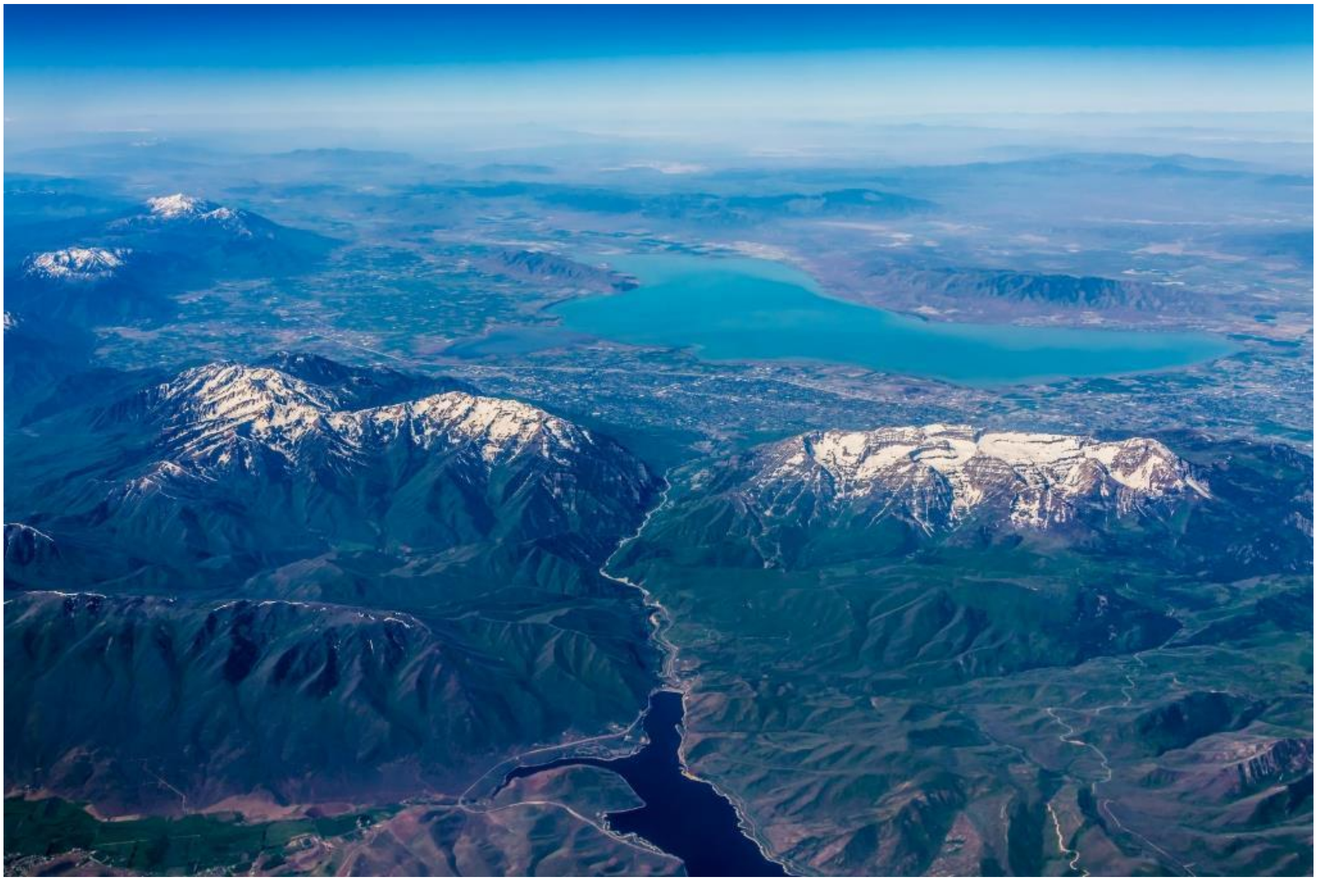
Utah Lake Carbon, Nitrogen, and Phosphorus Budgets Study

