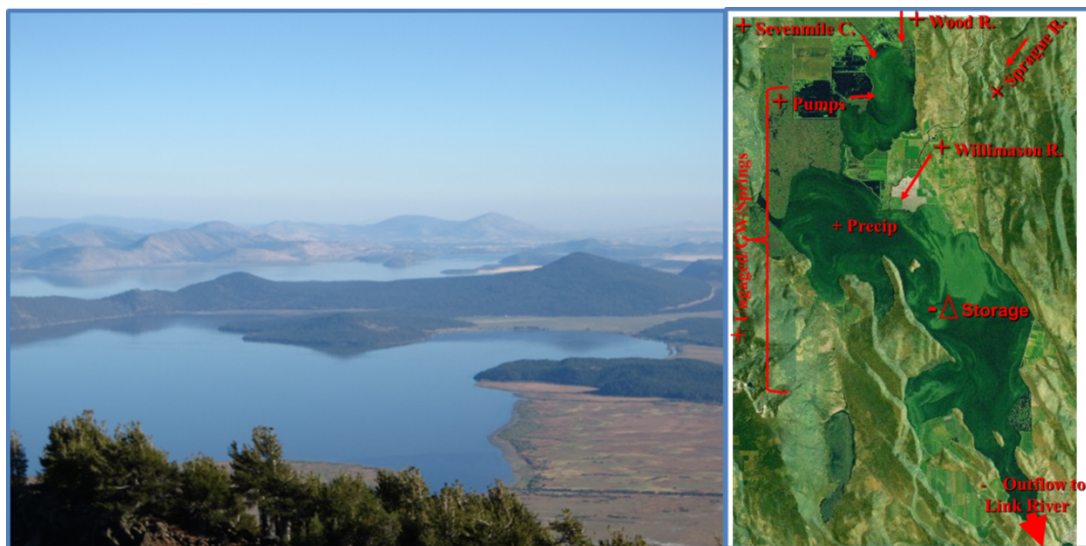


Water and Nutrient Balances of Upper Klamath Lake, Water Years 1992–2018



Prepared for
Klamath Tribes
Natural Resources Department

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Executive Summary

Background

Upper Klamath and Agency Lakes (UKL) comprise a large, shallow, hypereutrophic lake system located in south-central Oregon. UKL is seasonally dominated by large blooms of the nitrogen-fixing cyanobacterium *Aphanizomenon flos-aquae*. Extended periods of hypoxia, elevated pH, and toxic levels of un-ionized ammonia caused by the growth and decline of cyanobacterial blooms have been identified as important factors contributing to the decline of native endangered fish populations in UKL. Cyanobacterial blooms in UKL are tied to both external phosphorus (P) loading that is discharged directly into the lake from its watershed, as well as internal P loading, which is derived from external P loading that settles to the bottom of the lake (i.e., retained) and is subsequently released back into the water column (i.e., recycled) during the summer algal growing season. Therefore, there is a need to manage external P loading into UKL in order to reduce the occurrence and severity of cyanobacteria blooms and the subsequent water quality degradation impacting endangered fish populations. Although both P and nitrogen (N) reduction can be important for bloom control, the primary focus of this study (and lake and watershed management in general for UKL) is on P because N-limitation can be overcome by cyanobacteria, which can obtain N from the atmosphere through N-fixation.

Water and nutrient balances provide a basis for understanding lake and watershed hydrologic and nutrient dynamics. They are also essential for developing lake water quality models intended to evaluate the effects of land and water uses on water quality and to develop effective control programs for reducing water quality impairments. The initial versions of the water and nutrient balances for UKL were constructed using data from WY¹ 1992–1998 (Kann and Walker, 1999) and formed the basis for a Total Maximum Daily Load (TMDL) model showing that reducing external P loads by 40% would lead to lower in-lake P concentrations and algal biomass (ODEQ, 2002). A subsequent update to the balances (Walker et al., 2012) included an additional 12 years of data (WY 1999–2010) and was used to recalibrate and refine the original TMDL model (Wherry et al., 2015; Wood and Wherry, 2018), and to assess trends in major balance terms over the 19-year period, WY 1992–2010 (Walker et al., 2012). The updated balances were also used to analyze P inflow/outflow and sediment retention/release dynamics (Walker and Kann, 2020). The results of that study showed that seasonal release of sediment P appears to be more a function of recent P loading into the lake rather than of legacy P, which would be derived from sediment accumulation of historical inflow loads over long time periods.

¹ Water Year (WY) = October 1 – September 30 (e.g., WY 1992 = Oct 1, 1991 – Sep 30, 1992)

Since the previous mass balances update, an additional 8 years (WY 2011–2018) of hydrologic and water quality data were collected on UKL and its tributaries. With various watershed restoration efforts, corrections to the lake bathymetry (leading to increased lake volume), as well as hydrologic changes due to climate change and enforcement of Klamath Tribal water rights, the goal of this study was to update and extend the previous balances through WY 2018 and to re-evaluate the long-term hydrologic and water quality dynamics and trends. In addition, the updated mass balance dataset generated through this study will provide an important data source to inform future data analysis and modeling studies of nutrients and algal biomass in UKL.

Methods

The primary goal of this study was to generate a continuous dataset of monthly flows, nutrient loads, and flow-weighted mean (FWM) concentrations for total phosphorus (TP) and total nitrogen (TN) representing the overall water and nutrient mass balances of UKL (Figure ES1). To compute these balances, we compiled all relevant data (nutrient concentrations, flows, water levels, precipitation, evaporation) for the individual mass balances terms including tributaries, agricultural areas, lake storage, and outflow, and then used various methods to estimate the monthly flows, loads, and concentrations of each term.

For the water balance (Figure ES1a), each term was either directly measured or independently estimated except for inflows from ungauged drainage areas, which were calculated by difference from the following water balance equation, and net retention, which represents errors associated with constraining the ungauged inflows to non-negative values:

$$\Delta \text{ Lake Volume} = \text{Precipitation} + \text{Gauged Tributary Inflows} + \text{Pumped Inflows} + \text{Ungauged Inflows} - \text{Evaporation} - \text{Outflow} - \text{Net Retention}$$

Similarly, for the nutrient balances (Figure ES1b,c), the TP and TN loads (i.e., mass per unit time) of each term were generated based on direct measurements or independent estimates except for net retention, which was calculated by difference from the following mass balance equation. Concentrations of each term were then computed by dividing the loads by associated flow volumes.

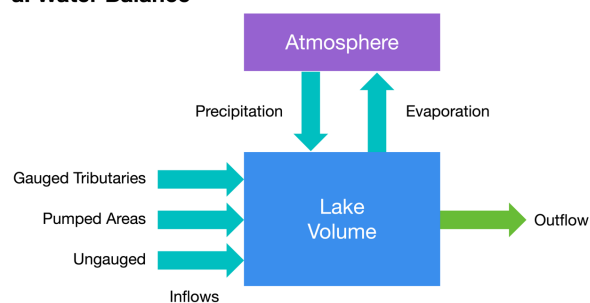
$$\Delta \text{ Lake Storage} = \text{Atmospheric Deposition} + \text{Gauged Tributary Loads} + \text{Pumped Loads} + \text{Ungauged Loads} - \text{Outflow Load} - \text{Net Retention}$$

For the nutrient balances, net retention represents the net loss (or gain) between the water column and sediment (as well as the atmosphere for N only). For P, positive values denote a net settling (i.e., loss) from the water column to the sediment and negative values denote a net

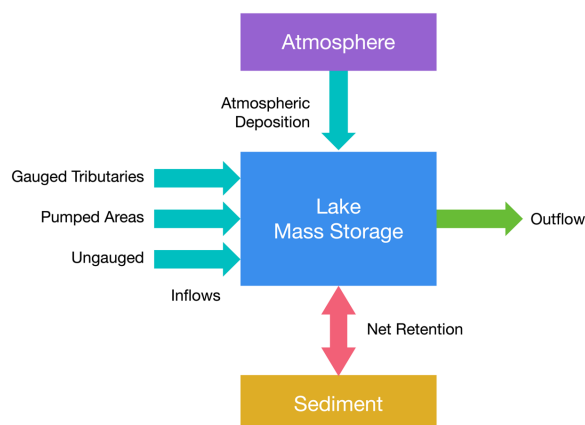
recycling (i.e., gain) from the sediment to the water column. For N, net retention incorporates exchange with not only the sediment but also the atmosphere through nitrogen fixation and, to a lesser extent, denitrification. Positive values of N net retention denote an overall net loss of N from the water column to both the sediment and atmosphere, while negative values indicate a net gain.

The water and nutrient mass balances terms were computed at monthly timesteps and then aggregated to seasonal and annual intervals over the WY 1992–2018 period of record. These datasets were then used to evaluate the overall dynamics and long-term trends in flows, nutrients loads, and FWM concentrations for each mass balance term.

a. Water Balance



b. Total Phosphorus Mass Balance



c. Total Nitrogen Mass Balance

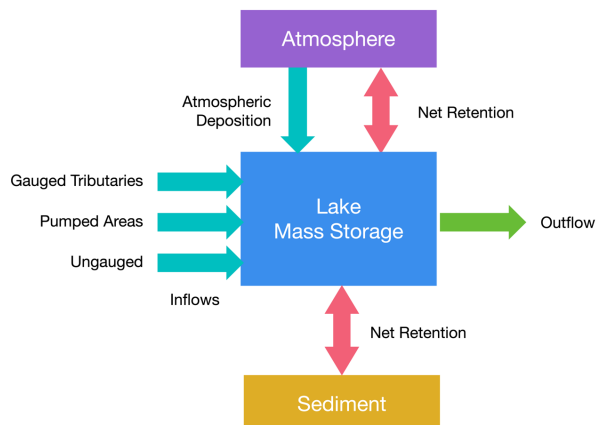


Figure ES1. Schematic diagrams of water and nutrient mass balances.

For phosphorus, net retention is the net exchange between the water column and sediment associated with sedimentation and recycling. For nitrogen, net retention includes exchanges between the water column and both the sediment (e.g., sedimentation) and the atmosphere (e.g., nitrogen fixation) independent of atmospheric deposition. For both parameters, positive values of net retention denote an overall net flux from water to sediment (and atmosphere for N) (i.e., a net loss from lake mass storage).

Results

Long-term Average Balances

A summary of the water and nutrient mass balances provide long-term mean annual flows, loads, FWM concentrations, runoff (flows per unit area), and export (loads per unit area) of each term over the period of record, WY 1992–2018 (Table ES1). Compared to the previous mass balances study (Walker et al., 2012), changes in the long-term average balances over the previous period (WY 1992–2010) were minimal (e.g., total external inflows changed by +1% for flow, -1% for TP loads, and +4% for TN loads). Therefore, the analyses and models that utilized the previous mass balances dataset are not expected to be impacted by the various changes incorporated in this study (e.g., updated lake bathymetry, dataset revisions, or other minor methodological changes).

Table ES1: Long-term mean annual water and nutrient mass balances of UKL, WY 1992–2018

Upper Klamath Lake Water & Nutrient Balances

Water Year(s): 1992 - 2018 (Period of Record)

	Flow hm ³ /yr	Nutrient Loads TP mt/y TN mt/y		Fraction of Total External Inflow Flow TP Load TN Load			Nutrient Concs TP ppb TN ppb		Dr. Area km ²	Runoff m/yr	P Export kg/km ²	N Export kg/km ²
Term												
Gauged Tributary Inflows												
Sevenmile Canal at Dike Rd	101.4	14.3	47.2	7%	9%	9%	141	466	96	1.06	149	494
Wood River above Weed Road	246.5	21.2	31.6	16%	14%	6%	86	128	333	0.74	64	95
Wood River below Weed Road	80.9	15.1	27.0	5%	10%	5%	186	334	61	1.33	248	444
Total Wood River at Dike Rd	324.7	36.2	57.9	21%	23%	11%	111	178	394	0.82	92	147
Sprague River	481.3	36.2	170.2	31%	23%	33%	75	354	4,171	0.12	9	41
Williamson River excluding Sprague	338.0	34.8	107.6	22%	22%	21%	103	318	3,702	0.09	9	29
Total Williamson River	819.3	70.7	274.8	53%	45%	54%	86	335	7,873	0.10	9	35

Overall Balance

Total Gauged Tributary Inflows	1,245.3	121.2	380.0	80%	78%	74%	97	305	8,362	0.15	14	45
Total Pumped Area Inflows	38.2	16.4	106.2	2%	11%	21%	430	2,778	92	0.41	178	1,153
Ungauged Inflows	274.5	17.8	27.2	18%	11%	5%	65	99	1,040	0.26	17	26
Total External Inflows	1,558.0	155.5	513.3	100%	100%	100%	100	329	9,494	0.16	16	54
Precipitation	117.3	9.2	63.3	8%	6%	12%	78	540	278	0.42	33	228
Evaporation	271.5			17%					278	0.98		
Net Inflow	1,403.8	164.7	576.6	90%	106%	112%	117	411	9,772	0.14	17	59
Lake Outflow	1,399.9	160.0	2,241.9	90%	103%	437%	114	1,602	9,772	0.14	16	229
Storage Increase	0.5	-2.5	-17.7	0%	-2%	-3%						
Net Retention	3.4	7.2	-1,647.6	0%	5%	-321%						

Natural Background vs. Anthropogenic Loads

Background / Natural	1,558.0	101.3	154.2	100%	65%	30%	65	99	9,494	0.16	11	16
Anthropogenic		54.2	359.0		35%	70%	35	230	9,494		6	38

Morphometry	Mean	Min	Max
Volume (hm ³)	722.9	385.2	952.3
Area (km ²)	278.2	262.7	296.9
Elevation (ft)	4,140.8	4,136.8	4,143.4
Mean Depth (meters)	2.6	1.5	3.2

Phosphorus Model Parameters

Hydraulic Residence Time	0.51 years
Net Water Load	5.60 m/yr
Areal Total P Load	0.56 g/m ² -yr
Total P Retention Coefficient	4.6 %

The water and mass balances over the entire WY 1992–2018 period showed that combined discharge from all external inflows had an annual average volume of 1,558 hm³/yr, nutrient loads of 155 and 513 mton/yr, and FWM concentrations of 100 and 329 ppb for TP and TN, respectively (Table ES1). Gauged tributaries (Williamson, Sprague, Wood and Sevenmile) accounted for 80% of that external inflow volume and 78 and 74% of the TP and TN loads, respectively. Total pumped inflows accounted for only 2% of the total external inflow volumes,

but 11 and 21% of the TP and TN loads due to higher concentrations (430 and 2,778 ppb). The remaining 18% of external inflow volumes and 11 and 5% of TP and TN loads were generated from groundwater seepage, springs, and surface runoff from the ungauged portions of the UKL basin.

The long-term average lake outflow volume was 1,400 hm³/yr, which amounts to 90% of total external inflows due to evaporative losses exceeding precipitation on the lake surface. Average outflow TP loads were 160 mton/yr and slightly less (4.7 mton/yr or 3%) than the net inflow² load (165 mton/yr) indicating that over the long term, outflow TP loads were relatively balanced by loads from total external inflows and atmospheric deposition. Because of the relative balance between inflow and outflow TP loads, the long-term average net retention of TP was small (7.2 mton/yr, 5% relative to the total external inflow load) indicating that over the entire period, the total amount of P sedimentation was approximately balanced by the amount of sediment recycling (i.e., release to the water column). This long-term balance between sedimentation and recycling suggests that P loading into the lake was derived primarily from external (i.e., watershed) sources instead of from internal loading from a large sediment storage of legacy P. If internal loading from legacy P were a significant source, then one would expect the long-term average net retention to reflect an overall net release of P (i.e., average net retention would have a large, negative value).

In contrast to TP, the overall mean outflow TN load (2,242 mton/yr) was 389% higher than the net inflow TN load (577 mton/yr). This imbalance between outflow and inflow TN loads resulted in an average net retention of -1,648 mton/yr, which was more than 3x the total external inflow load. Therefore, unlike TP for which the net retention was relatively small compared to external loads, the large, negative net retention of TN indicates a significant internal source of N, which was primarily due to nitrogen fixation from the atmosphere by cyanobacteria within the lake.

The total estimated background TP and TN loads were 101 and 154 mton/yr, which were 65 and 30% of the total external loads, based on assumed background concentrations of 65 and 99 ppb computed from samples of springs and seeps throughout the UKL basin. Anthropogenic loads accounted for the remaining 35 and 70% of the TP and TN external inflow loads and resulted in total external inflow concentrations being 35 and 230 ppb higher than the estimated background concentrations. Runoff and nutrient export rates in the Sprague and Williamson River basins were lower than the Wood and Sevenmile basins by a factor of 10 or more. The highest unit-area runoff and nutrient export rates occurred in the Wood River basin below

² Net Inflow = Total External Inflows + Precipitation (Atmospheric Deposition) – Evaporation
For nutrient loads, evaporation is zero so net inflow is the total combined load from the watershed and atmospheric deposition

Weed Rd and in the Sevenmile Canal basin. However, these unit-area runoff and export rates have higher uncertainty than the total flows and mass loads from these basins due to uncertainty in their drainage areas caused by cross-basin water transfers for irrigation and high discharge from springs feeding these systems.

Annual and Seasonal Variations

Total annual inflow volumes from gauged and ungauged drainage areas, pumped areas, and precipitation varied over approx. 1,000 – 2,500 hm³/yr across the entire period. Annual inflows were generally higher during the 1990s than in later years with total volumes exceeding the long-term mean (1,675 hm³/yr) in 7 out of the first 9 years (WY 1992–2000) and only 3 (WYs 2006, 2011, 2017) of the remaining 18 years (WY 2001–2018). However, the two years with lowest total inflows (WYs 1992 and 1994) also occurred during those first 9 years.

Total external inflow volumes and TP loads exhibited similar patterns indicating that year-to-year variations in loads were driven primarily by flows as opposed to TP concentrations, which were not related to flow. Total external inflow TN loads, on the other hand, were driven by both flows and, to a lesser extent, concentration. Annual variations in total external inflow volumes and nutrient loads were also both strongly correlated with variations in precipitation, underscoring the important effect of year-to-year variations in climate on nutrient loads. Thus, due to the effect of climate-driven flow variations on TP loads, FWM TP concentrations which were relatively independent of precipitation, provide a more reliable basis for tracking long-term trends related to watershed restoration.

Although the inflow and outflow TP loads were relatively balanced and net retention was small over the long term, seasonal variations in the mass storage, in-lake concentration, outflow load, and outflow concentration were driven primarily by large month-to-month changes in net retention (Figure ES2). This was especially true during the critical early summer (June – July) algal growing season in UKL, when large quantities of P were released into the water column³. Following this early summer release, and coinciding with the typical late-July to August period when cyanobacterial blooms peak and decline in UKL, the net retention flux switched direction⁴ indicating that sedimentation exceeded recycling and resulted in an overall net settling of P from the water column to the sediment from August through April.

³ In Figure ES2, flows and loads for net retention and outflow are shown using values with reversed sign (multiply by -1) so that positive values denote additions to the water column and negative values indicate losses from the water column. Therefore, the large, positive values of the “-(Net Retention)” TP load in June and July indicate large, negative net retention rates meaning P recycling from the sediment exceeded sedimentation and there was a large net release of P from the sediment to the water column.

⁴ As indicated by switch from positive to negative values for “-(Net Retention)” in Figure ES2 (see prev. footnote)

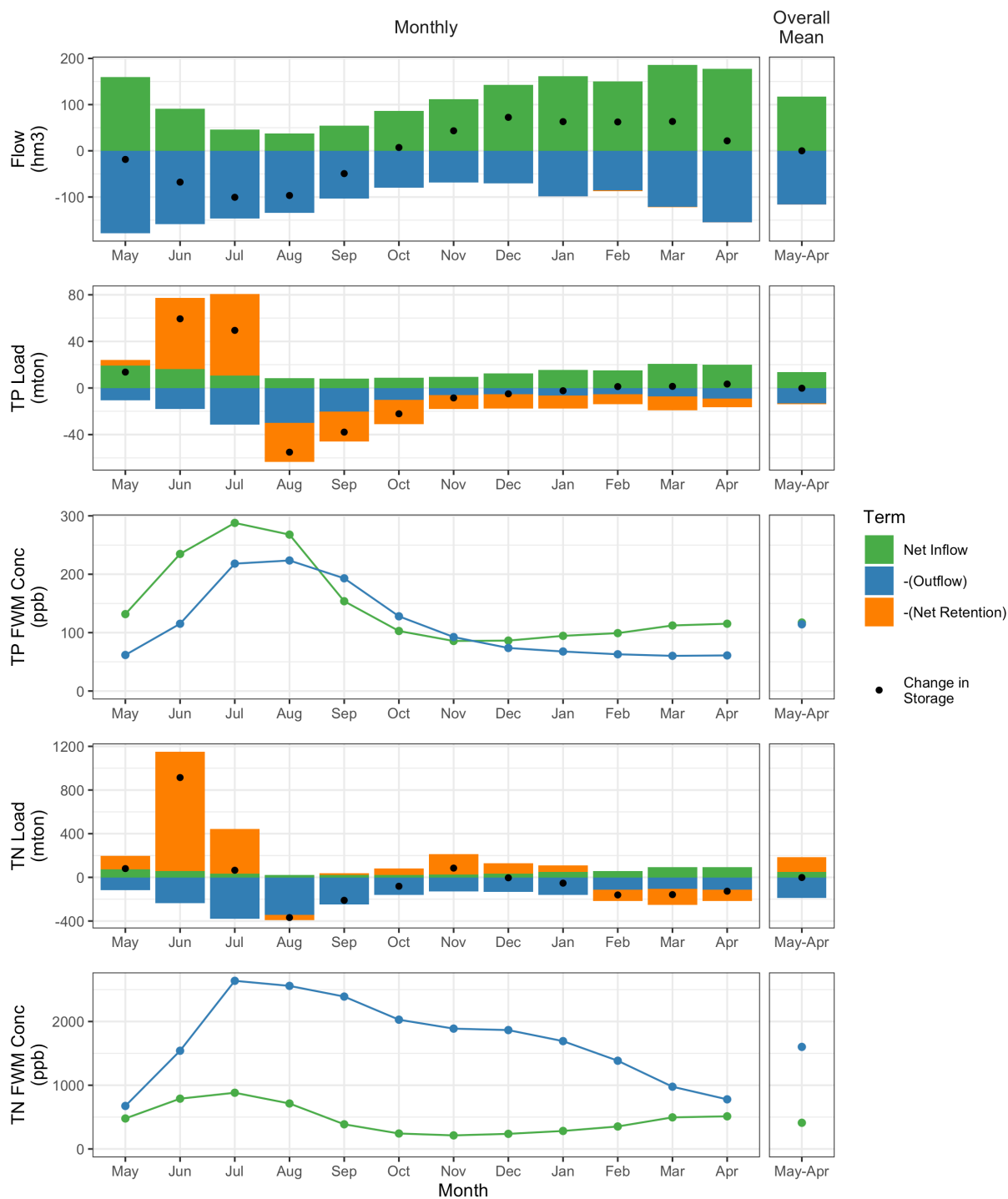


Figure ES2: Monthly and overall mean flows, nutrient loads, and FWM concentrations of the primary lake mass balance terms.

Flows and loads for net retention and outflow are shown using values with reversed sign (multiply by -1) so that positive values denote additions to the water column and negative values indicate losses from the water column. "Overall Mean" values represent average annual fluxes but were computed as the mean (not sum) of the 12 monthly values so that the y-axis scales would be similar (total annual flows/loads = 12 x overall mean flows/loads).

Although net inflow TP concentrations were also high during the early-summer growing season and thus may appear to drive the increase in outflow concentrations, the total net inflow TP loads were small relative to the net retention loads. Therefore, changes in outflow concentrations (as well as in-lake concentrations, which were highly correlated) were driven primarily by the large internal release of P into the water column. Net inflow volumes were also low during summer due to high evaporative water losses, which are accounted for in the net inflow term. However, because evaporation removes water but not mass, it also had a significant concentrating effect causing net inflow concentrations to be significantly higher (by nearly 200 ppb on average in July; see Figure 11, Section 3.1.3.1) than the actual concentrations from external watershed sources (e.g., tributary discharge).

Similar to TP, seasonal variation in the TN net retention loads was a major driver of month-to-month changes in in-lake N storage and outflow loads and concentrations. The majority of net internal N loading (primarily via N-fixation) occurred in June and, to a lesser extent, July, when cyanobacterial growth is typically highest (Figure ES-2). However, in contrast to TP, overall outflow TN loads and concentrations were higher than those for net inflows in all months due to the higher internal loads as well as lower rates of decline in TN concentrations following the growing season (TP outflow loads were only higher than inflow loads in July – September). Lastly, the net retention of TN indicated a net internal loading of N into the water column by varying amounts in late-fall and early-winter (September – January), although these loads were much lower than those during June and July.

In addition to the loads and concentrations of each nutrient, the N:P ratio of net inflows to UKL was consistently very low (< 5) indicating that inflows promote dominance by N-fixing cyanobacteria. During the growing season (May – September), in-lake and outflow TN concentrations increased at a greater rate relative to the net inflow TN concentration when compared to those for TP, causing a 2–5x increase in the in-lake and outflow TN:TP ratios. During the non-growing season (October – February), the TN:TP ratios of in-lake and outflow concentrations were 5–10x higher than for inflows. The increased N:P ratios as well as outflow N concentrations being approx. 5x higher than for inflows to UKL have important implications for downstream algal dynamics in the Klamath River.

Finally, monthly in-lake mean concentrations were highly correlated with outflow FWM concentrations for both TP and TN ($R^2 = 0.91$ and 0.92 , respectively). The similarity between in-lake and outflow concentrations provided a basis for using outflow concentrations as a surrogate for in-lake water quality when evaluating the inflow/outflow dynamics of P loading, retention, and recycling.

Inflow/Outflow Phosphorus Dynamics

An important management-related question regarding phosphorus dynamics within UKL is whether TP concentrations within the lake (as well as in the lake outflow) are driven primarily by 1) recent external inflow loads or 2) internal loads derived from long-term accumulation of P in the lake sediment (i.e., legacy P). Using the previous mass balances dataset (WY 1992–2010; Walker et al., 2012), Walker and Kann (2020) showed that correlations between the seasonal TP loads of net inflows, outflows, and net retention suggested short-term coupling between inflow and outflow loads due to rapid cycling of P between the water column and lake sediment. A simple linear regression model also provided evidence that annual outflow loads were driven primarily by recent inflow loads as opposed to large sediment storage of legacy P in UKL. And lastly, as mentioned above, the overall balance between long-term average annual inflow and outflow TP loads, which led to a relatively small amount of net retention, again suggests that loading to UKL was derived primarily from recent inflows as opposed to a large internal source of legacy P.

A comparison between the correlations derived over the previous period (WY 1992–2010) and those using the current period of record (WY 1992–2018) confirmed that inflow/outflow P loading dynamics during the last 8 years (WY 2011–2018) generally followed the same patterns as found in the original study (Walker and Kann, 2020). Based on the current mass balance dataset over the full period, the primary series of correlations that support these findings include (Figure ES3):

- a) **Winter (Nov – Apr) net retention TP loads** were positively correlated with **winter net inflow loads** ($r = 0.77$; Figure ES3a) meaning that during winter, the higher the inflow loads, the more net retention of those loads via sedimentation;
- b) **Summer (May – Oct) net retention loads** were negatively correlated with **winter net retention loads from the previous year** ($r = -0.70$; Figure ES3b) meaning the higher the winter net retention in one year, the more net release of P in the following summer;
- c) **Summer outflow loads** were negatively correlated to **summer net retention** ($r = -0.77$; Figure ES3c) indicating the higher the net release (negative net retention) of P, the higher the outflow loads; and
- d) **Summer outflow concentrations** were positively correlated to **summer outflow loads** ($r = 0.76$; Figure ES3d) indicating that the increase in outflow loads driven by rapid sediment cycling of inflow loads from the previous year (steps a – c) also impacts both outflow and in-lake concentrations, which are highly correlated (as mentioned above).

