A Nutrient-Balance Model for Agency Lake, Oregon

prepared for

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by

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Introduction

Agency Lake is a shallow, hyper-eutrophic impoundment located in the Upper Klamath Lake Basin, Oregon (Figure 1). The lake has a surface area of 35.6 km^2 and drainage area of approximately 614 km^2. This report develops water and nutrient balances for Agency Lake using data from an intensive monitoring program conducted by the U.S. Bureau of Reclamation and Klamath Tribes between 1991 and 1993 (USDI, 1993a, 1993b). Flows and nutrient loads at watershed monitoring stations are calculated and compared to identify important contributing areas of the watershed. Mass balances for water, conductivity, total phosphorus, and total nitrogen are developed over monthly and seasonal time scales. Spatial and temporal variations in lake water quality conditions are characterized. Application of empirical eutrophication models developed for reservoirs (Walker, 1987) provides further insights into factors controlling eutrophication in Agency Lake and a limited basis for predicting effectiveness of management strategies designed to improve lake water quality.

Monitoring Program

Watershed and lake monitoring stations operated in 1991-1993 are shown in Figure 2. Time series plots of watershed and lake monitoring data are given in Appendix A. Major tributaries include Wood River, Sevenmile Canal, and Fourmile Canal. Basic features of the watershed and monitoring program are described below.

The major tributaries originate as springs and mountain streams in the southern Cascades, which form the western and northern boundaries of the watershed. The lower portion of each watershed consists of former wetlands which have been diked, drained, ditched, and developed for agricultural use. Approximately 60 km^2 of the Agency Lake watershed was converted from wetland to upland between 1940 and 1989 (USDI, 1993b). Tributary canals supply water for irrigation purposes and accept irrigation return flows and runoff from grazing areas. Site visits in March 1995 revealed evidence of direct surface runoff from grazed areas, barnyards, and animal holding areas into lake tributaries. Other potential nutrient sources in the watershed include oxidation of former wetland soils, runoff from roads, runoff and/or point-source discharges from urban areas (Ft. Klamath) and a fish hatchery.

Watershed delineations shown in Figure 2 have been derived partially from a GIS data base maintained by the Winema National Forest. The remaining delineations have been estimated from maps and other available information. Ungauged areas draining directly into Agency Lake below monitoring points amount to approximately 43 km^2 or 7.3% of the entire watershed; this estimate is uncertain because of difficulties in delineating watersheds in the agricultural areas immediately northwest of the Lake, characterized by its flat topography and intensive water-management activities. These difficulties, combined with the apparent lack of a complete land-use inventory for the watershed, impose limitations on accuracy of the water-balance and nutrient-balance calculations developed below. Model predictions are fairly insensitive to the assumed delineation of ungauged drainage area, however.

Seven watershed stations were sampled monthly by the USBR during the 1991-1993 study period. Five of these stations (UK100-UK500) are located along the Wood River; these characterize variations in flow and water quality from spring-fed headwaters, through agricultural and wetland areas, and into Agency Lake. Sevenmile Canal (UK600) and Fourmile Canal (UK400) stations characterize drainage from the western and northwestern portions of the watershed. The study period included a dry year (precipitation = 8.7 inches in Water Year 1992) and a wet year (24 inches in Water Year 1993). The long-term-average precipitation is approximately 13.5 inches.

Three lake monitoring stations were sampled biweekly by the Klamath Tribe. As shown in Figure 2, two lake stations are located in Agency Lake (North & South) and one station is located in Klamath Lake. Details on sampling methods and analytical procedures are given in USDI (1993a, 1993b).

Runoff & Nutrient Loads

This section describes the computation of flows and nutrient loads at the tributary monitoring stations. A continuous record of daily flows was provided for one station (UK400 = Wood River at Weed Road). Although continuous stage readings were made at the remaining stations, these data were not available to support the present study. The flow record at the remaining stations consists of instantaneous measurements taken at monthly intervals using a velocity meter.

To provide a basis for mass-balance calculations, a complete daily flow record has been generated for each watershed station using the following procedure:

1. Pair each instantaneous flow measurement with the corresponding daily-mean flow at the Weed Road station.

2. Develop a regression equation relating the station flow to the Weed Road flow.

3. Apply the regression equation to generate a predicted flow for each day in the record.

4. Calculate the residual (observed - predicted) flow on the days with instantaneous flow measurements.

5. Interpolate the residuals over time to generate a residual value for each day in the record.

6. Calculate a daily flow for each day in the record by adding the predicted flow (3) and the interpolated residual (5).

In situations where the correlation between the Weed Road flow and the station flow is high, this procedure tends to track the Weed Road flow (with an appropriate adjustment in scale). In situations where the correlation is weak, this procedure approaches a direct interpolation of the monthly instantaneous flows over time. Estimates derived from this procedure are inferior to direct daily stream flow measurements, provided that adequate stage/discharge relationships can be developed. Accordingly, tributary flows and loadings should be recalculated once a continuous flow record is available for each station. This would be particularly important for Sevenmile Creek, which, based upon watershed characteristics and upon the limited flow and concentration data available, appears to be an important nutrient source.

Based upon application of the FLUX program (Walker, 1987), temporal variations in stream concentrations are relatively low. Concentrations tend to be weakly correlated or uncorrelated with flow. Correlations with season are more pronounced; at lower watershed stations, concentrations tend to be higher during summer months than during winter months. A continuous record of daily mass flux has been generated at each station by interpolating measured concentrations over time and applying the interpolated concentrations to the daily flows. Results are summarized by month, season, and year in Appendix B. Constituents include total phosphorus, ortho phosphorus, total nitrogen, inorganic nitrogen, and conductivity.

Figure 3 shows average flows, fluxes, and flow-weighted-mean concentrations for each station and constituent. These represent average conditions during April through September of each year (1991, 1992, 1993). Year-to-year variations at each station are depicted in Appendix B.

At the Wood River Stations (UK100-UK500), there is a small increase in flow between the most upstream station (UK100 = Dixon Road, April-September mean flow volume = 80 hm^3 = 80 million cubic meters) and the most downstream station (UK500 = Agency Dike, flow = 98.7 hm^3). Inflows from higher order tributaries (Annie Creek, Fort Creek, and Crooked Creek) are not evident in the Wood River flow profile. The net flow contribution from the lower portion of the Wood River watershed is small; this presumably reflects diversions, consumptive use by irrigation, and spatial differences in precipitation and evapotranspiration between the mountain headwaters and the semi-arid lake plain. In contrast, total phosphorus flux increases from 6,511 kg to 14,742 kg and the flow-weighted-mean total phosphorus concentration increases from 81 ppb to 149 ppb between these same two stations. As shown in Figure 3, most of the phosphorus increase occurs in the area between Weed Road (UK400) and Agency Dike (UK500).

Station UK500 is located just upstream of Agency Lake. Given the flat topography and resulting low hydraulic gradient, it is possible that concentrations measured at UK500 are influenced at times by hydraulic exchanges with Agency Lake. Comparisons of water-quality time series at UK500 with time series at Agency Lake stations (Appendix A) do not reveal evidence of this, however. Seasonal increases in total and ortho phosphorus concentrations at UK500 tend to occur 1-2 months earlier than increases at the Lake stations. Furthermore, elevated chlorophyll-a and pH values typical of Agency Lake stations during the summer months were not detected at UK500. Based upon these comparisons, it is assumed that concentrations measured at UK500 were representative of lake inputs from the Wood River watershed.

