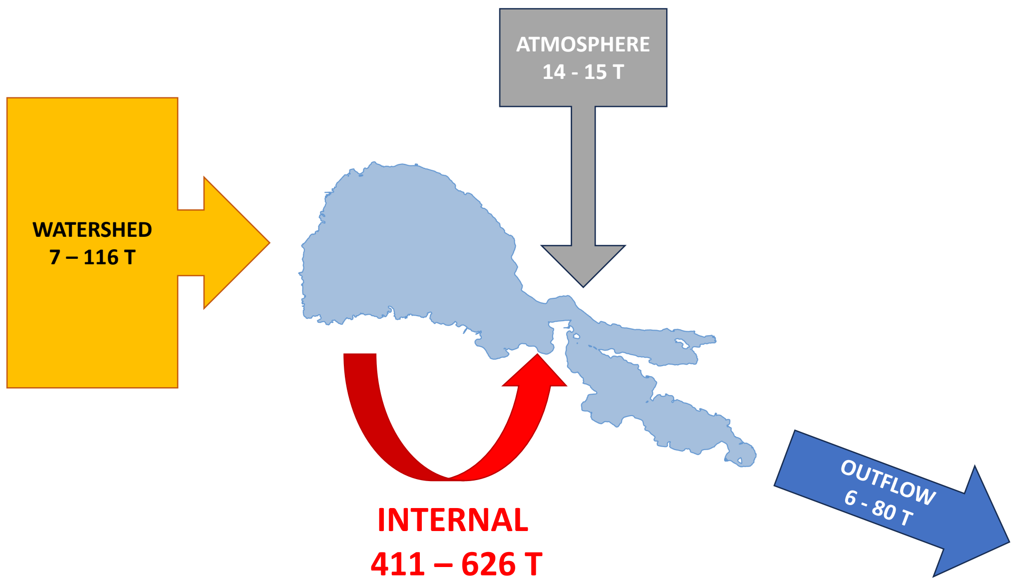
UC DAVIS Tahoe Environmental Research Center

Clear Lake Phosphorus Budget
2019 – 2022



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A report to the Blue Ribbon Committee for the Rehabilitation of Clear Lake

July 2023

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1 Executive Summary

This report details the phosphorus (P) budget for the Clear Lake watershed from 2019 – 2022. To control excessive algal growth and maintain beneficial uses of the lake (CVRWQCB 2006), Clear Lake has a total maximum daily load limit (TMDL) of 239.1 kg of total phosphorus. P is derived from both external (e.g. stream flow, urban runoff, and atmospheric deposition) and internal (anoxic lake sediments) sources. Here we quantify these various P inputs and outputs to Cache Creek during a four-year period to assess the current state of phosphorus cycling within the lake and support targeted lake management and restoration strategies. This four-year span a range of meteorological conditions, with 2019 being a wetter-than-average year and 2020-2022 recording drought conditions.

We quantified the external watershed load using flow-weighted loading estimates and the internal load released from lake sediments using two methods: observed increases in water column TP during the dry season and modeled releases based on measurements of hypoxia. Our results indicate:

1. The total TP load to Clear Lake was in the range of 412 – 626 tons. The majority of TP inputs to the lake were released from anoxic sediments during the summer. The variation in watershed loading was due to lower streamflow during drought years.

    a. Watershed: 7 – 116 tons (3-28%)
    b. Atmosphere: 14 – 15 tons (2-3%)
    c. Internal: 412 – 626 tons (70-95%)

2. Total TP output to Cache Creek ranged from 7 – 80 tons. The fact that outputs were lower than inputs indicates that TP is continuing to accumulate within lake sediments.

Results from this report confirm that internal loading from lake sediments constitutes the majority of phosphorus inputs into the lake annually. Thus, solutions targeting these in-lake sources are needed in conjunction with watershed restoration to reduce phosphorus loading in the long term.

2 Introduction

Eutrophication of recreational lakes is an important management issue across much of California. During the summer, many lakes experience significant growth of planktonic algae, which frequently contain nuisance blooms of cyanobacteria that pose human health risks. Phosphorus (P) is often identified as the limiting nutrient for algal growth in temperate, freshwater lakes and comes from a range of sources, including runoff, atmospheric deposition, groundwater, sewage, and lake sediments. By developing phosphorus budgets, researchers and water resource managers can better understand the relative contribution of these various sources of phosphorus entering the lake ecosystem. This knowledge allows for the implementation of targeted and effective management strategies to reduce phosphorus loadings and ultimately improve water quality.

Clear Lake is naturally highly productive due to its large drainage basin area, nutrient-rich soils, and high alkalinity. However, paleolimnological studies (Kim 2003) indicate eutrophication has been exacerbated since the mid-1800s by anthropogenic activities such as wetland conversion, shoreline development, agriculture, and mining (Suchanek et al. 2003). In addition to these external sources, lake sediments release large internal P loads each summer when bottom water oxygen concentrations are low. This internal flux from lake sediments has largely driven the annual oscillations of lake P concentrations evident in long-term monitoring data, with peak P observed in the late summer (Figure 1).

