid-reservoir and near-dam stations (SPAV01, SPAV02, EUCH01, and EUCH02) are averaged laterally in each monthly and then integrated vertically. These stations represent the vertically stratified middle and lower zone of each reservoir, where average phosphorus concentration are similar. Longitudinal variations (representing higher phosphorus concentrations in the uplake/riverine portions of each reservoir) are not simulated directly in the model but are implicit in the calibrations. The importance of this and other simplifying assumptions inherent in the model structure and equations would be reflected in comparisons between observed and predicted concentrations and outflow loads from each reservoir.

For calibration purposes, the Spavinaw model is run using measured outflow volumes and loads from Eucha. The SWAT model is used to estimate inflows from local watersheds, which accounted for only 6% of the total inflow volume and 8% of the total external load to Spavinaw. Because of these low percentages, the Spavinaw calibration and conclusions regarding the relative magnitudes of external and internal sources are largely independent of SWAT model results.

According to the model structure (Figure 2), the buildup of phosphorus in the hypolimnion during the summer depends upon (1) releases from bottom sediments, (2) entrainment from the epilimnion associated with thermocline formation in the spring, (3) erosion of the thermocline in the late summer and fall, and (4) diffusion across the thermocline. Factors 2-4 are determined by measured variations in thermocline depth and hypolimnion temperature. The parameter determining the sediment P release rate (K_2, m/yr, Figure 2) is adjusted to match the observed buildup of phosphorus in the hypolimnion during the summer (Figure 5). Based upon comparison of observed and predicted concentrations, anaerobic rates are applied between June and September. With the exception of Spavinaw in 1999, the model successfully predicts the buildup of phosphorus in the hypolimnion in each reservoir and year. The model over-predicts phosphorus levels in both the hypolimnion and epilimnion of Spavinaw in 1999 using both measured and predicted Eucha outflow time series (Figures 5 & 6). Apparently, there was greater net retention of phosphorus within the lake in 1999. The calibration focuses on the remaining years, when clear peaks in hypolimnetic P concentrations were observed.

Calibration results are consistent with average anaerobic release rates of 5.2 mg/m^2-day in Eucha and 4.4 mg/m^2-day in Spavinaw. These can be compared with estimates derived from laboratory studies of sediment P cores taken from Eucha Reservoir. The annualized anaerobic P release rate cited by Moore (2002) based upon these studies (18.8 kg/ha-yr over 50% of the year) is equivalent to a release rate of 11.2 mg/m^2-day during the anaerobic period. As shown in Figure 3, the model substantially over-predicts measured hypolimnetic P levels in both reservoirs using this rate. Independent computation of the anaerobic release rate using the same core data yields an estimate of 5.2 mg/m^2-day, which is consistent with the model calibration results. This computation uses phosphorus concentration data depicted in a file supplied by Moore (eucha flux data.ppt), an assumed core diameter of 6.3 cm, and accounts for P additions and removals associated with periodic sampling, as reported by Moore (2002). The reason for the discrepancy between these rates derived from the same laboratory data is unknown.

The parameter determining the sedimentation of P from the epilimnion (K_1, m/yr) is adjusted to match observed May-September average P concentrations in the epilimnion (Figures 4-6). Calibrated settling rates are 230 m/yr for Eucha and 45 m/yr for Spavinaw. This difference may reflect the fact that phosphorus entering Spavinaw is primarily tied up in algal cells with low sedimentation rates, whereas phosphorus loads entering Eucha contain both higher concentrations of inorganic particulate phosphorus with high settling rates and higher concentrations of dissolved phosphorus readily available for algal uptake and sedimentation.

Figure 5 shows observed and predicted values in Spavinaw when the model is driven by observed outflows from Eucha. Figure 6 shows corresponding results using predicted Eucha outflows. Reasonable agreement between observed and predicted outflow volumes and loads reservoir supports the validity of the combined linkage of the watershed and reservoir models. Differences in the timing of peaks and valleys in the observed and predicted values in Figures 4-6 partially reflect the simplified hydraulic representations in the watershed and reservoir models. These differences are expected. .

As in the case of chlorophyll-a, it is unrealistic to expect that a model of this type would accurately simulate month-to-month variations in epilimnetic P concentrations. Occasional spikes in the predicted epilimnetic P concentrations can be traced to high particulate phosphorus loads associated with storm events, as predicted by the watershed model. Capturing these spikes may require a model with more complex hydrodynamics, consideration of phosphorus species (dissolved vs. particulate), and use of measured (vs. simulated) watershed loads. The focus on May-September averages is adequate for predicting trophic state and characterizing the relative magnitudes of external loads and internal recycling.

Diagnostic Output

One of the primary purposes for the modeling effort is to provide a basis for evaluating the relative magnitudes of external vs. internal sources of phosphorus and implications for control algal productivity and taste-and-odor episodes in the Tulsa water supply system. The following diagnostic output is provided to facilitate interpretation of the modeling results by other experts:

Tables 3-4	Parameter Estimates & Average Annual Mass Balances
Figures 7-8	Average P Fluxes, May-September
Figures 9-10	Simulated Historical Time Series
Figures 11-12	Monthly Total P Inputs to the Epilimnion

Simulation of Management Measures

The model has been used to simulate the effects of hypothetical reductions in external phosphorus loads and/or phosphorus recycling from bottom sediments. These simulations are intended to illustrate sensitivity and do not reflect specific management recommendations. Simulating the 1998-2001 period provides a basis for evaluating changes resulting from management measures.

To evaluate sensitivity to external P load controls, a hypothetical reduction of 50% is applied to the Eucha watershed loads (point + nonpoint). The analysis is insensitive to the specific subwatersheds, specific sources (point vs. nonpoint, contributing land use, etc.), and specific control measures (BMP's, diversion, treatment, etc.). Given that it is relatively undeveloped, loads from the Spavinaw watershed are unchanged.

Effects of hypothetical alum applications to the bottom sediments of Eucha and/or Spavinaw Reservoirs are also simulated. The entire area of each reservoir is assumed to be treated. A reduction of 80% in aerobic and anaerobic phosphorus recycling is assumed. The longevity of the treatment is assumed to be infinite (no decline in effectiveness over time). The treatments are assumed to be repeated at an appropriate frequency to maintain the assumed 80% reduction in phosphorus recycling.

The following table summarizes results of five simulations, as expressed by May-September averages in Spavinaw Reservoir:

Scenario	Description	Epil TP (ppb)	Mean Chl-a (ppb)	Bloom Freq. (%)
BASE	1998-2001 Conditions	24	19	41%
LR50	50% Reduc. in Eucha Watershed Loads	14	11	15%
AL_SPAV	Spavinaw Alum Treatment	17	14	24%
AL_EUCH	Eucha Alum Treatment	22	18	38%
LR50_ALS	50% Reduc. in Eucha Loads + Spavinaw Alum Treatment	9.6	7.7	7.9%
LR50_ALSE	50% Reduc. In Eucha Loads + Eucha & Spavinaw Alum Tmt.	9.0	7.2	7.2%

Figure 13 shows epilimnetic phosphorus time series for each scenario. Figure 14 compares May-September average phosphorus and chlorophyll-a levels for each scenario and reservoir. Effects of alum treatment on P cycling in Spavinaw are illustrated by comparing monthly time series of P inputs to the epilimnion with and without treatment (Figures 15 and 12, respectively).

The above results reflect the long-term responses to treatments (after the bottom sediments and water columns have responded to the management measures). Recycling of phosphorus currently stored in reservoir sediments would delay responses of water column concentrations to reductions in external loads. Given the short hydraulic residence times of these reservoirs, initial reductions in water column concentrations would be expected to occur within a year or two. Further decreases would occur as the sediment phosphorus contents and recycling rates reach new equilibrium values.

To simulate transient responses, a 40-year model input time series has been created by repeating the 4-year time series used for model calibration. A hypothetical load reduction of 50% is applied to the Eucha watershed loads at the end of the first 4-year cycle. Simulated responses of epilimnetic phosphorus concentrations and algal bloom frequencies in each reservoir are shown in Figure 16, expressed as 4-year averages. Model results indicate a relatively rapid response in Eucha Reservoir, owing to its relatively high sedimentation rate. Average P levels reach a new-steady state within ~4 years. Spavinaw responds slowly, owing to its relatively low sedimentation rate and high sediment bulk density (i.e. low sediment P turnover rate). The actual response time is uncertain because it depends upon the assumed depth of the active sediment layer (5 cm vs. potential range of 1 – 10 cm). Most of the benefits of external load reduction are realized within 4 years and are independent of assumed sediment properties, however.

A substantial portion of the predicted benefits of alum treatment is attributed to reduction in recycling from the littoral sediments directly to the epilimnion, as compared with reduction in anaerobic releases to the hypolimnion. As shown in Figure 8, average fluxes for the baseline condition are 204 kg/mo (directly to the epilimnion), 241 kg/mo (thermocline erosion), and 29 kg/mo (diffusion across the thermocline). One question is whether an alum treatment would actually reduce the aerobic recycling rate by the assumed 80%, since the current release rate (1.6 mg/m^2-day) does not seem excessively high.

In interpreting the above simulations, it is important to consider the following factors that reflect model characteristics and limitations:

1. The benefits of alum treatment may be over-stated because the model does not account for co-precipitation of iron and phosphate in aerobic surface waters.

2. The model does not account for the expected reductions in the duration of the anaerobic period following reductions in external load and algal productivity. Therefore, responses to reductions in external load may be more favorable than those indicated. This effect is probably small, since

average P loads to the epilimnion during the growing season are dominated by watershed inputs.

3. Predicted response times are uncertain because they depend upon the assumed depths of the active sediment layer.

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Table 1 Input Data - Eucha Reservoir

Elevation/Capacity Table - December 1999 (OWRB, 2001)

Depth	Elev	Volume	Area
m	m	hm3	km2
0	235.2	93.67	11.37
2	233.2	73.09	9.26
4	231.2	55.45	8.39
6	229.2	40.09	7.00
8	227.2	27.68	5.45
10	225.2	17.82	4.43
12	223.2	10.41	3.03
14	221.2	5.56	1.87
16	219.2	2.51	1.21
18	217.2	0.78	0.56
20	215.2	0.19	0.09
22	213.2	0.05	0.04
24	211.2	0.00	0.01

Source:	SWAT Model --------->		TULSA Water Dept. --->						Monitoring Data (OWRB, 2001)		
	Watershed Inflows		Outflows --->					Thermo.	Volume-Weighted-Means		
	Volume	Load	Releases	W. Sup.**	Elev*	Evap	Rain	Depth*	TP-Epil	TP-Hyp	Chla-Epi
Month	hm3/mo	kg/mo	hm3/mo	hm3/mo	m	m	m	m	ppb	ppb	ppb
01/98	84.9	7036	67.3	0.12	237.2	0.03	0.14	24.8			
02/98	26.0	1034	23.5	0.11	237.1	0.05	0.03	25.0			
03/98	49.6	5454	53.6	0.12	237.2	0.10	0.14	21.0			
04/98	22.4	1243	27.6	0.12	237.2	0.17	0.06	12.0	9	12	9
05/98	38.9	11199	12.7	0.12	237.2	0.18	0.13	5.5	12	12	4
06/98	7.0	1693	10.1	0.13	237.0	0.24	0.06	6.6	19	31	9
07/98	1.1	1311	11.4	0.14	236.4	0.26	0.13	6.3	12	48	7
08/98	0.5	1307	11.2	0.12	235.5	0.24	0.06	7.0	13	65	18
09/98	7.7	4990	4.2	0.13	235.3	0.22	0.17	9.8	22	128	15
10/98	47.3	6571	28.0	0.12	237.2	0.12	0.20	25.0	65	145	15
11/98	23.6	1778	11.9	0.10	237.2	0.06	0.12	25.0	43	43	2
12/98	21.1	1317	10.0	0.13	237.2	0.05	0.06	25.0	60	60	26
01/99	18.2	1958	5.7	0.10	237.2	0.05	0.06	25.0	12	12	21
02/99	36.3	4721	38.3	0.10	237.2	0.09	0.10	25.0	42	42	7
03/99	48.2	5157	46.0	0.11	237.2	0.12	0.12	15.0	22	32	35
04/99	42.5	4006	40.7	0.10	237.3	0.14	0.20	12.4	10	18	7
05/99	78.8	11755	65.3	0.11	237.3	0.17	0.23	5.6	38	56	26
06/99	70.8	17275	47.6	0.11	237.4	0.16	0.22	3.6	19	28	46
07/99	32.6	3462	50.4	0.13	236.7	0.23	0.04	4.5	35	69	29
08/99	3.2	1688	14.2	0.12	236.2	0.27	0.06	6.5	30	109	25
09/99	19.8	16285	9.2	0.12	236.2	0.15	0.15	9.9	21	71	18
10/99	11.3	817	9.1	0.10	235.9	0.14	0.03	25.0	31	147	11
11/99	10.8	794	10.2	0.11	235.6	0.13	0.05	25.0	51	51	7
12/99	38.2	2631	17.3	0.10	235.5	0.08	0.06	25.0	37	37	18
01/00	22.0	1176	4.7	0.10	236.0	0.08	0.03	25.0	29	29	15
02/00	11.2	1439	9.7	0.11	236.3	0.11	0.06	25.0	22	22	11
03/00	13.9	1500	20.5	0.12	236.5	0.13	0.11	19.1	15	15	5
04/00	8.4	2372	12.2	0.10	236.5	0.17	0.05	8.8	7	18	8
05/00	11.6	4930	33.0	0.11	237.2	0.18	0.22	4.0	21	21	7
06/00	60.7	25599	68.7	0.11	237.4	0.24	0.23	3.5	29	38	29
07/00	21.0	3053	16.1	0.13	237.3	0.26	0.14	4.0	43	60	21
08/00	2.6	764	8.2	0.12	236.8	0.24	0.00	5.7	33	86	26
09/00	5.6	2851	12.0	0.12	236.2	0.22	0.07	9.9	34	112	18
10/00	0.5	629	11.5	0.10	235.9	0.12	0.06	25.0	69	120	19
11/00	11.1	1367	7.2	0.11	236.6	0.06	0.13	25.0	58	58	6
12/00	19.3	1105	6.4	0.10	237.2	0.05	0.06	25.0			
01/01	34.1	3956	18.0	0.10	237.3	0.05	0.08	25.0	22	22	22
02/01	78.4	8310	62.2	0.11	237.3	0.09	0.15	25.0	22	22	11
03/01	32.4	721	19.1	0.12	237.2	0.12	0.02	18.0	122	79	
04/01	12.9	550	6.3	0.10	237.1	0.14	0.05	7.0	47	80	
05/01	11.9	4033	7.9	0.11	237.2	0.17	0.12	6.7	15	39	
06/01	6.4	3691	4.7	0.11	237.2	0.16	0.12	5.4	23	50	
07/01	0.8	1488	12.1	0.13	236.5	0.23	0.03	5.8	18	36	
08/01	0.7	2258	16.8	0.12	235.6	0.27	0.09	6.9	22	55	
09/01	1.8	2760	14.2	0.12	234.9	0.15	0.09	9.1	22	96	
10/01	6.2	2698	10.8	0.10	234.9	0.14	0.11	25.0	37	119	
11/01	9.2	2203	9.1	0.11	235.1	0.13	0.07	25.0	24	24	
12/01	31.5	3972	5.6	0.10	236.7	0.08	0.08	25.0			

