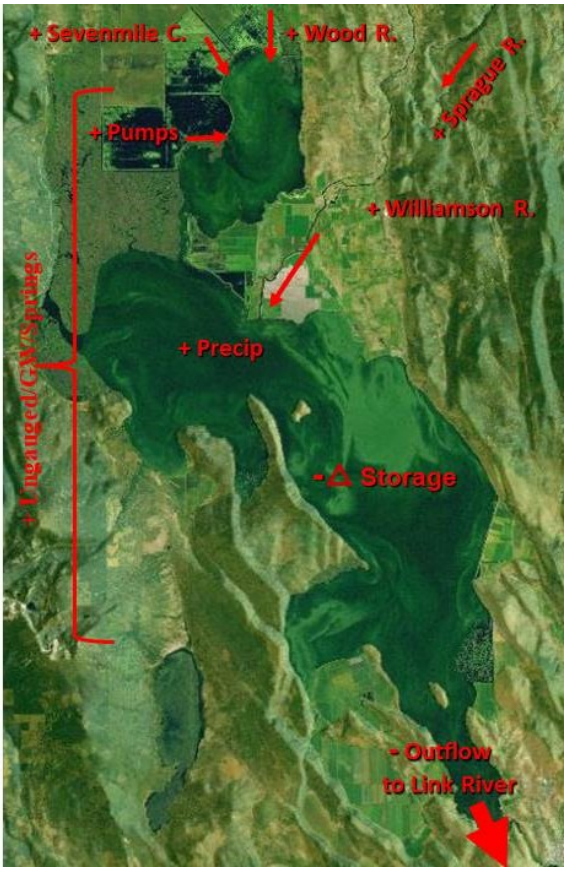
# INFLOW/OUTFLOW PHOSPHORUS LOADING DYNAMICS IN UPPER KLAMATH LAKE, OR




*Prepared For*

U.S. Fish & Wildlife Service

*by*

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Walker Environmental Resources LLC

*and*

Jacob Kann, PhD
Aquatic Ecosystem Sciences LLC

**November 2020**

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# EXECUTIVE SUMMARY

Upper Klamath Lake (UKL) is a hypereutrophic shallow lake located in southern Oregon, U.S. Poor water quality directly associated with the growth and decline of large cyanobacterial blooms has been identified as an important factor contributing to the decline of native and endangered sucker species. A major driver of these blooms is the release of phosphorus from lake sediments, which generally occurs in the early summer of each year. A preliminary model developed before this study, along with the results of other recent modeling studies of UKL, suggested that outflow total phosphorus (TP) loads may be closely coupled with recent inflow loads, and that in-lake and outflow water quality may respond relatively quickly to external load reductions. To evaluate this hypothesis, we used an existing mass balance dataset containing monthly total flows, TP loads, and flow-weighted mean (FWM) TP concentrations of the lake inflows, outflows, and net sediment fluxes (WY 1992–2010). Our approach focused on 1) developing a better understanding of whether (and how) outflow P loads and concentrations may be driven by recent inflow loads, and 2) determining whether the preliminary linear model that suggested both the current and previous years' inflow TP load had a large effect on outflow loads could be explained or if it was caused by random noise.

We first evaluated and refined a preliminary linear regression model that predicted annual outflow TP loads as a function of current and previous year's inflow loads. We then used exploratory data analysis (EDA) techniques to better understand the seasonal patterns and year-to-year variability of the water and TP budgets. Lastly, we generated correlation matrices of the annual and seasonal fluxes for each mass balance term to determine whether there was evidence supporting the model results that suggested outflow loads and concentrations were coupled with recent (current and previous years) inflow loads in UKL.

Correlations between seasonal and annual mass balance fluxes showed that higher inflow loads in a given year led to higher net retention during the winter, which in turn led to higher net release the following summer followed by higher outflow loads and concentrations. In other words, outflow loads (and concentrations) in any given year were driven in large part by the net release of P from the sediment during the summer growing season, which in turn was driven by inflow loads during the previous winter. Furthermore, because outflow TP concentrations are often representative of the lake-wide mean (i.e., in-lake) TP concentrations, these dynamics affect not only the TP loads and concentrations discharged from UKL, but also the water quality within the lake itself.

Although further research is needed to confirm that these results reflect not just correlation but also causation, they have important implications for implementation of watershed P reduction strategies and underscore the need to implement full scale watershed restoration strategies as rapidly as possible. And while some lag is to be expected between the implementation of watershed restoration activities and reductions in the associated external P loads to UKL, the potential for rapid cycling of external loads through the sediment suggests that improved UKL water quality may occur over relatively short timescales. This improvement in both the water quality within UKL as well as its outflow would benefit the endangered suckers residing within the lake and result in a reduction of nutrients exported downstream to Klamath River.

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# 1 INTRODUCTION

Upper Klamath Lake (UKL) is a hypereutrophic shallow lake located in southern Oregon that provides important habitat for endangered species of sucker fish. Poor water quality directly associated with the growth and decline of large cyanobacterial blooms has been identified as an important factor contributing to the decline of these endemic species (Rasmussen 2011; Perkins et al. 2000; Kann and Walker 2020). Cyanobacteria blooms are tied both to excessive external phosphorus (P) loading, as well as release of P from sediments (i.e., internal loading) during the summer algal growing period (Kann and Walker 1999; ODEQ 2002; Walker et al. 2012; Wherry and Wood 2018). Total Maximum Daily Load (TMDL) analyses indicated that 40 percent of the external load to UKL is anthropogenically derived, and reductions in that load would lead to lower in-lake P concentrations and improved water quality based on model simulations (ODEQ 2002; Walker 2001).

Building on the original TMDL model, subsequent modeling studies continued to show that reductions of external anthropogenic P loads would result in decreased in-lake P, chlorophyll-a, and pH levels (Wood et al. 2013; Wherry et al. 2015). Most recently, a modeling study of UKL P dynamics that included sediment P mass and associated water column-sediment feedbacks predicted that it would take 20–30 years for water column P and sediment P to reach a new equilibrium following instantaneous reductions in external P loads (Wherry and Wood 2018). However, the responses of water column P concentration and sediment P mass to the external load reduction were non-linear such that most of the changes towards the new equilibrium were achieved within the initial five (~50% achieved) to ten years (~80% achieved) (see Figures 17 and 18 in Wherry and Wood 2018). Therefore, although this model predicted that it would take 20–30 years for water column-sediment dynamics to reach a new equilibrium, the majority of changes in in-lake P concentration and sediment P mass would occur within the first 5–10 years.

Despite the long history of high external P loading to UKL due to land use alterations occurring during the past ~100 years[1], these recent modeling efforts suggest that the mobile fraction of the sediment P pool[2] may respond relatively rapidly to changes in external load. This in turn suggests that the bulk of sediment legacy P[3] is immobile and may not be a large net source of P to the water column. Therefore, in-lake P concentrations may respond rapidly to external P load reductions because they are driven in large part by the summer sediment P release[4]. In other words, the seasonal release of sediment P in UKL may be more a function of P recently loaded into the lake than of legacy P that is stored in the sediment and derived from historical inflows over long time

[1] Land use alterations included timber harvest, drainage of wetlands, agricultural activities associated with livestock grazing and irrigated cropland, and hydrologic modifications such as water diversions and channelization (Snyder and Morace 1997; ODEQ 2002; Bradbury et al. 2004; Eilers et al. 2004).
[2] The mobile fraction of the sediment P pool comprises the primary source of P that is released from the sediment during the growing season of each year (e.g., Hupfer et al. 2020).
[3] Legacy P is defined as P that has accumulated in sediments over time from historical external P loading.
[4] Large negative net retention values calculated from monthly P balances indicate sediment P release exceeds sedimentation during the summer in UKL (Walker et al. 2012).

periods. A preliminary analysis (Section 1.1) provided further evidence of this rapid cycling by indicating that annual outflow load and concentration, which is often representative of in-lake TP concentrations, were closely related to inflow loads over the near term. This preliminary analysis formed the basis for this study.

## 1.1 Preliminary Analysis

Preliminary modeling suggested that the annual outflow P load in any given year was strongly dependent on the annual inflow load of that same year as well as the previous year. This analysis was inspired by the observation that annual outflow P loads tended to lag inflow loads by one year (Figure 1). To evaluate the relationship between outflow loads and recent inflow loads, a linear regression model (Figure 2) was developed using the hydrologic and P mass balances of the lake for water years (WY[5]) 1992-2010 (Walker et al. 2012).

These preliminary results, coupled with the results of Wherry and Wood (2018), led to the hypothesis that there is rapid cycling of phosphorus through the sediment each year such that the amount of P released each summer is primarily driven by recent external loads and not necessarily by legacy P that has accumulated in the sediment over the long-term. Alternatively, if internal P recycling was relatively independent of external loads in a given year, the outflow P concentration would not necessarily be strongly related to recent external loads. To the extent rapid sediment cycling is occurring in UKL, implementation of full scale watershed restoration to reduce external P load has the potential to improve water quality for endangered suckers and reduce the export of nutrients from UKL to the Klamath River[6] on relatively short timescales.

[5] Water Year (WY) is defined as the 12 month period from October 1 to September 30 and designated by the calendar year in which it ends.

[6] Export of nutrients from UKL is tied to water quality impairments in both Oregon and California reaches of the Klamath River (ODEQ 2018; NCRWQCB 2010)

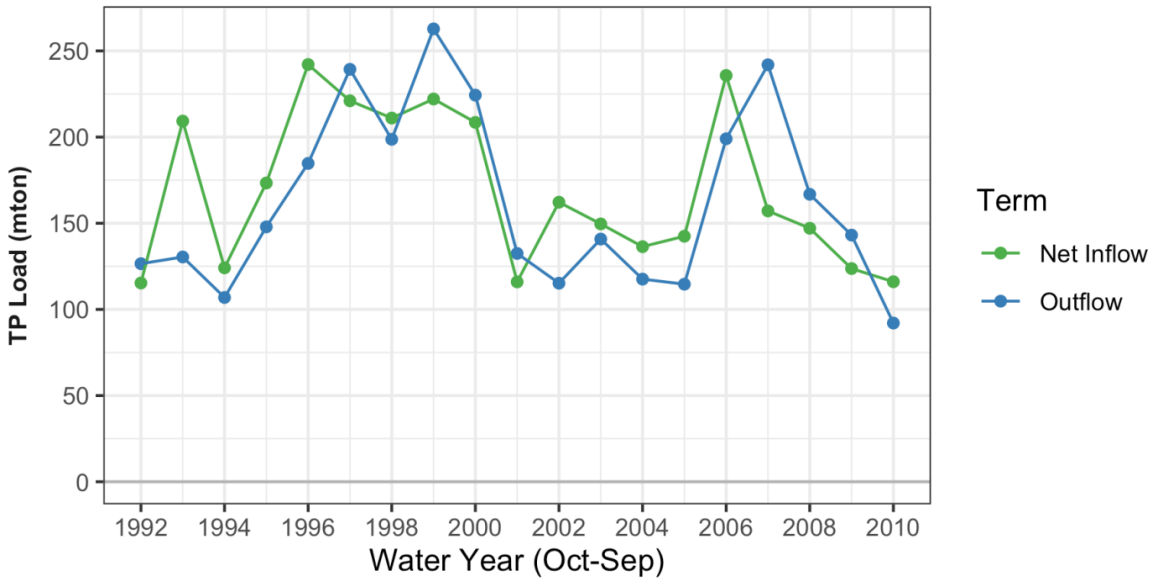
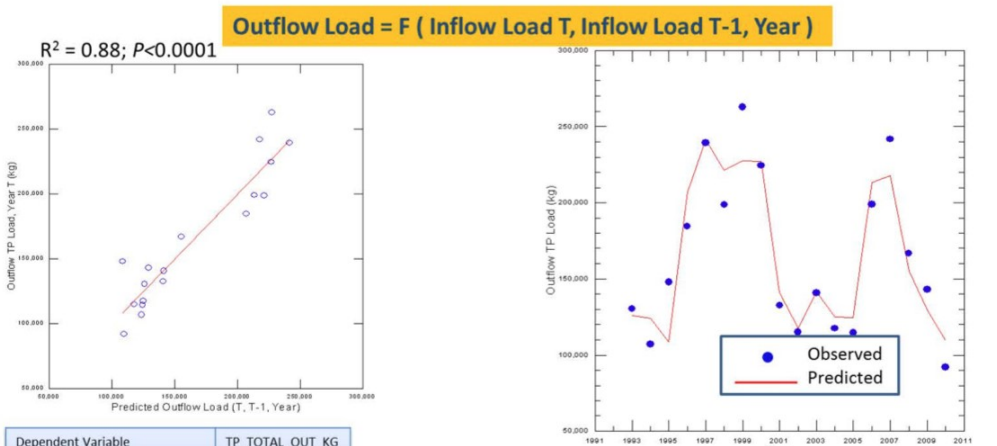



*Figure 1: Annual net inflow and outflow TP loads based on data from Walker et al. (2012).*




| Dependent Variable | TP_TOTAL_OUT_KG |
|---|---|
| N | 18 |
| Multiple R | 0.9363080819 |
| Squared Multiple R | 0.8766728242 |
| Adjusted Squared Multiple R | 0.8502455723 |
| Standard Error of Estimate | 2.02907E+004 |

| Analysis of Variance | | | | | |
|---|---|---|---|---|---|
| Source | SS | df | Mean Squares | F-Ratio | p-Value |
| Regression | 4.0973350E+010 | 3 | 1.365778E+010 | 3.317306E+001 | 0.0000012877 |
| Residual | 5.76398345E+009 | 14 | 4.117131E+008 | | |

| Effect | Coefficient | Standard Error | Std. Coefficient | Tolerance | t | p-Value |
|---|---|---|---|---|---|---|
| CONSTANT | -7.2330345E+006 | 2.1356943419E+006 | 0.0000000000 | . | -3.3867367705 | 0.0044281973 |
| TP_TOTAL_IN_KG | 0.8641003682 | 0.1282978879 | 0.7274196098 | 0.7551793537 | 6.7351098485 | 0.0000095463 |
| TP_TOTAL_IN_MINUS1_KG | 0.7203136180 | 0.1155153012 | 0.6067721872 | 0.9303441689 | 6.2356554521 | 0.0000217887 |
| WATER_YR | 3.56010018E+003 | 1.0606463E+003 | 0.3624742344 | 0.7553700041 | 3.3565385041 | 0.0047023920 |

Linear Model:
Outflow TP Load = -7037790 +(0.867*Inflow TP Load) + (0.722*Inflow Load T-1) + (3462*Water Yr)
$r^2 = 0.88$, $P < 0.0001$

*Figure 2: Preliminary linear regression model for predicting annual outflow TP loads based on annual inflow loads of the same and previous years in addition to a trend term.*

## 1.2 STUDY GOAL

Our goal was to evaluate the hypothesis that sediment P release (internal loading) in UKL is more closely coupled to recent inflow loads than to legacy P sediment storage associated with long-term inflow loading, which in turn leads to close coupling between recent inflow loads and outflow loads and concentrations. Our approach focused on 1) developing a better understanding of whether (and how) outflow P loads and concentrations may be driven by recent inflow loads, and 2) determining whether the preliminary linear model that suggested both the current and previous years' inflow TP load had a large effect on outflow TP loads could be explained or if it was the result of random noise.

# 2 METHODS

## 2.1 MASS BALANCE DATASET

This study utilized a mass balance dataset containing monthly hydrologic and nutrient fluxes of Upper Klamath Lake (UKL) in southwest Oregon for WY 1992–2010 (Oct 1991–Sep 2010) (Walker et al. 2012). In this section, we provide an overview of the equations and flux terms for the water and total phosphorus (TP) mass balances, and briefly describe how each term was calculated. More detailed descriptions of the specific data sources and methods used to generate this dataset can be found in Walker et al. (2012).

To explain how each mass balance was computed and what each flux represents, Figure 3 presents two versions of the water and TP budgets for the lake:

1. The **detailed budgets** (Figure 3a,c) include all of the primary fluxes into and out of the lake and represent basic conceptual models of the lake mass balances. Most of these fluxes were independently estimated based on observation data. However, for each budget, there was one term for which no observation data existed, and therefore it was computed by difference after all of the other terms were estimated.
2. The **consolidated budgets** (Figure 3b,d) are simplifications of the detailed budgets in which some of the fluxes have been combined in order to reduce the overall number of fluxes. These consolidated fluxes were the primary terms analyzed in this study.