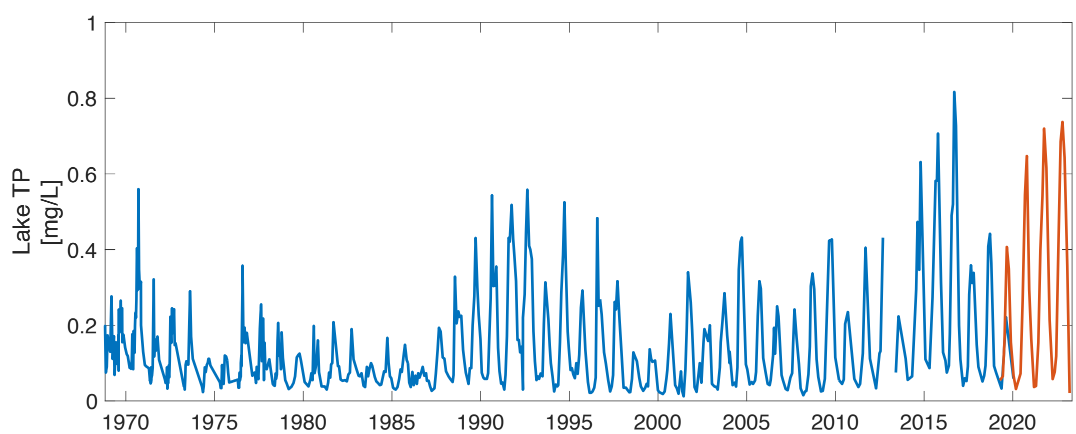

Figure 1. Clear Lake TP concentration 1969 – 2022 measured by DWR (blue) and UC Davis (orange).

As a result of its relatively high phosphorous concentrations, Clear Lake is susceptible to frequent cyanobacteria blooms. Significant blooms have been observed across the lake from April to October, preventing recreational activities, increasing water treatment costs, and posing serious health risks to users and their pets. Numerous investigations have been conducted to examine methods to reduce the frequency and intensity of cyanobacterial blooms in the lake (Richerson 1994; Suchanek et al. 2003). In 2006, a phosphorus total maximum daily load (TMDL) was established for Clear Lake, in an effort to reduce blooms by limiting and allocating the total amount of phosphorus input into the watershed. The TMDL established a daily P loading limit of 239.1 kg (87.3 T yr^{-1}) to limit algal growth in the lake (CVRWQCB 2006).

This report provides an overview of the phosphorus budget to Clear for a four-year period (2019 – 2022) in an effort to assess the current state of phosphorus cycling within the lake. These years capture the range of extreme variability in the meteorological and hydrological conditions of Northern California, with 2019 recording one of the highest precipitation accumulations and 2020-2022 being relatively dry years. The following sections detail data collection, methodologies, and results for the Clear Lake phosphorus budget.

This report is part of a more detailed analysis of phosphorus dynamics that is forming part of the dissertation research that has been conducted by Micah Swann.

3 Data Sources

3.1 Clear Lake Monitoring Data

Since March 2019, UC Davis has been conducting an extensive limnological monitoring program collecting both continuous *in situ* measurements of temperature and dissolved oxygen (DO) and periodic water quality sampling events (Figure 2). Water samples were collected from seven locations spanning Clear Lake's three subbasins (Upper, Oaks, and Lower Arms) at a frequency of ~6 weeks in summer and ~8 weeks in winter. At each location, samples were collected at 4 depths: 0.5 m from the surface and 1, 2, and 4 m above the bottom. Samples were analyzed for dissolved, particulate, and total phosphorus in addition to various forms of nitrogen. Continuous measurements of temperature throughout the water column and bottom-water DO concentrations were collected via sub-surface instrument arrays deployed at each sampling location. Lake water quality data prior to March 2019 was obtained from the California Department of Water Resources (DWR).