REVISED FINAL

January 27, 2022
Version 4.0



PRESENTED TO

Utah Department of Environmental Quality
Division of Water Quality
PO Box 144870
Salt Lake City, UT 84114

PREPARED BY

Tetra Tech Inc., Ecological Sciences
1 Park Drive, Suite 200, PO Box14409
Research Triangle Park, NC 27709

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
C	Carbon
DOC	Dissolved Organic Carbon
DMR	Discharge Monitoring Report
DO	Dissolved Oxygen
DWQ	Utah Division of Water Quality
EFDC	Environmental Fluid Dynamics Code
EPA	Environmental Protection Agency
GWLF-E	Generalized Watershed Loading Function Enhanced
HAWQS	Hydrologic and Water Quality System
HUC	Hydrologic Unit Code
LKSIM	Utah Lake Water Quality Salinity Model
N	Nitrogen
NH_3	Ammonia
NO_3^-	Nitrate
OM	Organic Matter
P	Phosphorus
PO_4^{3-}	Phosphate
SOD	Sediment Oxygen Demand
SP	Science Panel
STEPL	Spreadsheet Tool for Estimating Pollutant Loads
TDN	Total Dissolved Nitrogen\
TDP	Total Dissolved Phosphorus
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
ULWQS	Utah Lake Water Quality Study
USDA	United States Department of Agriculture
WASP	Water Quality Analysis Simulation Program
WFWQC	Wasatch Front Water Quality Council
WWTP	Wastewater Treatment Plant

INTRODUCTION

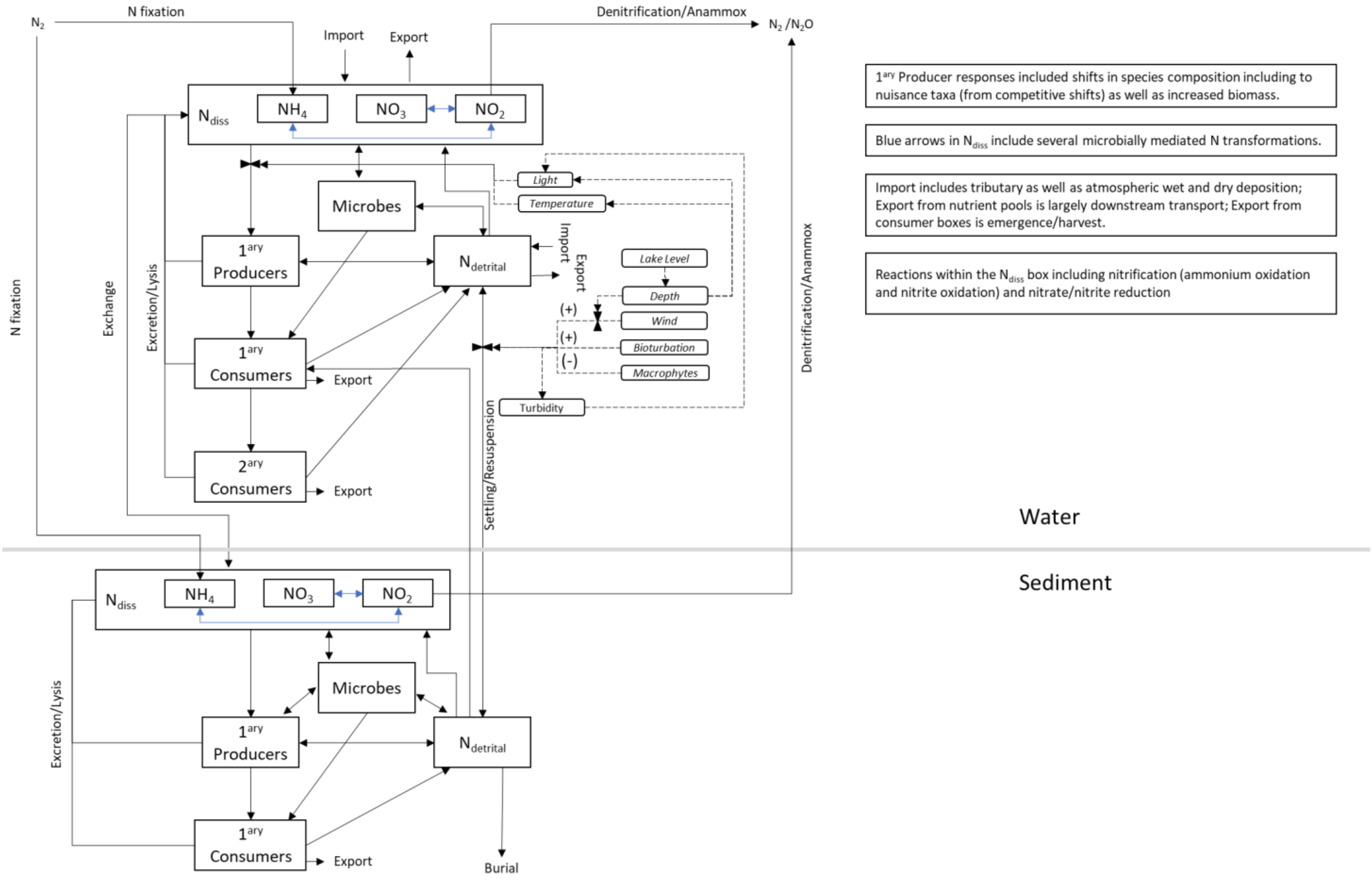
Utah Lake is a eutrophic, shallow, polymictic lake in the western United States with a mixed natural/urban/agricultural watershed. The Utah Lake Water Quality Study (ULWQS) is currently underway, with the goal of developing nutrient criteria for the lake to protect designated uses. As part of the strategic research planning portion of the ULWQS, a priority research need was identified to synthesize the existing external and internal mass balance information for carbon (C), nitrogen (N), and phosphorus (P) for the lake.