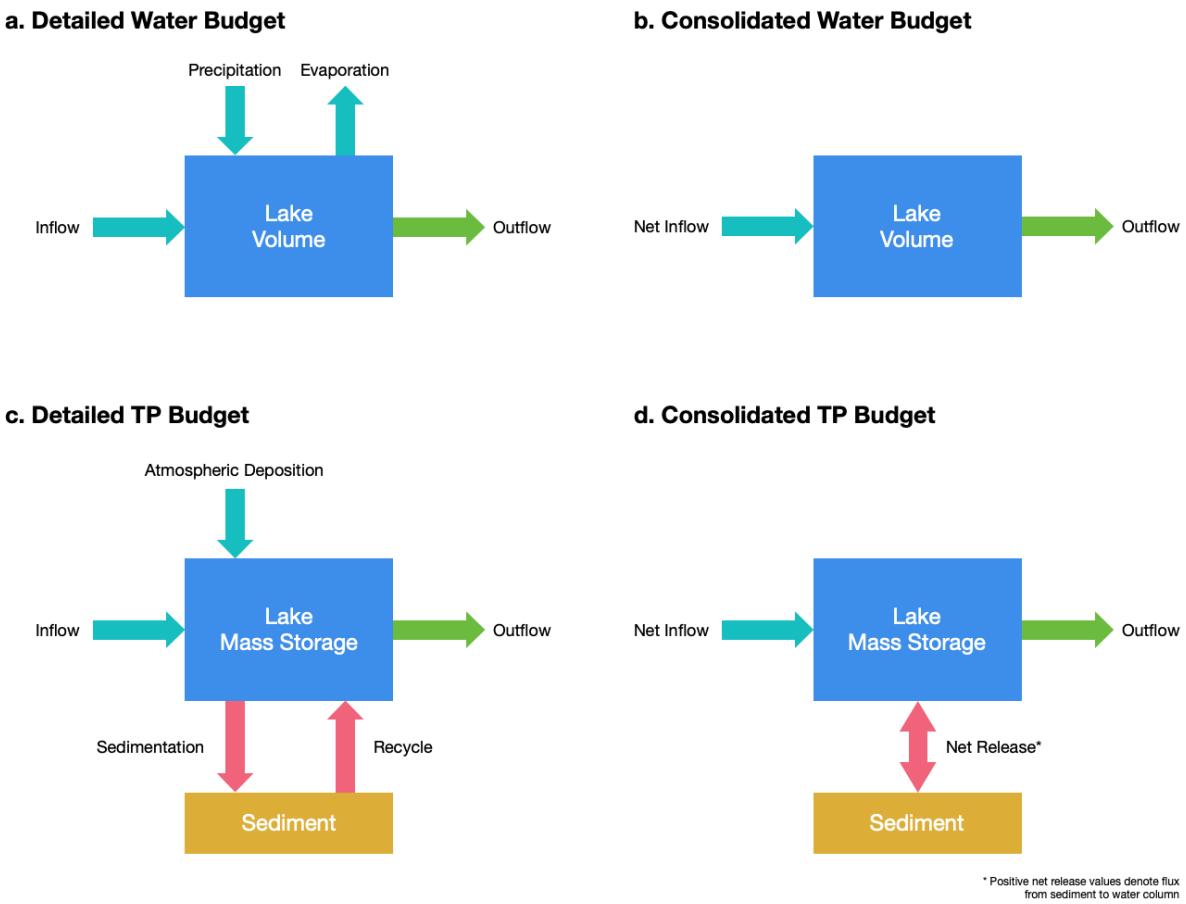



*Figure 3: Schematic diagrams of the detailed and consolidated water and TP budgets for UKL.*
*See Sections 2.1.1 and 2.1.2 below for definitions of each term.*

### *2.1.1 Water Budget*

The detailed water budget of UKL (Figure 3a) is represented by the following equation where each term is in volumetric units (thousands of acre feet; kacft). The data sources and methodologies used to calculate each term can be found in Walker et al. (2012).

$$\Delta Volume = Inflow + Precipitation - Evaporation - Outflow \quad (1)$$

The change in lake volume (*ΔVolume*), outflow, precipitation, and evaporation terms were each independently estimated from observation data leaving only the inflow term to be calculated by difference. However, because observation data were available for some inflow sources, the total inflow flux was divided into two separate fluxes:

$$Inflow = Gaged\ Inflow + Ungaged\ Inflow \quad (2)$$

The gaged inflow term includes any sources (watershed runoff, agricultural pumping) that could be estimated from available observation data (e.g., streamflow gages). The remaining ungaged inflows were then calculated by difference by substituting Eqn. (2) into Eqn. (1) and solving for the ungaged inflow term:

***Ungaged Inflow = ΔVolume – Precipitation + Evaporation + Outflow – Gaged Inflow*** (3)

The computed ungaged inflows were then combined with the estimated gaged inflows to calculate the total inflows, which thus completed the full accounting of the UKL water balance in Eqn (1).

To simplify the mass balance, the inflow, precipitation and evaporation fluxes were combined into a single term call net inflow:

***Net Inflow = Inflow + Precipitation – Evaporation*** (4)

Substituting Eqn. (4) into Eqn. (1) yields the mass balance equation for the consolidated water budget (Figure 3b), which was the focus of this study:

***ΔVolume = Net Inflow – Outflow*** (5)

### *2.1.2 TOTAL PHOSPHORUS BUDGET*

The detailed TP budget for UKL (Figure 3c) is represented by the following equation where each term is in mass units (metric ton, mton = 1,000 kg):

***ΔStorage = Inflow + Atmospheric Deposition – Outflow – Sedimentation + Recycle*** (6)

The data sources and methodologies for computing each term can be in Walker et al. (2012). Two of these terms represent transfer of TP between the water column and lake sediment: 1) sedimentation, which is the amount of TP that settles from the water column to the sediment, and 2) recycle, which is the release of TP from the sediments back into the water column. Because neither of these fluxes was directly measured, they were combined into a single term called net retention:

***Net Retention = Sedimentation – Recycle*** (7)

Substituting Eqn. (7) into Eqn. (6) then yields:

***ΔStorage = Inflow + Atmospheric Deposition – Outflow – Net Retention*** (8)

The change in storage of UKL (*ΔStorage*) was estimated from the observed change in lake volume combined with measured in-lake TP concentrations. Similarly, the outflow TP load was computed from the observed outflow flow rate combined with measured TP concentrations at the lake outlet. The atmospheric deposition flux included both dry and wet deposition; the latter was estimated using precipitation concentrations from the literature combined with measured precipitation quantities (Walker et al. 2012).

Similar to the water budget (Eqn. 2), the inflow load was computed as the sum of gaged and ungaged inflow loads. The gaged inflow loads included watershed runoff and agricultural pumping, each of which was computed using measured or estimated flows and TP concentrations (Walker et al. 2012). The ungaged loads were computed from the estimated ungaged flow rates that were calculated by difference in Eqn. (3) combined with an estimated concentration for background sources within the UKL watershed (primarily based on samples collected at springs) (Walker et al.

2012). The estimated gaged and ungaged inflows were then combined to estimate the total inflow TP load.

The inflow and atmospheric deposition TP fluxes were combined into a net inflow term[7], which is the TP mass associated with the net inflow flow defined by Eqn. (4) above for the water balance:

***Net Inflow = Inflow + Atmospheric Deposition*** (9)

For this study, we also defined a new term called the net release flux, which is simply the opposite of the net retention term:

***Net Release = –Net Retention = Recycle – Sedimentation*** (10)

Although Walker et al. (2012) reported the net sediment flux using net retention, we found that the net release flux was more intuitive when comparing it against the other lake fluxes since positive values (when recycle > sedimentation) denote the transfer of mass into the water column.

Substituting Eqns. (9) and (10) into Eqn. (8) yields the consolidated mass balance equation for TP (Figure 3d), which was the basis for this study:

***ΔStorage = Net Inflow – Outflow + Net Release*** (11)

After estimating the change in storage, net inflow loads, and outflow loads, the net release flux was calculated by difference by rearranging Eqn (11):

***Net Release = Outflow + ΔStorage – Net Inflow*** (12)

Because it was calculated by difference, the net release term thus incorporates the cumulative error associated with all other mass balance terms that were estimated from direct observation data or other sources.

## 2.2 PHOSPHORUS WATER YEAR

Hydrologic timeseries datasets are often analyzed by water year (WY), which is typically defined as the 12-month period from October 1 through September 31 and designated by the calendar year in which it ends. For example, WY 2010 is the period from October 1, 2009 to September 31, 2010. Water years are commonly used instead of calendar years because they generally align with the start and end of each hydrologic cycle (e.g., the seasonal filling and draining of a lake or reservoir). However, for this study we used an alternative definition of the water year that starts in May instead of October. We define this alternative water year as the **phosphorus water year** (PWY) spanning from May 1 to April 30. Similar to the hydrologic WY, the phosphorus WY is designated by the calendar year in which it ends (e.g., PWY 2010 spans May 1, 2009 through April 30, 2010).

[7] For P loads, the net inflow term is equal to the total (or gross) inflow load, which includes all external inflow sources plus atmospheric deposition. However, to be consistent with the water balance terminology, we have called this "net inflow." Note that Eqn. 9 could have been written the same as Eqn. 4 by including an evaporation term; however, that term would always be zero because evaporation does not cause a flux of P mass from the lake.

Compared to the hydrologic WY, the phosphorus WY better coincides with the annual cycling of TP within the lake as shown by the seasonal patterns of the monthly lake volume, TP storage mass, and TP concentration (Figure 4). For example, at the start of the hydrologic WY (Oct) the lake volume begins increasing and reaches its peak in late spring and early summer (Apr-Jun) following snowmelt-driven runoff each spring (Figure 4a). During the remainder of the hydrologic WY (Jul-Sep) the lake volume decreases, reaching its overall minimum at the end of the WY in September. Therefore, the start and end of the hydrologic WY coincide with the time when lake volume typically reaches its annual minimum over each hydrologic cycle.

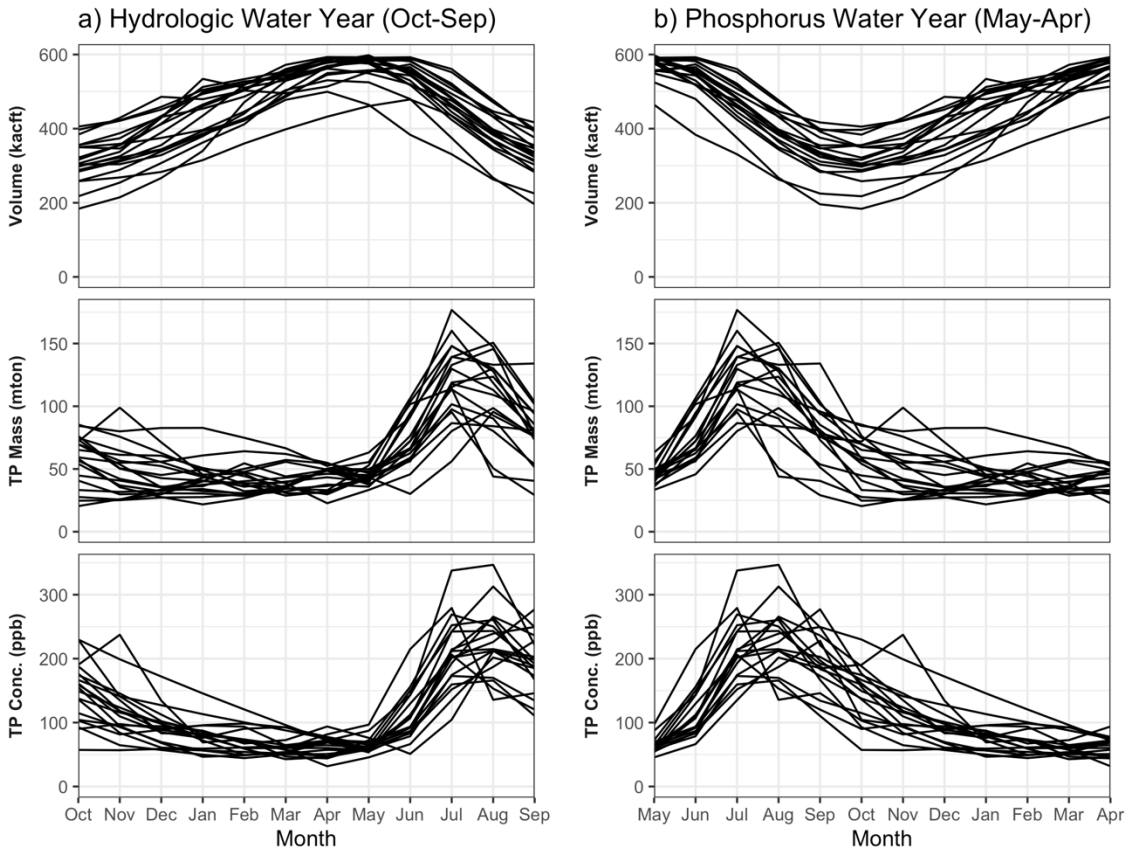



*Figure 4: Seasonal patterns of the monthly lake volume, TP mass, and TP concentration by a) hydrologic water year (Oct-Sep), and b) phosphorus water year (May-Apr).*
*Each line shows the monthly values for a single hydrologic or phosphorus water year.*

However, the TP mass storage in the lake exhibits a seasonal pattern that is different from lake volume. TP mass begins increasing in May or June of most years, reaches a peak in July or August, and then decreases until the following May when it begins increasing again (Figure 4b). Similar to the pattern observed for lake volume over each hydrologic WY, the lake TP mass storage first increases and then decreases over each phosphorus WY. As a result, the start and end of the phosphorus WY coincide with the time when TP mass and concentration reach their annual minima over each phosphorus cycle.

Coincidentally, the seasonal pattern of lake volume over each phosphorus WY is the inverse of its pattern over the hydrologic WY; the start and end of the phosphorus WY correspond to when the

lake volume is at its maximum instead of its minimum. Therefore, the phosphorus WY was used instead of the hydrologic WY because it better represents the seasonal dynamics of the lake water quality (TP mass and concentration) while also continuing to coincide with the dynamics of the lake hydrology (volume).

## 2.3 Analysis Approach

The seasonal and annual inflow/outflow loading dynamics of UKL were evaluated using a series of analyses:

1. Linear Regression Model
2. Exploratory Data Analysis (EDA) of Seasonal/Annual Mass Balance Dynamics
3. Correlations Between Seasonal and Annual Mass Balance Terms

We first evaluated and refined the preliminary linear regression model (Section 1.1) that predicted annual outflow TP loads as a function of current and previous year's inflow loads. We then used exploratory data analysis (EDA) techniques to better understand the seasonal patterns and year-to-year variability of the water and TP budgets. Lastly, we generated correlation matrices of the annual and seasonal fluxes for each mass balance term to determine whether there was evidence supporting the model results that suggested outflow loads and concentrations were coupled with recent (current and previous years) inflow loads in UKL.

Throughout this report, all concentrations are reported using the flow-weighted mean (FWM), which was calculated as the sum of loads divided by the sum of flows over each target period (e.g., month, season, or year).

All analyses were performed using the R statistical programming language version 6.3 (R Core Team 2020).

# 3 Results

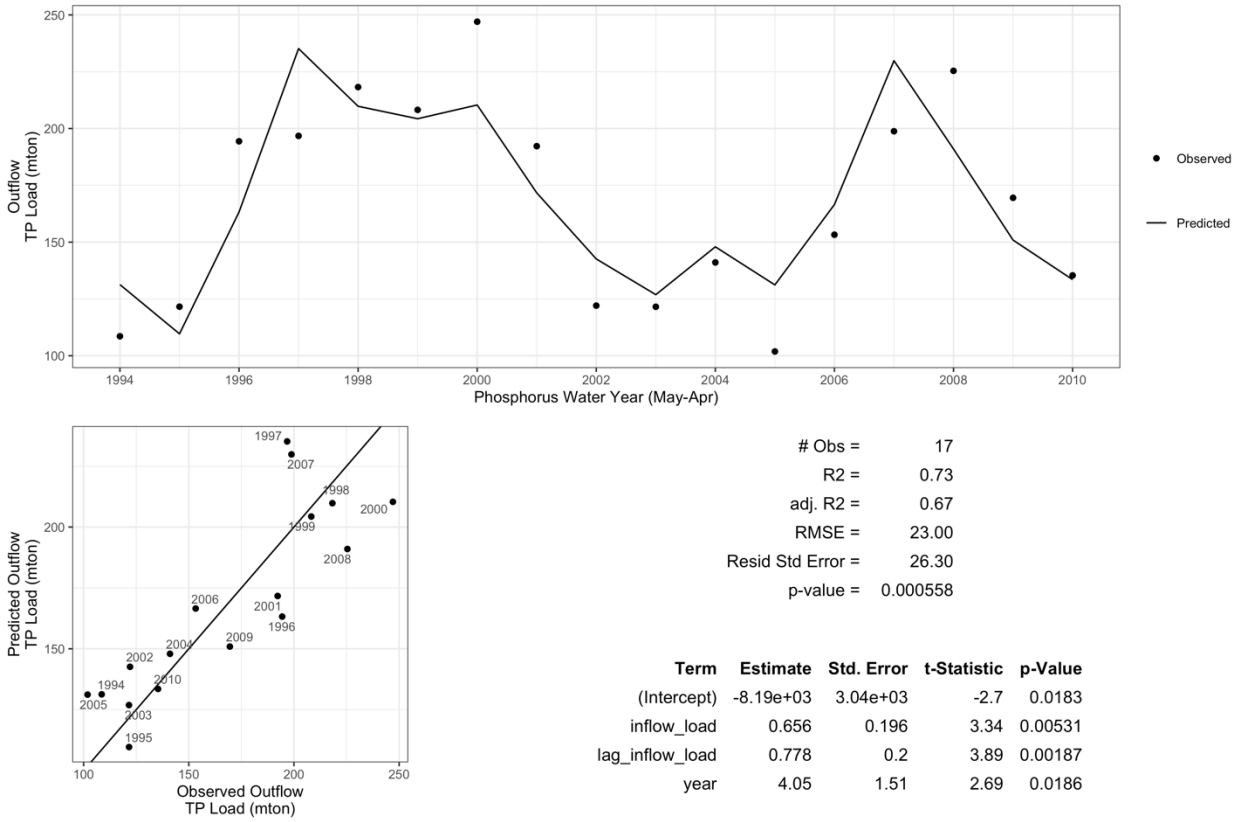
## 3.1 Linear Regression Model

This study was motivated by a linear regression model that predicted annual outflow TP load based on the annual inflow loads of the same and previous years as well as a trend term (see Section 1.1):

$$L_{out} = \beta_0 + \beta_1 L_{in} + \beta_2 L_{in,lag} + \beta_3 Year \quad (13)$$

where $L_{out}$ and $L_{in}$ are the outflow and inflow TP load (mton), respectively, in year $Year$, and $L_{in,lag}$ is the inflow TP load (mton) of the previous year ($Year - 1$). The $Year$ term accounts for an increasing trend in the annual outflow load, which was not explained by the other two terms (current and previous years' inflow load). Preliminary modeling showed that without this term, the model residuals reflected an increasing trend and were not homoskedastic. Adding this term not only yielded homoskedastic residuals, but also resulted in a significantly ($p > 0.05$, F Test) improved model fit (see Table 1 below).

This model was originally developed using annual loads computed by hydrologic WY (Oct-Sep). To be consistent with the rest of the study, the model was re-fitted using the annual loads computed instead by phosphorus WY (May-Apr) (see Section 2.2). Although the model performance was not as strong based on the phosphorus WY ($R^2$ fell from 0.88 based on the hydrologic WY to 0.73 based on the phosphorus WY), the three independent variables all remained statistically significant ($p < 0.05$) (Figure 5).




| Term | Estimate | Std. Error | t-Statistic | p-Value |
|---|---|---|---|---|
| (Intercept) | -8.19e+03 | 3.04e+03 | -2.7 | 0.0183 |
| inflow_load | 0.656 | 0.196 | 3.34 | 0.00531 |
| lag_inflow_load | 0.778 | 0.2 | 3.89 | 0.00187 |
| year | 4.05 | 1.51 | 2.69 | 0.0186 |

*Figure 5: Summary of the linear regression model predicting outflow loads using the annual mass balance dataset by phosphorus WY (May-Apr).*

An analysis of variance (ANOVA) table for the fitted model summarizes how much variance in the annual outflow load was explained by each independent variable (Table 1). Out of the total sum of squares, the net inflow load of the current year explained 34% of the variance, the net inflow load of the previous year explained 24%, and the trend term explained 15%[8]. The model residuals then accounted for the remaining 27% of the sum of squares. The coefficient of determination ($R^2$) was thus 0.73 meaning that in total 73% of the variability in annual outflow loads was explained by the

[8] Note that the sum of squares attributed to each term is based on the cumulative addition of each variable, and therefore the order of the terms affects the results in this table. This is similar to an ANOVA table comparing a series of linear regression models in which each term is added one at a time until the full model is constructed.

three independent variables[9]. The ANOVA table also indicated that the addition of each term resulted in a significant improvement of model performance ($p < 0.05$ for each term).