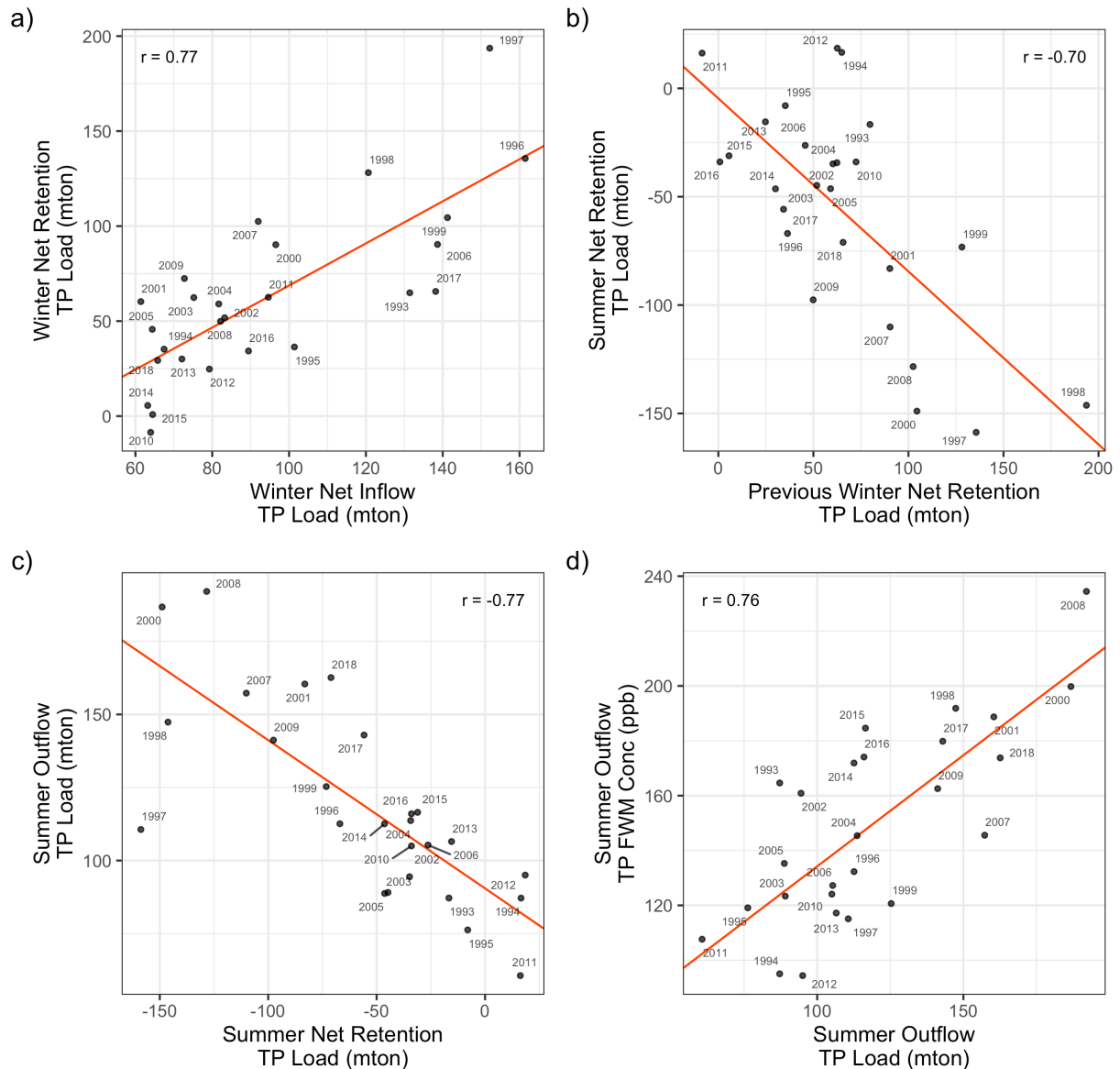


Figure ES3: Relationships between seasonal net inflows, net retention, outflow TP loads, and outflow TP concentrations.

Negative values for summer net retention (b, c) indicate a net release of P from the sediment to the water column. Points labeled using Phosphorus WY (May 1 – April 30; e.g., PWY 2010 = May 1, 2009 – April 30, 2010). Seasons defined as Summer = May – Oct, Winter = Nov – Apr.

These four correlations thus demonstrate the linkages between winter TP load, winter net retention, summer net release, and summer outflow load and concentration, providing evidence that outflow TP loads and concentrations were closely coupled to net inflow loads of the previous winter via seasonal net retention and release. In other words, outflow loads and concentrations appear to be driven primarily by recent inflow loads as opposed to large sediment storage of legacy P in UKL, in which case one would not expect a correlation between

summer net release and the inflow loads and net retention of the previous winter. Furthermore, given the high correlation between outflow and in-lake concentrations, these correlations also suggest that this rapid sediment cycling is a major driver of not only outflow, but also in-lake water quality.

Long-term Trends

Statistical trend tests revealed both increasing and decreasing long-term trends in the flows, nutrient loads, and FWM concentrations of various water and nutrient mass balance terms over the period of record (WY 1992–2018) (Figure ES4). Significant ($p < 0.05$) declining trends for flow, TP and TN load were detected for the Sevenmile Canal, Sprague River, total pumped inflows, and ungauged inflows. The decreasing trends observed for pumped inflows and loads were likely due to discontinued pumping and restoration of agricultural areas adjacent to UKL. Decreasing TP loads were also observed for the Williamson River, total external and net inflows, net retention, and anthropogenic sources. TN loads also showed declining trends for these same terms, in addition to a number of other inflow terms as well as lake outflow.

Significant increasing trends in flow occurred in the Wood River, Williamson River (excluding Sprague), and evaporation from the lake surface, which has important implications for lake management as discussed below. The only increasing trends in TP loads were in the Wood River above Weed Road (Wood@Weed) and at the outlet to Agency Lake (Wood@Dike). Overall, trends in TP loads generally mimicked those in flows, except for the Wood River sub-basin between Weed and Dike Roads (Wood@Dike – Wood@Weed) and the Williamson River basin excluding the Sprague (Williamson – Sprague), for which decreasing trends in TP concentrations offset the increasing trends in flow resulting in no trend in TP loads.

Significant decreasing trends in TP FWM concentrations were found for all terms except for the Sevenmile Canal, lake outflow, and lake mean storage, which had no significant trends, and Wood River above Weed Rd (Wood@Weed), which had a small, but significant, increasing trend. The largest declining trends were for the anthropogenic inflows, total pumped inflows due to restoration of former agricultural areas in Agency Lake Ranch (ALR) and the Williamson River Delta Preserve (WRDP), and for the Wood River basin below Weed Rd (Wood@Dike – Wood@Weed) likely due to restoration of the Wood River Ranch, which discharges directly to the Wood River above Dike Rd. The total estimated loads from all anthropogenic sources also showed a large significant decreasing trend. For TN FWM concentrations, there were significant decreasing trends in all terms except the lake outflow and lake mean storage, and a small, but significant, increasing trend for the total pumped inflows.

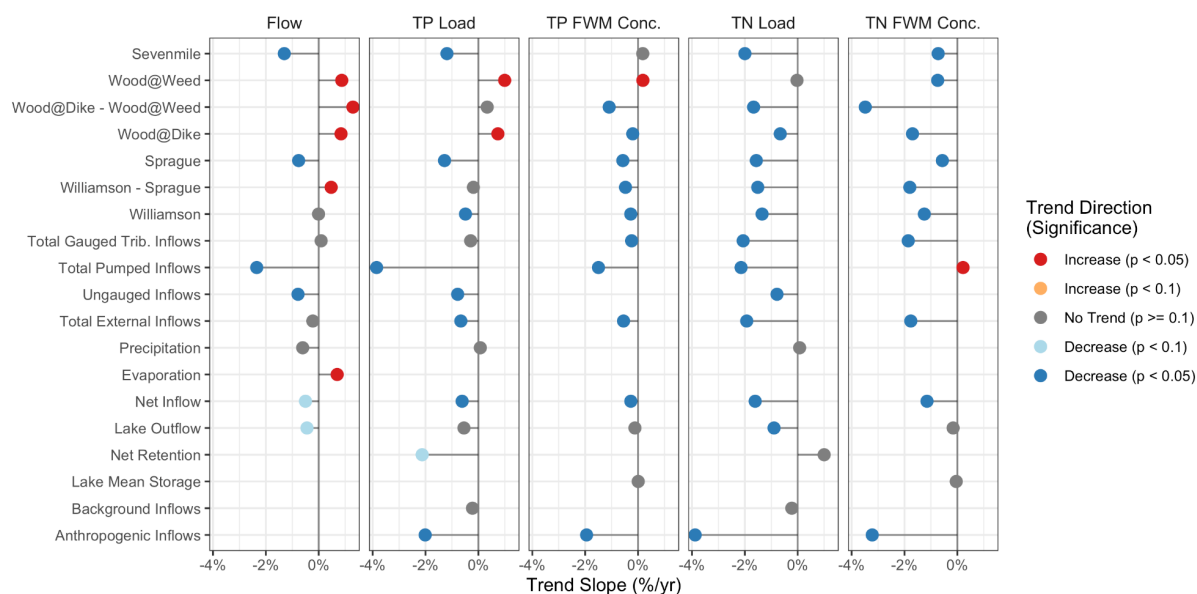


Figure ES4: Long-term trends in flows, nutrient loads, and FWM concentrations over the period of record, WY 1992–2018.

All tests computed using seasonal Kendall test with log10-transform values except for evaporation flows and net retention loads. For evaporation, the slope was estimated from Mann-Kendall test of untransformed annual values and divided by long-term mean annual evaporation to convert to relative slope (%/yr) due to the large number of zero values during winter, which affected the slope estimate of the seasonal Kendall test. For net retention, the slope was estimated from seasonal Kendall test of untransformed monthly values and the relative slope (%/yr) was computed by dividing slope in mton/yr by the long-term mean of total external inflow loads.

A sensitivity analysis of the trend test results using rolling periods (starting years varying from WY 1992 through WY 2009, and always ending in WY 2018) revealed that the significance levels (i.e., p-values) of the long-term trend results were sensitive to the first year in the period of record, WY 1992, which was also one of the driest years with the lowest total inflow volume. For example, when WY 1992 was excluded, decreasing trends in the flow volumes of total external inflows, net inflows, and lake outflow became more significant (p-values fell below 0.05). The rolling trend results also showed that many of the long-term decreasing trends in flows and TP loads were driven by the relatively wet conditions throughout the 1990s (except WYs 1992 and 1994). When the trend analysis was performed on data beginning in WY 2001 or later, the majority of these decreasing trends were no longer significant. These results suggest that many of these long-term trends over the period of record (especially without WY 1992) reflect the relatively high flows and wetter climate conditions that occurred in the 1990s as compared to later years. Notable exceptions to this were the decreasing trends in TP FWM concentrations for the Sprague River basin, total external inflows, and anthropogenic inflows, all of which were significant in all periods beginning in WY 2006 or earlier.

The significant increasing trend in evaporation may have important implications for meeting minimum UKL lake levels for ESA fish species, as well as for irrigation water supply and for meeting downstream Klamath River flow requirements for native fisheries. Moreover, increasing evaporation (likely due to the effects of climate change) may offset decreasing trends in total external inflow nutrient concentrations. As mentioned above, high evaporation rates can have a significant impact on water quality by effectively increasing the net inflow concentrations as well as in-lake concentrations by removing water volume but not nutrient mass. Therefore, despite decreasing trends in total external inflow nutrient concentrations and loads, there were no significant long-term trends in the FWM concentrations of net inflows (when WY 1992 is excluded), lake mean storage, or lake outflow likely due to the long-term increases in evaporation.

Progress Towards TMDL Targets

The TMDL study for UKL (ODEQ, 2002) specified a target TP load of 109 mton/yr with an associated FWM concentration of 66 ppb for the total inflows from all external sources (i.e., tributaries, groundwater seepage, pumped agricultural areas, etc.). Those targets were developed based on the hydrologic and climate conditions that occurred over the first 7 years of the period of record (WY 1992–1998). However, as mentioned above, the 1990s were a relatively wet period compared to more recent decades, with 7 of the 10 highest annual inflow years occurring before WY 2001. Therefore, the 109 mton/yr TMDL target is tied directly to the above-average flows that occurred during the TMDL study period (WY 1992–1998), making it difficult to evaluate progress towards the TMDL targets using loads alone because they reflect changes in both flow and concentration. However, unlike TP loads, annual FWM concentrations of external inflows are relatively independent of variations in precipitation and flow. Therefore, comparing the FWM TP concentration of total external inflows against the target 66 ppb provides a more reliable indicator of progress made towards achieve the goals of the TMDL as concentrations are not confounded by changes in climate and hydrology relative to the TMDL baseline period.

Over the entire period, the 10-year rolling FWM TP concentration of total external inflows fell by 7.5% from an average of 101 ppb over the first 10 years (WY 1992–2001) to 93 ppb over last 10 years (WY 2009–2018). Relative to the TMDL targets, these declines amount to a 23% reduction from 35 to 27 ppb above the 66 ppb target over those same periods. This decline is similar to the average decreasing trend rate found for the total external inflow FWM TP concentration ($-0.7\ \%/yr = -19\%$ over all 27 years).

The 10-year rolling FWM TP concentration also showed a steady decline from those first 10 years to the last 10. These changes indicated that external load reductions over the entire

period were not due solely to changes in the hydrologic conditions from the relatively wet years during the TMDL baseline period in the 1990s, but also reflect continuous declines in the FWM concentration over the following two decades. However, average concentrations for the last three 10-year periods (ending in WYs 2016–2018) were relatively constant (93 ppb) suggesting reductions may have levelled off more recently, though more data are needed to confirm. Overall, the 23% reduction from 35 to 27 ppb above the 66 ppb TMDL target (101 to 93 ppb total) of external inflow FWM TP concentrations indicates the cumulative benefits of restoration measures implemented over the period of record. However, further reductions of approx. 27 ppb in the 10-yr rolling FWM TP concentration of total external inflows are needed to achieve the TMDL target of 66 ppb.

Conclusions

A dataset representing the complete water and nutrient mass balances of UKL was generated for the current 27-year period of record (WY 1992–2018). The dataset provides monthly flows, nutrient (TP and TN) loads, and FWM concentrations of each mass balance term, and incorporates not only eight additional years of data since the previous UKL mass balance update, but also revisions to the data sources (most notably lake bathymetry), as well as other minor methodological changes. The current dataset is thus meant to supersede all previous versions for use in future data analysis and modeling studies⁵. Development of this dataset strongly depended on the long-term UKL tributary and lake monitoring programs, the intensity, consistency, and duration of which are unique relative to typical monitoring programs designed to support lake management decisions.

The updated mass balance dataset was used to evaluate the seasonal, annual, and long-term hydrologic and nutrient dynamics of UKL. These analyses indicated that over the long term, inflow TP loads were roughly balanced by outflow loads and that there was relatively little overall net retention or release of P from the lake sediment. However, on a seasonal basis, net sediment P fluxes were the primary driver of in-lake and outflow water quality, more so than inflows from the lake watershed. Further analyses indicated that outflow TP loads and concentrations, as well as in-lake water quality, were closely coupled to recent TP inflow loads through rapid cycling between the water column and sediment. Therefore, although seasonal changes in outflow and in-lake water quality were driven primarily by the net release of P from the sediment during the early summer growing season, that net release in turn was related to recent inflow loads.

⁵ The current water and mass balance dataset is available at: <https://doi.org/10.5281/zenodo.6476840>

These findings have important management implications as they suggest that watershed restoration efforts should have near-term benefits by reducing inflow TP concentrations and loads, which in turn should reduce the amount of P released during the summer growing season. However, the lack of trends in the in-lake and outflow TP concentrations also suggests that long-term decreases in TP concentrations from external watershed inflows may have been offset by rising evaporation rates, which can have a concentrating effect on inflow and in-lake water quality, effectively causing those concentrations to increase. Nevertheless, relative to the TMDL for UKL, the long-term declines in total external inflow TP concentrations have achieved 23% (or 8 ppb) of the reductions necessary to reach the target concentration of 66 ppb. However, the remaining 77% (or 27 ppb) of those reductions are still needed in order to achieve the TMDL goals for addressing water quality degradation caused by cyanobacteria blooms and the subsequent impacts on native endangered fish populations in UKL.

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ABBREVIATIONS

Abbreviation	Description
AgriMet	Pacific Northwest Cooperative Agricultural Weather Network
ALR	Agency Lake Ranch
FWM	Flow Weighted Mean (= Load / Flow Volume)
GMA	Graham Matthews & Associates
KBRT	Klamath Basin Range Trust
NCDC	National Climatic Data Center
ODEQ	Oregon Department of Environmental Quality
PET	Potential Evapotranspiration
ppb	Parts per Billion (ug/L)
PWY	Phosphorus Water Year (May 1 – April 30) e.g., PWY 2018 = May 1, 2017 – April 30, 2018
SRP	Soluble Reactive Phosphorus
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Phosphorus
UKL	Upper Klamath and Agency Lakes
USBLM	U.S. Bureau of Land Management
USBR	U.S. Bureau of Reclamation
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WY	Water Year (October 1 – September 30) e.g., WY 2018 = October 1, 2017 – September 30, 2018

UNITS

Multiply	By	To obtain
hm	100	m
hm	328.1	ft
km²	247.1	acres
km²	0.386	mi ²
hm³	10 ⁶	m ³
hm³	810.7	acre-ft
hm³	0.8107	kacre-ft
hm³/d	408.7	ft ³ /sec
mton	1,000	kg

1 Introduction

Upper Klamath and Agency Lakes (UKL) comprise a large, shallow, hypereutrophic lake system located in south-central Oregon (Figure 1) that is seasonally dominated by large blooms of the nitrogen-fixing cyanobacterium *Aphanizomenon flos-aquae* (Kann and Smith, 1999; Kann and Welch 2005; Nielsen et al., 2018). Based on exceedances of water quality standards for dissolved oxygen, pH, and chlorophyll-a (algal biomass), both lakes were designated as water quality limited for resident fish and aquatic life (ODEQ, 1998). Extended periods of hypoxia, elevated pH, and toxic levels of un-ionized ammonia directly associated with the growth and decline of the cyanobacterial blooms have been identified as important factors contributing to the decline of native endangered fish populations⁶ in UKL (Perkins et al., 2000; Rasmussen, 2011; USFWS, 2012; Kann and Walker, 2020). Hypoxia associated with bloom declines has been linked to large die-offs and redistribution of the endangered sucker species in UKL (Perkins et al., 2000; Kann and Welch, 2005; Banish et al., 2009).

1.1 Importance of Phosphorus

Given the need to support recovery of endangered fish in UKL by improving water quality, it is necessary to manage factors that can control algal biomass. Cyanobacterial blooms in UKL are tied to both external phosphorus (P) loading that is discharged directly into the lake from its watershed, as well as internal P loading, which is derived from external P loads that are retained and subsequently recycled from lake sediments during the summer algal growing season (ODEQ, 2002; Walker et al., 2012; Wherry and Wood, 2018). The seasonal release of sediment P in UKL appears to be driven more by recent P loading into the lake than by legacy P, which would be derived from accumulation of historical inflow loads in the lake sediment over long time periods (Walker and Kann, 2020; see Section 3.2 below).

Watershed land use alterations⁷ associated with increased erosion and loading of nutrients (particularly P) to UKL are generally contemporaneous with the increase in UKL's trophic state and shift to dominance by large blooms of cyanobacteria (Bradbury et al., 2004; Eilers et al., 2004). A Total Maximum Daily Load (TMDL) study found that 40% of the external P load to UKL was generated by anthropogenic activities during 1991–1998, and that reductions in those external loads would lead to lower in-lake P concentrations and improved water quality based

⁶ Federally Listed shortnose (*Chasmistes brevirostris*) and Lost River (*Deltistes luxatus*) suckers

⁷ Land use alterations include 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).

on model simulations (ODEQ, 2002; Walker, 2001). ODEQ's (2002) conclusion that reduction of P loads from anthropogenic sources would be an effective means of improving water quality conditions in the lake was supported by the elevated P concentrations and unit area P loads observed in discharges from pumped agricultural areas and tributary outflows, as compared with background levels observed in springs and tributary headwaters. In addition, pasture-level monitoring showed that first-flush irrigation events and storm events have the potential to export large quantities of P from irrigated grazing land in the UKL basin (Ciotti et al., 2010).

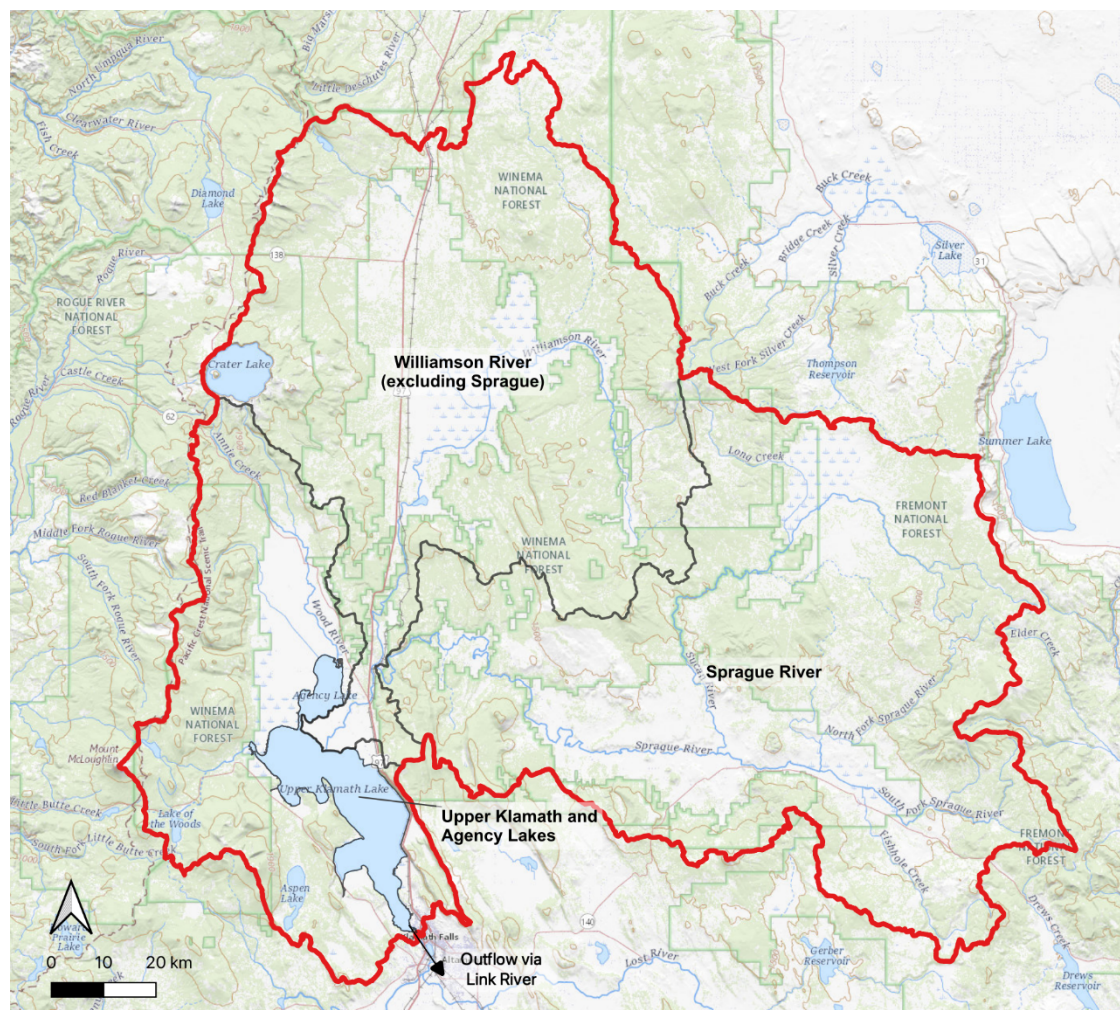


Figure 1: Map of Upper Klamath Lake watershed.

Lake extent does not reflect inundation of the Williamson River Delta Preserve in 2007-2008.

Although nitrogen (N) can also be important for algal bloom control, P reduction is especially important in systems such as UKL where low N:P ratios in the total nutrient supply favor bloom-forming cyanobacteria. In these types of systems, N-limitation can be overcome through fixation of atmospheric N by the cyanobacteria itself, which can generate enough N to support continued growth of biomass in proportion to phosphorus (e.g., Schindler et al., 2008).

Updates to the TMDL model by the U.S. Geological Survey (USGS) also predicted that reductions of external anthropogenic P loads would lead to decreases of in-lake P, chlorophyll-a, and pH levels (Wood et al., 2013; Wherry et al., 2015). Further modeling by USGS 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). Consistent with Wherry and Wood (2018), Walker and Kann (2020) provided evidence that external P loads may rapidly cycle through lake sediment and suggested that improved UKL water quality may occur over relatively short timescales if P loading to UKL can be reduced.

1.2 Previous Water and Nutrient Mass Balances

Given the importance of nutrients (especially P) in controlling the severe algal blooms and adverse water quality conditions in UKL, water and nutrient mass balances are needed to evaluate the effects of land and water uses on water quality and to develop effective control programs for reducing water quality impairments. External P sources include 1) runoff and irrigation-return water pumped from agricultural areas adjacent to the lake and tributaries, 2) fluvial inputs from streams draining from the lake sub-basins, 3) diffuse sources such as springs and marshes, and 4) atmospheric deposition. Lake and outflow P levels are driven by external P loads and cycling between the water column and bottom sediments. As noted above, while internal P loading from lake sediments in early summer is a major contributor to algal blooms, these loads appear to be related to recent external P loads, which are recycled between the sediments and water column over short time frames in UKL.

Kann and Walker (1999) developed initial water and nutrient balances over April 1991 – September 1998 using water quality and hydrologic data collected by various agencies, including the Klamath Tribes, U.S. Bureau of Reclamation (USBR), and USGS. These balances were used to develop a P mass-balance model simulating the linkage between external phosphorus load, internal P cycling processes, and spatially-averaged algal biomass and lake water quality (Walker, 2001). This model formed the basis for TMDL management targets for lake P concentrations and external P loads necessary to achieve lake water quality standards for algal biomass (expressed as chlorophyll-a) and pH (ODEQ, 2002). A subsequent review and modification of the TMDL model by USGS was also based on the Kann and Walker (1999) balances (Wood et al., 2013). Wood et al. (2013) concluded that predictions based on their modifications were qualitatively consistent with those of the original TMDL model (Walker,

2001) in simulating long-term reductions in P and chlorophyll a concentrations relative to current conditions.

In 2012, the UKL water and nutrient balances were updated with an additional 12 years of data (1999–2010) to evaluate watershed nutrient export and long-term trends in flows and nutrient loads and concentrations for each mass balance term over a 19-year period (water years⁸ (WY) 1992–2010) (Walker et al., 2012). The results of that study revealed long-term decreases in the total inflow nutrient concentrations and loads, but no significant trends in outflow loads or net retention. That study also found anthropogenic loads and concentrations of P and N had declined relative to those based on the TMDL period (WY 1992–1998) likely due to reduced agricultural pumping from adjacent farmland into UKL.

Two subsequent USGS studies also utilized the extended Walker et al. (2012) balances in their modeling efforts. Wherry et al. (2015) recalibrated the original TMDL model with the extended balances and concluded that the qualitative prediction of reduced concentrations in response to external load reductions was consistent across model versions and was a reliable feature of the equations that describe a coupled sediment and water column system. Additional model refinements and incorporation of net primary production were subsequently added, and the model was used to project equilibrium P concentrations in UKL over various load reduction scenarios (see above; Wherry and Wood, 2018).

Recently, Walker and Kann (2020) utilized the extended balance dataset in their evaluation of inflow, outflow, and net sediment retention/release dynamics in UKL. Based on a summary of annual and seasonal P fluxes, Walker and Kann (2020) found that higher external 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, as well as higher in-lake concentrations. In other words, relatively high inflow loads in one year appeared to drive higher outflow and in-lake concentrations the following year due to rapid cycling of P between the sediment and water column. As noted above, these findings have important implications for the implementation of watershed P reduction strategies and underscore the need to rapidly implement full-scale watershed restoration strategies to improve water quality conditions for suckers and other sensitive fish species⁹ in UKL.

⁸ A water year is defined as the 12-month period from October 1 to September 30. For example, WY 2018 is the period October 1, 2017 – September 30, 2018.

⁹ In addition to endangered suckers, water quality in UKL also impacts other culturally and biologically important fish species such as redband rainbow trout. With pending removal of downstream dams, adequate water quality will be required to support Chinook salmon migration through the lake (ODFW & Klamath Tribes, 2021).

1.3 Goals and Objectives

Since the previous UKL water and nutrient mass balances study (Walker et al., 2012), the Klamath Tribes and others continued to collect hydrologic and water quality data on UKL and its tributaries, providing an additional 8 years of available data (WY 2011–2018)¹⁰. During these recent years, there have been various watershed restoration efforts to reduce nutrient loads, as well as hydrologic changes related to both climate and enforcement of the Klamath Tribes' water rights. Water and nutrient mass balance datasets provide a quantitative basis for evaluating the impacts of these changes and activities, for identifying any potential long-term hydrologic and water quality trends, and for providing the necessary inputs to support development and refinement of lake P models and other data analyses.

The primary goal for this study was therefore to update and extend the water and nutrient mass balances of UKL over the 27-year period of record (WY 1992–2018), and to evaluate the long-term and seasonal dynamics and trends in the lake hydrology and water quality. Specific objectives of this study include:

1. Compile all relevant meteorological, hydrologic, and water quality datasets (e.g., nutrient concentrations, flows, water levels, precipitation, evaporation) for tributaries, agricultural areas, in-lake storage, and lake outflow.
2. For each lake mass balance component (i.e., inflows, outflow, storage, and net retention), develop monthly and annual time series of flows, loads, and flow-weighted mean (FWM) concentrations for total phosphorus (TP) and total nitrogen (TN).
3. Update the previous hydrologic and nutrient balances for UKL using the above generated timeseries data and summarize the average flows, loads, and concentrations of each term at monthly, seasonal, annual, and multi-year intervals.
4. Provide tabular and graphical analyses of inter-annual and seasonal variations in TP and TN loading for inflow and outflow terms, and for storage and net retention of nutrients in the lake.

¹⁰ The USBR discontinued funding for the Klamath Tribes' long-term monitoring program beginning in 2019. Although the USGS was funded to provide limited monitoring of UKL and its tributaries, these efforts did not target the same sampling locations as the Klamath Tribes' program, and in some cases utilized different methodologies. Potential integration of the Klamath Tribes' and USGS datasets would necessitate a comprehensive evaluation, which is beyond the scope of this study.