The flow-weighted-mean phosphorus concentration at the mouth of the Wood River (149 ppb) was similar to that measured at the mouth of Sevenmile Canal (156 ppb). The phosphorus concentration in Fourmile Canal was identical to that measured at headwaters of the Wood River (81 ppb). Station UK700 is located considerably upstream of the lake (Figure 2) and may be more heavily influenced by drainage from eastern mountainous areas than by drainage from the developed lake plain. The difference between 81 ppb and 149-150 ppb is one estimate of anthropogenic impact on stream phosphorus concentrations. Nitrogen concentrations (organic nitrogen, in particular) were much higher at the Sevenmile Canal station (697 ppb) and Fourmile Canal station (462 ppb), as compared with the Wood River Stations (108 to 314 ppb).

Water & Nutrient Balances

In order to construct water balances and nutrient balances for Agency Lake, estimates of contributions from ungauged portions of the watershed are required. Based upon the watershed delineations given in Figure 2, ungauged watersheds amount to 7.3% of the total watershed. These include areas on the west and east side of the lake.

Ungauged flows and loads have been estimated by drainage area proportioning against gauged flows and loads from Sevenmile Canal and Fourmile Canal, based upon proximity. The following equation is used:

$$W_u = W_g A_u / A_g = .283 W_g$$

where,

W_g = gauged flow or load (sum of Fourmile & Sevenmile)

W_u = ungauged flow or load

A_g = gauged drainage area (150.3 km^2)

A_u = ungauged drainage area (42.5 km^2)

This estimation procedure assumes that ungauged watersheds are similar to Fourmile & Sevenmile Canals with respect to land uses, soil types, and other factors determining runoff and nutrient export.

The Agency Lake water balance has been formulated at monthly intervals using the following equation:

External Inflows + Precipitation =

Evaporation + Outflow + Storage Increase

External inflows are derived from the watershed monitoring stations and the estimated ungauged contributions. Precipitation is estimated from regional measurements supplied by USBR. Longterm-average precipitation values have been used for months when direct measurements are missing. Fixed monthly evaporation rates are average pan evaporation rates for 1961-1990, adjusted with a pan coefficient of 0.7. The change-in-storage term is calculated from Upper Klamath Lake elevation records and a capacity vs. elevation table for Agency Lake supplied by USBR.

Outflow is calculated by difference from the other terms, each of which are directly measured or independently estimated. In typical reservoir studies, the accuracy of the water-balance calculations can be checked by comparing observed and predicted outflow rates (Walker, 1987). Direct measurements of Agency Lake outflow would be difficult and are not available, however.

Results of monthly water-balance calculations are summarized in Table 1 and displayed in Figures 4 and 5. Figure 4 shows monthly inflows, outflows, and storage terms. Figure 5 shows lake morphometric and hydrologic features which are significant with respect to nutrient-balance modeling. Generally, variance in outflow is much less pronounced than variance in the inflow. The seasonal inflow cycle (lower in summer, higher in winter) is offset by the seasonal decrease in lake elevation and storage. Mean depth varies from 2.2-2.5 meters in April-May to 0.8-1 meter in October. Hydraulic residence time (computed as the ratio of the average monthly lake volume divided by the net inflow (= external inflow + precipitation - evaporation)) varies from 90 to 150 days in summer months to 30-40 days in winter months.

Mean depth, hydraulic residence time, and surface overflow rate are important factors regulating nutrient cycling and biological response in reservoirs (Walker, 1985, 1987). Shallow depths tend to promote nutrient recycling from bottom sediments and to promote algal growth by reducing the potential for light limitation. Based upon depth and residence time, low nutrient retention efficiencies are expected. The low surface overflow rate (averaging ~8 m/yr) provides limited dilution of sediment nutrient sources and increases sensitivity to nutrient recycling processes. Summer hydraulic residence times in Agency Lake are well above the 0-14 day range in which flushing rate has been shown to control algal densities (Walker, 1985). The morphometric and hydrologic characteristics of Agency Lake are more or less ideal for promotion of algal growth in response to external or internal sources of nutrients.

Using a similar computational framework, monthly mass balances have been formulated for conductivity, total phosphorus, and total nitrogen (Tables 2-4, Figures 7-15). The mass-balance equation includes an additional term to reflect net retention or loss:

Net Retention = External Inputs + Atmospheric Inputs
- Outputs - Storage Increase

External inputs are derived from the tributary flux calculations described in the previous section. Atmospheric inputs (sum of wetfall and dryfall) are estimated at fixed areal rates of 7 $uS/cm^2*m/yr$ for conductivity, 18 kg/km^2-year for phosphorus, 1080 kg/km^2-year for nitrogen (USEPA, 1975). Outputs are estimated by multiplying the monthly outflow volume times the monthly-average lake concentration. A continuous daily time series has been generated for lake concentration by interpolating lake-mean concentrations (average of North and South stations, Figure 2) between adjacent sampling dates. A corresponding time series of month-end mass storage has been generated by multiplying the month-end concentration times the month-end lake volume. The storage increase term of the mass balance has been calculated as the mass storage at the end of the current month minus the storage at the end of the previous month.

The mass-balance framework ignores diffusive inputs or outputs resulting from hydraulic exchanges between Agency Lake and Upper Klamath Lake. Such exchanges would depend upon exchanges of flow between the two basins, driven by wind and/or elevation differences. Sufficient data are not available to estimate these terms directly. The restricted nature of the channel linking the two lakes and general similarities in water quality between the two lake basins would tend to limit the magnitude and significance of such exchanges. More detailed modeling of both lake basins could provide information on the extent to which the nutrient balances of the two basins are linked by diffusive hydraulic exchanges. Only advective transport from Agency Lake into Upper Klamath Lake is considered in the mass balances formulated here.

The net retention term has been calculated by difference. This term reflects net losses from the water column resulting from sedimentation, atmospheric fixation (nitrogen), nutrient releases from bottom sediments, and the cumulative effects of errors or omissions in the other mass-balance terms. The net retention term is positive during periods when sedimentation or other removal processes dominate and negative during periods when nutrient releases from bottom sediments, atmospheric fixation, or other internal nutrient sources dominate.

Tables 2-4 summarize mass-balance results for each term, on monthly, seasonal, and yearly-average time scales. Monthly series are displayed in Figures 7, 10, 13 for conductivity, total phosphorus, and total nitrogen, respectively. Seasonal series (September-March and April-September of each Water Year) are displayed in Figures 8, 11, and 14. Cumulative mass balances (running sum of monthly input, output, storage, and retention terms starting in April 1991 and ending in October 1993) are shown in Figures 9, 12, and 15; these elucidate the relative magnitudes of each mass-balance term over long time scales.

The conductivity balance has been formulated to provide a means of testing the water-balance and mass-balance framework. If conductivity is assumed to be proportional to the concentration of conservative ions, the net retention term of the mass balance should average close to zero. One limitation of using conductivity for checking the water balance is that it can be influenced by non-conservative ions (such as nitrate, sulfate, phosphate), it is temperature-dependent, and the field-measured values for conductivity are probably less precise than laboratory analyses for conservative ions. While chloride or sodium balances would be preferred for this purpose, the required tributary and lake concentration measurements are not available for these constituents. Because conductivity "concentration" units are in uS/cm^2, mass balance terms have units of $uS/cm^2 \times hm^3$. The relative magnitudes of the terms are of concern, however, rather than the absolute values or units.

