# Evaluation of Water and Nutrient Balances for the Upper Klamath Lake Basin in Water Years 1992-2010

*Prepared for*

***Klamath Tribes Natural Resources Department***

*By*

***Aquatic Ecosystem Sciences LLC***
In association with

***W. Walker, Ph.D. and J. Walker, M.Eng. Environmental Engineers***

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***KLAMATH TRIBES NATURAL RESOURCES DEPARTMENT***
P.O. Box 436
Chiloquin, OR 97624

By

**William W. Walker, Jr., Ph.D.**
**Jeffrey D. Walker, M.Eng.**
***ENVIRONMENTAL ENGINEERS***
1127 Lowell Road
Concord, Massachusetts 01742
e-mail: bill@wwwalker.net
http://www.wwwalker.net

**and**

**Jacob Kann, Ph.D.**
***AQUATIC ECOSYSTEM SCIENCES LLC***
295 East Main St., Suite 7
Ashland, OR 97520
e-mail: aqecoscillc@gmail.com
http://www.aquatic-ecosciences.com

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# ABBREVIATIONS

| Abbreviation | Description |
|---|---|
| **AgriMet** | Pacific Northwest Cooperative Agricultural Weather Network |
| **ALR** | Agency Lake Ranch |
| **FWM** | Flow Weighted Mean (= Load/Flow Volume) |
| **GMA** | Graham Matthews & Associates |
| **KBRT** | Klamath Basin Range Trust |
| **NCDC** | National Climatic Data Center |
| **ODEQ** | Oregon Department of Environmental Quality |
| **PET** | Potential Evapotranspiration |
| **ppb** | Parts per Billion (ug/L) |
| **SRP** | Soluble Reactive Phosphorus |
| **TMDL** | Total Maximum Daily Load |
| **TN** | Total Nitrogen |
| **TP** | Total Phosphorus |
| **UKL** | Upper Klamath and Agency Lakes |
| **USBLM** | U.S. Bureau of Land Management |
| **USBR** | U.S. Bureau of Reclamation |
| **USEPA** | U.S. Environmental Protection Agency |
| **USGS** | U.S. Geological Survey |
| **WY** | Water Year (October – September) |

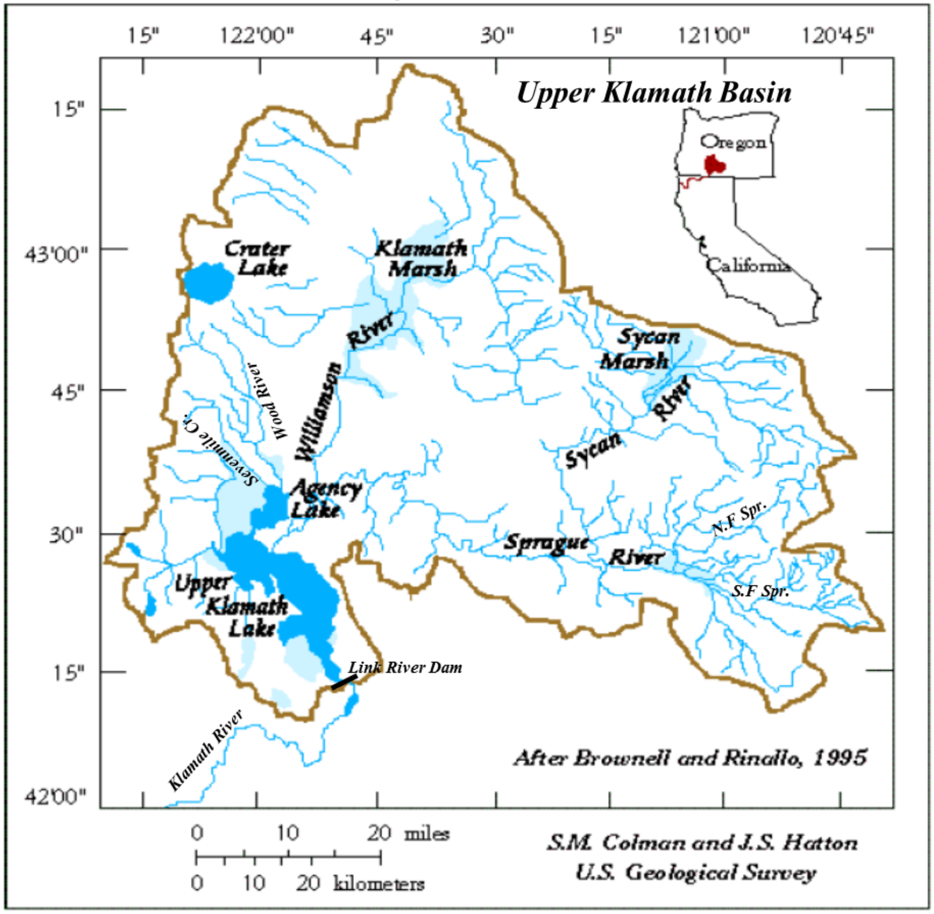
# UNITS

| Multiply | By | To obtain |
|---|---|---|
| hm | 100 | m |
| hm | 328.1 | ft |
| $km^2$ | 247.1 | acres |
| $km^2$ | 0.386 | $mi^2$ |
| $hm^3$ | $10^6$ | $m^3$ |
| $hm^3$ | 0.001 | $km^3$ |
| $hm^3$ | 810.7 | acre-feet |
| $hm^3/yr$ | 1.12 | $ft^3/s$ (cfs) |
| $hm^3/yr$ | 0.0317 | $m^3/s$ |
| kg | 2.205 | lb |
| mt | 1,000 | kg |
| mt/yr | 2.74 | kg/day |
| mt/yr | 6.042 | lb/day |
| $kg/km^2$ | $8.92 \times 10^{-3}$ | lb/acre |
| µg/L (ppb) | 0.001 | mg/L (ppm) |

# 1 INTRODUCTION

Upper Klamath and Agency Lakes (UKL) comprise a large, shallow, hypereutrophic lake system located in south-central Oregon (Figure 1) that is seasonally dominated by large blooms of the nitrogen-fixing cyanobacterium *Aphanizomenon flos-aquae* (Kann, 1998; Kann and Smith, 1999). Bloom-driven water quality degradation that includes extended periods of low dissolved oxygen, elevated pH, and toxic levels of un-ionized ammonia has been associated with the decline of native endangered fish populations, including the Federally Listed shortnose (*Chasmistes brevirostris*) and Lost River (*Deltistes luxatus*) suckers (Perkins et al., 2000). More specifically these conditions have been linked to large die-offs and redistribution of the endangered sucker species in UKL (Perkins et al., 2000; Kann and Welch, 2005; Banish et al., 2009).

**Figure 1: Map of Upper Klamath Lake Basin**



Several studies have documented that recurring algal blooms and their decline are associated with periods of elevated pH, toxic levels of un-ionized ammonia, and depressed dissolved oxygen concentrations (Wood et al., 2006; Hoilman et al., 2008; Lindenberg et al., 2009; Kannarr et al., 2010; Jassby and Kann, 2010). Based on exceedances of water quality standards for dissolved oxygen, pH, and chlorophyll (algal biomass), both lakes were designated as water quality limited for resident fish and aquatic life (ODEQ, 1998).

## 1.1 Historical Perspective

Paleolimnological evidence indicates that *Aphanizomenon flos-aquae* blooms (as indicated by *Aphanizomenon flos-aquae* akinetes preserved in lake sediments) did not appear in UKL until the latter part of the 19th century and increased substantially after that time (Bradbury et al., 2004; Eilers et al., 2004). These studies as well as a more recent coring study also showed increases in various indicators (e.g. Ti, Al, tephra, and charcoal) of watershed erosional inputs to UKL in the 20th century (Bradbury et al., 2004; Eilers et al., 2004; Simon and Ingle, 2011). Increases in the sediment accumulation rate, sediment enrichment in upper layers of both nitrogen (N) and phosphorus (P) compared to pre-settlement sediment (Eilers et al., 2004), and a decrease in the ratio of N to P in the upper sediment layers (likely due to an increase in P loading relative to N loading in the 20th century) have also been documented (Eilers et al., 2004; Simon and Ingle, 2011).

Watershed activities beginning in the late 1800s and accelerating though the 1900s included: 1) timber harvest, 2) drainage of wetlands, 3) agricultural activities associated with livestock grazing and irrigated cropland, and 4) hydrologic modifications such as water diversions and channelization (ODEQ, 2002; Bradbury et al., 2004; Eilers et al., 2004). These activities are the main causes for the increased erosion and loading of nutrients (particularly P) from the watershed that are generally contemporaneous with the increase in Upper Klamath Lake's trophic state and shift to dominance by large blooms of blue-green algae (ODEQ, 2002).

## 1.2 Importance of Phosphorus

Excessive P loading linked to watershed development has been determined to be a key factor driving the massive *Aphanizomenon* blooms that dominate Upper Klamath Lake. Based upon analysis of extensive water quality monitoring datasets and mathematical modeling of the lake phosphorus, algal bloom, and pH dynamics, the Oregon Department of Environmental Quality (ODEQ, 2002) determined that reduction of phosphorus loads from anthropogenic sources would be the most effective means of improving water quality conditions in the lake. This approach was supported by the elevated P concentrations and unit area P loads observed in discharges from pumped agricultural areas and tributary outflows, as compared with background levels observed in springs and tributary headwaters. This approach is further supported by recent pasture-level monitoring showing that first-flush irrigation events and storm events have the potential to export large quantities of P from irrigated grazing land in the UKL basin (Ciotti et al., 2010). While other researchers hypothesized that reduced humic substances associated with the loss of wetlands may also play a role in the shift to *Aphanizomenon* dominance, they ultimately concluded that the ODEQ (2002) approach of reducing algal biomass and improving water quality through phosphorus reduction was complementary but not inconsistent with their hypothesis (Milligan et al., 2009).

The management strategy of reducing excessive P loads to achieve water quality standards is consistent with several recent reviews of nutrient control concluding that reduction of P inputs rather than N is the most effective means to reduce eutrophication (Schindler et al., 2008;

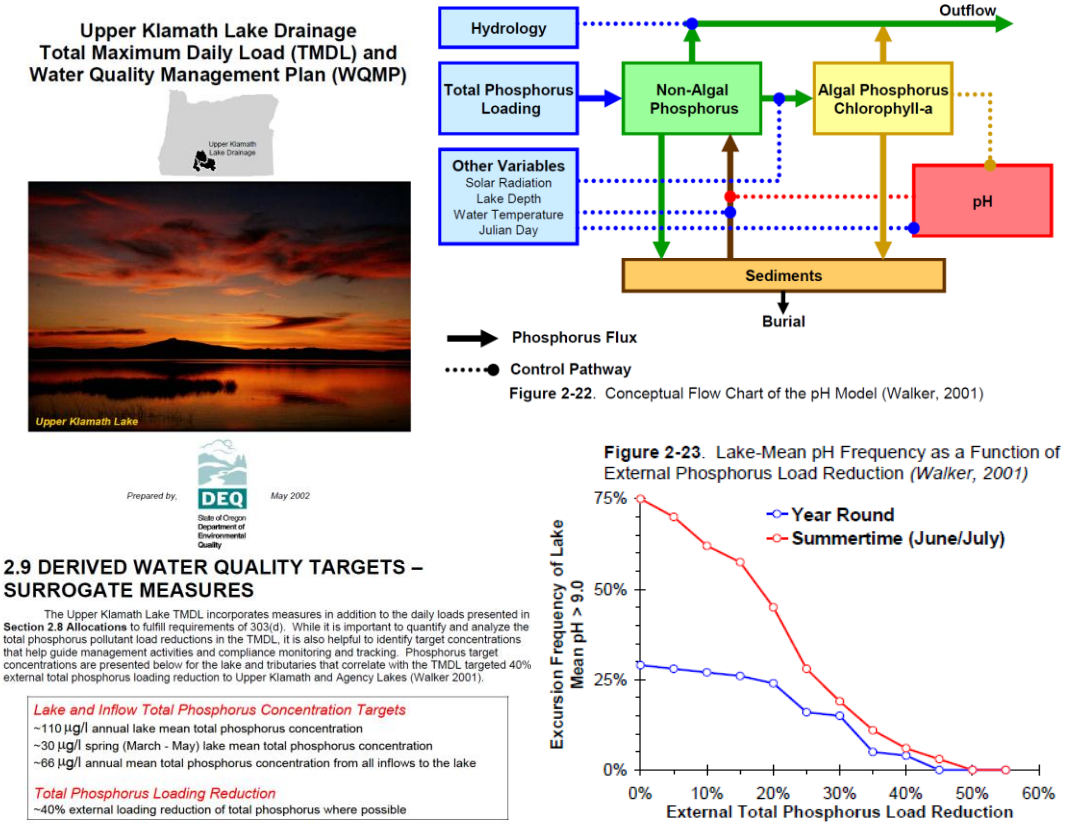
Carpenter, 2008; Smith and Schindler, 2009). P reduction in systems such as UKL where low N:P ratios (especially when caused by high phosphorus) in the total nutrient supply favor bloom-forming blue-green algae is especially important because N-limitation can be overcome through fixation of atmospheric N in sufficient quantities to allow continued growth of biomass in proportion to phosphorus (Schindler et al., 2008). Further evidence for P limitation of algal biomass in UKL has been shown by suppressed concentrations of bioavailable P (soluble reactive phosphorus (SRP) or ortho-P) during bloom development in June-July and by observed chlorophyll-a to total phosphorus ratios exceeding 1.0 during peak bloom conditions, which indicates that nearly all of the phosphorus is tied up in algal cells (Kann, 2011a; Lindenberg et al., 2009). To some extent, any remnant debates over which nutrient should be controlled are irrelevant because management measures taken to reduce loads, such as wetland restoration and improvements in agricultural operations, would be likely to reduce both N and P loads

Given the importance of P in controlling the severe algal blooms and adverse water quality conditions, a P budget (mass balance accounting of the various external P sources, outflows, storage, and net retention within the lake) is needed to evaluate effects of land and water uses on water quality and to develop effective control programs for achieving water quality standards. External P sources include 1) fluvial inputs from streams draining the catchment, 2) runoff and irrigation-return waters pumped from agricultural areas adjacent to the lake and tributaries 3) diffuse sources such as springs and marshes, and 4) atmospheric deposition. Lake and outflow P levels are driven by external P loads and cycling between the water column and bottom sediments (Figure 2). While “internal P loads” released from bottom sediments in early summer contributes to algal blooms, they ultimately reflect antecedent external P loads that are stored and recycled from the bottom sediments over long time frames. Although the P mass balance allows estimation of the net retention of P within the lake sediments (difference between sedimentation and release, which essentially represents assimilative capacity), mathematical modeling of the various processes would be required to evaluate P fluxes to and from the sediments and lake water quality responses, as measured by seasonal variations in P concentration, chlorophyll-a, and pH, in response to variations in external P load, climate, and other controlling factors.

## 1.3 Previous Nutrient Budget and TMDL Development

Kann and Walker (1999) developed initial water and nutrient budgets for the April 1991-September 1998 period using water quality and hydrologic data collected by various agencies, including the Klamath Tribes, U.S. Bureau of Reclamation (USBR), and U.S. Geological Survey (USGS). A P mass-balance model (Figure 2) was subsequently developed for simulating the linkage between external phosphorus load, internal P cycling processes, and spatially-averaged lake water quality, expressed in terms of means and frequency distributions of total phosphorus (TP), chlorophyll-a, and pH (Walker, 2001). The historical P budgets and model were utilized by ODEQ (2002) to establish a management targets for lake P concentrations and external P loads consistent with achieving lake water quality standards for algal biomass (expressed as chlorophyll a), and pH, as required under the Total Maximum Daily Load (TMDL) regulations established under the Clean Water Act (Figure 2). The TMDL was expressed in terms of a long-term-average P load (TMDL terminology notwithstanding) under hydrologic conditions that occurred in that 7-year historical period of record (Water Years (WY) 1992-1998, or October 1991-September 1998). Achieving the loading target (109 metric tons/year of TP) would require a 40% reduction in external P load relative to the historical baseline. The corresponding average inflow TP concentration (66 ppb) was similar to average value measured in springs and other relatively un-impacted sources in the watershed, which were assumed to represent natural background conditions.

**Figure 2: Upper Klamath Lake TMDL (ODEQ, 2002)**



Upper Klamath Lake Drainage
Total Maximum Daily Load (TMDL) and
Water Quality Management Plan (WQMP)

Prepared by, DEQ State of Oregon Department of Environmental Quality May 2002

2.9 DERIVED WATER QUALITY TARGETS – SURROGATE MEASURES

The Upper Klamath Lake TMDL incorporates measures in addition to the daily loads presented in **Section 2.8 Allocations** to fulfill requirements of 303(d). While it is important to quantify and analyze the total phosphorus pollutant load reductions in the TMDL, it is also helpful to identify target concentrations that help guide management activities and compliance monitoring and tracking. Phosphorus target concentrations are presented below for the lake and tributaries that correlate with the TMDL targeted 40% external total phosphorus loading reduction to Upper Klamath and Agency Lakes (Walker 2001).

*Lake and Inflow Total Phosphorus Concentration Targets*
~110 μg/l annual lake mean total phosphorus concentration
~30 μg/l spring (March - May) lake mean total phosphorus concentration
~66 μg/l annual mean total phosphorus concentration from all inflows to the lake

*Total Phosphorus Loading Reduction*
~40% external loading reduction of total phosphorus where possible

**Figure 2-22**. Conceptual Flow Chart of the pH Model (Walker, 2001)

**Figure 2-23**. Lake-Mean pH Frequency as a Function of External Phosphorus Load Reduction *(Walker, 2001)*

## 1.4 Recent Efforts

Substantial research, water quality monitoring, watershed management, and wetland restoration management efforts have occurred since development of the WY 1992-1998 nutrient budgets (Kann and Walker, 1999) that provided a baseline for the TMDL (ODEQ, 2002). Several of the large drained wetlands on the periphery of UKL are no longer grazed or farmed, and are in varying stages of restoration (e.g. Wong et al., 2011; USBLM, 2005; Carpenter et al., 2009; Duff et al., 2011). Watershed conservation projects such as those implemented by the Klamath Basin Rangeland Trust (KBRT) in the Wood River and Sevenmile Creek drainages have sought to reduce water use and decrease nutrient export from grazed areas (e.g. GMA, 2011a; GMA, 2011b). While the effectiveness of individual management measures and lake responses are difficult to predict, net benefits and progress towards achieving the TMDL goal can be assessed by continued monitoring of the tributaries and lake after implementation of the control program. An additional 12 years (WY

1999-2010) of biweekly concentration and flow data are currently available from long-term monitoring programs undertaken by the Klamath Tribes in 1991 and used as the primary basis for constructing the WY 1992-1998 budgets (Kann, 2011a; Kann, 2011b). The Tribe monitoring program was expanded in 2001 to include additional stations in the Sprague River basin. Additional monitoring data from other agencies including U.S. Geological Survey (USGS), Klamath Basin Range Trust (KBRT), U.S. Bureau of Reclamation (USBR), and U.S. Bureau of Land Management (USBLM) provide a basis for evaluating discharges from agricultural watersheds and restored wetlands. These additional data support recalculation of the water and nutrient budgets for the entire 19 year period of record (WY 1992-2010), as well as analysis of trends in individual sources and components of the overall lake nutrient budgets.