* Month-end values (others are monthly means)

** Water supply releases for April 2000-Dec 2001 assumed to equal April 1998-Dec 1999 values (data not available).

Table 2 Input Data - Spavinaw Reservoir

Elevation/Capacity Table - August 1999 (OWRB, 2002)

Depth	Elev	Volume	Area
m	m	hm3	km2
0	206.3	32.59	6.38
1	205.3	26.84	5.13
2	204.3	21.92	4.71
3	203.3	17.41	4.30
4	202.3	13.32	3.87
5	201.3	9.77	3.24
6	200.3	6.84	2.62
7	199.3	4.47	2.14
8	198.3	2.67	1.47
9	197.3	1.50	0.89
10	196.3	0.75	0.62
11	195.3	0.28	0.33
12	194.3	0.07	0.11
13	193.3	0.01	0.02
14	192.3	0.00	0.00

Source:	SWAT Model --------->		TULSA Water Dept. -->						Reservoir Monitoring Data (OWRB, 2002)			
	Watershed Inflows			Outflows --------->					Thermo.	Volume-Weighted-Means		
	Volume	Load	Eucha	Releases	W. Sup.**	Elev*	Evap	Rain	Depth*	TP-Epil	TP-Hyp	Chl-a Epil
Month	hm3/mo	kg/mo	hm3/mo	hm3/mo	hm3/mo	m	m	m	m	ppb	ppb	ppb
01/98	3.4	151	67.3	67.2	2.4	207.4	0.03	0.12	13.8			
02/98	0.9	0	23.5	8.3	6.4	207.3	0.05	0.01	13.8			
03/98	1.4	45	53.6	53.3	7.1	207.4	0.10	0.17	13.8			
04/98	0.7	0	27.6	16.2	6.8	207.3	0.17	0.06	9.0	15	17	8
05/98	1.7	72	12.7	11.7	7.3	207.3	0.18	0.11	6.3	15	17	7
06/98	0.3	0	10.1	0.6	7.7	207.3	0.24	0.03	6.9	12	19	21
07/98	0.1	0	11.4	0.1	8.3	207.2	0.25	0.13	7.1	29	74	13
08/98	0.1	0	11.2	0.0	9.1	207.3	0.21	0.06	8.0	21	120	7
09/98	1.1	61	4.2	0.0	7.3	207.3	0.18	0.23	10.7	27	257	15
10/98	4.2	401	28.0	20.5	7.3	207.3	0.11	0.25	13.8	16	62	18
11/98	1.3	28	11.9	7.8	6.8	207.4	0.06	0.09	13.8	31	31	11
12/98	0.9	0	10.0	6.2	7.1	207.3	0.05	0.04	13.8	21	21	15
01/99	0.6	2	5.7	3.0	7.0	207.3	0.05	0.05	13.8	25	25	11
02/99	1.2	38	38.3	39.5	6.4	207.3	0.09	0.06	13.8	46	46	8
03/99	2.5	139	46.0	53.7	6.4	207.4	0.12	0.15	13.2	21	24	17
04/99	3.5	213	40.7	50.3	6.1	207.5	0.14	0.21	7.5	19	19	13
05/99	4.5	266	65.3	74.5	7.1	207.5	0.17	0.21	4.1	16	14	25
06/99	5.8	396	47.6	40.5	6.8	207.9	0.16	0.32	5.8	23	28	22
07/99	1.6	38	50.4	64.0	7.3	207.3	0.23	0.04	4.3	14	16	24
08/99	0.2	0	14.2	0.0	9.6	207.2	0.25	0.05	7.3	15	31	14
09/99	0.6	13	9.2	0.0	7.8	207.2	0.14	0.16	11.1	19	50	17
10/99	0.5	0	9.1	0.0	7.1	207.2	0.13	0.03	13.8	19	34	13
11/99	0.7	22	10.2	0.3	6.8	207.3	0.11	0.05	13.8	20	20	9
12/99	1.7	56	17.3	15.1	7.0	207.3	0.06	0.09	13.8	41	41	10
01/00	0.7	0	4.7	0.6	7.0	207.1	0.07	0.03	13.8	14	14	13
02/00	0.3	2	9.7	0.0	6.6	207.2	0.10	0.06	13.8	17	17	10
03/00	0.5	2	20.5	15.2	7.1	207.4	0.12	0.10	13.0	24	40	12
04/00	0.2	0	0.0	2.6	6.8	207.3	0.17	0.03	7.0	22	27	9
05/00	0.6	25	0.0	25.3	7.3	207.4	0.18	0.21	6.9	15	19	16
06/00	0.6	23	0.0	74.6	7.7	207.6	0.24	0.24	6.8	30	116	26
07/00	0.4	14	0.0	20.5	8.3	207.4	0.25	0.11	6.2	29	140	27
08/00	0.2	0	0.0	2.6	9.1	207.3	0.21	0.00	7.2	29	162	15
09/00	0.1	0	0.0	0.0	7.3	207.3	0.18	0.07	10.2	36	170	13
10/00	0.1	0	0.0	0.0	7.3	207.2	0.11	0.07	13.8	27	25	12
11/00	0.4	10	0.0	0.2	6.8	207.3	0.06	0.14	13.8	32	32	8
12/00	0.7	0	0.0	1.6	7.1	207.4	0.05	0.05	13.8			
01/01	2.3	114	0.0	20.3	7.0	207.5	0.05	0.07	13.8	16	16	5
02/01	3.9	233	0.0	80.9	6.4	207.5	0.09	0.14	13.8	21	21	13
03/01	1.3	0	0.0	18.2	6.4	207.3	0.12	0.02	10.1	49	47	27
04/01	0.7	15	0.0	4.8	6.1	207.3	0.14	0.07	7.0	15	19	
05/01	0.3	0	0.0	0.4	7.1	207.4	0.17	0.09	6.2	13	24	
06/01	0.1	2	0.0	1.7	6.8	207.3	0.16	0.09	5.5	12	16	
07/01	0.1	0	0.0	1.3	7.3	207.3	0.23	0.00	6.1	33	52	
08/01	0.1	0	0.0	0.0	9.6	207.3	0.25	0.07	7.8	26	159	
09/01	0.1	0	0.0	0.0	7.8	207.3	0.14	0.08	11.6	27	202	
10/01	0.1	0	0.0	0.0	7.1	207.2	0.13	0.09	13.8	31	40	
11/01	0.2	6	0.0	0.0	6.8	206.7	0.11	0.12	13.8	17	17	
12/01	0.9	58	0.0	0.0	7.0	206.1	0.06	0.07	13.8			

* Month-end values (others are monthly means)

** Water supply releases for April 2000-Dec 2001 assumed to equal April 1998-Dec 1999 values (data not available).

Table 3 Parameter Estimates & Mass Balances - Eucha Reservoir

Input Variable	Units	Value	Calibration Basis
Atmos P Deposition	kg/km2-yr	30	Assumed (Insensitive), Walker (1982)
Thermocline Diffusion Rate	m/yr	2	Calibrated to Hypolimnetic Temperature Increase
Settling Rate	m/yr	230	Calibrated to Lake Water Column P Measurements
Aerobic Sed P Recycle	cm/yr	0.35	Adjusted to Yield Aerobic Release Rate = 37% of Anaerobic Rate
Anaerobic Sed P Recycle	cm/yr	0.60	Calibrated to Hypolimnetic P Concentrations
Labile Sed. Thickness	cm	5	Assumed (Insensitive), 1-10 cm, Chapra & Reckhow (1983)
Sedimentation Rate	g/m2-yr	55	Calibrated to Sediment Accretion Rate Data
Sediment Bulk Density	g/cm3	0.18	Measured Sediment Core, Flett Research, 2002.
Initial Sediment P	mg/kg	980	Sediment Cores, Aquatic Research Inc, 2002 Range 714 - 1254 mg/kg
Chl-a / Total P Ratio	-	0.65	Calibrated to Lake Chl-a Data, May-September
Chl-a Resid Std Error	%	60%	For Computing Algal Bloom Frequency

Calibration Results	Units	Model	Data	
Epilimnetic TP, May-Sept	ppb	25	24	Lake Monitoring Data, 1998-2001
Hypolimnetic TP, May-Sept	ppb	61	61	Lake Monitoring Data, 1998-2001
Chlorophyll-a, May-Sept	ppb	18	19	Lake Monitoring Data, 1998-2001
Max Chlorophyll-a, May-Sept	ppb	55	46	Lake Monitoring Data, 1998-2001
Freq Chl-a > 20 ppb	%	35%	35%	Lake Monitoring Data, 1998-2001
Sediment TP	mg/kg	1017	714-1254	Sediment Cores, Aquatic Research Inc, 2002; 714 - 1254 mg/kg range for 2 c
Sediment Accretion	cm/yr	2.1	1.1	Measured Sediment Accretion Rate , 1954-1999 (OWRB, 2002, p 18)
Aerobic Sed P Release	mg/m2-d	1.9	1.9	Assumed 37% of Anaerobic Rate (Moore, 2002)
Anaerobic Sed P Release	mg/m2-d	5.2		Calibrated to Hypolimnetic P Concentrations
Outflow Volume	hm3/yr	299	248	Tulsa Water Dept, April 1998 - March 2001
Outflow Load	kg/yr	8789	8272	Observed Flow x Observed Epilimnetic Conc

Predicted Conditions May-Sept 2000-2001

Variable	Units	Epil	Hypo	Total
Area	km2	10.8	6.5	10.8
Volume	hm3	49.6	39.0	88.6
Mean Depth	m	4.6	6.0	8.2
Outflow	hm3/yr	165.1		165.1
HRT	years	0.30		0.54
Water Load	m/yr	15.2		15.2
Sediment P Flux	mg/m2-d	1.9	5.2	
Sediment P Content	mg/kg	1017		
Total P	ppb	25	61	38
Mean Chl-a	ppb	18		
Max Chl-a	ppb	55		
Frequency Chl-a > 20 ppb	%	35%		

Mass Balance for the Period April 1998 - March 2001

Epilimnion	Flow hm3/yr	Load kg/yr	Conc ppb
Upstream Reservoir	0.0	0	0
Watershed	304.4	53911	177
Rainfall	13.5	323	24
Thermocline Diffusion		515	
Thermocline Erosion	66.2	5985	90
Sediment Release		5260	
Total Input	384.2	65995	172
Evaporation	19.3		
Settling to Littoral Zone		34406	
Settling to Hypolimnion		21479	
Thermocline Setup	66.5	1627	24
Outflow	298.6	8789	29
Total Outputs	384.4	66301	172
Storage Increase	-0.2	-306	
Mass Balance Check	0.0	0	

Hypolimnion	Flow hm3/yr	Load kg/yr	Conc ppb
Sediment Release		4874	
Settling from Epil		21479	
Thermocline Setup	66.5	1627	24
Total Inputs		27981	
Thermocline Diffusion		515	
Thermocline Erosion	66.2	5985	90
Sedimentation		21479	
Total Outputs		27979	
Storage Increase		1	
Mass Balance Check	0.0	0	

Sediment	Flow hm3/yr	Load kg/yr	Conc ppb
Settling from Epilimnion		34406	
Settling from Hypolimnion		21479	
Total Inputs		55885	
Release to Epilimnion		5260	
Release to Hypolimnion		4874	
Burial		43532	
Total Outputs		53666	
Storage Increase		2218	
Mass Balance Check		0	