*Table 1: Analysis of variance table for linear regression model.*

| Term | Deg. of Freedom | Sum of Squares | % Total Sum of Squares | F Statistic | p-value |
|---|---|---|---|---|---|
| **Net Inflow Load** | 1 | 11,254 | 34% | 16.27 | 0.0014 |
| **lag(Net Inflow Load)** | 1 | 7,840 | 24% | 11.34 | 0.0051 |
| **Year** | 1 | 4,997 | 15% | 7.23 | 0.0186 |
| **Residuals** | 13 | 8,990 | 27% | | |
| **Total** | **16** | **33,080** | **100%** | | |

Because TP loads are often highly correlated with flows, we first considered whether the model was reflecting only the hydrologic relationship between the flow rates of inflows and outflows[10]. Therefore, in addition to predicting the annual outflow loads, the model was also used to predict annual outflow TP FWM concentrations by dividing the predicted total annual outflow loads by the corresponding total annual outflow for each PWY. The predicted outflow concentrations were then compared to observed outflow concentrations from the mass balance dataset to determine whether this model was predictive of concentrations as well as loads (Figure 6). The predicted concentrations had an RMSE of 16 ppb and were almost as well correlated with the observed concentrations ($R^2 = 0.58$; Figure 7) as the predicted loads ($R^2 = 0.73$). Therefore, these results suggested that the modeled relationship between inflow and outflow loads was not driven solely by the flow rates, and that it did in fact reflect, at least to some degree, dynamics related to inflow and outflow TP loads and concentrations.

[9] $R^2$ can be calculated as either the sum of the sum of squares attributes to each independent variable (34% + 24% + 15%) or as the fraction of the sum of squares that is not represented by the residuals (100% - 27%).
[10] Because load is equal to flow multiplied by concentration, the model could not include both flows and loads due to potential multicollinearity.

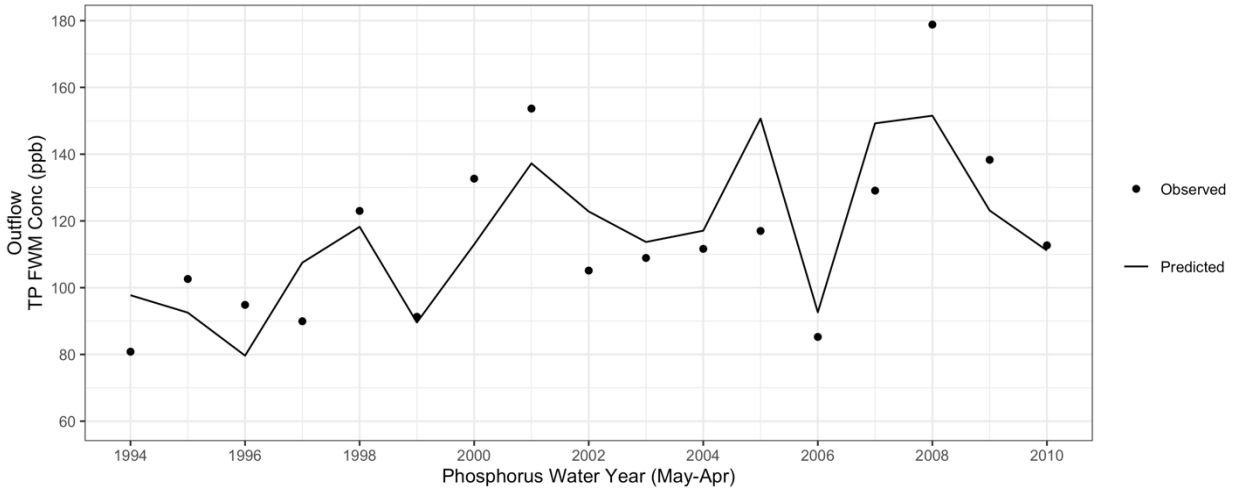



*Figure 6: Timeseries of observed and predicted annual outflow FWM TP concentrations by phosphorus water year.*

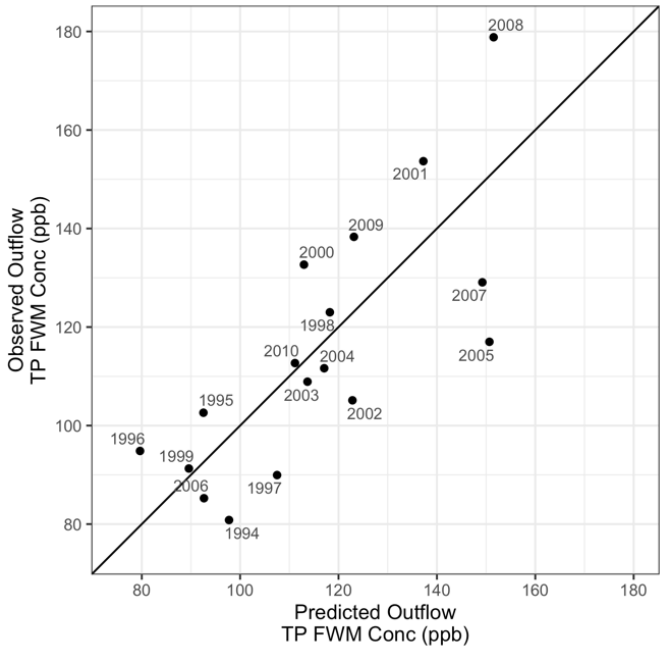



*Figure 7: Predicted vs. observed annual outflow FWM concentrations.*
*Diagonal line is the 1:1 line of equality. Points are labelled by phosphorus water year (May-Apr).*

Our overall conclusion from this model was that annual outflow TP loads do appear to be related to the inflow TP load of the same and previous phosphorus WYs. This result led to our hypothesis that inflow and outflow TP loads may be closely coupled over the short-term and that external loads may comprise a significant portion of the sediment recycle flux (i.e., internal load) in any given year. If legacy P was the primary driver of sediment recycle flux, then outflow loads and concentrations would not be expected to be related to near-term external loading. However, the model results suggest this may not be the case for UKL. The remainder of this study focused on 1) better understanding the seasonal and year-to-year variability in the water and TP mass balance fluxes, and 2) determining whether there was any evidence to support this hypothesis based on correlations between seasonal and annual fluxes of the mass balance terms.

## 3.2 SEASONAL AND ANNUAL MASS BALANCE DYNAMICS

### *3.2.1 MEAN MONTHLY AND ANNUAL FLUXES*

To better understand the seasonal and annual dynamics of the hydrologic and TP mass balances, the mean flux rates were computed for each month over the period of record, PWY 1993–2010 (Figure 8; Table 2). In this section, the average annual fluxes of each term are represented using the overall mean of the 12 monthly mean values[11]. The fluxes are shown using a stacked bar chart such that the total height of each bar equals the total TP mass and flow entering (or leaving when the values are negative) the lake. The overall net change in TP mass storage and volume (black circles) is equal to the net sum of both the positive and negative fluxes in each month (i.e., the total net height of all bars, both positive and negative, within each month).

[11] The total annual flows and loads of each term can be calculated by multiplying the respective overall mean by 12.

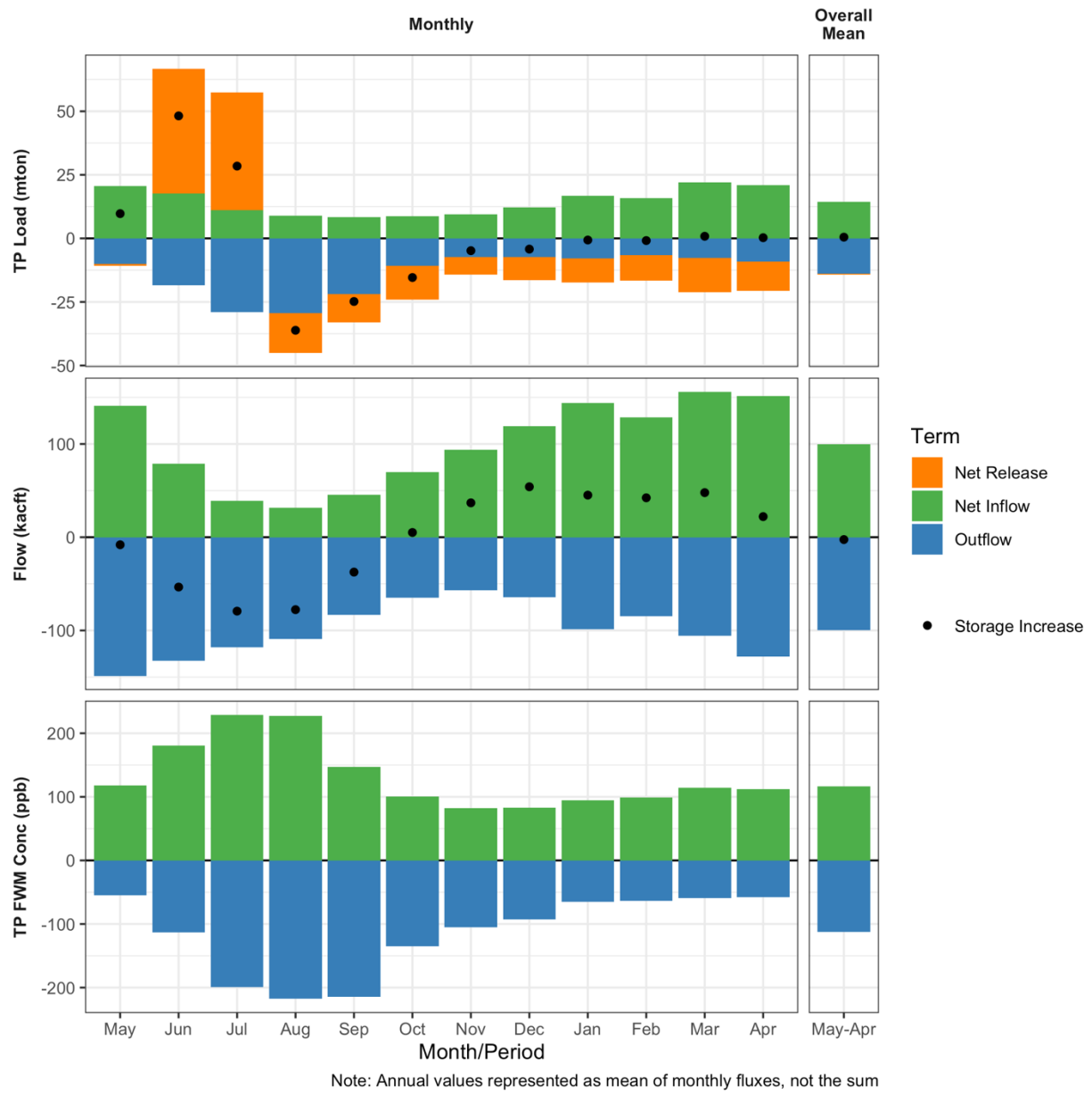



*Figure 8: Mean monthly and overall mean TP loads, flows, and TP FWM concentrations for each mass balance term over PWY 1993–2010.*

*Outflow flows, loads are represented as negative values to be consistent with the storage increase and net release terms where negative values indicate a loss from lake storage. Outflow concentrations are also represented as negative values to be visually consistent loads and flows. The Overall Mean values were computed as the mean of the 12-monthly values and represent the average annual fluxes.*

*Table 2: Mean monthly TP loads, flows, and TP FWM concentrations for each mass balance term over PWY 1993–2010.*

| Variable | Term | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | Overall Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **TP Load (mton)** | Net Inflow | 21 | 18 | 11 | 8.9 | 8.3 | 8.7 | 9.5 | 12 | 17 | 16 | 22 | 21 | 14.3 |
| | Outflow | 10 | 19 | 29 | 29 | 22 | 11 | 7.4 | 7.4 | 7.9 | 6.7 | 7.7 | 9.2 | 13.8 |
| | Net Release | -0.7 | 49 | 46 | -16 | -11 | -13 | -6.9 | -9.0 | -9.5 | -10 | -13 | -11 | -0.5 |
| | Storage Increase | 10 | 48 | 28 | -36 | -25 | -15 | -4.8 | -4.2 | -0.7 | -0.9 | 0.8 | 0.3 | 0.04 |
| **Flow (kacft)** | Net Inflow | 141 | 79 | 39 | 32 | 46 | 70 | 94 | 119 | 144 | 129 | 156 | 151 | 99.9 |
| | Outflow | 149 | 132 | 118 | 109 | 83 | 65 | 57 | 65 | 99 | 85 | 105 | 128 | 99.6 |
| | Storage Increase | -8.1 | -53 | -79 | -78 | -37 | 5.1 | 37 | 54 | 45 | 42 | 48 | 22 | -0.2 |
| **TP FWM Conc (ppb)** | Net Inflow | 118 | 180 | 229 | 227 | 147 | 100 | 82 | 83 | 94 | 99 | 114 | 112 | 116* |
| | Outflow | 55 | 113 | 199 | 218 | 214 | 135 | 105 | 93 | 65 | 64 | 59 | 58 | 113* |

* *Computed as the FWM concentration of the mean loads and flows*

On an annual basis, the overall mean TP loads and flows for net inflow (14.3 mton/mon, 99.9 kacft/mon) were nearly equal to those for outflow (13.8 mton/mon, 99.6 kacft/mon) (Table 2). The overall mean changes in TP mass storage (0.04 mton/mon) and volume (-0.2 kacft/mon) were much smaller compared to the inflow and outflow fluxes. Furthermore, the annual net release of TP was also relatively small (-0.5 mton/mon) indicating that the long-term average sedimentation and recycle fluxes were approximately balanced and that there was only a small net accumulation of TP in the sediment over the period of record (PWY 1993–2010). Therefore, the long-term average fluxes of both water and TP entering the lake (inflows) were approximately balanced by the fluxes leaving the lake (outflows) over this period.

On a monthly basis, inflow and outflow TP loads exhibited different seasonal patterns due to differences in their associated flows and concentrations (Figure 8). Net inflow TP loads were primarily driven by changes in flow, which were highest in the spring (Mar-May) due to snowmelt-driven runoff and lowest in the dry season from late summer to early fall (Jul-Sep) when base flows are reduced. In contrast, seasonal changes in outflow TP loads were more closely related to the associated TP concentrations. Both the outflow TP loads and concentrations were highest in July–September and lowest in winter and early spring, while flows reached a maximum earlier in the summer (May) and a minimum later in the fall (November). In other words, the seasonal pattern of inflow TP loads was more similar to that of the associated *flows*, while the pattern for outflow TP loads was more similar to the associated *concentrations*. As a result, the inflow and outflow TP loads exhibited different seasonal patterns despite having very similar annual average values. Similarly, although the flow rates for inflows and outflows were approximately equal on an annual basis, the seasonal patterns differ such that outflows were higher than inflows in the summer when the lake drains, and inflows were higher than outflows in the winter and spring when the lake refills.

Compared to inflows and outflows, the net release term exhibited greater seasonal variability with very large positive values in the summer and smaller negative values during the rest of the year[12] (Figure 8). In June and July, the large positive net release indicated a large flux of phosphorus from the sediments to the water column[13]. This large phosphorus release from the sediment coincides with the onset of cyanobacteria blooms in UKL (Kann 2019), and the associated bioavailable fraction is considered to be the main source of P for the initial bloom increase and peak (Caldwell-Eldridge and Wood 2020). In August and September, the net release values flip from positive to negative likely due to an increase in the sedimentation flux associated with the decline of the bloom. However, because the individual sedimentation and recycle fluxes (see Figure 3c) were not directly estimated, the relative changes in magnitude of the two fluxes are unknown. For example, the change in net release from 836 mton in July to -282 mton in August (Table 2) could be caused by a large increase in sedimentation with no change in the recycle, or, alternatively, by a large

[12] Positive values indicate a net release from the sediment to the water column (recycle > sedimentation), negative values indicate a net retention from the water column to the sediment (sedimentation > recycle)
[13] Drivers of the flux of P from the sediments to the water column in UKL are due to a variety of mechanisms including microbial mineralization related to temperature, diffusion, redox potential, ligand exchange, bioturbation and excretion by macroinvertebrates, and wind resuspension (Wood et al. 2013).

decrease in the recycle flux with no change in sedimentation. Realistically, this change was most likely driven by some intermediate scenario in which both the sedimentation flux increased and the recycle flux decreased, which together add up to the overall net flux switching from net release (positive) in July to net retention (negative) in August.

After the growing season, the net release term remained negative throughout the fall, winter and spring indicating a net retention of inflow TP loads to the lake sediment. From January to April, the net release flux was approximately equal to the difference between the inflow and outflow TP loads resulting in a negligible change in TP mass storage despite an increase in lake volume in these months. This suggests that during the winter and early spring, a large portion of the inflow TP loads, which were relatively high during these months, settled out and were retained in the lake sediment. As a result, winter/spring outflow loads were significantly lower than inflow loads, with the difference being equal to the net release flux.

Overall, the mean monthly TP loads, flows and FWM concentrations for the net inflow, outflow and net release fluxes provided a general understanding of the seasonal and annual water and TP mass balance dynamics of UKL. However, to evaluate the relationships between these fluxes and to determine whether sediment release rates were tightly coupled with recent inflow loads over time, we next evaluated the year-to-year variability in both the magnitudes and seasonal distributions of each mass balance term.

### *3.2.2 Year-to-Year Variability*

#### 3.2.2.1 Annual Fluxes

Timeseries of annual TP loads, flows and FWM concentrations show the variability of each mass balance term from year to year (Figure 9; Table 3). During the first three years (PWY 1993-1995) flow rates were relatively low (~1,000 kacft/yr) indicating dry conditions, and net inflow TP loads exceeded outflow loads leading to overall net retention (negative net release) of P in the sediment. The next five years (PWY 1996-2000) were wetter with flows greater than ~1,500 kacft/yr, and inflow TP loads exceeded outflow loads (net retention) in three of the five years and outflow loads exceeded inflow loads (net release) in the other two years. This wet period was followed by another dry period (PWY 2001-2005) with flows once again at ~1,000 kacft/yr and inflow TP loads generally exceeded outflow loads (net retention) except in the first year (PWY 2001). PWYs 2006 and 2007 were moderately wet followed by another three dry years (PWY 2008-2010). From PWY 2006 through 2008, the TP mass balance switched from the largest net retention (-67 mton/yr in PWY 2006) to the largest net release (77 mton/yr in PWY 2008) followed by two years of net release (PWY 2009-2010). Because annual flows were approximately equal between inflows and outflows in each year, the difference in associated loads was driven solely by differences in the annual FWM concentrations.