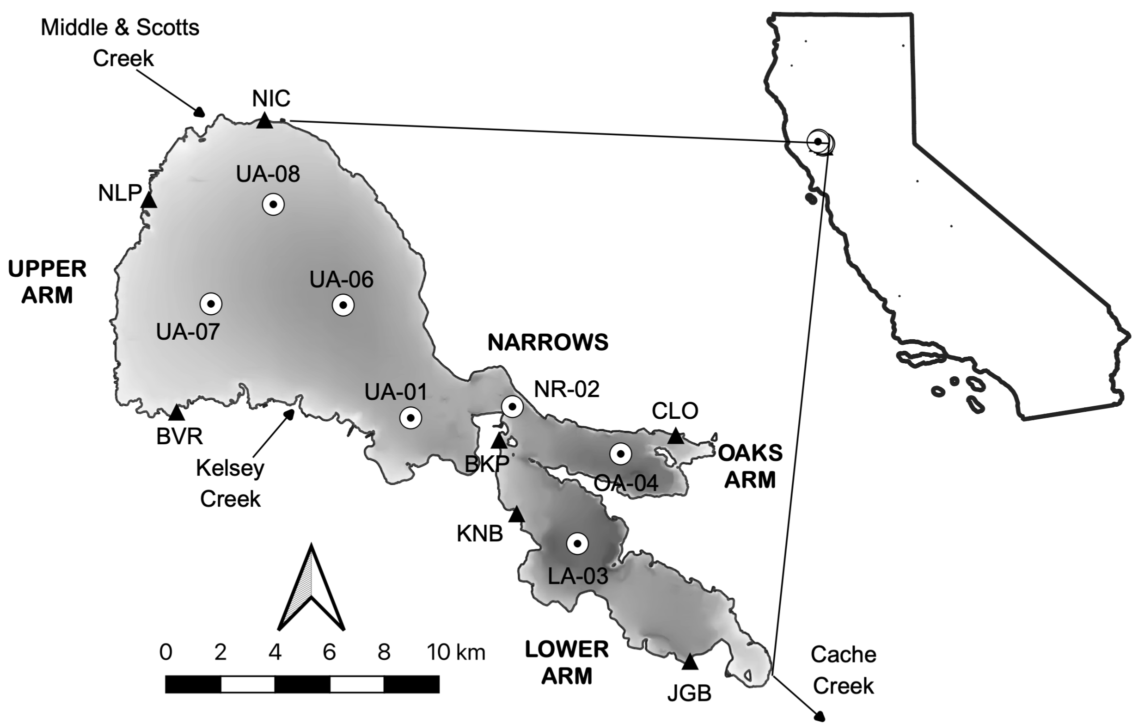

Figure 2. UC Davis Clear Lake monitoring sites. Site prefix indicates location in Upper Arm (UA), Oaks Arm (OA), Lower Arm (LA), and Narrows (NR). Location of subsurface monitoring moorings marked with white circles and locations of shoreline meteorological stations are shown by black triangles.

3.2 Stream Monitoring Data

Nutrient sampling of Clear Lake's major tributaries is conducted each winter during storm events by the Lake County Water Resource Department and tribal environmental monitoring agencies. Samples are collected across a range of flow conditions to develop stream-specific curves that relate discharge to ambient nutrient concentrations. Regression curves for Clear Lake's three gauged tributaries (Kelsey, Middle, and Scotts Creek, Figure 3) were developed using samples collected from 2008 – 2018. Samples from 2019 – 2021 were excluded due to the large variability in concentrations and the limited number of samples collected during this time frame. Additional information comparing these stream samples can be found in the Appendix.

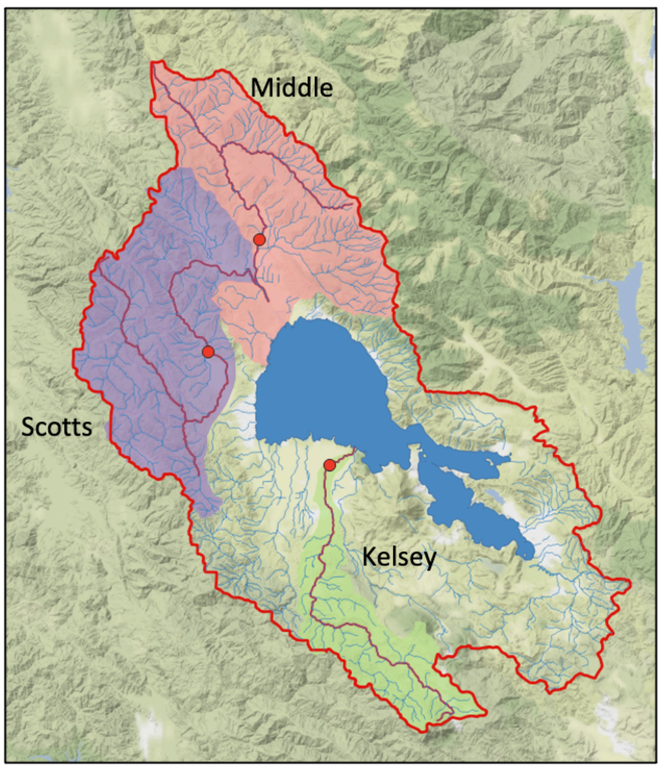

Figure 3. Overview of Clear Lake watershed. Shaded areas delineate gaged watersheds: Scotts, Middle and Kelsey Creek. Red dots indicate location of stream gages.

4 Load Calculations

4.1 Lake Phosphorus Budget

Clear Lake's P budget can be expressed in terms of a mass balance.

$$\Delta\ \mathrm{Lake_{TP}} = (L_{ext} + L_{atm} + L_G + L_W) - L_{OUT} \pm L_{int} \quad (1)$$

Here $\Delta\mathrm{Lake_{TP}}$ is the change in mass of total phosphorus in the lake, $L_{ext}, L_{atm}, L_G, L_W$ are the external loads from the watershed, atmospheric deposition, groundwater and wastewater effluent respectively, L_{OUT} is the outflow conveyed to Cache Creek and L_{int} is the mass flux of TP into and out of the sediments. Phosphorus inputs from groundwater were considered negligible as groundwater flows contribute less than <0.3% of the total inflow (Richerson et al. 1994). Wastewater effluent discharges are not permitted to Clear Lake and were likewise excluded.