Reasonable conductivity balances are established for April-September of each year. Results for 1991 are relatively uncertain because of the scarcity of lake conductivity measurements. The net retention term ranges from 1.4% to 5.7% of the total inputs. Conductivity balances are less satisfactory during winter periods; net retention amounts to -15.5% of the external inputs between October 1991 and March 1992 and -57.0% of the total inputs between October 1992 and March 1993. These negative values may reflect low sampling intensity or additional conductivity sources during winter months. The relatively large excursion in Winter 92-93 is traced to high conductivity readings at the Agency South station on two sampling dates. Further analyses suggest a positive correlation between the monthly retention term for conductivity and lake temperature. It is possible that the poor conductivity balance during winter months is an artifact of the temperature-correction factor inherent in the conductivity measurements. Despite possible problems with the mass balance during winter months, the summer conductivity balances are consistent with reasonable representations of the lake's water balance. More definitive evaluation of potential problems during the winter months would be derived from more intensive winter sampling of the lake stations and construction of chloride or sodium balances in place of conductivity balances.

Phosphorus balances (Figures 10-12) indicate that outputs approximately equaled inputs over the two complete water years studied (1992 and 1993). Seasonal mean total phosphorus concentrations in Agency Lake ranged from 60 to 130 ppb in winter and from 140 to 240 ppb in summer. Over Water Years 1992-1993, the net retention term of the phosphorus balance amounted to 0.6% of the total inputs. Periods of significant positive and negative phosphorus retention are apparent in the monthly (Figure 10) and seasonal (Figure 11) balances. The rapid doubling in lake phosphorus concentration which occurred in early summer of each year reflected periods of negative phosphorus retention, especially in July 1991, June 1992, and July 1993. Phosphorus retention during these months ranged from approximately -10,000 to -20,000 kg/month, as compared with the average external phosphorus load of approximately 3,000 kg/month. Expressed per unit area of lake sediment, these negative retention rates corresponded to phosphorus release rates ranging from 9 to 18 mg/m^2-day during these extreme months. As indicated in Figure 10, these high rates were not sustained throughout the growing season.

Periods of markedly negative phosphorus retention rates most likely reflect phosphorus recycling from lake bottom sediments triggered by photosynthetically-induced increases in pH. Figure 16 shows that monthly phosphorus retention rates are negatively correlated with monthly-average lake pH and chlorophyll-a levels in Agency Lake. The three months with the most negative retention rates (highest apparent internal loading rates) corresponded to months with the highest pH levels. Retention rates tended to be positive in late summer during the declining phase of the seasonal algal bloom. Overlaying the pH and chlorophyll-a time series (Figure 16) suggests that an increase of one log unit in chlorophyll-a was generally accompanied by an increase of one pH unit, except for an anomalous period in late summer 1992, when high pH levels were measured, despite extremely low chlorophyll-a concentrations.

Chemical mechanisms for release of iron-bound phosphorus from lake bottom sediments during periods of high pH have been documented (Stumm and Leckie, 1970) and are thought to be important in Upper Klamath Lake (Klamath Tribe, 1994). In hardwater lakes, release of iron-bound phosphorus at high pH is typically offset by precipitation of insoluble calcium phosphates (Golterman, 1982). Calcium concentrations averaged 5-7 mg/liter at tributary stations, but were not measured at lake stations. Apparently, calcium levels in the moderately soft waters of Agency Lake are insufficient to control release of iron-bound phosphorus at high pH. This mechanism promotes recycling of phosphorus previously deposited to lake bottom sediments during winter and late summer periods, when positive retention rates are apparent. The recycling occurs during early summer when light and temperature levels are most conducive to algal blooms.

The nitrogen balance (Table 4, Figures 13-15) indicates that Agency Lake is a net source of nitrogen over short and long time scales. Mean total nitrogen concentrations in Agency Lake ranged from 400-500 ppb in winter to 1000-1300 ppb in summer. Over Water Years 1992-1993, the net retention term of the nitrogen balance amounted to -102% if the external inputs. In other words, the external and internal sources of nitrogen were approximately equal. The apparent internal nitrogen source probably reflects fixation of atmospheric nitrogen by bluegreen algae (USDI,1993ab, Barbiero & Kann, 1994). Average summer and winter retention rates correspond to areal fixation rates of 18.2 and 2.2 mg/m^2-day, respectively.

Lake Water Quality

Time series plots of data from three lake monitoring stations (Agency Lake North, Agency Lake South, and Upper Klamath Lake) are included in Appendix A. Box plots depict seasonal (Figure 17), annual (Figure 18), and spatial variations (Figure 19) in lake water quality.

Seasonal variations in nutrient concentrations and chlorophyll-a are pronounced. Figure 17 summarizes data from Agency North and South grouped into four, three-month seasons (March-May, June-August, September-November, December-February). Maximum concentrations of chlorophyll-a, organic nitrogen, total phosphorus, ortho phosphorus, and total nitrogen were observed during the summer (June-August) season. The ratio of chlorophyll-a to total phosphorus (CHLA/TP) was also highest during this season. The strong seasonality in these response variables reflects seasonal variations in environmental factors (temperature, light) and the apparent mechanistic linkages between chlorophyll-a and internal nutrient sources, as described in the previous section. Further analyses indicate that nutrient concentrations, chlorophyll-a concentrations, and Chl-a/P ratios in May and September were significantly below June-August values. For this reason, modelling efforts in the subsequent section are focused on the June-August period.

Within the June-August period, temporal variations in chlorophyll-a are unusually high in relation to variations observed typically observed in other lakes and reservoirs. The coefficient of variation (standard deviation of natural log) is 1.3, as compared with typical values in the range of 0.4 to 0.7 estimated from regional and nationwide data sets (Smeltzer et al., 1989). The high variability partially reflects the episodic character of algal blooms apparently triggered by sediment phosphorus releases (Figure 16). Difficulties associated with sampling algal flakes may also contribute to high variability in Agency Lake chlorophyll-a measurements.

Year-to-year variations are shown in Figure 18, based upon June-August samples from Agency Lake stations. Yearly means and standard errors are listed in Table 5. Following the algorithm included in the PROFILE program for reduction of reservoir water quality data (Walker, 1987), yearly means have been computed by first averaging across stations on each sampling date and subsequently averaging across dates within each year. Chlorophyll-a data from Agency South included one extremely high value (986 ppb on 6/17/92); this is more than three times the next highest value recorded at this station and more than four times the value recorded at Agency North on the same date. When this value is included, the three-year-average chlorophyll-a is 97 ppb and the standard error is 27 ppb. When this value is replaced with the chlorophyll-a concentration measured at Agency North on the same date (195 ppb), the three-year-average decreases to 78 ppb and the standard error decreases to 13 ppb. It is possible that the unusually high value reflects difficulties in collecting representative samples in waters containing large algal flakes. Given the high influence of this single sample on the long-term mean and standard error, the latter summary values (mean = 78 ppb, standard error = 13 ppb) are assumed to represent the average chlorophyll-a response.

Based upon paired t-tests, significant differences in yearly means are indicated only in the case of water depth and ortho phosphorus. Both depth and ortho phosphorus concentration were significantly lower during the 1992 drought year. Significant differences in yearly means are not indicated for the primary measures of trophic response (total phosphorus, total nitrogen, chlorophyll-a, or transparency). Accordingly, modeling efforts in the subsequent section focus on average conditions (between June and August) for all three years.

Spatial variations (June-August) are summarized in Figure 19. Stations are arranged in a north-to-south direction (Agency North, Agency South, Klamath Lake); this follows the major flow axis. Spatial variations are most pronounced in the case of Total N/P ratio and inorganic N/P ratio, both of which increase from north to south. These reflect weaker increasing gradients in nitrogen species and decreasing gradients in phosphorus species. The chlorophyll-a/phosphorus ratio in Agency Lake (median ~.2) is significantly lower than that observed in Upper Klamath Lake (median ~.4). This may reflect a greater influence of nitrogen limitation on algal growth in Agency Lake, as indicated by lower Total and Inorganic N/P ratios. Because of the N/P and Chl-a/P gradients, a single phosphorus/chlorophyll-a ratio (or regression) would not be sufficient to describe spatial variations in chlorophyll-a response across both lakes. Significant differences between Agency North and South stations are apparent only in the case of the Total N/P ratio. Otherwise, spatial variations within Agency Lake are not considered strong enough to warrant a spatially-segmented model.