5. Summarize seasonal and annual variations in concentrations of nutrient species (TP, Soluble Reactive Phosphorus (SRP), TN, Inorganic N¹¹) at major tributary monitoring stations.
6. Perform trend analyses using both non-parametric (seasonal Kendall and Mann-Kendall tests) and parametric (linear regression) statistical tests to evaluate long-term changes in the flows, nutrient loads, and FWM concentrations associated with each component of the lake mass balance.
7. Differentiate between background and anthropogenic nutrient sources based upon spatial variations in unit area export (load per unit drainage area) and FWM concentration across watershed inflow sources.
8. Evaluate short-term, seasonal dynamics between inflow and outflow TP loads over the new period of record, WY 1992–2018. This evaluation provides an update to Walker and Kann (2020), which, as described above, presented evidence that internal P cycling between the lake water column and sediment occurs relatively rapidly based on seasonal correlations between inflow TP loads, net retention, and outflow loads over the previous period of record, WY 1992–2010.

2 Methodology and Data Sources

2.1 Water and Nutrient Mass Balances

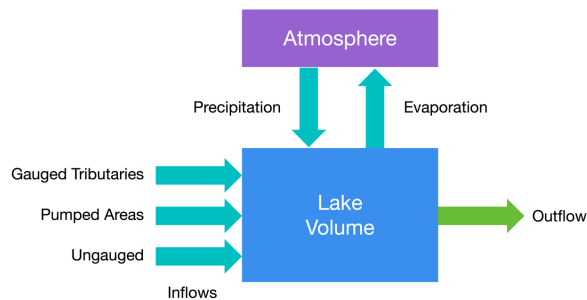
The overall water balance of the lake (Figure 2a) is represented by the following equation:

$$\Delta \text{ Lake Volume} = \text{Precipitation} + \text{Gauged Tributary Inflows} + \text{Pumped Inflows} + \text{Ungauged Inflows} - \text{Evaporation} - \text{Outflow} - \text{Net Retention}$$

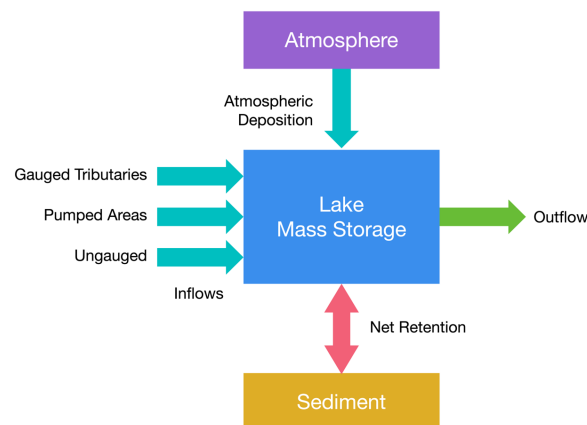
Except for ungauged inflows and net retention, each term was either directly measured or independently estimated as described in the following sections. Gauged tributary inflows include the Wood River, Sevenmile Canal, and Williamson River. Pumped inflows from agricultural areas and restored wetlands adjacent to the lake were estimated using a limited amount of flow and concentration data. Ungauged inflows, which include groundwater seepage, springs, and runoff from local ungauged watersheds, were computed by difference and constrained to non-negative values. The net retention term in the water balance represents the overall error in the water budget due to constraining the computed ungauged inflows to non-negative values.

¹¹ Inorganic N is the sum of NH₄-N (ammonia) and NO₂+NO₃-N (nitrite + nitrate)

a. Water Balance



b. Total Phosphorus Mass Balance



c. Total Nitrogen Mass Balance

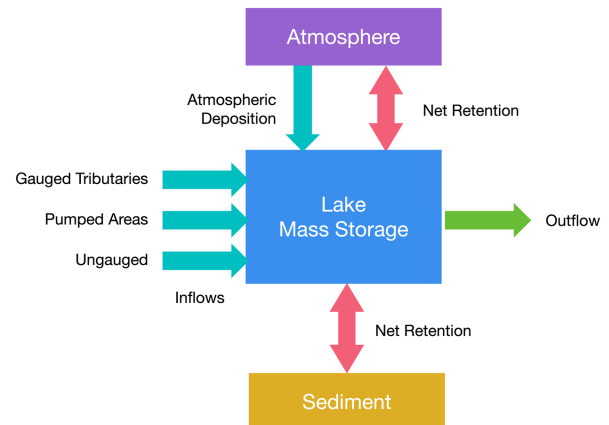


Figure 2: Schematic diagrams of water and nutrient mass balances.

For phosphorus, net retention is the net exchange between the water column and sediment associated with sedimentation and recycling. For nitrogen, net retention includes exchanges between the water column and both the sediment (e.g., sedimentation) and the atmosphere (e.g., nitrogen fixation) independent of atmospheric deposition. For both parameters, positive values of net retention denote an overall net flux from water to sediment (and atmosphere for N) (i.e., a net loss from lake mass storage).

The nutrient (TP and TN) mass balances of the lake (Figure 2b,c) are represented by the following equation:

$$\Delta \text{ Lake Storage} = \text{Atmospheric Deposition} + \text{Gauged Tributary Loads} + \text{Pumped Loads} + \text{Ungaaged Loads} - \text{Outflow Load} - \text{Net Retention}$$

For the nutrient balances, each term was generated based on direct measurements or independent estimates except for net retention, which was calculated by difference. Net retention captures the net nutrient losses from the lake water column in addition to the cumulative effects of errors in the other directly measured or estimated loading terms. For TP, net retention represents the exchange of P between the sediment and water column; positive values denote a net settling of P from the water column to the sediment, and negative values denote a net release (i.e., recycling) from the sediment back into the water column. For TN, net

retention represents the exchange of N between the water column and both the sediment and atmosphere. TN exchange with the sediment is primarily driven by settling and resuspension of organic matter, while exchange with the atmosphere is driven by nitrogen fixation and, to a lesser extent, denitrification.

The overall lake mass balances for flow, TP, and TN can be represented by four aggregated terms: net inflow, outflow, increase in storage, and net retention. Together, these four terms provide a complete accounting of the water and nutrient balances according to the equation:

$$\text{Storage Increase} = \text{Net Inflow} - \text{Outflow} - \text{Net Retention}$$

where the net inflow term is defined as the net increase due to external inflows and exchange with the atmosphere:

$$\text{Net Inflow} = \text{Total External Inflow} + \text{Precipitation} - \text{Evaporation}$$

and the total external inflow is the sum of inflows from the pumped areas, gauged tributaries and ungauged areas:

$$\text{Total External Inflow} = \text{Total Pumped Inflow} + \text{Gauged Tributaries} + \text{Ungauged Inflow}$$

A list of the equations used to compute water and mass balance terms that were derived from the directly measured or estimated terms is provided in Table D1 (Appendix D). The data sources used to generate each water and nutrient balance term are summarized in Table 1 and described in more detail in the following sections. All analyses and computations were performed using the R statistical programming language v4.1 (R Core Team, 2021) with the *Tidyverse* suite of packages (Wickham et al., 2019).

Table 1: Data sources

Term	Water Years		Source
	Start	End	
Lake Storage and Outflow			
Lake Elevation	1992	2018	USGS Station 11507001 (USGS, 2022)
Lake Volume & Area	1992	2018	USBIA (2019) Bathymetry for Agency Lake, UKL, Tulana, Goose Bay
	2006	2007	USBR Net Inflow Spreadsheet for Caledonia Bathymetry (USBR, 2019) ¹²
Link River Outflow	1992	2018	USGS Station 11507500 (USGS, 2022)
A Canal Outflow	1992	2018	Hydromet Station ACHO (USBR, 2022b) with linear adjustment beginning April 2003 (Dunsmoor, 2017)
Keno Canal Outflow	1992	2018	USBR Net Inflow Spreadsheet (USBR, 2019)
Lake Water Quality	1992	2018	Klamath Tribes (Kann, 2019a and earlier reports)
Link River Water Quality	1992	2018	Klamath Tribes (Kann, 2019a and earlier reports)
	2007	2010	USBR/PacifiCorp Stations KRLR, KLLD (PacifiCorp, 2022; Watercourse Engineering, 2019)
Precipitation & Evaporation			
Evaporation	1992	2003	Oregon State University, Klamath Lake Experiment Station (Kann and Walker, 1999)
	2004	2018	AgriMet Station KFLO (USBR, 2022a)
Precipitation	1992	2018	GHCND Stations USW00094236, USC00354506, USC00354501, USC00351574 (Menne et al., 2012)
	1992	2018	GSOD Stations 72589594236, 72589599999 (NCEI, 2022)
	2000	2018	AgriMet Stations KFLO, AGKO (USBR, 2022a)
Tributaries			
Flow - Williamson River	1992	2018	USGS Station 11502500 (USGS, 2022)
Flow - Sprague River	1992	2018	USGS Station 11501000 (USGS, 2022)
Flow - Wood River, Sevenmile Canal	1992	1996	USBR (Campbell et al., 1993)
	1992	2011	KBRT (GMA 2011a, 2011b, and earlier reports)
	1992	2018	Klamath Tribes (Kann, 2019b and earlier report)
	2013	2018	USGS Stations 11504115 and 11504290 (USGS, 2022)
Water Quality - Williamson River, Sprague River, Wood River, Sevenmile Canal	1992	2018	Klamath Tribes (Kann, 2019b and earlier report)
Water Quality - Ungauged Areas	1992	2018	Walker et al. (2012)
Agricultural and Wetland Restoration Projects			
Agency Lake Ranch	2000	2018	USBR Pumping Records (pers. comm.)
	1992	1995	USGS (Snyder and Morace, 1997)
Other Pumped Areas	1992	2018	Klamath Tribes (pers. comm.), Walker et al. (2012)
	1992	1995	USGS (Snyder and Morace, 1997)

¹² Excel Spreadsheet Created by USBR and provided by Adam Johnson, Deputy Field Supervisor, U.S. Fish and Wildlife Service, Klamath Falls, OR. January, 23, 2020.

2.2 Lake Volume and Storage

The total lake volume and surface area were generated from daily lake surface elevation¹³ measurements at USGS station 11507001 (USGS, 2022). Lake volumes and areas were computed using elevation-area-capacity curves generated from an updated bathymetric model of the lake (USBIA, 2019).

Previous versions of the UKL water and nutrient balances (Kann and Walker, 1999; Walker et al., 2012) used a bathymetric model of the lake developed by USBR in 1996. However, the USBR later determined that their 1996 bathymetric model was inaccurate and underestimated the actual depths of the lake. In 2019, a new bathymetric model of the lake was developed (USBIA, 2019). A comparison of elevation-area-volume curves generated from these two bathymetric models shows that the mean depth of UKL (including Agency Lake) is approximately 2 ft deeper based on the updated bathymetry (Figure 3). The elevation-area curves also show that the lake surface area remains relatively constant over the full range of historical lake elevations (4,137 – 4,143 ft), whereas the original bathymetry indicated a decrease in surface area at lower elevations.

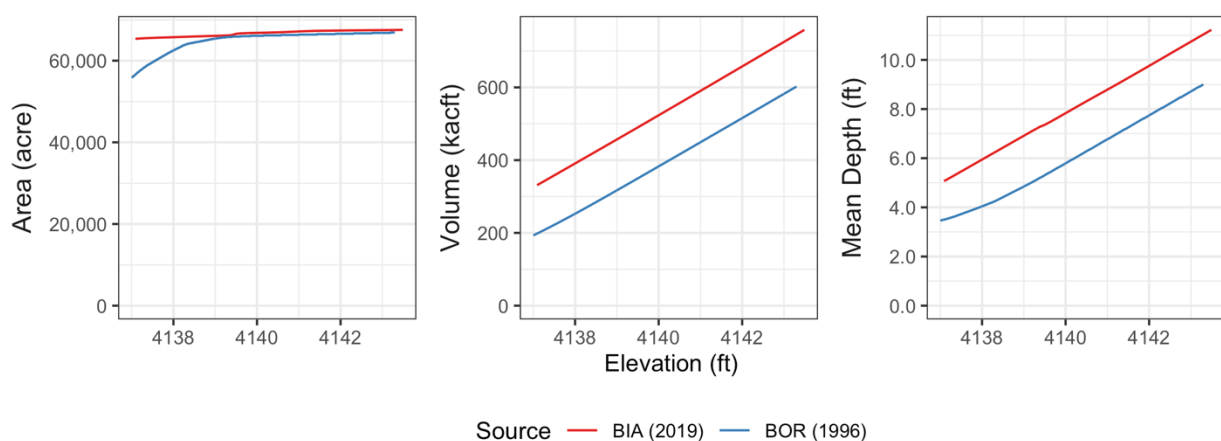


Figure 3: Comparison of the area, volume, and mean depth curves for UKL and Agency Lake.
Excludes areas inundated after dike breaching in order to compare to the previously utilized 1996 bathymetry.

¹³ All lake surface elevations are reported relative to the U.S. Bureau of Reclamation Klamath Basin (USBRKT) vertical datum.

The elevation-area-volume curves for the lake were adjusted over time to account for inundation of the Williamson River Delta Preserve in 2007 and 2008, which increased the lake surface area by approximately 5,500 acres¹⁴. The surface area and volume for the Caledonia marsh/farm was also included for July 8, 2006 through September 30, 2007¹⁵ based on the elevation-area-capacity curve used in the USBR net inflow analysis (USBR, 2019). Section 2.6 below provides more details about these inundated areas.

Total nutrient mass storage in the lake was computed based on biweekly water quality sampling data collected at ten in-lake stations primarily by the Klamath Tribes (Kann, 2019a; Figure 4). Daily lake-wide average concentrations of TP and TN were estimated by first spatially aggregating the in-lake water quality sampling data, and then linearly interpolating between each biweekly event. Because nutrient concentrations tend to vary between Agency Lake and UKL, the sampling data were first spatially aggregated for the two lakes separately by computing the geometric mean of the stations within each lake (2 stations in Agency Lake, 8 in UKL; Figure 4). For each sampling event, the geometric means of the two lakes were then combined into a single lake-wide average concentration using the area-weighted mean based on areas for Agency Lake and UKL of 35.6 km² and 235.4 km², respectively. Finally, the lake-wide average concentrations were linearly interpolated between the approximately biweekly sampling events to generate a continuous timeseries of daily lake-wide TP and TN concentrations. These concentrations were multiplied by the daily lake volume to generate a daily timeseries of nutrient mass storage within the lake. Monthly changes in water and nutrient storage were computed from the interpolated daily values at the end of each month.

¹⁴ Elevation-area-capacity curves for the inundated areas (Tulana Farms and Goose Bay) were developed from USBIA (2019) bathymetry.

¹⁵ The Caledonia farm area was temporarily inundated in 2006 due to a break in the surrounding levee (Lindenberg and Wood, 2009).

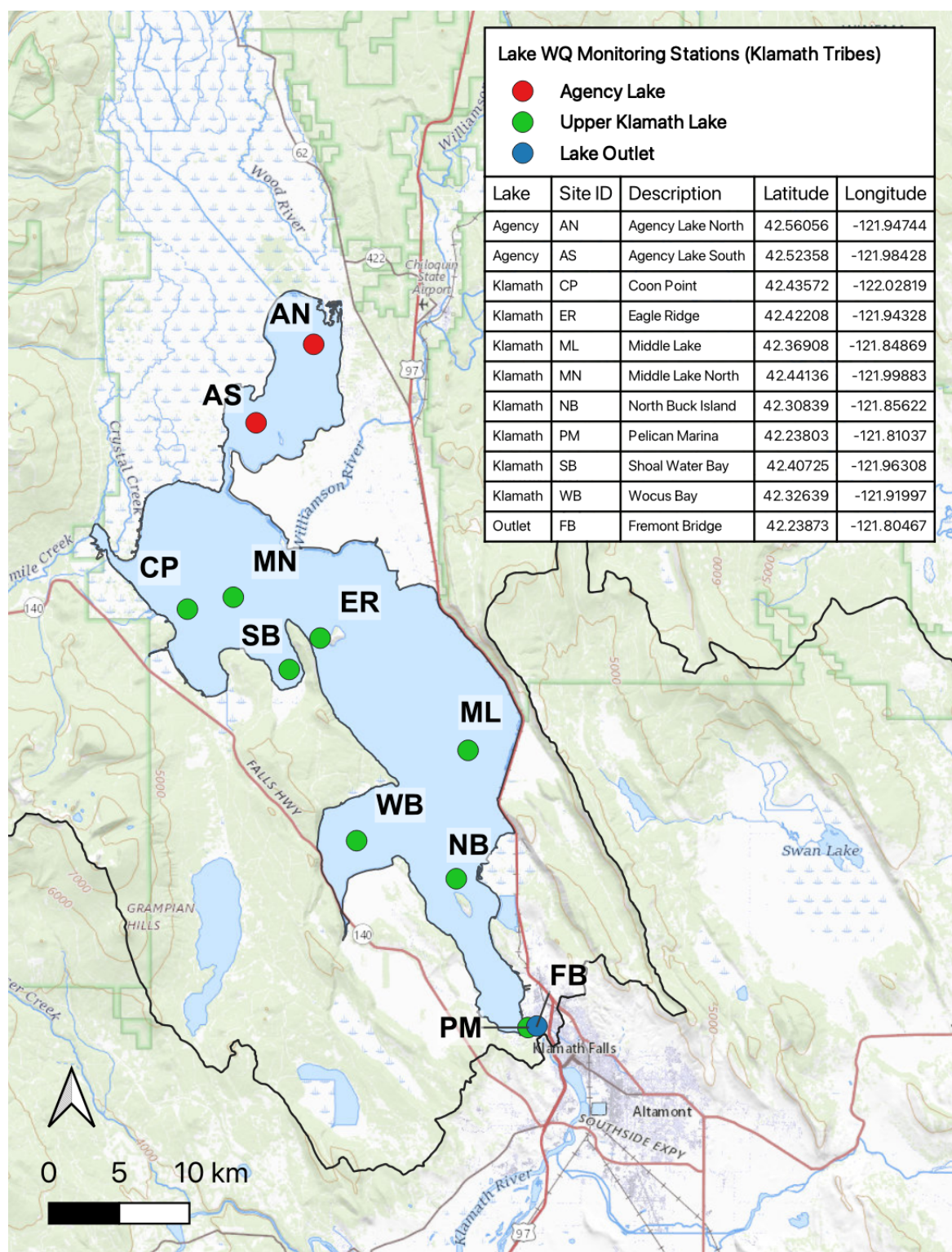


Figure 4: Map of Klamath Tribes in-lake and outlet water quality monitoring stations.

2.3 Lake Outflow

Daily lake outflow volumes were computed as the sum of flows from UKL to the A Canal, Link River, and West Side Canal. Continuous daily flow measurements for A Canal were obtained from USBR HydroMet Station ACHO (USBR, 2022b). Beginning on April 1, 2003, the reported A Canal flows were increased by 4.41% based on an recommendations from Dunsmoor (2017). Flow measurements for Link River below the outlet of the lake were obtained from USGS NWIS Station 11507500 (USGS, 2022). The Link River flows were augmented to include West Side Canal (a.k.a. Keno Canal) flows as described by Risley et al. (2006) and using data obtained from the USBR net inflow analysis (USBR, 2019).

Outflow loads were computed from the total outflow volumes and nutrient concentrations measured by the Klamath Tribes at the Fremont Bridge (FB) or at the southernmost lake site (PM) when data at FB were not available (Kann, 2019a; Figure 4). Water quality data at the lake outlet stations were also supplemented with winter (November – April) sampling data from USBR and PacifiCorp¹⁶ during 2007–2010 and USGS¹⁷. Continuous daily concentrations and loads were estimated from the daily flows and biweekly sampling data using a regression/interpolation algorithm, which was also used to estimate loads from the gauged tributaries (see Section 2.5 and Figure C3 in Appendix C).

2.4 Precipitation, Evaporation, and Atmospheric Deposition

Daily precipitation to the lake was based on records from the National Centers for Environmental Information (NCEI) and the Pacific Northwest Cooperative Agricultural Weather Network (AgriMet) (Menne et al., 2012; NCEI, 2022; USBR, 2022a). Because of the large spatial gradient in precipitation across the Klamath basin (Walker et al., 2012), direct precipitation to the lake surface was estimated by averaging records from stations located both north and south of UKL. Appendix A provides more details on the stations and datasets used to generate the continuous precipitation timeseries.

The primary northern station (GHCND Station USC00351574; Menne et al., 2012), located in Chiloquin, OR near Agency Lake, was active over the entire period (WY 1992–2018). Missing values were estimated by linear regression using total monthly precipitation measured at the AgriMet station at Agency Lake (Station AGKO; USBR, 2022a) and at the GHCND station at Klamath Falls (Station USC00354506; Menne et al., 2012).

¹⁶ Station KR254444 - Link Dam (PacifiCorp, 2022; Watercourse Engineering, 2019)

¹⁷ USGS Stations 421420121481700 (Fremont Bridge) and 421401121480900 (Link River Dam) (USGS, 2022)

For the southern region, there were two primary stations both located in Klamath Falls, OR. The first primary southern station was located about 4 miles northwest of Klamath Falls Airport (GHCND Station USC00354506; Menne et al., 2012) and was active over the period WY 1992–2001. The second primary station was located at Klamath Falls International Airport (GHCND Station 94236; Menne et al., 2012) and was active over WY 1998–2018. Missing values were filled using linear regressions based on monthly precipitation at the AgriMet station at Klamath Falls (Station KFLO; USBR, 2022a) and the Global Summary of the Day (GSOD) dataset for Klamath Falls (Station 725895; NCEI, 2022).

Evaporation from the lake surface was estimated using two data sources. For the first 12 years (WY 1992–2003), we used daily measurements of class A pan evaporation from the Oregon State University (OSU) Experiment Station near Klamath Falls, which is the same data source used in the previous water and nutrient balances (Kann and Walker, 1999; Walker et al., 2012). The measured pan evaporation rates were converted to open-water evaporation using a pan coefficient of 0.7. Because this dataset only extended through 2003, evaporation for the remaining years (WY 2004–2018) was estimated from potential evapotranspiration (PET) measurements at the AgriMet station in Klamath Falls (Station KFLO; USBR, 2022a). The AgriMet PET data were converted to open-water evaporation estimates using a linear regression model based on the monthly OSU open-water evaporation during the period of overlap between the two datasets (WY 1999–2003). See Appendix A for details on the evaporation datasets. Evaporation rates were set to zero during winter months (December – February).

Atmospheric deposition of TP was computed assuming an average total areal deposition rate of 33 kg P/km²-yr based on measurements from Lake Tahoe in California (approx. 400 km from UKL) over WY 1989–1991 (Jassby et al., 1994). This total deposition rate is similar to the median rate (32 kg P/km²-yr) observed in North America based on 38 studies, most of which were located in the midwest and northeast U.S. (Tipping et al., 2014). In the previous mass balance study, Walker et al. (2012) used a lower total deposition rate of 18 kg P/km²-yr based on the National Eutrophication Study (NES) (USEPA, 1975). However, the NEST report describes this value as “likely conservative”; it was also not based on any direct measurements, but rather was an estimate of the average flux nationwide. Therefore, the current assumed total deposition rate (33 kg P/km²-yr) was considered more representative for UKL as it was based on measurements from a near-by lake and also based on more recent data than the NES study from the 1970s.

Atmospheric deposition of TN was based on an estimated total deposition rate of 228 kg N/km²-yr obtained from a global dataset of precipitation chemistry and deposition (Vet et al., 2020). This dataset was generated using physical measurements averaged over 2000–2002

coupled with global model simulations (Vet et al., 2014). In the previous mass balance study, Walker et al. (2012) reported using a total deposition rate of 108 kg N/km²-yr based on the NES (USEPA, 1975). However, the original NES publication reported a value of 1,080 kg N/km²-yr (an order of magnitude higher than what was previously used) suggesting there may have been an error or other unreported assumption in the previous analysis. Regardless, the current total N deposition rate of 228 kg N/km²-yr was considered more accurate and representative than the NES study as it is based on more recent data.

For both P and N, we assumed that half of the total atmospheric deposition occurred as dry deposition (constant loading rates) and the other half as wet deposition (concentration of precipitation) when averaged over the entire WY 1992–2018 period. The assumed wet deposition rates (16.5 and 114 kg/km²-yr for P and N, respectively, which are half of the assumed total deposition rates) were divided by the long-term mean annual precipitation rate (16.6 in/yr) to yield estimate precipitation concentrations of 39 and 270 ppb, respectively. Monthly wet deposition rates were computed from monthly precipitation rates multiplied by these constant concentrations, and then added to the constant dry deposition rates (16.5 and 114 kg/km²-yr for P and N, respectively) to compute total atmospheric deposition for each month. Note that throughout this report, any nutrient loads labelled as “precipitation” include both dry and wet atmospheric deposition.

2.5 Gauged Tributary Inflows

Daily inflow volumes and nutrient loads to UKL were computed for three gauged tributaries:

$$\text{Total Gauged Tributary Inflows} = \text{Williamson River} + \text{Wood River} + \text{Sevenmile Canal}$$

Figure 5 shows the gauged and ungauged watersheds and locations of the Klamath Tribes water quality monitoring sites (Kann, 2019b).

Inflows from the Williamson River were partitioned into two sub-watersheds including the Sprague River basin and the Williamson River basin excluding the Sprague (denoted as Williamson – Sprague). Continuous daily flows for both the Williamson and Sprague Rivers were obtained from USGS Stations 11502500 and 11501000, respectively (USGS, 2022). Net daily flows for the portion of the Williamson River basin excluding the Sprague River basin (Williamson – Sprague) were computed by difference using the total flows over each river and constrained to non-negative values.

Similar to the Williamson River, inflows from the Wood River were partitioned into two sub-watersheds above and below the streamflow gauge at Weed Road (Figure 5). Net inflows and loads from the downstream segment between Weed Road and Dike Road (referred to as

Wood@Dike – Wood@Weed, or Wood River below Weed Rd.) were computed based on the difference between the two gauges. Results for this sub-watershed reflect the net impacts of inflows from the adjacent pumped areas and withdrawals for irrigation or wetland restoration (Agency Lake Ranch and Wood River Ranch), as well as discharges from the Crooked Creek watershed.

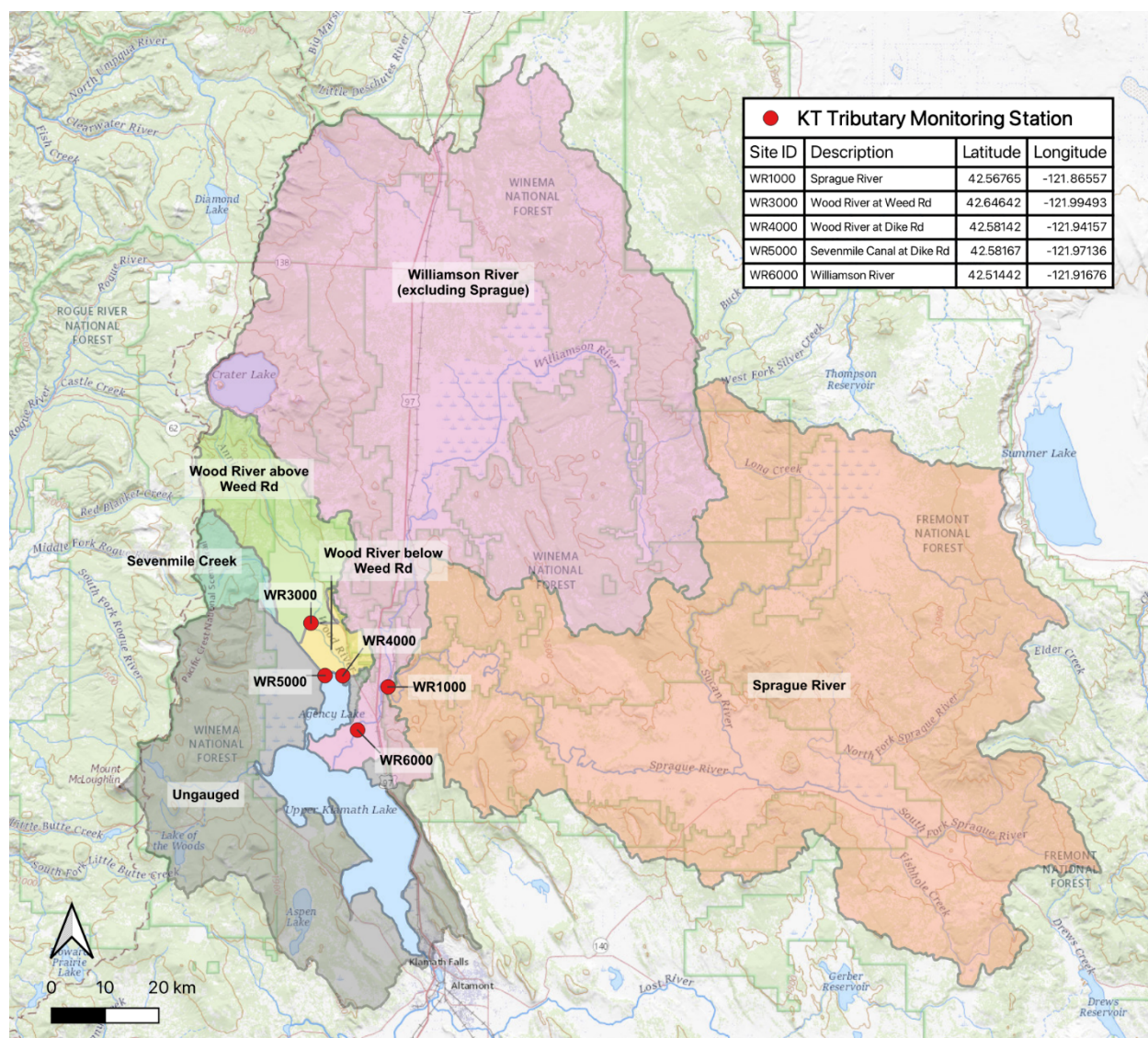


Figure 5: Map of tributary basins and Klamath Tribes monitoring stations

Daily flows for the two Wood River (at Weed and Dike Roads) and single Sevenmile Canal (at Dike Road) stations were estimated using a combination of discrete and continuous data sources over various periods obtained from Klamath Tribes, KBRT, USBR, and USGS (Campbell et al., 1993; GMA 2011a, 2011b; Kann, 2019b; USGS, 2022). Figure C2 (Appendix C) provides more details on the methods and datasets used to generate continuous flows at each of these stations. Missing flows were estimated using a linear regression/interpolation algorithm similar

to that used to estimate continuous daily concentrations (see below and Figure C3 in Appendix C). Linear regression models were used to adjust estimated flows between biweekly observed flows, and to reflect daily variations between those measurements (e.g., to reflect increases in flow during storm events that occurred between biweekly sampling events). The resulting daily flow estimates are similar to those based upon simple linear interpolation in periods without major data gaps, especially when averaged on a monthly or annual basis.