Previous mass balance analyses for Utah Lake estimate most nutrient load is retained within the lake rather than exported by the Jordan River (PSOMAS and SWCA 2007; Merritt and Miller 2016), demonstrating Utah Lake is a net sink for N and P; organic C budgets were not developed. It is clear there is a large, actively cycling pool of N and P, which interacts with C stocks. However, there are no known studies that have attempted to compile the known information about C, N, and P stocks and fluxes for the lake, especially the sediments. This information is vital not only for understanding Utah Lake biogeochemistry, but also for improving the EFDC/WASP water quality models being developed to simulate nutrient effects in Utah Lake.

Constraining the budgets of C, N, and P will allow for more informed management of water quality issues in Utah Lake. The balance of external inputs and outputs of nutrients, and the variability observed in this relationship, informs the role of Utah Lake as a nutrient processor and sink as well as its sensitivity to external nutrient inputs. Preliminary evidence suggests that algal productivity may be co-limited by both N and P, necessitating a synthesis of knowledge about both nutrients. A major step forward in the understanding of nutrient dynamics in Utah Lake will be to define and quantify (1) the balance of inputs and outputs (i.e., updating the external mass balance models with the most recent data on inputs and outputs), (2) the key processes responsible for internal transformations within the lake, particularly those that involve exchanges across the sediment-water interface, and (3) the mediating factors that impact the magnitudes of sources and sinks. Further, bioavailable pools of nutrients need to be separated from total pools to determine the magnitude of active cycling within the biotic community.

A conceptual model of pools and processes associated with N and P was developed by Tetra Tech (Figure 1, Figure 2). A literature review will allow the Science Panel (SP) to amend the conceptual model with existing estimates of magnitudes for these stocks and fluxes. Components of C, N, and P cycling that have not been quantified in Utah Lake can be amended with estimated values from the literature. These stock and flux components can then be used as inputs for a relatively simple spreadsheet nutrient model like SedFlux. Lastly, this synthesis will allow the SP to identify key gaps in understanding and how to resolve them, namely rates and stocks that can be leveraged from studies in comparable systems vs. those that should be measured directly in future Utah Lake research.