Entire System	Flow hm3/yr	Load kg/yr	Conc ppb
External Inputs	304.4	53911	177
Rainfall	13.5	323	24
Total Inputs	317.9	54234	171
Evaporation	19.3	0	0
Outflow	298.6	8789	29
Burial		43532	
Storage Increase	-0.2	1913	
Mass Balance Check	0.0	0	
Outflow to Spavinaw	297.3	8759	29
Outflow to Water Supply	1.4	31	23

Table 4 Parameter Estimates & Mass Balances - Spavinaw Reservoir

Input Variable	Units	Value	Calibration Basis
Atmos P Deposition	kg/km2-yr	30	Assumed (Insensitive), Walker (1982)
Thermocline Diffusion Rate	m/yr	2	Calibrated to Hypolimnetic Temperature Increase
Settling Rate	m/yr	45	Calibrated to Epilimnetic Water Column P Measurements, 2000-2001
Aerobic Sed P Recycle	cm/yr	0.18	Adjusted to Yield Aerobic Release Rate = 37% of Anaerobic Rate
Anaerobic Sed P Recycle	cm/yr	0.30	Calibrated to Hypolimnetic P Concentrations
Sediment Thickness	cm	5	Assumed (Insensitive), 1-10 cm, Chapra & Reckhow (1983)
Sedimentation Rate	g/m2-yr	12	Calibrated to Sediment TP Data
Sediment Bulk Density	g/cm3	0.39	Measured Sediment Core, Flett Research, 2002.
Initial Sediment P	mg/kg	820	Sediment Cores, Aquatic Research Inc, 2002 Range 714 - 1254 mg/kg
Chl-a / Total P Ratio	-	0.8	Calibrated to Lake Chl-a Data, May-September
Chl-a Resid Std Error	%	50%	For Computing Algal Bloom Frequency

Calibration Results	Units	Model	Data	
Epilimnetic TP, May-Sept	ppb	22	22	Lake Monitoring Data, Stations SPA01 & SPA02, 1998-2001
Hypolimnetic TP, May-Sept	ppb	106	84	Lake Monitoring Data, Stations SPA01 & SPA02, 1998-2001
Chlorophyll-a, May-Sept	ppb	17	18	Lake Monitoring Data, Stations SPA01 & SPA02, 1998-2001
Max Chlorophyll-a, May-Sept	ppb	26	27	Lake Monitoring Data, Stations SPA01 & SPA02, 1998-2001
Freq Chl-a > 20 ppb	%	38%	35%	Lake Monitoring Data, Stations SPA01 & SPA02, 1998-2001
Sediment TP	mg/kg	852	820	Sediment Cores, Aquatic Research Inc, 2002 Range 800-840 mg/kg
Sediment Accretion	cm/yr	0.10	<1.2	Accretion Rate , 1935-1999 (OWRB, 2002, p 18)
Aerobic Sed P Release	mg/m2-d	1.6	1.6	Assumed 37% of Anaerobic Rate, based upon Eucha Core Study
Anaerobic Sed P Release	mg/m2-d	4.4		Calibrated to Hypolimnetic P Concentrations
Outflow Volume	hm3/yr	275	277	Tulsa Water Dept, April 1998 - March 2001
Outflow Load	kg/yr	6674	7194	Observed Flow x Observed Epilimnetic Conc

Predicted Conditions May-September, 1998-2001

Variable	Units	Epil	Hypo	Total
Area	km2	6.4	2.1	6.4
Volume	hm3	27.6	5.5	33.1
Mean Depth	m	4.3	2.7	5.2
Outflow	hm3/yr	229.8		229.8
HRT	years	0.12		0.14
Water Load	m/yr	36.1		36.1
Sediment P Flux	mg/m2-d	1.6	4.4	
Sediment P Content	mg/kg	852		
Total P	ppb	22	106	33
Mean Chl-a	ppb	17		
Max Chl-a	ppb	26		
Frequency Chl-a > 20 ppb	%	38%		

Mass Balance for the Period April 1998 - March 2001

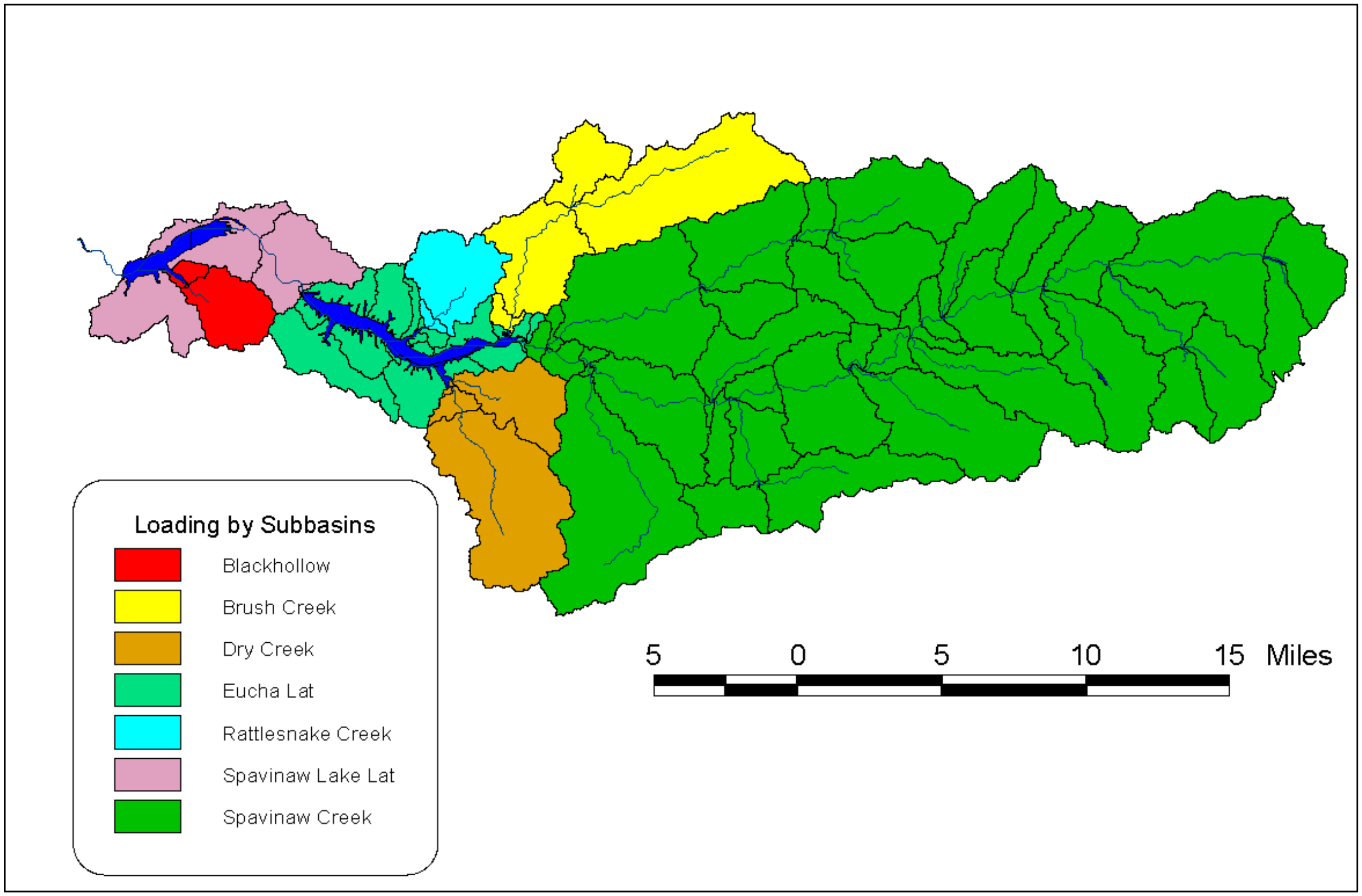
Epilimnion	Flow hm3/yr	Load kg/yr	Conc ppb
Upstream Reservoir	262	8533	33
Watershed	15	722	47
Rainfall	8	191	24
Thermocline Diffusion		140	
Thermocline Erosion	12	1410	114
Sediment Release		3130	
Total Input	298	14126	47
Evaporation	11		
Settling to Littoral Zone		5752	
Settling to Hypolimnion		1016	
Thermocline Setup	13	203	16
Outflow	275	6674	24
Total Outputs	298	13645	46
Storage Increase	0	481	
Mass Balance Check	0	0	

Hypolimnion	Flow hm3/yr	Load kg/yr	Conc ppb
Sediment Release		1354	
Settling from Epil		1016	
Thermocline Setup	13	203	16
Total Inputs		2573	
Thermocline Diffusion		140	
Thermocline Erosion	12	1410	114
Sedimentation		1016	
Total Outputs		2566	
Storage Increase		7	
Mass Balance Check	0	0	

Sediment	Flow hm3/yr	Load kg/yr	Conc ppb
Settling from Epilimnion		5752	
Settling from Hypolimnion		1016	
Total Inputs		6768	
Release to Epilimnion		3130	
Release to Hypolimnion		1354	
Burial		2096	
Total Outputs		6581	
Storage Increase		187	
Mass Balance Check		0	

Entire System	Flow hm3/yr	Load kg/yr	Conc ppb
Eucha Outflow	262	8533	33
Local Watershed	15	722	47
Total External Inputs	277	9255	33
Rainfall	8	191	24
Total Inputs	285	9446	33
Evaporation	11		
Outflow	275	6674	24
Burial		2096	
Storage Increase	0	675	
Mass Balance Check	0	0	

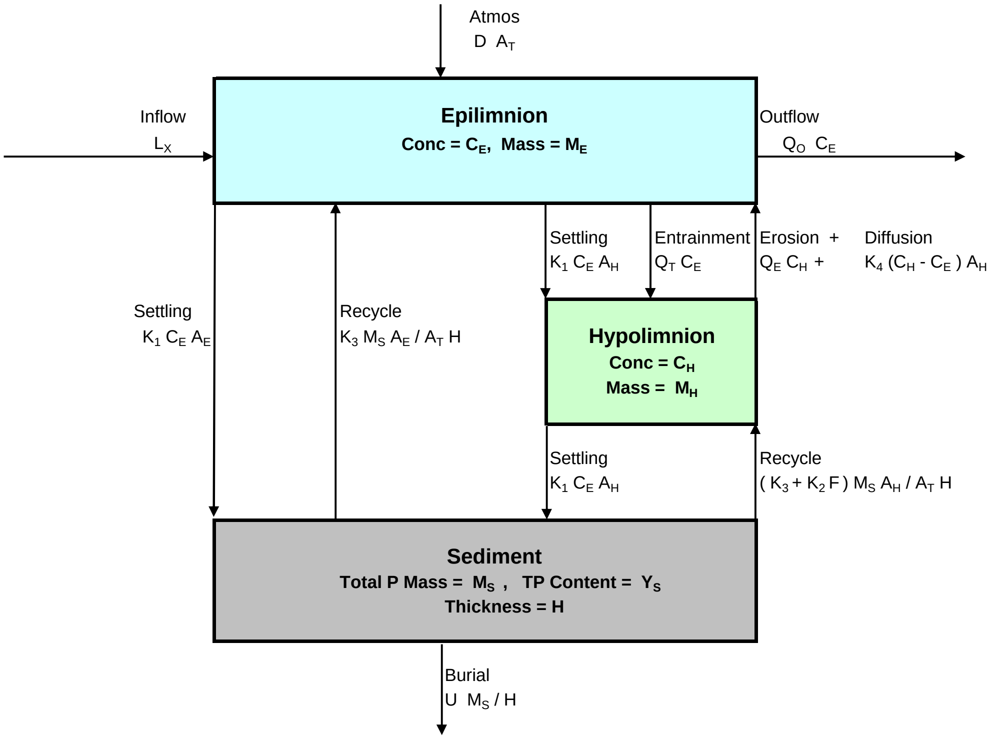
Figure 1 **Basin Map & Average Phosphorus Loads**



Average Total Phosphorus Loads (kg/yr) Reported by Storm et al (2002)
Period of Record: April 1998 - March 2002

Eucha Watershed Non Point	36407
Eucha Watershed Point Source	11348
Spavina Watershed Non Point	566
Total Basin	48320