Based upon the spatial and temporal variations described above, modeling efforts in the subsequent section are focused on predicting Agency Lake responses averaged across stations, years, and months between June and August. Table 6 compares average trophic state indicators in Agency Lake with the distributions of values in 40 Corps of Engineer (CE) reservoirs used in developing the empirical models applied below. Appendix C (extracted from Walker, 1987) describes the diagnostic variables listed in Table 6.

By all measures, Agency Lake is highly eutrophic. Values for chlorophyll-a, organic nitrogen, the first two principle components of reservoir response measurements (PC-1 & PC-2) are all above the CE reservoir range. The Inorganic N/P ratio is below the CE reservoir range; this suggests Agency Lake is more strongly nitrogen limited than any of the reservoirs in the CE data set. Other diagnostic variables indicate that light limitation is not important in Agency Lake, primarily because of its shallow depth and dominance by flake-forming algae, which absorb less light per unit chlorophyll than algal types with smaller cells. Despite the low N/P ratio, the average Chl-a/P ratio (0.31) is in the 67th percentile of CE reservoir values. The shallow depth, nitrogen fixation, and phosphorus recycling mechanisms apparently support a high algal response to phosphorus, despite the potential growth-limiting effects of nitrogen.

Average morphometric and hydrologic features are within the range of the CE reservoir data set (Table 6). As expected, Agency lake is at the low end with respect to mean depth (8th percentile) and surface overflow rate (4th percentile). These characteristics are conducive to nutrient recycling and a high algal response. Lakes and reservoirs with low surface overflow rates are more susceptible to internal nutrient recycling (Walker, 1987). Internal nutrient sources (releases from bottom sediments) are typically expressed on an areal basis (mg/m^2-yr). Dividing the areal release rate by the surface overflow rate (areal water load, m/yr) provides a measure of the potential impact of internal recycling on water-column concentration (mg/m^3 or ppb). At a given recycling rate, this impact is inversely proportional to overflow rate. Thus, the importance of internal sources identified in the previous section is consistent with Agency Lake's morphometric and hydrologic characteristics.

BATHTUB Model Network

The following sections apply empirical models previously developed for evaluating eutrophication problems in Corps of Engineer reservoirs (Walker, 1985, 1987) to data from Agency Lake. The models are derived from the BATHTUB program (Walker, 1987), but are implemented here in a spreadsheet format (adaptation of CNET.WK1, Walker, 1990). The structure of the model network is shown in Figure 20. Equations are summarized in Table 7. This effort provides quantitative perspectives on trophic state and controlling factors in Agency Lake. To a limited extent, modeling also provides a basis for predicting potential water-quality responses to changes in external nutrient loadings, pool elevations, and/or measures designed to reduce internal nutrient recycling.

The BATHTUB model network (Figure 20) contains two categories of models: nutrient-balance models and trophic response models. Trophic response models relate observed or predicted nutrient concentrations to other measures of trophic state (chlorophyll-a, transparency, organic nitrogen, etc.). Nutrient-balance models predict lake nutrient concentrations based upon external loads, morphometry, and hydrology. Each model category is discussed below.

Trophic Response Models

Table 8 summarizes the results of applying empirical models predicting chlorophyll-a, transparency, and other measures of trophic response based upon observed nutrient concentrations and other driving variables. Five alternative equations for predicting mean chlorophyll-a are tested (Chlorophyll-a Models 1-5, see Appendix C). Based upon error statistics derived from the CE reservoir data set and the uncertainty in the observed mean chlorophyll-a, predictions of the first four models (71 - 81 ppb) are not significantly different from the observed mean (78 ± 14 ppb). Model 5 (exponential P/ Chl-a relationship) substantially over-predicts chlorophyll-a in Agency Lake, probably because of its low N/P ratio and relatively high phosphorus concentrations.

Chlorophyll-a model (Model 1) predicts chlorophyll-a based upon total phosphorus, total nitrogen, non-algal turbidity, mixed layer depth, and hydraulic residence time. This model was designed to account for potential effects of algal growth limitation by phosphorus, nitrogen, light, and/or flushing rate. Applied to the CE reservoir data set, errors are independent of nutrient concentrations, N/P ratios, hydraulic residence time, and indicators of light limitation (turbidity, mixed layer depth, etc.). Because it is the most general formulation, Model 1 has been selected for application to Agency Lake. Following the control pathways shown in Figure 20, predictions of other trophic response variables (transparency, organic nitrogen, Total P - Ortho P, principle components) are driven by predicted chlorophyll-a concentrations.

Further testing against data from individual stations (Agency North, Agency South, Upper Klamath Lake) indicates that error distributions are independent of station only for the chlorophyll-a models which account for nitrogen limitation (Models 1 and 3). When any of the remaining chlorophyll-a models are calibrated to predict chlorophyll-a levels in Agency Lake, they under-predict chlorophyll-a levels in Upper Klamath Lake. This is consistent with the north-to-south increasing gradient in N/P and Chl-a/P ratios (Figure 19). This further suggests that algal populations in Agency Lake are sensitive to both phosphorus and nitrogen, despite the observed nitrogen fixation.

All three transparency models under-predict the observed mean Secchi Depth by more than a factor of two. This is probably related to the importance of flake-forming bluegreen algae (USDI,1993ab), which cause less light attenuation per unit of chlorophyll than other algal types. The transparency model represents the inverse of transparency as a linear function of chlorophyll-a. Based upon CE reservoir data, the slope of this relationship was originally calibrated to 0.025 m^2/mg. This slope is also a parameter in chlorophyll-a Models 1 & 2; lower values will increase algal response to high nutrient concentrations by decreasing self-shading effects. Experience in other applications of the models indicates that a downward adjustment of this slope is frequently necessary in lakes and reservoirs dominated by large-celled bluegreen algae (Heiskary & Walker, 1995; Walker & Havens, 1995).

Table 9 summarizes results after calibration of the model network to Agency Lake response measurements. The primary calibration is downward adjustment of chlorophyll-a/Secchi slope from 0.025 to 0.012 m^2/mg. As discussed above, this is justified based upon type of algae found in Agency Lake. With this adjustment, the observed and predicted transparency values are in agreement; predicted chlorophyll-a concentrations for the two models which consider light limitation (1 and 2) increase to 90 and 135 ppb, respectively. The secondary calibration is the application of a scale factor (0.87) to the predicted chlorophyll-a concentration (Model 1). Based upon the fact that the observed and predicted chlorophyll-a concentrations are not significantly different without calibration, this relatively minor adjustment is not necessary. With the adjustment, observed and predicted chlorophyll-a concentrations are numerically equal.

The remaining response models predict organic nitrogen and non-ortho phosphorus based upon predicted chlorophyll-a and non-algal turbidity. These variables reflect "utilized" nutrient forms; in the absence of high humic or inorganic turbidity levels, they are good surrogates for chlorophyll-a. The remaining equations predict the first two principle components of reservoir response measurements (chlorophyll-a, transparency, organic nitrogen, and composite nutrient concentration). Since observed and predicted values are not significantly different for any of these models, no recalibrations have been performed.