A visual comparison of the annual timeseries suggested that there was a lag effect between annual inflow loads and outflow loads (Figure 9). For example, there were two instances when inflow TP loads increased significantly from one year to the next (PWY 1996 and PWY 2006). In the years following each of these instances, the outflow FWM concentrations increased, which led to outflow loads exceeding inflow loads, and thus the net release switched from negative (net retention) to

positive (net release) values. This suggests that an increase in the inflow load was apparently followed by a switch from net retention to net release in subsequent years over the near term. This switch in the net sediment flux in turn drove an increase in the outflow concentration, which may explain the above described correlation between outflow loads and inflow loads for the previous year.

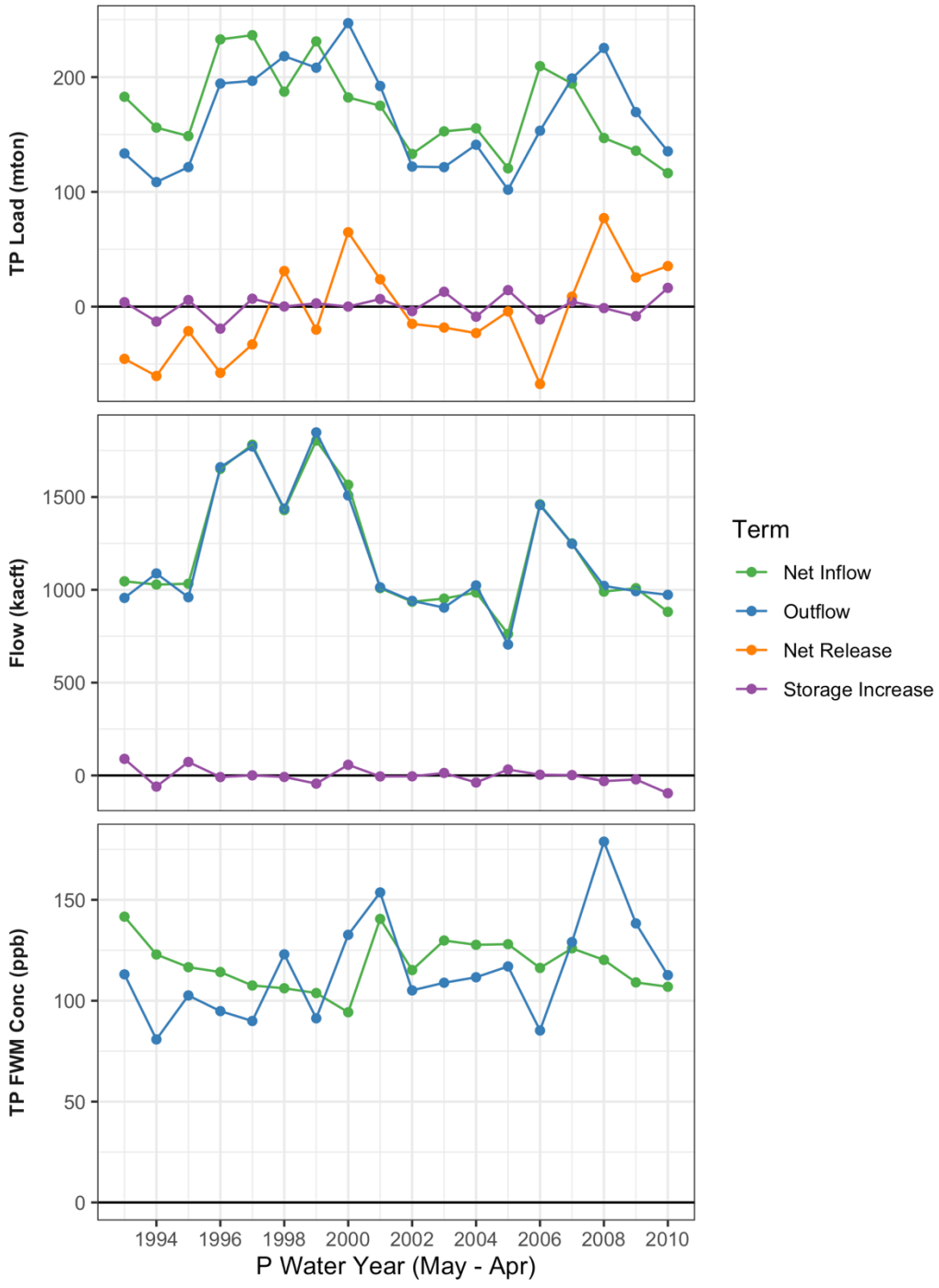



*Figure 9: Annual TP load, flow, and TP FWM concentration of each mass balance term over phosphorus WY 1993–2010.*

*Table 3: Annual TP load, flow, and TP FWM concentration of each mass balance term with summary statistics over PWY 1993–2010.*

| | TP Load (mton/yr) | | | | Flow (kacft/yr) | | | TP FWM Conc. (ppb) | |
|---|---|---|---|---|---|---|---|---|---|
| **P Water Year (May-Apr)** | Net Inflow | Outflow | Net Release | ΔStorage | Net Inflow | Outflow | ΔStorage | Net Inflow | Outflow |
| **1993** | 183 | 133 | -45 | 3.9 | 1,046 | 956 | 89 | 142 | 113 |
| **1994** | 156 | 109 | -60 | -13 | 1,028 | 1,088 | -60 | 123 | 81 |
| **1995** | 149 | 122 | -21 | 5.8 | 1,033 | 960 | 73 | 117 | 103 |
| **1996** | 233 | 194 | -58 | -19 | 1,652 | 1,660 | -8.7 | 114 | 95 |
| **1997** | 237 | 197 | -33 | 6.9 | 1,782 | 1,772 | 0.7 | 108 | 90 |
| **1998** | 187 | 218 | 31 | 0.1 | 1,429 | 1,437 | -8.0 | 106 | 123 |
| **1999** | 231 | 208 | -20 | 2.9 | 1,804 | 1,848 | -44 | 104 | 91 |
| **2000** | 182 | 247 | 65 | 0.1 | 1,566 | 1,508 | 57 | 94 | 133 |
| **2001** | 175 | 192 | 24 | 6.6 | 1,009 | 1,013 | -5.3 | 141 | 154 |
| **2002** | 133 | 122 | -15 | -4.0 | 936 | 941 | -4.7 | 115 | 105 |
| **2003** | 153 | 122 | -18 | 13 | 953 | 904 | 13 | 130 | 109 |
| **2004** | 155 | 141 | -23 | -8.7 | 986 | 1,024 | -38 | 128 | 112 |
| **2005** | 121 | 102 | -4.2 | 14 | 762 | 705 | 32 | 128 | 117 |
| **2006** | 210 | 153 | -67 | -11 | 1,460 | 1,456 | 4.0 | 116 | 85 |
| **2007** | 194 | 199 | 8.7 | 4.3 | 1,250 | 1,248 | 2.0 | 126 | 129 |
| **2008** | 147 | 225 | 77 | -1.3 | 990 | 1,021 | -31 | 120 | 179 |
| **2009** | 136 | 170 | 25 | -8.3 | 1,009 | 993 | -21 | 109 | 138 |
| **2010** | 116 | 135 | 35 | 16 | 881 | 973 | -96 | 107 | 113 |
| **Min** | 116 | 102 | -67 | -19 | 762 | 705 | -96 | 94 | 81 |
| **Max** | 237 | 247 | 77 | 16 | 1,804 | 1,848 | 89 | 142 | 179 |
| **Mean** | 172 | 166 | -5.5 | 0.5 | 1,199 | 1,195 | -2.5 | 116* | 113* |
| **Median** | 166 | 161 | -17 | 1.5 | 1,030 | 1,022 | -5.0 | 116 | 112 |
| **St. Dev.** | 38 | 45 | 42 | 9.8 | 328 | 334 | 46 | 13 | 25 |

** Computed as the FWM concentration of the mean loads and flows*

As a side note, the annual change in storage term was relatively small compared to the other mass balance terms for both TP loads and flows (Figure 9). As a result, the net release flux primarily reflected the difference between net inflow and outflow TP loads. If the change in storage term were larger, then the net release would have had different values that integrated both the change in storage and the difference in inflow and outflow loads since it was computed by difference using Eqn. (12). By using the phosphorus WY in this study, the magnitude of the annual change in storage term was reduced compared to the fluxes based on the hydrologic WY (Oct-Sep)[14]. This effectively simplified the relationships between inflows, outflows and net release loads because the impact of the change in storage on any potential relationships between the other fluxes was reduced compared to the impacts based on higher change in storage values calculated using the hydrologic WY.

#### 3.2.2.2 Monthly Fluxes

In Section 3.2.1 above, we described the average seasonal patterns of the mass balance terms based on the mean monthly fluxes computed over all phosphorus WYs (Figure 8). Those results showed that, on average, there was a large net release of phosphorus from the sediment to the water column in early summer (Jun-Jul) followed by net retention (negative net release when sedimentation > recycle) for the remainder of the water year. We also found that the long-term average net release flux was relatively small compared to the average inflow and outflow TP loads, which were approximately equal. Then, in Section 3.2.2.1, we evaluated how much the annual fluxes of each term varied from year to year and found that some years had a high net release and others a high net retention. A visual comparison of the annual time series suggested that there was a lag effect between inflow and outflow loads, and that this pattern was related to changes in both the net release term and the outflow FWM concentration. However, because each flux varied seasonally, and monthly fluxes often deviated widely from the annual average flux (especially for the net release term), we then used the full monthly mass balance timeseries to determine whether year-to-year changes in the seasonal magnitudes and patterns of each flux provided any evidence supporting our hypothesis that inflow and outflow loads are closely coupled over relatively short timescales due to rapid sediment cycling.

In this section, the figures show the same set of fluxes as in the previous sections (net inflow, outflow, net release, and change in storage) in addition to the lake storage term[15]. The first timeseries chart shows changes in the magnitude and variability of each monthly flux and storage term over the period of record, PWY 1993–2010 (Figure 10). This figure is useful for identifying long-term patterns as well as for determining when the highest and lowest monthly fluxes occurred. For example, the highest monthly inflow and outflow flows occurred in PWY 1996 and

[14] Based on the phosphorus WY, the annual change in TP mass storage ranged from -19 to 16 mton/yr (Table 3) while for the hydrologic WY, it ranged from -52 to 70 mton/yr (data not shown), which was comparable in magnitude to the net release term.

[15] For convenience, the TP mass storage and lake volume associated with the storage term were plotted along with the TP loads and flows, respectively, of the other flux terms since they share the same units (mton for TP load and storage mass, kacft for flow and lake volume). Also note that the storage term only includes water column storage (not sediment), and represents conditions at the end of each month, unlike the fluxes, which represent the total flux over each month.

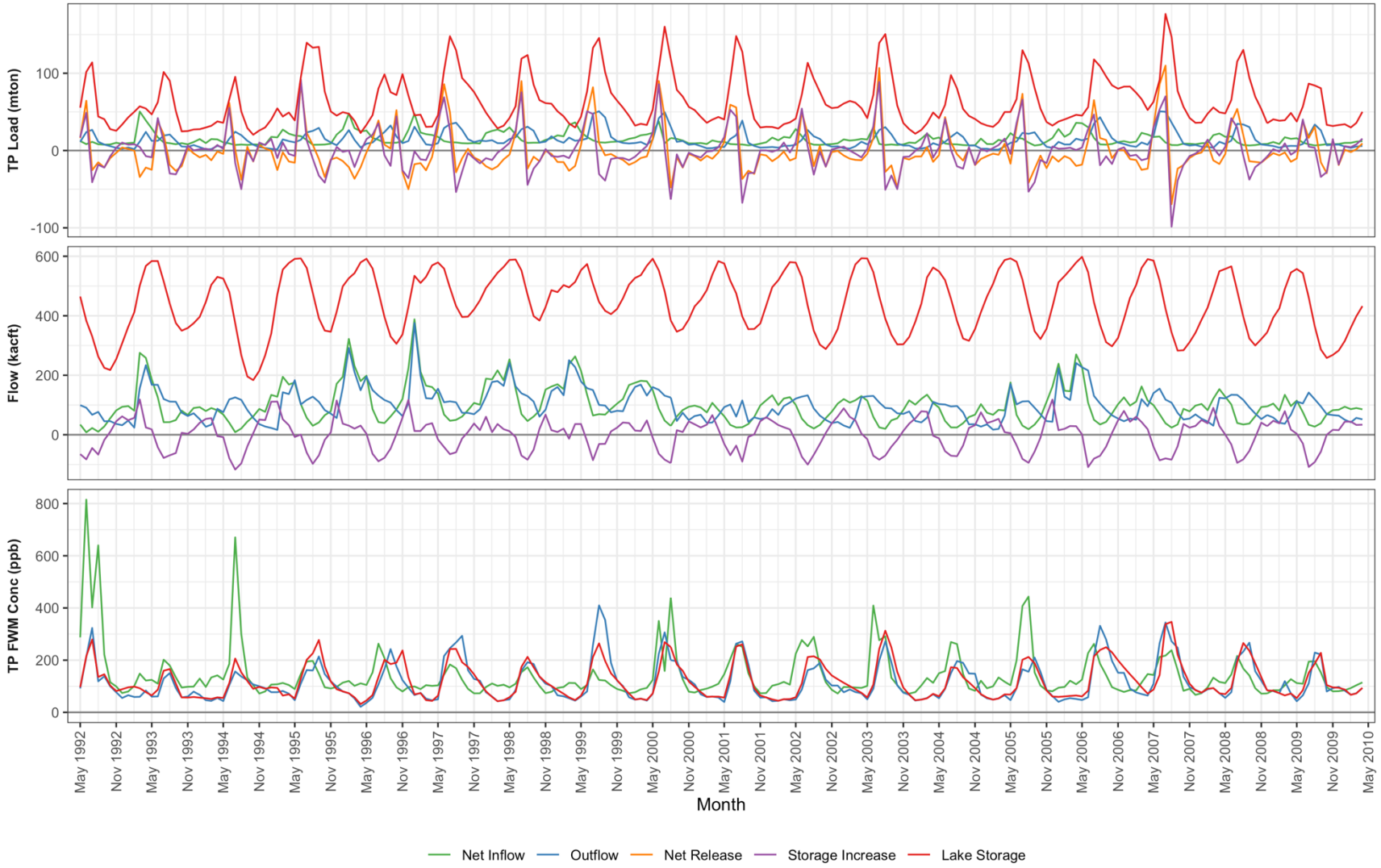



*Figure 10: Timeseries of monthly TP load, flow, TP FWM concentration for mass balance flux and storage terms over phosphorus WY 1993–2010.*

1997, and the highest monthly net release load occurred in PWY 2008. This figure also shows that the lake hydrology was more variable during the first half of the period of record (PWY 1993–2000), with both the inflow/outflow flows and lake storage volume showing greater variability compared to the later years (PWY 2001–2010) when the volume and flows were more consistent from year to year. The TP water column mass storage in the lake ("Lake Storage"), however, had a similar amount of variability over the entire period of record. Lastly, the monthly FWM concentrations for the lake storage, which represents the area-weighted mean concentration within the lake itself, were similar to the outflow FWM concentrations. A direct comparison between these two terms showed that they were highly correlated indicating that outflow concentrations are a good representation of in-lake water quality ($r$ = 0.91, Figure 11).

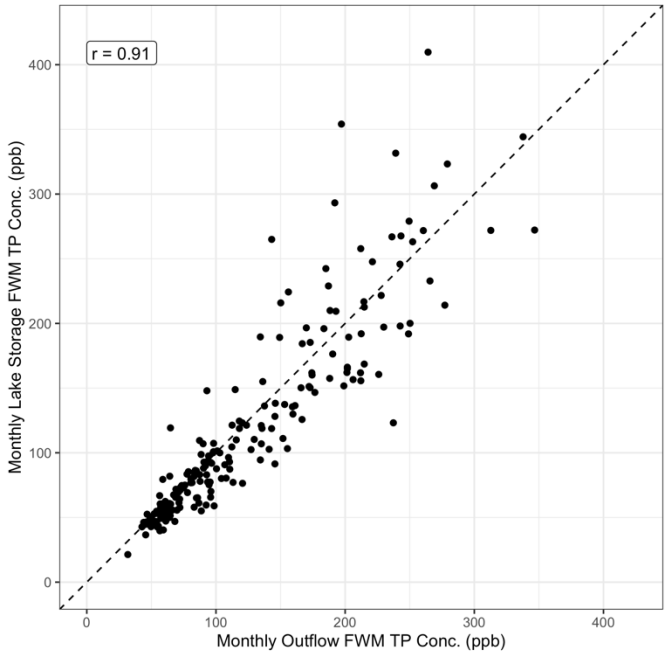



*Figure 11: Scatterplot of monthly FWM TP concentration for lake storage and outflow, PWY 1993-2010.*
*Diagonal line is the 1:1 line of equality.*

Although these monthly timeseries are useful for evaluating the long-term trends and extreme values of each term, they are not conducive to understanding changes in the seasonal patterns from year to year. Therefore, a variety of alternative figures were generated, each providing a different perspective on the dataset designed to highlight specific patterns.

Boxplots were generated to compare the monthly distribution of each flux and storage term over all years in the period of record (Figure 12). For TP loads, the net release flux exhibited the greatest monthly variability, primarily in summer (Jun-Aug). The monthly inflow flux showed greater variability and higher magnitude during winter and spring relative to the summer, whereas the outflow flux was larger and more variable in summer than in other months. The change in TP mass storage showed similar patterns and variability as the net release term suggesting that monthly changes in TP mass storage were primarily driven by the net release (and retention) of P from (to) the lake sediment. The lake storage term reflected a rapid increase in TP mass from May to July associated with the large summer net release, followed by a gradual decline for the rest of the PWY.