Figure 2 Phosphorus Balance Model Structure & Equations



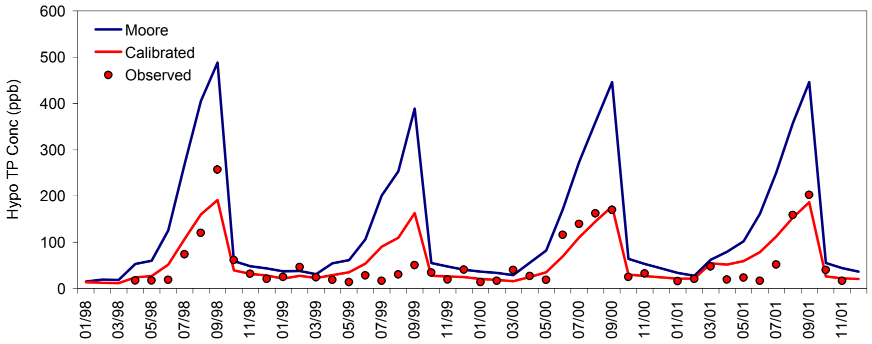
Symbol	Variable	Units	Computation
M_E	Epilimnetic P Mass	kg	State Variable - Computed from Mass Balance
M_H	Hypolimnetic P Mass	kg	State Variable - Computed from Mass Balance
M_S	Sediment Total P Mass	kg	State Variable - Computed from Mass Balance
A_T	Reservoir Surface Area	km^2	Computed from Water Surface Elevation
A_E	Sediment Area Exposed to Epilimnion	km^2	$A_E = A_T - A_H$
A_H	Sediment Area Exposed to Hypolimnion	km^2	Computed from Thermocline Elevation
V_E	Epilimnetic Volume	hm^3	Computed from Thermocline Elevation
V_H	Hypolimnetic Volume	hm^3	Computed from Thermocline Elevation
A(E)	Area vs Elevation Curve (Morphometry)	km^2	Input Constant Table
V(E)	Volume vs. Elevation Curve (Morphometry)	hm^3	Input Constant Table
C_E	Epilimnetic P Concentration	ppb	$C_E = M_E / V_E$
C_H	Hypolimnetic P Concentration	ppb	$C_H = M_H / V_H$
Q_O	Lake Outflow	hm^3/yr	External Inflow + Rainfall - Evap. - Volume Increase
Q_T	Thermocline Entrainment Flow (Epi -> Hyp)	hm^3/yr	Maximum (0, Increase in Hypol. Volume)
Q_E	Thermocline Erosion Flow (Hyp -> Epi).	hm^3/yr	Maximum (0, Decrease in Hypol. Volume)
D	Atmospheric Deposition Rate	kg/km^2-yr	Input Constant
K_1	Settling Rate	m/yr	Calibrated to Epilimnetic P Conc
K_2	(Anaerobic - Aerobic) Sed P Release Coef	cm/yr	Calibrated to Anerobic Sed P Release Meas.
K_3	Aerobic Sed P Release Coefficient	cm/yr	Calibrated to Aerobic Sed P Release Meas.
K_4	Thermocline Diffusive Transport Coefficient	m/yr	Constant, Estimated from Temperature Profiles
K_5	Sediment Mass Accretion Parmameter	-	Constant, Calibrated to Sediment Accretion Meas.
F	Dummy Variable for Anaerobic Conditions	-	= 1 in May - October, = 0 in November - April
Y_S	Sediment P Content	mg/kg	$Y_S = 10^{-7}\ M_S\ /\ H\ B\ A_T$
H	Thickness of Active Sediment Layer	cm	Assumed = 5 cm (Insensitive)
B	Sediment Bulk Density	g/cm3	Sediment Core Measurements
U	Sediment Accretion Rate	cm/yr	$U = 10^{-4}\ K_5\ G^{0.5}\ /\ B$
G	Gross P Sedimentation Rate	kg/km^2-yr	$G = K_1\ C_E\ (A_E + A_H)$
RAIN	Rainfall on Reservoir Surface	m	Input Monthly Time Series
EVAP	Evaporation from Reservoir Surface	m	Input Monthly Time Series
E_S	Reservoir Surface Elevation	m	Input Monthly Time Series
Q_X	External Inflow Volume	hm^3/yr	Input Monthly Time Series
L_X	External Inflow Load	kg/yr	Input Monthly Time Series
Z_T	Thermocline Depth	m	Input Monthly Time Series
E_T	Thermocline Elevation	m	$E_T = E_S - Z_T$

Phosphorus Mass Balance Equations:

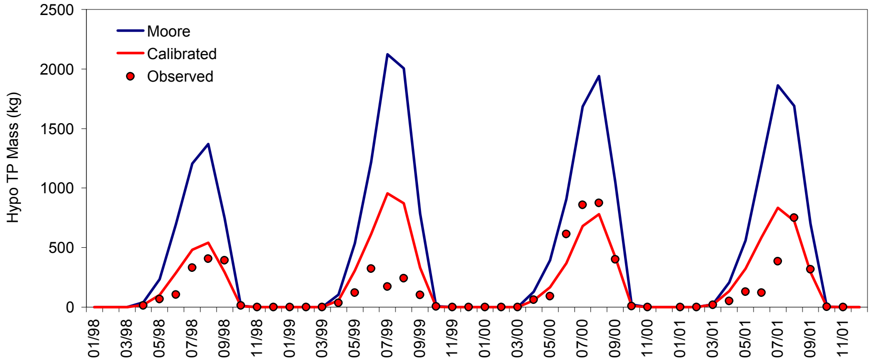
Epi Mass Change = External + Atmos + Recycle + Erosion + Diffusion - Settling - Outflow - Entrainment
Hyp Mass Change = Entrainment + Recycle - Erosion - Diffusion
Sed Mass Change = Total Settling - Total Recycle - Burial

Figure 3 **Hypolimnetic P Levels Predicted Using Two Estimates of Sediment P Release**

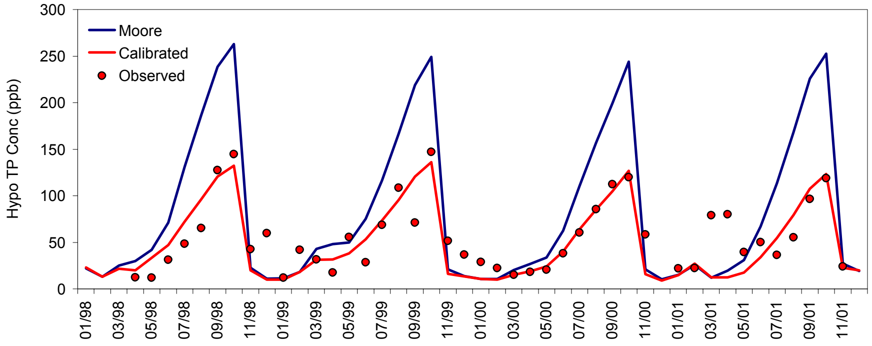
Spavinaw



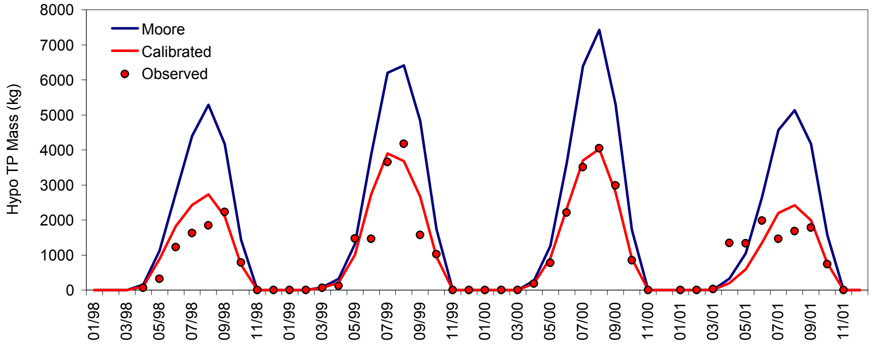
Spavinaw



Eucha



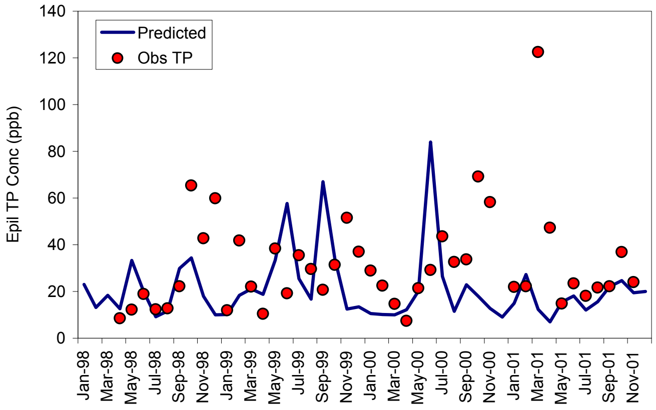
Eucha

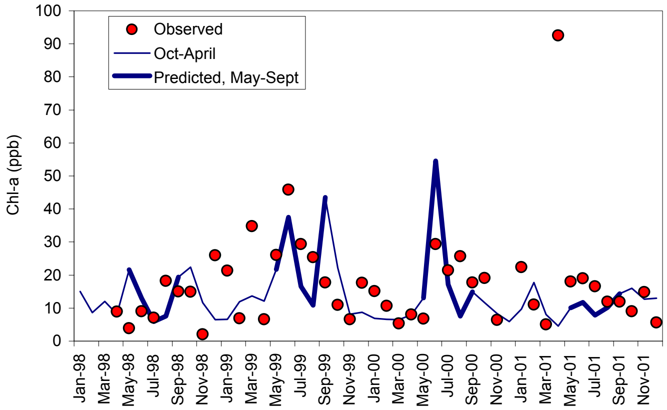


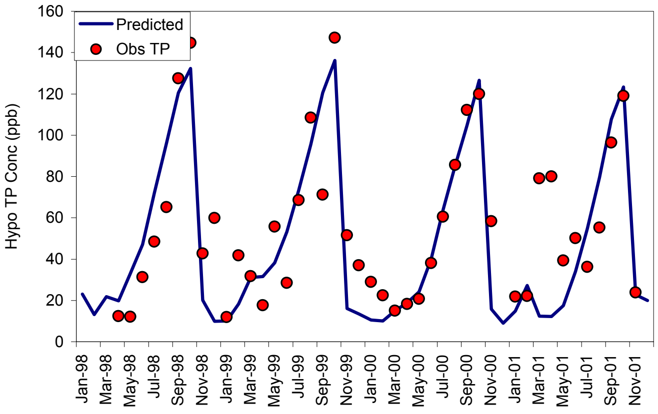
Instantaneous Sediment P Release Rate (mg/m2-day)

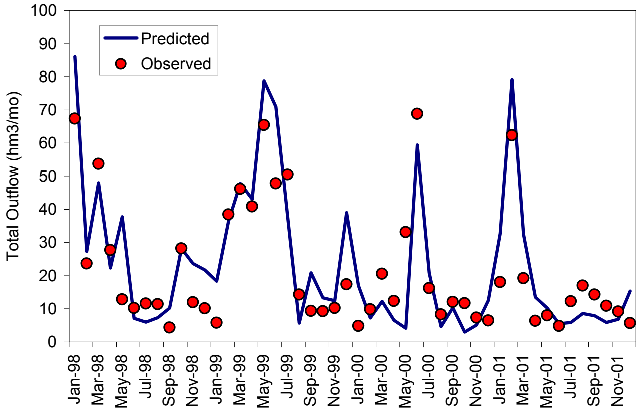
	Aerobic	Anaerobic	
From Core	1.6	5.2	recomputed from core data (eucha flux data.ppt), accounting for sample volumes, assuming diam. = 6.3 cm
Moore (2002)	4.2	11.2	inferred from moore's annualized estimates (7 & 18.8 kg/ha-yr over 50% of year)
Calibrated to Eucha	1.9	5.2	calibrated to observed hypolimnetic P time series, eucha reservoir
Calibrated to Spavinaw	1.6	4.4	calibrated to observed hypolimnetic P time series, spavinaw reservoir

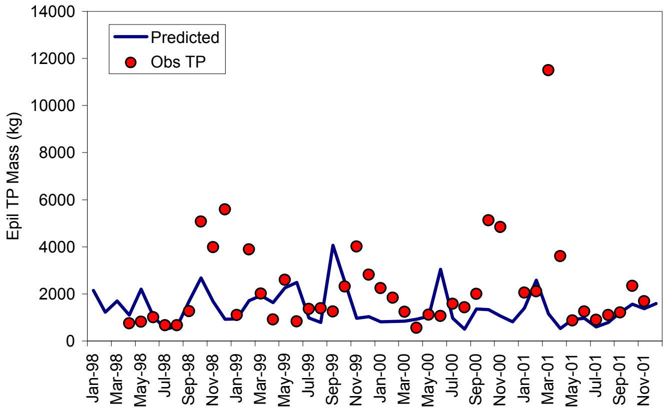
Figure 4 Calibration Charts - Eucha Reservoir