## 1.5 Objectives and Tasks

The primary objective of the current effort is to develop hydrologic and nutrient budgets for UKL for the 19- year period record (WY 1992-2010). The updated analysis utilizes substantial hydrologic and water quality data collected by various agencies in the lake, lake outflow, major tributaries, sub-watersheds, and agricultural areas adjacent to the lake, portions of which were restored to wetlands over the WY 1998-2010 period. Relatively minor refinements to WY 1992-1998 budgets are made to reflect adjustments to the historical hydrologic data, additional water quality data from pumped agricultural areas and restored wetlands, and an improved method for computing daily nutrient loads based upon daily flow and biweekly water quality measurements at the major monitoring sites.

One secondary objective is to evaluate time-series trends in flow, nutrient load, and concentrations in each inflow and in the overall lake nutrient budget terms (total inflow, outflow, storage, retention) to determine whether changes occurred over the WY 1992-2010 time period in response to management efforts or other factors.

Another secondary objective is to differentiate between background and anthropogenic nutrient sources based upon spatial variations in unit area export (load / drainage area) and flow-weighted-mean concentration (FWM = load / flow volume) across watershed monitoring sites.

Specific tasks for the WY 1992-2010 analysis include:

1. Compile all relevant data (nutrient concentration, flow, water level, precipitation, evaporation) for tributaries, pumped agricultural areas, lake, and lake outflow to develop monthly time series for flow, load, and FWM concentration at watershed sites and components of the overall lake nutrient balances (inflow, outflow, storage, net retention).

2. Update the previous hydrologic and nutrient budgets for UKL using the above generated time-series data and summarize at monthly, seasonal, yearly, and multi-year time intervals.

3. Provide tabular and graphical analyses of inter-annual and seasonal variations in TP and total nitrogen (TN) loading for inflow and outflow stations, and for storage and net retention of nutrients in the lake.

4. Summarize seasonal and annual variations in concentrations of nutrient species (TP, SRP, TN, NH4-N and NO23-N) at major tributary monitoring sites.

5. Perform trend analyses using both nonparametric (seasonal Kendall test) and parametric (linear regression) statistical techniques to evaluate time-series trajectories in the flow volumes, total nutrient loads, and FWM concentrations associated with each individual source and component of the lake mass balances over the 19-year period of record.

6. Evaluate spatial variations in flow, total nutrient loads and FWM concentrations throughout the watershed. These variations reflect the relative contributions of natural background and anthropogenic sources. To the extent possible with the existing data, parse out sub-watershed loading and unit area export for various reaches of the Wood River, Sevenmile Creek, and Sprague River systems.

Detailed results of the mass balance computations are contained in Appendix E. The main goal of this effort is not to comprehensively analyze and interpret the budgets and trends, but rather to generate the information needed to support further analyses, interpretation, and modeling. Additional efforts would be needed to place results in the context of the specific management measures implemented during this period, assess the magnitude and effect of climatic trends on inflows and nutrient loads, and evaluate responses of the lake internal nutrient dynamics to variations in external nutrient loads and other controlling factors.

# 2 METHODOLOGY AND DATA SOURCES

Whole-lake water and nutrient balances were computed at a monthly time step for WY 1992-2010 and summarized by water year and multi-year periods in Appendix E. Nutrient balances were computed for total phosphorus (TP) and total nitrogen (TN). Mass balances for individual nutrient species were not included as they would be difficult to interpret due to their strong dependence on transformations occurring within the lake as result of various physical and biogeochemical mechanisms. Seasonal and annual variations in individual nutrient species at the primary sampling stations are presented in Appendix H. TP inflows and mass balances are of major importance from a management perspective because they are linked to the TMDL goal (ODEQ, 2002) and reflect the net performance of ongoing efforts to achieve lake water quality goals by reducing anthropogenic sources in the watershed. The benefits of the source controls would also be reflected in the external TN loads, although the lake mass balances are incomplete because they do not differentiate between sediment regeneration and fixation of atmospheric nitrogen by blue-green algae within the lake. Methods used to quantify each water and mass balance term are generally similar to those used by Kann and Walker (1999) except where noted below.

Details on the data sources, methods, and results are contained in several Appendices:

| | |
|---|---|
| A | Precipitation and Evaporation Datasets |
| B | Flows & Nutrient Loads from Gauged Tributaries |
| C | Flows & Nutrient Loads from Pumped Farmlands and Restored Wetlands |

D Spatial Variations in Flow, Nutrient Loads, and Nutrient Concentrations
E Lake Water & Nutrient Mass Balances
F Seasonal & Annual Variations in Mass Balance Terms
G Seasonal Kendall Tests for Trends in Flow, Load, and Flow-weighted Mean Concentration
H Annual and Seasonal Variations in Nutrient Species Concentrations

## 2.1 Water and Nutrient Budgets

The overall water budget of the lake was computed at monthly time intervals as follows:

*ΔLake Storage = Precipitation + Gauged Tributary Inflows + Pumped Inflows + Ungauged Inflows – Evaporation – Outflow – Net Retention*

Each term except for ungauged inflows and net retention was either directly measured or independently estimated, as described in the following sections. The gauged tributary inflows include the Wood River, Sevenmile Canal, and Williamson River. Pumped inflows from agricultural areas and restored wetlands adjacent to the lake were estimated using limited flow and concentration data. Ungauged inflows, which include groundwater seepage, springs and runoff from local ungauged watersheds, were then computed by difference and constrained to non-negative values. The net retention term represents the overall error in the water budget that results in months when the computed ungauged inflows are negative.

The nutrient (TP and TN) budgets of the lake were computed at monthly intervals as follows:

*Δ Lake Storage = Atmospheric Deposition + Gauged Tributary Load + Pumped Loads + Ungauged Inflow Loads – Outflow Load - Net Retention*

Each term was evaluated based on direct measurements or independent estimates except for net retention, which was calculated by difference. Net retention captures the cumulative effects of errors in the water budget, uncertainty in the measurements or estimates of the individual loading terms, and net nutrient losses from the lake water column associated with exchanges with the bottom sediments and/or atmosphere.

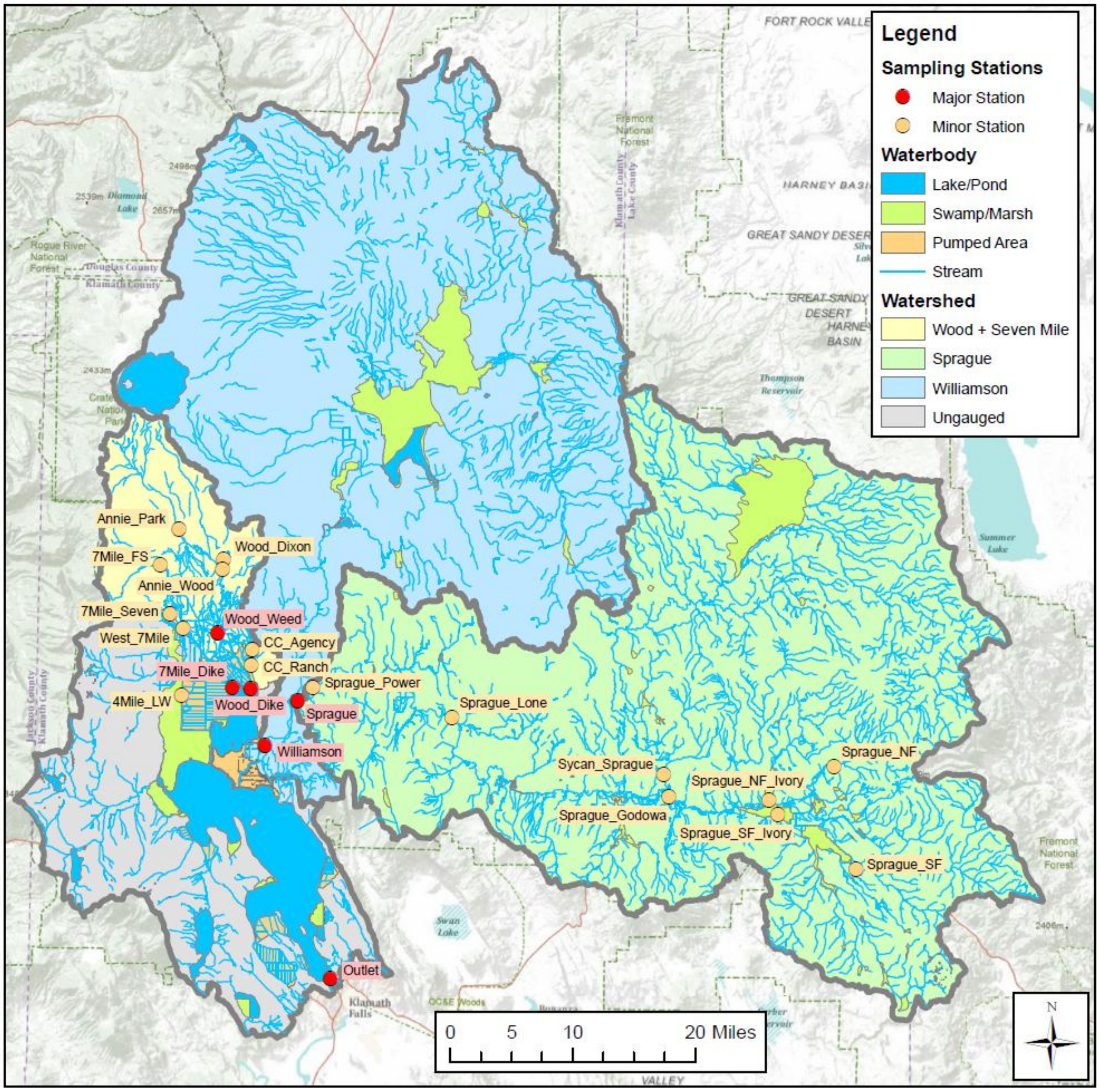
## 2.2 Data Sources

Sources of data used to evaluate the water and nutrient budget terms are summarized in Table 1. Figure 3 shows the gauged and ungauged watersheds, pumped areas, and locations of major monitoring sites (red) used to construct the lake budgets over the WY 1992-2010 period. Data from additional stations (yellow) were used to evaluate spatial variations in nutrient concentrations across the watershed in WY 2002-2010 (Section 3.5). Maps with higher spatial resolution are contained in Appendices C and D.

## Table 1: Data Sources

| Mass Balance Term | Water Years | | Source |
|---|---|---|---|
| | First | Last | |
| **Lake Storage and Outflow** | | | |
| Lake Elevation | 1992 | 2010 | USBR Hydrology Data for Upper Klamath Lake<br>http://www.usbr.gov/mp/kbao/operations/water/korep1.cfm?lakeid=ukldata1 |
| Lake Volume & Area | 1992 | 2010 | USBR Elevation/Capacity Table (personal communication) |
| Link River - Flow | 1992 | 2010 | USGS - Station 11507500<br>http://waterdata.usgs.gov/usa/nwis/uv?11507500 |
| A Canal - Flow | 1992 | 2010 | USBR Hydrology Data for A Canal<br>http://www.usbr.gov/mp/kbao/operations/water/korep1.cfm?lakeid=ukldata3 |
| Lake - Water Quality | 1992 | 2010 | Klamath Tribes (Kann, 2011a and earlier reports) |
| Link River - Water Quality | 1992 | 2010 | Klamath Tribes (Kann, 2011a; Kann, 2011b and earlier reports) |
| | 2007 | 2010 | USBR (personal communication) |
| | 2009 | 2010 | Pacificorp (personal communication) |
| **Precipitation and Evaporation (Appendix A)** | | | |
| Evaporation | 1992 | 2003 | Oregon State University, Klamath Lake Experiment Station (Kann and Walker, 1999) |
| | 2004 | 2010 | AgriMet - Station KFLO (USBR, 2012) |
| Precipitation | 1992 | 2010 | NCDC - Stations in Klamath Falls and Chiloquin (NCDC, 2012a and 2012b; see Table A1 in Appendix A for details) |
| | 2000 | 2010 | Agrimet - Stations KFLO and AGKO (USBR, 2012) |
| **Tributary Inflows (Appendix B)** | | | |
| Williamson River - Flow | 1992 | 2010 | USGS - Station 11502500<br>http://waterdata.usgs.gov/usa/nwis/uv?11502500 |
| Williamson River - Water Quality | 1992 | 2010 | Klamath Tribes (Kann, 2011b and earlier reports) |
| Sprague River - Flow | 1992 | 2010 | USGS - Station 11501000<br>http://waterdata.usgs.gov/usa/nwis/uv?11501000 |
| Sprague River - Water Quality | 1992 | 2010 | Klamath Tribes (Kann, 2011b and earlier reports) |
| Wood River at Weed Road and Dike Road, Sevenmile Canal at Dike Road - Flow and Water Quality | 1992 | 2010 | Klamath Tribes (Kann, 2011b and earlier reports) |
| | 2002 | 2007 | KBRT (GMA, 2011a, 2011b and earlier reports) |
| | 1992 | 1993 | USBR (Campbell et al, 1993) |
| Minor Tributary Stations - Flow and Water Quality | 1990 | 2006 | Klamath Tribes (Kann, 2011b and earlier reports; Kann and Walker 1999) |
| Ungauged Areas - Flow | 1992 | 2010 | Computed from Water Budget (Section 2.7) |
| Ungauged Areas - Water Quality | 1992 | 2010 | Klamath Tribes - Spring Stations (Kann, 2011b and earlier reports; Kann and Walker 1999) |
| **Agricultural & Wetland Restoration Projects (Appendix C)** | | | |
| Wood River Ranch | 1995 | 2010 | USBLM (2005 and personal communication) |
| | 1992 | 1995 | USGS (Snyder and Morace, 1997) |
| Agency Lake Ranch | 2000 | 2010 | USBR (personal communication) |
| | 1992 | 1995 | USGS (Snyder and Morace, 1997) |
| Other Pumped Areas | 1992 | 2010 | Klamath Tribes (personal communication); Kann and Walker (1999) |
| | 1992 | 1995 | USGS (Snyder and Morace, 1997) |

Figure 3: Map of Watersheds and Tributary Sampling Stations

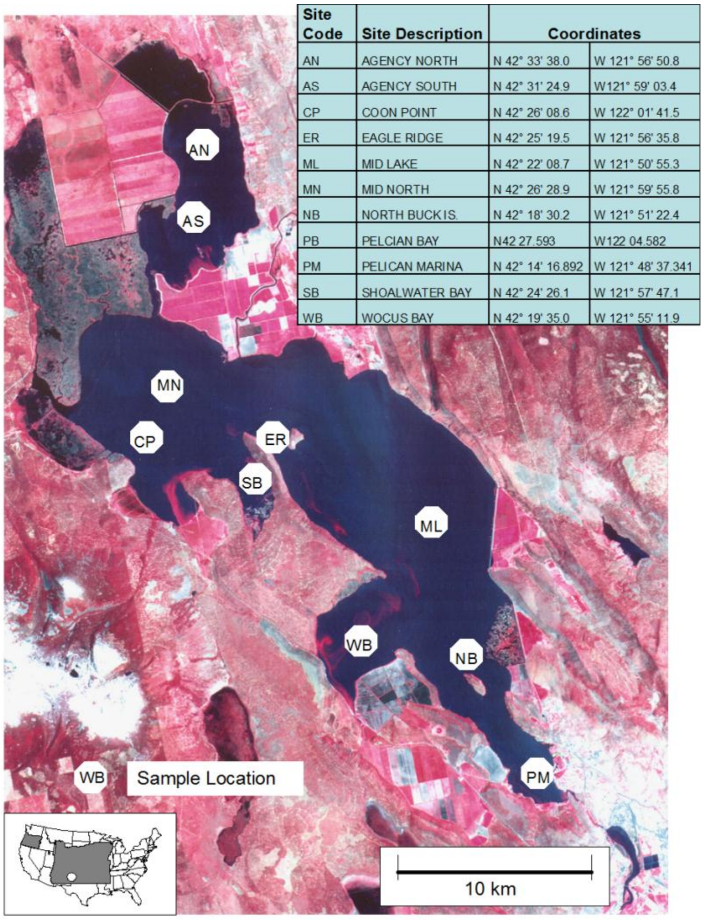


## 2.3 Lake Storage and Outflow

The total volume of water stored in the lake was computed from daily water level observations using an elevation-capacity relationship provided by USBR. Water level data were obtained from USGS station 11507001 as reported by USBR (Table 1).

The storage of nutrients in the lake was computed based on biweekly concentration data provided primarily by the Klamath Tribes (Kann, 2011a) for ten in-lake stations (Figure 4). Lake outlet concentrations provided by USBR, Pacificorp, and the Klamath Tribes were used in the winter

**Figure 4: Map of Klamath Tribes Upper Klamath Lake biweekly sampling stations.**



| Site Code | Site Description | Coordinates | |
|---|---|---|---|
| AN | AGENCY NORTH | N 42° 33' 38.0 | W 121° 56' 50.8 |
| AS | AGENCY SOUTH | N 42° 31' 24.9 | W121° 59' 03.4 |
| CP | COON POINT | N 42° 26' 08.6 | W 122° 01' 41.5 |
| ER | EAGLE RIDGE | N 42° 25' 19.5 | W 121° 56' 35.8 |
| ML | MID LAKE | N 42° 22' 08.7 | W 121° 50' 55.3 |
| MN | MID NORTH | N 42° 26' 28.9 | W 121° 59' 55.8 |
| NB | NORTH BUCK IS. | N 42° 18' 30.2 | W 121° 51' 22.4 |
| PB | PELCIAN BAY | N42 27.593 | W122 04.582 |
| PM | PELICAN MARINA | N 42° 14' 16.892 | W 121° 48' 37.341 |
| SB | SHOALWATER BAY | N 42° 24' 26.1 | W 121° 57' 47.1 |
| WB | WOCUS BAY | N 42° 19' 35.0 | W 121° 55' 11.9 |

months (November – April) when the lake was not sampled. The spatial geometric means of the measured biweekly lake concentration data were linearly interpolated to a daily time step and multiplied by the lake volume to compute daily nutrient storage. Because the magnitude of Agency Lake TP means tended to be higher than those for UKL, measurements from Agency Lake and the main lake were averaged separately before computing the lake-wide mean (for each sampling interval when both lakes were sampled the area-weighted lake mean from the Agency and Klamath Lake stations were computed using weights of 35.6 km2 and 235.4 km2, respectively). Monthly changes in water and nutrient storage were computed from the interpolated daily values at the end of each month.