Nitrogen model



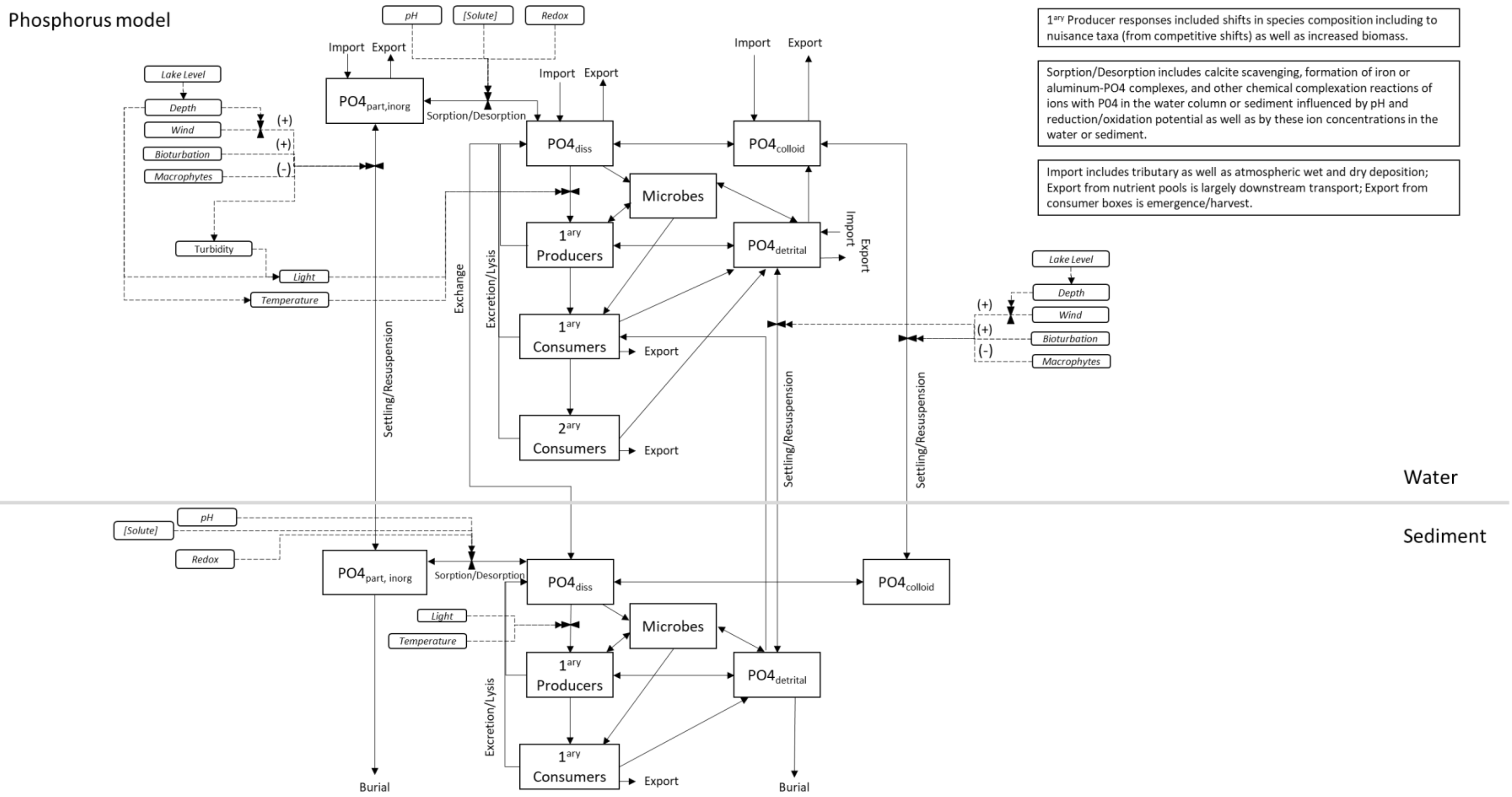
1^{ary} Producer responses included shifts in species composition including to nuisance taxa (from competitive shifts) as well as increased biomass.