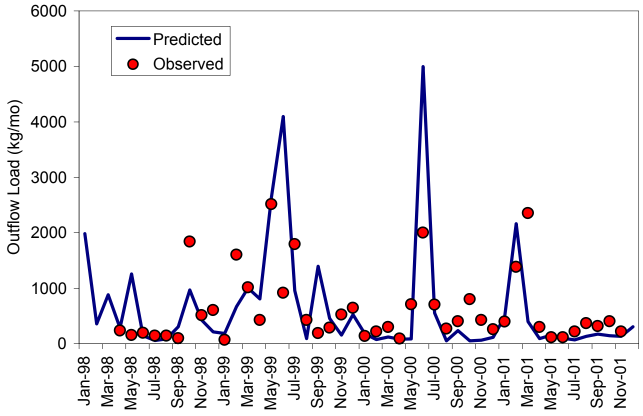


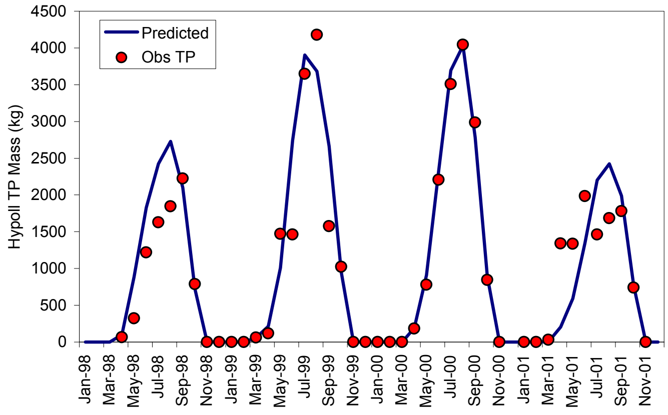












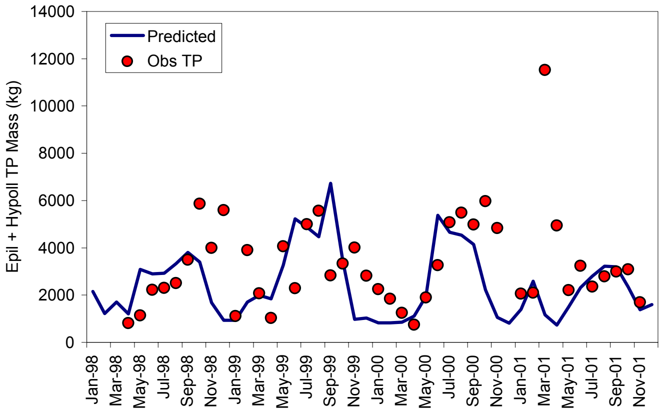


Figure 5 Calibration Charts - Spavinaw Reservoir Using Observed Eucha Outflows

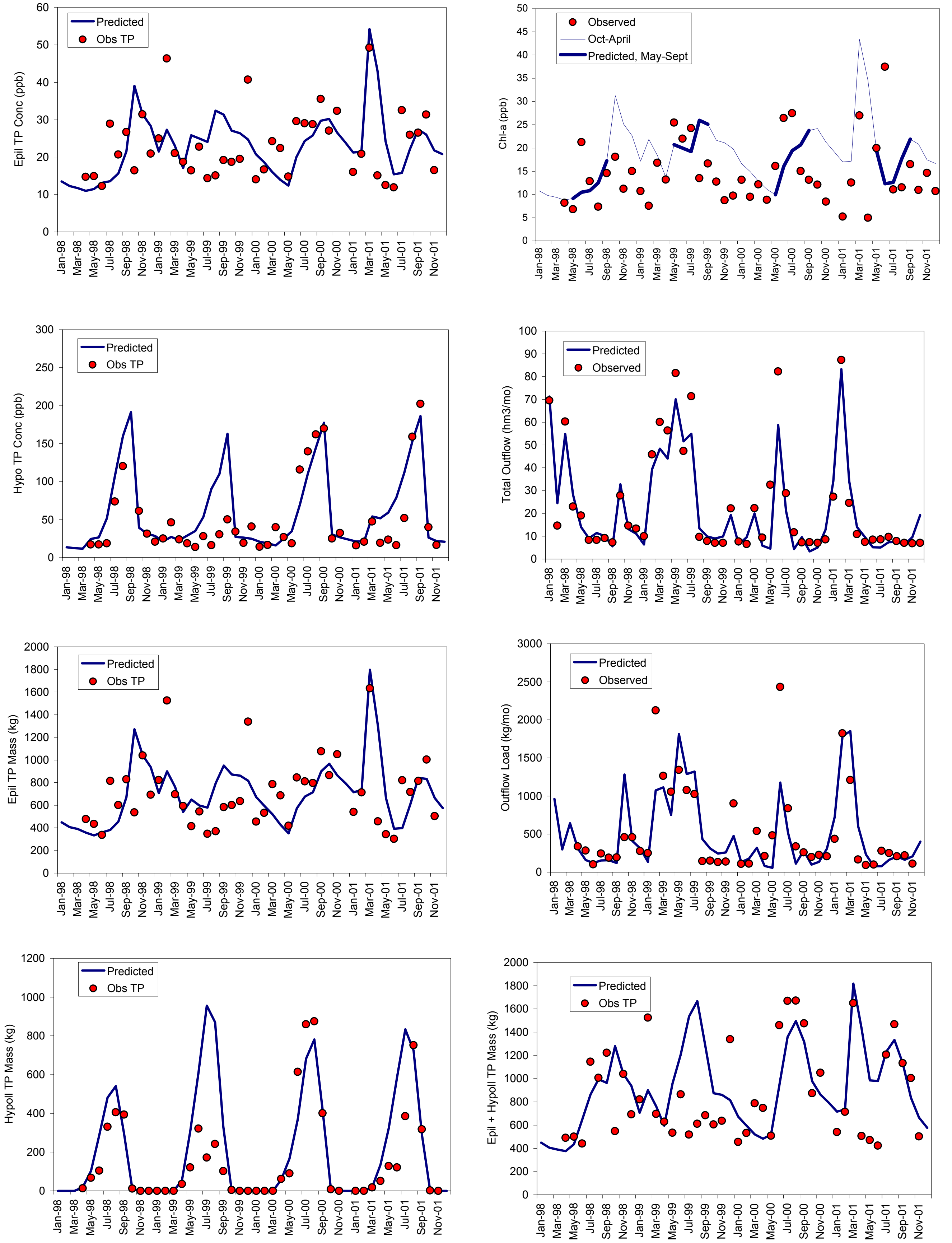


Figure 6 Calibration Charts - Spavinaw Reservoir Using Predicted Eucha Outflows

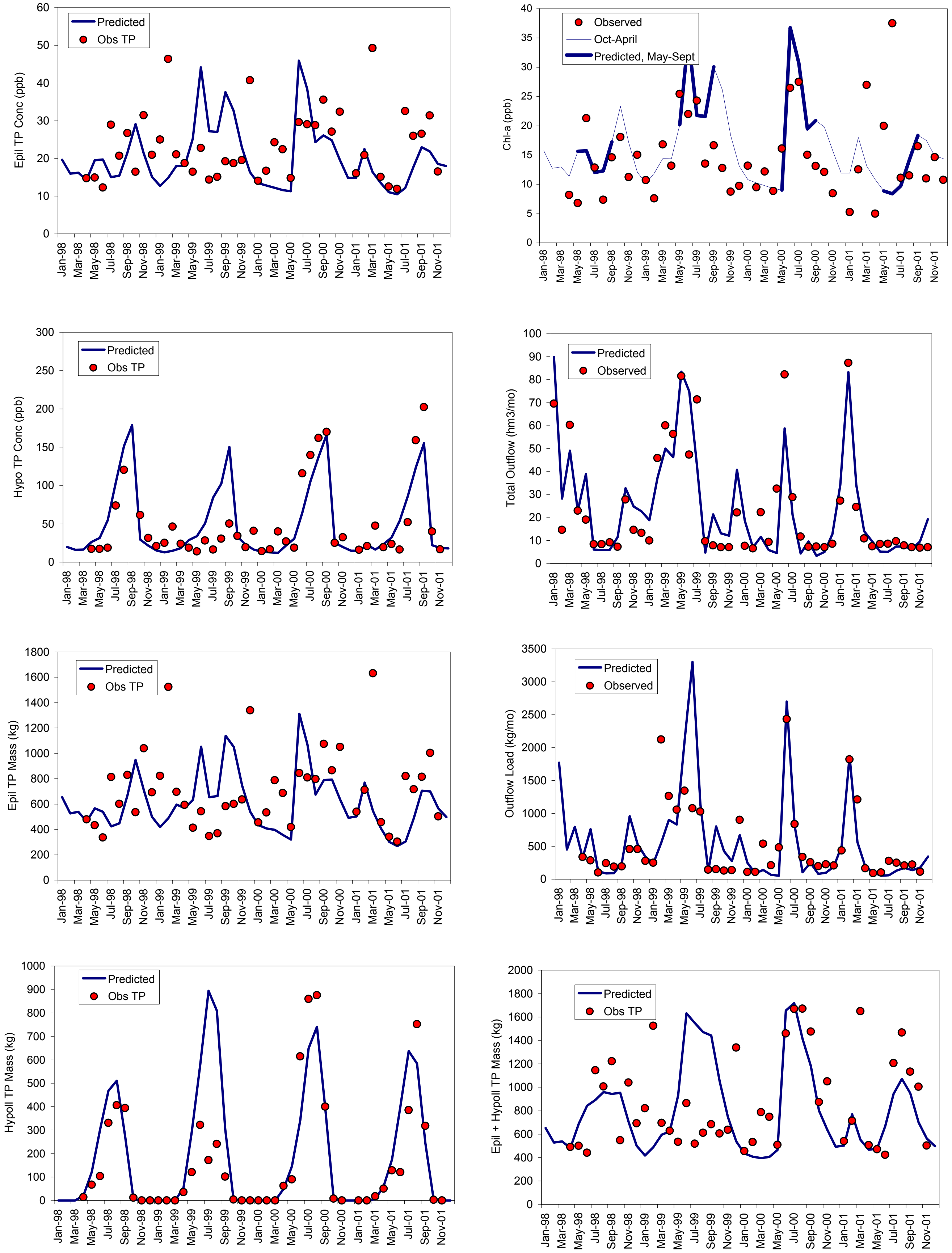
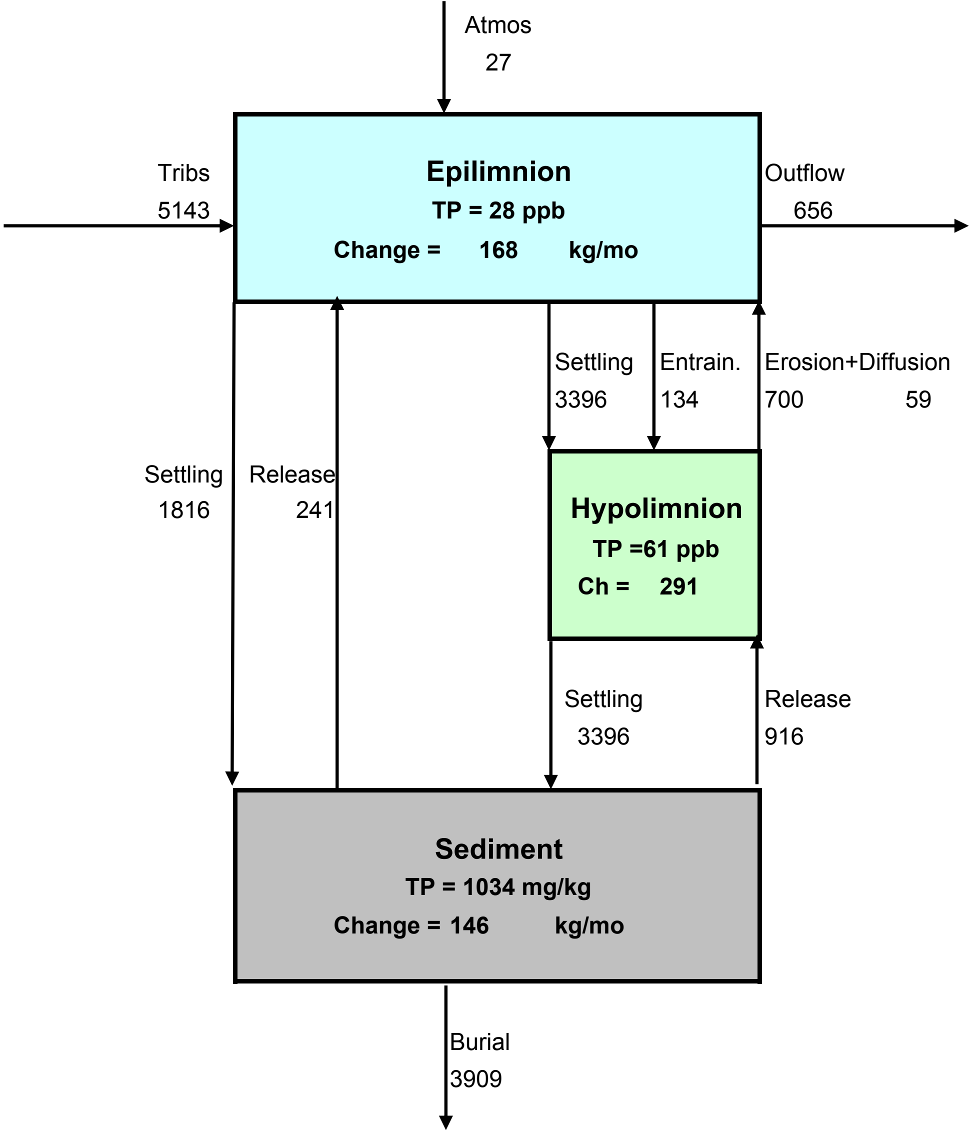


Figure 7 Phosphorus Fluxes - Eucha Reservoir

May-September, 1998-2001

Mean Phosphorus Fluxes (kg/mo)



Epil Mean Total P	28	ppb
Hypo Mean Total P	61	ppb
Mean Chlorophyll-a	18	ppb
Max Chlorophyll-a	55	ppb
Yearly Inflow Load	4493	kg/yr
Sed P Content	1034	mg/kg

Epil P Storage	1139	kg
Hypol P Storage	2230	kg
Total WC Storage	3369	kg
Sedim P Storage	105799	kg
Total P Storage	109169	kg