4.2 External Load Estimates (L_{ext})

Annual external P loads (Jan - Dec) were quantified for Clear Lake's three gauged tributaries using 15-minute stream gauging data collected by the California Department of Water Resources (DWR) and stream-specific linear regressions relating discharge to TP, derived from routine stream monitoring data collected by the Lake County Department of Water Resources from 2014-2018 (Figure 4). To calculate cumulative stream loads, estimated TP concentrations were multiplied by the discharge volumes every 15 minutes. These 3 streams account for 46% of the external watershed P inputs (Lake County Watershed Protection District 2009), so the cumulative nutrient load was multiplied by a factor of 2.18 to account for the ungauged portion of the watershed. P inputs from atmospheric deposition were calculated using wet (0.25 mg TP m^{-2} d^{-1}) and dry (2 mg TP m^{-2} d^{-1}) phosphorus deposition rates from Lake Tahoe (Jassby et al. 1994), located approximately 220 km east of Clear Lake. Rates were multiplied by lake surface area to calculate the daily atmospheric TP load, depending on the form of deposition determined from precipitation data.

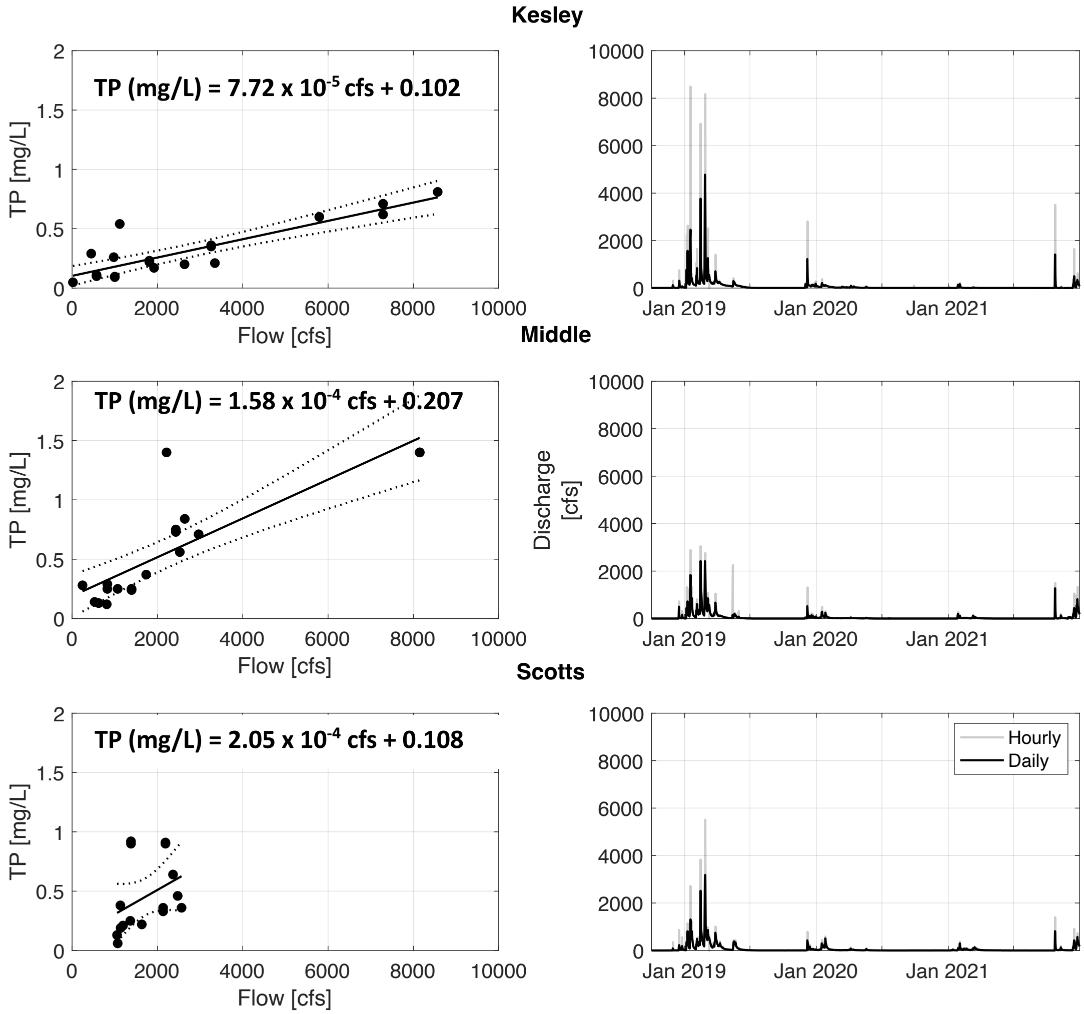

Figure 4. Left) Discharge vs TP curves based on Lake County stormwater monitoring data (2014-2018). Dotted lines indicate 95% confidence interval. Right) Hourly and daily stream hydrographs for gaged tributaries.

4.3 Output Estimates (L_{out})

Phosphorus outputs to Cache Creek, Clear Lake's only outflow, were likewise calculated via flow-based estimates. Streamflow data were obtained from the US Geological Survey (USGS) Cache Creek Rumsey Gauge (USGS Site 11451800), located ~20 miles downstream from the Clear Lake outlet. No nutrient data was available from this stream, so outflow TP concentrations were assumed to be equivalent to Lower Arm surface concentrations.