The monthly flow distributions showed that inflows and outflows both exhibited greater variability during the winter and spring months (Jan-May) compared to the rest of the year. However, the seasonal patterns of the median monthly flows differed, with the lowest inflows occurring in August and the lowest outflows in November. The change in lake volume reflected net decreases in the first half of the PWY (May-Oct) when outflows exceed inflows, followed by net increases during the second half (Nov-Apr) when inflows exceed outflows. The variability of the change in volume was relatively constant across all months. The lake storage term reflected the annual cycle of the lake draining from May to October, and then refilling until the end of the PWY in April.

Finally, the monthly distributions of the inflow and outflow TP FWM concentrations both exhibited similar patterns with the greatest magnitudes and variabilities during the summer (Jun-Sep), and relatively small and less variable values in the winter (Jan-Apr). However, although the inflow and outflow terms had similar monthly distributions of TP FWM concentrations, the associated monthly TP loads differed due to differences in the monthly flow distributions.

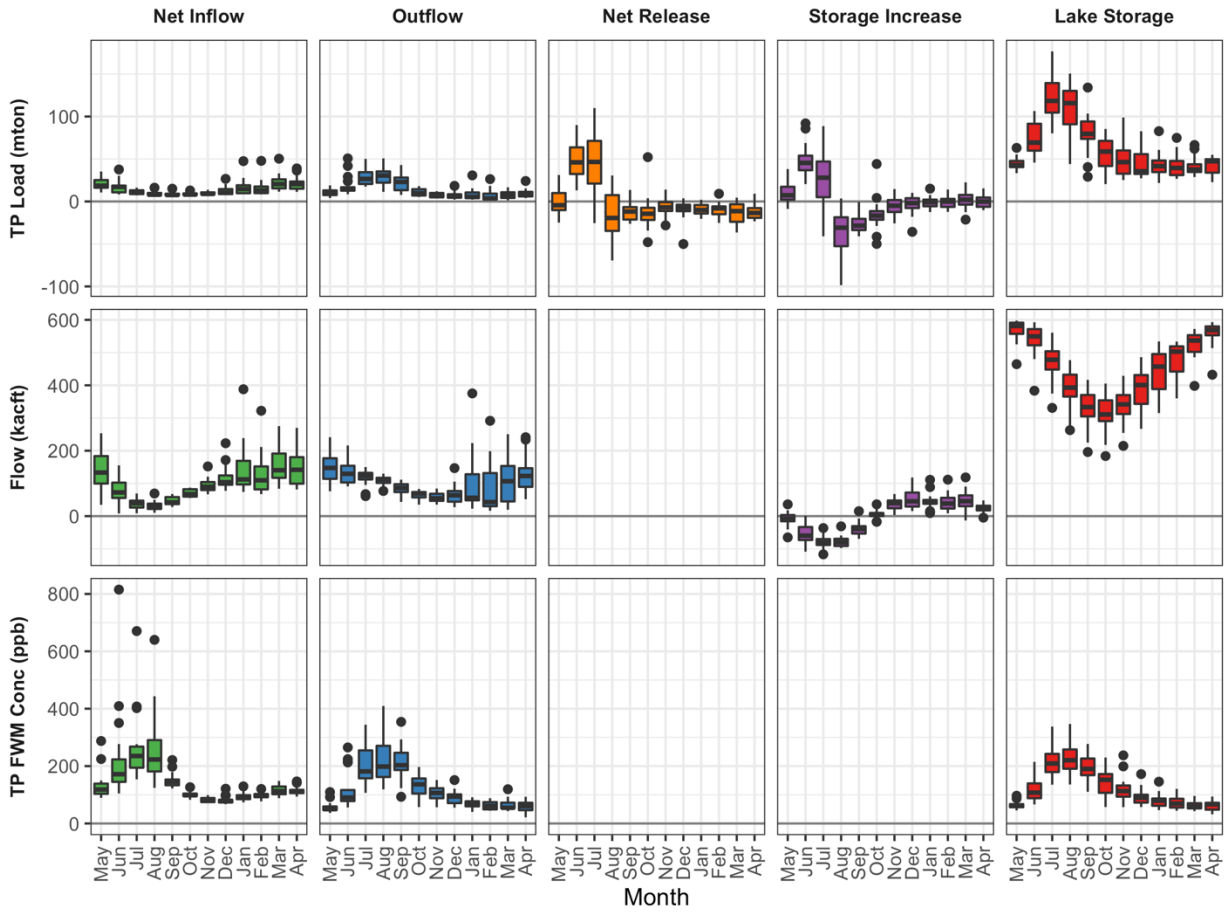



*Figure 12: Distributions of TP load, flow, and TP FWM concentration for each mass balance flux and storage term by month of the phosphorus loading year (May-Apr).*

*Middle line = median, lower and upper box hinges = 25th and 75th percentiles, lower and upper whiskers = 1.5 * IQR from box hinges or minimum/maximum value, whichever is smaller, points = values more than 1.5 * IQR from box hinges.*

Although the monthly boxplots (Figure 12) were useful for depicting the seasonal patterns in terms of both the magnitude and variability of each mass balance term, they did not indicate which specific years had relatively high, low, or average values, or whether there were any long term trends within each month for a given term. Therefore, we created a variety of alternative plots of the monthly fluxes for evaluating the year-to-year change of each mass balance term both within and between months (Appendix A, Figures A1–A4). Although these figures provide a useful context for evaluating long-term trends or patterns for each monthly flux, they did not ultimately lead to any new insights about the relationships among the various flux terms. However, we have included them for reference and because they allow for further evaluation of individual years having extreme values (e.g., PWY 1998, 2000, 2008 had highest annual outflow loads), which can be identified from the figures in the following section.

## 3.3 Variable Correlations

Our final approach for evaluating whether inflow and outflow loads were closely coupled due to rapid sediment cycling focused on using correlation matrices to identify whether significant relationships existed between each unique pair of mass balance terms on both annual and seasonal timescales.

### *3.3.1 Annual Fluxes*

A correlation matrix was generated for the annual (PWY, May-Apr) TP loads and FWM concentrations of net inflow, outflow, and net release as well as the 1-year lag of net inflow and net release (Figure 13). The flow volumes were not included in this matrix because flows are often highly correlated with loads; therefore, their inclusion in this matrix would have resulted in many duplicated associations due to cross-correlation.

The lagged versions of the net inflow and net release terms correspond to the annual TP loads and FWM concentrations of the previous PWY for each term. For example, the correlation between the outflow load and the lag(net inflow) load was computed using the outflow loads for PWY 1994–2010 paired against the net inflow loads of each previous year over PWY 1993–2009. Because each lagged variable did not have a value for the first year of the dataset (PWY 1993), the correlations were computed using only the years with complete observations over all years (PWY 1994–2010).

For each unique pair of variables, the Pearson's product moment correlation coefficient was computed using the `cor()` function in R. This correlation coefficient is a measure of the linear relationship between each pair of variables and ranges from -1 to +1 with 0 indicating no association between the two variables. Figure 13 presents the correlation coefficients and shows both the numeric value (upper triangle), and circles (lower triangle) with both the color and size of each circle proportional to the value of the correlation coefficient ($r$). For each correlation coefficient, a hypothesis test was also performed to determine whether the correlation was significantly different from zero. These tests were run using the `cor.test()` function in R, which assumes that the correlation coefficient follows a $t$ distribution with n-2 degrees of freedom. Significant ($p < 0.05$) correlations were denoted by marking the corresponding circle with an asterisk (*) in Figure 13, and generally had values of $r > 0.5$.

The correlation matrix of annual fluxes revealed only five significant ($p < 0.05$) correlations out of the 28 total pairwise comparisons (Figure 13). Four of the five significant correlations included the annual outflow TP load as one of the two variables. Outflow loads were positively correlated with lagged and current net inflow loads ($r$ = 0.67 and 0.58, respectively) and the net release load ($r$ = 0.51), and negatively correlated with the lagged inflow concentration ($r$ = -0.62). Scatterplots show the relationship between annual outflow TP loads and each of these four related variables (Figure 14).

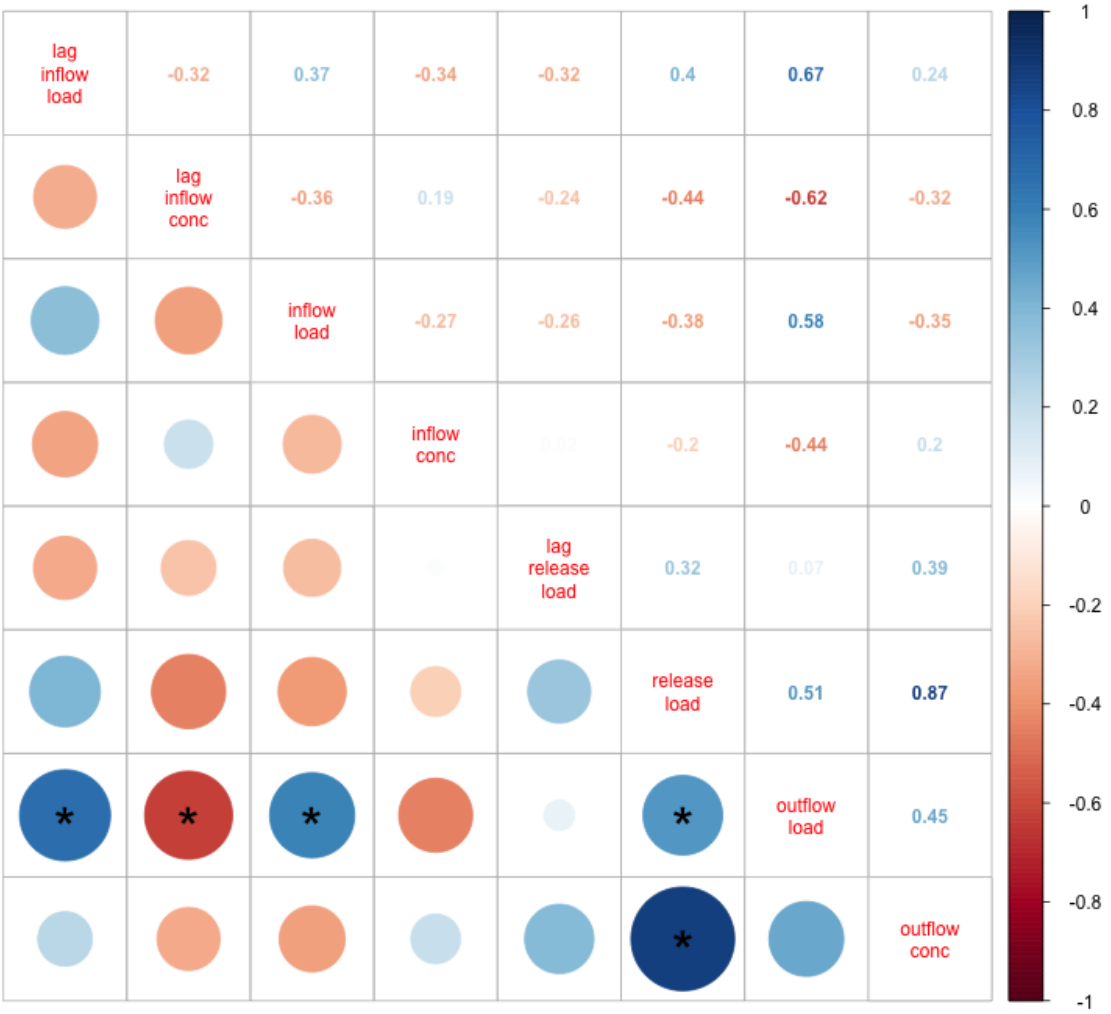



*Figure 13: Correlation matrix of annual TP loads and FWM concentrations for lag(net inflow), net inflow, lag(net release), net release, and outflow over phosphorus WY 1994–2010.*
*Both the color and size of each circle represent the correlation of the corresponding pair of variables.*
*Circles marked by an "*" indicate statistically significant ($p < 0.05$) correlation.*

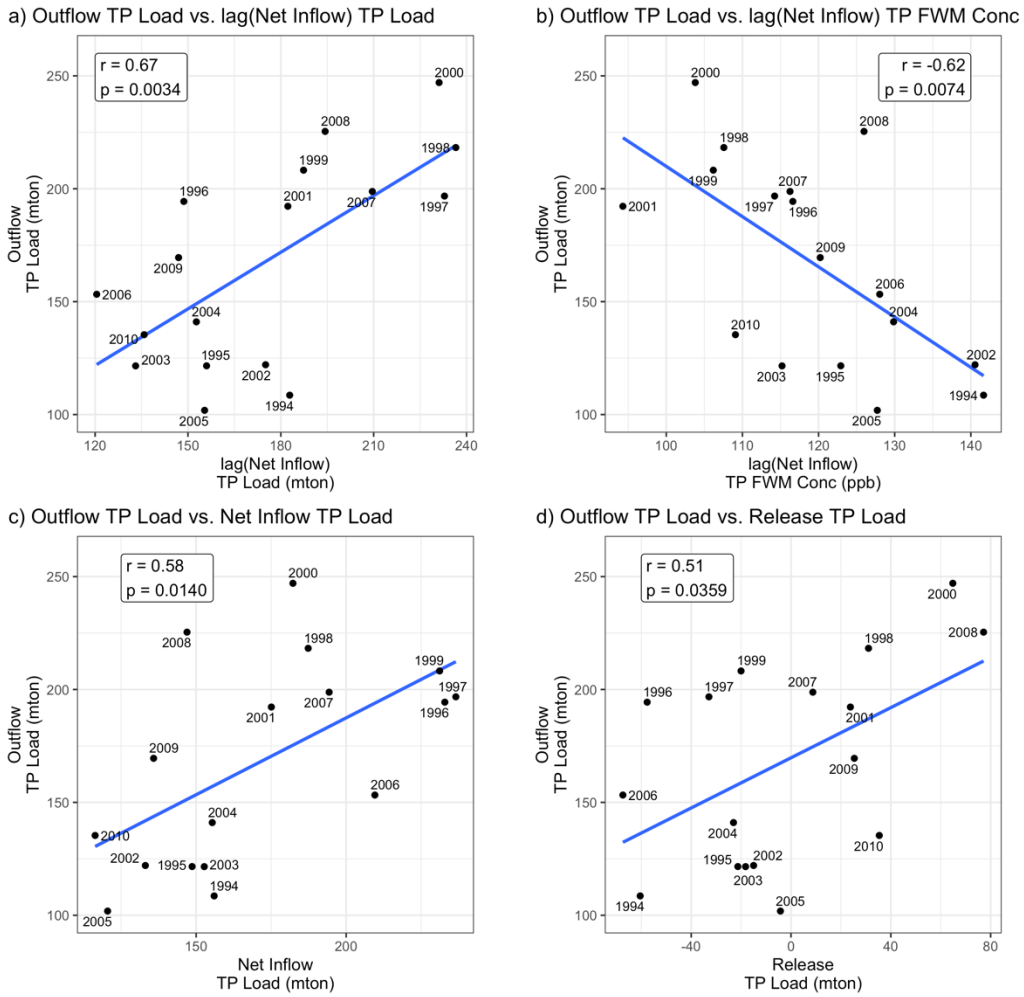



*Figure 14: Relationships between annual outflow TP load and a) lag(net inflow) TP load, b) lag(net inflow) TP FWM concentration, c) net inflow TP load, and d) net release TP load over phosphorus WY 1994–2010.*
*Points are labeled by phosphorus WY (May-Apr).*

The correlations between outflow load and both the current and lagged net inflow loads (Figure 14a,c) support the results of the linear regression model, which included both of these terms as significant predictors of annual outflow loads (Section 3.1). However, the negative correlation between the outflow load and lagged net inflow concentration was a new finding (Figure 14b), perhaps related to the relationships between net inflow loads, flows, and concentrations. Lastly, the net release TP load was positively correlated with both the outflow TP load ($r$ = 0.51; Figure 14d) and FWM concentration ($r$ = 0.87; Figure 15a). These correlations confirmed our observations from Section 3.2 that the net release was a major driver of in-lake TP mass storage, which in turn drives the outflow concentration and load.

Furthermore, we found a very high correlation between the net release load and the difference between the net inflow and outflow FWM TP concentrations ($r$ = 0.95, p = 8.9e-9; Figure 15b), which was a variable not originally included in the correlation matrix. Although this high correlation was to be expected since the net release load was calculated by difference from the other flux terms using Eqn. (12), it also has the following mechanistic explanation. On an annual

basis, the change in storage term was very small compared to the other terms, and thus the net release term was approximately equal to the difference in the net inflow and outflow TP loads (Figure 9). And since the annual flows for inflows and outflows were approximately equal, the difference in inflow and outflow loads was primarily due to differences in their concentrations. Therefore, a strong correlation between the difference in inflow and outflow concentrations and the net release flux was not surprising since the net release was estimated mainly from the difference in inflow and outflow loads, which in turn was primarily due to differences in their concentrations.

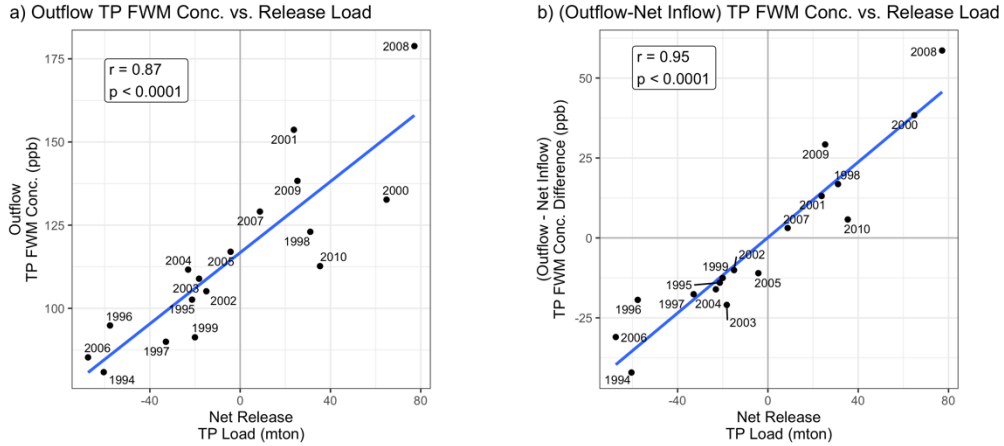



*Figure 15: Scatterplots of annual net release TP load versus a) outflow TP FWM concentration and b) difference between outflow and net inflow FWM TP concentrations over phosphorus WY 1994–2010.*
*Points are labeled by phosphorus WY (May-Apr).*

In summary, the correlation matrix of annual fluxes revealed various associations between inflows and outflows as well as between outflows and the net release flux. However, the correlations did not show any significant relationship between the inflows and net release. Therefore, although these results were consistent with our hypothesis about the close coupling between inflow and outflow loads, they did not provide a full mechanistic explanation for how that coupling may occur. We next considered correlations between seasonal subsets of each annual flux based on the theory that the potential effects of inflow loads on sediment flux dynamics likely differ between the summer and winter.