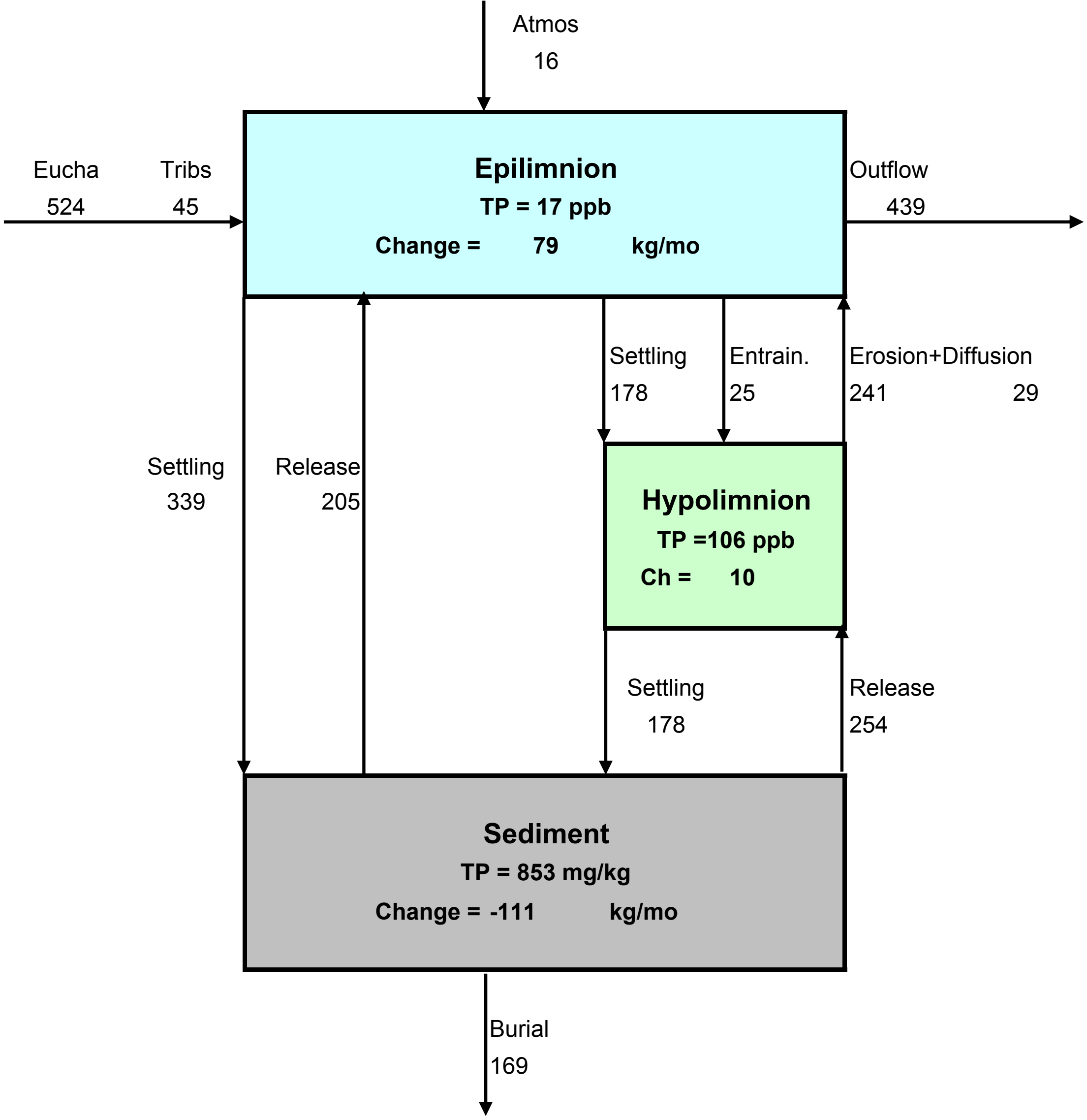
Mass Balance Check

Term	Epil	Hypo	Sedim	WC	Overall
Inputs	6169	4445	5212	6327	5170
Outputs	6001	4154	5066	5867	4565
Storage	168	291	146	459	605
Net	0	0	0	0	0

Figure 8 Phosphorus Fluxes - Spavinaw Reservoir

May-September, 1998-2001

Mean Phosphorus Fluxes (kg/mo)



Epil Mean Total P	22	ppb	Epil P Storage	594	kg
Hypo Mean Total P	106	ppb	Hypol P Storage	498	kg
Mean Chlorophyll-a	17	ppb	Total WC Storage	1092	kg
Max Chlorophyll-a	26	ppb	Sedim P Storage	106053	kg
Yearly Inflow Load	771	kg/yr	Total P Storage	107146	kg
Sed P Content	853	mg/kg			

Mass Balance Check

Term	Epil	Hypo	Sedim	WC	Overall
Inputs	1060	457	517	1045	586
Outputs	981	448	628	956	608
Storage	79	10	-111	89	-22
Net	0	0	0	0	0