Daily nutrient loads from gauged tributaries as well as the lake outflow were computed using the measured or estimated daily flows and biweekly sampling concentrations obtained primarily by the Klamath Tribes. A combined regression/interpolation algorithm was used to estimate concentrations and loads between sampling events. This algorithm is similar to that described by Walker and Havens (2003) and Goolsby et al. (1999), and was used by Asarian et al. (2009, 2010) to construct nutrient balances for reservoirs in the Lower Klamath basin, and by Walker et al. (2015) to evaluate nutrient loading for sub-basins within the Sprague River watershed.

For each nutrient and station, the regression/interpolation algorithm uses paired flow and concentration data to calibrate a multiple linear regression model to predict concentration as a function of season (Julian day), flow, flow derivative (increasing or decreasing), and year (reflecting long-term trend). The algorithm uses the measured concentrations on days when a sample was collected. The measured concentrations are then interpolated between sampling events using a linear interpolation of the regression model residuals (ratio of observed to predicted). This process effectively scales the continuous regression model predictions so that they pass through the measured concentration on each sampling date. See Figure C3 (Appendix C) for more details and an example application of this algorithm.

The regression/interpolation algorithm is similar to a simple linear interpolation of sampled concentrations, but is able to better incorporate short-term, flow-driven variations in concentrations due to, for example, storm events that may occur between samples. At monthly and annual timesteps, the estimated loads generated from this method were comparable those estimated using linear interpolation (Figure C5, Appendix C). Some larger differences between the two methods occurred primarily in earlier years during periods of infrequent sampling.

The estimated tributary and outflow loads in more recent years (e.g., WY 2008–2018) are likely to be more accurate than those estimated for previous years (e.g., Walker et al., 2012) for a few reasons:

- The frequency of winter (November – March) samples at the outflow station was higher in the latter years. The increase in winter sampling frequency improves the precision of

not only the computed annual outflow loads, but also the estimated net retention of the lake, which is computed in part from the outflow loads, as well as the assessment of trends in these mass-balance terms. However, the precision of estimated summer (e.g., May – September) loads for these terms are not affected by the change in winter sampling frequency.

- Sampling frequencies were lower for the major tributaries during a portion of the period (WY 1997–2003) when the number of samples per water year at each station typically ranged from 8 to 20 (compared with the biweekly design of 26 samples per water year).
- Continuous streamflow gauges were installed by USGS at the outlets of the Wood River and Sevenmile Canal beginning in WY 2013 and WY 2017, respectively.

2.6 Pumped Inflows

Pumped inflows were partitioned into three components:

$$\text{Pumped Inflows} = \text{Agency Lake Ranch (ALR)} + \text{Williamson River Delta Preserve (WRDP)} + \text{Ungauged Pumped Areas}$$

The pumped inflows term only includes areas that are adjacent to UKL and pumped directly into the lake; other pumped agricultural areas (e.g., Wood River Ranch) that discharged to tributaries before entering the lake were not included as their loads would be incorporated in the gauged tributary inflow terms. Figure C1 (Appendix C) provides a map showing the extent of each pumped area. Limited data were available for estimating discharge volumes and nutrient loads pumped into UKL from adjacent agricultural areas, portions of which were converted to water storage projects (e.g., Agency Lake Ranch) or restored wetlands (e.g., Williamson River Delta Preserve). Due to this limited data availability, the pumped inflows represent a major source of uncertainty in the overall nutrient balances of UKL.

Daily pumped discharge volumes of each term were estimated using a polynomial regression model to estimate daily unit area runoff (m/day) based on discharge from the Williamson River¹⁸. This model was developed using limited pump records collected prior to 1999 (Kann and Walker, 1999; Snyder and Morace, 1997) and is the same as that used in the previous mass balances study (Walker et al., 2012). For each pumped area term, the total runoff volume was computed by multiplying the estimated unit area runoff by the associated area for that term (Table C1, Appendix C). Nutrient loads were then computed by multiplying the estimated daily

¹⁸ Based on the regression model between Williamson River discharge and unit area pumping estimated for years when pumping volumes were available ($R^2=0.96$, $p=0.015$; Kann and Walker, 1999).

flows by the area-weighted mean nutrient concentrations of each term, which was computed using pump sampling data from the Klamath Tribes in 1992–1998 and Snyder and Morace (1997) (Table C1, Appendix C). Additional sampling of agricultural areas draining to UKL showed that nutrient concentrations were generally in agreement with the earlier measurements (Rykboost and Charlton, 1999).

The previous UKL nutrient balance study (Walker et al., 2012) included the Williamson River Delta Preserve (WRDP) as part of the ungauged pumped areas. However, a review of the water quality sampling data showed that nutrient concentrations discharged from the agricultural areas within the WRDP (Tulana) were significantly higher than the other ungauged areas (Table C1). Therefore, for this study, both pumped areas within the WRDP (Tulana and Goose Bay) were treated as a separate term having their own nutrient concentrations (TP = 965 ppb, TN = 3,501 ppb; Table C1). Due to this change, concentrations for the ungauged areas were estimated using area-weighted mean concentrations of 225 and 2,893 ppb for TP and TN, respectively, based on the sampling stations in the other ungauged areas (Table C1). These concentrations are lower for TP and higher for TN relative to those used previously for ungauged pumped areas (TP = 413 ppb, TN = 2,390 ppb; Walker et al., 2012).

In WY 1998, USBR began converting Agency Lake Ranch (ALR) from agricultural usage to a restored wetland to be used for water storage. Beginning in WY 2000 when cattle grazing had been discontinued on ALR, the flows and nutrient loads discharged to Agency Lake were estimated using daily pumping records and limited water quality samples collected by USBR¹⁹. Loads during this period suggest large nutrient releases from antecedent agricultural soils (e.g., Aldous et al., 2005; Graham et al., 2005; Aldous et al., 2007), which have been shown for other restored wetlands around UKL including the WRDP (Wong et al., 2011) and Wood River Delta (Duff et al., 2011).

Prior to WY 2000, flows discharged from ALR were estimated using the unit area runoff model that was also applied to the ungauged pumped areas (see above). Loads were then estimated using the geometric mean of nutrient concentrations from grab samples collected by Klamath Tribes over 1991–1998 (TP = 272 ppb, TN = 1,596 ppb; Table C1). After the initial flooding of ALR in 2000, concentrations increased significantly (TP ≈ 1,800 ppb, TN ≈ 4,800 ppb in 2000) and, apart from a smaller increase in 2005 when an additional 2,631 acres (Barnes Ranch) were added to the project, gradually declined through 2009 (TP ≈ 90 ppb, TN ≈ 1,500 ppb in 2009). USBR reported that no pumping occurred in WYs 2010 and 2014–2016. In 2013, no water quality data were available, and thus the FWM mean concentrations of the previous five years

¹⁹ Data provided electronically by Rick Carlson (USBR, Klamath Basin Area Office).

(2008–2012) (TP = 321 ppb, TN = 2,543 ppb) were used to compute the nutrient loads. In 2017 and 2018, pumping records were not available; however, USBR reported that through an agreement with USFWS, pumping from ALR was limited to 4.4 metric tons of TP in each of those two years²⁰. The total annual flow was then computed by dividing that load by the mean TP concentration measured in each year (665 and 861 ppb in 2017 and 2018, respectively). Monthly flows were then estimated by apportioning the annual flows according to the mean monthly fractions pumped in 2012–2013, which were the previous two years when pumping occurred. Lastly, the TN loads were computed using those estimated flows along with the mean TN concentrations (4,300 and 4,895 ppb for 2017 and 2018, respectively). Based on the water quality sampling data, TP and TN concentrations discharged from ALR have been steadily rising from the annual minimum in WY 2009 (approx. 90 and 1,500 ppb, respectively) to WY 2018 (approx. 860 and 4,900 ppb).

Similar to ALR, the WRDP was converted from agricultural land to restored wetland by The Nature Conservancy beginning in WY 1998. The total area associated with pumping from WRDP was assumed to be 22.8 km² from WY 1992–1997 and then decreased linearly from the start of WY 1998 down to 3 km² at the end of WY 2000 as agricultural activities were phased out. From WY 2001–2016, approximately 3 km² (750 acres) of the WRDP continued to be leased for alfalfa production until 2017 when the specified instream flows (SIFs) were eliminated and all pumping from WRDP had ceased²¹. Total pumped volumes were computed by applying these areas to the unit-area runoff rates estimated from the Williamson River flow for ungauged pumped areas (see above). Nutrient loads were then computed using the geometric mean concentration of grab samples collected by Klamath Tribes over 1991–1998 (TP = 965 ppb, TN = 3,501 ppb; Table C1).

In 2007 and 2008, the northern (Tulana Farms) and southern (Goose Bay) parcels, respectively, were flooded and these areas became part of the lake itself (see Section 2.2). Nutrient releases from antecedent agricultural soils in the WRDP were not directly pumped to the lake as the converted areas and pumped flows were either isolated from the lake or passively connected to the lake (Stevens, 2008). Although the nutrient budgets do not specifically delineate releases of antecedent soil nutrients that could have occurred after the lake dikes were partially breached between 2000 and 2004 and fully breached in 2007 (the west side of the Williamson River) and 2008 (the east Goose Bay area), the loads associated with those areas are captured in the overall net retention term for those years. Similarly, the nutrient budget net retention term

²⁰ Pers. comm., Rick Carlson (USBR)

²¹ Pers. comm., Megan Skinner (USFWS)

reflects any increase in load that may have been associated with an unintentional breach of the Caledonia Marsh dike in 2006, which was subsequently repaired (Lindenberg and Wood, 2009).

Estimated pumping loads are likely more accurate in recent years as most of the pumped inflows were either directly measured (Agency Lake Ranch) or eliminated (Williamson River Delta Preserve) (see Section 2.6), and it is likely that transient unmonitored nutrient loads reaching the lake from antecedent agricultural soils in the restored wetlands had largely attenuated.

2.7 Ungauged Inflows

Ungauged inflows represent the combined inputs from groundwater seepage, springs, and unmonitored runoff from local watersheds adjacent to the lakes. Ungauged inflow volumes were estimated by difference using the water balance equation, which was rearranged to solve for the ungauged term as a function of all other terms (Section 2.1):

$$\text{Ungauged} = \Delta \text{ Lake Volume} + \text{Outflow} + \text{Evaporation} - \text{Gauged Tributary Inflows} - \text{Pumped Inflows} - \text{Precipitation}$$

Because the ungauged term is computed by difference, it incorporates the cumulative uncertainty in measurements or estimates of the other water budget terms. Ungauged flows were constrained to zero when the computed flows were negative, which likely occurred due to errors in the estimates of one or more of the other water budget terms. In a previous water budget of UKL, Hubbard (1970) included several small west side tributaries (e.g., Denny Cr., Moss Cr., Varney Cr., and Rock Cr.) as gauged tributaries; however, in this study, these tributaries were incorporated into the estimated ungauged term due to the lack of sufficient flow and water quality data.

Nutrient loads from ungauged areas were estimated by applying the estimated flows to mean nutrient concentrations (TP = 65 ppb, TN = 99 ppb) measured across eight springs by the Klamath Tribes in 1992–1998 (Walker et al., 2012)²². Additional studies since 1998 for similar springs showed comparable mean TP measurements of 63 ppb (TN not measured; Rykbost and Charlton, 2001) and 60 ppb (TN= 122 ppb; ASR, 2005). For this analysis, we retained the original concentrations used in Walker et al. (2012) because these subsequent studies were relatively similar but also based on different laboratory methods and detection limits. Moreover,

²² These values are likely an overestimate of the mean ungauged concentration because, in addition to the contribution of the springs, other small tributaries coming off forested areas to the west of UKL that contribute to the ungauged term are known to have nutrient concentrations lower than those of the springs. For example, Rock Creek TP concentration was measured at approximately 3 ppb (Geiger et al., 2000).

incorporation of the newer spring concentration data would not appreciably change the overall mean concentrations.

2.8 Net Retention

For the water budget, the net retention term was computed by difference after estimating the ungauged inflows (see Section 2.7):

$$\text{Net Retention} = \text{Gauged Tributary Inflows} + \text{Pumped Inflow} + \text{Ungauged Inflows} + \text{Precipitation} - \text{Evaporation} - \text{Outflow} - \Delta \text{ Lake Storage}$$

The net retention term for the water budget reflects the overall error due to constraining the computed ungauged inflows to non-negative values. On average, this error was less than 1% of the long-term average inflow (Table 2 in Section 3.1.1 below) and ranged from 0 to 3% in individual water years (Appendix E, Table E1).

For the nutrient (TP and TN) mass balances, net retention was also computed by difference from the other directly measured or estimated terms:

$$\text{Net Retention} = \text{Gauged Tributary Loads} + \text{Pumped Loads} + \text{Ungauged Inflow Loads} + \text{Atmospheric Deposition} - \text{Outflow Load} - \Delta \text{ Lake Storage}$$

The amount of retention reflects the difference between sedimentation, atmospheric fixation (nitrogen only), nutrient releases and resuspension from bottom sediments, as well as the cumulative effects of errors in the other mass balance terms. Negative net retention values for P indicate net release (i.e., recycling) from the lake sediments to the water column, and for N indicate both recycling from lake sediments and atmospheric input from nitrogen fixation by cyanobacteria.

2.9 Anthropogenic and Background Loads

The nutrient mass balances were partitioned into loads from human activities (anthropogenic loads) and loads under ‘natural’ or ‘pristine’ conditions (background loads). Following Walker et al. (2012), background loads were estimated as the total inflow volume from external sources (Gauged Tributaries + Ungauged Inflows + Pumped Inflows) multiplied by the concentrations used to compute the ungauged inflow loads (TP = 65 ppb and TN = 99 ppb; see Section 2.7). For TP, the assumed background concentration of 65 ppb is only 1 ppb less than the TMDL target of 66 ppb (ODEQ, 2002).

Because many of the tributaries either originate from springs or have significant spring input in their upper reaches (e.g., Wood River, Sevenmile Canal, Williamson River, etc.), the background

loads provide an estimate of the loads that would be expected in the absence of anthropogenic inputs²³. Anthropogenic loads were computed as the difference between total inflow nutrient and background loads. The concentrations associated with the anthropogenic loads were then computed by dividing those loads by the total external inflow volumes. The anthropogenic concentrations are thus equal to the *difference* between the historical total inflow concentrations and the background concentration. Equations for computing the background and anthropogenic loads are as follows:

$$\text{Background Load} = \text{Background Concentration} \times \text{Total External Inflow Volume}$$

$$\text{Anthropogenic Load} = \text{Total External Inflow Load} - \text{Background Load}$$

$$\text{Anthropogenic Concentration} = \text{Anthropogenic Load} / \text{Total External Inflow Volume}$$

2.10 Trend Analysis

Long-term trends in monthly, seasonal, and annual flows, nutrients loads, and FWM concentrations were evaluated for each term in the water and nutrient mass balances over the period of record. The trends were evaluated using both parametric and non-parametric statistical tests. Parametric methods generally require several underlying assumptions about the distribution (i.e., normality) and independence of the data (i.e., random with low serial correlation). Non-parametric methods are based on the ranks of the observations rather than the values themselves and are typically more robust to outliers and other abnormalities common to water quality observations.

The primary trend test was based on the non-parametric Seasonal Kendall test, which is commonly used to evaluate trends in hydrologic timeseries exhibiting seasonal patterns and is more robust than parametric methods that require assumptions regarding the distributions of the data (Helsel et al., 2020). The Seasonal Kendall test was applied to the entire timeseries of each term, as well as seasonal subsets to determine whether trends occurred primarily during one or more seasons. In addition to the Seasonal Kendall test, trends in annual flows, loads, and FWM concentrations were evaluated using the non-parametric Mann-Kendall test. The Mann-Kendall test was also applied to annual timeseries of each month individually (i.e., total flows during October of each year) to identify long-term trends within a single month. Trends in the

²³ Because relatively unimpacted headwater areas (e.g., North and South Forks of the Sprague River) have lower concentrations than those of the springs (Walker et al., 2015), the 65 ppb TP concentration used for the background load may be overestimated. This would have the effect of underestimating the anthropogenic load since it is calculated by the difference between the total external load and the background load.

annual values were also tested using a simple linear regression, which is a type of parametric test. The Seasonal Kendall and Mann-Kendall tests were computed using the *kendallSeasonalTrendTest* and *kendallTrendTest* functions in the *EnvStats* R package (Millard, 2013).

All trend tests were computed on \log_{10} -transformed values of the flows, loads, and concentrations except evaporation and net retention loads, which were not transformed due to values sometimes being zero (evaporation) or negative (net retention). The use of \log_{10} -transformed values deviates from the methodology used in the previous study (Walker et al., 2012), which used untransformed values. Because a \log_{10} -transformation is a monotonic transformation of the data, it does not affect the significance level (p-value) of the non-parametric tests (Seasonal Kendall and Mann Kendall). However, the estimated trend slopes of the \log_{10} -transformed values reflect a relative (or percentile) change over time as opposed to an absolute change in flow (hm^3/yr), load (kg/yr) or concentration (ppb/yr) that would be generated from untransformed values. Because flows, loads, and concentrations cannot be negative (aside from net retention), the relative slopes were considered more appropriate than the absolute slopes, for which any decreasing trends would eventually predict negative values.

The significance of each trend test was evaluated by comparing the p-value to critical thresholds of $\alpha=0.05$ ($p \leq 0.05$ indicating high significance) and $\alpha=0.10$ ($0.05 < p \leq 0.10$ indicating moderate significance). The slope and intercept of each trend were estimated using the Sen slope estimator for the non-parametric methods (Millard, 2013; Helsel et al., 2020). The estimated slopes for flows, loads and concentrations were converted from \log_{10} -transformed units per year to percent per year by:

$$\text{Slope } [\%/yr] = 10^{\text{Slope}[\log(\text{units})/yr]} - 1$$

For net retention loads, which were not \log_{10} -transformed due to its negative values, the relative trend slope in $\%/yr$ was computed by dividing the estimated absolute slope in mton/yr by the long-term mean total external inflow load computed over the period of record. For evaporation, which was also not transformed, the relative slope was computed by dividing the estimated slope in hm^3/yr by the long-term mean annual evaporation volume.

Because long-term trend tests can be sensitive to the period over which they are computed, a sensitivity analysis was performed by computing the primary trend test (Seasonal Kendall test) over periods with varying lengths. The initial year across these periods varied from WY 1992 (the first year in the period of record) to WY 2009, while the final year was fixed at WY 2018. Applying the trend test to these periods yielded results for each mass balance term and parameter over periods ranging from 27 years (WY 1992–2018) to 10 year (WY 2009–2018) in duration with all periods ending in the last year in the period of record (WY 2018).

3 Results

Using the various data sources and methods described in Section 2, a dataset containing monthly and annual flows, nutrient (TP and TN) loads, and FWM concentrations representing the water and nutrient mass balances of UKL was generated over the period of record (WY 1992–2018). This dataset has been published in an online and publicly accessible data repository²⁴ to support subsequent studies, data analyses, and modeling efforts (Walker and Kann, 2022).

The followings sections of this report present and discuss key results with respect to:

- 3.1 Water and Nutrient Mass Balances
- 3.2 Inflow/Outflow Phosphorus Dynamics
- 3.3 Long-term Trends
- 3.4 Progress Towards TMDL Targets

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

- A Precipitation and Evaporation Datasets
- B Annual and Seasonal Variations in Tributary Nutrient Species Concentrations
- C Flow and Nutrient Load Calculations for Pump Areas and Gauged Tributaries
- D Annual and Seasonal Variations in Mass Balance Terms
- E Water and Nutrient Mass Balance Summaries
- F Inflow/Outflow Total Phosphorus Loading Dynamics
- G Trends in Flow, Load, and Concentrations of Mass Balance Terms

3.1 Water and Nutrient Mass Balances

Timeseries plots of the monthly, annual, and seasonal variations in flows, nutrients loads, and concentrations of each mass balance term are provided in Figure D1 (Appendix D). The equations used for computing the flows and loads of terms derived from other directly measured or estimated terms are listed in Table D1 (Appendix D). Appendix C provides water quality data summaries for the pumped areas, and diagnostics of the daily flow and load estimation algorithms for the gauged tributaries and lake outflow terms. Appendix B shows annual and monthly variations in individual nutrient species for TP, SRP, TN, and inorganic N (NH₄ + NO₃N) based on the sampled concentration data at each gauged tributary station.

²⁴ The current water and mass balance dataset is available at: <https://doi.org/10.5281/zenodo.6476840>

3.1.1 Long-term Balances

Over the period of record (WY 1992–2018), the combined discharge from all external inflows²⁵ had an annual average volume of 1,558 hm³/yr, nutrient loads of 155 and 513 mton/yr, and FWM concentrations of 100 and 329 ppb for TP and TN, respectively (Table 2). Gauged tributaries (Williamson, Sprague, Wood and Sevenmile) accounted for 80% of that external inflow volume and 78 and 74% of the TP and TN loads, respectively. Total pumped inflows accounted for only 2% of the total external inflow volumes, but 11 and 21% of the TP and TN loads due to higher concentrations (430 and 2,778 ppb). The remaining 18% of external inflow volumes and 11 and 5% of TP and TN loads were generated from groundwater seepage, springs, and surface runoff from the ungauged portions of the UKL basin. This ungauged portion of total external inflow volumes is similar to other estimates of approximately 15% ground water input to UKL (Hubbard, 1970; Gannett et al., 2007)²⁶.

In addition to external inflows, atmospheric deposition supplied 9.2 and 63 mton/yr of P and N loading to the lake (6 and 12% relative to total external inflows), and precipitation contributed 117 hm³/yr (8%), while evaporation losses amounted to 271 hm³/yr (17%). Combining the total external inflows with precipitation and evaporation yields overall net inflows²⁷ of 1,404 hm³/yr with loads of 165 and 577 mton/yr and concentrations of 117 and 411 ppb for TP and TN, respectively.

The annual average lake outflow volume was 1,400 hm³/yr, which was 90% of total external inflows due to evaporative losses exceeding precipitation to the lake surface. Average outflow TP loads were 160 mton/yr and slightly less (4.7 mton/yr or 3%) than the net inflow load, which, combined with a small overall change in storage, yielded a small, positive net P retention of 7.2 mton/yr over the entire period. This small net P retention was only 5% relative to the total external inflow load indicating that *over the long-term*, phosphorus loading into the lake was derived from external (i.e., watershed) sources instead of from internal loading associated with sediment recycling. However, as discussed in Sections 3.1.3 and 3.2 below, large seasonal (i.e., month-to-month) variability in the loads from internal and external sources plays an important role in the nutrient dynamics of UKL.

²⁵ Total External Inflows = Gauged Tributaries + Ungauged Basins + Pumped Areas

²⁶ Although authors of these studies use the term groundwater, it was computed similarly to our ungauged inflow term, and thus also includes all ungauged tributaries, diffuse runoff, and discharge from large springs adjacent to UKL.

²⁷ Net Inflow = Total External Inflows + Precipitation – Evaporation. For loads, precipitation represents total atmospheric deposition and evaporation is zero.

In contrast to TP, for which inflow and outflow loads were relatively balanced, the overall mean outflow TN load of 2,242 mton/yr was 389% higher than that for net inflow (577 mton/yr) primarily due to nitrogen fixation by cyanobacteria within the lake. In other words, the overall net internal loading of N (mostly from nitrogen fixation) was nearly 4x the amount of N discharged into the lake from external watershed sources and atmospheric deposition. As with P, both internal and external N loads exhibit strong seasonal patterns, which are important for understanding the water quality dynamics within UKL (Section 3.1.3).

Using constant background concentrations of 65 and 99 ppb for TP and TN, respectively (Section 2.9), the total estimated background loads were 101 and 154 mton/yr, which were 65 and 30% relative to the total external loads. Anthropogenic loads thus accounted for the remaining 35 and 70% of the TP and TN external inflow loads and resulted in total external inflow concentrations being 35 and 230 ppb higher than the estimated background concentrations²⁸.

In addition to the volumetric flows and mass loads of each mass balance term, Table 2 also provides estimates of the unit-area runoff (computed by dividing flow volume by drainage area) and nutrient export (load divided by area) rates. Due to the restoration of some agricultural areas (see Section 2.6) and inundation of surrounding wetlands (Section 2.2), the drainage areas of some terms (e.g., pumped areas, ungauged inflows) varied over time. Therefore, the drainage areas as well as the average annual runoff and export rates were computed as the mean values over the period of record²⁹. Among the gauged tributaries, the highest unit-area runoff and nutrient export rates occurred in the Wood River basin below Weed Rd (1.3 m/yr, 248 and 444 kg/km²-yr for P and N) and in the Sevenmile Canal basin (1.1 m/yr, 149 and 494 kg/km²-yr for P and N). Runoff and nutrient export rates in the Sprague and Williamson River basins were lower than the Wood and Sevenmile basins by a factor of 10 or more³⁰. From the pumped areas, total P export was 178 kg/km²-yr, which is comparable to that from the lower

²⁸ Anthropogenic loads and concentrations are both equal to the difference between those from the total external inflows and the background sources. Anthropogenic concentrations thus refer to the observed *increase* in total external inflow concentrations above background levels associated with human activities in the watershed, and do *not* represent the overall concentration of water from anthropogenic sources (e.g., the concentration of runoff from agricultural areas).

²⁹ The runoff and export rates were first computed on a monthly basis, and then aggregated by computing the long-term annual mean values of each term. These values may differ slightly from those that would be directly computed by dividing the volumetric flow and mass loading rates by the average drainage areas shown in Table 2.

³⁰ As discussed for the Sprague River (Walker et al., 2015), when the total area of a watershed is large relative to its lower riparian and floodplain areas, the overall unit-area export rates may not reflect higher export rates that can occur in those lower areas where agricultural land use is often the most intensive and can have large impacts on instream water quality of receiving streams.

Wood River and Sevenmile canals. However, TN export from pumped areas (1,153 kg/km²-yr) was higher than those basins by more than a factor of two.

It is important to note that the drainage areas for some basins may be inaccurate as they were based on delineations using surface topography³¹. Cross-basin water transfers for irrigation are known to occur in some areas, especially between the Sevenmile Canal and Wood River basins, but were not accounted for in our calculations. In addition, the contributing areas from spring-fed basins (e.g., Wood River, Williamson excluding Sprague) may be larger than the surface water basin delineations. For example, the nutrient export rates for Wood River above Weed Road may be over-estimated because the drainage area determined from surface topography may not reflect the groundwater recharge areas for springs that feed the Wood River. Because of these issues, there is greater uncertainty in the unit-area runoff and nutrient export rates than their volumetric and mass loading equivalents, especially for the Sevenmile Canal and Wood River basins.

The annual TP loads for the Williamson and Wood Rivers estimated in this study based on daily flows and biweekly TP concentrations (see Section 2.5) were similar to those computed from continuous turbidity measurements by the USGS (Schenk et al., 2016)³². Thus, even though continuous data provide higher temporal resolution that can better capture short-term variability (e.g., during storm events), the total loads over longer (e.g., annual) periods can be similarly estimated using either method in large part because loads are primarily driven by flows, which are measured continuously and used in both methods.

Appendix E provides water and nutrient mass balance summary tables similar to Table 2 for individual water years (Table E1) and for various multi-year periods (Table E2). This appendix also provides figures showing the monthly timeseries and annual average flows, loads, and concentrations over the various multi-year periods for major inflow and lake mass balance terms (Figures E1–E8).

³¹ Gauged tributary basins were delineated using the level-12 Hydrologic Unit Code (HUC) Watershed Boundary Layer (WBD) layer in the National Hydrography Dataset Plus (NHDPlus) High Resolution (HR) (Moore et al., 2019).