4.4 Internal Load Estimates (L_{int})

While watershed loads can be directly quantified via stream discharge and nutrient concentration data, internal loads are more difficult to assess because internal P sources cannot be easily measured *in situ* before biotic uptake (Nurnberg 2009). Methods for quantifying internal loads include regression analysis (Nurnberg 1988), mass-balance techniques (Håkanson 2004; Nurnberg 2009), time-dynamic modeling (Håkanson 2004), and coupled hydrodynamic-ecological modeling (Burger et al. 2008). We calculated basin-specific internal loads using two methods: observed increases of in-lake TP during the dry season and modeled estimates based on experimentally determined sediment P release rates.

4.4.1 Method 1 – Change in Lake TP Mass

The net internal total phosphorus (TP) load (L_{int_1}) was calculated as the observed increase within the water column during the dry season (May – October).

$$L_{int\_1} = \frac{(P_{t_2} \times V_{t_2})}{A_{o_2}} - \frac{(P_{t_1} \times V_{t_1})}{A_{o_1}} \qquad (2)$$

Here t_1 and t_2 are the dates of the annual minimum and maximum water column TP and SRP concentrations, respectively, P_t is the corresponding depth-averaged P concentration through the entire water column, V_t is basin volume (m^3) and A_o is basin surface area (km^2). Hydro-acoustic survey data (ReMetrix 2003) was used in conjunction with the USGS Clear Lake level gauge at Lakeport (USGS Site 11450000) to determine basin surface areas and volumes at a daily timestep. Lake-wide loading rates were calculated from a surface area-weighted average of the three arms. L_{int_1} yields a net estimate, integrating both inputs and losses to sedimentation and biotic uptake. While external loading was excluded in this method, most of Clear Lake's tributaries are seasonal, and are not expected to impact loading estimates.

4.4.2 Method 2 – Lake Sediment Flux

Modeled estimates of gross internal P loading released from anoxic lake sediments (L_{int_2}) were quantified as the product of 2 component terms: an active anoxic sediment area (AA), presented in units of days per year that an entire basin's surface area is actively releasing P, and areal sediment P release rate (RR), (equation 3, Nurnberg 2009).

$$L_{int\_2} = AA \times RR \quad (3)$$

AA was directly estimated as the number of days that the deepest near-sediment DO logger of each arm recorded hypoxic conditions. When the hypolimnion is hypoxic, underlying sediments can become completely anoxic and release P into the water column (Eimers and Winter 2005; Nurnberg et al. 2013) as microbial-mediated sediment anoxia does not require anoxia in the overlying water column (Holdren and Armstrong 1980). A hypoxic threshold of <3.5 mg/L was selected to indicate elevated sediment P release. This threshold was calibrated by comparing observed bottom-water DO measurements against modeled estimates calculated via the regression in Nürnberg 1996 which has been previously applied to quantify hypoxia in polymictic lakes.

Arm-specific oxic and anoxic sediment P flux rates were quantified via incubations of quadruplicate sediment cores collected from all monitoring sites (excluding UA-07) in November 2019, (Framsted, unpublished). At each site, duplicate cores were incubated under both anoxic and oxic conditions. All incubations were maintained at a constant temperature of 15°C and sampled approximately every three days for a 30-day period.

Internal loading rates were calculated at an hourly timestep by applying anoxic release rates to the entire surface area of each arm if hypolimnetic DO dropped below 3.5 mg/L. To account for the temperature dependence of reaction rates, fluxes were modified by Van't Hoff's Q_{10} rule of 3 (i.e., a 10°C temperature increase, corresponds to a tripling of the P flux rate. This Q_{10} coefficient has been widely used to model the temperature effects of diffusive P fluxes (Liikanen et al. 2002 ; Nurnberg 2009).

$$RR_{Temp} = RR_{core} \times Q_{10}^{(ti-15)/10} \quad (4)$$

Here RR_{core} is the observed P flux at 15 °C, ti is the observed temperature of the hypolimnion and are, $Q_{10} = 3$ and RR_{Temp} is the temperature-corrected hourly P flux rate.

5 Results

The following results detail the total mass of P exchanged into, within, and out of Clear Lake from January 2019 to December 2022.

Table 1. Cumulative estimates of watershed, atmospheric and internal loads to Clear Lake and outputs to Cache Creek for calendar years 2019 – 2022. Estimates for internal loads based on observed increases in water column phosphorus (L_{int_1}) and modeled release from anoxic sediment (L_{int_2}) are presented for comparison. All terms are presented in units of tons per year.s

YEAR	L_{EXT}	L_{ATM}	L_{INT_1} (Δ LAKE TP)	L_{INT_2} (MODELED)	L_{OUT}	CL TMDL
2019	116.2	13.9	411.6	306.3	80.3	
2020	6.6	14.9	604.7	432.2	36.7	87.3
2021	12.9	14.1	597.1	492.4	18.0	
2022	9.0	14.8	625.9	439.8	5.7	

5.1 External Loads and Outputs

Total external TP loads from the watershed to Clear Lake during 2019, 2020, 2021, and 2022 were 116.2, 6.6, 12.9, and 9.0 metric tons (t), respectively, while loads from atmospheric deposition were 13.9, 14.9, 14.1, 14.8 tons in each respective year. The interannual variation in L_{ext} resulted from the extreme variability in the region's precipitation, with 2019 being a wetter than average year, while precipitation accumulation in 2020-2022 was below average (Figure 5). External TP inputs from tributaries are primarily conveyed to UA (>90% of watershed inflows) and varied seasonally. External loads were greatest during the winter (October to March), declined throughout the spring and reached near zero during the summer. Total phosphorus outputs to Cache Creek were 80.3, 36.7, 18.0, and 5.7 tons of TP in 2019, 2020, 2021, and 2022. Releases to Cache Creek in summer 2022 were significantly lower than the average summer discharge due to low lake levels.