With the above adjustments, the model network provides a basis for predicting relationships among trophic state indicators in Agency Lake. Of primary interest is the relationship between mean chlorophyll-a concentration and total phosphorus concentration. In a predictive mode, one difficulty is that predicted chlorophyll-a also depends upon total nitrogen concentration. Prediction of nitrogen concentrations using an empirical nutrient loading model is not feasible in Agency Lake because of the apparent importance of nitrogen fixation.

Figure 21 shows predicted mean chlorophyll-a concentrations as a function of total phosphorus for two alternative assumptions regarding nitrogen behavior. Under the first assumption, total nitrogen is constant at the 1991-1993 mean (1816 ppb) and independent of phosphorus. Under the second assumption, the model term which reflects nitrogen limitation (Total N - 150) / Total P is fixed at the 1991-1993 mean (6.5); i.e., nitrogen levels are assumed to vary approximately in proportion to phosphorus levels. As total phosphorus concentrations decrease, the first assumption results in a nonlinear response; this reflects a transition from co-limitation by nitrogen and phosphorus to limitation by phosphorus alone. The second assumption results in a linear chlorophyll-a/phosphorus response. Repeating this exercise using chlorophyll-a Model 3 yields essentially equivalent results. Because nitrogen fixation cannot be reliably modeled/predicted, it is difficult to determine which of the above assumptions is most appropriate for modeling chlorophyll-a response to phosphorus in Agency Lake. The following concepts seem to support the second assumption, however:

(1) Given the watershed nutrient sources, any control program designed to reduce external phosphorus loads would also reduce external nitrogen

loads.

(2)If it is assumed that algal populations are ultimately controlled by phosphorus because of the facility for nitrogen fixation, one would expect the amount nitrogen fixation to decrease with phosphorus concentration.

Because of these factors, results for the second assumption are emphasized, although results for both assumptions are presented.

Correlations between phosphorus and chlorophyll-a using data from the entire growing season (May thru September) have been developed for the entire Upper Klamath Lake system (Klamath Tribe,1994). Seasonal effects are evident in phosphorus concentrations, chlorophyll-a concentrations, and chlorophyll-a/phosphorus ratio (Figure 17). All three values are significantly lower in May and September, as compared with June thru August. Some of the apparent correlation between phosphorus and chlorophyll-a in the May-September data reflects seasonal variations, as opposed to a mechanistic linkage between phosphorus and chlorophyll-a. For this reason, such correlations should not be used to predict chlorophyll-a response to changes in average phosphorus concentration.

To supplement response predictions based upon the BATHTUB model network, site-specific models predicting algal bloom frequency as a function of total phosphorus concentration have been developed using Agency Lake data (Figure 22). These are based upon cross-tabulation of paired chlorophyll-a and phosphorus concentrations measured at Agency Lake stations between June and August (Heiskary & Walker, 1988; Walker & Havens, 1995). To develop the relationships, 40 paired samples collected between 1991 and 1993 have been sorted based upon increasing phosphorus concentration and bloom frequencies (% of chlorophyll-a > 30 ppb and > 60 ppb) have been computed from each successive set of 10 samples (samples 1-10, 2-11, 3-12, etc.. 31-40). This results in four independent sample sets (samples 1-10, 11-20, 21-30, 31-40). The computed bloom frequencies have been regressed against the mean phosphorus concentration in each sample set. Figure 22 indicates strong linear correlations between total phosphorus and bloom frequency for both bloom criteria. These results further suggest a linear chlorophyll-a/phosphorus response in Agency Lake, consistent with a fixed N/P ratio (Figure 21).

Nutrient Balance Models

Nutrient-balance models predict lake nutrient concentrations based upon external nutrient loadings, morphometric factors, and hydrologic factors.
A fundamental assumption in this type of model is that trophic response is controlled by external nutrient inputs, reservoir morphometry, and reservoir hydrology. Mass-balance calculations described in a previous section indicate that internal sources or recycling of nutrients triggered episodically by biological and chemical mechanisms are important in

Agency Lake. A second assumption is that reservoir trophic state is at equilibrium or steady-state with respect to external nutrient inputs over time scales ranging from 6 months (growing season) to a year. Pronounced temporal variations in nutrient retention rates, lake nutrient concentrations, chlorophyll-a concentrations suggest that if an "equilibrium" condition exists in Agency Lake, it is a very dynamic one. A further difficulty is that empirical models are generally designed to predict response to phosphorus loading, whereas algal populations in Agency Lake appear to be limited by nitrogen and nitrogen levels are supplemented by nitrogen fixation.

Conditions in Agency Lake are far from ideal for application of empirical nutrient loading models. To the extent that they are based upon the fundamental principle of mass balance, however, loading models can be used to place bounds on reservoir response, given certain assumptions. Modeling objectives, assumptions, methods, and results are described below.

It is assumed that the objective of nutrient-balance modeling is to predict lake response to potential management strategies. Three potential management strategies are considered:

(1)<u>Decrease in External Nutrient Loading</u>. Spatial variations in flow-weighted-mean nutrient concentrations and loads at tributary monitoring stations (Figure 3) suggest anthropogenic impacts. These impacts might be at least partially offset by implementation of agricultural best management practices and/or other source-control measures. One approximate measure of anthropogenic impact is the difference between the combined flow-weighted-mean phosphorus concentration of 144 ppb for the inflows to Agency Lake, as compared with the 81 ppb concentration measured at the most upstream station on the Wood River and at Fourmile Creek (April-September values, 1991-1993, Table 3). Estimation of anthropogenic impacts on flow (and nutrient load) would require much more intensive monitoring, detailed analysis, and modeling of watershed hydrology. Accordingly, flows are assumed to be fixed and the model is applied to predict response to a 44% reduction in average inflow concentration (144 to 81 ppb) and external phosphorus load (23.8 to 13.3 metric tons. Results provide (a) estimates of reservoir conditions in the absence of anthropogenic phosphorus inputs; and (b) estimates of potential responses to watershed management or other measures designed to reduce external nutrient load. Design and modeling of specific watershed management measures is beyond the scope of this report.

(2)<u>Increase in Water Elevation.</u> Mean depth declines seasonally from ~2.4 to ~1 meter (Figure 6). Shallow depths are conducive to nutrient recycling and promote algal growth; increases in water level have been suggested as an appropriate measure for improving water quality in Upper Klamath and Agency Lakes (Klamath Tribe, 1994). As indicated in Figure 20, water depth is a factor is predicting nutrient retention and in predicting algal response to nutrients. A hypothetical increase of 30% in the average April-September pool volume and mean depth is simulated to provide indications of depth sensitivity. This corresponds approximately to maintaining typical spring pool elevations throughout the summer (Figure 6).

(3)Reduction of Internal Phosphorus Recycling. Mass-balance calculations indicate that internal recycling of phosphorus is important, particularly during early summer months. Theoretically, there are several potential mechanisms which would cause internal recycling to decrease in response to a decrease in external load and/or an increase in water level. Treatment of sediments with alum or lime might also be effective in reducing phosphorus recycling (Cooke et al. ,1993). The model network is not designed for simulating mechanisms determining the effectiveness of these control methods; however, it can be used to predict, by mass-balance, lake response to assumed reductions in internal recycling. To place bounds on this effect, the model network is run with and without an internal recycling term initially calibrated to the 1991-1993 lake data.