Blue arrows in N_{diss} include several microbially mediated N transformations.

Import includes tributary as well as atmospheric wet and dry deposition; Export from nutrient pools is largely downstream transport; Export from consumer boxes is emergence/harvest.

Reactions within the N_{diss} box including nitrification (ammonium oxidation and nitrite oxidation) and nitrate/nitrite reduction

Figure 1. Conceptual model of the nitrogen cycle in Utah Lake.



1^{ary} Producer responses included shifts in species composition including to nuisance taxa (from competitive shifts) as well as increased biomass.

Sorption/Desorption includes calcite scavenging, formation of iron or aluminum-PO4 complexes, and other chemical complexation reactions of ions with P04 in the water column or sediment influenced by pH and reduction/oxidation potential as well as by these ion concentrations in the water or sediment.

Import includes tributary as well as atmospheric wet and dry deposition; Export from nutrient pools is largely downstream transport; Export from consumer boxes is emergence/harvest.

Figure 2. Conceptual model of the phosphorus cycle in Utah Lake.

Previous work has applied the Utah Lake Water Quality Salinity Model (LKSIM; Liljenquist 2012), a hydrodynamic model that balances hydrologic inputs and outputs for streams, springs, groundwater, drains, precipitation, and evaporation. PSOMAS and SWCA (2007) presented a hydrologic budget of all inflows and outflows, broken down by both monthly and annual averages. This LKSIM application also included TP loads for each inflow and outflow with the same temporal resolution. A major finding of this study was that inflow TP loads (average 297.5 tons/yr) are substantially higher than outflow loads (average 83.5 tons/yr), and that wastewater treatment plants (WWTPs) make up the majority (76.5 %) of TP loading to the lake, in comparison to loading from inflow tributaries (20.7 %). An additional LKSIM-based study by Merritt and Miller (2016) demonstrated similar results, showing that 90 % of P loading and 84 % of N loading is retained by the lake. The hydrology of Utah Lake was modeled for a different set of years (2009-2013), broken down by year and input type (individual rivers, groundwater, precipitation). Further analysis of this dataset has been provided by SP member Michael Brett (2019). These studies set the stage for a well-constrained external mass budget of N and P inputs and outputs for Utah Lake, but there is similar need for understanding internal lake transformations, especially between the water column and sediment; understanding the extent to which nutrient stocks are bioavailable and actively cycling through the food web, especially primary producers and, eventually, harmful algal bloom (HAB) taxa.

C, N, and P budgets, particularly as they relate to bioavailable nutrient stocks and transformations, are relevant to direct management activities in Utah Lake. Nutrient inflows to the lake have an N:P ratio of 8:1 which would typically indicate N limitation of primary productivity, but Merritt and Miller (2016) propose that concentrations of both elements are sufficiently high to be non-limiting. However, it is also hypothesized by the same authors that substantial portions of P are inextricably bound to minerals like calcite, removing them from the bioavailable pool. Elemental stocks are bound in biomass across trophic levels (Gaeta et al. 2019), and biotic interactions are a key component of the C, N, and P budgets to quantify. Knowing the portions of nutrients in the water column that are bioavailable and actively support food web is, therefore, critical.

A recently completed study funded by the ULWQS, peer reviewed by Tetra Tech, demonstrates that sediments are a critical component of N and P cycling in Utah Lake (Goel et al. 2020). Under *in situ* conditions, sediments were a sink for soluble reactive P and ammonium and a source of total dissolved P, suggesting that the net source of P to the water column is in non-soluble fractions. This experiment captured the water column equilibrium P concentration at which the sediments change from a source to a sink of P, an important threshold to define for the purposes of quantifying internal loading rates of P. As indicated earlier, further manipulations of oxygen concentrations and pH suggest that calcite formation is an important sink for P and that redox and pH represent key modulating factors for sediment P fluxes. A closer review of these rates in context with the literature will help to quantify the processes responsible for fluxes at the sediment-water interface.