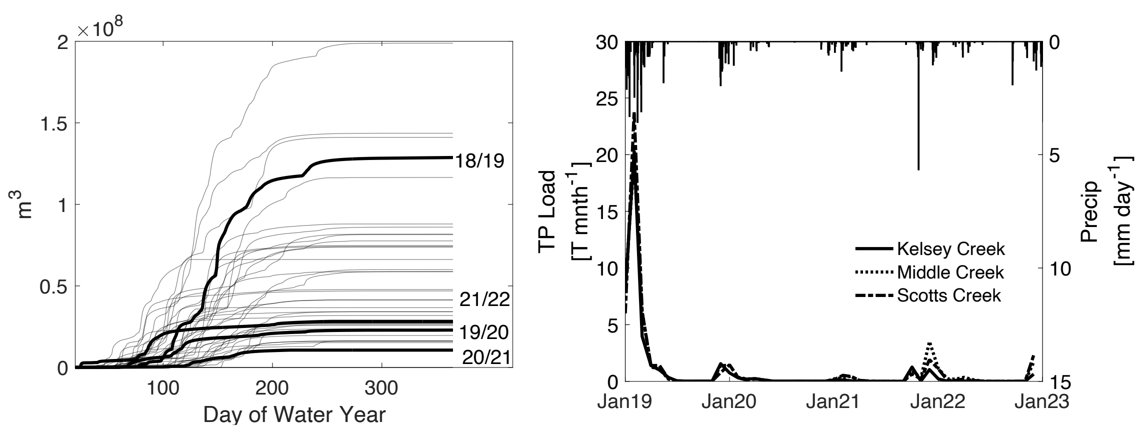

Figure 5. Left) Water year cumulative discharge from Middle Creek (1980 – 2022). Monitored years are shown in bold. Right) Monthly TP load estimates from gauged Clear Lake tributaries and observed precipitation.

5.2 **Internal Loads**

Lake-wide TP concentrations followed a consistent seasonal pattern in all three arms, with annual minimums observed each spring (< 0.05 mg L^{-1}), increasing throughout the summer, and peaking in early fall. Maximum annual concentrations were observed in September 2019 and in October 2020-2022. Elevated TP concentrations in bottom waters in early summer preceded increases in surface waters, indicating the accumulation of TP in deep layers during stratified conditions.

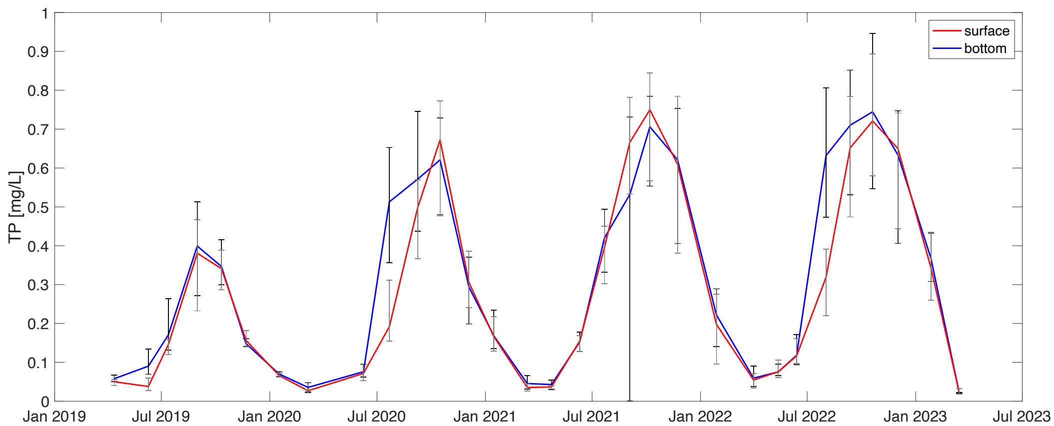

Figure 6. Average TP concentrations in Clear Lake surface (red) and bottom (blue) waters. Vertical lines indicate range of values across monitoring sites.

Net lake-wide, internal TP loads estimated from water column nutrient measurements during the dry season (L_{int_1}) were 411.6 ,604.7, 597.1, and 625.9 tons in 2019, 2020, 2021 and 2022, respectively, with more than 40% variation in loading rates observed between the three arms. As these are net estimates, they do not consider external inputs from the previous winter. In comparison, modeled estimates based on the measured duration of hypoxia and sediment incubation release rates were lower: 306.3, 432.2, 492.4 during each consecutive year. However, both estimates were of the same order of magnitude, reflecting the large mass of P that is cycled between lake sediments and the water column. Increasing loading rates for each consecutive year coincided with longer durations of hypoxia each summer. The discrepancy between the two internal load estimates was primarily due to differences in the estimated Upper Arm internal load. Estimates based on observed changes in Lake TP were used for basin-wide P budget calculations to be conservative.