The above cases have been represented in a matrix of 3 "Methods" and 4 "Scenarios". The Methods are different representations or models of phosphorus retention in Agency Lake:

(1)**Method A - Uncalibrated / "Typical Reservoir"**. Response is predicted using a phosphorus retention model originally calibrated to CE reservoir data (Table 7) using low, median, and high estimates for sedimentation rate (90% confidence interval). This represents the expected response of a "typical" reservoir with phosphorus retention predicted based upon inflow Total P concentration, inflow Ortho P/Total P ratio, mean depth, and hydraulic residence time. In this case, phosphorus retention and recycling would be typical of other reservoirs with similar inflow concentrations, morphometry, and hydrology. This method substantially under-predicts phosphorus levels in Agency Lake because it does not account for the unusually high rates of internal recycling. From a management perspective, Method A provides an indication of reservoir response if chemical treatment or other manipulations (increases in pool level, reduction in external load) were effective in substantially reducing internal phosphorus recycling.

(2)**Method B - Calibrated using Sedimentation and Internal Loading Terms**. The phosphorus retention model is calibrated to predict the observed seasonal mean phosphorus concentration in Agency Lake (mean = 255 ppb, standard error = 29 ppb). Calibration is achieved by setting the sedimentation term to zero (treating external phosphorus loads as conservative in the lake) and specifying an additional "internal" phosphorus source of 1.78 mg/m^2-day (calibrated value). These terms are held fixed in simulating the Scenarios described below.

(3)**Method C - Calibrated using a Constant Scale Factor**. A scale factor of 2.51 is applied to the phosphorus concentration predicted by Method 1, so that the predicted concentration matches the observed concentration of 255 ppb. This assumes that the "typical" reservoir response is amplified by a constant factor which reflects internal loading or other unspecified mechanisms. The factor is held fixed in simulating the Scenarios described below.

Methods B and C represent the two methods which are available in BATHTUB for calibrating the phosphorus retention model to data from a specific reservoir. These represent alternative assumptions; lack of modeling studies documenting modelled responses to changes nutrient loading precludes identification of the "best" calibration procedure. Results discussed below are insensitive to these assumptions (i.e. results for Methods B and C are similar).

Four Scenarios represent different management strategies in a factorial design:

(1)**Scenario 1** - Existing Conditions (1991-1993 average)

(2)**Scenario 2** - 44% decrease in external phosphorus load

(3)**Scenario 3** - 30% increase average pool volume

(4)**Scenario 4** - 44% decrease in external phosphorus load and 30% increase in average pool volume

Table 10 summarizes flow and nutrient inputs for the modeled period (April-September, 1991-1993 average). Model inputs and outputs for each Method and Scenario are listed in Table 11. Figure 23 shows predicted phosphorus, mean chlorophyll-a, and bloom frequencies.

Discussion

Differences between the uncalibrated (Method A) and calibrated (Methods B,C) account for most of the variance among predictions. This reflects the strong influence of internal phosphorus recycling on the trophic state of Agency Lake. Under 1991-1993 conditions (Scenario 1), Method A predicts a mean total phosphorus concentration of 102 ppb (90% confidence interval = 81 to 122 ppb) and mean chlorophyll-a concentration of 30 ppb (90 % c.i. = 23 to 37 ppb). These are estimates of "typical" responses of a reservoir with external nutrient loadings, hydrology, and morphometry identical to those measured in 1991-1993. The importance of internal phosphorus recycling is indicated by comparing these predictions with the 1991-1993 observed values or with results predicted by the calibrated models (Total P = 255 ppb, Mean Chlorophyll-a = 78 ppb). Generally, predictions using calibration Methods B and C are similar for all four Scenarios.

Scenario 2 predicts lake conditions with a 44% reduction in external phosphorus load. This is intended to reflect lake conditions in the absence of anthropogenic phosphorus loads, using the concentration at Dixon Road (81 ppb) as an estimate of unimpacted lake inflow concentration. Method A predicts a mean phosphorus concentration of 67 ppb (90% c.i. = 55 to 77 ppb) and mean chlorophyll-a concentration of 18 ppb (90% c.i. = 14 to 22 ppb) in the absence of excessive internal recycling. This suggests that Agency Lake was eutrophic under natural or unimpacted conditions, but chlorophyll-a concentrations were below the classical hyper-eutrophic boundary (25-30 ppb, NALMS, 1988). Methods B and C predict much higher phosphorus levels (168-180 ppb) and chlorophyll-a levels well into the hypereutrophic range (70-72 ppb). This suggests a naturally hypereutrophic state, if phosphorus recycling rates were also high before watershed development occurred. Similarly, if a 44% reduction in external phosphorus loads were accomplished and if the current recycling rates were to continue, a decrease in trophic state from hypereutrophic to eutrophic would not be expected.

Results for Scenarios 3 and 4 suggest that a 30% increase in volume (depth) would result in relatively small decreases in phosphorus and chlorophyll-a concentrations. As for Scenarios 1 and 2, differences between Methods A and B/C are pronounced.

Based upon these results, excessive internal recycling is the primary factor driving hypereutrophic conditions in Agency Lake. It would be a mistake to conclude, however, that implementation of watershed nutrient controls or raising pool elevation would not have significant beneficial impacts. It is possible, if not likely, that decreases in external load or increases in depth would cause a decrease in internal phosphorus recycling, via the following mechanisms:

(1) Higher pool levels would decrease wind-induced turbulence at the sediment-water interface and thereby decrease sediment resuspension and other vertical phosphorus fluxes controlled by transport processes. Because Agency Lake is at the lower end of the CE model development data set with respect to depth (Table 6), these mechanisms may not be reflected in empirical phosphorus retention model.

(2) Strong correlations among pH, chlorophyll-a, and phosphorus releases from

bottom sediments (Figure 16) suggest that recycling is enhanced by high photosynthesis rates. Conversely, recycling would be expected to decrease in response to a decrease in algal productivity. This important feedback loop is not represented in the model.

(3)A portion of the recycled phosphorus may enter the lake during runoff events in the form of particulates rich in available phosphorus (characteristic of runoff from animal holding pens, for example). These materials may settle on the lake bottom and release nutrients to the water column following decomposition. Potential benefits of reducing these particulate inputs (in both winter and summer months) are not reflected in the model.

None of the above mechanisms are directly reflected in model predictions using calibration Methods B and C. With reductions in external load and/or increases in pool level, these mechanisms may cause a drift towards predictions generated by Method A. Direct modeling of these mechanisms is not possible with existing models, but may be feasible with substantial additional data-collection and modeling effort. Such an effort would dynamic modeling of water-column and sediment compartments at a time step no longer than one month.

The positive feedback loop inherent in the phosphorus recycling mechanism (i.e., phosphorus --> algae --> high pH --> more phosphorus --> more algae, etc.) poses an important chicken-or-egg type question. Once it is operating, this mechanism accelerates Agency Lake algal booms in early summer. Periods of negative phosphorus retention are associated with pH levels above ~9.4 and chlorophyll-a concentrations above ~40 ppb. It is possible, if not likely, that initiation of this process requires elevated lake phosphorus concentrations in Spring. Lake phosphorus concentrations must be high enough at the start of the growing season to generate the initial algal bloom which triggers phosphorus releases from bottom sediments and further accelerates the bloom during summer. This (albeit hypothetical) sequence of events may be important to understanding the linkage between the trophic state of Agency Lake and external nutrient inputs.

As a consequence of linkages between external and internal nutrient sources discussed above, algal populations in Agency Lake may be more sensitive to external loads than predicted by the model. This is further supported by observed differences in response between 1992 (dry year) and 1993 (wet year):

	1992	1993
Net Inflow (hm^3)	96	206
External P Load (mtons)	18.6	34.9
P Retention (mtons)	.8	-5.7
Lake P - April (ppb)	82	133
Mean Chl-a (ppb)	66	86
Frequency > 60 ppb	43%	58%

Frequency > 100 ppb	29%	43%

The lower external phosphorus load in 1992 was accompanied by a less internal recycling (more retention, 0.8 vs. -5.7 mtons) and a lower April phosphorus concentration. Although mean chlorophyll-a concentrations were not statistically different, algal blooms in the relatively dry summer of 1992 were less pronounced and shorter than those observed in the relatively wet summer of 1993 (see time series plots in Appendix A). These yearly differences cannot be successfully predicted with the existing model network, probably because of the network does not include the mechanistic linkages or feedback loops discussed above.