### *3.3.2 Seasonal Fluxes*

To evaluate whether the mass balance terms were related on a seasonal basis, the annual fluxes for each term were split into two seasons, each six months long and coinciding with the start/end of the phosphorus WY:

1. **Summer (May – October)** encompasses the growing season when the large P release from the sediment drives algal bloom formation, which then declines resulting in large sedimentation of organic matter and nutrients. During this season, the lake volume typically decreases as outflows exceed inflows.
2. **Winter (November – April)** encompasses the period of lower biological activity and during which sediment fluxes tend to yield a net retention of P to the sediment. During this season, the lake refills and receives the majority of its annual inflows due to high spring snowmelt-driven runoff.

The seasonal correlation matrix was generated using the same methodology and for the same set of mass balance terms as the annual correlation matrix (Section 3.3.1) including TP load and FWM concentration of the net inflow, net release, and outflow terms as well as lagged versions of net inflow and net release (Figure 16). For each term, both the seasonal and annual fluxes were included to determine not only season-to-season but also season-to-annual relationships. The lagged versions of the seasonal fluxes correspond to the value for that season during the previous phosphorus WY. For example, the lag(winter net inflow) TP load for PWY 2010 (May 2009 – April 2010) is the net inflow TP load in the winter of PWY 2009 (November 2008 – April 2009). The lag(winter) variables are thus the fluxes that occurred in the winter prior to the start of each PWY, and the lag(summer) variables are the fluxes in the summer before that. For example, the correlation between the annual outflow TP load and the lag(winter net inflow) TP load pairs the annual outflow load of each PWY against the winter inflow load of the previous PWY.

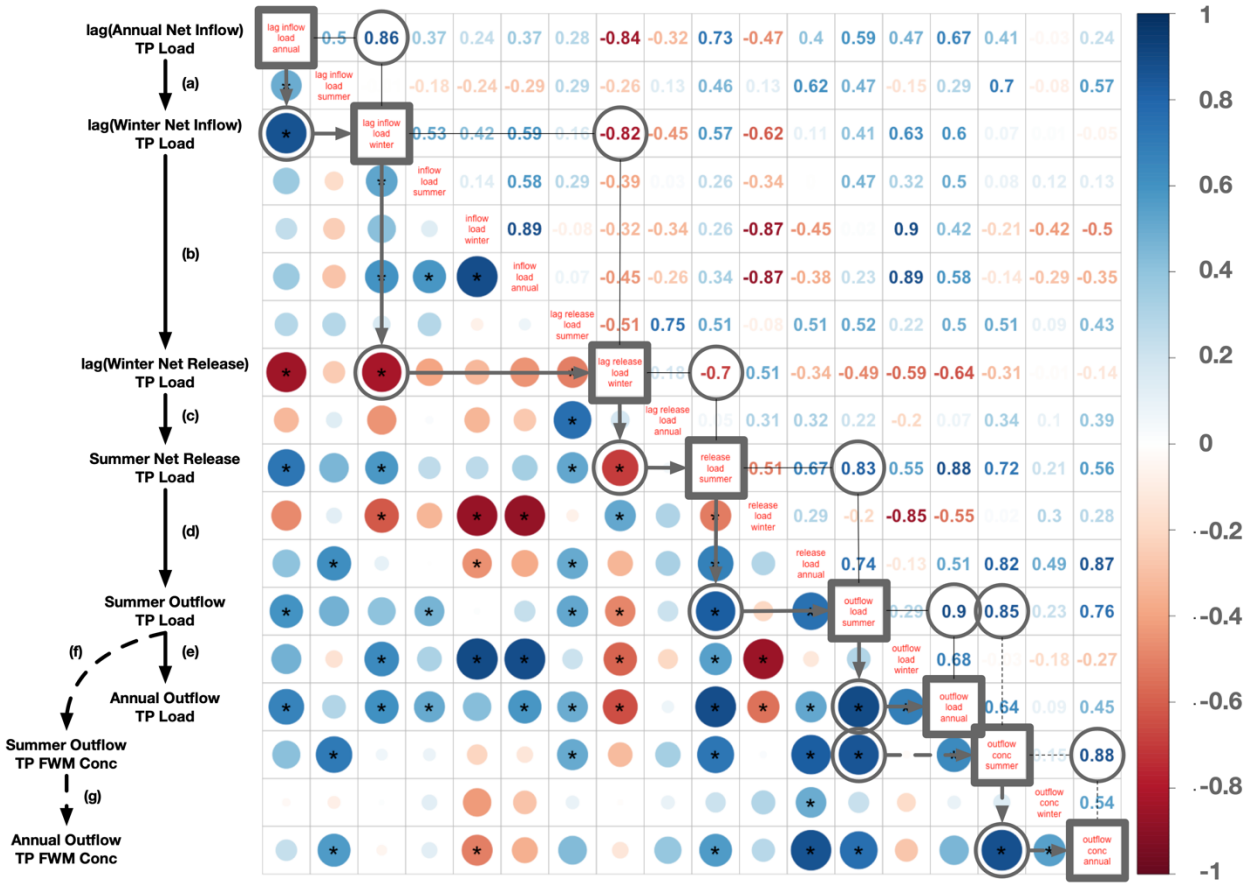



*Figure 16: Correlation matrix of seasonal and annual TP loads and FWM concentrations for lag(net inflow), net inflow, lag(net release), net release, and outflow fluxes over phosphorus WY 1994–2010.*
*Both the color and size of each circle represent the correlation coefficient for the corresponding pair of variables.*
*Circles marked by an "*" indicate statistically significant ($p < 0.05$) correlation.*
*Dashed lines denote alternative pathway (f–g) ending with annual outflow TP FWM concentration instead of annual outflow TP load.*

From the seasonal correlation matrix, we identified a series of significant ($p < 0.05$) correlations that explain how annual outflow TP loads may be coupled with the previous inflow loads through a

sequence of relationships between the annual and seasonal inflow, net release, and outflow fluxes (Figure 16):

a) Lagged annual (May-Apr) net inflow loads were positively correlated with lagged winter (Nov-Apr) net inflow loads ($r$ = 0.86),
b) Lagged winter net inflow loads were negatively correlated with lagged winter net release loads ($r$ = -0.82),
c) Lagged winter net release loads were negatively correlated with current summer net release loads ($r$ = -0.70),
d) Summer net release loads were positively correlated with summer outflow loads ($r$ = 0.83), and
e) Summer outflow loads were positively correlated with annual outflow loads ($r$ = 0.90).

A secondary pathway was also identified that relates the lagged annual inflow loads to the annual outflow FWM concentration by using the following two relationships:

f) Summer outflow loads were positively correlated with summer outflow FWM concentrations ($r$ = 0.85), and
g) Summer outflow FWM concentrations were positively correlated with annual outflow FWM concentrations ($r$ = 0.88).

These series of correlations thus provide a pair of pathways that potentially explain how annual outflow loads and concentrations were each related to the lagged annual inflow loads of the previous PWY. To better understand these relationships, a series of scatterplots were generated depicting the correlation between each pair of variables (Figure 17, panels a-g correspond to relationships a-g above and as shown in Figure 16).

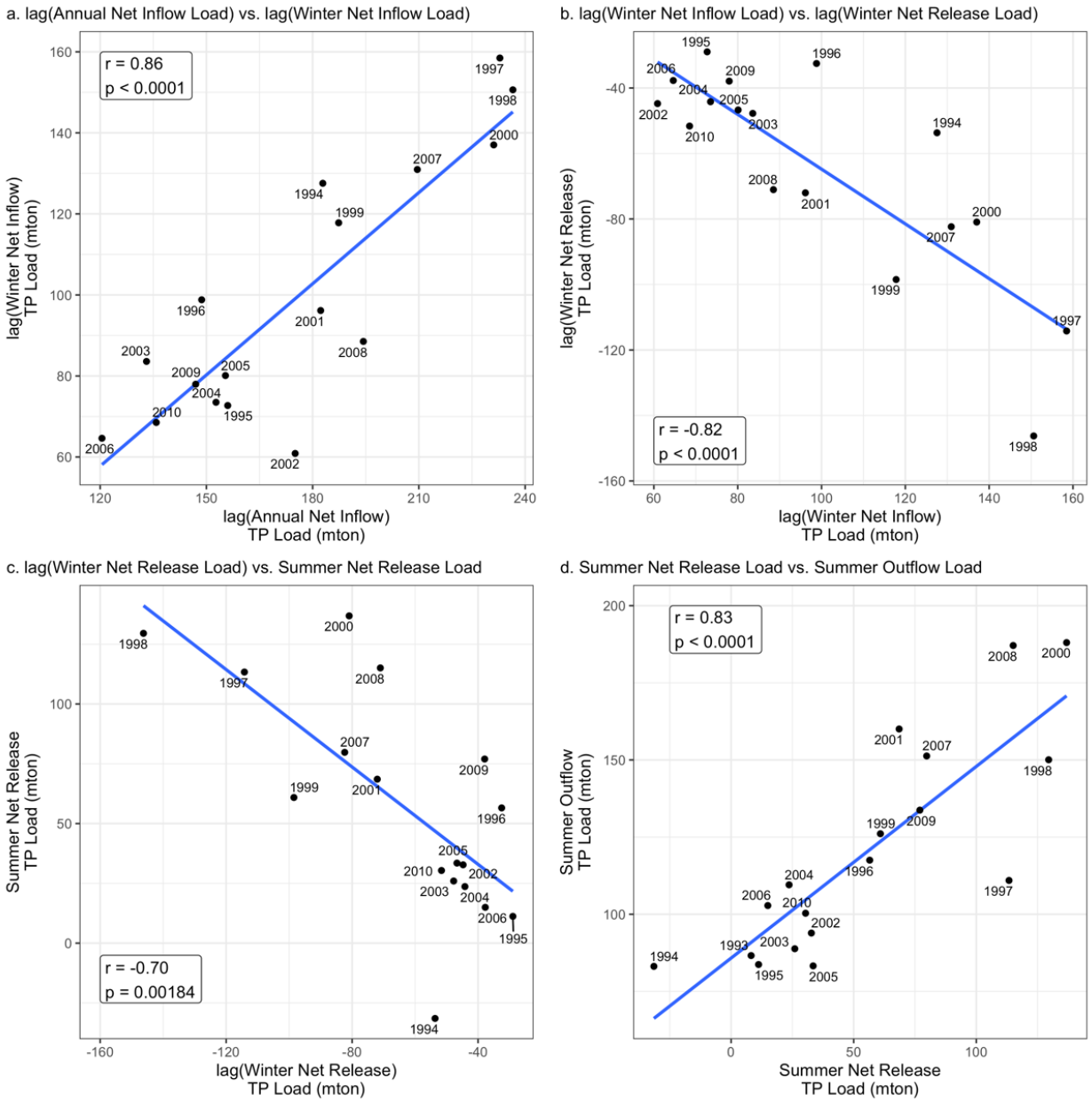



*Figure 17: Scatterplots of the primary seasonal and annual mass balance fluxes from the seasonal correlation matrix.*
*Points are labeled by phosphorus WY (May-Apr), and lagged metrics are labelled using the current year although values are from the previous year.*

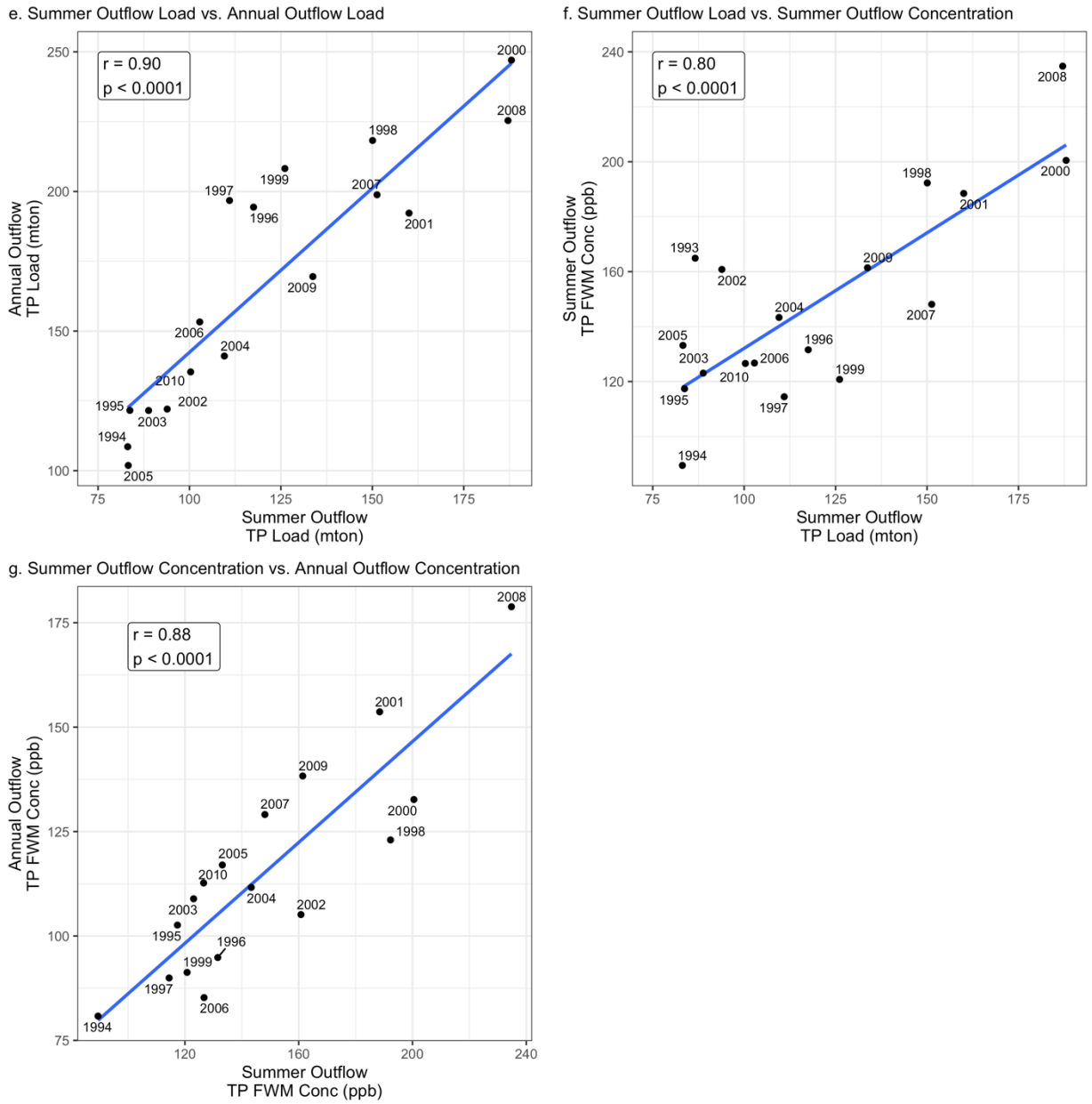



*Figure 17 (cont'd): Scatterplots of the primary seasonal and annual mass balance fluxes from the seasonal correlation matrix.*
*Points are labeled by phosphorus WY (May-Apr).*

The pathway begins with a positive correlation relating the lagged annual and winter inflow TP loads ($r$ = 0.86, Figure 17a). Since both variables are lagged, this relationship is the same as that between the current (un-lagged) annual and winter inflow TP loads. In other words, the variables are paired by the same phosphorus WY, but the lagged versions simply shift both variables back one year. This correlation is likely driven by the fact that most of the annual inflow load typically occurs during winter due to the snow-melt driven spring runoff (Figure 8).

Next, the lagged winter inflow load was negatively correlated with lagged winter net release ($r$ = -0.82, Figure 17b). Because both variables are based on the lagged winter season, each pair of

values reflects the same time period. For example, the lagged winter net inflow and net release loads for PWY 2010 (May 2009 – April 2010) correspond to the net inflow and net release both during the winter of PWY 2009 (November 2008 – April 2009). The negative relationship indicates that higher winter inflow loads lead to lower (more negative) net release, which is the equivalent of higher net retention. During winter, the recycle flux of P from the sediment to the water column is expected to be relatively small due to lower temperatures, lower pH and reduced biological activity within the sediment. Therefore, the winter net release flux primarily reflects the amount of sedimentation. This relationship could also be described as higher winter inflow loads lead to greater *net retention* (opposite of net release) whereby sedimentation exceeds the opposing recycle flux. Sedimentation during the period of higher winter inflow loads is likely facilitated by the increased particulate P and TSS concentrations that occur during winter/spring higher flow periods in some UKL tributaries (Walker et al. 2015).

The next relationship showed that the net release flux in winter was negatively correlated with that of the following summer ($r$ = -0.70, Figure 17c). This suggests that the more phosphorus that accumulated on the sediment during the winter (higher net retention = more negative net release), the more was later released during the following summer (higher positive net release). This correlation is the primary link connecting the inflow and net retention dynamics from the winter of one PWY to the release and outflow dynamics during the summer of the following PWY.

The summer net release flux was then positively correlated with the summer outflow load ($r$ = 0.83, Figure 17d). As discussed above in Section 3.2, the large net release of P in June and July appeared to be the main driver for a large increase in TP mass storage in the lake during the summer, and that in turn was a main driver for the summer outflow concentration and thus the outflow load.

Finally, the summer and annual outflow loads were positively correlated ($r$ = 0.90, Figure 17e). Similar to the correlation between the annual and winter inflow loads, the annual and summer outflow loads were highly correlated because the majority of annual outflow loads occur during the summer (Figure 8). In total, this series of relationships (steps a – e in Figure 16) suggested that annual outflow loads were correlated with the lagged inflow loads via a series of intermediary seasonal fluxes, the most important of which was that higher net retention (more negative net release) in winter led to higher net release in the following summer.

Due to the complexity of this analysis and its terminology, we created an example to demonstrate the relationships among each specific annual and seasonal flux (Figure 18). This example steps through each of the five correlations (a – e) starting with the lagged annual inflow load and ending with the annual outflow load. The data are shown for phosphorus WY 1998 along with its previous year (PWY 1997), which in this case represents the lag year.