³² Schenk et al. (2016) used continuous turbidity measurements as a surrogate for estimating daily TP concentrations based on a regression model of the two parameters. Coupled with daily flows, they estimated TP loads of 39 and 28 mton/yr for the Williamson and Wood Rivers, respectively, during WY 2014 (a relatively dry year). For comparison, in this study, we estimated annual TP loads of 44 and 33 mton/yr for the same basins.

Table 2: Long-term average annual water and nutrient mass balances of UKL, WY 1992–2018

Upper Klamath Lake Water & Nutrient Balances

Water Year(s): 1992 - 2018 (Period of Record)

	Flow hm ³ /yr	Nutrient Loads TP mt/y TN mt/y		Fraction of Total External Inflow Flow TP Load TN Load			Nutrient Concs TP ppb TN ppb		Dr. Area km ²	Runoff m/yr	P Export kg/km ²	N Export kg/km ²
Gauged Tributary Inflows												
Sevenmile Canal at Dike Rd	101.4	14.3	47.2	7%	9%	9%	141	466	96	1.06	149	494
Wood River above Weed Road	246.5	21.2	31.6	16%	14%	6%	86	128	333	0.74	64	95
Wood River below Weed Road	80.9	15.1	27.0	5%	10%	5%	186	334	61	1.33	248	444
Total Wood River at Dike Rd	324.7	36.2	57.9	21%	23%	11%	111	178	394	0.82	92	147
Sprague River	481.3	36.2	170.2	31%	23%	33%	75	354	4,171	0.12	9	41
Williamson River excluding Sprague	338.0	34.8	107.6	22%	22%	21%	103	318	3,702	0.09	9	29
Total Williamson River	819.3	70.7	274.8	53%	45%	54%	86	335	7,873	0.10	9	35

Overall Balance

Total Gauged Tributary Inflows	1,245.3	121.2	380.0	80%	78%	74%	97	305	8,362	0.15	14	45
Total Pumped Area Inflows	38.2	16.4	106.2	2%	11%	21%	430	2,778	92	0.41	178	1,153
Ungauged Inflows	274.5	17.8	27.2	18%	11%	5%	65	99	1,040	0.26	17	26
Total External Inflows	1,558.0	155.5	513.3	100%	100%	100%	100	329	9,494	0.16	16	54
Precipitation	117.3	9.2	63.3	8%	6%	12%	78	540	278	0.42	33	228
Evaporation	271.5			17%					278	0.98		
Net Inflow	1,403.8	164.7	576.6	90%	106%	112%	117	411	9,772	0.14	17	59
Lake Outflow	1,399.9	160.0	2,241.9	90%	103%	437%	114	1,602	9,772	0.14	16	229
Storage Increase	0.5	-2.5	-17.7	0%	-2%	-3%						
Net Retention	3.4	7.2	-1,647.6	0%	5%	-321%						

Natural Background vs. Anthropogenic Loads

Background / Natural	1,558.0	101.3	154.2	100%	65%	30%	65	99	9,494	0.16	11	16
Anthropogenic		54.2	359.0		35%	70%	35	230	9,494		6	38

Morphometry

	Mean	Min	Max
Volume (hm ³)	722.9	385.2	952.3
Area (km ²)	278.2	262.7	296.9
Elevation (ft)	4,140.8	4,136.8	4,143.4
Mean Depth (meters)	2.6	1.5	3.2

Phosphorus Model Parameters

Hydraulic Residence Time	0.51 years
Net Water Load	5.60 m/yr
Areal Total P Load	0.56 g/m ² -yr
Total P Retention Coefficient	4.6 %

3.1.2 Annual Variations

The long-term average water and nutrient mass balances discussed in the previous section (Table 2) provide a high-level summary of the relative contributions of each term to the overall balances for the entire period of record. In this section, we present and discuss annual (year-to-year) variations of the major inflow and lake budget terms that reflect long-term changes to the climate, hydrology, and watershed activities and management of the UKL basin.

3.1.2.1 Inflows

Over the period of record, total annual inflow volumes from gauged and ungauged drainage areas, pumped areas, and precipitation varied over approx. 1,000 – 2,500 hm³/yr (Figure 6a). Total annual inflows³³ were generally higher during the 1990s than in later years with values exceeding the long-term mean (1,675 hm³/yr) in 7 out of the first 9 years (WY 1992–2000) and only 3 (WYs 2006, 2011, 2017) of the remaining 18 years (WY 2001–2018). However, the two years with lowest total inflows (WYs 1992 and 1994) also occurred during those first 9 years.

Total external inflow TP loads exhibited similar patterns (Figure 6b) indicating that year-to-year variations in loads were driven primarily by flows as opposed to TP concentrations ($R^2 = 0.93$ and 0.19, respectively; Figure 7a,b). Total external inflow TN loads, on the other hand, were driven by both flows and, to a lesser extent, concentration ($R^2 = 0.87$ and 0.69, respectively; Figure 7d,e). The relative fraction of total flows and nutrient loads contributed from each source was relatively consistent with the exception of pumped inflows, which decreased over time (Figure 6a,b,d) as confirmed by the statistical trend analysis (Section 3.3 below).

The annual FWM TP and TN concentrations of some terms exhibited different patterns than the inflow volumes and loads (Figure 6c,e). Ungauged inflows had constant concentrations because they were based on the average concentrations estimated from measurements of seeps and springs (TP = 65 ppb, TN = 99 ppb; Section 2.7). Precipitation concentrations were computed by dividing the total atmospheric deposition (including both wet and dry deposition; Section 2.4) by the precipitation volume. Therefore, variations in concentration reflect an inverse relationship with respect to precipitation volumes (higher precipitation volume → lower concentration).

For the pumped inflows, concentrations were constant over the first few years (WY 1992–1997) based on the average values computed for each pumped area (Section 2.6; Table C1 in Appendix C). Pumped inflow concentrations began varying in WY 1998 due to changes in the

³³ Total Inflow = Total External Inflows + Precipitation

total pumped area associated with the restoration of WRDP and ALR, as well as the use of sampled concentrations for the discharge from ALR beginning in WY 2000. Sampled concentrations from ALR were initially high likely due to nutrient releases from the antecedent agricultural soils after initial inundation of the land.

Lastly, annual FWM concentrations of the gauged tributary inflows showed relatively little variability compared to the other terms (aside from the constant ungauged inflow concentration) (Figure 6c,e). The gauged tributary inflow concentrations also exhibited decreasing trends, especially for TN, which was confirmed by the statistical trend tests (Section 3.3 below). Because gauged tributaries comprised the greatest proportion of total external inflow volumes (Figure 6a; long-term mean = 80%, Table 2), the annual FWM nutrient concentrations of the total external inflows were relatively similar to those from the gauged tributaries in each year, with some differences occurring in years when pumped inflow loads were relatively high (Figure 6c,e). Total external inflow TP concentrations were not related to flow ($R^2 = 0.036$, Figure 7c), while those for TN were somewhat related ($R^2 = 0.34$, Figure 7f).

Year-to-year variations in flow due to climate are important to consider when interpreting variations in nutrient loads and, to a lesser extent, concentrations. Annual variations in total external inflow volumes and nutrient loads were strongly correlated with variations in precipitation depth³⁴ (Figure 8). Additional variations not related to precipitation can be attributed to uncertainty in the measured values, trends related to implementation of management measures, spatial variations, and other random factors. Inter-annual variation in snowpack is also expected to be highly related to external inflow volumes and nutrient loads, but was not evaluated in this study. The correlations shown in Figure 8 were all statistically significant (R^2 ranged from 0.42 to 0.69, $p < 0.001$; Figure 8b,c,e,f), except for FWM TP concentration ($R^2 = 0.10$, $p > 0.1$; Figure 8d). These correlations against precipitation generally show similar patterns as those against flow (Figure 7). As compared with TP loads, TP concentrations were relatively independent of precipitation and thus provide a more reliable basis for tracking long-term trends related to non-climate factors (e.g., watershed restoration). Interpretation of trends in TN are complicated by the fact that both loads and FWM concentrations are correlated with precipitation ($R^2 = 0.69$ and 0.42 , respectively; Figure 8e,f) and thus may reflect changes associated with both climate and non-climate factors.

³⁴ The volumes used here represent direct precipitation to the lake surface (Section 2.4). Using spatially-averaged precipitation across the individual watersheds would be expected to yield stronger correlations, but was not computed for this study.

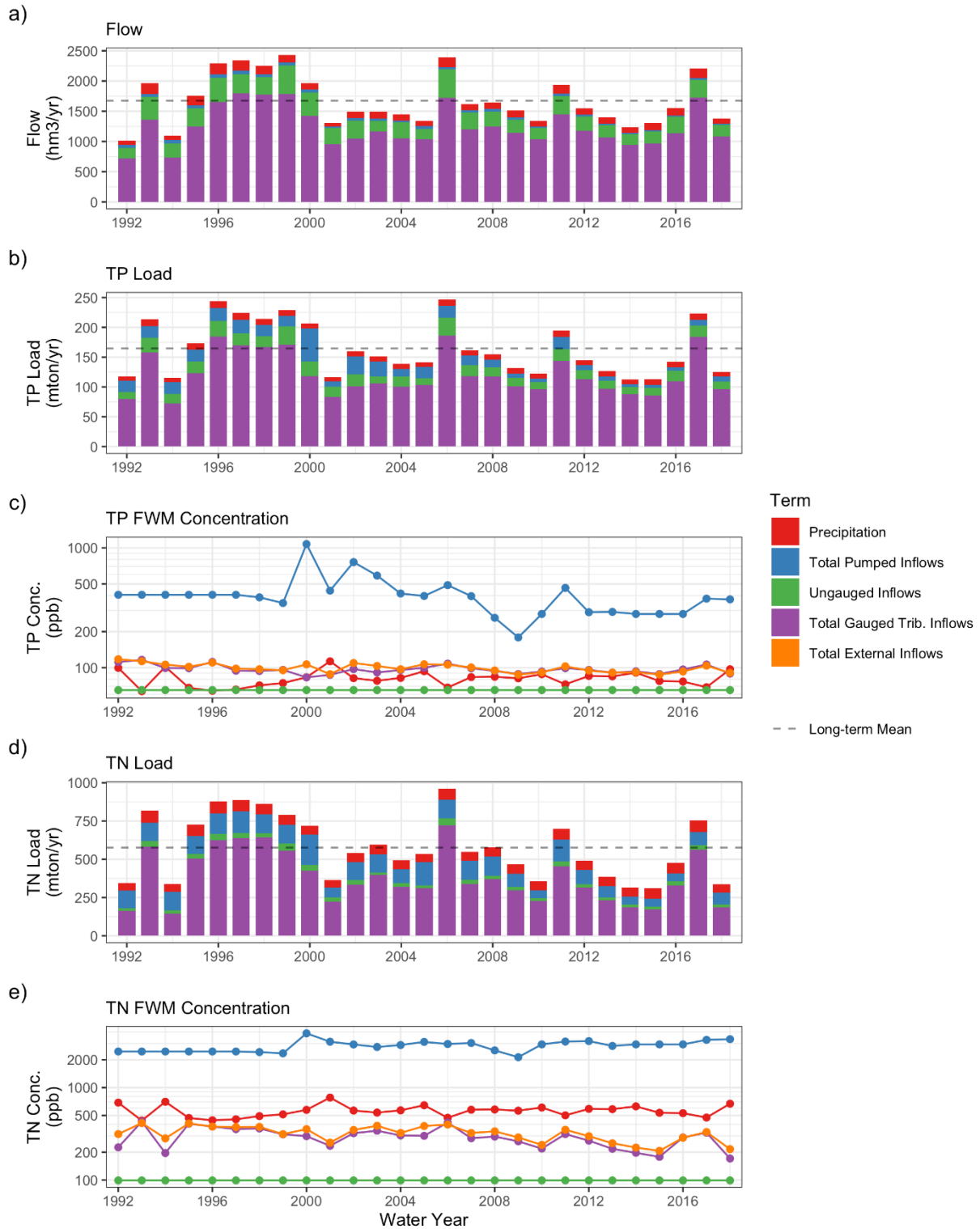


Figure 6: Annual flows, nutrient loads, and FWM concentrations of primary inflow terms.
Total External Inflows = Total Pumped Inflows + Total Gauged Tributaries + Ungauged Inflows. Precipitation loads include both dry and wet (i.e., total) atmospheric deposition and concentrations computed by dividing total deposition loads by precipitation volume.

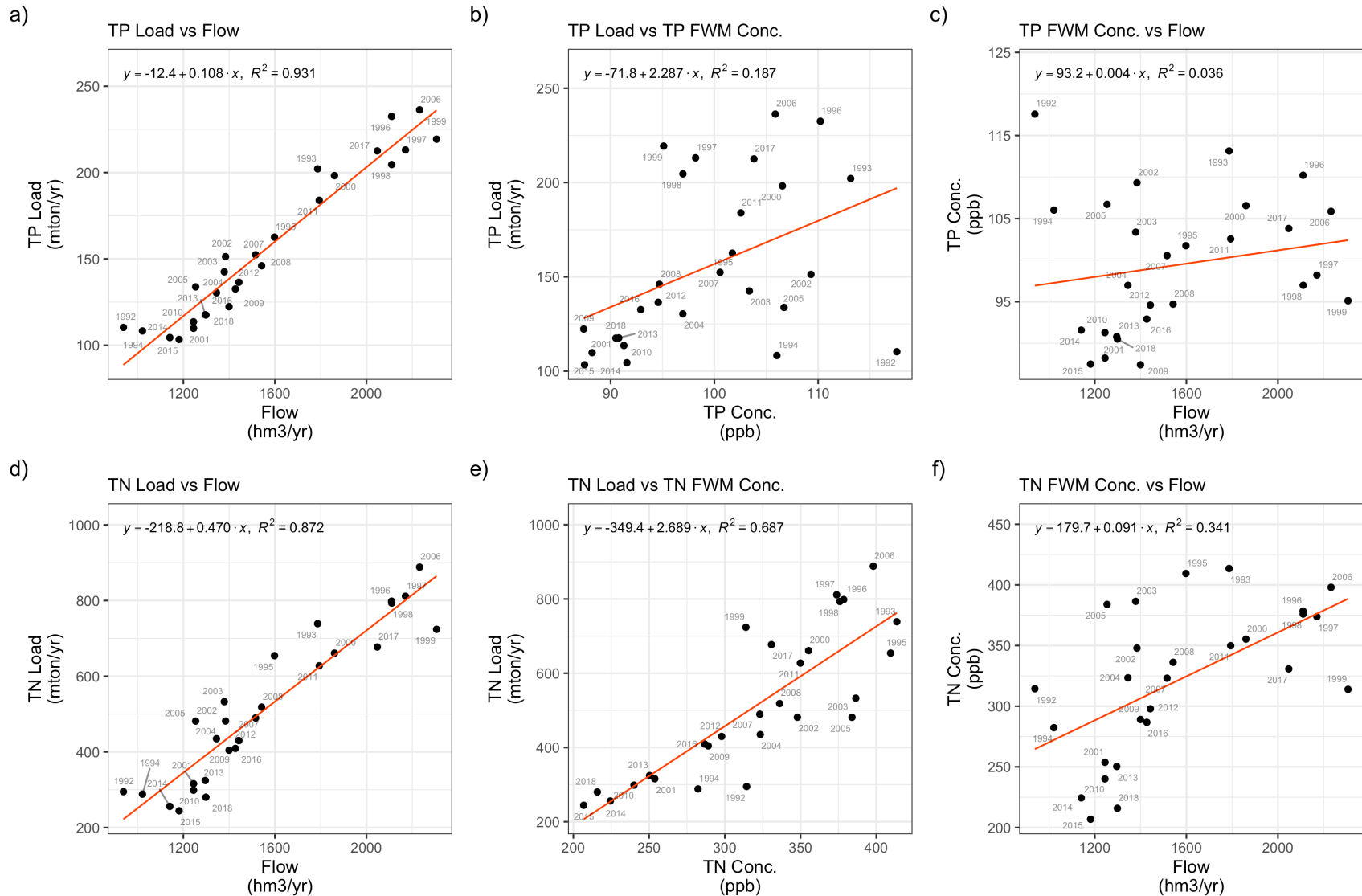


Figure 7: Relationships between annual flows, nutrient loads, and concentrations of total external inflows.

Total External Inflows = Total Pumped Inflows + Gauged Tributary Inflows + Ungauged Inflows. Points labelled by water year.

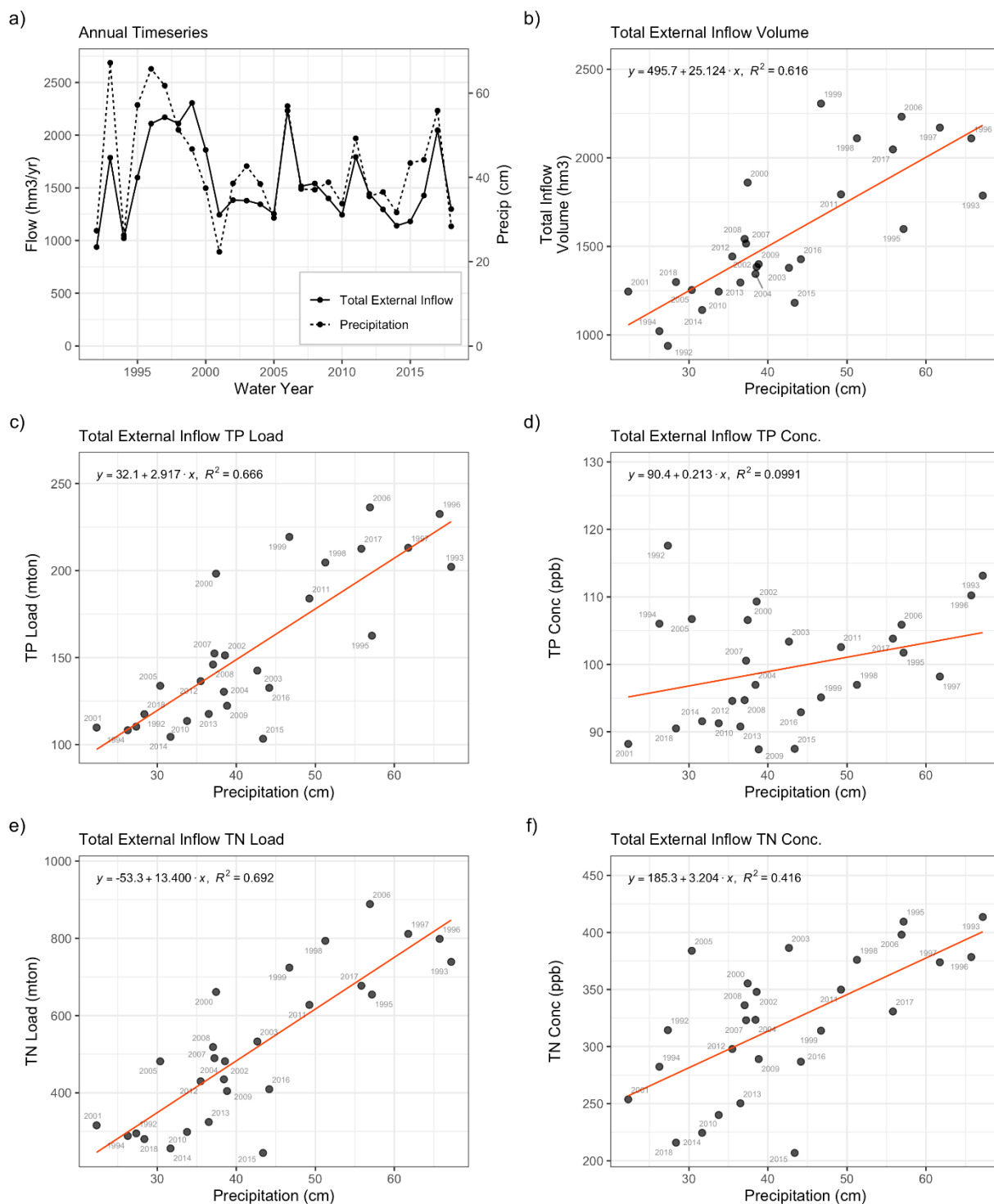


Figure 8: Relationships between annual precipitation and total external inflow volumes, nutrient loads, and FWM concentrations.

Total External Inflows = Total Pumped Inflows + Gauged Tributary Inflows + Ungauged Inflows. Points labelled by water year.

3.1.2.2 Lake Budgets

The overall water and nutrient mass balances can be represented based on four primary lake budget terms:

$$\text{Storage Increase} = \text{Net Inflow} - \text{Outflow} - \text{Net Retention}$$

Net inflow is the sum of all external inflows and precipitation minus evaporation. For the water balance, net retention reflects the cumulative error in the other estimated terms and is non-zero only when the ungauged inflow volumes are constrained to non-negative values. For nutrient, net retention was computed by difference from the other mass balance terms and thus incorporates additions and losses of nutrient mass in the water column (e.g., via sedimentation, recycling, nitrogen fixation), as well as the cumulative errors in the other terms (see Sections 2.1 and 2.8).

The annual water balance was dominated by net inflows and outflows, which were very similar in each year (Figure 9a). Differences between net inflow and outflow volumes indicate an overall change in storage and occurred when the lake volume and surface elevation differed between the start and end of a given water year. Net retention of flow represents error in the water balance due to constraining ungauged inflows to non-negative values and was negligible relative to the net inflow and outflow volumes. Compared to the water balance, the annual nutrient mass balances show greater differences between net inflow and outflow loads due to variations in both the storage increase and net retention terms (Figure 9b,d). The annual change in storage reflects an overall increase (or decrease) in nutrient mass within the lake based on changes in both volume and concentration between the start and end of each water year.

For TP, annual inflow and outflow loads were generally of similar magnitudes but differed by 50 mton/yr or more in some years depending on the combined effects of net retention and changes in storage (Figure 9b). The annual net retention of TP reflects the overall balance between sedimentation (flux from the water column to the sediment) and sediment recycling (from sediment to the water column). Years with positive net retention indicate when sedimentation exceeded recycling, resulting in an overall accumulation of phosphorus in the lake sediment. Negative values of net P retention indicate years when recycling exceeded sedimentation, and thus more phosphorus was released into the water column than settled out. In some years, TP loads from net retention were of similar magnitudes (though always less than) net inflow loads. For example, in WY 2004, the TP load from net retention was 88 mton, which was 68% of the net inflow loads (130 mton) (Table E1, Appendix E). However, over the entire period, annual TP loads for the net retention term were approximately balanced as years

with negative net retention (i.e., net release) were offset by other years with positive net retention yielding a long-term annual average net TP retention of only 7 mton/yr (Table 2).

Annual net inflow and outflow TP FWM concentrations were generally comparable, with outflows having greater year-to-year variability than net inflows (Figure 9c). Because net inflow and outflow volumes were relatively similar (Figure 9a), differences in concentrations were primarily driven by variations in net retention and changes in storage, which in turn caused differences between the net inflow and outflow TP loads (Figure 9b). Lake mean storage TP concentrations were similar to outflow concentrations; although, outflows tended to be higher by approx. 25 ppb in 5 of the last 6 years (WY 2013–2018). On a monthly basis, lake storage concentrations were also highly correlated with outflow concentrations for both TP and TN ($R^2 = 0.91$ and 0.92 , respectively; Figure 10).

In contrast to TP, annual outflow TN loads were consistently much higher than net inflow loads by a factor of 3 or more (Figure 9d). These differences are reflected by the consistently negative annual net retention rates, which were primarily driven by nitrogen fixation of cyanobacteria within the lake. Outflow TN concentrations were also consistently higher and more variable than net inflows concentrations, which were relatively constant and also exhibited a steady decline over the period of record (Figure 9e; see trend results in Section 3.3). As for TP, the outflow and lake mean storage TN concentrations were similar in most years.

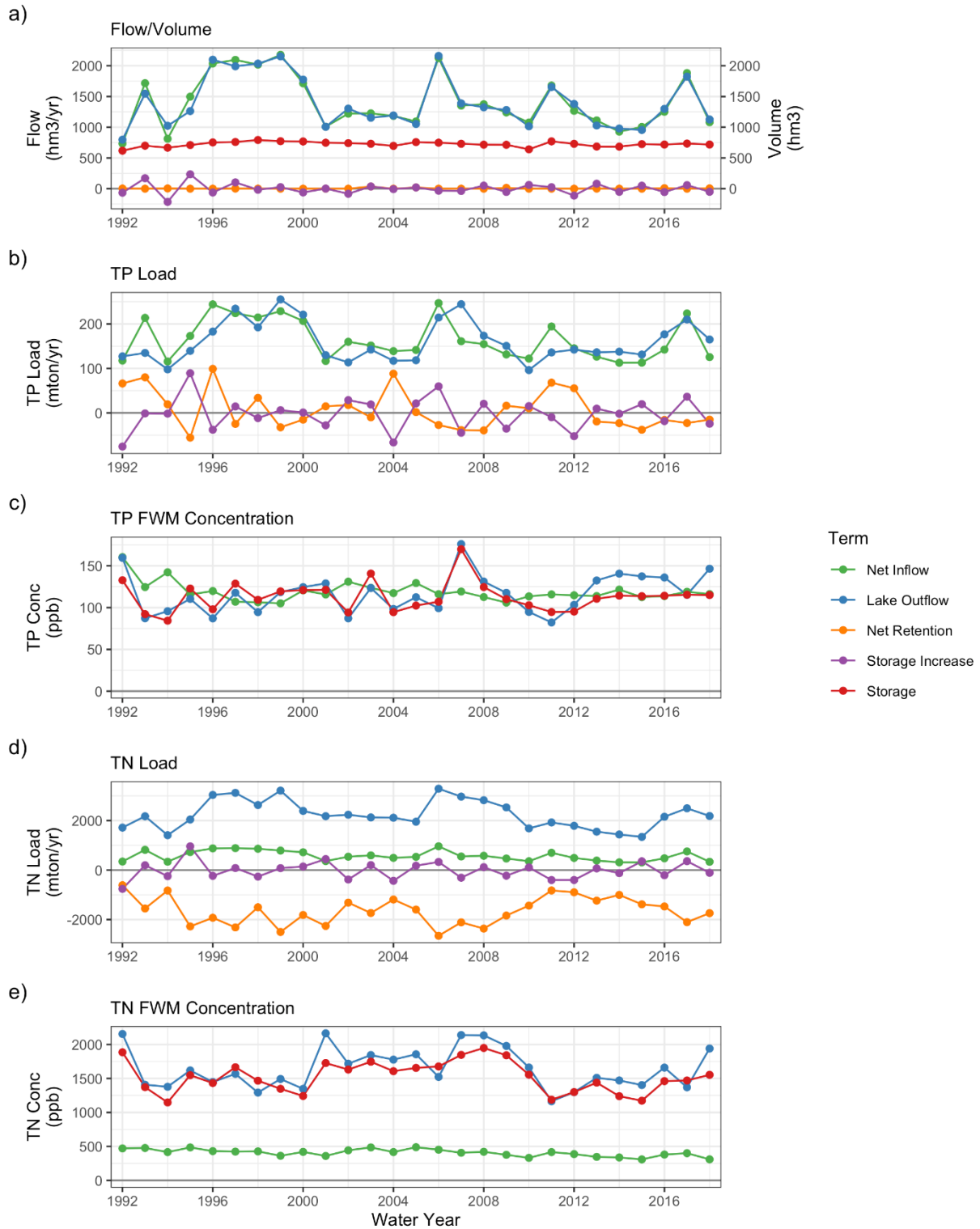


Figure 9: Annual volume, flow, nutrient loads, and FWM concentrations of primary lake budget terms.

Storage volume and concentrations computed as the arithmetic mean of daily values within each water year. Total nutrient mass storage (mton) not shown as variations are similar to the storage concentrations.

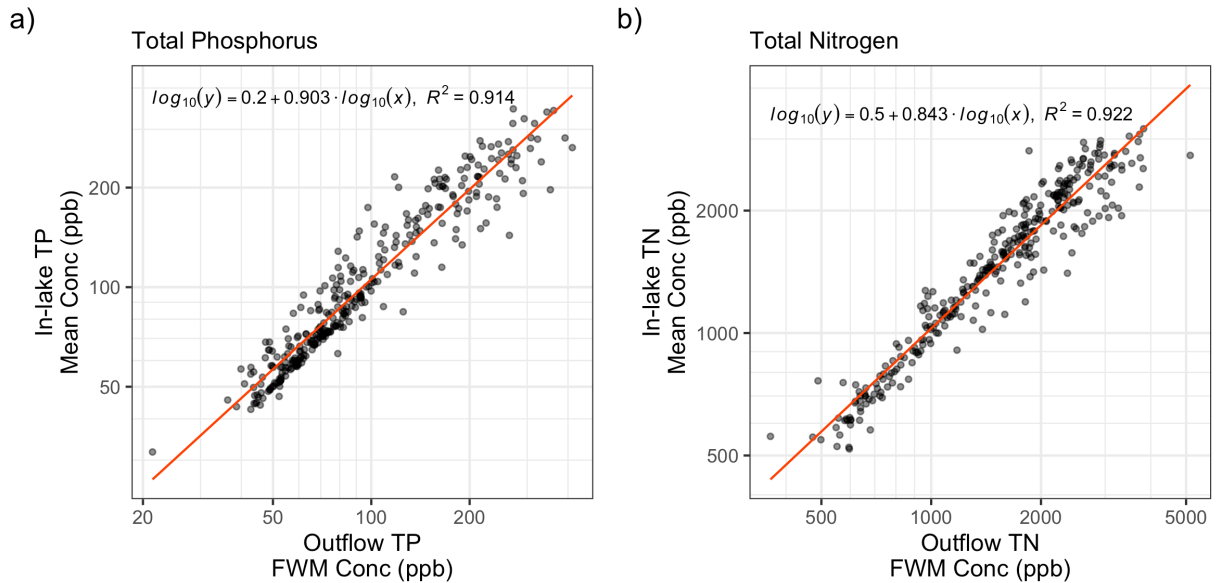


Figure 10: Relationships between monthly in-lake and outflow nutrient concentrations.