As discussed above, approximately 44% of the external load (Scenario 2) is attributed to anthropogenic impacts. On an annual basis, this corresponds to an anthropogenic load of 23 metric tons. This is a relatively small quantity relative to the phosphorus contained in animal waste generated in the watershed each year. The cattle population is estimated to exceed 75,000 (Kann, J., Personal Communication, 1995). At a phosphorus-equivalent of 17.6 kg/animal/year (Omernik, 1978), the cattle population generates more than 1,320 metric tons of phosphorus per year. The anthropogenic load reaching the lake (23 metric tons) amounts to less than 2% of the phosphorus contained in animal waste. Apparently, most of phosphorus in animal waste is retained in watershed soils or exported as crops. The fact that a small percentage of the animal waste is equivalent to the entire anthropogenic load reaching the lake reflects the potential sensitivity of the lake to agricultural practices. Even if adequate protection measures existed on most of the grazing lands, the load from only a few locations with inadequate protection measures could account for most of the anthropogenic impact. Examples of such locations would include holding areas or farmsteads discharging runoff directly into major tributaries and unfenced range lands allowing cattle access to streams. From a control perspective, this situation is desirable because it suggests that high percentage of the existing anthropogenic load might be controlled by applying control measures to relatively few source areas. Such areas could be identified in watershed inspections and areal photos.

Limitations in the data should also be considered in interpreting model results. The major limitation is the lack of continuous flow data at the mouth of each tributary. Although low variance in the concentration data suggests that the monthly sampling frequency is adequate for calculating loads, this could be misleading if significant loading events occurred between sampling dates. The estimated average phosphorus load from Sevenmile canal (~6 metric tons in April-September, 1991-1993) is ultimately based upon only 7 paired instantaneous flows and grab samples. More intensive flow and concentration data are needed to develop more reliable load estimates. Automated sampling equipment may be needed to capture loads generated by pumping events. Direct monitoring of runoff from the ungauged area on the west side of the lake below the Fourmile Canal station (Figure 2) is also recommended.

Given the above data limitations, it is possible external loads have been under-estimated. Phosphorus retention/recycling has been estimated by difference from lake inputs, outflows, and storage terms. If external loads have be under-estimated, the relative importance of internal nutrient recycling would be diminished and the potential benefits of external load reductions would be greater than those estimated above.

Conclusions & Recommendations

1. Based upon its morphometric and hydrologic features, Agency Lake is an ideal environment for algal growth.

2. Based upon phosphorus, chlorophyll-a, organic nitrogen, and other measures of trophic state, Agency Lake is hypereutrophic.

3. Nutrient mass-balance calculations indicate that there is no net phosphorus retention in Agency Lake on an annual-average basis. Internal sources of nitrogen approximately equal external sources on an annual-average basis.

4. Substantially negative retention rates are indicated for both phosphorus and nitrogen during the growing season. Negative phosphorus retention rates are highly correlated with pH and chlorophyll-a. These tend to occur in the early summer and are likely to reflect release of iron-bound phosphorus from lake bottom sediments during periods of photosynthetically-elevated pH. Negative nitrogen retention rates are likely to reflect fixation of atmospheric nitrogen by bluegreen algae.

5. Based upon the observed low nitrogen/phosphorus ratios in the water column, algae populations appear to be limited by nitrogen. Because of the high rates of nitrogen fixation, however, nitrogen concentrations are self-regulating and phosphorus is likely to be the ultimate limiting nutrient. Empirical trophic response models developed for Corps of Engineer reservoirs indicate an approximately linear chlorophyll-a/phosphorus response. This is further supported by linear relationships between summer phosphorus concentration and algal bloom frequency developed from Agency Lake data. Because of the shallow depth and dominance by flake-forming algae, light limitation is unimportant.

6. Based upon comparison of flow-weighted-mean phosphorus concentrations measured at various watershed monitoring stations, a increase in lake inflow concentration from 81 ppb to 144 ppb (44%) is one estimate of anthropogenic impact on Agency Lake.

7. Because of the importance of internal nutrient recycling and role of nitrogen limitation,

empirical nutrient loading models can be used in a limited way to evaluate benefits of nutrient management, water-level management, or other water quality control measures. Potential linkages between external and internal sources are not reflected in existing empirical models. For this reason, projections have been made for a range of assumed internal recycling rates.

8. The model has been used to predict lake response to various management scenarios, including existing conditions, a 44% reduction in external phosphorus load, and 30% increase in average summer volume and mean depth. A high sensitivity to internal recycling rates is indicated for all scenarios. Without anthropogenic loads (44% reduction), chlorophyll-a levels would range from eutrophic to hypereutrophic, depending upon whether the existing high rates of phosphorus recycling are maintained. A 30% increase in volume/depth would result in relatively small improvements. Actual improvements in water quality resulting from these scenarios may be substantially greater than those predicted by the model because the model does not directly simulate mechanisms linking the external and internal nutrient sources.

9. The modeling concept is useful for examining lake monitoring data in light of empirical relationships developed from other reservoir data sets. This provides useful insights on factors controlling eutrophication under existing conditions. Diagnostic insights gained through mass-balance calculations (model independent) are also useful.

10. In a predictive mode, the modeling effort is limited by (a) the extreme conditions in Agency Lake relative to the CE model development data set (shallow depth, high internal cycling rates, high chlorophyll-a concentrations, extreme nitrogen limitation) (b) the requirement for substantial recalibration of the phosphorus retention model; (c) lack of an independent data set (from a different time period, for example) to test the phosphorus calibration; and (d) the wide divergence of responses predicted for different assumptions regarding phosphorus recycling and nitrogen responses. For these reasons, model predictions are not definitive and should be interpreted cautiously.

11. The estimated anthropogenic phosphorus load corresponds to less than 2% of the phosphorus contained in waste from the watershed's cattle population. This suggests that targeting controls in potent source areas may be effective in reducing lake loads. Based upon watershed reconnaissance, potent source areas would include animal holding areas adjacent to streams and unfenced range adjacent to streams.

12. The low intensity of flow and concentration measurements at tributary stations is the major data limitation possibly influencing the mass-balance calculations and model results. More intensive data collection is recommended in the future, if

more accurate modeling results are needed or if the data are to be used for identifying important nutrient source areas. More accurate watershed delineations and land use inventories would also be useful.

13. Refinements to the mass balances and model calibrations could be developed within the constraints of historical data and other ongoing monitoring programs. Expansion of the model scope to include the entire Upper Klamath basin and additional years of monitoring data (1989-1994 vs. 1991-1993 analyzed here) would provide an improved basis for calibrating the trophic response models, evaluation of interactions between Upper Klamath and Agency Lakes, and a means for testing water budgets, based upon comparison of observed and predicted lake outflows.

References

Barbiero, R.P. and J. Kann, "The Importance of Benthic Recruitment to the Population Development of Aphanizomenon flow-aquae and Internal Loading in a Shallow Lake", Journal of Plankton Research, Volume 16, No. 11, pp. 1581-1588, 1994.

Cooke, G.D., E.B. Welch, S.A. Peterson, P.R. Newroth, Restoration and Management of Lakes and Reservoirs, Lewis Publishers, Second Edition, 1993.