Outflow volumes were based on data from continuous gaging stations located on the A Canal (USBR, 2011) and Link River near the outlet of the lake (USGS Station 11507500). The Link River flows used by Kann and Walker (1999) were augmented to include West Side Canal flows as described by Risley et al. (2006). The total lake outflow volume was computed as the sum of flows measured at the A Canal and corrected Link River gauges. Outflow loads were computed from the combined outflow volumes and nutrient concentrations measured by the Klamath Tribes at the Link River Bridge or at the southernmost lake site (PM) when Link River Bridge data were not available.

## 2.4 Precipitation, Evaporation and Atmospheric Deposition

Daily precipitation to the lake was based on records from the National Climatic Data Center (NCDC) and the Pacific Northwest Cooperative Agricultural Weather Network (AgriMet) (NCDC, 2012a; USBR, 2012). Because of the large spatial gradient in precipitation across the Klamath basin (see Figure A2 in Appendix A), direct precipitation to the lake surface was estimated by averaging records from stations located both north and south of UKL. The primary northern station was located in Chiloquin, OR near Agency Lake and was active over the period 1991-2010. Missing values were estimated by linear regression based on monthly precipitation measured at the AgriMet station at Agency Lake (Station AGKO) and at the NCDC station at Klamath Falls (Station 35406).

For the southern region, there were two primary stations both located in Klamath Falls, OR. The first primary southern station was located about 4 miles northwest of Klamath Falls Airport (Station 354506) and was active over the period 1991-2001. The second primary station was located at Klamath Falls International Airport (Station 94236) and was active over 2000-2010. Missing values were filled using linear regressions based on monthly precipitation at the Agrimet station at Klamath Falls (Station KFLO) and the NCDC Global Summary of the Day (GSOD) dataset for Klamath Falls (Station 725895; NCDC, 2012b). See Appendix A for details on the precipitation datasets.

Evaporation from the lake surface was estimated using two data sources. For the first 12 years (WY 1992-2003), daily measurements of class A pan evaporation at the OSU Experiment Station near Klamath Falls were used, which is the same data source used by Kann and Walker (1999). A pan coefficient of 0.7 was used to convert the measured pan evaporation to open-water evaporation. Because this dataset only extended through 2003, evaporation for the remaining years (WY 2004-2010) was computed using estimated potential evapotranspiration (PET) at the Agrimet station in Klamath Falls (Station KFLO). Based on Hostetler (2009) and Snyder et al. (2005), the PET measurements were first converted to pan evaporation estimates using a coefficient of 1.27, and then to open-water evaporation using a pan coefficient of 0.7. See Appendix A for details on the evaporation dataset.

Total atmospheric deposition was computed as the sum of dry and wet deposition. Kann and Walker (1999) previously used constant total deposition rates of 18 and 108 kg $km^2$ $yr^{-1}$ based on results of the US EPA's National Eutrophication Survey (USEPA, 1975). The updated budgets assume that half of the atmospheric inputs occurred as dry deposition (constant loading rates) and half as wet deposition when averaged over the entire WY 1992-2010 period. Monthly wet deposition rates were computed from monthly precipitation volumes applied to constant concentrations (18 ppb for TP and 108 ppb for TN), which were derived so that the WY 1992-2010 wet deposition accounted for half of the total deposition. Results are insensitive to the assumed split between wet and dry deposition because the total deposition accounted for only 3% of the lake inflow TP load and 5% of the TN load over the WY 1992-2010 period.

## 2.5 Gauged Tributary Inflows and Loads

Gauged tributary inflows were computed on a daily basis (Appendix B) and summarized on monthly and annual bases for purposes of constructing the lake water and nutrient budgets (Appendices E and F). Gauged inflows were comprised of three major tributaries and partitioned into five sub-watersheds:

*Gauged Inflows = Williamson River + Wood River at Agency Dike + Sevenmile Canal at Dike*

Inflows from the Williamson River were further partitioned into two sub-watersheds including the Sprague River basin and the Williamson River basin excluding the Sprague River basin (generally denoted as Williamson-Sprague). Daily flows at the Williamson and Sprague River sites were obtained from USGS stations 11502500 and 11501000, respectively. Two missing values at the Williamson River site were filled by linear interpolation. Monthly net flows and loads from the Williamson excluding the Sprague were estimated based upon the differences between the Williamson and Sprague values.

Inflows from the Wood River were further partitioned into sub-watersheds above and below the Weed Road gauge (Figure 3). Net inflows and loads from the downstream segment were computed at monthly time steps based on the difference between the Weed Road and Dike Road values. Results for this sub-watershed reflect the net impacts of inflows from the adjacent pumped areas and withdrawals for irrigation or wetland restoration (Agency Lake Ranch and Wood River Ranch), as well as discharges from the Crooked Creek watershed.

Data sources and methods used to develop daily flow datasets for Wood River and Sevenmile Creek sites are summarized below (see Appendix B for details):

- *Wood River at Weed Road.* Daily flows for 1991-2006 were computed by the KBRT based primarily upon historical Klamath Tribes data. Biweekly flows measured by Klamath Tribes were used as the primary dataset for 2007-2010. Missing values were filled by interpolation and regression against paired KBRT data for the Weed Road site.
- *Wood River at Dike Road.* Biweekly data from Klamath Tribes were used as the primary dataset for 1991-2010. Missing values for were filled by interpolation and regression against flows at Weed Road.
- *Sevenmile Canal at Dike Road.* The primary dataset was provided by Klamath Tribes and supplemented with data from USBR and KBRT. Missing data were filled by interpolation and regression against flows in the Wood River at Weed Road.

The combined regression/interpolation algorithms used to estimate missing flows in each case utilized the measured flows for the primary datasets when they were available (generally biweekly). Regressions were used only to adjust interpolated values to reflect daily variations between sampling events observed at the reference sites, as driven by storm events, for example. Results are similar to those based upon simple interpolation in periods without major data gaps, especially when averaged on an annual basis.

Daily nutrient loads from gauged tributaries and outlet were computed based upon daily flows and biweekly concentrations measured primarily by the Klamath Tribes (Table 1). A combined regression/interpolation algorithm was used to estimate loads on days between sampling events (Appendix B). The algorithm is similar to those described by Walker and Havens (2003) and Goolsby et al. (1999) and utilized by Asarian et al. (2009, 2010) to construct nutrient balances for reservoirs in the Lower Klamath basin. Paired flow and concentration data for each nutrient and site were used to calibrate a multiple regression model that predicted concentration as a function of season (Julian day), flow, flow derivative (increasing or decreasing), and year (reflecting long-term trend). The algorithm used measured concentrations on days when they were available. Concentrations on other days were computed as the sum of the concentration predicted by the regression model plus the regression residual (observed - predicted) linearly interpolated between dates with measurements. On yearly and long-term time scales, computed loads were generally similar to those based upon direct interpolation in periods without data gaps, as utilized by Kann and Walker (1999), and other simpler algorithms included in the FLUX program developed for the U.S. Army Corps of Engineers to evaluate nutrient loadings to reservoirs (Walker, 1999). Comparisons of long-term average loads computed using several methods are displayed along with daily and yearly time series for each tributary and nutrient in Appendix B.

Limitations in the datasets used to estimate flows and loads at the major tributary and outlet sites include:

- Limited sampling of the lake and lake outlet during the winter months of Water Years 1999-2007, when samples were collected in only 38% of months between November and March, as compared with 86% in WY 1992-1998 and 92% in WY 2008-2010. This change in winter sampling frequency limits the precision of the computed annual outflow loads, nutrient mass stored within the lake, and net nutrient retention, as well as the assessment of trends in these mass-balance terms. However, the precision of seasonal (e.g., May-September) computations for these terms is not affected by the change in winter sampling frequency.
- Relatively low sampling frequencies for the major tributaries in WY 1997-2003, when the number of samples per water year and site typically ranged from 8 to 20, as compared with the biweekly design (26 samples per water year).
- Differences in discharge rating curves developed by KBRT and the Klamath Tribes for the Weed Road site could not be resolved and further analysis is recommended. The Tribe flow estimates were used as the primary basis for deriving the daily flow dataset because they were available for the entire record, whereas KBRT data were available only for 2007-2010.
- Difficulties in measuring inflows to Agency Lake from Wood River and Sevenmile Creek resulted from the stage at monitoring sites being partially controlled by lake water level during some periods.
- TN concentrations were frequently below detection limit at sites with relatively un-impacted watersheds (e.g., Williamson River, Sprague River, Wood River at Weed Road). Concentrations were set at 50 ppb (one half of the nominal 100 ppb detection limit). Analytical precision apparently increased after 2007.

The nutrient budgets for WY 2008-2010 are likely to be more accurate than those estimated for previous years because the tributary and outflow datasets were reasonably complete, most of the pumped inflows were either directly measured (Agency Lake Ranch) or eliminated (Williamson River Preserve), and it is likely that transient unmonitored nutrient loads reaching the lake from antecedent agricultural soils in the restored wetlands had largely attenuated.

## 2.6 Pumped Inflows and Loads

Limited data were available for estimating inflow volumes and loads pumped into the lake from adjacent agricultural areas, portions of which were converted to water storage projects and wetlands over the 1998-2010 period (Williamson River Preserve, Wood River Ranch, Agency Lake Ranch). Evaluations of lake nutrient budgets and long-term trends in the total and anthropogenic nutrient loads are subject to uncertainties in the estimated pumped loads. See Appendix C for details on the data sources, methods, and results.

Pumped inflows were partitioned into two components to reflect direct discharges to Agency Lake and Klamath Lake, respectively:

*Pumped Inflows = Agency Lake Ranch + Other*

Monthly discharge volumes from agricultural areas were estimated using a regression model relating unit area runoff from pumped areas to unit runoff from the Williamson River. This equation was derived from limited pump records collected prior to 1999 (Kann and Walker, 1999). The total runoff volume was computed by multiplying the estimated unit area runoff rate by the total agricultural area. The estimated flows were applied to nutrient concentrations derived from limited pump sampling by the Klamath Tribes in 1992-1998 (Appendix C).

Approximately 76% of the pumped agricultural areas draining directly into UKL were closed and incorporated into water storage/wetland restoration projects over the 1998-2010 period (Agency Lake Ranch and Williamson River Preserve). Discharges from Agency Lake Ranch were estimated based on pump records and water quality monitoring data provided by USBR for 2000-2010 (Table 1). Discharges and drainage areas associated with Williamson River Preserve decreased as the project was implemented in phases between 1998 and 2008, when re-flooding was complete and the lake dikes were breached. Any additional flows and loads from restored wetland areas are implicit in the ungauged inflow volumes and loads computed from the lake water budget and background nutrient concentrations, as described below.

Flows and loads from the Wood River Ranch restoration project were estimated from pumping records and water quality data provided by USBLM and USGS (Table 1). Because that project discharged directly to the Sevenmile Canal and Wood River above the gauged inflows to the Lake, flows and loads from this area were not used in the mass balance calculations but are reported in Appendix C for comparison with other pumped sources. Implementation of this project contributed to reductions in loads reaching Agency Lake via Sevenmile Canal and Wood River, which are captured in the lake nutrient budgets.

Flows and loads from Agency Lake Ranch were directly monitored by USBR after farming stopped and the area was used for water storage in WY 2000-2010. Loads during this period suggest large nutrient releases from antecedent agricultural soils (Aldous et al., 2005; 2007; Graham et al., 2005), which have been shown for other restored wetlands around UKL including the Williamson River Delta (Wong et al., 2011) and Wood River Delta (Duff et al., 2009). Nutrient concentrations in discharges from Agency Lake Ranch during the active agricultural period up to 2000 were estimated from limited grab sampling and estimated flow (TP~270 ppb, TN~1600 ppb). Concentrations increased significantly after initial flooding in 2000 (TP~1800 ppb, TN ~4800 ppb) and with the exception of a smaller increase in 2005 when an additional 2,631 acres (Barnes Ranch) were added to the project, gradually declined between 2001 and 2009 (TP~90 ppb, TN~1400 ppb in 2009); no pumping occurred in 2010 (Appendix C).

The flows and loads discharged to the lake from the Williamson River Preserve were not directly monitored but assumed to decrease gradually as the restoration project was implemented over the 1998-2008 period. Nutrient releases from antecedent agricultural soils in the Williamson River Preserve were not directly pumped to the lake as the converted areas and pumped flows were either isolated from the lake or passively connected to the lake (Stevens, 2008). The nutrient budgets do not capture releases of antecedent soil nutrients that could have occurred after the lake dikes were partially breached between 2000 and 2004 and fully breached in 2008. Similarly, the nutrient budgets do not reflect any increases in loads associated with an unintentional breach of the Caledonia Marsh dike in 2006, which was subsequently repaired (Lindenberg and Wood, 2009). Flows and loads in 2006 were assumed to equal those estimated for previous years.

## 2.7 Ungauged Inflows

Ungauged inflows include groundwater seepage, springs, and unmonitored runoff from local watersheds adjacent to the lakes. Flows were estimated by difference using the above water balance equation and therefore incorporate the cumulative uncertainty in measurements or estimates of the other water budget terms. Ungauged flows were set to zero in months when the computed flows were negative, likely as a consequence of errors in the estimates of one or more of the other water budget terms (see Appendix B, Figure B4). Although further reviews of the data and assumptions used to construct the water budget and estimate of ungauged inflows are recommended, the overall computed ungauged inflow was 18% of the total inflow, a value similar to previous estimates of 15% ground water input to UKL (Hubbard, 1970; Gannett et al., 2007).

Nutrient loads from ungauged areas were estimated by applying the estimated flows to average nutrient concentrations (TP = 65 ppb, TN = 99 ppb) measured in eight springs by the Klamath Tribe in 1992-1998 and summarized in Appendix D. These values differ slightly from those estimated by Kann and Walker (1999; TP = 63 ppb, TN = 119 ppb) because they reflect additional data collected after 1998. Although high nutrient concentrations (about 6,000 ppb of SRP) have been measured in artesian wells discharging into the Wood River Ranch wetland, these only accounted for 1% of the water input to the wetland and were decommissioned in 2008 (Carpenter et al., 2009). The artesian well phosphorus concentrations are much higher than those measured in springs directly entering the lake. Although a portion of the ~15% ground water inflow to the lake occurs at unknown locations, there is no evidence indicating that deep aquifers characterized by the type of artesian wells pumped to the Wood River Ranch contribute to natural groundwater discharges directly to Upper Klamath Lake. Loads discharged from Wood River Ranch wetland are reflected in the measured loads reaching UKL via Sevenmile Creek and the Wood River.

The precision of the TN concentration estimate is likely to be relatively low because measurements were frequently below the detection limit (100 ppb) and assigned values of 50 ppb when averaging the data. As described below (Section 3.5), concentrations at spring sites were in some cases similar to, but generally higher than values measured at surface water monitoring sites in the headwaters of each basin.

## 2.8 Net Retention

The net retention of water reflects error in the water budget that occurs as a consequence of constraining the computed ungauged inflows to non-negative values at each monthly time step. On average, this error is less than 1% of the long-term average inflow and ranges from 0 to 3% in individual water years (Appendix B, Figure B4). Negative ungauged flows and resulting water budget errors were typically observed in dry years and winter/spring months. These results may reflect random measurement errors in the individual measured or estimated water budget terms, as well as difficulties in measuring stream-flow and lake storage under icy conditions.

The net retention of nutrients was computed by difference from the other measured or estimated mass balance terms. The amount of retention reflects the difference between sedimentation, atmospheric fixation (nitrogen only), nutrient releases from bottom sediments, and the cumulative effects of errors in the other mass-balance terms. Negative net retention values for P indicate net recycling from the lake sediments to the water column, and for N indicate both recycling from lake sediments and atmospheric input by nitrogen-fixing blue-green algae.

## 2.9 Anthropogenic and Background Loads

One of the primary objectives of this project was to determine the magnitudes of and current trends in nutrient loads from anthropogenic sources. The nutrient mass balances were used to estimate loads due to human activities (anthropogenic loads) and loads under 'pristine' conditions (background loads). Following Kann and Walker (1999), background loads were estimated as the total inflow volume from external sources (Gauged Tributaries + Ungauged Inflows + Pumped Inflows) multiplied by the concentrations used to compute the ungauged inflow loads (TP= 65 ppb and TN=99 ppb, respectively). Because many of the tributaries either originate from springs or have significant spring input in their upper reaches (e.g., Wood River, Sevenmile, Williamson River, etc.), this provides an estimate of loading in the absence of anthropogenic inputs. Anthropogenic loads were estimated as the difference between total inflow nutrient load and background load.

The computations of background and anthropogenic loads are summarized as follows:

*Background Load = Background Concentration x Total External Inflow Volume*

*Anthropogenic Load = Total External Inflow Load – Background Load*

*Anthropogenic Concentration = Anthropogenic Load / Total Inflow Volume*

*Total Inflow Load = Background + Anthropogenic + Atmospheric Deposition*

The anthropogenic concentration represents the difference between the total observed inflow concentration and the background concentration. The inflow TP concentration corresponding to the TMDL goal (66 ppb) is slightly above the background estimate of 65 ppb. Explicit consideration of data from surface water sites in basin headwaters with TP concentrations below 65 ppb (Annie Creek, Sevenmile at Forest Service, and North and South Forks of the Sprague River) could result in slightly lower estimates of background concentration (and thus higher estimates of anthropogenic load), as discussed in Section 3.5.

## 2.10 Trend Analysis

Long-term trends in inflows, loads, and FWM concentrations were evaluated from monthly time-series representing each term in the water and nutrient budgets. A number of statistical methods can be used to analyze trends in water quality data (Helsel and Hirsch, 2002). Such methods can be broadly categorized as either parametric or non-parametric. Parametric methods generally require a number of underlying assumptions about the distribution (i.e. normality) and independence of the data (i.e. random with low serial correlation). Non-parametric methods are based on the ranks of the observations rather than the values themselves, and are typically more robust to outliers and other abnormalities common to water quality observations. They can also be more powerful (lower risk of Type II error, incorrectly rejecting the null hypothesis, or “false negative”). The presence/absence of trends was assessed at significance levels (p-values) of 0.05 and 0.10 (maximum Type I error or “false positive”).