5.3 Summary Phosphorus Budget

The net total load of P to Clear Lake was 412 tons in 2019, 605 tons in 2020, 597 tons in 2021, and 627 tons in 2022 (Figure 7). Interestingly there was a larger load of P in the water column during the drought years (2020-2022) than following the wet winter in 2019. By subtracting external load contributions from the observed increase in water column TP during the dry season (i.e., L_{int_1}) we determined that internal fluxes accounted for the majority (70 – 95%) of TP in the lake each summer.

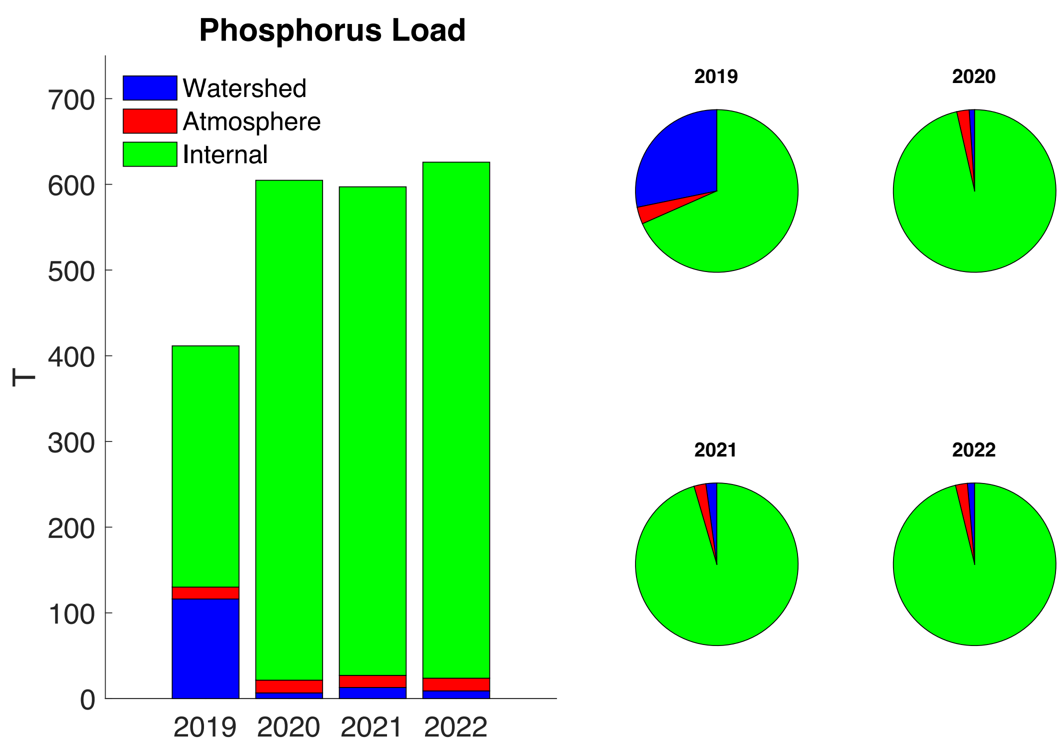

Figure 7. Clear Lake Phosphorus load allocations (2019 – 2022). Internal load shown is calculated as $L_{int\_1} – L_{ext}$. Pie charts show the relative contribution of each loading term to the total phosphorus input.

6 Conclusions

A phosphorus budget developed for Clear Lake indicates that the lake typically receives between 400-600 tons of phosphorus each year from external and internal sources. Internal loads release from lake sediments under hypoxic conditions comprise the majority of phosphorus inputs.

While P loads from the watershed are greatest during the wet winter season, the highest water column TP concentrations were observed during each summer and fall, demonstrating the prevalence of internal P loading in the system. While atmospheric loads varied interannually by <10%, watershed loads were significantly less in 2020 - 2022 due to below average stream inputs as a result of a prolonged drought resulting in a higher relative contribution of internal loading to the overall P budget. Higher internal loading rates observed in 2020-2022 coincided with longer periods of hypoxia in each lake arm.

The magnitude of the estimated P loading components was consistent with the previous Clear Lake P budget developed in the Clean Lakes Report (Richerson 1994). Based on monitoring data collected from 1969 to 1993, this previous P budget estimated an average of 158 tons P loaded from the watershed, 26 tons output to Cache Creek, and internal loads contributed on average 130 tons (up to 500 tons during drought years). Atmospheric deposition was not accounted for in this analysis. The budget developed for 2019-2022 shows loading rates comparable in magnitude.

Clear Lake's P budget demonstrates that the annual cycling of P in the system is largely controlled by internal fluxes between lake sediments and the water column. The overwhelming influence of internal process on P cycling in Clear Lake suggests that focusing on controlling in-lake internal P loading will be critical to mitigating cyanobacteria blooms in the future. Osgood (2016) estimated that for shallow lakes with a drainage basin to surface area ratio larger than 5:1 (Clear Lake ≈ 6.5:1) internal P loads need to be reduced by more than 90% to limit P concentrations below eutrophic levels. Engineering approaches including hypolimnetic oxygenation, artificial mixing and chemical treatments that bind nutrients into sediments (Bormans et al. 2016) have all been employed with varying levels of success to alleviate internal P loads in shallow reservoirs. Solutions targeting sediment resuspension (e.g., eradication of invasive sediment disturbing fish, dredging) may also be required to address P loading in shallower regions of the lake.