In-lake concentrations refer to the “storage” mass balance term.

3.1.3 Seasonal Variations

Seasonal variations in the water and nutrient mass balances of UKL are driven by various factors and processes including temperature, light availability, algal bloom dynamics, and basin hydrology, among others. In this section, we present and discuss the major seasonal patterns of the primary inflow and lake budget mass balance terms using the means and ranges³⁵ of flows, nutrient loads, and concentrations within each month of the year. The N:P ratio of each term is also provided and shown relative to a reference line of N:P = 5, below which the N:P ratio typically promotes dominance by N-fixing cyanobacteria³⁶. The seasonal patterns are shown over the months of May – April instead of October – September (i.e., the water year) as May generally coincides with the start of each growing season. This sequence of months (May – April) thus better reflects the seasonal algal growth and nutrient dynamics than the water year months, which better reflect the watershed hydrology.

³⁵ Ranges represented by the 10–90th percentile of values within each month computed across all years

³⁶ Although absolute N and P concentrations are also important for structuring phytoplankton communities (e.g., cyanobacteria require relatively high P concentrations), low N:P ratios can indicate nitrogen limiting conditions that allow N-fixing cyanobacteria, such as the *Aphanizomenon* in UKL, to dominate over other non-N-fixing species. While the exact in-lake N:P ratios in eutrophic lakes that denote N limitation may vary between 10 and 20 (e.g., Dolman and Wiedner, 2015), the reference N:P ratio of 5:1 is shown to indicate the very low ratios for UKL inflows.

3.1.3.1 Inflows

Total inflows to UKL can be represented using either the total external inflow or the net inflow mass balance terms (see Table D1, Appendix D for equations). Total external inflows represent all inflows discharged into the lake from its surrounding watershed³⁷. Net inflows reflect the combination of those external inflows along with precipitation volumes (atmospheric deposition loads) as well as the loss of water due to evaporation³⁸. During summer, high evaporative losses can have a significant concentrating effect on the water quality of external inflows. Although lake volume is reduced due to evaporation, the total mass of nutrients is not changed, and thus concentrations (= mass / volume) are effectively increased. As a result, total external inflows are considered a better measure of the inflow water quality as it is discharged from the watershed into the lake, and thus better reflects the hydrology and management of the watershed. Net inflows, on the other hand, better represent the impact of those external inflows on the water quality within the lake itself as net inflows incorporate the effects of evaporative water losses on the effective concentration of those discharges after being combined with precipitation/atmospheric deposition inputs.

Mean monthly flows and nutrient loads were relatively similar between total external inflows and net inflows (Figure 11a-c). Differences in flows and loads between the two terms were equal to the net sum of precipitation (atmospheric deposition) minus evaporation. During summer, evaporation exceeds precipitation and total external inflow volumes were reduced by as much as 50% (Figure 11a). During winter, precipitation exceeded evaporation and thus net inflow volumes were slightly higher than total external inflows. For nutrient loads, net inflows were slightly greater than total external inflows in all months by an amount equal to the total atmospheric deposition, which was relatively minor compared to the external inflows (Figure 11b,c).

Despite the similarities in flows and loads between total external inflows and net inflows, there were large differences in TP and TN concentrations due to evaporative water losses during the summer growing season. These evaporative losses effectively reduced the volumes of the external inflows without changing the amount of nutrient mass associated with those inflows (Figure 11e,f). Over the course of the year, total external inflow TP concentrations were relatively stable across all months (approx. 100 ppb), while TN concentrations showed somewhat larger seasonality with highest values in spring and lowest values in fall. In contrast, the concentrations of net inflows exhibited much greater seasonal variability in both TP and TN

³⁷ Total External Inflow = Gauged Tributaries + Ungauged Basins + Pumped Areas

³⁸ Net Inflow = Total External Inflows + Precipitation – Evaporation. For loads, precipitation represents total atmospheric deposition and evaporation is zero.

due to the concentrating effect of evaporation. This effect was greatest in June, July, and August when net inflow concentrations exceeded the total inflow concentrations by a factor of 3 or more due to significant reductions in the net inflow volumes from high evaporative water losses (Figure 11a). During winter months when evaporation was negligible, the total external and net inflow concentrations were much more similar.

Lastly, because evaporation had the same effect on both P and N, there was relatively little difference in the N:P ratios between the two inflow terms, both of which were consistently below the threshold of $N:P = 5$ indicating favorable conditions for N-fixation (Figure 11d). Both terms also exhibited the same seasonal pattern with lowest N:P ratios in fall (Oct – Nov) indicating relatively higher P content, and highest in spring (May – Apr) indicating higher N content.

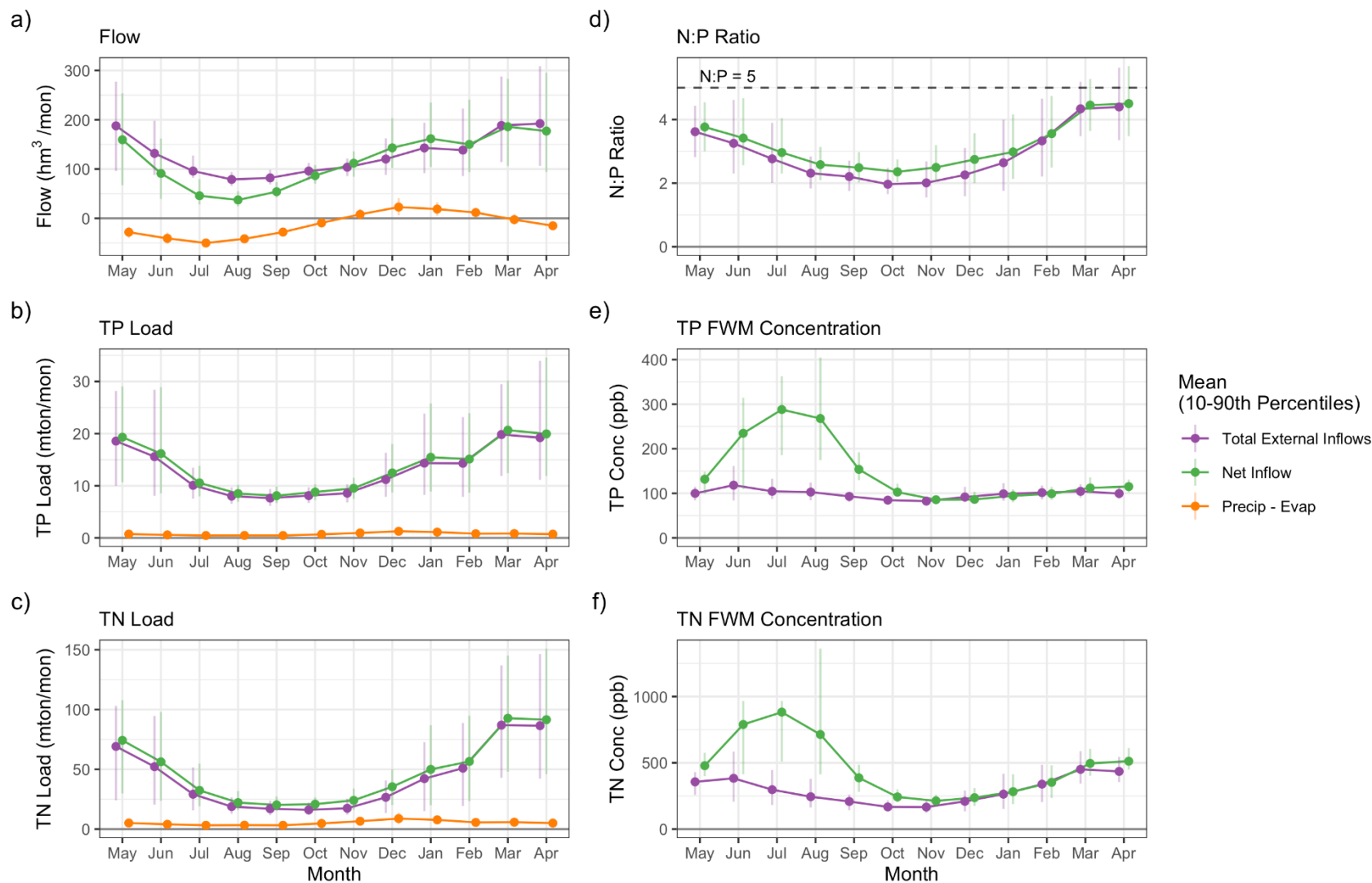


Figure 11: Monthly means and ranges of flows, nutrient loads, concentrations, and N:P ratios for primary inflow terms.

Points denote mean and vertical lines reflect ranges (10–90th percentiles) of monthly values for each term across all years. Nutrient loads for net precipitation (Precip – Evap) represent total (dry + wet) atmospheric deposition. Nutrient concentrations not shown for precipitation.

3.1.3.2 Lake Budgets

Seasonal variations in net inflow and lake outflow volumes exhibited opposing patterns with outflows exceeding inflows during the summer leading to a decline in lake volume (and also surface elevation), followed by greater inflows during winter causing the lake to refill (Figure 12a). Net inflows were higher in the winter and spring (Nov – May) due to snowmelt-driven runoff and higher precipitation, and lowest in the summer and fall (Jun – Oct) due to higher evaporation, lower precipitation, and lower baseflows from the lake tributaries.

TP loads exhibited a similar pattern with higher outflow loads in summer and higher net inflow loads during winter (Figure 12b). However, outflow TP loads were driven primarily by seasonal variations in the outflow FWM concentration and to a lesser extent by flow, while net inflow loads were more related to flow than concentration (Figure 12a,b,e). Both the outflow TP loads and concentrations were highest in summer (Jul – Sep) and lowest in winter and early spring, while outflow volumes were highest in May and lowest in the fall (Nov).

Unlike for the lake volume, changes in TP mass storage were driven primarily by the net retention term, especially during the summer growing season (May – Oct) (Figure 12b). In June and July, net retention TP loads had large, negative values indicating a major net release of P from the sediment to the water column, which in turn caused a large increase in P mass storage within the lake³⁹. Following this summer release, the net retention term switched from negative to positive values in August indicating sedimentation began exceeding recycling.

The switch in the direction of the net retention load coincides with the timing of the algal bloom decline, which generally occurs from late-July to early-September of most years (Kann, 2018; Nielsen et al., 2018). Therefore, the increase in sedimentation from July – August likely reflects the loss of P from the water column associated with settling of dead algal biomass, as well as a potential reduction in sediment recycling rates as temperatures begin falling. However, because the individual sedimentation and recycle rates were not directly estimated in this study, the relative changes in magnitude of the two fluxes are unknown.

Net inflow TP concentrations exceeded outflow concentrations for all months except Sep – Nov (Figure 12e). As discussed above, the net inflow concentrations are significantly higher than the total external inflow concentrations (i.e., concentrations of the total watershed discharge into

³⁹ Drivers of P flux from 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).

the lake) during summer due to evaporative water losses (Figure 11e, Section 3.1.3.1). Despite the high net inflow concentrations, net inflow TP loads were relatively low during the early summer due to lower flow volumes. Increases in the in-lake and outflow TP concentrations during the growing season were instead driven primarily by internal loading via sediment recycling in June and July as represented by the large, negative TP loads for the net retention term (Figure 12b).

Similar to TP, seasonal changes in mass storage and in-lake concentration of TN were driven primarily by a large internal loading during June and, to a lesser extent, July (Figure 12c). However, unlike internal loading of P via sediment recycling, internal loading of TN was derived primarily from the atmosphere through nitrogen fixation by cyanobacteria. Outflow TN loads were also consistently higher than net inflow TN loads due to the substantial internal loading during summer (large, negative net retention values in June and July), followed by lower net retention rates (small positive and negative values) during the rest of the year.

Net retention of P is likely higher than that of N outside of the growing season because P readily binds to inorganic particles that settle out of the water column. N losses from the water column are limited to settling of organic matter as well as flushing, and thus storage of N mass within the lake declines more slowly than for P. These differences between TP and TN dynamics within the lake are also reflected in storage concentrations with in-lake TP concentrations declining more rapidly than TN following the initial rise during the growing season (Figure 12e,f).

Seasonal variations in TN concentrations showed that the lake storage and outflow concentrations were consistently higher than the net inflow concentrations in all months (Figure 12f) despite the significant concentrating effect of evaporative losses during the summer (Figure 11f, Section 3.1.3.1). This difference is believed to be caused by both the high internal loading via nitrogen fixation during summer, as well as the lower retention rates as N water column losses are limited to the settling of organic matter and lake flushing.

For both TP and TN, lake outflow concentrations were relatively similar to the lake-wide mean concentrations (i.e., storage term) suggesting that outflow concentrations can be used as a surrogate for lake-wide mean concentrations (Figure 12e,f). Lastly, the N:P ratios of net inflows were consistently less than the threshold of 5 indicating that the nutrient composition of inflows promotes dominance by N-fixing cyanobacteria. In-lake and outflow TN concentration then increase at a greater rate relative to the net inflow TN concentration when compared to those for TP, causing a 2–5x increase in the June – September (5–10x higher October – February) in-lake and outflow N:P ratios (Figure 12d).

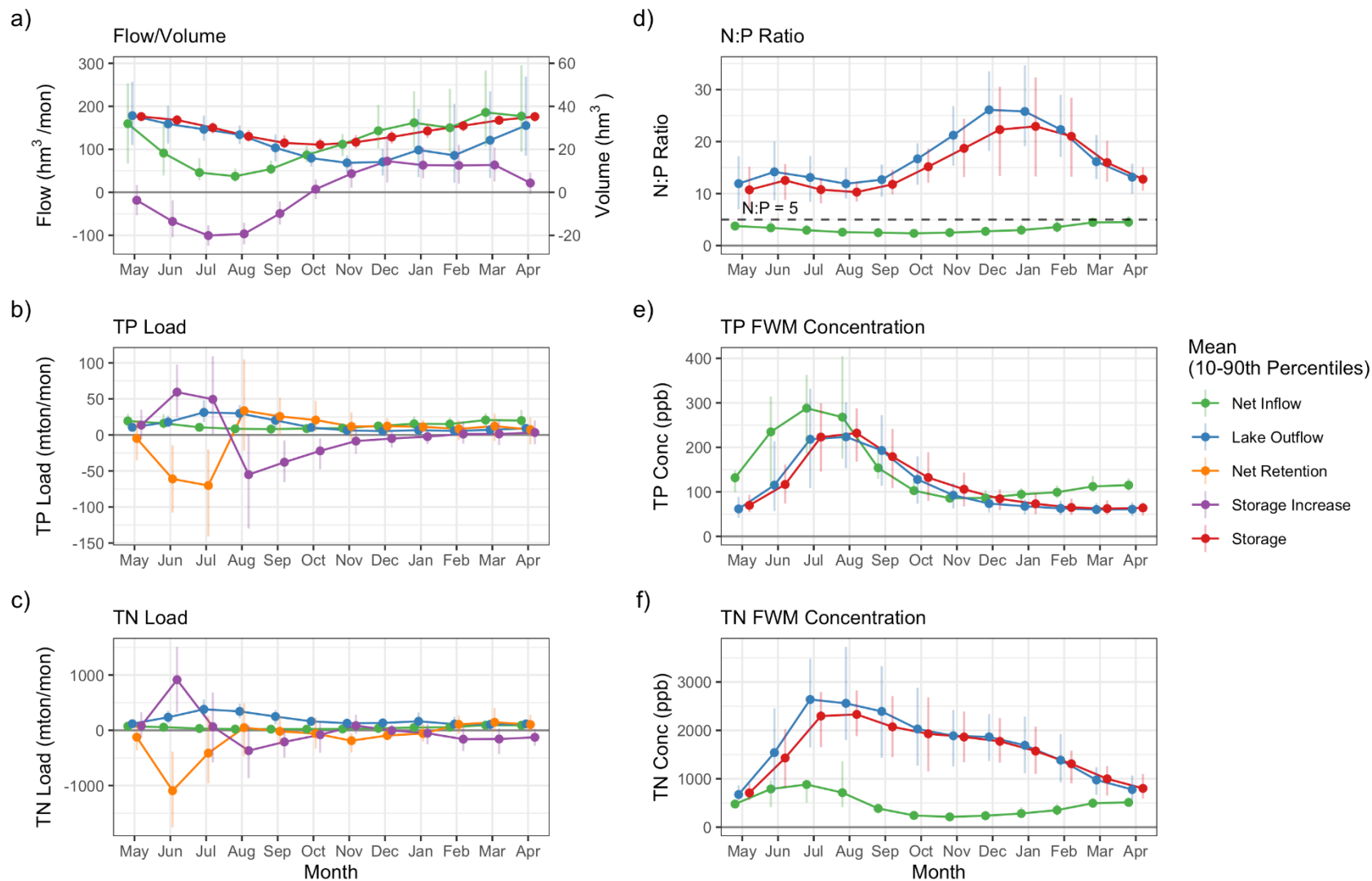


Figure 12: Monthly means and ranges of flows, nutrient loads, concentrations, and N:P ratios for primary lake budget terms.

Points denote mean and vertical lines reflect ranges (10–90th percentiles) of monthly values for each term across all years. Flows for net retention not shown due to negligible values. Nutrient mass storage also not shown.

3.2 Inflow/Outflow Phosphorus Dynamics

An important management-related question regarding phosphorus dynamics within UKL is whether TP concentrations within the lake (as well as in the lake outflow) are driven primarily by 1) recent external inflow loads or 2) internal loads derived from long-term accumulation of P in the lake sediment (i.e., legacy P). In the previous mass balances study, Walker et al. (2012) noticed an apparent one-year lag in the response of annual outflow TP loads to variations in net inflow loads over the previous period of record (WY 1992–2010) (see Figure 9b). That observation led to more detailed analysis and modeling of the annual and seasonal inflow/outflow TP dynamics over that period (Walker and Kann, 2020).

Using a simple linear regression model, Walker and Kann (2020) found that annual outflow TP loads in any given year were related not only to the inflow loads in that year but also loads from the previous year. Furthermore, correlations between the seasonal TP loads of net inflows, outflows, and net retention suggested that this short-term coupling between inflow and outflow loads was driven by rapid P cycling through the water column and sediment. Based on those results, Walker and Kann (2020) concluded that there was evidence suggesting outflow loads are driven primarily by recent inflow loads as opposed to large sediment storage of legacy P in UKL. Recently, Tammeorg et al. (2022) also found evidence that rapid sediment P cycling was more likely to occur than long-term accumulation of legacy P in a similar large, shallow lake (Võrtsjärv) in Estonia.

For this study, the models and data analyses presented in Walker and Kann (2020) were updated using the current mass balance dataset with the extended period of record (WY 1992–2018). In the following sections, we present a concise version of the results using data from all years of the current period. Appendix F provides a more complete set of results using both the current period as well as the previous period of record. Results based on the previous period of record were generated to show 1) that updates to the data sources and methodologies (e.g., new bathymetry) for the mass balance calculations had negligible impacts on the original results based on the previous version of the mass balance dataset, and 2) that the 8 years of additional data confirmed the original results by serving as an independent validation dataset. The updated results from this study generally confirmed the original findings as the additional 8 years of data were consistent with the patterns identified using the previous period of record.

To be consistent with the previous report (Walker and Kann, 2020), some of the following analyses were based on an alternative form of the water year, which we referred to as a phosphorus water year (PWY) and defined as the period from May – April (e.g., PWY 2018 = May 1, 2017 – April 31, 2018). This period was used instead of the traditional water year (Oct – Sep) as it coincides better with the seasonal phosphorus loading dynamics beginning with the

growing period (May – Oct) followed by a non-growing period (Nov – Apr). In this section, we also refer to a new mass balance term called “net release,” which has the same values as net retention but with the sign reversed (*Net Release* = – *Net Retention*).

3.2.1 Conceptual Model

To better illustrate the seasonal dynamics of the water and nutrient mass balances, the monthly and overall mean flows, nutrient loads, and FWM concentrations were plotted for the net inflow, outflow, net retention, and storage increase terms (Figure 13). This figure shows the same monthly mean values computed over the period of record (WY 1992–2018) as shown above in Figure 12 (Section 3.1.3.2); however, the flows and loads for outflows and net retention have been plotted using reversed signs so that positive values always indicate the addition of water or nutrient mass to the water column, and negative values indicate losses from the water column. As mentioned above, Walker and Kann (2020) referred to the negative net retention term as “net release” since positive values denote a net flux from the sediment to the water column, and negative values vice versa. Figure 13 was designed to more clearly show the relative balance between the primary lake budget terms by visually depicting the gains or losses associated with each term. This figure also includes the overall mean values of each term, which were computed as the mean of the 12 monthly values⁴⁰. Lastly, Figure 13 includes results for both nutrients (TP and TN) for comparison; however, the subsequent analyses (Sections 3.2.2 and 3.2.3) focused solely on the inflow/outflow dynamics of P (as did Walker and Kann, 2020) due to 1) the additional complexities of N dynamics (e.g., atmospheric exchange), and 2) the greater management focus on P load reduction as P is generally the limiting nutrient for algal growth in UKL.

3.2.1.1 Total Phosphorus

Based on overall mean values, the flows and TP loads of net inflows were nearly equal to those for the lake outflow, while values for net retention were negligible as were those for the change in storage (Figure 13). As mentioned above (Section 3.1.1), the balance between the overall mean net inflow and outflow TP loads suggests that *over the long-term* 1) external sources are the primary source of P into the lake, and 2) external P loads do not accumulate in the sediment. If internal loading from legacy P were a major source over the long-term then the overall mean net retention would have a larger negative value indicating an overall release of P from the sediment. However, although TP loads from net retention were negligible relative to

⁴⁰ The overall mean values reflect the long-term annual averages of each term, but are computed as the mean of the monthly values instead of the sum in order to have similar y-axis scales. Total annual flows and loads can be computed by multiplying the overall means by 12.

inflow and outflow loads on a long-term annual basis, net retention loads exhibited large month-to-month variations and were the primary drivers of seasonal P dynamics within UKL.

Early in the growing season (May – July), the net retention term released large quantities of P into the water column as indicated by the high, positive values for the $-(\text{Net Retention})^{41}$ term in Figure 13. These releases then drove an increase in TP mass stored within the lake, which in turn increased outflow TP concentrations. Although net inflow concentrations were also high during these months due to the concentrating effects of evaporative water loss (see Section 3.1.3.1), the net inflow TP loads were relatively small due to low flow volumes and thus had less of an effect on in-lake P storage and outflow P concentrations than the net release of P from the lake sediment. Following the initial net release of P, the net retention term reflected a net loss of P from the water column (negative values) beginning in August and extending over the rest of the PWY through April. This net retention of TP (i.e., losses from the water column) during the late summer (Aug – Sep) likely reflects settling of organic matter as this timing generally coincides with that of the algal bloom decline in UKL (Kann, 2019).

Following the algal growing season (Jun – Sep), the mean monthly TP loads for net retention indicated continuous losses of TP to the lake sediment throughout the fall, winter, and spring (Figure 13). From January to April, the net retention 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 retention flux.

Lastly, inflow and outflow TP loads exhibited different seasonal patterns due to differences in their associated flows and concentrations (Figure 13). Net inflow TP loads were primarily driven by changes in flow, which were highest in the winter to spring (Jan – May) due to snowmelt-driven runoff and lowest in the dry season from late summer to early fall (Aug – Nov) 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 the late-summer (Jul – Sep) and lowest in winter and early spring (Dec – May), while outflows reached a maximum earlier in the summer (May) and a minimum later in the fall (Nov). 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

⁴¹ The term “ $-(\text{Net Retention})$ ” refers to the net retention values with reversed sign such that positive values denote additions to the water column (net release), and negative values denote losses (net sedimentation).

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 differed 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.

3.2.1.2 Total Nitrogen

In contrast to TP, the overall mean TN loads were not balanced between net inflows and lake outflows (Figure 13). For TN, mean outflow loads were significantly higher than net inflow loads due to high internal loading of TN into the water column as reflected by the net retention term. As mentioned previously, this internal loading of N is primarily derived from atmospheric nitrogen fixation by cyanobacteria. Therefore, over the long-term, outflow TN loads from UKL are driven more by internal loading via nitrogen fixation than by external inflows from the lake watershed. And similar to TP, seasonal variations in the TN loads associated with the net retention term are major drivers of month-to-month variations in in-lake N storage and outflow loads and concentrations.

The majority of net internal N loading via nitrogen fixation occurred in June and, to a lesser extent, July, which are the months of highest cyanobacterial growth, as indicated by the large $-(\text{Net Retention})$ values (Figure 13). In June, this internal loading drives a large increase in the N storage within the lake, which is reflected by the increase in outflow TN concentrations. In July, those higher outflow concentrations led to the highest outflow TN loads of all months. Those high outflow loads were roughly balanced with the additional internal loading of N via the net retention term, and thus the change in N storage was negligible. In August, the net retention term indicated a minor loss of N from the water column, likely due to sedimentation of decaying algal biomass, which was nearly balanced by inputs of N via N fixation or sediment resuspension. However, unlike P, the net retention term indicated an overall net loading of N into the water column by varying amounts from September – January, with the highest loads occurring in November. Lastly, from February – April, net retention TN loads again flipped indicating net losses of N from the water column. Due to the greater number and complexity of chemical and biological processes affecting N, additional research is needed to better understand the mechanisms explaining these dynamics.

Similar to TP, seasonal variations in TN loads from net inflows were primarily driven by changes in flow while variations in outflow loads were primarily driven by changes in concentration. Outflow TN loads and concentrations were highest in late-summer (Jul – Sep) and lowest in winter and early spring. However, unlike for TP, outflow TN loads and concentrations were

always higher than those for inflow over all months due to the higher relative internal loads as well as lower rates of decline in TN concentrations following the growing season.

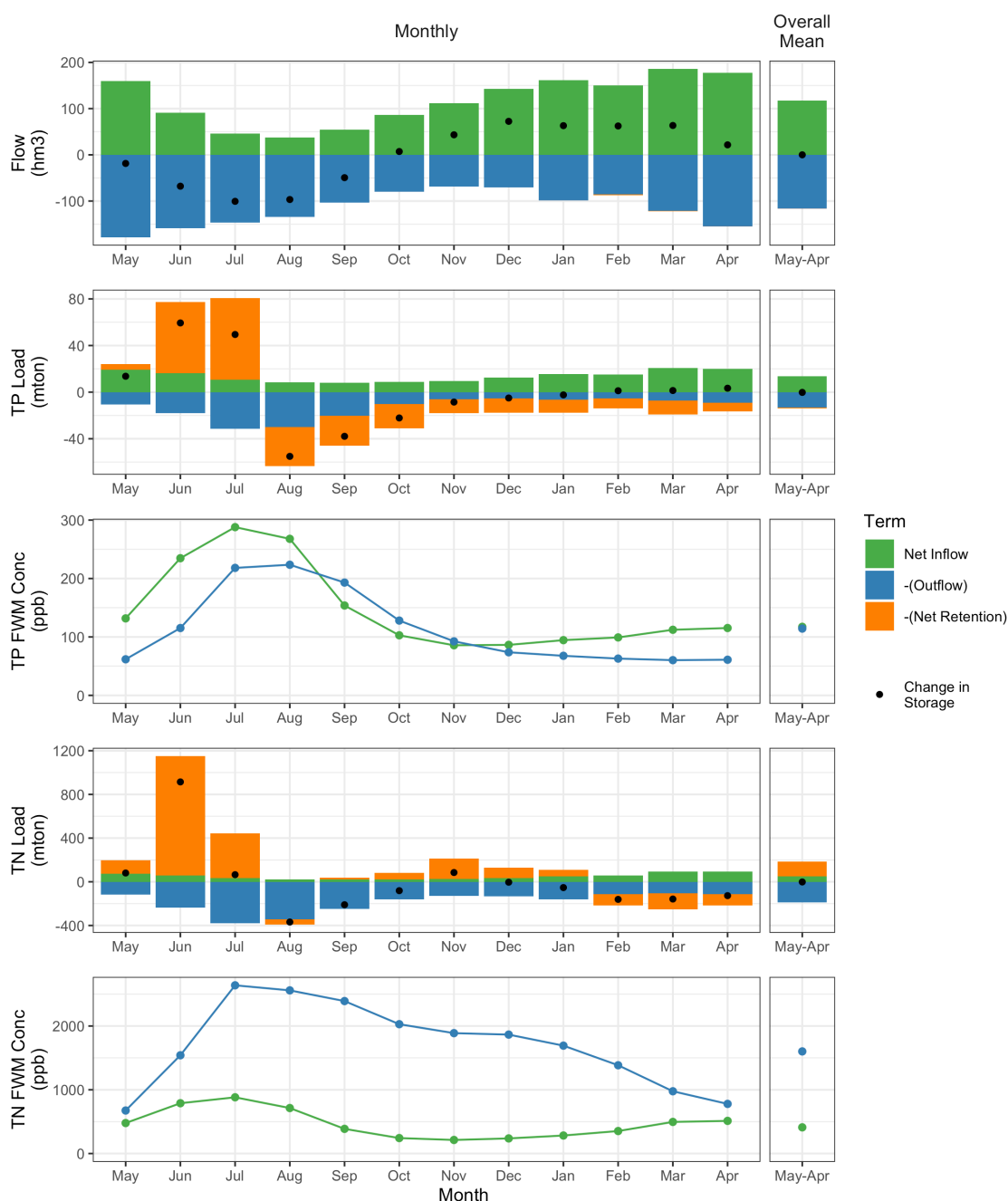


Figure 13. Monthly and overall mean flows, nutrient loads, and FWM concentrations of the primary lake mass balance terms.