Concentration, flow, and load data in the UKL tributaries are often not normally distributed. Thus, for this analysis, the Mann-Kendall and Seasonal Kendall tests were used, both of which are non-parametric methods that compare the changes in observation ranks over time. The Mann-Kendall test is computed using annual mean values (FWM for concentration) and thus represents changes in the total annual flows, loads and FWM concentrations over time but does not account for differences in trend slopes within individual seasons (Helsel and Hirsch, 2002). The Seasonal Kendall test is a variation of the Mann-Kendall test where the data are first grouped by month of the year and the Mann-Kendall test is then performed on each group of monthly data (Helsel and Hirsch, 2002). The results of each month are combined into an overall measure of trend significance. For both tests, the Sen slope provides a non-parametric estimate of the change in each variable over time. The percent change in each term is computed relative to the mean value over the entire period with the exception of the net retention load. Because net retention can have both positive and negative values, the percent slope was computed relative to the total external inflows.

# 3 RESULTS

The followings sections present and briefly discuss key results with respect to:

3.1 Water and Nutrient Balances
3.2 Lake Dynamics
3.3 Trends
3.4 Progress in Achieving TMDL Goal
3.5 Spatial Variations

The mass balance database (monthly flows and loads for each mass balance term, Appendix E) provides a basis for more detailed analyses and interpretations related to watershed and lake dynamics, effectiveness of management measures, and progress relative to the TMDL goal. Given the data limitations and assumptions required to construct the budgets within the limited scope of the current effort, more detailed exploratory and sensitivity analyses of the output may identify needs for refining the datasets, assumptions, and computations involved in constructing the historical budgets and evaluating trends, as well as enhancements to the monitoring programs.

Detailed results and diagnostic plots are contained in the following appendices:

D – Spatial Variations in Flow, Nutrient Loads and Concentrations
E – Lake Water and Nutrient Balances
F – Seasonal and Yearly Variations in Mass Balance Terms
G – Seasonal Kendall Test for Trends in Flow, Load, and Flow-weighted Mean Concentration
H – Annual and Seasonal Variations in Nutrient Species Concentrations

## 3.1 Water and Nutrient Balances

The overall water and mass balances for the entire period are summarized in Table 2. Appendices E and F provide additional summary tables and figures by month, year, multi-year periods, and seasons. Results for WY 1992-1998 (TMDL base period) were slightly different from those derived previously (Kann and Walker, 1999) because of refinements to the datasets and methods. Changes amounted to +3% for annual average inflow volume, +2% for TP load, and -6% for TN Load.

Year-to-year variations in flow attributed to climate are important to consider when interpreting variations in nutrient loads and, to a lesser extent, concentrations. Annual variations in total external inflow volumes and nutrient loads were strongly correlated with variations in precipitation (Figure 5). The remaining variations can be attributed to uncertainty in the measured values, trends related to implementation of management measures, spatial variations in precipitation, and other random factors. The precipitation rates represent lake-mean estimates (Appendix A); spatial averaging across the individual watersheds would be expected to yield stronger correlations. All of the correlations shown in Figure 5 are statistically significant; $R^2$ ranges from 0.50 to 0.73 ($p< 0.01$), with the exception of FWM TP concentration ($R^2 = 0.01$). As compared with TP Loads, FWM concentrations are relatively independent of precipitation ($R^2 =$ 0.01 vs. 0.65) and provide a more stable signal for tracking trends relative to the TMDL goal, which can expressed as a long-term FWM concentration of 66 ppb (ODEQ, 2002). Interpretation of trends in TN are complicated by the fact that both loads and FWM concentrations are correlated with precipitation ($R^2 = 0.74$ and 0.50, respectively).

# Table 2: Water and Nutrient Mass Balances for Water Years 1992-2010

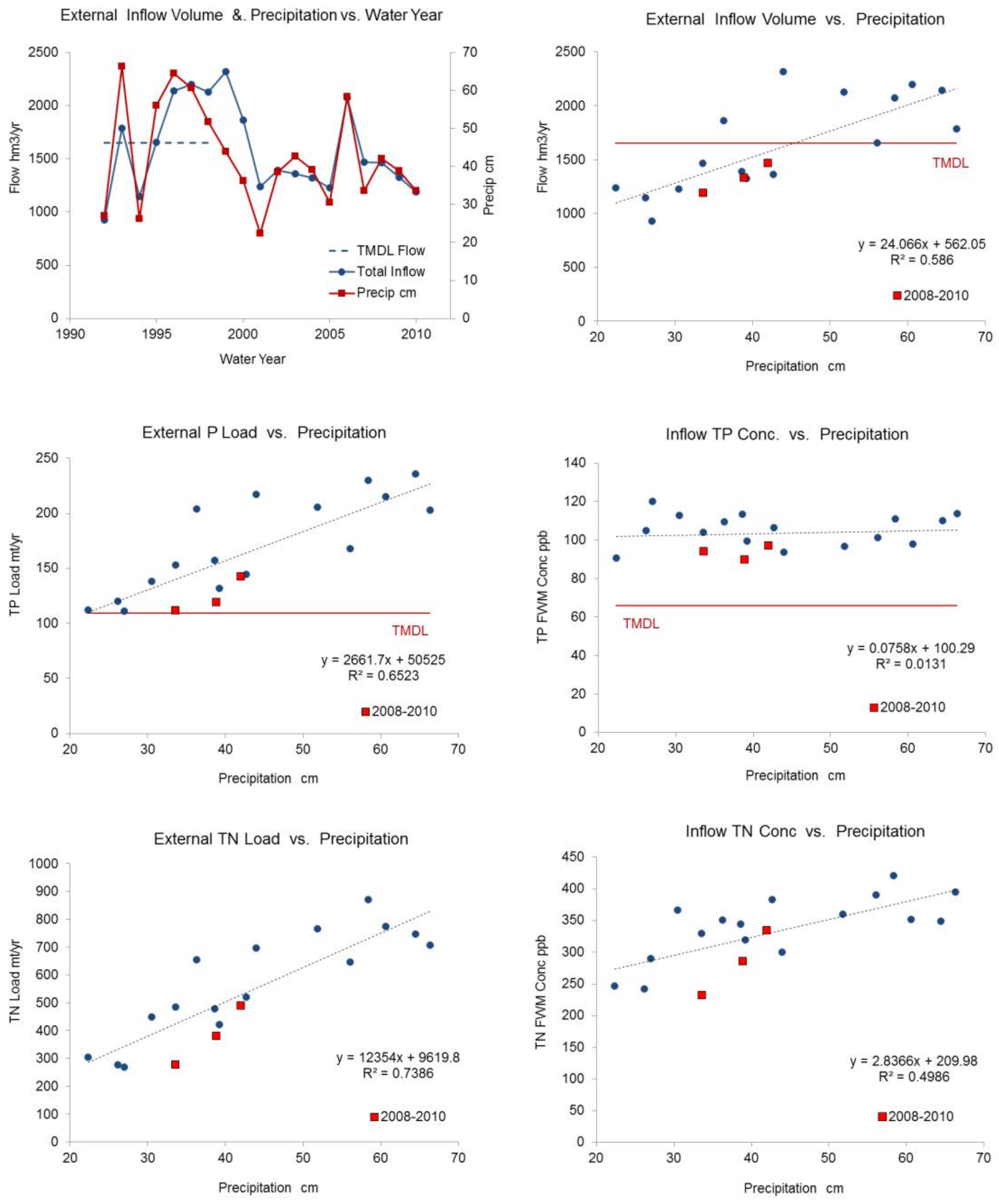
**Upper Klamath Lake Water & Nutrient Balances** **Water Years: 1992- 2010**

| Term | Flow | Nutrient Loads | | Percent of Inflow | | | Nutrient Concs | | Dr. Area | Runoff | P Export | N Export |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $hm^3$/yr | TP mt/y | TN mt/y | Flow | TP | TN | TP ppb | TN ppb | $km^2$ | m/yr | kg/$km^2$ | kg/$km^2$ |
| **Major Gauged Sites** | | | | | | | | | | | | |
| Wood River @ Weed Road | 246.9 | 21.0 | 28.0 | 16% | 13% | 5% | 85 | 114 | 333 | 0.74 | 63 | 84 |
| Wood River @ Dike Road | 317.7 | 35.6 | 55.7 | 20% | 22% | 10% | 112 | 175 | 394 | 0.81 | 90 | 141 |
| 7-Mile Canal | 103.4 | 14.8 | 49.2 | 6% | 9% | 9% | 143 | 476 | 96 | 1.07 | 153 | 510 |
| Sprague River | 501.9 | 38.1 | 177.3 | 32% | 23% | 33% | 76 | 353 | 4171 | 0.12 | 9 | 43 |
| Williamson River | 845.9 | 73.4 | 296.3 | 53% | 45% | 55% | 87 | 350 | 7812 | 0.11 | 9 | 38 |
| Klamath L Outlet | 1439.2 | 162.4 | 2364.2 | 90% | 99% | 440% | 113 | 1643 | 9771 | 0.15 | 17 | 242 |
| **Agency Lake Inflows** | | | | | | | | | | | | |
| Wood River above Weed Rd | 246.9 | 21.0 | 28.0 | 56% | 34% | 18% | 85 | 114 | 333 | 0.74 | 63 | 84 |
| Wood River below Weed Rd | 70.9 | 14.5 | 27.7 | 16% | 24% | 18% | 205 | 391 | 61 | 1.17 | 239 | 455 |
| 7-Mile Canal | 103.4 | 14.8 | 49.2 | 23% | 24% | 32% | 143 | 476 | 96 | 1.07 | 153 | 510 |
| Agency Lake Ranch | 21.0 | 11.0 | 49.0 | 5% | 18% | 32% | 525 | 2330 | 46 | 0.45 | 238 | 1056 |
| Total Agency Inflow | 442.1 | 61.4 | 153.9 | 100% | 100% | 100% | 139 | 348 | 537 | 0.82 | 114 | 287 |
| **Klamath Lake Inflows** | | | | | | | | | | | | |
| Sprague River | 501.9 | 38.1 | 177.3 | 58% | 45% | 50% | 76 | 353 | 4171 | 0.12 | 9 | 43 |
| Williamson - Sprague | 344.0 | 35.3 | 118.9 | 40% | 42% | 33% | 103 | 346 | 3641 | 0.09 | 10 | 33 |
| Pumped Inflows to KL | 23.8 | 11.4 | 59.9 | 3% | 13% | 17% | 479 | 2520 | 50 | 0.47 | 227 | 1194 |
| Total Klamath Inflow | 869.7 | 84.8 | 356.2 | 100% | 100% | 100% | 98 | 410 | 7862 | 0.11 | 11 | 45 |
| **Overall Balance** | | | | | | | | | | | | |
| Total Tributaries | 1267.0 | 123.8 | 401.3 | 80% | 75% | 75% | 98 | 317 | 8302 | 0.15 | 15 | 48 |
| Total Pumped to Lake | 44.8 | 22.4 | 108.9 | 3% | 14% | 20% | 501 | 2431 | 97 | 0.46 | 232 | 1128 |
| Ungauged Inflows | 279.1 | 18.1 | 27.6 | 18% | 11% | 5% | 65 | 99 | 1105 | 0.25 | 16 | 25 |
| Total External Inflows | 1590.8 | 164.3 | 537.7 | 100% | 100% | 100% | 103 | 338 | 9504 | 0.17 | 17 | 57 |
| Precipitation | 114.2 | 4.8 | 28.7 | 7% | 3% | 5% | 42 | 251 | 267 | 0.43 | 18 | 107 |
| Evaporation | 255.6 | | | 16% | | | | | 267 | 0.96 | | |
| Net Inflow | 1449.4 | 169.1 | 566.4 | 91% | 103% | 105% | 117 | 391 | 9771 | 0.15 | 17 | 58 |
| Lake Outflow | 1439.2 | 162.4 | 2364.2 | 90% | 99% | 440% | 113 | 1643 | 9771 | 0.15 | 17 | 242 |
| Storage Increase | 2.6 | -0.9 | 0.1 | 0% | -1% | 0% | | | | | | |
| Retention | 7.6 | 7.6 | -1797.8 | 0% | 5% | -334% | | | | | | |
| **Natural Background vs. Anthropogenic Loads** | | | | | | | | | | | | |
| Background / Natural | 1590.8 | 103.4 | 157.5 | 100% | 63% | 29% | 65 | 99 | 9504 | 0.17 | 11 | 17 |
| Anthropogenic | 1590.8 | 60.9 | 380.2 | 0% | 37% | 71% | 38 | 239 | | | 6 | 40 |

| **Morphometry** | **Mean** | **Min** | **Max** |
|---|---|---|---|
| Volume ($hm^3$) | 546.1 | 224.2 | 743.5 |
| Area ($km^2$) | 267.1 | 217.4 | 270.9 |
| Elevation (ft) | 4140.9 | 4136.8 | 4143.3 |
| Mean Depth (meters) | 2.0 | 1.0 | 2.7 |

| **Phosphorus Model Parameters** | | |
|---|---|---|
| Hydraulic Residence Time | 0.38 | years |
| Net Water Load | 5.96 | m/yr |
| Areal Total P Load | 0.62 | g/$m^2$-yr |
| Total P Retention Coefficient | 5% | |

**Figure 5: Annual Inflow Volumes, Loads, and FWM Concentrations vs. Precipitation**



Yearly time series of inflow volumes, TP loads, and TN loads from each source are displayed in Figure 6, Figure 7, and Figure 8, respectively. Results for nutrients are expressed in terms of average load and flow-weighted mean (FWM) concentration by source. Annual results are also aggregated over various multi-year periods:

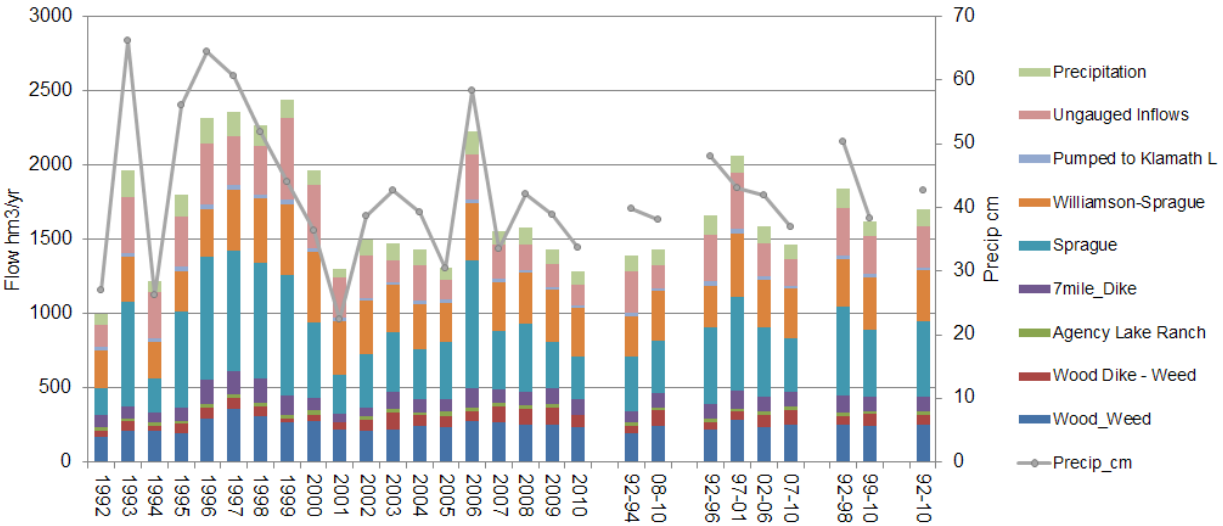
- First and last 3 water years (1992-1994 vs. 2008-2010). The average inflow volumes in these two periods were approximately equal, but slightly below the long-term mean. The latter period most closely reflects load reductions provided by wetland and watershed restoration projects, although discharges from Agency Lake Ranch and other restored wetlands were apparently still influenced by nutrient releases from antecedent farmland soils (e.g., Duff et al. 2011; Wong et al. 2011).

- 5-year intervals. These periods provides smoothing of the annual time series. The last period spans 4 years (2007-2010).
- Before and after the TMDL baseline period (1992-1998 vs. 1999-2010).
- Entire period of record (1992-2010).

The values for each water and mass balance term are tabulated by month, season, year and multi-year intervals in Appendix E. Additional plots of annual and monthly variations are shown by year and season in Appendix F and Appendix G. Appendix H shows annual and monthly variations in individual nutrient species for TP, SRP, TN, Ammonia Nitrogen (NH4), and Nitrite+Nitrate Nitrogen (NO23N) based on the sampled concentration data at the primary long-term sampling stations.

Figure 6 shows that inflow volumes varied over a wide range (~1,000 to ~2,500 $hm^3$/yr) and generally increased during the TMDL baseline period (1992-1998). Both flows and precipitation were relatively stable and below the average for the TMDL baseline period (~1,650 hm3/yr) in each water year between 2001 and 2010 (~1,400 to ~1,600 $hm^3$/yr), except for 2006 (~2,300 $hm^3$/yr). Variations in inflow volume driven by precipitation (Figure 5) make it difficult to compare measured TP loads directly with the TMDL goal, which is anchored in the WY 1992-1998 flows.

**Figure 6: Annual Inflow Volumes and Precipitation Depth**



Annual variations in TP loads and FWM concentrations for each inflow term are shown in Figure 7. Year-to-year variations reflect variations in precipitation, flow, random errors in the measurement or estimation of loads from the individual sources, and long-term decreasing trends potentially linked to implementation of source controls and water management measures in the basin. Figure

7 includes reference lines indicating the TMDL target TP load of 109 mt/yr and FWM concentration of 66 ppb (ODEQ, 2002).