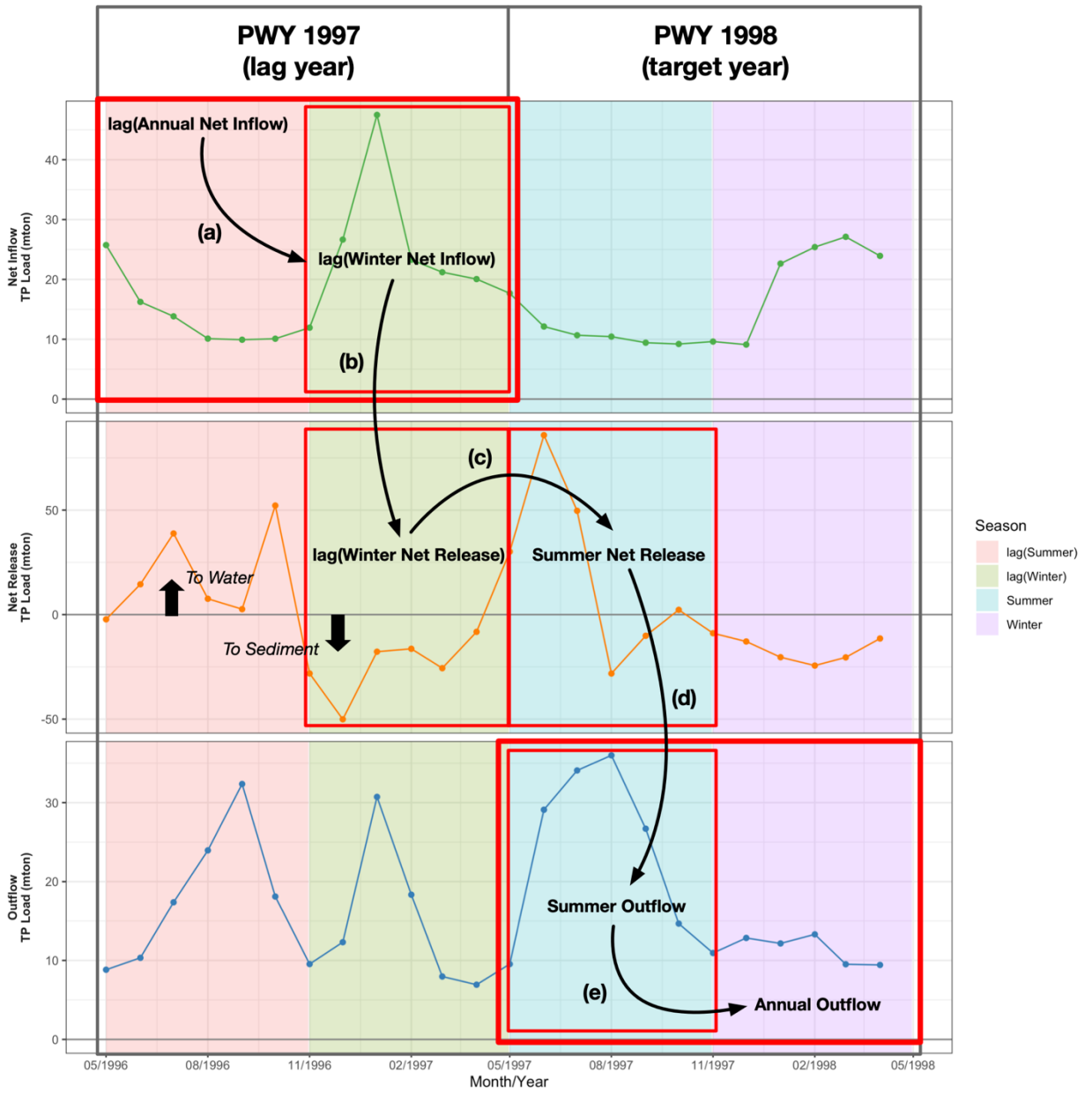



*Figure 18: Monthly timeseries of net inflow, net release, and outflow TP loads demonstrating the sequence of anunal and seasonal flux relationships for phosphorus WY 1998.*

In addition to relating outflow loads to the lagged inflow loads, we also identified an alternative pathway relating the annual outflow TP FWM concentration to lagged inflow loads (steps a – d followed by f – g in Figure 16). This relationship supports the results of the linear regression model, which predicted outflow FWM concentrations by dividing the predicted loads by the annual outflow flows (see Section 3.1). In addition to being positively correlated with annual outflow loads (Figure 17e), the summer outflow loads were also positively correlated with summer outflow concentrations ($r$ = 0.80, Figure 17f). The summer concentrations, in turn, were positively correlated with annual outflow concentrations ($r$ = 0.88, Figure 17g). As with outflow loads, the

correlation between the summer and annual outflow FWM concentrations is likely due to the fact that the majority of annual outflow occurs during summer.

### *3.3.3 DIRECT CORRELATIONS*

In the previous Section 3.3.2, we identified a series of intermediary correlations that explain how lagged annual net inflow loads were related to both annual outflow loads and FWM concentrations. These results confirmed our initial findings from the linear regression model (Section 3.1), which predicted both outflow loads and FWM concentrations based on the current and previous years' net inflow loads (plus a trend term). However, when directly compared, the lagged annual net inflow load was only significantly correlated with the outflow load ($r$ = 0.67, p = 0.0034, Figure 19a), but not the outflow FWM concentration ($r$ = 0.24, p = 0.355, Figure 19b). Therefore, although there was agreement among all three methods (linear regression model, intermediary correlations, and direct correlations) for the relationship between lagged net inflow loads and outflow *loads*, there appeared to be disagreement for the relationship between lagged net inflow loads and outflow *concentrations*. Specifically, both the linear regression model indicated that outflow concentrations were related to lagged net inflow loads, but there did not appear to be a direct correlation between these two terms.

One possible explanation for the discrepancy between these methods is that the dilution effect of flow on loads and concentrations[16] was only accounted for in the linear regression model results but not in the direct comparison between lagged net inflow loads and outflow concentrations. In general, for a given annual outflow load, the associated outflow concentration would be lower under high flows, and higher under low flows. Because a portion of outflow loads are derived from the net release of P from the sediment in any given year, the effect of that release on changing the outflow concentration depends on the volume of outflow. In other words, for a given mass released from the sediment in one year, the resulting change in outflow (and in-lake, which is highly correlated with outflow, Figure 11) concentrations depends on whether flows were high or low in that year.

For the linear regression model results (Section 3.1), this dilution effect was accounted for when we divided the predicted outflow loads by corresponding flows in order to predict outflow concentrations. However, the direct correlation between lagged net inflow loads and outflow concentrations did not account for this dilution effect, which we suspect is why this correlation was not significant ($r$ = 0.24, p = 0.355, Figure 19b). Therefore, to account for this dilution effect, we divided the lagged net inflow load by the outflow flow and found a significant positive correlation between that ratio and the outflow concentration ($r$ = 0.54, p = 0.0258, Figure 19c). Although dividing the lagged net inflow load from the previous year by the outflow flow of the current year may appear counter-intuitive, it does have the following mechanistic explanation.

[16] In general, for any given load (mass) of TP, the associated concentration will be lower when flows are higher and vice versa.

Following from our hypothesis, lagged net inflow loads are potentially tied to summer net release rates[17] (and subsequently the outflow loads) through a series of seasonal fluxes involving winter net retention and summer net release (i.e., steps a – e in Figure 16 of Section 3.3.2). Based on these relationships, the net inflow load in any given year would determine (at least in part) the net release load during the following summer. Therefore, dividing the lagged net inflow load by the current flow is a way to account for dilution of the net release load in the current year because that load is derived from the lagged net inflow load of the previous year (assuming our hypothesis is correct).

In addition to this mechanistic explanation, there is also a mathematical derivation for the ratio between the lagged net inflow load and the current outflow flow. As noted above, in Section 3.1 we used the linear regression model to predict annual outflow FWM concentrations by dividing the predicted annual loads by corresponding flows. Mathematically, this operation can be represented by dividing both sides of Eqn. 13 (Section 3.1) by the annual outflow flow term ($Q_{out}$), which yields the predicted concentration ($C_{out}$) on the left-hand side (the predicted load, $L_{out}$, divided by associated flow, $Q_{out}$) and the sum of the independent variables, each divided by the outflow flow, on the right-hand side:

$$C_{out} = \frac{L_{out}}{Q_{out}} = \beta_0 \frac{1}{Q_{out}} + \beta_1 \frac{L_{in}}{Q_{out}} + \beta_2 \frac{L_{in,lag}}{Q_{out}} + \beta_3 \frac{Year}{Q_{out}} \quad (14)$$

As mentioned above, dividing each of the independent variables by the outflow flow effectively adjusts the portion of the outflow load associated that term to account for the dilution of that mass by the flow volume. Therefore, this equation provides a mathematical basis for directly comparing the outflow concentration ($C_{out}$) to the ratio of the lagged inflow load and outflow flow ($L_{in,lag}/Q_{out}$).

In summary, by dividing the lagged net inflow loads by outflow flows to account for flow dilution, the direct correlation method yielded results that agreed with the linear regression model. Although not definitive, there are sound mechanistic and mathematical bases for this comparison.

[17] Lagged annual net inflow loads were also directly correlated with summer net release loads ($r$ = 0.73, p < 0.001, Figure 16)

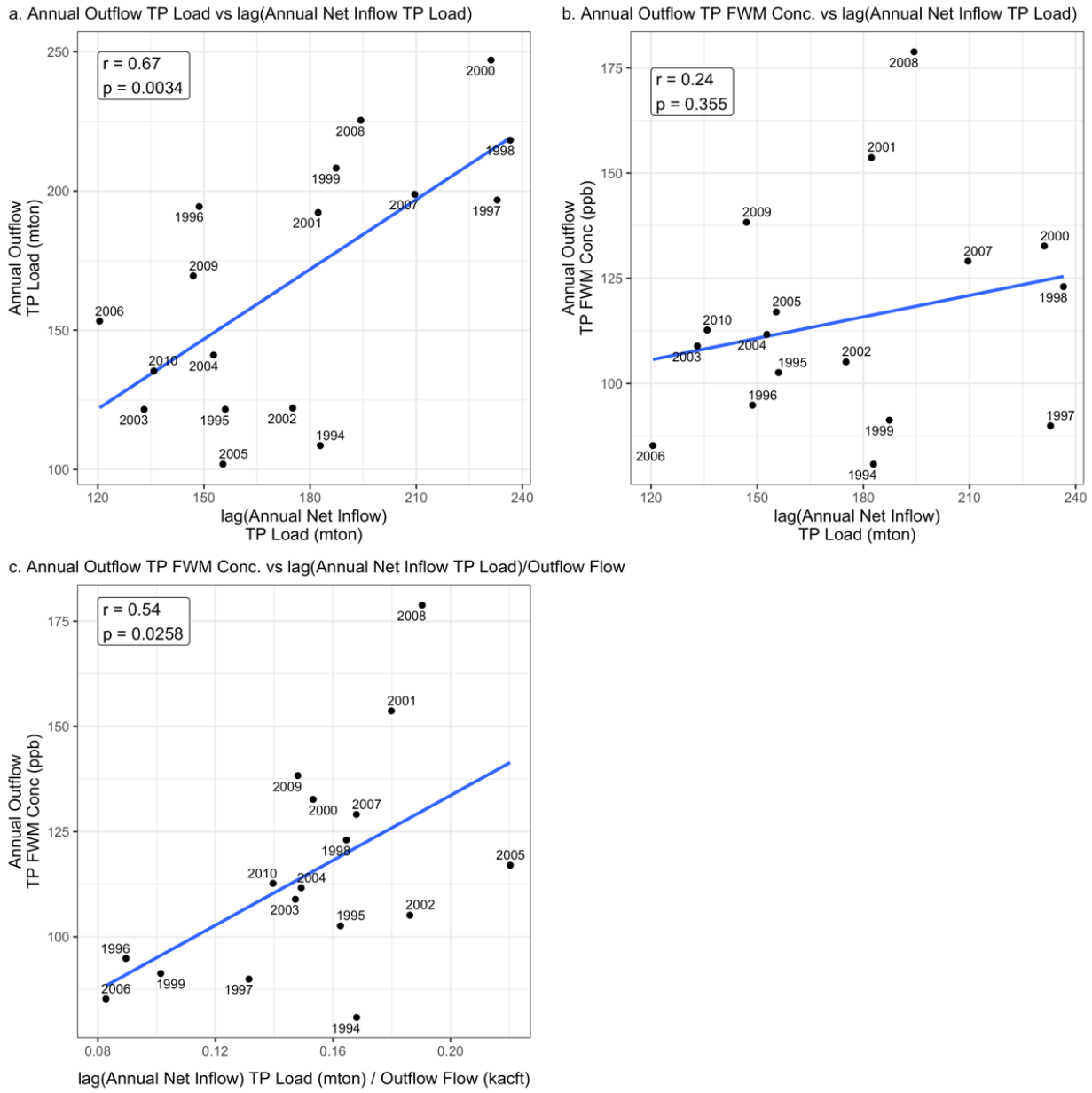



*Figure 19: Scatterplots of a) annual outflow TP load vs lag(annual net inflow) TP load, b) annual outflow TP FWM concentration vs. lag(annual net inflow) TP load, and c) annual outflow TP FWM concentration vs. ratio of lag(annual net inflow) TP load to outflow flow.*
*Points are labeled by phosphorus WY (May-Apr).*

# 4 Discussion and Conclusions

In general, the response of internal P recycling to reductions in external loads can be highly variable among different lakes. This response depends on the quantity of mobile P in the sediment, which includes both legacy P that has accumulated over long timescales and a continuous supply of mobilizable P from the settling of recent inflow loads (e.g., Hupfer et al. 2020). P mobilization (i.e., the recycle flux) depends on a variety of morphometric, climatic, chemical and biological factors that vary both seasonally and annually (Orihel et al 2017; Søndergaard and Jeppesen 2020).

Furthermore, the duration and quantity of P released from the sediment following external load reductions depends on loading history and the capacity of the sediment to retain P (Søndergaard et al. 2012).

In some cases, a significant fraction of internal loading is comprised of legacy P derived from historical external P loading, which can delay the recovery of water quality following external load reductions (e.g., Orihel et al. 2017; Tammeorg et al. 2020). In other cases, external load reductions can lead to improved water quality over relatively short time scales, especially if internal loads are primarily derived from the sedimentation of recent external loads as opposed to long-term legacy P. For example, Jeppesen et al. (2005) studied a cross-section of northern temperate lakes and found that although internal loading delayed recovery, for most lakes a new equilibrium TP concentration was reached after 10–15 years. For UKL, modeling results indicated that equilibrium P concentration could be reached 20–30 years after load reduction (Wherry and Wood 2018)—slightly longer than the 10–15 years found in the Jeppesen et al. (2005) study. However, as noted in Section 1, in-lake TP concentrations in UKL achieved approximately 50% of the final equilibrium concentration in five years and 80% in ten years. While our study was not intended to determine the timescale over which in-lake TP concentrations in UKL would reach a new equilibrium following external load reductions, our preliminary linear model indicated that near-term external P loads explained a large amount of the variability in outflow loads and concentration, which suggests that outflow loads would respond relatively quickly to changes in inflow loads. This result would not be expected if mobilized legacy P was the dominant pool contributing to summer sediment recycling, in which case outflow loads and concentrations would not be as closely coupled with recent external loads.

Our goal in this study was to evaluate the hypothesis that there is rapid cycling of phosphorus through the sediment each year in UKL such that the amount of P released each summer is more closely coupled to recent inflow loads than to legacy P associated with long-term external loading. Because in shallow, eutrophic lakes, high sediment release rates typically occur in the summer when high temperatures favor cyanobacterial blooms, detailed information on monthly or seasonal loading dynamics is often needed to make realistic predictions of P dynamics (e.g., Søndergaard et al. 2012). Therefore, in addition to evaluating annual relationships among hydrologic and P mass balance terms (e.g., net inflow, net release, and outflow), we evaluated relationships between seasonal fluxes and also included lagged terms to accommodate antecedent fluxes.

For our analyses, we summarized annual and seasonal fluxes based on the phosphorus WY defined as the 12-month period from May through April. The phosphorus WY was used instead of the traditional hydrologic WY (Oct–Sept) because it better coincided with the annual cycling of TP mass in UKL. The start and end of each phosphorus WY roughly coincided with the time when the TP mass and concentration in UKL both reached their annual minima. In addition, because the magnitude of the annual change in storage term was reduced using the phosphorus WY compared to the hydrologic WY, the relationships between net inflows, outflows, and net release loads were simplified. Therefore, by using the phosphorus WY, we were able to evaluate the potential relationships among these fluxes more directly than if we had used the hydrologic WY.

Based on the monthly mean fluxes of each mass balance term, the average seasonal pattern of TP fluxes in UKL showed that the net release of P from the sediment was a major component of the phosphorus mass balance during the summer growing season (Section 3.2.1). This release primarily occurred in June-July and was the main driver of increases in in-lake P storage and concentration as well as outflow concentrations and loads. The remainder of the year (August–May), the net release rate was negative indicating that the sedimentation flux exceeded the recycle flux causing a net retention of P in the sediments.

An evaluation of the year-to-year variability in the annual fluxes confirmed our original observation that there appeared to be a 1-year lag between annual inflow and outflow TP loads (Section 3.2.2.1). This analysis also suggested that in the years immediately following a large increase in the inflow load, the annual net release flux tended to switch from net retention (negative values) to net release (positive values). This switch in the net sediment flux, in turn, drove an increase in the outflow concentration, and thus the outflow load. Further evaluation of the year-to-year variability in the monthly fluxes provided additional observations about the magnitude and variability of each flux (Section 3.2.2.2). For example, the seasonal pattern of inflow TP loads was more similar to that of the associated *flows*, while the pattern for outflow TP loads was more similar to the associated *concentrations*. As a result, the inflow and outflow TP loads exhibited different seasonal patterns despite having very similar annual average values. Additionally, the monthly time series confirmed that monthly outflow concentrations were strongly correlated to in-lake concentrations, and thus the water quality of UKL outflow serves as a good indicator of in-lake water quality. In order to identify a mechanistic basis for explaining how the outflow, net release, and lagged inflow loads might be closely coupled in the near-term, we then used correlation matrices to identify specific pairwise relationships between various seasonal and annual mass balance fluxes.