Flows and loads for net retention and outflow are shown using values with reversed (multiply by -1) so that positive values denote additions to the water column and negative values indicate losses from the water column. "Overall Mean" values represent average annual fluxes but were computed as the mean (not sum) of the 12 monthly values so that the y-axis scales would be similar (total annual flows/loads = 12 x overall mean flows/loads).

3.2.2 Linear Regression Model

Walker and Kann (2020) showed a short-term coupling between annual outflow TP loads and recent net inflow loads using a simple linear regression model. This model indicated that the annual outflow load in a given year was driven by the net inflow load in that year as well as that of the previous year. This result suggested that the portion of net inflow loads that settle out of the water column during fall and winter are subsequently released back into the water column the following summer⁴². This model thus provided initial evidence that inflow loads to UKL undergo rapid cycling through the sediment as opposed to accumulating within sediment storage and becoming legacy P.

The annual outflow model is defined by the equation:

$$L_{out}[t] = \beta_0 + \beta_1 \cdot L_{in}[t] + \beta_2 \cdot L_{in}[t - 1] + \beta_3 \cdot t + \epsilon$$

where $L_{out}[t]$ is the annual outflow TP load in PWY⁴³ t (mton/yr), $L_{in}[t]$ and $L_{in}[t - 1]$ are the annual net inflow TP loads in PWYs t and $t - 1$, respectively (mton/yr), β_0 is the model intercept, β_i is the slope of the i^{th} term, and ϵ is the regression error term.

This model was fit using the updated mass balance dataset over current period of record (PWY 1994–2018)⁴⁴. Appendix F contains details about the model calibration over different periods and compares the results against those from Walker and Kann (2020) using the previous period of record (Figure F1). Overall, the model performance was slightly lower using the complete period of record compared to the previous period (adjusted R^2 fell from 0.69 to 0.58; Table F2, Appendix F). Predicted annual outflow loads were generally comparable to the original model (Figure 14); however, there were some noticeable differences in PWYs 2011–2013 when the model over-predicted outflow loads due to a high net inflow load in WY 2011 (see Figure 9b). Nevertheless, the estimated model parameters all remained statistically significant ($p < 0.05$) using the extended period, including the 1-year lag term for net inflows (Table F1, Appendix F). Therefore, using the current mass balance dataset, this model continues to provide evidence

⁴² From Jan – Apr, more than half of the mean monthly net inflow loads were retained within the lake (net release indicated overall loss from the water column) and the remainder was discharged in lake outflow since there was no change in storage (Figure 13). This period of net retention was followed by a large net release of P in June and July (Figure 13).

⁴³ PWY = Phosphorus Water Year (May 1 – Apr 30), which was used here instead of water years (WYs) to be consistent with Walker and Kann (2020).

⁴⁴ PWY 1994–2018 = May 1, 1993 – Apr 30, 2018. The full period did not start until PWY 1994 due to the lag term in the model; input values for PWY 1994 include annual net inflow loads in PWYs 1993 and 1994, and PWY 1993 was the first complete PWY in the period of record. PWY 1992 begins on May 1, 1991 which is before the start of the first water year (Oct 1, 1991 = start of WY 1992) in the mass balances dataset.

suggesting that recent net inflow loads are closely coupled to outflow loads via rapid cycling through the sediment.

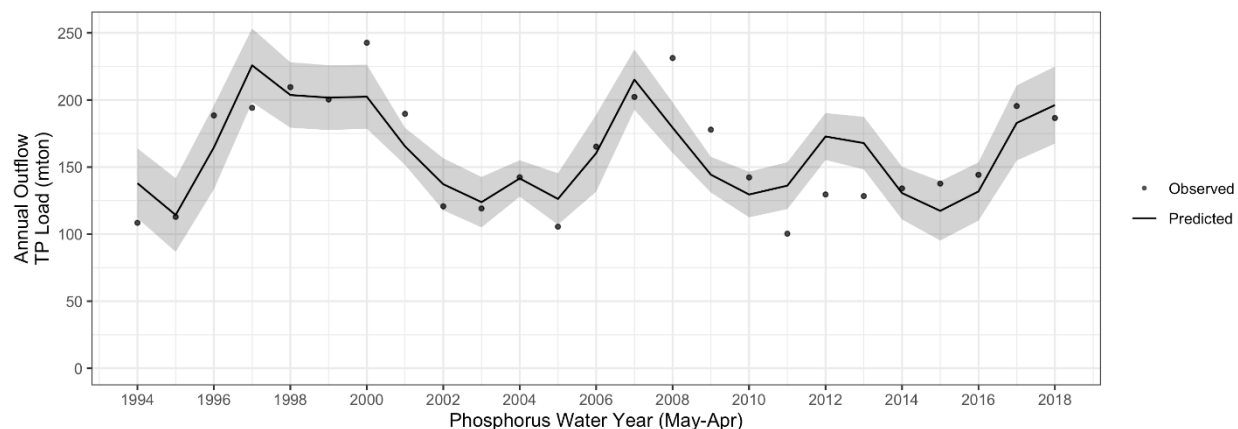


Figure 14: Observed and predicted annual outflow TP loads from the linear regression model.
Shaded band shows 95% confidence interval of model predictions.

3.2.3 Seasonal Correlations

In addition to the linear regression model of annual net inflow and outflow loads, Walker and Kann (2020) evaluated the correlations between seasonal net inflow, outflow, and net retention TP loads. These correlations ultimately revealed a series of relationships between these terms suggesting that outflow loads in one PWY are driven at least in part by net inflow loads from the previous PWY via a coupling between the net retention of P in winter and net release in the following summer. Using the current mass balance dataset, this series of correlations was updated using the 8 additional years of data in the extended period of record. A comparison between the correlations using the original and extended periods confirmed that the P loading dynamics in recent years followed the same general patterns as found in the original study (Figure F2, Appendix F).

The primary series of correlations that support these findings:

- a) **Winter (Nov – Apr) net retention TP loads** were positively correlated with **winter net inflow loads** ($r = 0.77$; Figure 15a) meaning that during winter, the higher the inflow loads, the more net retention of those loads via sedimentation,
- b) **Summer (May – Oct) net retention loads** were negatively correlated with **winter net retention loads** from the previous year ($r = -0.70$; Figure 15b) meaning the higher the

winter net retention in one year, the more net release of P in the following summer⁴⁵, and

- c) **Summer outflow loads** were negatively correlated to **summer net retention** ($r = -0.77$; Figure 15c) indicating the higher the net release (negative net retention) of P, the higher the outflow loads⁴⁶.
- d) **Summer outflow concentrations** were positively correlated to **summer outflow loads** ($r = 0.76$; Figure 15d) indicating that the increase in outflow loads driven by rapid sediment cycling of inflow loads from the previous year (steps a – c) also impacts both outflow and in-lake concentrations, which are highly correlated (Figure 10).

All correlations were statistically significant ($p < 0.01$) based on Pearson's product moment correlation test⁴⁷. Additional correlations between annual outflow and net inflow loads and concentrations are provided in Figure F2 (Appendix F) and contain the full sequence of relationships as identified in Walker and Kann (2020). The four primary correlations presented here (Figure 15) provide the main evidence suggesting outflow TP loads and concentrations are closely coupled to net inflow loads of the previous PWY via seasonal net retention and release.

⁴⁵ Because net retention loads in summer generally have negative values indicating a net release of P, the negative correlation between summer net retention and previous winter net retention can also be interpreted as a *positive* correlation between summer net *release* and the previous winter net retention.

⁴⁶ This correlation can also be interpreted as a *positive* correlation between summer net *release* and summer outflow loads due to summer net retention values being negative in sign (see previous footnote).

⁴⁷ Computed using the `cor.test()` function in R (R Core Team, 2021)

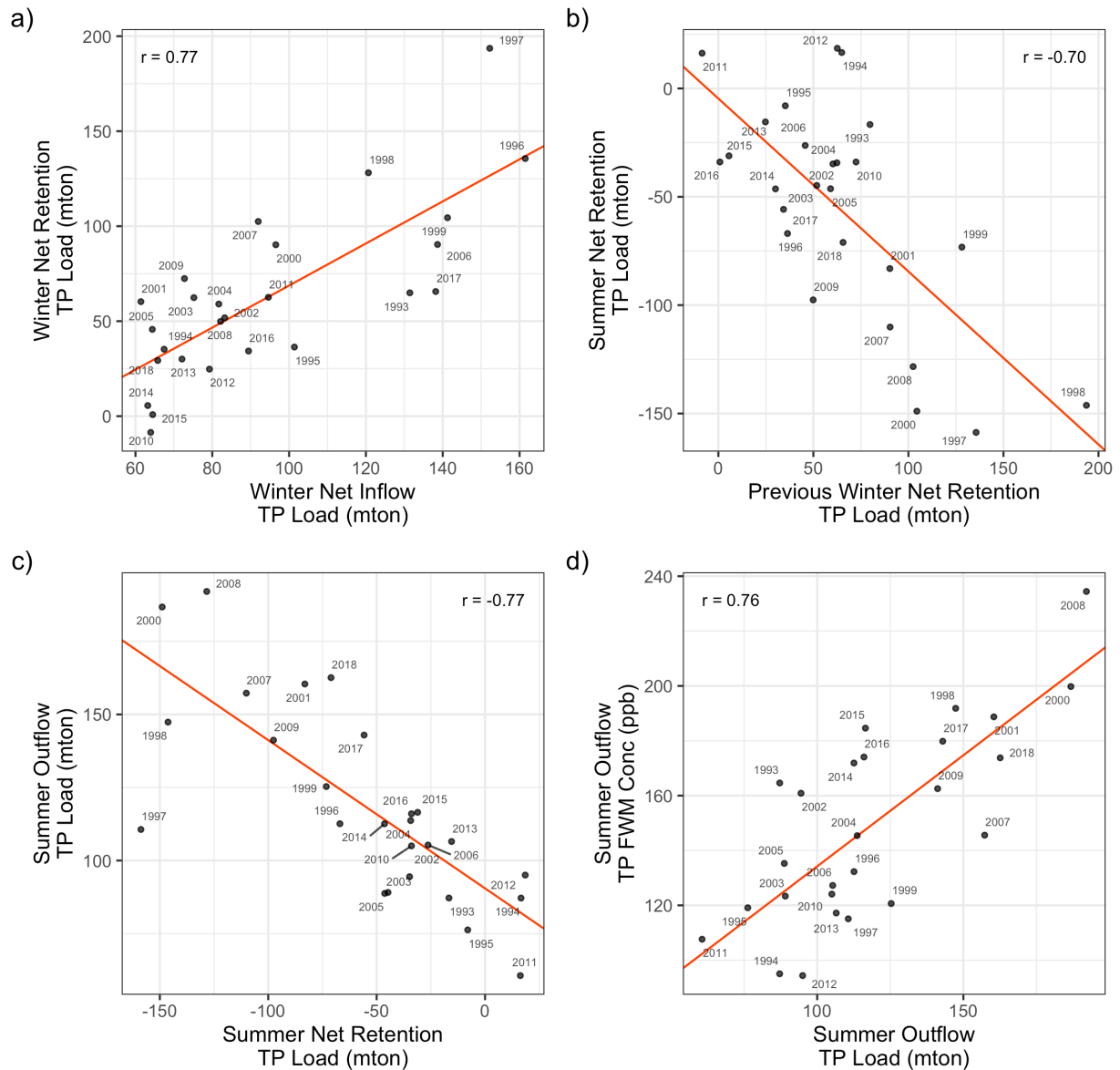


Figure 15: Relationships between seasonal net inflows, net retention, outflow TP loads, and outflow FWM TP concentrations.

Points labeled using Phosphorus WY (May 1 – April 30; e.g., PWY 2010 = May 1, 2009 – April 30, 2010). Seasons defined as Summer = May – Oct, Winter = Nov – Apr.

3.2.4 Example of Inflow/Outflow Dynamics

To better illustrate the coupling between net inflow and outflow loads via seasonal net retention and release, Figure 16 shows the monthly timeseries of net inflow, net retention (release), and outflow loads over a 2-year period (PWY 1997–1998). This figure shows that:

- a. In PWY 1997, the majority of the total **annual net inflow TP loads** occur during the winter;
- b. A portion of those **winter net inflow loads** are then retained within the lake via sedimentation;
- c. The **winter net retention** in PWY 1997 is then related to the amount of P released the following summer in PWY 1998;
- d. That **summer net release** drives higher summer outflow loads; and
- e. The **summer outflow loads** make up the majority of total annual outflow loads in PWY 1998.

This series of relationships demonstrate 1) the relationship between annual outflow loads in one year and the net inflow loads of the previous as indicated by the linear regression model (Section 3.2.2), and 2) how that relationship may be driven through the coupling between winter net retention and summer net release (Figure 15, Section 3.2.3).

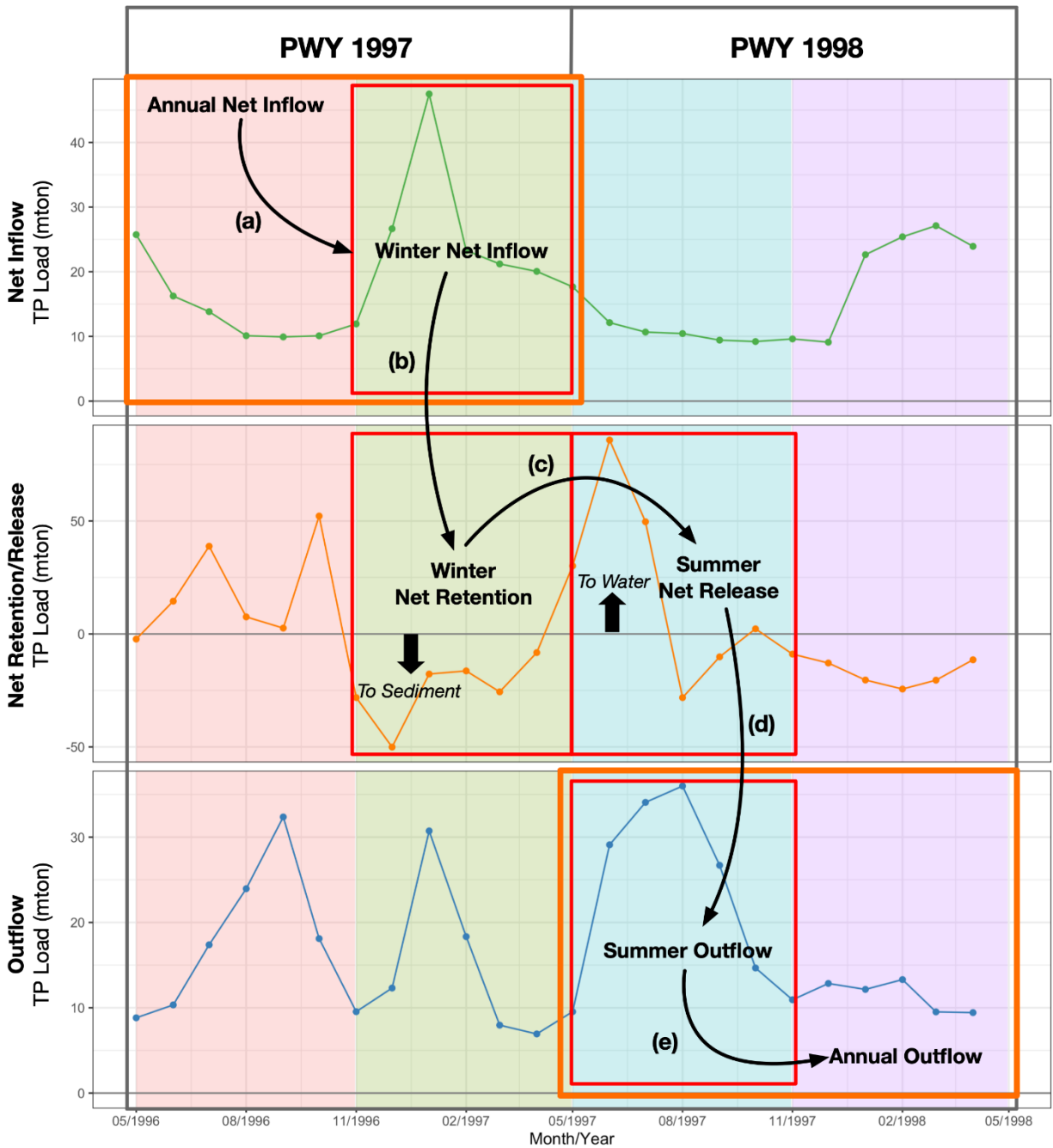


Figure 16: Monthly timeseries of net inflow, net retention, and outflow TP loads in PWY 1997 and 1998.

Demonstrates the sequence of annual and seasonal flux relationships from one year to the next. Adapted from Walker and Kann (2020).

3.3 Long-term Trends

Both increasing and decreasing long-term trends were detected in the flows, loads, and FWM concentrations of various water and nutrient mass balance terms (Figure 17). These results are based on the seasonal Kendall test and computed using the full period of record, WY 1992–2018. The magnitude of each trend is expressed as a relative slope (%/yr) due to the use of \log_{10} -transformed values, except for evaporation and net retention which were computed with untransformed values⁴⁸. The shades and colors of the trend slopes indicate the significance level (p-value) and direction (positive or negative) of each trend. Trends were not evaluated for some terms and parameters when they were based on constant values (e.g., ungauged and background concentrations) or equal to other terms (e.g., background and anthropogenic inflow volumes were both equal to total external inflows).

Following an initial review of the trend test results, it became clear that the significance levels of some trends were sensitive to the starting year of the period of record. For example, a decreasing trend in the total external inflow volumes was not significant over the full period of record (WY 1992–2018, $p = 0.26$), but was significant when the first year (WY 1992) was excluded (WY 1993–2018, $p = 0.003$). Therefore, in addition to the primary results over the full period, the primary seasonal Kendall test was also computed for a rolling series of periods with start years ranging from WY 1992 to WY 2009⁴⁹ and end years fixed at WY 2018 (Figure 18). These rolling trend test results are summarized based solely on the direction and significance of the trend over each period and for each term (trend magnitudes (i.e., slopes) are not shown).

Appendix G provides a series of trend diagnostics for each term and parameter showing results for various monthly, seasonal, and annual timeseries and using alternative statistical methods (i.e., linear regression and the Mann-Kendall test, see Section 2.10) (Figure G2). A table listing the trend slopes and significance values for each term and parameter is also provided (Table G1). Lastly, Figure G1 provides a summary plot of the trend results based on the previous period of record (WY 1992–2010) for comparison against the results previously reported by Walker et al. (2012)⁵⁰.

⁴⁸ Relative trend slopes were computed for evaporation by dividing the slope in volumetric units (hm^3/yr) from the annual Mann Kendall trend test by the long-term mean annual evaporation rate, and for net retention by dividing the seasonal Kendall test slope in mass units (mton/yr) by the long-term mean total external inflow load.

⁴⁹ WY 2009 was chosen as the last starting year as it yielded a period with 10 full years of data (WY 2009–2018), which was assumed to be a reasonable minimum length for a long-term trend evaluation.

⁵⁰ This comparison was performed to determine whether the change in methodology (i.e., using \log_{10} -transformed values) or changes in the data sources (e.g., updated bathymetry) had any effect on the previous trend results reported by Walker et al. (2012). In general, the results over the previous period using the current dataset were consistent with the previous study.

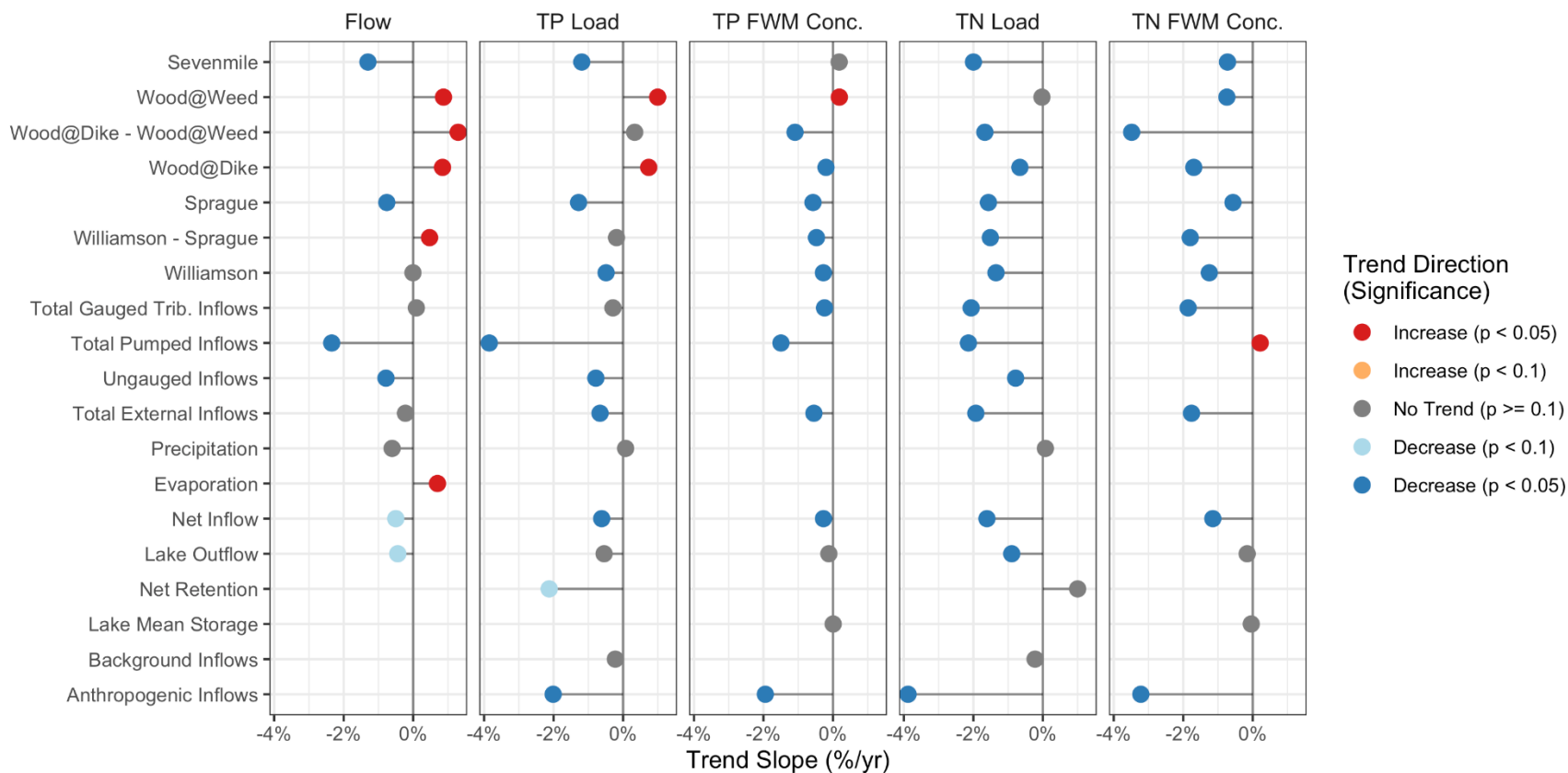


Figure 17: Long-term trends in flows, nutrient loads, and FWM concentrations over the period of record, WY 1992–2018.

All tests computed using seasonal Kendall test with \log_{10} -transform values except for evaporation flows and net retention loads, which were computed using untransformed values. For evaporation, the slope was estimated from Mann-Kendall test of untransformed annual values and divided by long-term mean annual evaporation to convert to relative slope (%/yr) due to the large number of zero values during winter, which affected the slope estimate of the seasonal Kendall test. For net retention, the slope was estimated from seasonal Kendall test of untransformed monthly values and the relative slope (%/yr) was computed by dividing slope in mton/yr by the long-term mean of total external inflow loads.

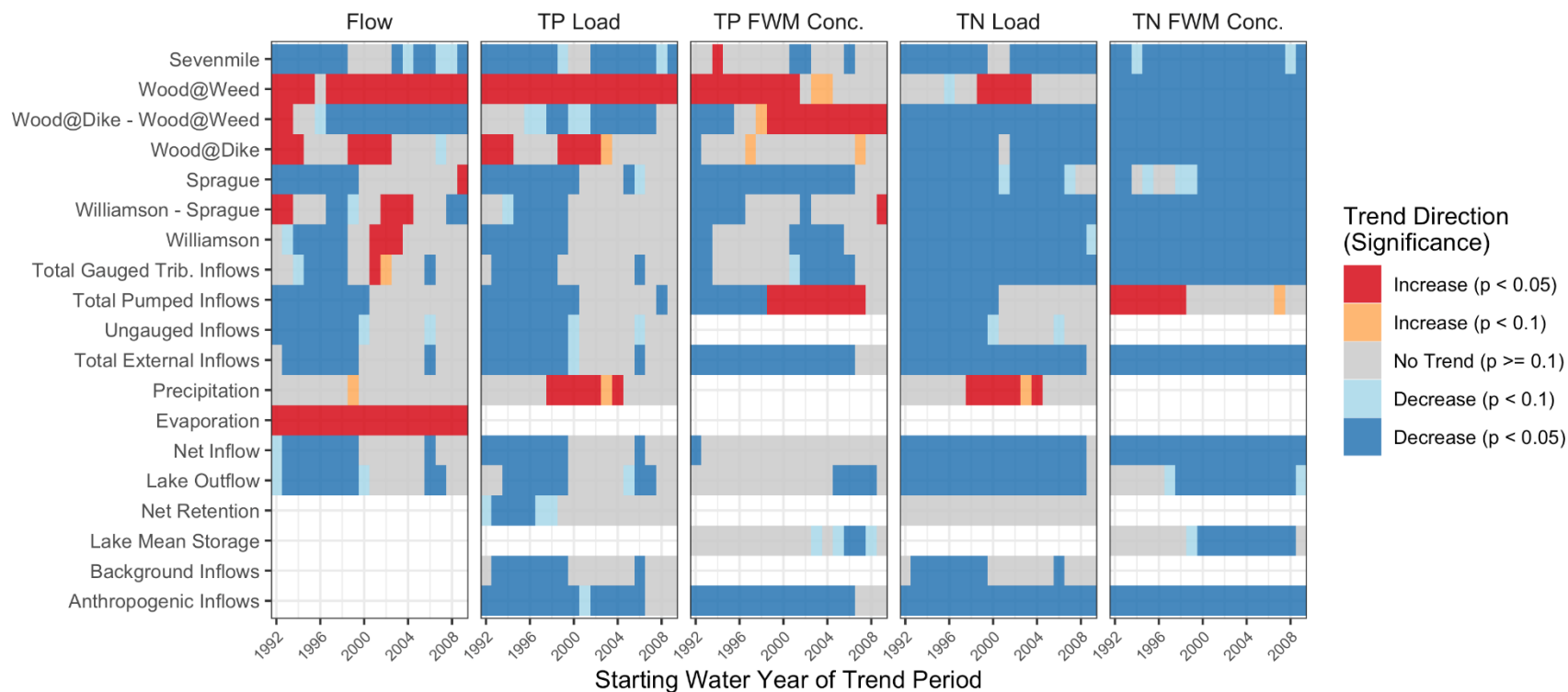


Figure 18: Rolling trend results based on periods from varying start years through WY 2018.

All tests computed using seasonal Kendall test based on all months (Oct-Sep) of data. Each value (tile) shows the trend direction and significance based on the period from the corresponding start water year (x-value) through WY 2018 for the given term and parameter.

3.3.1 Flow Volumes

Based on the full period of record (WY 1992–2018), the seasonal Kendall test indicated significant ($p < 0.05$) declining trends in flow in the Sevenmile Canal (-1.3 %/yr) and Sprague River (-0.8 %/yr) basins, as well as from total pumped (-2.3 %/yr) and ungauged inflows (-0.8 %/yr) (Figure 17). The decline in pumped inflow volumes was driven primarily by the restoration of former agricultural areas in ALR and the WRDP, which effectively reduced the total area being pumped into UKL. There were also relatively small trends having lower significance ($0.05 \leq p < 0.1$) for the net inflow (-0.5 %/yr) and lake outflow (-0.4 %/yr) terms, although these trends became more significant ($p < 0.05$) when WY 1992 was excluded (Figure 18). Similarly, decreasing trends in total external inflows (-0.5 %/yr) were significant over WY 1993–2018, but not over the full period. Increasing trends in flow occurred in the Wood River (0.8 %/yr) and Williamson River excluding Sprague (0.5 %/yr) basins, as well as for evaporation (0.7 %/yr) (Figure 17).