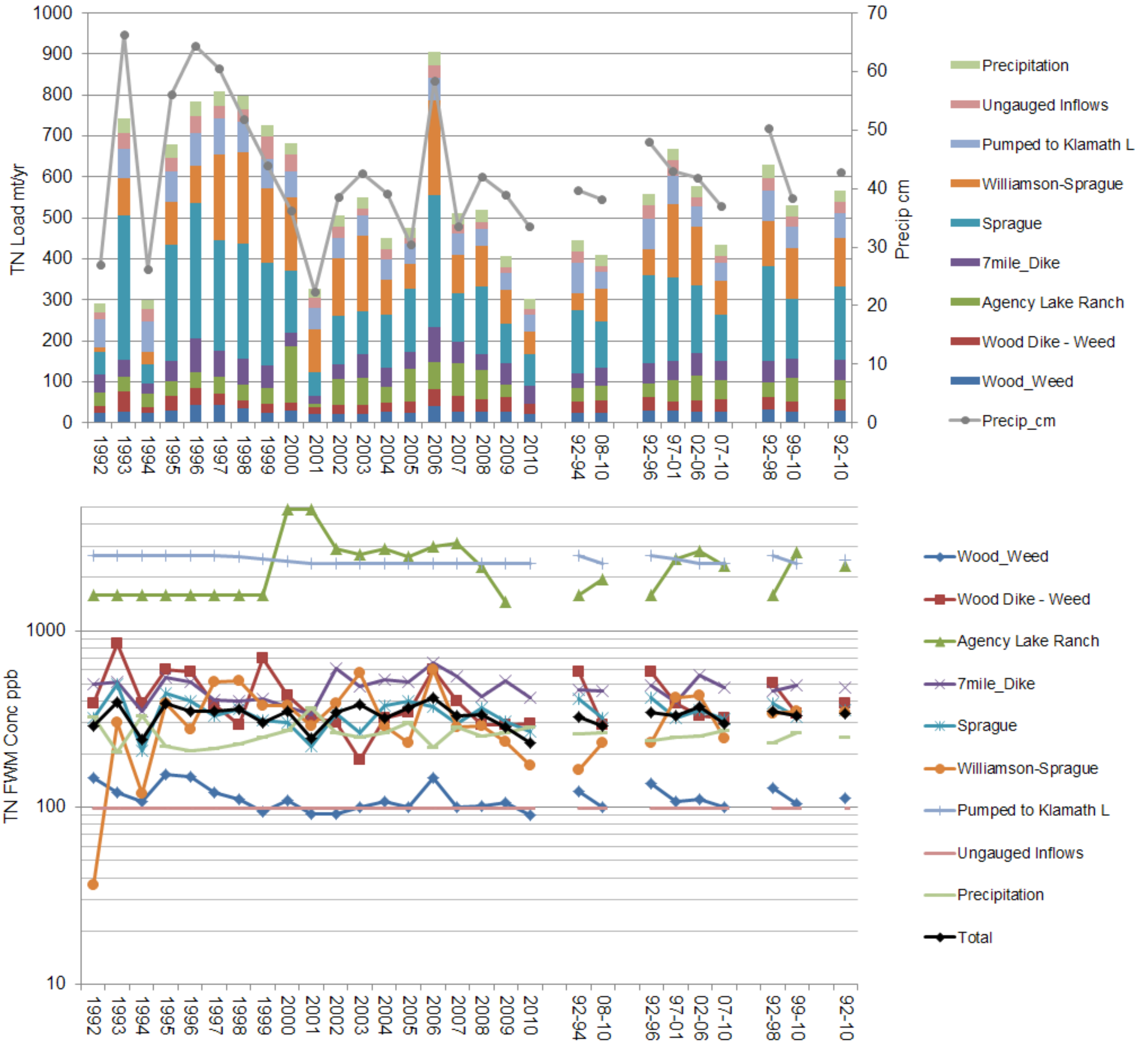
As discussed below, significant decreasing trends in FWM TP concentrations are identified for the Wood River (below Weed Road), pumped inflows, Williamson River (excluding the Sprague River basin), and the combined FWM inflow TP concentration to each lake. The sudden increase in the FWM concentration in discharges from Agency Lake Ranch in 2000 can be attributed to nutrient releases from the antecedent agricultural soils after flooding and wetland restoration (Graham et al., 2005), similar to those observed in the Wood River and Williamson River Delta wetlands (Duff et al. 2001; Wong et al. 2011). However, the 1992-1998 baseline FWM concentrations and loads from Agency Lake Ranch are highly uncertain because they are based upon estimated flows and limited concentration data (Section 2.6). The precipitation FWM TP concentrations reflect the total atmospheric deposition load (dry + wet) divided by precipitation volume; year-to-year variations in concentration reflect dilution of the dry deposition load, which is assumed to be constant (Section 2.4).

Annual variations in TN loads and FWM concentrations for each inflow term are shown in Figure 8. While apparent decreasing trends are identified in some of the inflow terms, trend magnitudes are lower than those observed for phosphorus and interpretations are complicated by the fact that both TN load and FWM concentrations are correlated with precipitation ($R^2 = 0.74$ and 0.50, respectively, Figure 5). Compared with TP, variations in external TN load are less important from management perspective because algal productivity in the lake is limited by phosphorus and fixation of atmospheric nitrogen by blue-green algae is a major component of the lake nitrogen balance.

The lower range of TN concentrations (~100 ppb) is uncertain because high percentages of the measurements were below detection limits in the relatively undeveloped watersheds. As a result, nitrogen loads from the upper portion of the Williamson River computed based on the difference between loads measured at the Williamson and Sprague sites were negative in some months, particularly in the earlier periods. This artifact is responsible for the relatively low FWM concentration computed for this watershed in 1992 (~40 ppb vs. >=100 ppb for other years and sites).

## Figure 7: Inflow Phosphorus Loads and FWM Concentrations

**Figure 8: Inflow Nitrogen Loads and FWM Concentrations**



## 3.2 Lake Dynamics

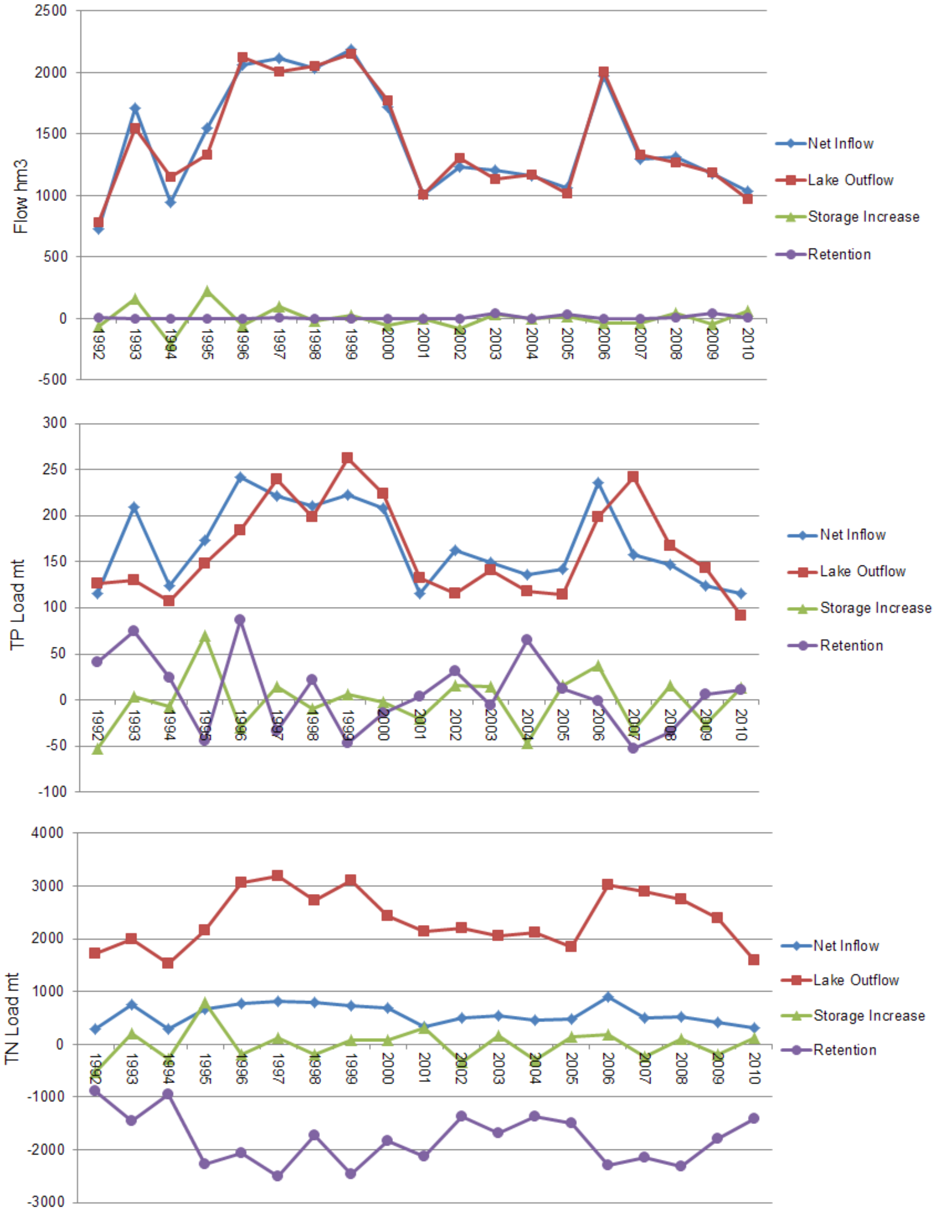
Figure 9 shows the overall lake mass balances for flow, TP, and TN, as represented by the annual net inflow, outflow, increase in storage, and net retention. Figures in Appendix E show yearly mass balances and inflow components averaged separately by season (October-April vs. May-September) and multi-year intervals. As discussed above, the precision of the annual outflow load and retention estimates is limited by infrequent sampling of the lake and outlet during the winter months of water years 1999-2007. While the external loading estimates are based upon fewer months, the precision of seasonal May-September lake budget terms is not limited by less frequent winter sampling in water years 1999-2007.

The yearly water budgets are dominated by net inflows and outflows. The net inflow is defined as:

*Net Inflow = Total External Inflow + Precipitation - Evaporation*

Net retention of flow represents error in the water balance (<1% overall) due to constraining ungauged inflows to non-negative values. Net retention of nutrients incorporates both in-lake dynamics and cumulative errors in the estimates of individual inflow and outflow terms, as discussed above. Changes in TP storage and net retention are highly variable from year to year but of lower magnitude than the inflows and outflows. The negative TN retention values primarily reflect atmospheric fixation of nitrogen by blue green algae and exceed the average inflow load by more than 3-fold.

**Figure 9: Annual Water and Nutrient Balances**



The middle panel in Figure 9 suggests that there is a one-year lag in the response of the annual outflow TP loads to variations in the inflow TP loads. This may reflect storage and recycling processes occurring within the lake and could be further evaluated with mass-balance modeling. Figure 10 shows the lake TP budget time series averaged separately by season (October-April and May-September). Positive retention rates in October-April (averaging 73 mt in WY 1992-2010) reflect net P removal from the water column and build-up in the bottom sediments. Negative retention rates in May-September (averaging -65 mt) reflect P releases from the sediments back to the water column. Similar figures for TN are provided in Appendix E.

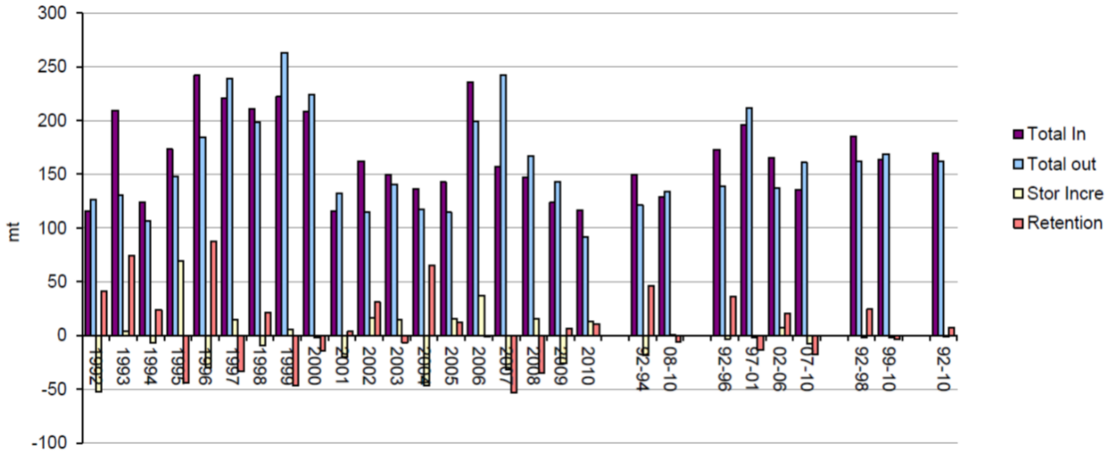
The dynamics of the phosphorus budget are more evident when viewed at monthly intervals. Figure 11 shows monthly flows and FWM concentrations in the inflow and outflow (top and bottom), as well as the total lake volume and volume-weighted-mean concentration (middle). These figures were extracted from more detailed monthly and yearly time series charts for each mass balance term and nutrient in Appendix F.

Apparent spikes in the inflow TP concentrations in WY 2000-2007 (top panel in Figure 11) were driven largely by measured inflows from Agency Lake Ranch, after it was flooded and used for water storage. These high loads likely reflect phosphorus releases from antecedent agricultural soils, as discussed in Section 2.6. Similar spikes could have occurred in the farm discharges before 2000 but are not apparent in Figure 11 because discharges from Agency Lake Ranch (ALR) and other pumped areas were not directly monitored but estimated from the Williamson River flow and limited grab sampling (Appendix C).

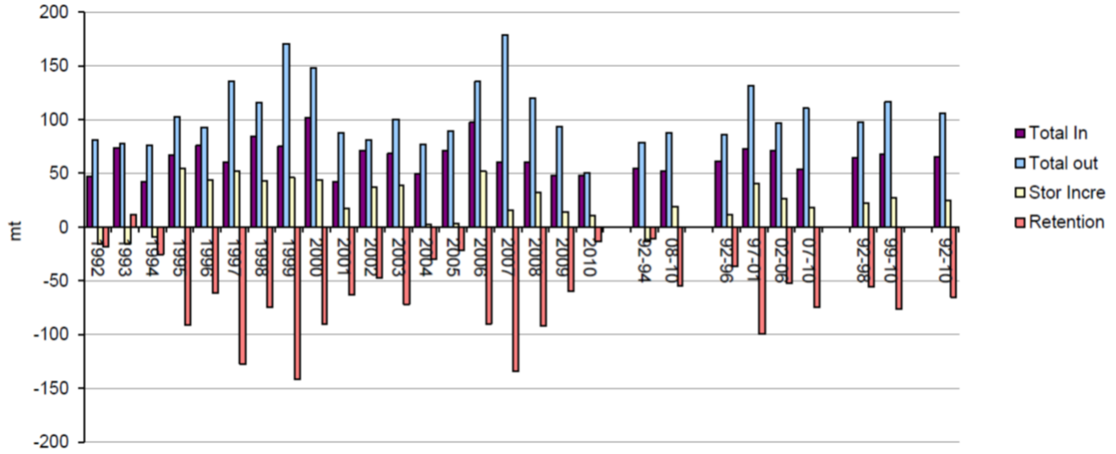
The monthly dynamics of the lake and outflow TP concentrations reflect cycling between the water column and sediments (middle and bottom panels of Figure 11), as manifested in the seasonal means (Figure 10). Concentration spikes generally occurred in June-July as algal growth increased and phosphorus was recycled from the bottom sediments at relatively high rates, as described below (Figure 12).

**Figure 10: Annual Phosphorus Balances Averaged by Season**

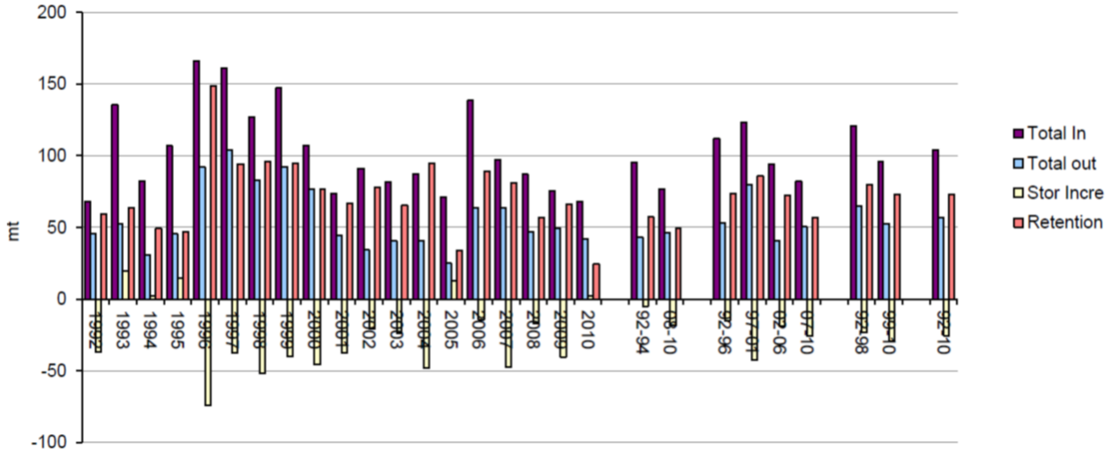
Water Year (October - September)



Growing Season (May - September)

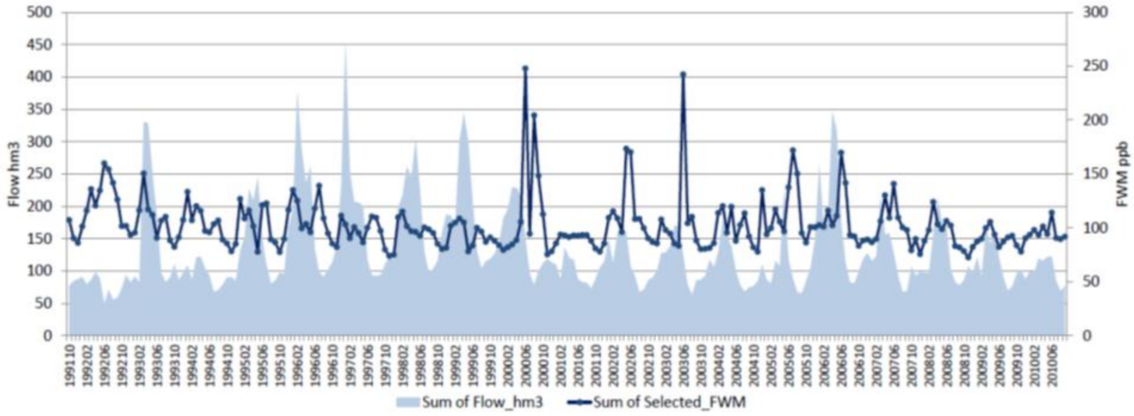


Non-Growing Season (October - April)