Based on only the annual fluxes, we found significant correlations between outflow loads and the lagged and current inflow loads as well as the current net release load (Section 3.3.1). Although these results confirmed our initial linear regression model, they did not indicate a significant correlation between annual inflow loads and net release, which was an important component for supporting our hypothesis. We suspected that these two fluxes were not correlated on an annual basis because the annual net release flux includes both the net release in summer and the subsequent net retention during the rest of the year, while the lagged annual inflow loads were expected to only contribute to the net release in the following summer. Therefore, we then evaluated the correlations between both the annual and seasonal fluxes of the mass balance terms. From this, we found a series of significant correlations that provided a basis for supporting our hypothesis that lagged net inflow loads are closely coupled to outflow loads through rapid recycling in the sediments.

Correlations between seasonal and annual mass balance fluxes showed that higher inflow loads in a given year led to higher net retention during the winter, which in turn led to higher net release the next summer followed by higher outflow loads and concentrations (Section 3.3.2). In other words, outflow loads (and concentrations) in any given year were driven in large part by the net release of P from the sediment during the summer growing season, which in turn was coupled to inflow loads during the previous winter. If the sediment release and inflow loads were not closely coupled in the

short term, then the outflow loads would not necessarily be expected to respond to changes in inflow loads due to persistent internal loading associated with the release of long-term legacy P from the sediment. Although these correlations do not prove causation between these fluxes, they do provide evidence in support of our hypothesis and are consistent with the underlying theory regarding the specific mechanisms by which inflow loads could be rapidly recycled through the sediment. Further research, as discussed below, is needed to definitively determine if this theory is correct.

Overall, these findings have important implications for the implementation of watershed P reduction strategies, and underscore the need to implement full scale watershed restoration strategies to restore ecosystem process and function as rapidly as possible. This is especially true given the lag expected between the implementation of watershed restoration activities and reductions in the associated external P loads to UKL (e.g., Mueller et al. 2015). However, once external load reductions are achieved, the rapid cycling of those loads through the sediment as indicated by our results suggests that improved water quality may occur over relatively short timescales. This improvement in both the water quality within UKL as well as its outflow would benefit both the endangered suckers residing within the lake and the reduction of nutrients exported downstream to Klamath River.

As noted above, the results of this study were not intended to estimate the timescale over which a final equilibrium P concentration would be achieved in UKL following external load reductions, but rather to show that near-term inflow loads appear to explain a significant portion of the inter-annual variability in net release of P from sediments and subsequent lake outflow loads and concentrations. The variability in these terms that was not explained by recent inflow loads is likely related to other factors that control sediment recycling rates and can vary from year to year. Although the seasonal net release fluxes computed from the monthly mass balance dataset have the advantage of incorporating many different release mechanisms that may operate over short (e.g., wind resuspension) or longer time scales (e.g., diffusion dynamics), these estimates do not explicitly incorporate factors such as growth and decline of algal blooms, temperature, dissolved oxygen, pH, etc. that control sediment recycling in a given year. The impacts of these factors on sediment release dynamics and subsequent in-lake water quality could be further explored using a mechanistic water quality model, as recommended below. Furthermore, because it was computed by difference from the other mass balance terms (Section 2.1.2, Eqn. 12), the net release term incorporates the cumulative error associated with all of the other terms, which were estimated using observation data or literature values. Therefore, alternative methods for estimating the net sediment flux rates could be useful for validating these estimates.

Because P released from lake sediments does not represent a “new” source of P to a water body, but rather represents remobilization of P previously retained from external sources, internal P loading is ultimately a function of the rate of external loading (Oriel et al. 2017). However, whether the internal P loading is comprised primarily of recently added P from external sources or of older legacy P that accumulated over the long-term can vary among lakes. For UKL, our analyses suggest that legacy P caused by excessive external loading over the long term (e.g., from wetland soil oxidation and agricultural runoff to UKL) may not be the dominant mechanism driving outflow

loads and concentrations during the WY 1992-2010 study period. Rather, our results suggest that a significant portion of summer sediment releases may be comprised of recent external loads. These results are therefore contrary to any expectation that water quality improvements in UKL can only be achieved over the long term in response to inflow load reductions due to the continued release from a large storage pool of legacy P in the sediment. Furthermore, our results suggest that watershed P reduction efforts could have near-term benefits. However, the timescale over which water quality may improve in UKL depends not only on the rate at which the lake responds to external load reductions, but also on the timescale over which those reductions can be achieved through the implementation of watershed restoration and other management strategies.

Finally, we provide some recommendations for future research to continue understanding the coupling between inflow loads, outflow loads and sediment fluxes in UKL:

- Extend the period of record for the mass balance dataset by incorporating most recent years of available data (e.g., PWY 2011 – 2019), and then update the analyses performed in this study to see if the various relationships remain significant in light of the additional data.
- Apportion the phosphorus mass balance dataset into particulate and dissolved forms of phosphorus for each flux to better understand the seasonal dynamics of each form, which may inform the relative rates of sedimentation and recycle.
- Use a mechanistic model or other means to estimate the individual sediment fluxes (sedimentation and recycle; see Figure 3c), and evaluate the impacts of the inter-annual variability in pH, temperature, dissolved oxygen, and other factors controlling sediment release rates.

# 5 Acknowledgements

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# APPENDIX A: ALTERNATIVE FIGURES SHOWING MONTHLY LOADING DYNAMICS

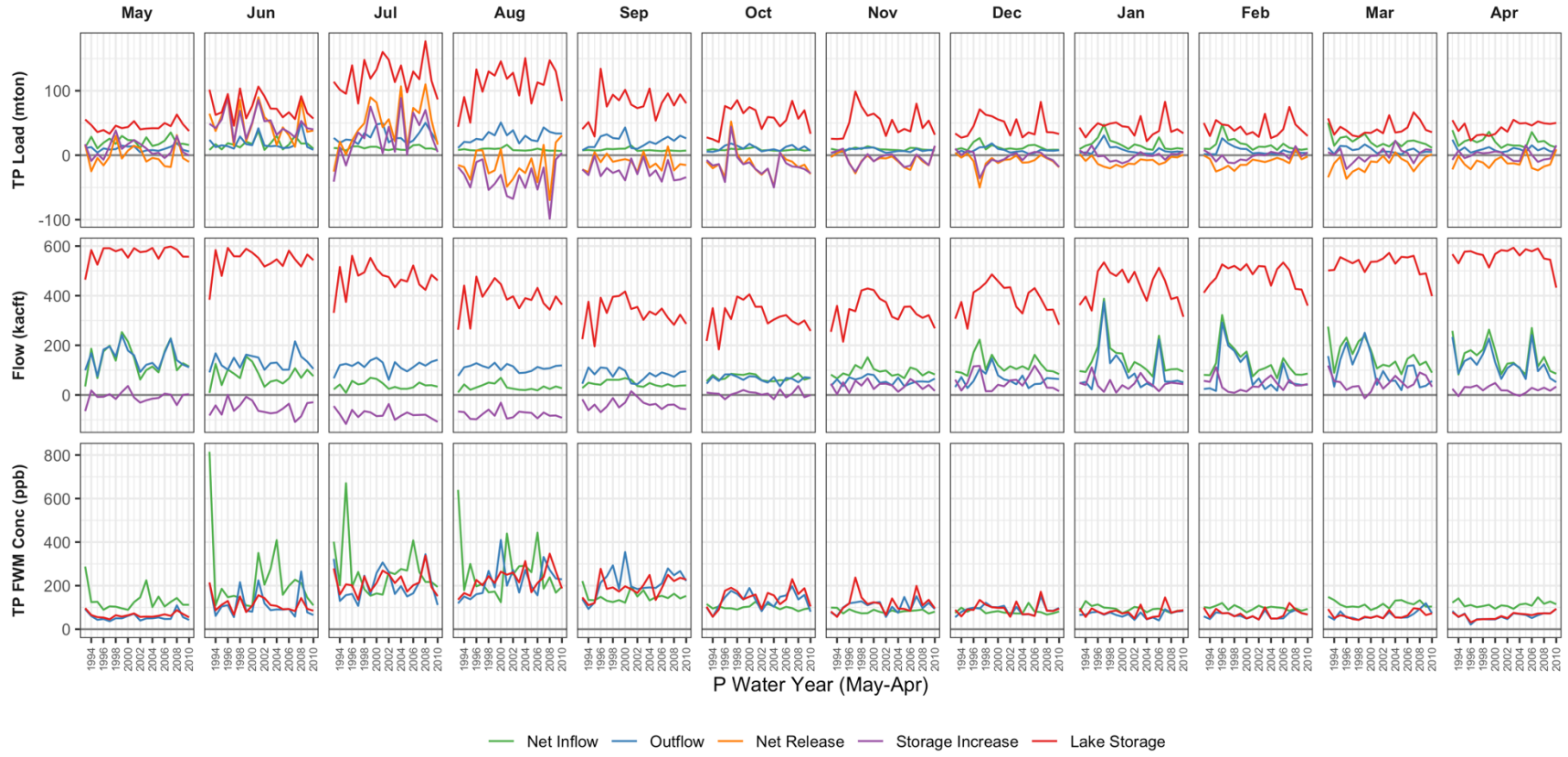


*Figure A1: Timeseries of monthly mass balance fluxes showing year-to-year changes within each month over phosphorus WY 1993–2010.*
*The distributions of the timeseries in each panel are represented by the boxplots for the May TP loads of each term in Figure 12.*


*Figure A2: Stacked bar charts of monthly mass balance fluxes faceted by year for phosphorus WY 1993–2010.*
*Note: outflow flows and loads are represented as negative values to be consistent with the storage increase and net release terms.*

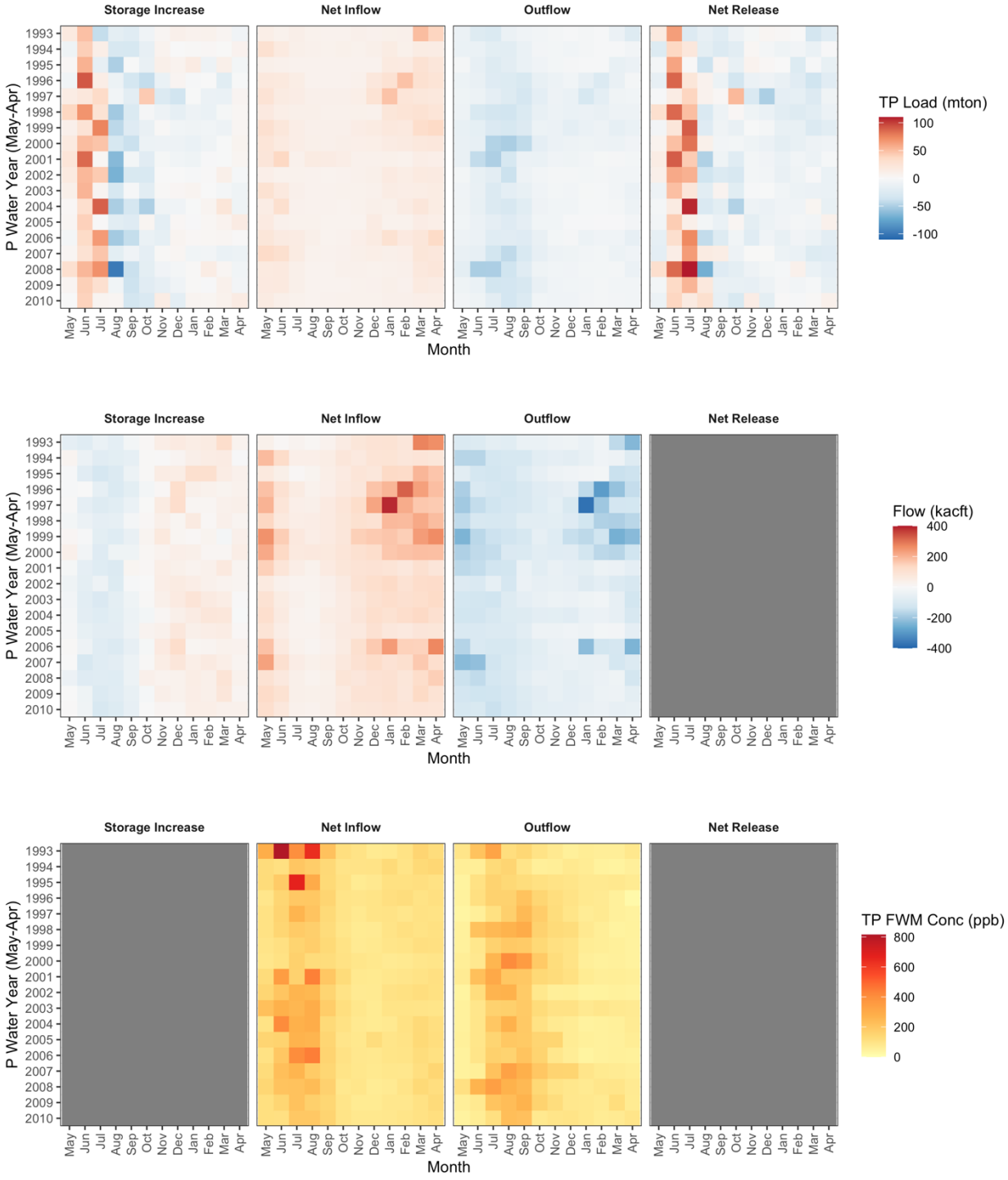


*Figure A3: Heatmap of monthly TP load, flow, and TP FWM concentration for each mass balance flux term, PWY 1993–2010.* *The loads and flows are shown using divergent color scales with red indicating positive values (flux into the lake water column) and blue indicating negative values (fluxes out of the water column). Outflow flows and loads are represented as negative values to be consistent with the storage increase and net release terms. The concentration scale uses a different color scale (yellow to red) since concentrations are always positive.*

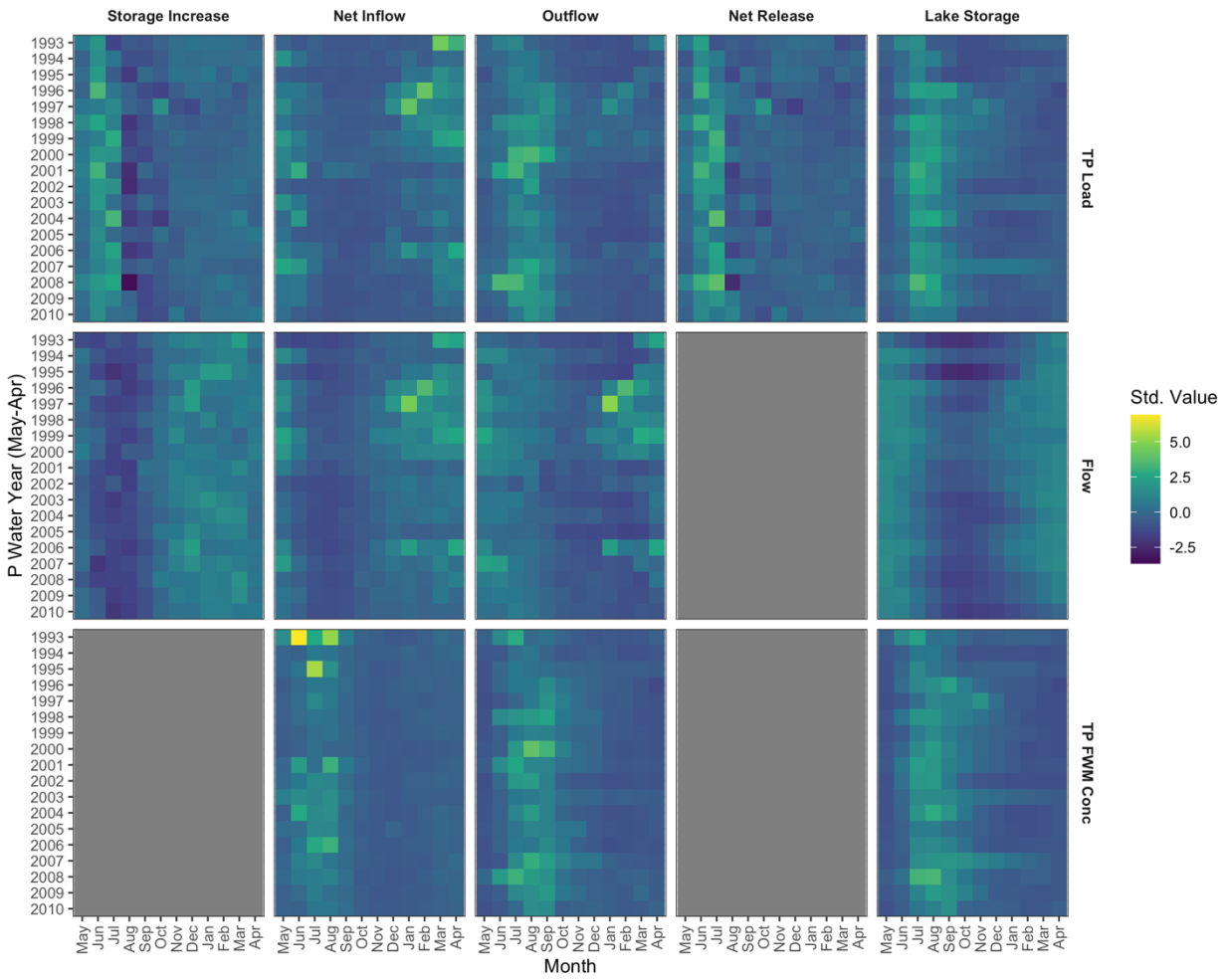


*Figure A4: Standardized heatmap of monthly TP load, flow, and TP FWM concentration for each mass balance flux term, PWY 1993–2010.*

*For each mass balance term and flux type (load, flow, FWM concentration), the monthly values were standardized by subtracting the overall mean and dividing by the standard deviation of those values.*

### *Notes about Heatmaps (Figures A3 and A4)*

Because the heatmaps in Figure A3 use a consistent color scale across all the terms, the flux magnitudes can be directly compared between terms (e.g., net release fluxes are clearly larger than inflows and outflows during June and July). However, as a result, it is difficult to see the seasonal pattern for terms with relatively smaller magnitudes (i.e., the variability in the inflow and outflow TP loads are not as clear due to their lower magnitudes relative to the net release term). Therefore, Figure A4 shows standardized values of each mass balance flux. For each term and variable (i.e., load, flow, concentration), the monthly values were standardized by subtracting the mean and dividing by the standard deviation. As a result, the standardized values for each term and flux variable (i.e., each panel of Figure A4) have a mean of zero and standard deviation of one. The color scale thus reflects the number of standard deviations each monthly flux value deviated from its long-term mean. The standardized heatmap is useful for comparing the relative seasonal patterns with each flux and term, while the heatmap in Figure A3 compares the patterns in absolute units and is better for comparing magnitudes across the mass balance terms.