3.3.2 Total Phosphorus

Trends in TP loads were generally similar to those in flow with decreases in the Sevenmile canal (-1.2 %/yr) and Sprague River (-1.3 %/yr) basins, total pumped inflows (-3.9 %/yr), and ungauged inflows (-0.8 %/yr) (Figure 17). Decreasing TP loads from total external inflows (-0.7 %/yr) were also significant over the full period, as were the loads from net inflow (-0.6 %/yr). Decreasing trends in the TP loads associated with net retention (-2.1 %/yr) were moderately significant for the full period, but that significance increased ($p < 0.05$) when WY 1992 was excluded (Figure 18). The loads from anthropogenic sources also showed a significant declining trend (-2.0 %/yr). The only increasing trends in TP loads were in the Wood River above Weed Road (Wood@Weed; 1.0 %/yr) and at the outlet to Agency Lake (Wood@Dike; 0.7 %/yr). There was no significant trend for the Wood River basin between Weed and Dike Roads (Wood@Dike – Wood@Weed) and for the Williamson River basin excluding the Sprague (Williamson – Sprague) likely due to the offsetting trends in flows (increasing) and TP concentrations (decreasing). Overall, the TP loads generally mimic those in flows, except in a few cases when there were opposing trends in TP concentrations.

Significant decreasing trends in TP FWM concentrations were found for all terms (-0.2 to -1.9 %/yr) except for the Sevenmile Canal basin, lake outflow, and lake mean storage, which had no significant trends, and Wood River above Weed Rd (Wood@Weed), which had a small, but significant, increasing trend (0.2 %/yr). The largest declining trends were for total pumped loads (-1.5 %/yr) due to restoration of former agricultural areas in ALR and the WRDP, the Wood River basin below Weed Rd (Wood@Dike – Wood@Weed; -1.1 %/yr) likely due to restoration of the Wood River Ranch, which discharges directly to the Wood River above Dike Rd (Figure

C1, Appendix C), and for the total estimated loads from all anthropogenic sources (-1.9 %/yr). These trends were generally consistent whether WY 1992 was included or not in the trend period (Figure 18), with the exception of Wood River at Dike Rd and the net inflows, both of which were not significant when WY 1992 was excluded.

The rolling trend results show that the majority of decreasing trends in flows and TP loads were only significant when the trend period began in approx. WY 2000 or earlier (Figure 18). The total external inflows, net inflow, lake outflow and various individual inflow terms (except Wood River between Dike and Weed Roads) no longer exhibited decreasing trends when the analysis period began in WY 2001 or later. This suggests that many of these long-term trends reflect the relatively high flows and wetter climate conditions that occurred in the 1990s as compared to later years (Figure 6, Section 3.1.2.1). As discussed below (Section 3.4), this change in hydrologic conditions has important consequences when evaluating progress made towards achieving the TMDL targets for UKL, which were defined using historical flows and loads during the WY 1992–1998 baseline period.

The rolling trend results also reveal an important distinction in changes to the TP FWM concentrations of total external inflows versus net inflows⁵¹. TP concentrations of the total external inflows had significant decreasing trends for all periods with starting years between WYs 1992 and 2006 (Figure 18). However, net inflows only had a significant decreasing trend over the full period of record beginning in WY 1992; without WY 1992, there were no trends in the net inflow TP concentrations. Therefore, these results indicate consistent declines in TP concentrations from the combined discharge of all gauged tributaries, ungauged drainage areas, and total pumped inflows, but no consistent declines in the concentrations of net inflow. As discussed above (Section 3.1.3.1), evaporative water losses can have a significant impact on net inflow water quality by increasing the concentrations of the total external inflows, especially during summer. Therefore, the lack of trend in FWM TP concentration for net inflows (with 1992 excluded) may be explained by the increasing trend in evaporation (0.7 %/yr), which could effectively offset the declining trends in total external inflow concentrations. This increasing trend in evaporation rates is expected based on regionally hotter and drier weather conditions (Dalton and Fleishman, 2021). Large and shallow polymictic lakes such as UKL are expected to be more sensitive than deep lakes to physical drivers (e.g., Tuvikene et al., 2011). Variability (including long-term trends) in drivers such as evaporation can also make it difficult to discern the intended effect of management activities on water quality.

⁵¹ Recall that Net Inflow = Total External Inflow + Precipitation (Atmospheric Deposition) - Evaporation

Overall, these results suggest that while watershed restoration and management efforts may be driving a decline in the TP concentration of inflows from the lake's watershed, an increasing trend in evaporation driven by climate change may be offsetting those water quality improvements resulting in effectively a zero net change regarding the impact of those inflows on the water quality within UKL⁵².

3.3.3 Total Nitrogen

Compared to TP, there was widespread and consistent declining trends in the TN loads and concentrations across most of the mass balance terms (Figure 17). These trends were also less sensitive to the period of record, and in particular to whether the first year (WY 1992) was included or not (Figure 18).

Over the full period (WY 1992–2018), significant decreasing trends in TN concentrations occurred in all terms except the lake outflow and lake mean storage, which had no trends, and in the total pumped inflows, which had a significant but small increasing trend (0.2 %/yr). The largest trends were in the Wood River basin below Weed Rd (Wood@Dike – Wood@Weed; -3.5 %/yr) and for the estimated loads from anthropogenic sources (-3.2 %/yr). Total gauged tributary and total external inflows had similar declining trends (-1.9 and -1.8 %/yr, respectively), which were larger than the trends in net inflow (-1.1 %/yr) potentially due to the increasing trend in evaporation as discussed above (Section 3.3.2).

The decreasing trends in TN concentrations as well as those of flows in some terms led to widespread decreases in TN loads across all terms except precipitation (atmospheric deposition), net retention, and the estimated loads from background sources (Figure 17). TN loads from the gauged tributaries, pumped areas, and all external sources combined had similar decreasing trends (-1.9 to -2.1 %/yr).

3.4 Progress Towards TMDL Targets

To address the water quality impairments that commonly occur in UKL, a TMDL study established a target of 109 mt/year for the total external TP loads (including atmospheric deposition), which corresponds to a FWM concentration of 66 ppb at the average annual inflow (1,653 hm³/yr) observed over the TMDL baseline period (WY 1992–1998) (ODEQ, 2002). The TMDL target inflow concentration of 66 ppb is similar to the natural background concentration (65 ppb) estimated from sampling data collected at springs throughout the basin (Section 2.9).

⁵² As mentioned in Section 3.1.3.1, total external inflows represent the water quality of discharges from the watershed, while net inflows better reflect the impact of those inflows on water quality in the lake itself as they account for the concentrating effect of evaporative water losses.

In this section, we use the mass balance dataset to evaluate progress made towards achieving the TMDL target TP loads and FWM concentrations.

Annual inflow volumes, TP loads, and FWM concentrations derived from anthropogenic and background sources as well as precipitation (atmospheric deposition) were first compared relative to the TMDL targets (Figure 19). However, year-to-year variations in flows and loads driven by precipitation (Figure 8, Section 3.1.2.1) and snowpack⁵³ make it difficult to evaluate long-term changes in the lake inflows. Therefore, the 10-year rolling means (FWM for concentrations) of the annual values were computed to provide a more stable metric for evaluating progress towards meeting the TMDL targets (solid black line in Figure 19).

Comparisons between the observed loads and TMDL targets is also complicated by changes in the inflow volumes since the target load (109 mton/yr) was based on the average flows during the TMDL study period (WY 1992–1998). As mentioned above (Sections 3.1.2.1 and 3.3.1), annual flows were relatively high during first 9 years (WY 1992–2000) compared to the rest of the period of record (WY 2001–2018) (Figure 19a). Therefore, average annual TP loads have fallen by 22% from 185 mton/yr over the first 10 years (WY 1992–2001) down to 144 mton/yr over last 10 years (WY 2009–2018), but annual average flows have also fallen by 16% from 1,840 to 1,541 hm³/yr between those same periods. Since WY 2009, the rolling 10-year average total inflow volume has been below average flows used in the TMDL study (1,653 hm³/yr). Therefore, due to the confounding effects of flow changes on TP loads relative to the TMDL baseline period, the annual FWM TP concentration provides a more reliable indicator of load reduction progress.

Over the entire period, the 10-yr rolling FWM TP concentration fell by 7.5% from 101 ppb over the first 10 years (WY 1992–2001) down to 93 ppb over last 10 years (WY 2009–2018) (Figure 19c). Relative to the TMDL, these declines amount to a 23% reduction from 35 to 27 ppb above the 66 ppb target over those same periods. In the previous section, the statistical trend tests also confirmed that FWM TP concentrations of total external inflows had declined at an average rate of -0.7 %/yr over the entire period (Figure 17, Section 3.3.2), which leads to a similar overall change of -19% over the 27 year period of record. Furthermore, the trajectory of the 10-yr rolling FWM concentration indicates that the long-term trends were not due solely to reductions since the TMDL baseline period when flows (and FWM concentrations) were relatively high but had continued to steadily decline over the following decades. However, the rolling mean values for periods ending in the last three years (WYs 2016–2018) were relatively

⁵³ Although snowpack was not directly evaluated here, that interannual variability in inflow volume was related to on-lake precipitation indicates that variations in watershed snowpack and precipitation are captured by estimates of on-lake precipitation.

constant (93 ppb) suggesting reductions may have levelled off more recently, although more data are needed to confirm.

Subject to uncertainties associated with the limited data for pumped inflows prior to 2000, these results estimate the cumulative benefits of restoration measures implemented over the period of record. Further decreases may result from continued stabilization of soils in the restored wetlands and implementation of additional watershed load-reduction measures such as intensive riparian and floodplain restoration. Reductions in the lake and outflow concentrations may also occur as sediment nutrient storage and cycling equilibrate to the reduced inflow loads.

Overall, these results suggest that while some progress (approx. 25%) has been made towards reducing external inflow concentrations to achieve the TMDL target of 66 ppb, further reductions in the long-term (i.e., 10-year) FWM concentration of approximately 27 ppb are still needed.

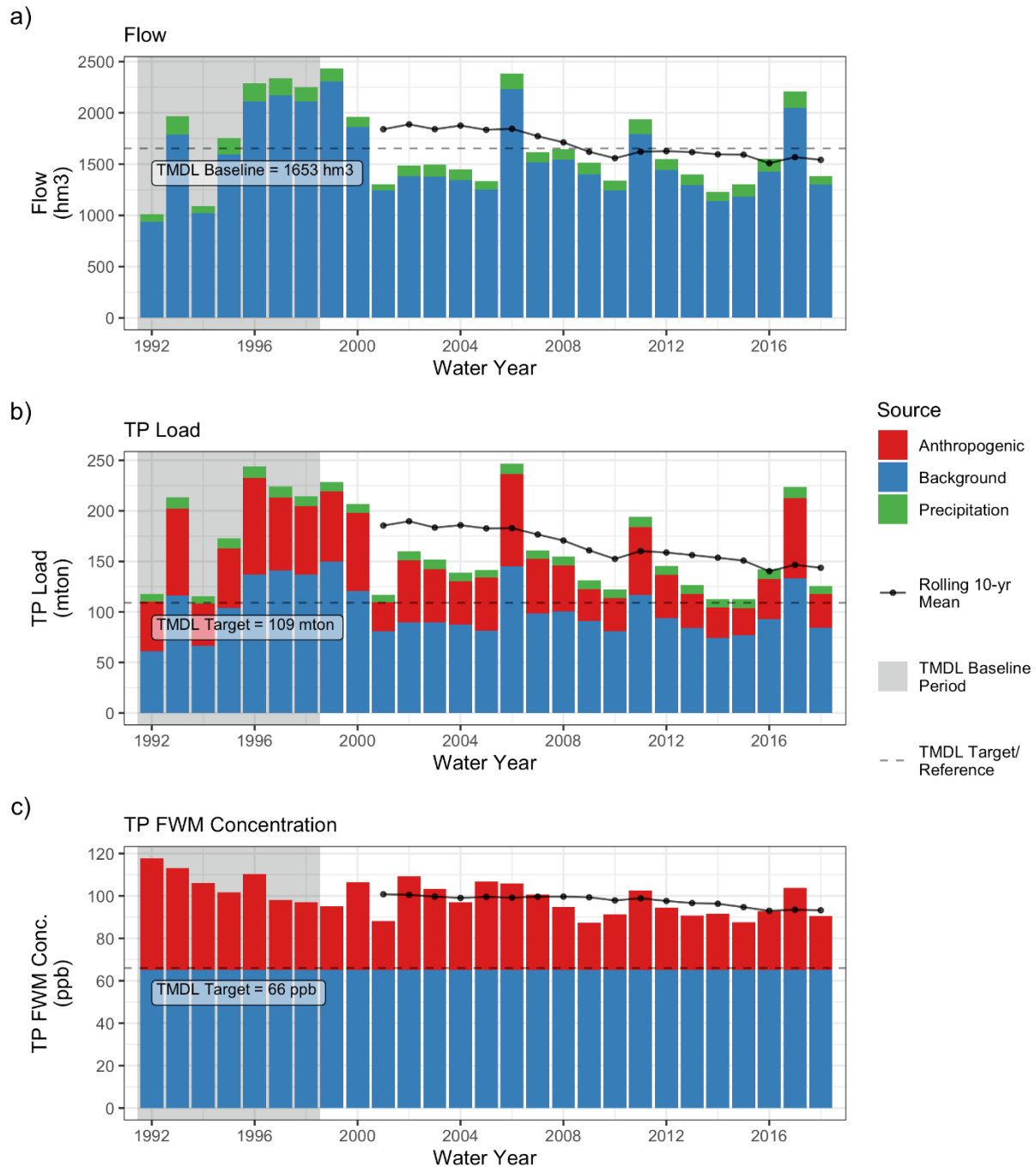


Figure 19: Annual flows, TP loads, and FWM concentrations from anthropogenic, background, and precipitation sources relative to TMDL targets.

Anthropogenic flows not shown as the differentiation between background and anthropogenic sources are only estimated for TP loads and concentrations (flows for both sources are assumed to equal total external inflows). Anthropogenic loads and concentrations computed as the difference between those for total external inflows and background sources based on a constant background concentration of 65 ppb (see Section 2.9). Precipitation loads include both dry and wet atmospheric deposition. Solid black line shows rolling 10-year mean flow, load, and FWM concentration from the first (WY 1992–2001) to the last 10-year sub-periods (WY 2009–2018).

4 Conclusions

A dataset representing the complete water and nutrient mass balances of UKL was generated for the current 27-year period of record (WY 1992–2018). The dataset provides monthly flows, nutrient (TP and TN) loads, and FWM concentrations of each mass balance term, and incorporates not only eight additional years of data since the previous UKL mass balance update, but also revisions to the data sources (most notably lake bathymetry), as well as other minor methodological changes. Compared to the previous update (Walker et al., 2012), there were relatively little change in the overall water and nutrient balances for the prior period of record (WY 1992–2010). The current dataset is thus meant to supersede all previous versions for use in future data analysis and modeling studies⁵⁴.

The updated mass balance dataset documents the long-term and seasonal dynamics of the hydrology and water quality of UKL and its watershed. This dataset provides a basis for evaluating changes in these dynamics and for detecting trends in the lake inflows, storage, and outflows in response to variations driven by climate, land use, and other factors. Development of this dataset strongly depended on the long-term UKL tributary and lake monitoring programs, the intensity, consistency, and duration of which are unique relative to typical monitoring programs designed to support management decisions.

The primary goals of this study were to update and extend the previous UKL mass balance dataset, and then re-evaluate the dynamics and long-term trends in the flows, nutrient loads, and concentrations of each mass balance term over the current period (WY 1992–2018). Although it was not our goal to comprehensively analyze and interpret all aspects of the mass balance dynamics and trends, the dataset as well as additional supporting information provided in this report (Appendices A – G) can be used to support subsequent analyses, interpretation, and model development. Future analyses may include placing results in the context of the specific management measures implemented during all or a portion of the WY 1992–2018 period, assessing the magnitude and effect of climatic trends, evaluating impacts of the Klamath Tribes water rights enforcement on inflows and nutrient loads, and developing better understandings of the hydrologic and nutrient dynamics of the lake in response to variations in external nutrient loads and other controlling factors.

Major conclusions from this study include:

⁵⁴ The current mass balance dataset is available at: <https://doi.org/10.5281/zenodo.6476840>

Long-term Average Balances

- Based on the long-term average water and nutrient mass balances for the entire WY 1992–2018 period, the total combined discharge from all external inflows (i.e., gauged and ungauged tributaries, pumped areas) had an annual average volume of 1,558 hm³/yr, nutrient loads of 155 and 513 mton/yr, and FWM concentrations of 100 and 329 ppb for TP and TN, respectively.
- Total discharge from the gauged tributaries (Williamson, Sprague, Wood and Sevenmile) accounted for 80% of the external inflow volume and 78 and 74% of the TP and TN loads, respectively. Total pumped inflows accounted for only 2% of the total external inflow volumes, but 11 and 21% of the TP and TN loads due to higher concentrations (430 and 2,778 ppb). The remaining 18% of external inflow volumes and 11 and 5% of TP and TN loads were generated from groundwater seepage, springs, and surface runoff from the ungauged portions of the UKL basin.
- The annual average lake outflow volume was 1,400 hm³/yr or 90% of total external inflows due to evaporative losses exceeding precipitation to the lake surface. Average outflow TP loads were 160 mton/yr and slightly less than the net inflow load (165 mton/yr) indicating that over the long term, outflow TP loads were relatively balanced by loads from total external inflows and atmospheric deposition.
- Because of the relative balance between inflow and outflow TP loads, the long-term average net retention of TP was small (7.2 mton/yr, 5% relative to the total external inflow load) indicating that over the entire period, the total amount of P sedimentation was approximately balanced by the amount of sediment recycling (i.e., release to the water column). The long-term balance between sedimentation and recycling suggests that P loading into the lake was derived primarily from external (i.e., watershed) sources instead of from internal loading from a large sediment storage of legacy P.
- In contrast to TP, for which inflow and outflow loads were relatively balanced, the overall mean outflow TN load of 2,242 mton/yr was 389% higher than the net inflow TN load (577 mton/yr) primarily due to nitrogen fixation by cyanobacteria within the lake. In other words, the net internal loading of N (primarily by nitrogen fixation) was nearly 4x the amount discharged into the lake from external watershed sources and atmospheric deposition.
- The total estimated background loads were 101 and 154 mton/yr, which were 65 and 30% relative to the total external loads. Anthropogenic loads thus accounted for the remaining 35 and 70% of the TP and TN external inflow loads and resulted in total

external inflow concentrations being 35 and 230 ppb higher than the estimated background concentrations (65 and 99 ppb).

- Runoff and nutrient export rates in the Sprague and Williamson River basins were lower than the Wood and Sevenmile basins by a factor of 10 or more. The highest unit-area runoff and nutrient export rates occurred in the Wood River basin below Weed Rd and in the Sevenmile basin. However, these values have high uncertainty due to cross basin water transfers for irrigation (e.g., from the Wood River basin to the Sevenmile basin) and high discharge from springs feeding these systems.

Annual and Seasonal Variations

- Total annual inflow volumes from gauged and ungauged drainage areas, pumped areas, and precipitation varied over approx. 1,000 – 2,500 hm³/yr, and annual inflows were generally higher during the 1990s than in later years with values exceeding the long-term mean in 7 out of the first 9 years (WY 1992–2000) and only 3 (WYs 2006, 2011, 2017) of the remaining 18 years (WY 2001–2018). However, the two years with lowest total inflows (WYs 1992 and 1994) also occurred during those first 9 years.
- Total external inflow and external TP loads exhibited similar patterns indicating that year-to-year variations in loads were driven primarily by flows as opposed to TP concentrations, which were not related to flow. Total external inflow TN loads, on the other hand, were driven by both flows and, to a lesser extent, concentration.
- Annual variations in total external inflow volumes and nutrient loads were also both strongly correlated with variations in precipitation, underscoring the important effect of year-to-year variations in climate on nutrient loads. Thus, TP concentrations that were relatively independent of precipitation, provide a more reliable basis for tracking long-term trends related to watershed restoration than do loads which were highly related to annual variations in flow and precipitation.
- On an overall annual basis, net P retention was small (5% relative to the total external inflow load) indicating that over the long-term, phosphorus loading into the lake was ultimately derived from external (i.e., watershed) sources instead of from internal loading associated with sediment recycling of legacy P.
- On a seasonal basis, however, net retention and release of P between the sediment and the water column was a critical driver of in-lake and outflow water quality, more so than net inflows, which had high concentrations during early summer but small loads and low volumes due in part to evaporative water losses.

- Both internal and external P and N loads exhibit strong seasonal patterns, where changes in TP mass storage, lake concentration, outflow load, and outflow concentration were driven primarily by month-to-month variations in net retention and release. This was especially true during the critical early summer (June – July) algal growing season in UKL, when large quantities of P were released into the water column.
- Following the large net release of P in the early summer, the net retention term reversed direction indicating that sedimentation exceeded recycling beginning in August when cyanobacterial blooms generally begin declining in UKL.
- Similar to TP, seasonal variations in the TN loads associated with the net retention term were major drivers of month-to-month variations in in-lake N storage and outflow loads and concentrations. The majority of net internal N loading via nitrogen fixation occurred in June and, to a lesser extent, July, which are typically the months of highest cyanobacterial growth. However, in contrast to TP:
 - a. Overall mean TN loads were not balanced between net inflows and lake outflows, and over the long-term, outflow TN loads from UKL were driven more by internal loading via nitrogen fixation than by external inflows from the lake watershed.
 - b. Outflow TN loads and concentrations were higher than those for inflow over all months due to the higher relative internal loads as well as lower rates of decline in TN concentrations following the growing season (for TP outflow loads were higher than inflow loads only July-September).
 - c. The net retention term for TN indicated an overall net loading of N into the water column by varying amounts from September – January (for TP, the net retention indicated net losses of TP from the water column to the sediment throughout the fall, winter, and spring).
- N:P ratios of net inflows to UKL were consistently very low (< 5) indicating that inflows promote dominance by N-fixing cyanobacteria. During the growing season (June – September), in-lake and outflow TN concentration increased at greater rates relative to the net inflow TN concentration when compared to those for TP, causing a 2–5x increase in the in-lake and outflow N:P ratios. During the non-growing season (October – February), the N:P ratios of in-lake and outflow concentrations were 5–10x higher than for inflows. The increased N:P ratios as well as outflow TN concentrations being approx. 5x higher than for inflows have important implications for downstream algal dynamics in the Klamath River.

- Monthly mean lake storage concentrations were highly correlated with FWM concentrations of lake outflow for both TP and TN. These relationships provide a basis for using outflow concentrations as a surrogate for in-lake water quality when evaluating the inflow/outflow dynamics of P loading, retention, and discharge.

Inflow/Outflow Phosphorus Dynamics

- A simple linear regression model of annual inflow and outflow TP loads indicated that outflow loads were driven at least in part by inflow loads from the previous water year.
- A series of correlations between the seasonal TP loads of net inflows, outflows, and net retention showed that summer outflow loads and concentrations were related to inflow loads from the previous winter through rapid cycling of P between the water column and lake sediment. These results suggest that inflow loads during the winter were retained in the lake sediment, and subsequently released during the following summer, which in turn were related to the in-lake and outflow TP concentrations.
- These findings have important management implications as they suggest that watershed restoration efforts should have near-term benefits by reducing inflow TP concentrations and loads, which in turn should reduce the amount of P released during the summer growing season.
- The results in this study confirmed those from a recent study of inflow/outflow P dynamics (Walker and Kann, 2020), which was based on the previous mass balance dataset (WY 1992–2010; Walker et al., 2012). Data from the additional 8 years of data (WY 2011–2018) generally followed similar dynamics as previous years providing an independent validation of the original study.

Long-term Trends

- Seasonal Kendall tests using the full period of record (WY 1992–2018) revealed both increasing and decreasing long-term trends in the flows, loads, and FWM concentrations of various water and nutrient mass balance terms.
- Significant ($p < 0.05$) decreasing trends for flow, TP and TN load were detected for Sevenmile Canal, Sprague River, total pumped inflows, and ungauged inflows. Large decreasing trends in the pumped inflow loads and concentrations were likely caused by discontinued pumping and restoration of agricultural areas adjacent to UKL (e.g., Agency Lake Ranch, Williamson River Delta Preserve).

- Decreasing TP loads were also observed for the Williamson River, total external inflows, net inflow, net retention, and anthropogenic sources. TN loads also showed declining trends for these same terms, in addition to numerous other inflow terms and for lake outflow.
- Significant increasing trends in flow occurred in the Wood River and Williamson River excluding Sprague basins, as well as for evaporation, which has important management implications as mentioned below. The only increasing trends in TP loads were in the Wood River above Weed Rd and at Dike Rd (outlet to Agency Lake).
- Observed increases in flow from the Wood River basin may be related to decreases in agricultural withdrawals due to implementation of the Klamath Tribes water rights. Despite decreasing FWM concentrations, TP loads from the Wood River also increased as a result of the increasing flows.
- Overall, the TP loads generally mimicked those in flows, except in cases such as the Wood River basin between Weed and Dike Roads and for the Williamson River basin excluding the Sprague when there were opposing trends in TP concentrations.
- Significant decreasing trends in TP FWM concentrations were found for all terms except for the Sevenmile basin, lake outflow, and lake mean storage, which had no significant trends, and Wood River above Weed Rd, which had a small, but significant, increasing trend. The largest declining trends were for total pumped loads due to restoration of former agricultural areas in ALR and the WRDP, the Wood River basin below Weed Rd likely due to restoration of the Wood River Ranch, and for the total estimated loads from all anthropogenic sources.
- Significant decreasing trends in TN concentrations occurred for all terms except the lake outflow and lake mean storage.
- A sensitivity analysis of the trend test results using rolling periods (starting years varying from WY 1992 through WY 2009, and always ending in WY 2018) revealed that the significance levels (i.e., p-values) of the long-term trend results were sensitive to the first year in the period of record, WY 1992, which was also one of the driest years with the lowest total inflow volumes.
- The significant increasing trend in evaporation may have implications for meeting minimum UKL lake levels for ESA fish species, as well as for irrigation water supply and for meeting downstream Klamath River flow requirements for native fisheries.

- Increasing evaporation (likely due to the effects of climate change) may have offset decreasing trends in total external inflow nutrient concentrations. High evaporation rates can have a significant impact on the water quality by effectively increasing the net inflow concentrations as well as in-lake concentrations by removing water volume but not nutrient mass. Therefore, despite decreasing trends in total external inflow nutrient concentrations and loads, there were no significant long-term trends in the FWM concentrations of net inflows (when WY 1992 is excluded), lake mean storage, or lake outflow likely due to the long-term increases in evaporation.
- The rolling trend results showed that many of the long-term decreasing trends in flows and TP loads were driven by the relatively wet conditions throughout the 1990s (except WYs 1992 and 1994). When the trend analysis was performed on data beginning in WY 2001 or later, the majority of these decreasing trends were no longer significant. These results suggest that many of these long-term trends over the period of record (especially without WY 1992) reflect the relatively high flows and wetter climate conditions that occurred in the 1990s as compared to later years.
- Notable exceptions to the previous point were the decreasing trends in TP FWM concentrations for the Sprague River basin, total external inflows, and anthropogenic inflows, all of which were significant in all periods beginning in WY 2006 or earlier.

Progress Towards TMDL Targets

- Changes in hydrologic conditions (annual flows were relatively high during first 9 years, WY 1992–2000) compared to the rest of the period of record (WY 2001–2018) have important consequences when evaluating progress made towards achieving the TMDL targets for UKL (TP load of 109 mton/yr, FWM TP concentration of 66 ppb for all external inflows), which were developed based on historical conditions during WY 1992–1998.
- Because the TMDL target load (109 mton/yr) is tied directly to the above-average flows that occurred during the TMDL study period (WY 1992–1998), it is difficult to evaluate progress towards the TMDL targets based on loads alone because they reflect changes in both flow and concentration. However, unlike TP loads, the annual FWM concentration of external inflows is relatively independent of variations in precipitation and flow and is thus a more reliable indicator of progress made towards achieve the goals of the TMDL as concentrations are not confounded by changes in climate and hydrology relative to the TMDL baseline period.

- Over the entire period, the 10-yr rolling FWM TP concentration fell from 101 ppb over the first 10 years (WY 1992–2001) down to 93 ppb over last 10 years (WY 2009–2018), which represents a 23% reduction from 35 to 27 ppb above the 66 ppb TMDL target over those same periods. This decline is similar to the estimated decreasing trend rate ($-0.7\ \%/yr = -19\%$ over all 27 years) for the total external inflow FWM TP concentration.
- The 10-year rolling FWM TP concentration also showed a steady decline indicating that external load reductions over the entire period were not due solely to changes in the hydrologic conditions from the relatively wet years during the TMDL baseline period in the 1990s, but also reflect continuous declines in the FWM concentration over the following decades. However, average concentrations for the last three 10-year periods (ending in WYs 2016–2018) were relatively constant (93 ppb) suggesting reductions may have levelled off more recently, though more data are needed to confirm.
- Overall, the 23% reduction from 35 to 27 ppb above the 66 ppb TMDL target (101 to 93 ppb total) of external inflow FWM TP concentrations indicates the cumulative benefits of restoration measures implemented over the period of record. However, further reductions of approx. 27 ppb in the 10-yr rolling FWM TP concentration of total external inflows are needed to achieve the TMDL target of 66 ppb.

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