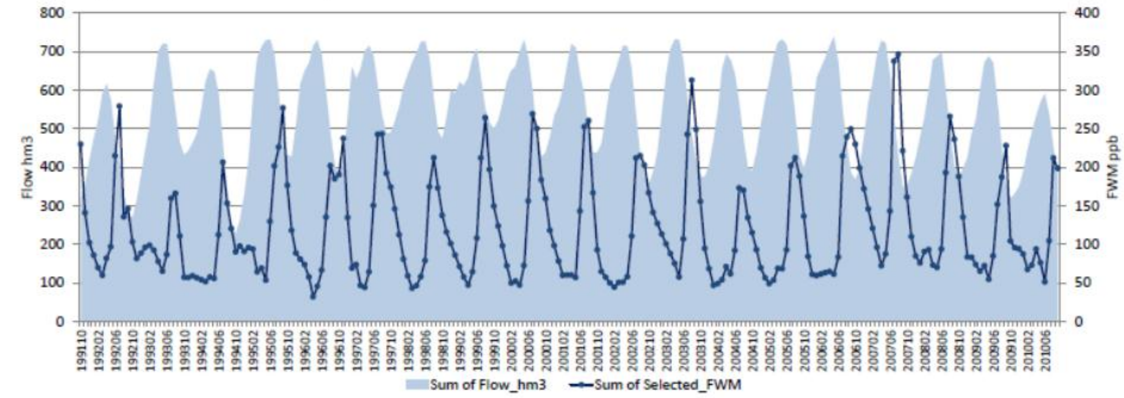


### Figure 11: Monthly Variations in TP Inflow, Lake Storage, and Outflow

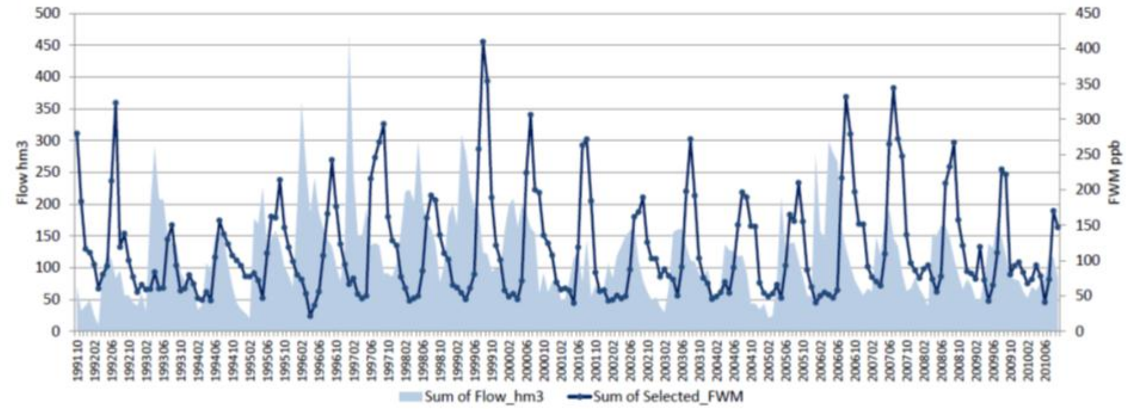
Total External Inflow & Flow-Weighted-Mean TP Conc.



Lake Storage Volume & Volume-Weighted Mean TP Conc.

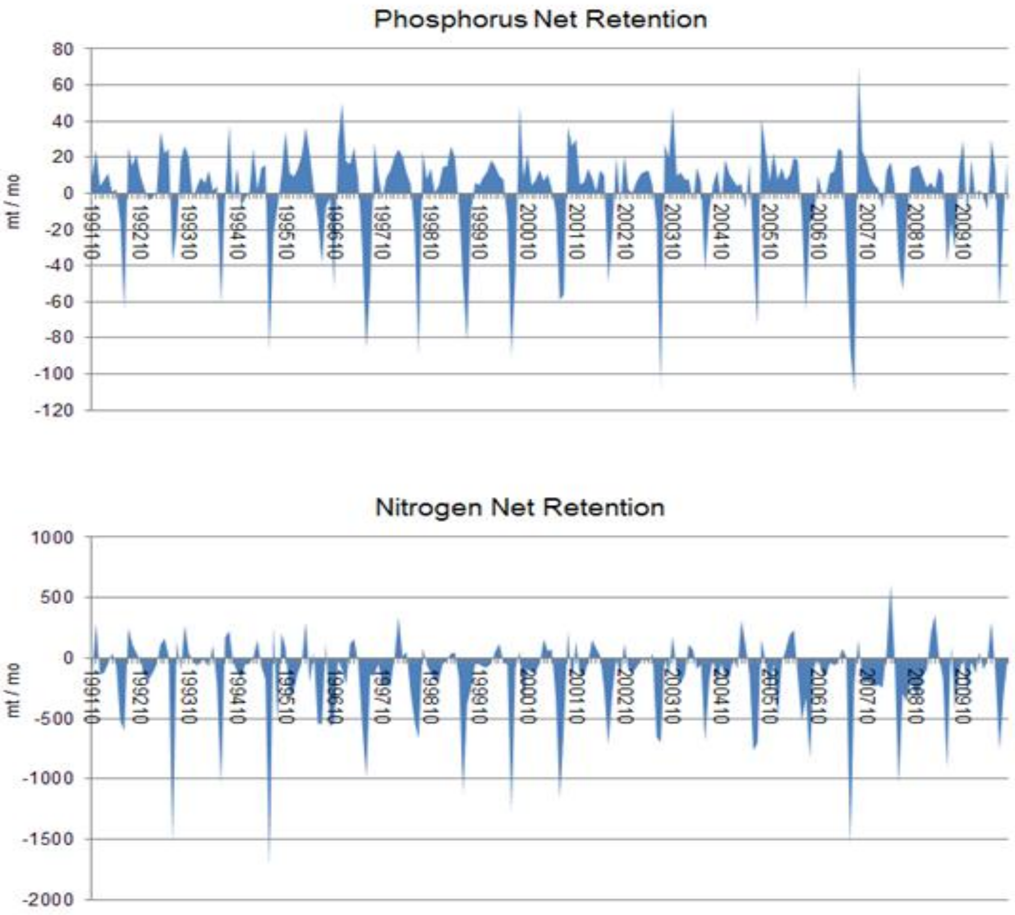


Lake Outflow & Flow-Weighted-Mean TP Conc.



The monthly net retention rates for TP and TN are shown in Figure 12. These were computed by difference from the other measured or estimated mass balance terms. Positive values reflect net losses from the water column. The large negative spikes in net retention occur in June and July and reflect high rates of P recycling from bottom sediments and N fixation by blue-green algae. The long-term average retention rates were 5% of the total inflow load for TP and -334% for TN (Table 2). While retention rates were apparently higher in the first few years (Figure 9), long-term trends were not detected in the context of the high variability induced by lake dynamics, climate, and uncertainties in the individual mass balance terms used to compute the net retention values.

**Figure 12: Monthly Variations in Net TP & TN Retention**



Apparent declining trends in the inflow, lake, and outlet TP concentrations during the winter and spring of WY 1992-1998 observed previously (Walker, 2001) were not sustained in WY 1999-2007, although uncertainty in these results arises due to limited lake and outlet sampling during that period, as discussed above. TP concentration ranges generally decreased in WY 2008-2010, when the data were more complete and transient nutrient releases from antecedent agricultural soils in the restored wetland areas decreased.

Figure 9-Figure 12 indicate that lake P concentrations and cycling dynamics did not change appreciably over the years, despite the observed decreases in inflow P loads. This is not unexpected, given the relatively small magnitude of the load reductions, storage and recycling of antecedent phosphorus loads from the bottom sediments, hydrologic variability, and uncertainty in the storage, loading, and retention estimates. Evaluation of the lake response to external loads is also complicated by variations in water levels driven by climate and changes in management. In

particular, the extremely low water levels and associated storage volumes in the summers of 1992 and 1994 did not recur in subsequent years (middle panel of Figure 11).

More detailed analysis and modeling would help to further elucidate and interpret variations in nutrient retention and lake water quality responses to variations in inflow volumes, nutrient loads, water levels, and other driving factors.

## 3.3 Long-Term Trends

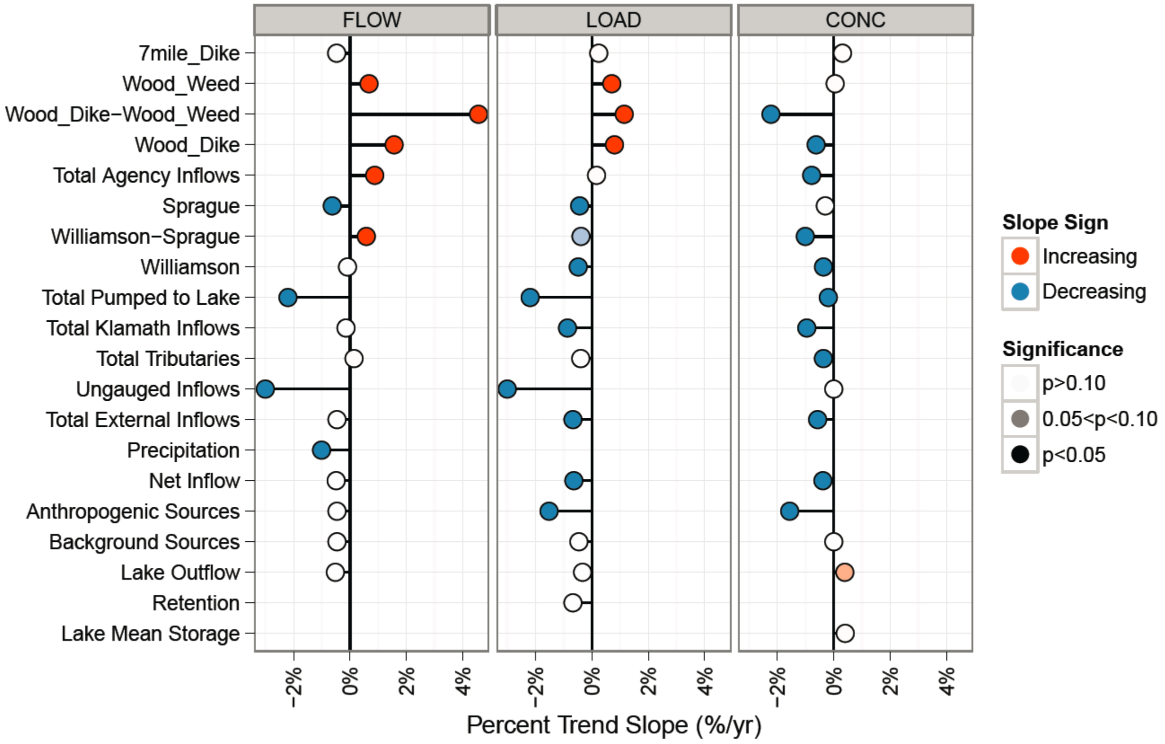
Figure 13 shows long-term trends in each mass-balance term over the period of record (WY 1992-2010) using the Seasonal Kendall Test applied at a monthly time step. Trends in flow, load, and FWM concentration are expressed as percentages of the long-term mean values, with the exception of the retention term which is computed relative to the mean total inflow load. The shades and colors of the trend slopes indicate the significance level and direction (positive or negative) of each trend. Trends in flow are shown in both panels to facilitate interpretation of the trends in load, which are influenced by year-to-year hydrologic variability and thus reflect trends in both flows and concentrations. Appendix G provides additional summary plots for seasonal subsets (growing season and non-growing season), diagnostic plots of each mass balance term showing the trends in individual months and seasons, and tabular summaries of the trend slopes and significance values. Estimates of trend slopes based upon linear regression are also shown in Appendix F and yield results that are generally similar to those based upon the more robust and powerful Seasonal Kendall test.

Figure 13 indicates that there were increasing trends in the total inflow volume to Agency Lake and discharges from the Wood River basin, despite general decreases in precipitation over the period of record (Figure 5). The increases in Wood River flows may be related to decreased agricultural withdrawals and management programs aimed at increasing Wood River flow (e.g., GMA 2011a). No trends were observed in the total nutrient loads to Agency Lake because increases in flow were offset by decreases in concentration. The apparent decreasing trend in FWM concentrations likely reflect KBRT watershed management and grazing strategies aimed at reducing nutrient input in Agency Lake tributaries (e.g., GMA 2011b), as well as implementation of wetland restoration projects (Agency Lake Ranch and Wood River Ranch). Although no significant trends in flows, nutrient loads, or FWM were observed for the Sevenmile Creek basin, such trends would be confounded by inter-drainage flow and load transfer via irrigation canals. For example, flow from the Wood River is diverted, used for irrigation, and enters the Sevenmile system via the West Canal and other irrigation canals.

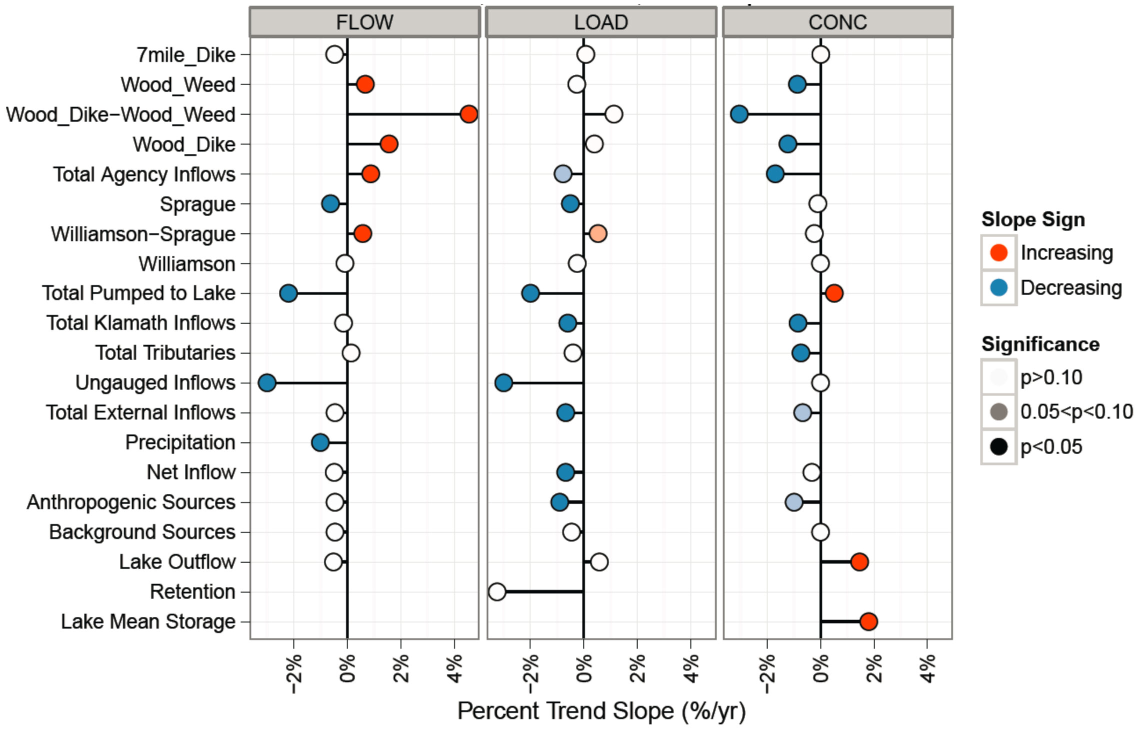
While there was no overall trend in total flow from the Williamson River, flows from the Sprague apparently decreased and flows from the Williamson excluding the Sprague increased. The Williamson River TP loads and concentrations decreased, but trends in TN loads and concentrations were not detected. Reasons for the flow increase and TP concentration decrease in the Williamson River excluding Sprague may reflect upstream management activities on the large Klamath Marsh National Wildlife Refuge, but the possibility of such a connection requires further evaluation.

## Figure 13: Long-term Trends in Flow, Nutrient Loads, and FWM Concentrations

*Total Phosphorus*



*Total Nitrogen*



Decreasing trends in the total pumped inflow volumes and nutrient loads reflect wetland restoration projects (Agency Lake Ranch and Williamson River Preserve). Trend magnitudes should be interpreted with caution because little data on pumped inflows were available prior to 2000. As discussed above, pumped inflow loads from the restored wetlands were also influenced by transient releases from antecedent agricultural soils. The total loads to Agency Lake were strongly influenced by loads from Agency Lake Ranch after it was flooded in 2000, especially in May-September (see Figures in Appendices C and E).

The estimated flow volumes and nutrient loads attributed to ungauged inflows showed overall decreasing trends over the period of record. While these trends could be related to decreases in precipitation (Figure 5), there is considerable uncertainty in ungauged inflows computed from the water budget residuals (Section 2.7). Further analyses of the ungauged inflow estimates and factors associated with the apparent trends are recommended.

Decreasing trends in TP and TN loads and/or concentrations were observed in the total inflows to Klamath Lake (Pumped + Williamson + Ungauged), total external inflows to both lakes, and in the anthropogenic components of the total inflow loads (amount above background, as discussed below).

Despite the long-term decrease in inflow TP concentrations and loads, a weak increasing trend ($p=0.096$) in lake outflow TP concentration was detected but was small in magnitude and no significant trends in outflow TP loads or net retention of TP were observed over the 1992-2010 period. Similarly, outflow TN concentrations showed a significant increasing trend despite small decreasing trends in TN loads and concentrations for total external inflows. The increasing TP concentration in the outflow was not apparent in the lake volume-weighted mean TP concentration, but an increasing trend in TN concentration was found in both the outflow and lake mean concentration. For the May-September period, which was not affected by limited outflow sampling in the winter (1999-2007), no significant trends were observed for lake outflow or storage terms for either TP or TN (Appendix G).

Apparent shifts in the monthly lake TP retention and concentration trends were observed where retention increased in June and decreased in July while lake concentrations decreased in June but increased in August and September (Appendix G). These trends may indicate a forward-shift in the timing of internal loading and bloom dynamics, and are consistent with Jassby and Kann (2010), who indicated a shift towards a later maximum in the timing of peak algal biomass.

Interpretations and power for detecting trends are limited by the high seasonal and year-to-year variability (Figure 11), limited sampling of the lake and outlet in winter months in 1999-2007, changes in water level management, transient nutrient releases associated with the wetland restoration projects, and the expected lag in lake response due to recycling of antecedent nutrient loads stored in the lake bottom sediments (Barbiero & Kann, 1994; Walker, 2001; Kuwabara et al, 2009).