The objectives of this study are to:

1. Develop a contemporary mass balance of the external inputs and outputs of C, N, and P for Utah Lake.
2. Compile all known data on standing stocks and flux rates for C, N, and P in Utah Lake.
3. Create a mass balance model for each element that incorporates information from objectives 1 and 2 and a quantification of uncertainty around estimates.
4. Identify major gaps and uncertainties in existing data and propose future studies to fill these gaps.

This study addresses two of the priority research topics outlined in the ULWQS Strategic Research Plan (Tetra Tech 2020a): (1) How large is internal vs. external loading, and (2) sediment budgets. These research topics relate to several of the identified charge questions:

- What is the current state of the lake with respect to nutrients and ecology? (Science Panel charge 2)
- What are current sediment equilibrium P concentrations (EPC) throughout the lake? What effect will reducing inputs have on water column concentrations? If so, what is the expected lag time for lake recovery after nutrient inputs have been reduced? (Science Panel charge 2.4.i)

- What is the sediment oxygen demand of, and nutrient releases from, sediments in Utah Lake under current conditions? (Science Panel charge 2.4.ii)
- What would be the current nutrient regime of Utah Lake assuming no nutrient inputs from human sources? (Science Panel charge High Level Questions 4.1.)

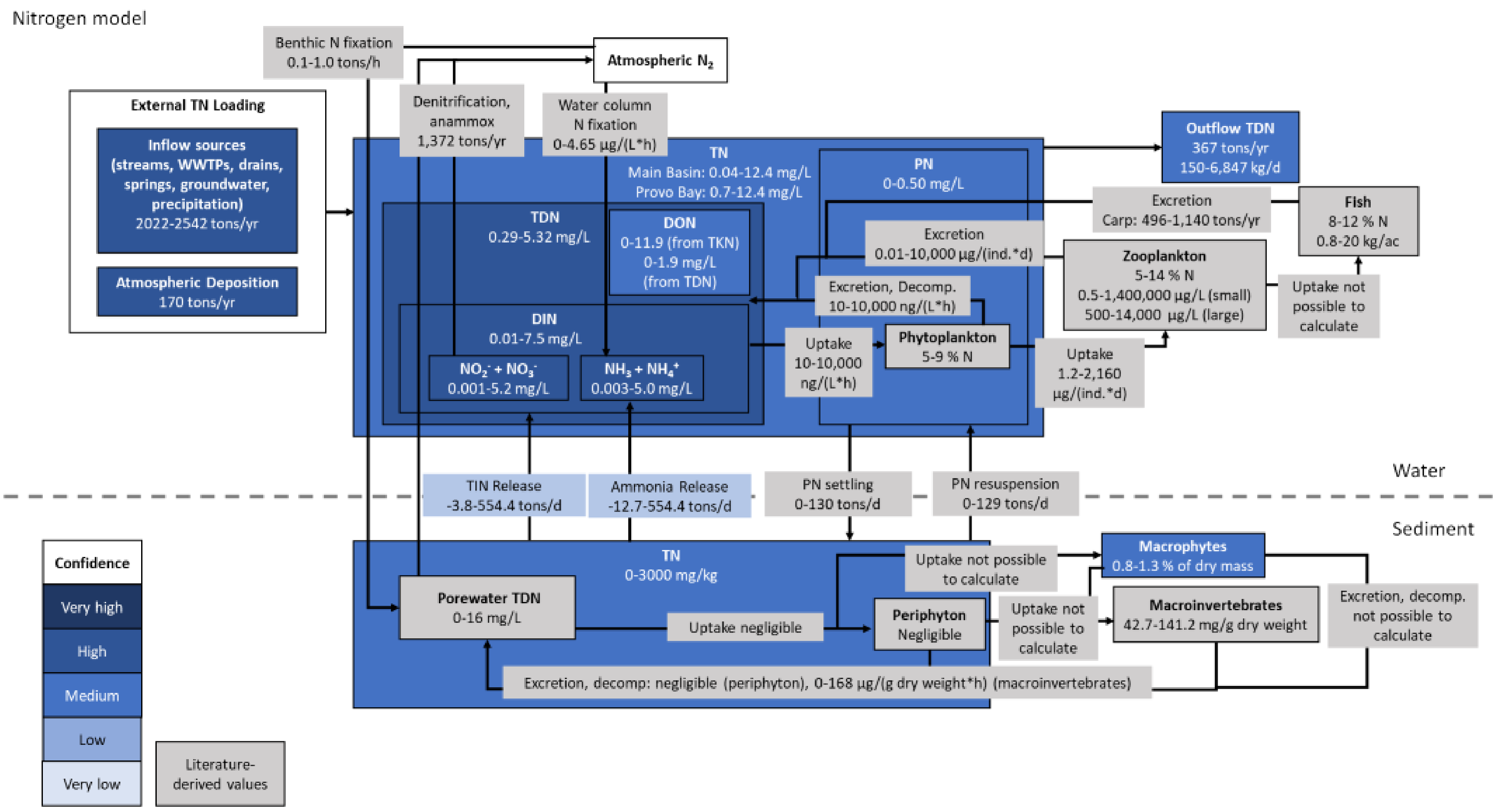
LITERATURE REVIEW

The literature review gathered information from published peer reviewed literature and gray literature relevant to Utah Lake. Topics that Tetra Tech reviewed include: (1) hydrologic and atmospheric inputs of elements to the lake, namely through tributaries, groundwater, drains, direct precipitation, and atmospheric deposition; (2) water column transformations of elements; (3) sediment transformations of elements; (4) elemental fluxes between the water column and sediment; and (5) elemental standing stocks in various pools in the water column and sediment. The final literature list contained 79 documents, comprising journal articles, reports, theses, and memos. Of these documents, 38 contain data on C, N, and/or P, 30 contain data on Utah