Figure 9 **Simulated Historical Time Series - Eucha Reservoir**

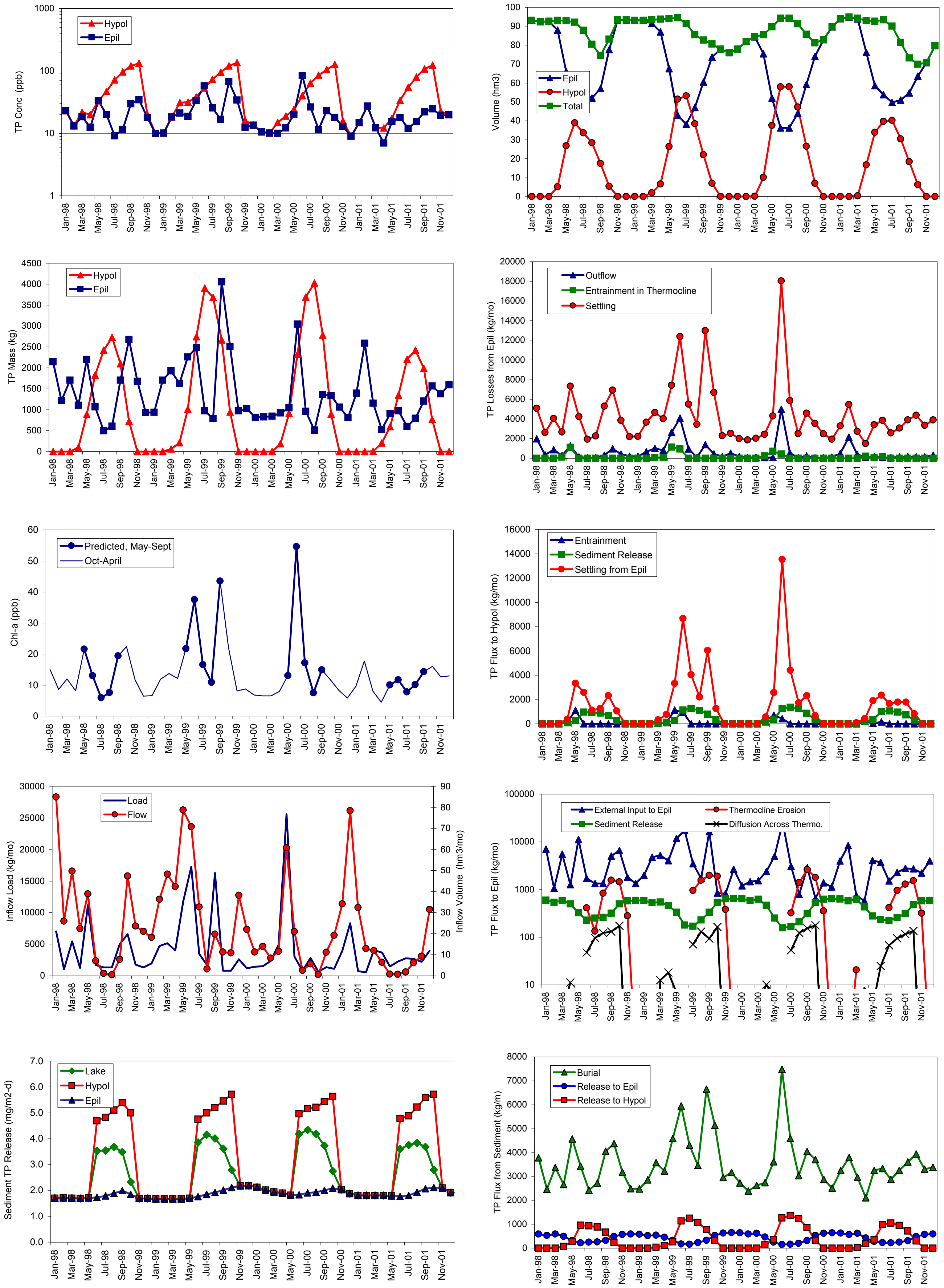


Figure 10 Simulated Historical Time Series - Spavinaw Reservoir

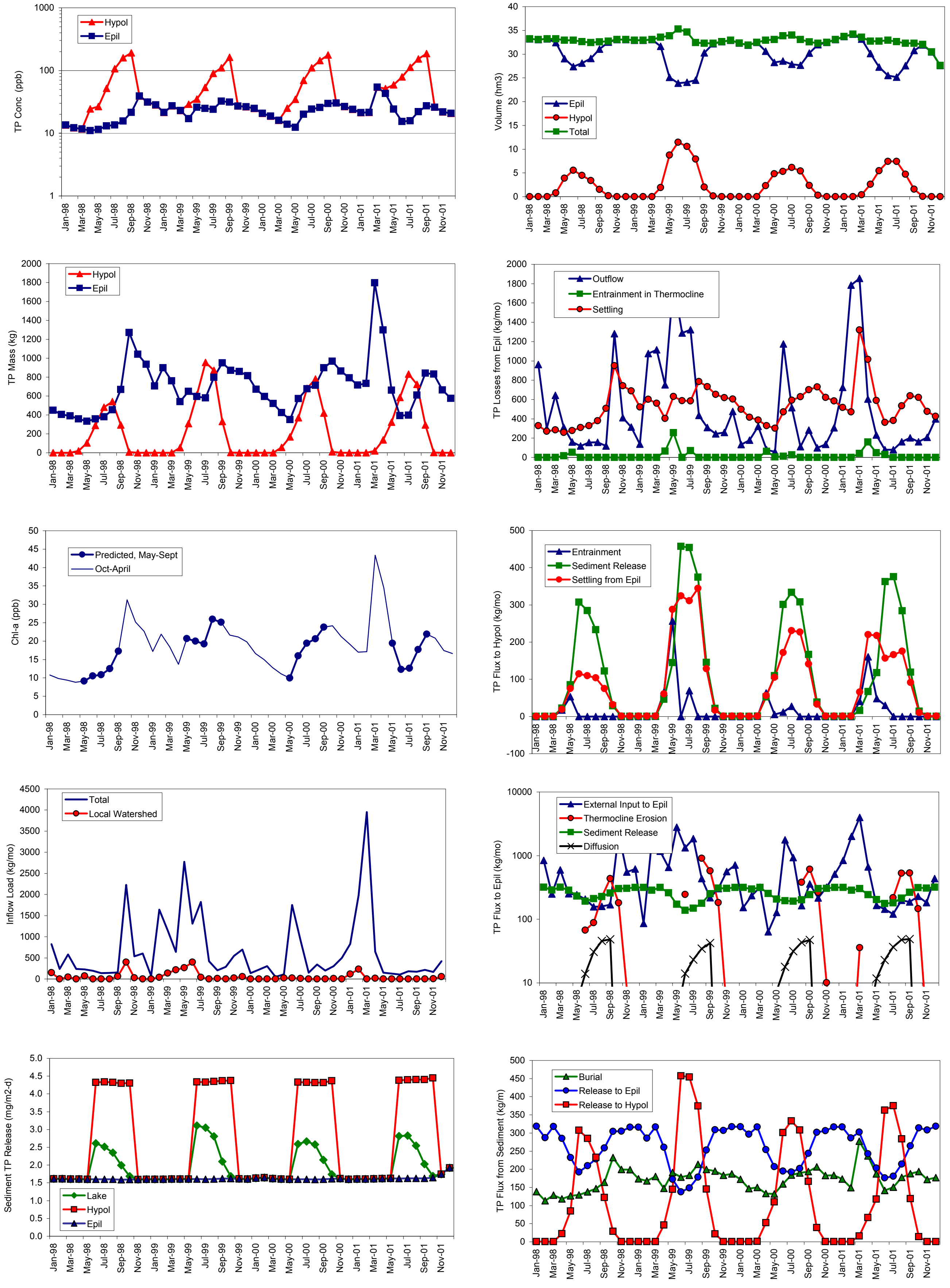


Figure 11 **Monthly Total P Inputs to Eucha Reservoir Epilimnion**

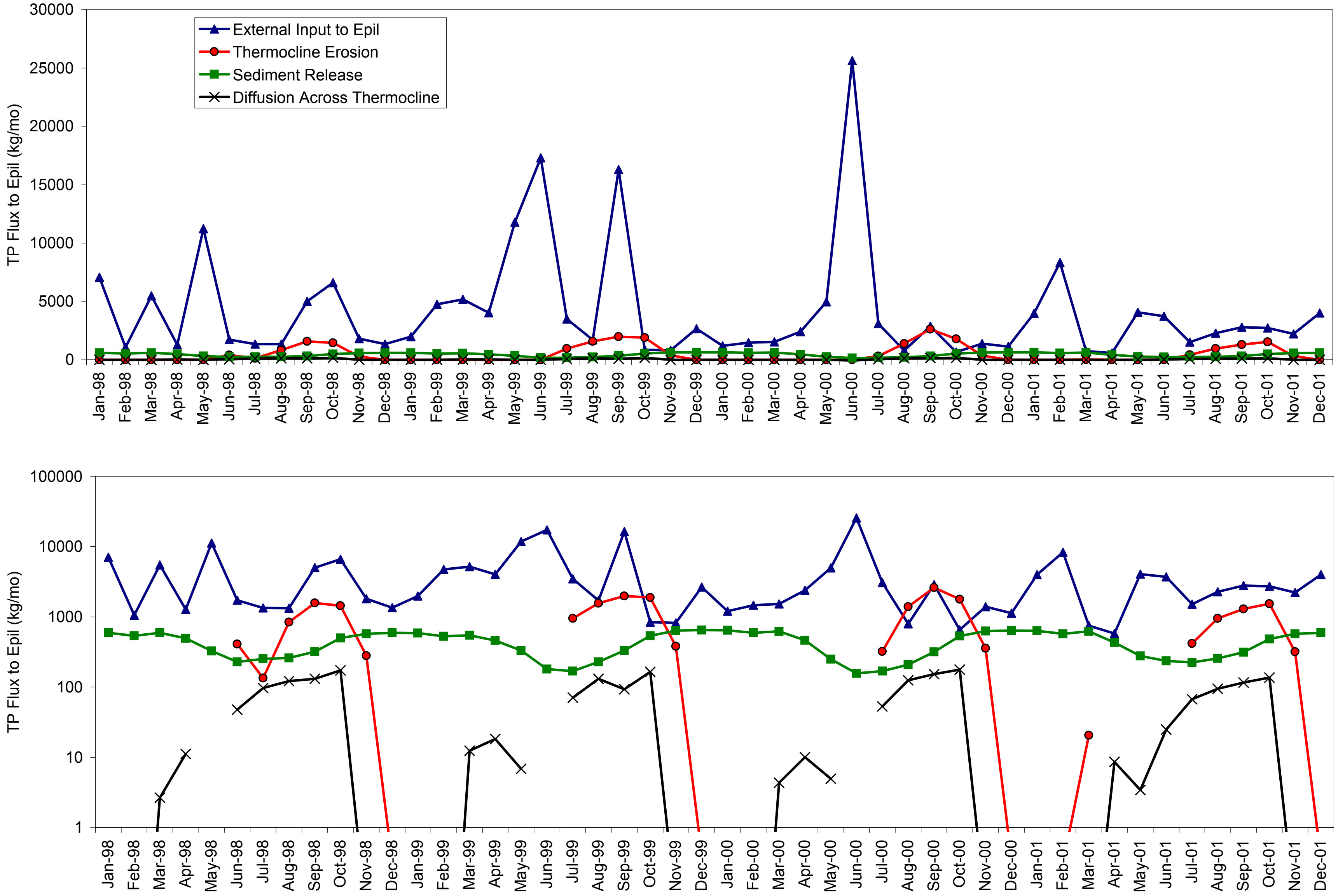


Figure 12 **Monthly Total P Inputs to Spavinaw Reservoir Epilimnion**

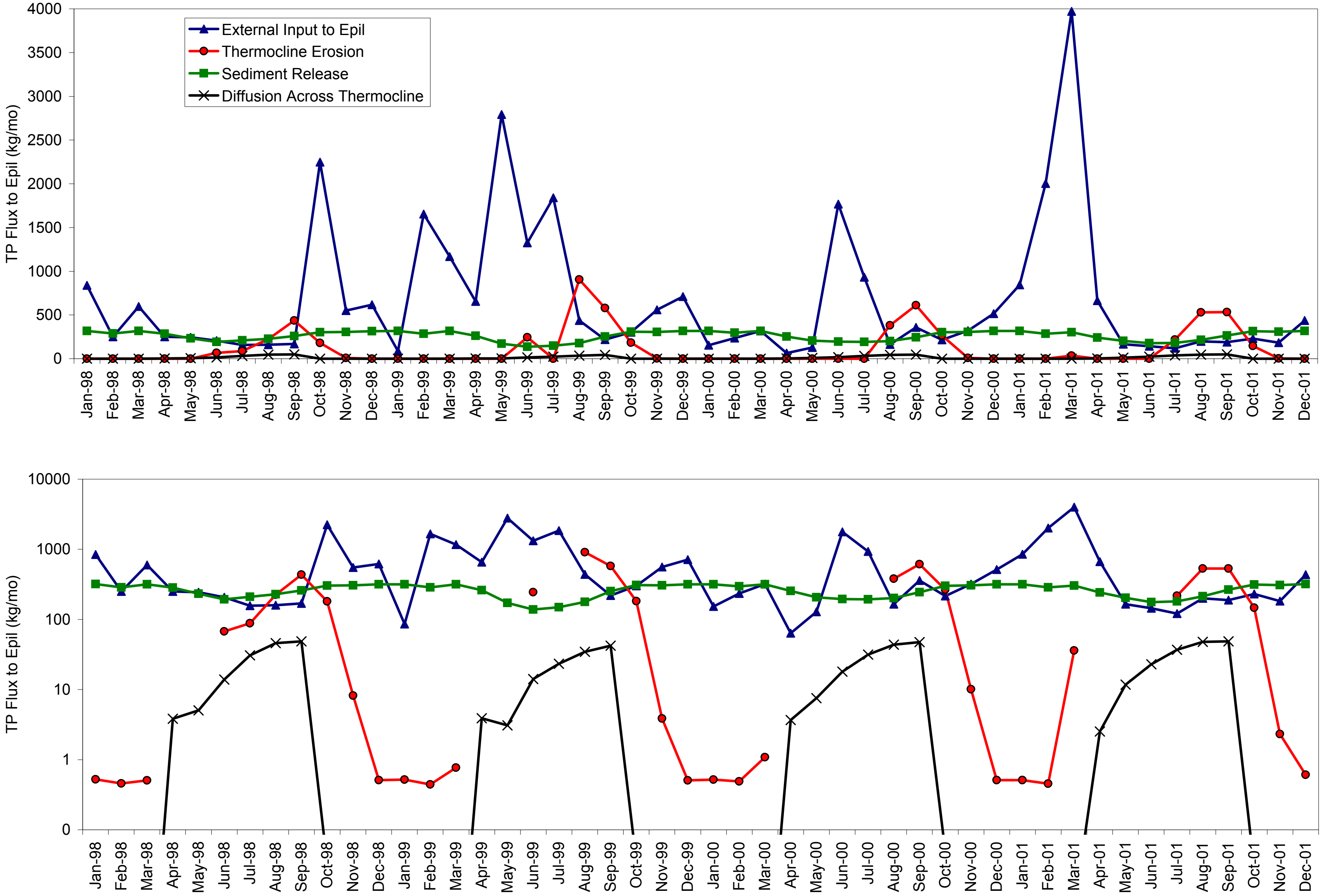
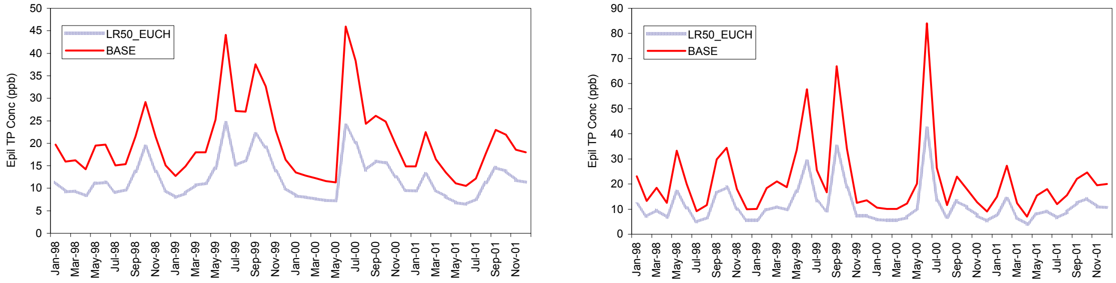


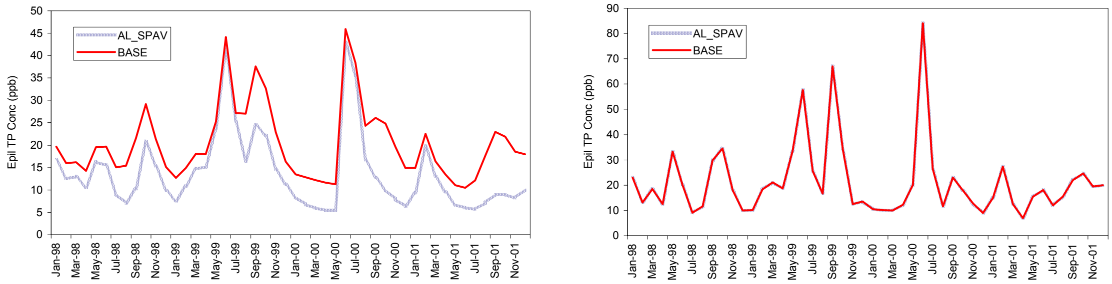
Figure 13 Epilimnetic Phosphorus Time Series for Various Management Scenarios

SPAVINAW Reservoir **EUCHA Reservoir**

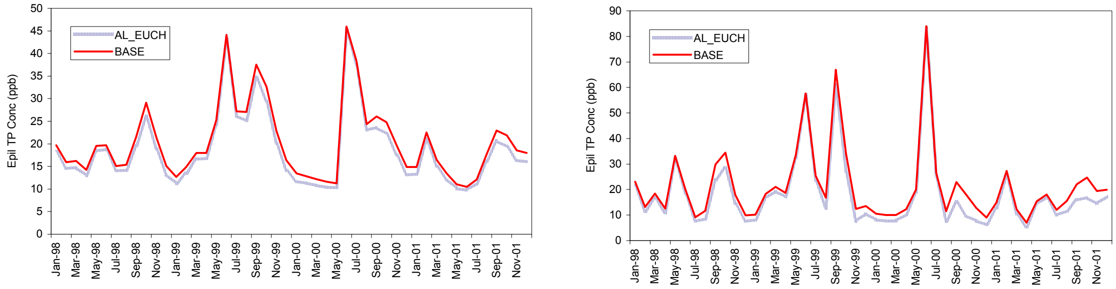
Scenario: 50% Reduction in External Load to Eucha Reservoir



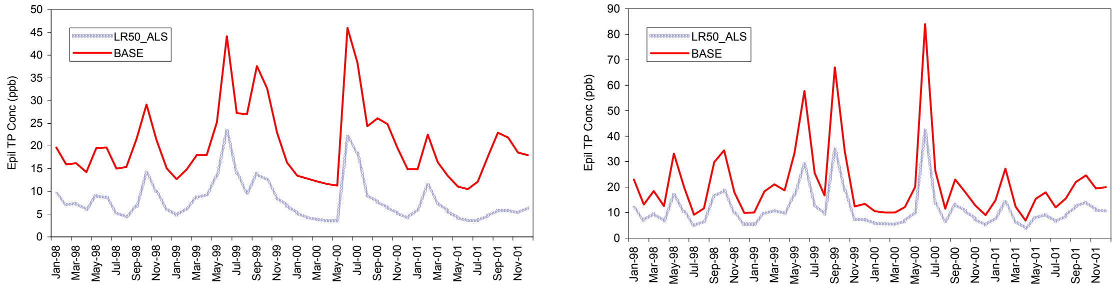
Scenario: Spavinaw Alum Treatment



Scenario: Eucha Alum Treatment



Scenario: 50% Reduc. in Eucha Load + Spavinaw Alum Treatment



Scenario: 50% Reduc. in Eucha Load + Eucha Alum Treatment + Spavinaw Alum Treatment