. Appendix H shows seasonal and annual variations in individual species as well as TP and TN at the major long-term sampling stations based on monthly and annual geometric means computed from the original sample data. The measured concentrations were constrained to the maximum detection limits over the period of record for TN (100 ppb), Ammonia (10 ppb) and Nitrite+Nitrate (10 ppb). Formal trend analysis for the inorganic species would be limited by high percentages of values below detection limits, which varied over time. Locally-weighted scatterplot smooth (LOESS) curves are included to indicate changes in the annual and seasonal concentrations over the period of record.

## 3.4 Trends Related to Nutrient Mangement Goals

The target TMDL for TP established by ODEQ (2002) is 109 mt/year, which corresponds to a FWM inflow concentration of 66 ppb at the average inflow observed in WY 1992-1998 (1,650 $hm^3$/yr). Direct comparisons of measured annual loads to the TMDL target is complicated by year-to-year variations in inflow volumes driven primarily by variations in precipitation (Figure 5). The 66 ppb inflow concentration target for the TMDL is similar to the natural background concentration estimated from sampling data collected at springs throughout the basin (65 ppb, Appendix D).

Achieving the nutrient management goals will require reduction of the anthropogenic load, or the amount in excess of the background load computed as follows:

*Background Load = Total External Inflow Volume x Background Concentration*

*Anthropogenic Load = Total External Inflow Load – Background Load*

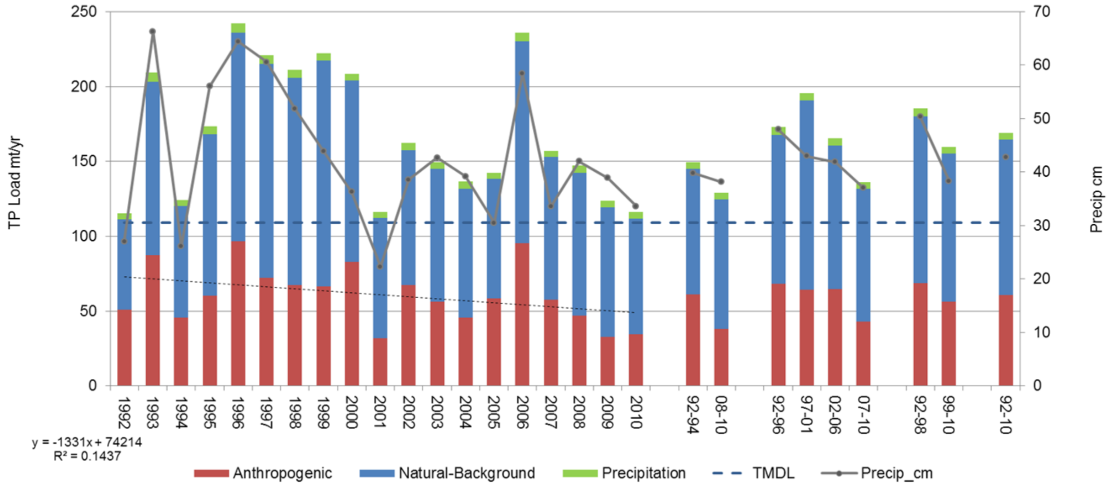
*Anthropogenic Concentration = Anthropogenic Load / Total External Inflow Volume*

Figure 14 shows the annual anthropogenic TP load and FWM concentration by water year and for multi-year intervals including reference lines for the TMDL targets and annual precipitation. The thin dotted lines are linear regressions.

Both Seasonal Kendall tests and linear regressions indicated that there were small but statistically significant decreasing trends in the total and anthropogenic inflow TP loads and concentrations over the WY 1992-2010 period. The trends in concentrations are more evident than the trends in yearly loads, which are strongly dependent on variations in precipitation. Most of the decreases apparently occurred in the earlier (WY 1992-1999) and later years (WY 2008-2010). Loads and concentrations in the intervening years were highly variable and influenced by variations in precipitation and nutrient releases from sediments in the restored wetland areas (Williamson River Preserve, Agency Lake Ranch, Wood River Ranch).

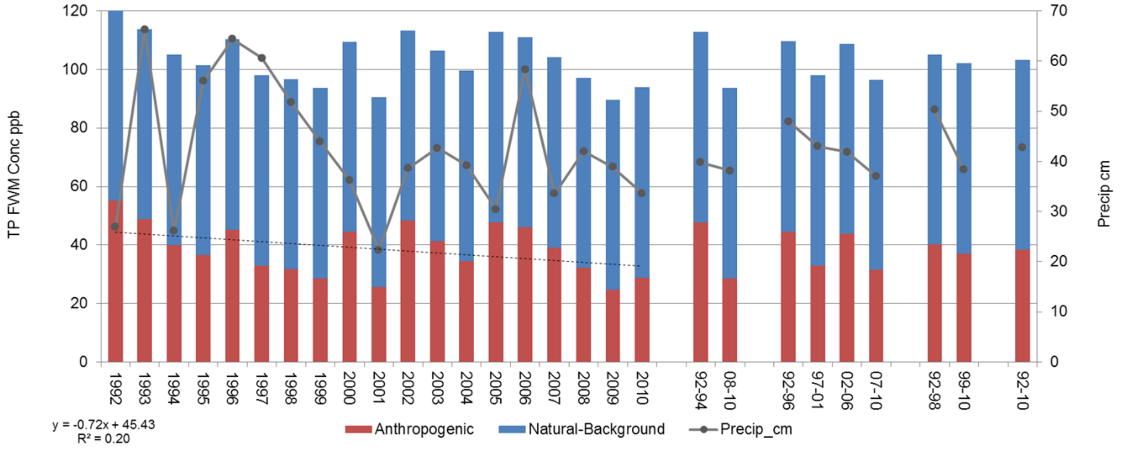
Table 3 compares average inflow volumes, nutrient loads, and nutrient concentrations in three periods: 1992-1998 (TMDL baseline), 1992-1994 (first three years), and 2008-2010 (last three years). Detailed water and mass balances for 2008-2010 are listed in Table 4; results for other periods are provided in Appendix E. Results for 2008-2010 provide the best estimates of current conditions, although inflow loads and concentrations may continue to decrease in the future as soils in the restored wetlands are stabilized and/or other management efforts are implemented. The average inflow volume in WY 1992-1998 (1,711 $hm^3$/yr) differs slightly from that used as a basis for the TMDL (1,653 hm³/yr) because of minor revisions to the flow and precipitation data used to construct the water budget (see comparisons in Appendix E).

**Figure 14: Total and Anthropogenic TP Loads and Concentrations**



Anthropogenic Load = Total External Load - Total External Inflow x Background Conc 65 ppb Trend = -1.3 +/- .8 mt/yr/ yr, p = 0.11

TMDL Goal: Total External Inflow Load (Anthropogenic + Background ) = 109 mt/yr



Anthropogenic Conc = Anthropogenic Load / Total External Inflow Volume Trend = -.6 +/- .3 ppb / yr, p = 0.08

TMDL Goal: Total External Inflow Concentration (Anthropogenic + Background ) = 66 ppb

## Table 3: Total and Anthropogenic Inflows for Different Time Periods

| | Total External Inflow | | | Anthropogenic | | |
|---|---|---|---|---|---|---|
| | Flow | Load | Conc | Load | Conc | % of Total |
| Period | hm3/yr | mt/yr | ppb | mt/yr | ppb | Load & Conc |
| Total Phosphorus | | | | | | |
| 1992-1998 | 1,711 | 180 | 105 | 69 | 40 | 38% |
| 1992-1994 | 1,286 | 145 | 113 | 61 | 48 | 42% |
| 2008-2010 | 1,328 | 124 | 94 | 38 | 29 | 31% |
| TMDL (ODEQ, 2002) | 1,653 | 109 | 66 | 2 | 1 | 2% |
| Reductions vs. 1992-1998 (TMDL Base Period) | | | | | | |
| 2008-2010 | 22% | 31% | 11% | 45% | 29% | 8% |
| Reductions vs. 1992-1994 (First vs. Last Three Years) | | | | | | |
| 2008-2010 | -3% | 14% | 17% | 38% | 40% | 12% |
| Total Nitrogen | | | | | | |
| 1992-1998 | 1711 | 598 | 349 | 429 | 250 | 72% |
| 1992-1994 | 1286 | 417 | 324 | 290 | 225 | 69% |
| 2008-2010 | 1328 | 382 | 288 | 251 | 189 | 66% |
| Reductions vs. 1992-1998 (TMDL Base Period) | | | | | | |
| 2008-2010 | 22% | 36% | 18% | 42% | 25% | 6% |
| Reductions vs. 1992-1994 (First vs. Last Three Years) | | | | | | |
| 2008-2010 | -3% | 8% | 11% | 14% | 16% | 4% |

Anthropogenic Load = Total External Load - Total Inflow x Background Conc (TP = 65 ppb, TN = 99 ppb).

Anthropogenic Conc = Anthropogenic Load / Total External Inflow

## Table 4: Water and Mass Balances for Water Years 2008-2010

**Upper Klamath Lake Water & Nutrient Balances** **Water Years: 2008- 2010**

| | Flow | Nutrient Loads | | Percent of Inflow | | | Nutrient Concs | | Dr. Area | Runoff | P Export | N Export |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Term | $hm^3$/yr | TP mt/y | TN mt/y | Flow | TP | TN | TP ppb | TN ppb | $km^2$ | m/yr | $kg/km^2$ | $kg/km^2$ |
| **Major Gauged Sites** | | | | | | | | | | | | |
| Wood River @ Weed Road | 244.9 | 21.1 | 24.5 | 18% | 17% | 6% | 86 | 100 | 333 | 0.74 | 63 | 74 |
| Wood River @ Dike Road | 347.1 | 35.9 | 54.5 | 26% | 29% | 14% | 103 | 157 | 394 | 0.88 | 91 | 138 |
| 7-Mile Canal | 101.4 | 13.5 | 46.0 | 8% | 11% | 12% | 133 | 454 | 96 | 1.05 | 140 | 477 |
| Sprague River | 349.4 | 22.9 | 112.2 | 26% | 18% | 29% | 65 | 321 | 4171 | 0.08 | 5 | 27 |
| Williamson River | 690.0 | 54.7 | 191.4 | 52% | 44% | 50% | 79 | 277 | 7812 | 0.09 | 7 | 25 |
| Klamath L Outlet | 1143.6 | 134.0 | 2242.6 | 86% | 108% | 587% | 117 | 1961 | 9771 | 0.12 | 14 | 230 |
| **Agency Lake Inflows** | | | | | | | | | | | | |
| Wood River above Weed Rd | 244.9 | 21.1 | 24.5 | 53% | 40% | 18% | 86 | 100 | 333 | 0.74 | 63 | 74 |
| Wood River below Weed Rd | 102.2 | 14.8 | 30.0 | 22% | 28% | 22% | 145 | 294 | 61 | 1.68 | 243 | 493 |
| 7-Mile Canal | 101.4 | 13.5 | 46.0 | 22% | 26% | 34% | 133 | 454 | 96 | 1.05 | 140 | 477 |
| Agency Lake Ranch | 17.3 | 3.2 | 34.1 | 4% | 6% | 25% | 185 | 1969 | 46 | 0.37 | 69 | 737 |
| Total Agency Inflow | 465.8 | 52.6 | 134.7 | 100% | 100% | 100% | 113 | 289 | 537 | 0.87 | 98 | 251 |
| **Klamath Lake Inflows** | | | | | | | | | | | | |
| Sprague River | 349.4 | 22.9 | 112.2 | 49% | 37% | 48% | 65 | 321 | 4171 | 0.08 | 5 | 27 |
| Williamson - Sprague | 340.6 | 31.9 | 79.2 | 48% | 52% | 34% | 94 | 233 | 3641 | 0.09 | 9 | 22 |
| Pumped Inflows to KL | 16.9 | 7.0 | 40.4 | 2% | 11% | 17% | 413 | 2390 | 37 | 0.45 | 186 | 1079 |
| Total Klamath Inflow | 706.9 | 61.7 | 231.9 | 100% | 100% | 100% | 87 | 328 | 7849 | 0.09 | 8 | 30 |
| **Overall Balance** | | | | | | | | | | | | |
| Total Tributaries | 1138.4 | 104.1 | 292.0 | 86% | 84% | 76% | 91 | 256 | 8302 | 0.14 | 13 | 35 |
| Total Pumped to Lake | 34.3 | 10.2 | 74.6 | 3% | 8% | 20% | 297 | 2177 | 84 | 0.41 | 122 | 890 |
| Ungauged Inflows | 155.5 | 10.1 | 15.4 | 12% | 8% | 4% | 65 | 99 | 1118 | 0.14 | 9 | 14 |
| Total External Inflows | 1328.2 | 124.4 | 382.0 | 100% | 100% | 100% | 94 | 288 | 9504 | 0.14 | 13 | 40 |
| Precipitation | 101.6 | 4.5 | 27.1 | 8% | 4% | 7% | 45 | 267 | 267 | 0.38 | 17 | 102 |
| Evaporation | 251.7 | | | 19% | | | | | 267 | 0.94 | | |
| Net Inflow | 1178.1 | 128.9 | 409.1 | 89% | 104% | 107% | 109 | 347 | 9771 | 0.12 | 13 | 42 |
| Lake Outflow | 1143.6 | 134.0 | 2242.6 | 86% | 108% | 587% | 117 | 1961 | 9771 | 0.12 | 14 | 230 |
| Storage Increase | 16.5 | 0.8 | 8.6 | 1% | 1% | 2% | | | | | | |
| Retention | 18.0 | -5.8 | -1842.1 | 1% | -5% | -482% | | | | | | |
| **Natural Background vs. Anthropogenic Loads** | | | | | | | | | | | | |
| Background / Natural | 1328.2 | 86.3 | 131.5 | 100% | 69% | 34% | 65 | 99 | 9504 | 0.14 | 9 | 14 |
| Anthropogenic | 1328.2 | 38.0 | 250.5 | 0% | 31% | 66% | 29 | 189 | | | 4 | 26 |

| Morphometry | Mean | Min | Max |
|---|---|---|---|
| Volume ($hm^3$) | 497.7 | 298.8 | 719.5 |
| Area ($km^2$) | 266.5 | 249.4 | 270.5 |
| Elevation (ft) | 4140.3 | 4137.8 | 4143.0 |
| Mean Depth (meters) | 1.9 | 1.2 | 2.7 |

| Phosphorus Model Parameters | | |
|---|---|---|
| Hydraulic Residence Time | 0.42 | years |
| Net Water Load | 4.98 | m/yr |
| Areal Total P Load | 0.47 | $g/m^2$-yr |
| Total P Retention Coefficient | -5% | |

Inflow TP concentrations averaged 94 ppb in WY 2008-2010, as compared with 113 ppb in WY 1992-1994, 105 ppb in WY 1992-1998, and the TMDL goal of 66 ppb. Evaluation of load reductions relative to the TMDL baseline is complicated by the fact that precipitation and flow volumes were significantly lower in WY 2008-2010, as compared with WY 1992-1998 (1,327 vs. 1,711 hm3/yr). The estimate of TP load reduction relative to the TMDL baseline (31%) reflects both reductions in flow driven by climate (22%) and reductions in FWM concentration potentially attributed to management efforts (11%).

The first three-year period (WY 1992-1994) can be used as an alternative basis for comparison with WY 2008-2010 because the average inflow volumes differed by only 3%, the two periods are of equal duration, and the comparison captures the entire range of conditions over the period of record (Table 3). One limitation of this comparison is that yearly flows spanned a wider range in WY 1992-1994 as compared with WY 2008-2010 (Figure 6). This comparison indicates a 3% increase in flow, 14% decrease in TP load, and a 17% decrease in FWM TP concentration in WY 2008-2010 relative to WY 1992-1994. The corresponding reductions in TN load and FWM concentration were 8% and 11%, respectively. The lower magnitudes of the load reductions can be partially attributed to the apparent increases in flow volume from the Wood River discussed above.

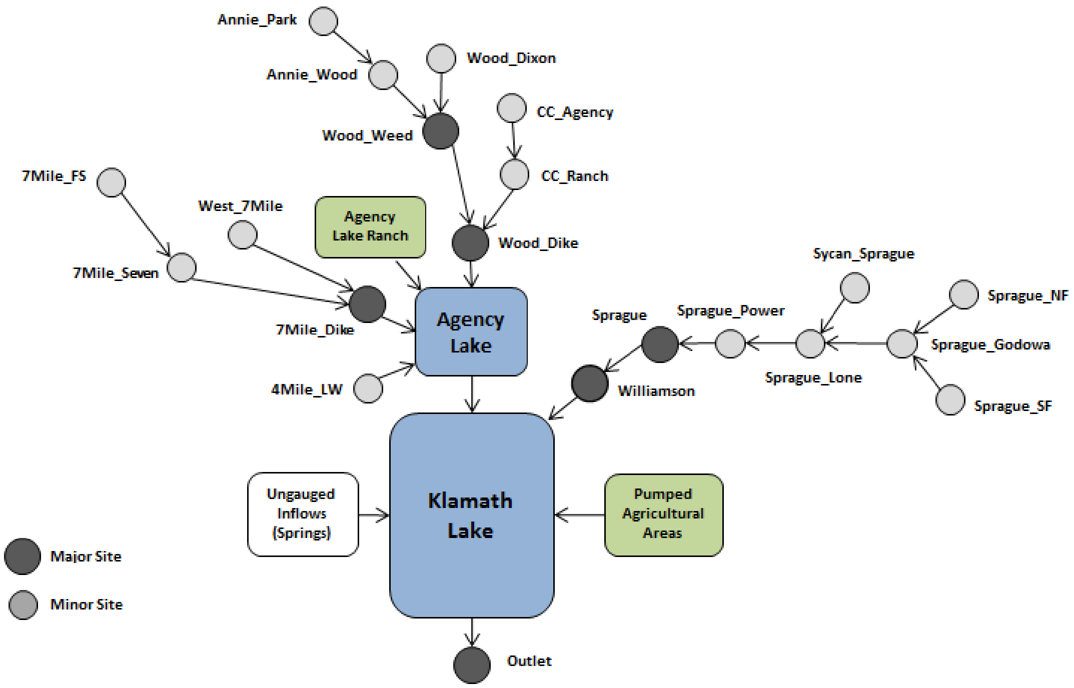
Inflow TP concentrations from anthropogenic sources (above 65 ppb background) averaged 29 ppb in WY 2008-2010, as compared with 48 ppb in WY 1992-1994 and 40 ppb in in WY 1992-1998, and the TMDL goal of ~ 1 ppb (Table 3). Anthropogenic TP concentrations decreased by 40% relative to WY 1992-1994 and by 29% relative to WY 1992-1998. Corresponding reductions in anthropogenic TN concentration were 16% and 25%, respectively. Subject to uncertainties associated with the limited data for pumped inflows prior to 2000, these results estimate the cumulative benefits of restoration measures implemented over the period of record. Further decreases may result from continued stabilization of soils in the restored wetlands and implementation of additional load-reduction measures. Reductions in the lake and outflow concentrations may also occur as sediment nutrient storage and cycling equilibrate to the reduced inflow loads.