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- Lindsay Vaughan – Technical Staff

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9 Appendix

External loading estimates were calculated based on stream-specific flow vs TP regression curves estimated from stream nutrient samples collected across a range of flow conditions. All stream samples collected from Kelsey, Middle and Scotts Creek between 2014 – 2021 are shown in Figure A1. Samples collected during the WY2018-19 first flush (November 2018) through January 2019, had significantly higher TP concentrations in Middle and Scotts Creek. Higher nutrient concentrations reflect the impacts of the Mendocino Complex which burned much of the Middle and Scotts Creek watersheds during summer 2019. Subsequent sampling events in February and March 2019 and January 2020 are lower (Figure A2), indicating a return to pre-2018 stream conditions. We chose to exclude stream samples from 2019-2021 and use only pre-2018 samples to estimate external loads due to the following reasons:

1. Due to the limited number of samples collected in Kelsey and Scotts Creek (n = 4) from 2018 – 2021, the flow vs TP regressions developed from these samples were not significant (Table S1).

2. Increased stream TP due to wildfires appeared to be temporary and likely did not impact external loads in 2020 – 2022.

3. Data from the 2021-2022 WY was not available at the time this analysis was conducted.

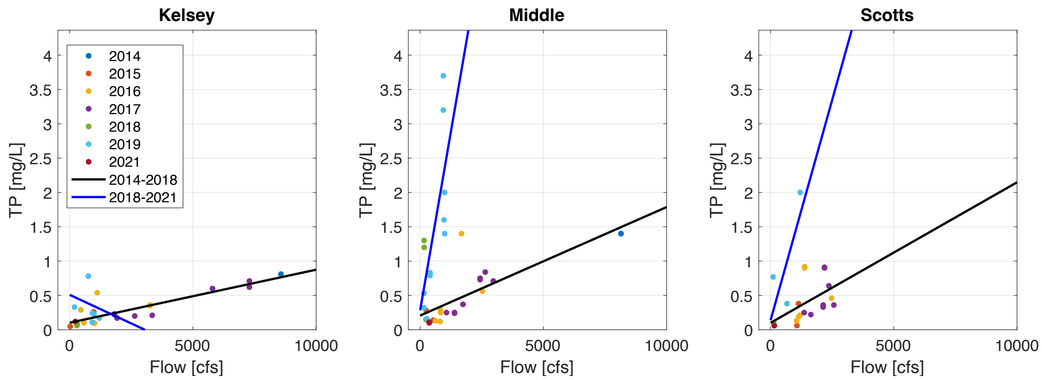

Figure A1. Stream TP measurements during storm sampling events (2014 – 2021). Samples are colored by sampling year. Black and blue lines show linear regressions for discharge vs TP curves based on 2014 – 2018 and 2019 – 2021 sampling data.

		Kelsey	Middle	Scotts
2014-2018	n	19	18	16
	R^2	0.75	0.63	0.10
	P value	<0.01	<0.01	0.1
2018 - 2021	n	4	12	4
	R^2	-0.40	0.50	0.45
	P value	0.75	<0.01	0.2

Table A1. Comparison of the number of observations used to develop linear regressions and r^2, and p-values of regressions. P-

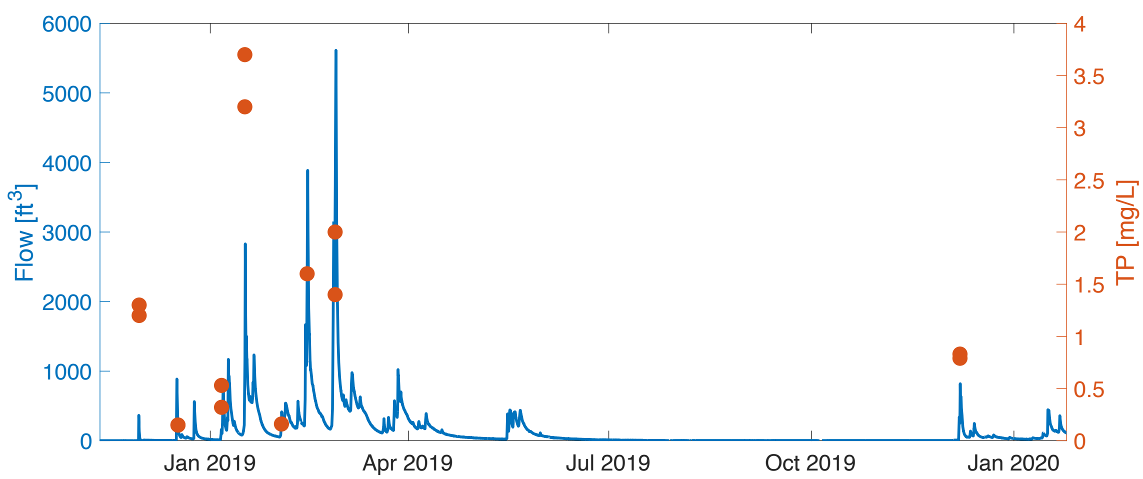

Figure A2. Timeseries of discharge and TP concentrations measured in Middle Creek (Nov 2018 – Feb 2020)