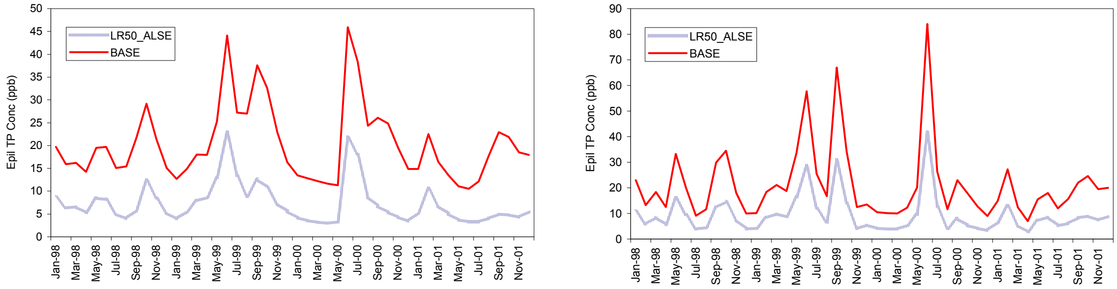
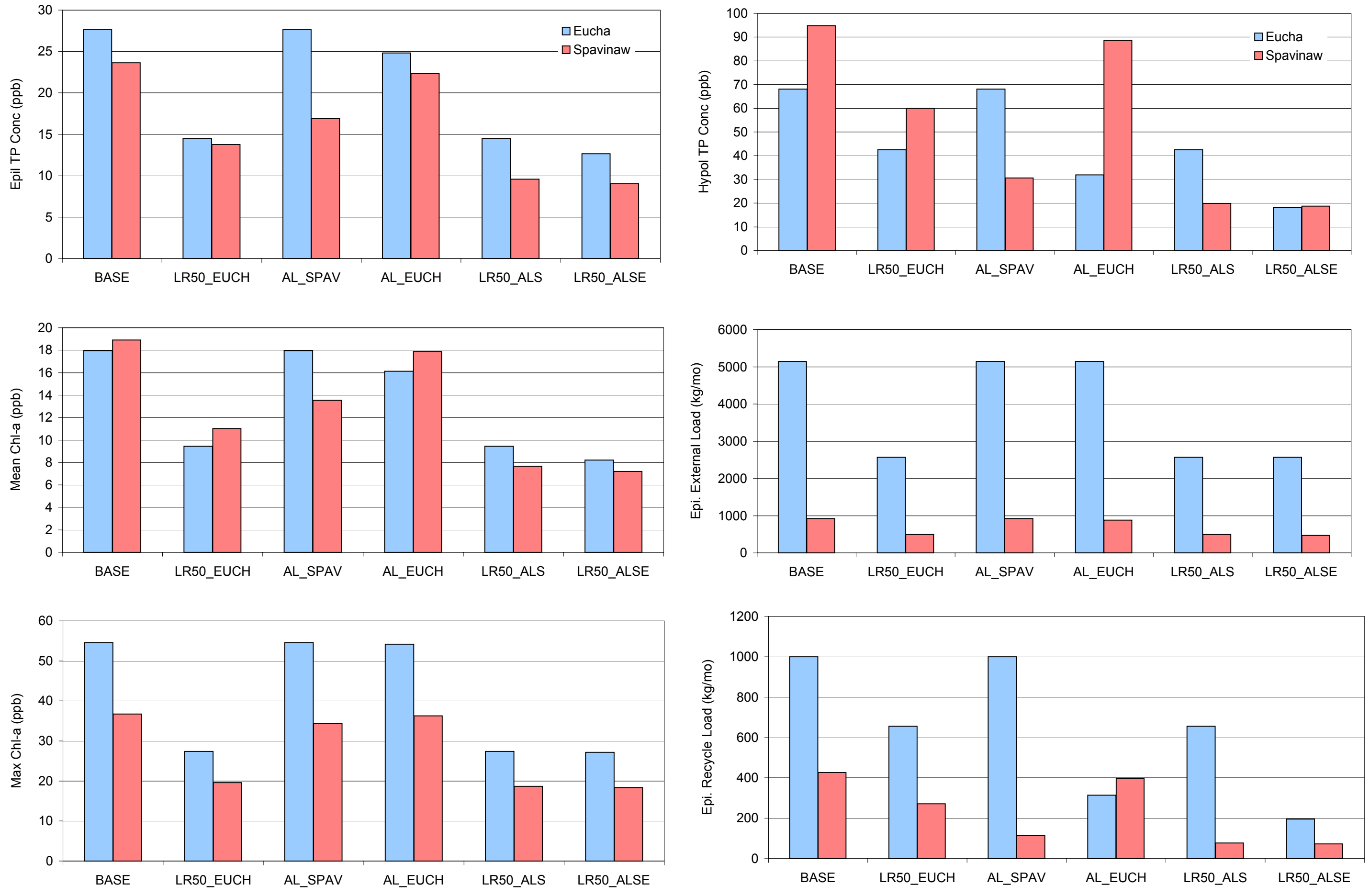
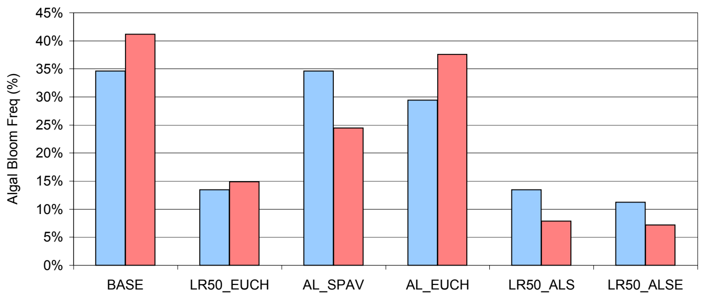


Figure 14 May-September Average Responses to Management Scenarios





Scenario	Description
Base	Current Conditions (1998 - 2001 Hydrology)
LR50_EUCH	50% Reduction in External Load to Eucha Reservoir
AL_SPAV	Spavinaw Whole-Lake Alum Treatment
AL_EUCH	Eucha Whole-Lake Alum Treatment
LR50_ALS	50% Reduction in Eucha External Load + Spavinaw Alum Treatment
LR50_ALSE	50% Reduction in Eucha External Load + Spavinaw & Eucha Alum Treatments

Figure 15 **Monthly Total P Inputs to Spavinaw Reservoir Epilimnion - With Alum Treatment**

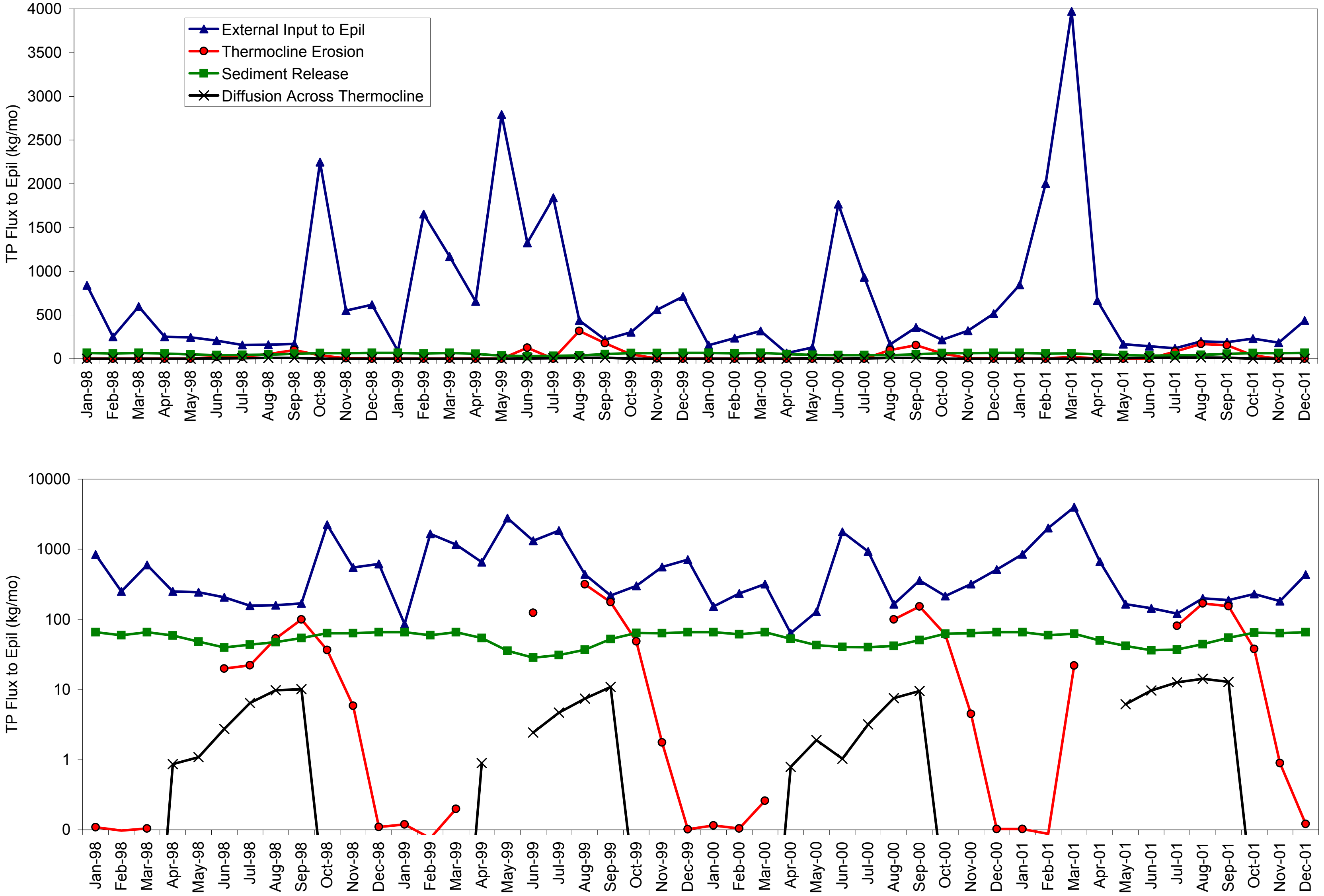
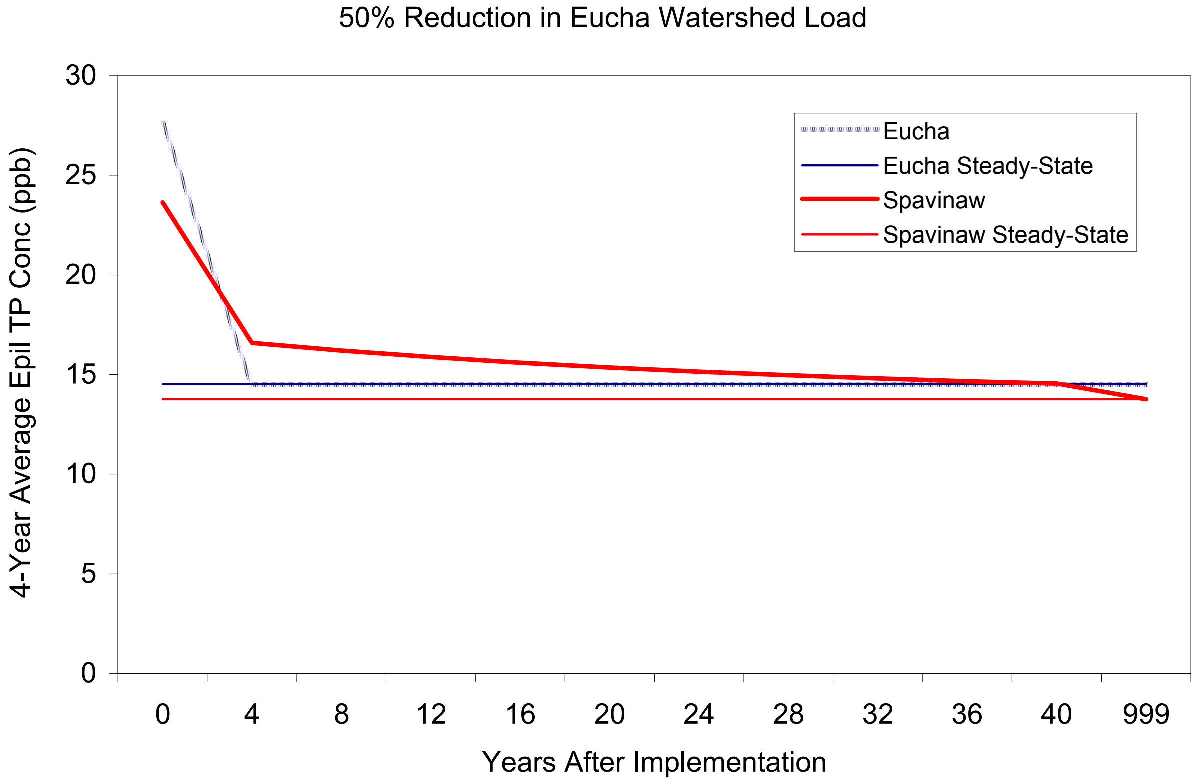
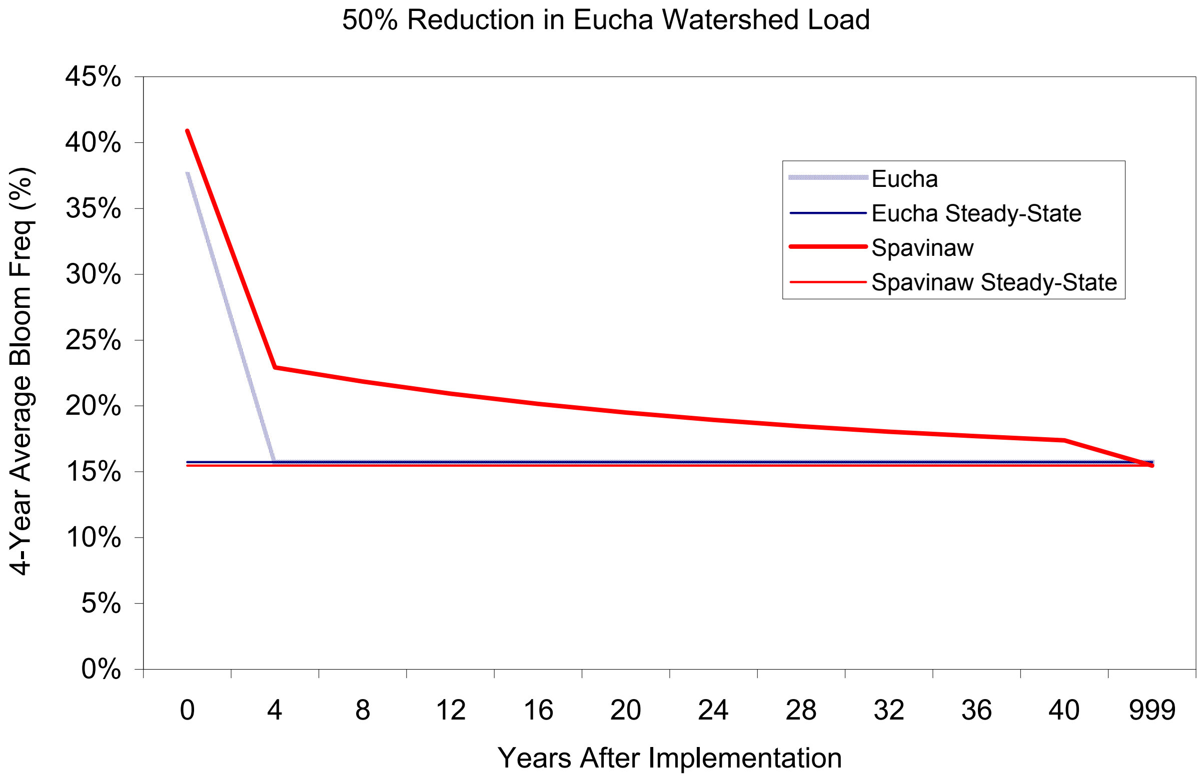


Figure 16 **Transient Responses to 50% Reduction in Eucha Watershed Load**





Bloom Frequency = Percent of Chl-a Values > 20 ppb, May-September