## 3.5 Spatial Variations

Spatial variations in nutrient concentrations reflect the cumulative impacts of human activities as well as variations in geology and potential ground water input along each tributary in the UKL basin. Figure 15 shows a schematic of the 20 sampling stations above the lake with sufficient data to support spatial analysis, as summarized in Appendix D. Stations locations are shown in Figure 3. The network includes the 5 major tributary sites used in the mass balance and 15 minor sites that provide greater spatial resolution but were sampled less consistently. The analysis is based upon data from WY 2002-2010, when the Klamath Tribes monitoring network was expanded to include biweekly sampling at 6 stations in the upper Sprague River basin. The 9 additional minor sites in the western basins were sampled less frequently but provided at least 20 samples collected in 2 or more years. As compared with sites closer to the lake, nutrient concentrations at many of the minor sites in the western basins were less variable because they were dominated by discharges from springs.

For each station, the overall mean flows, nutrient loads, and FWM concentrations were computed along with standard errors using paired concentration and flow measurements (Appendix D). The load-calculation algorithm used for the major sites in formulating the mass balances (Appendix E) could not be used because continuous daily flow records were not available for the minor sites. While including data from the minor sites provides useful perspectives on spatial variations in the basin, the average flows, loads, and concentrations are subject to uncertainty because they do not reflect flow variations between sampling dates and the sampling frequencies varied widely across the minor sites. The results for FWM concentrations are emphasized because they are likely to be more robust to variations in sampling frequency, as compared with flows or loads. Development of daily flow datasets for each site using regression or interpolation methods would provide a basis for more accurate assessment of spatial variations in concentrations and unit area loads normalized to a common hydrologic baseline.

**Figure 15: Schematic Diagram of Sampling Stations used for Spatial Analysis**



Unit area runoff and nutrient export values for the major basins used in the mass balance calculations are tabulated in Appendix E for various time periods. Based upon the WY 1992-2010 results (Table 2), the unit area TP export averaged 153 to 239 kg/km$^2$-yr in the predominately agricultural basins (Pumped Loads, Sevenmile Creek, Wood River below Weed Road), as compared with 63 kg/km$^2$-yr in the upper Wood River basin (above Weed Road), and 9 to 10 kg/km$^2$-yr in the Williamson and Sprague basins. The Weed Road export value is likely an over-estimate because the drainage area determined from surface topography does not reflect the groundwater recharge areas for springs that feed the Wood River above Weed Road.

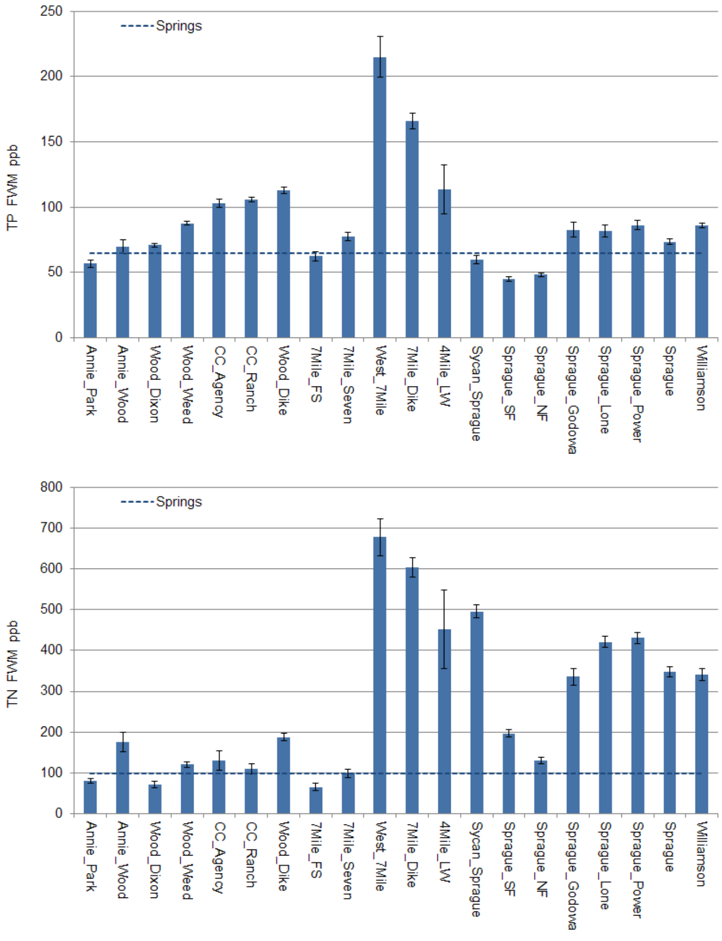
Attempts to compute unit-area runoff and export from using the expanded network were made but considered inaccurate for the following reasons:

1. The complex hydrologic alterations in Wood River and Seven Mile Creek watersheds due to extensive drainage networks made it difficult to delineate drainage areas in these basins, as is typically done based on surface topography.

2. Separation of loads from the Wood, Sevenmile and Fourmile basins was complicated by inter-basin transfers reflecting agricultural water management and wetland restoration projects.
3. The headwaters of the Wood and Sevenmile basins are dominated by discharges of groundwater from springs. It is likely that actual drainage areas required to compute unit area runoff and nutrient export are considerably larger than those estimated based upon surface topography.
4. The precision of incremental loads computed based upon the differences in loads between adjacent monitoring sites along each tributary is likely to be low.

Given limitations in the datasets and other factors discussed above, spatial variations in FWM concentrations moving downstream from the relatively un-impacted headwaters in each basin provide the best basis for assessing cumulative impacts of human activities in the lower watersheds (Figure 16). The stations are sorted in downstream order within each watershed (Annie Creek, Crooked Creek, Wood River, Sevenmile Creek, Sprague River, and Williamson River). Reference lines indicate background concentrations estimated from spring monitoring sites. Figures in Appendix D show corresponding spatial variations in sampling frequencies, flows, loads and FWM concentrations averaged by season for each nutrient.

**Figure 16: Spatial Variations in FWM Nutrient Concentrations, WY 2002-2010**



Means +/- 1 Standard Error, Paired Flow & Concentration Data, ~Biweekly Sampling, WY 2002-2010; Details in Appendix D
Dashed Lines = Average Value for Spring Sites Used to Estimate Ungauged Loads to Lake

FWM TP concentrations ranged from 45 ppb at the Sprague River South Fork (Sprague_SF) to 215 ppb in the West Canal at the confluence with Seven Mile Canal (West_7Mile) and generally increased moving downstream within each basin. TP concentrations at 6 headwater stations (Annie_Park, Wood_Dixon, 7Mile_FS, Sycan, Sprague_SF, Sprague_NF; Figure 15) ranged from 45 to 71 ppb. Increases in FWM TP concentration moving downstream from the headwaters in each basin reflect the cumulative impacts of loads from anthropogenic sources. TP concentrations at lake inflow points ranged from 84 to 166 ppb, as compared with headwater concentrations of 45 to 71 ppb and 413 ppb in discharges from farm pumps (Appendix C). With the exception of Wood River at Dixon Road (71 ppb), TP concentrations measured at the headwater stations were below those measured in regional springs (65 ppb) and assumed to reflect background or natural conditions. This result suggests that incorporating data from surface-water sites in the basin headwaters would likely provide lower estimates of background concentration (~60 ppb, Figure D8, Appendix D) and thus correspondingly higher estimates of anthropogenic loading. Such estimates could potentially be influenced by downstream inflows with naturally occurring higher concentrations relative to the headwaters (e.g., ground water inputs or unmeasured tributaries draining areas reflecting different geology). However, major inputs are reflected by the spatial variations in measured concentrations; using Sevenmile Creek as an example, concentrations in irrigation return flow from the West Canal (station West_7Mile) are substantially elevated compared with the irrigation source water (upper Wood River) and with Sevenmile Creek directly upstream from the West Canal confluence (station 7Mile_Seven, Figure 16).

Spatial gradients in FWM TN concentrations were less pronounced than those observed in TP. Headwater TN concentrations ranged from 65 to 80 ppb in the western basins (Annie_Park, Wood_Dixon, 7Mile_FS) and from 131 to 496 ppb in the eastern basins (Sycan, Sprague_NF, Sprague_SF), as compared 99 ppb in springs, 188 to 603 ppb at lake inflow sites, and 2390 ppb in discharges from farm pumps. The higher TN values in the eastern basins may reflect the fact that the headwaters of the Sprague are dominated by snowmelt, as compared with springs and wetlands in the eastern basins and upper Williamson. Consideration of data from headwater sites results in slightly higher concentrations of background TN concentration (~105 ppb vs. 99 ppb, Figure D9, Appendix D).

# 4 CONCLUSIONS AND RECOMMENDATIONS

1) This study evaluated reductions in TP and TN loads and concentrations in the inflows to UKL over the 1992-2010 period and associated progress towards achieving nutrient management goals (ODEQ, 2002). The effects of wetland restoration and other watershed management activities were partially reflected in the observed trends of inflow volumes, loads and flow-weighted mean concentrations from various sources around the lake.

2) Long-term trends in nutrient loads were to some extent masked by year-to-year variations in climate and hydrology. Basin precipitation and flows generally increased over the 1992-1998 period and were generally at or below average in 1999-2010, with the exception of 2006 which was a relatively wet year. As compared with nutrient loads, FWM concentrations provided a better basis for evaluating long-term trends in the tributaries and combined inflows relative to the TMDL goal because they were less variable from year-to-year and less dependent on precipitation and flow volumes.

3) Decreases in nutrient inflow concentrations were apparent in WY 1992-1999 and again in WY 2008-2010. Concentrations and loads in WY 2000-2007 were highly variable and influenced by transient nutrient releases from antecedent agricultural soils in the restored wetland areas (Agency Lake Ranch, Wood River Ranch, and Williamson River Preserve). Data from WY 2008-2010 are considered to be the most accurate and representative of current conditions, although further decreases in nutrient loads may result from continued stabilization of soils and vegetation in the restored wetlands (Williamson River Preserve, Agency Lake Ranch, Wood River Ranch).

4) The combined inflow TP concentration from external sources (tributaries + pumps + ungauged inflows) averaged 94 ppb in WY 2008-2010 (last three years), as compared with 113 ppb in WY 1992-1994 (first three years), 105 ppb in WY 1992-1998 (TMDL baseline), and the TMDL

goal of 66 ppb (ODEQ, 2002). Average TP loads in those periods were 124, 145, and 180 mt/yr, respectively, as compared with the TMDL goal of 109 mt/yr.

5) The estimate of TP load reduction in WY 2008-2010 relative to the TMDL baseline (31%) reflected both reductions in flow (22%) attributed to variations in precipitation and reductions in FWM concentration (11%) attributed to restoration and management efforts or other factors. Corresponding reductions in TN load and concentration relative to the TMDL baseline were 36% and 18%, respectively.

6) Comparisons of results for WY 2008-2010 with results for WY 1992-1994 were less dependent on variations in precipitation and indicated a 3% increase in flow, 14% decrease in TP load, and a 17% decrease in FWM TP concentration. Corresponding reductions in TN load and concentration relative to WY 1992-1994 were 8% and 11%, respectively.

7) Inflow TP concentrations from anthropogenic sources (above 65 ppb background estimated from regional springs) averaged 29 ppb in WY 2008-2010, as compared with 48 ppb in WY 1992-1994, 40 ppb in WY 1992-1998, and the TMDL goal of ~1 ppb. Anthropogenic TP concentrations decreased by 40% relative to WY 1992-1994 and by 29% relative to WY 1992-1998. Corresponding decreases in anthropogenic TN concentration were 16% and 25%, respectively.

8) Seasonal Kendall tests indicated that there were significant decreasing trends in FWM TP concentrations in discharges from the Williamson River excluding the Sprague River, lower Wood River (below Weed Road), pumped inflows, and in the total inflows. No trends in FWM TP concentrations were observed in the upper Wood River (above Weed Road), Sevenmile Creek, or the Sprague River. Results for TN were qualitatively similar, with the exception that trend magnitudes were slightly lower and no significant trend was detected in the lower Williamson.

9) Observed increases in flow from the Wood River basin may be related to decreases in agricultural withdrawals and management programs aimed at increasing flow. As a result of increasing flows, TP loads from the Wood River also increased but were partially offset by decreases in FWM concentration consistent with wetland restoration (Wood River Ranch) and other management efforts in this sub-watershed.

10) Despite long-term decreases in the total inflow nutrient concentrations and loads, significant trends in outflow loads or net retention were not observed over the 1992-2010 period. Nutrient concentrations apparently increased in the outflow ($p < 0.1$ for TP and $p < 0.05$ for TN) but not in the lake volume-weighted mean concentrations on an annual basis, and no trends were observed during the May-September period. Interpretations of lake responses are complicated by the high seasonal and year-to-year variability, limited sampling of the lake and outlet in winter months in 1999-2007, changes in water level management, and the expected lag in lake response due to recycling of antecedent nutrient loads stored in the lake bottom

sediments on a seasonal and inter-annual basis.

11) Analysis of WY 2002-2010 data from an expanded watershed monitoring network of 20 sites revealed decreasing spatial gradients in TP and TN concentrations that reflected cumulative impacts of anthropogenic inputs along each tributary, as well as potential spatial variations in local inflows related to geology and other unknown factors. Surface-water sites in the basin headwaters with relatively undeveloped watersheds had TP concentrations ranging from 48 ppb to 71 ppb and were generally below the 65 ppb background concentration measured in regional springs, which was assumed to estimate the lake inflow concentration under natural conditions. Consideration of data from headwater sites would likely provide lower estimates of background loads, although the estimates could also be influenced by contributions from naturally occurring inflows to the downstream segments.

12) The 19-year databases documenting the hydrology and water quality in the UKL tributaries and lake provide powerful bases for evaluating the lake mass balances and detecting trends in the inflows and lake in the presence of wide variations driven by climate and other factors. The intensity, consistency, and duration of the tributary and lake monitoring programs are unusual relative to typical monitoring programs designed to support management decisions.

13) A number of data limitations were identified that may impact the results and conclusions of this study:

    a) Reduced outlet and lake sampling frequencies in November-March of WY 1999-2007 limited the evaluation of magnitudes and trends in nutrient loads and concentrations in the outflow, as well as in the storage and net retention of nutrients within the lake on an annual basis.

    b) Relatively low sampling frequencies for the major tributaries in WY 1997-2003, when the number of samples per water year and site typically ranged from 8 to 20, as compared with the biweekly design (26).

    c) Direct flow and nutrient concentration data for pumped inflows from agricultural areas prior to restoration were limited over the entire period. Inflow volumes were estimated based on a regression against Williamson River flow. Limited grab samples collected without regard to flow were used as basis for estimating nutrient loads and FWM concentrations.

    d) The constructed lake nutrient budgets may not fully reflect loads associated with transient nutrient releases from antecedent agricultural soils following re-flooding for wetland restoration projects; these loads are reflected in the discharges from Agency Lake Ranch but not from the Williamson River Preserve or Caledonia Marsh.

e) Uncertainty in estimating missing daily flows using biweekly data collected under different monitoring programs, particularly in the Wood River and Sevenmile Creek basins.

f) Difficulties in measuring inflows to Agency Lake from Wood River and Sevenmile Creek resulted from the stage at monitoring sites being partially controlled by lake water levels.

g) Ungauged inflows were estimated to account for 18% of inflow volume and 11% of TP load. Negative values computed for some months (primarily winter months of relatively dry years) were constrained to zero and possibly reflect errors in the measurements or estimates of the other water budget terms.

14) The nutrient budgets for WY 2008-2010 are likely to be more accurate than those estimated for previous years because the tributary and outflow datasets were more complete, most of the pumped inflows were either directly measured (Agency Lake Ranch) or eliminated (Williamson River Preserve), and it is likely that unmonitored nutrient loads reaching the lake from antecedent agricultural soils in the restored wetlands had largely attenuated.

15) Given the data limitations and assumptions required to construct the budgets within the limited scope of the current effort, more detailed exploratory analysis of the output may identify needs for refining the datasets, assumptions, and computations involved in constructing the historical budgets and evaluating trends, as well as enhancements to the monitoring programs to support development of more accurate water and mass balances in future years.

16) Suggested future tasks designed to improve, interpret, and apply the results include:

a) Evaluation of trends in lake concentrations of nutrients, chlorophyll-a, pH and other water quality indicators using robust statistical methods (e.g., Seasonal Kendall Test), and comparison with variations in the lake inflows, storage, and retention.

b) Investigation of errors in the water budget that occur in months with negative ungauged inflows.

c) Detailed evaluation of loads in the Sprague River basin including development of daily flow and load datasets using the biweekly data collected in WY 2002-2010.

d) Refinement of methods used to estimate historical flows and loads from agricultural areas and restored wetlands adjacent to the lake, including effects of transient loads associated with re-flooding of agricultural soils.

e) Sensitivity and uncertainty analyses of the methods and assumptions used throughout this study, such as the estimates of background nutrient conditions, daily flow and load datasets for the gauged tributaries, assumed concentrations and estimated flows for pumping from agricultural areas over the period of record, and statistical measures used to represent long-term average conditions.

f) Interpretation of year-to-year variations and long-term trends relative to variations in climate, lake management, and implementation of specific management measures.

g) Development of multiple regression models to increase statistical power for detecting long-term trends in loads relative to the TMDL goal in the presence of year-to-year variations driven by precipitation (Walker, 2000; 2002). Correlations linking inflow volumes and loads to precipitation over the lake could be refined by utilizing precipitation data averaged over the individual watersheds.

h) Update water and mass balances at five-year intervals (or more often) to provide current information on the status of the inflows and lake water quality relative to management objectives; updates could be streamlined considerably by maintaining consistent databases and developing software to automate computations and report results.

i) Update and refinement of the lake phosphorus model used as a basis for estimating the TMDL (Walker, 2001; ODEQ, 2002) using the extended period of record.

j) Develop segmented water and nutrient budgets for the entire Klamath Basin. This would involve merging these results for Upper Klamath with previous results for the Lower Klamath (Asarian et al., 2009; Asarian et al., 2010) and additional sub-basins, depending on data availability.

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