Drake, E. T., G.L. Larson, J. Dymond, R. Collier, "Crater Lake - An Ecosystem Study", Sixty-Ninth Annual Meeting of the Pacific Division, American Association for the Advancement of Science, Oregon State University, Corvallis, Oregon, June 18-22, 1988.

Golterman, H.L., "Loading Concentration Models for Phosphate in Shallow Lakes", Hydrobiologia, 91, pp. 169-174, 1982.

Heiskary, S.A. and W.W. Walker, "Developing Phosphorus Criteria for Minnesota Lakes", Lake and Reservoir Management, Volume 4, No. 1, pp. 1-9, 1988.

Heiskary, S.A. and W.W. Walker, "Establishing a Chlorophyll-a Goal for a Run-of-the-River Reservoir", accepted for publication in Lake and Reservoir Management, 1995.

Klamath Tribe, Letter from Craig Bienz to Mark Buettner (USBR) and Rollie White (USFWS), 8 pp. & 12 Figures, December 1994.

North American Lake Management Society, "Lake and Reservoir Restoration Guidance Manual", U.S. Environmental Protection Agency, EPA 440/5-88-002, First Edition, February 1988.

Omernik, J. "Nonpoint Source - Stream Nutrient Level Relationships: A Nationwide Study", U.S. Environmental Protection Agency, EPA-600/3-77-105, September 1977.

Smeltzer, E., W.W. Walker, V. Garrison, "Eleven Years of Lake Eutrophication Monitoring in Vermont: A critical Evaluation", Enhancing States' Lake Management Programs, U.S. Environmental Protection Agency, pp. 53-62, 1989.

Stumm, W. and J.O. Leckie, "Phosphate Exchange with Sediments: Its Role in the Productivity of Surface Waters", Advances in Water Pollution Research, III-26, pp. 1-16, 1970.

U.S. Department of Interior, "Environmental Research in the Klamath Basin, Oregon", Bureau of Reclamation, Denver Office, Report R-93-13, April 1993.

U.S. Department of Interior, "Environmental Research in the Klamath Basin, Oregon", Bureau of Reclamation, Denver Office, Report R-93-16, September 1993.

U.S. Environmental Protection Agency, "National Eutrophication Survey Methods, 1973-1976", Working Paper No. 175, Pacific Northwest Environmental Research Laboratory, Corvallis, Oregon, June 1975.

Walker, W.W., "Empirical Methods for Predicting Eutrophication in Impoundments, Report 3 - Model Refinements", prepared for Office of Chief, U.S. Army Corps of Engineers, Technical Report E-81-9, Waterways Experiment Station, Vicksburg, Mississippi, March 1985.

Walker, W.W., "Empirical Methods for Predicting Eutrophication in Impoundments, Report 4 - Applications Manual", prepared for Office of Chief, U.S. Army Corps of Engineers, Technical Report E-81-9, Waterways Experiment Station, Vicksburg, Mississippi, July 1987.

Walker, W.W., "Reservoir Eutrophication Modeling Worksheet - CNET.WK1", North American Lake Management Society, Technology Transfer, Software Package No. 2, 1990.

Walker, W.W. and K. Havens, "Relating Algal Bloom Frequencies to Phosphorus Concentrations in Lake Okeechobee", accepted for publication in Lake and Reservoir Management, 1995.

Table 7
BATHTUB Model Network Applied to Agency Lake

Variable Definitions:

a	=	Nonalgal Turbidity (m^{-1})
b	=	Chlorophyll-a / Secchi Slope (m^2/mg)
As	=	Surface Area of Segment (km^2)
B	=	Chlorophyll-a Concentration (mg/m^3)
Bx	=	Nutrient-Potential Chlorophyll-a Concentration (mg/m^3)
Bo	=	Observed Mean Chlorophyll-a (mg/m^3)
Cp	=	Calibration Factor for P Sedimentation Rate
Cb	=	Calibration Factor for Chlorophyll-a
Fot	=	Tributary Ortho-P Load/Tributary Total P Load
G	=	Kinetic Factor Used in Chlorophyll-a Model
Kp	=	Scale Factor for Predicted Total P Concentration
N	=	Reservoir Total Nitrogen Concentration (mg/m^3)
Norg	=	Organic Nitrogen Concentration (mg/m^3)
Nr	=	Dimensionless Second-Order Sedimentation Rate for Phosphorus
P	=	Total Phosphorus Concentration (mg/m^3)
Pi	=	Inflow Total P Concentration (mg/m^3)
PC-1	=	First Principal Component of Response Measurements
PC-2	=	Second Principal Component of Response Measurements
Qs	=	Surface Overflow Rate (m/yr)
S	=	Secchi Depth (m)
So	=	Observed Secchi Depth (m)
T	=	Hydraulic Residence Time (years)
V	=	Mean Volume (hm^3)
Xpn	=	Composite Nutrient Concentration (mg/m^3)
Z	=	Total Depth (m)
Zmix	=	Mean Depth of Mixed Layer (m)
Qnet	=	Net Inflow = External Inflow + Precip - Evap. (hm^3/yr)
Wp	=	External Total P Load (kg/yr)
Wint	=	Net Internal P Recycling Rate (mg/m^2-day)

Calibration Factors:

Phosphorus Retention

Method A - Cp = 1.0, Wint = 0.0, Kp = 1.0

Method B - Cp = 0.0, Wint = 1.78, Kp = 1.0

Method C - Cp = 1.0, Wint = 0.0, Kp = 2.51

Chlorophyll-a Model

b = .012 (from .025)

Cb = 0.87 (from 1.0)

Table 7 (ct)

Model Equations:

Phosphorus Retention (BATHTUB P Model 2):

$T = V / Qnet$

$Qs = Qnet / As$

$Pi = Wp / Qnet$

$Nr = Cp\ Pi\ T\ 0.056\ Fot^{-1}\ Qs / (Qs + 13.3)$

$P = Kp \{ Pi [-1 + (1 + 4\ Nr)^{0.5}] / (2\ Nr) + 365.25\ Wint / Qs \}$

Chlorophyll-a (BATHTUB Chl-a Model 1):

$a = 1 / (Bo - b\ So)$

$Xpn = [P^{-2} + ((N-150)/12)^{-2}]^{-0.5}$

$Bx = Xpn^{1.33} / 4.31$

$G = Zmix\ (0.14 + 0.0039 / T)$

$B = Cb\ Bx / [(1 + b\ Bx\ G) (1 + G\ a)]$

Transparency:

$S = 1 / (a + b\ B)$

Organic Nitrogen:

$Norg = 157 + 22.8\ B + 75.3\ a$

Total P - Ortho P:

$P - Portho = -4.1 + 1.78\ B + 23.7\ a$

Principal Components:

$PC\text{-}1 = 0.554 \log(B) + 0.359 \log(Norg) + 0.583 \log(Xpn) - 0.474 \log(S)$

$PC\text{-}2 = 0.689 \log(B) + 0.162 \log(Norg) - 0.205 \log(Xpn) + 0.676 \log (S)$

Figure 1
Regional Map

Figure 17
Seasonal Variations in Trophic State Indicators
1=Mar-May, 2=June-Aug, 3=Sept-Nov, 4=Dec-Feb

Figure 18
Annual Variations in Trophic State Indicators
June-August Samples
1=1991, 2=1992, 3=1993

Figure 19
Spatial Variations in Trophic State Indicators
June-August Samples, 1991-1993
1=Agency North, 2=Agency South, 3=Upper Klamath Lake

Figure 20
BATHTUB Empirical Model Network
(Walker, 1987)

Percentiles
90%
75%
50%
25%
10%

90% C.I. for Median