Lake but not for C, N, or P, and 5 are relevant studies in other systems. Data and metadata were compiled in the Utah Lake C, N, and P Data Compilation Spreadsheet (Tetra Tech 2021a). Uncertainty associated with specific data values was qualified using the procedures outlined in the Utah Lake Water Quality Study Uncertainty Guidance document (Tetra Tech 2020b), which incorporates the amount and strength of evidence, agreement among sources, and confidence. The complete procedures and outcomes of the literature review are detailed in the Literature Review and Data Compilation Memo (Tetra Tech 2021b).

CONCEPTUAL MODEL

Conceptual models for N and P cycles in Utah Lake were quantified, where possible, with data from Utah Lake studies compiled as part of the literature review. Stocks and processes were color coded according to their determined level of confidence from the uncertainty evaluation (Figure 3, Figure 4). When data for a specific stock or process was not available for Utah Lake, we searched the literature for established values. As much as was possible, data were compiled from systems anticipated to act similarly to Utah Lake (e.g., eutrophic, shallow, and/or high alkalinity lakes) or from reviews that included data from multiple systems. Further documentation of literature-based values and calculations is detailed in the Conceptual Model Memo (Tetra Tech 2021c). Literature-based values for stocks and processes were color coded as gray in Figure 3 and Figure 4.

Results from this study may be used to update the information in the conceptual models. Relevant stocks and processes are external loading and outflows (section 4.5) and exchanges between the water column and sediments (section 5.3). The bioassay study conducted by Aanderud et al. (2021) can be used to update N fixation rates in the conceptual models, though this study was completed concurrently with the progress of this study and thus does not appear in the model.



Nitrogen model

Figure 3. Quantified nitrogen cycle conceptual model for Utah Lake. Items in blue indicate estimates generated from Utah Lake data, with a determination of confidence. Items in gray indicate estimates generated from literature-based measurements in other systems.

Phosphorus model

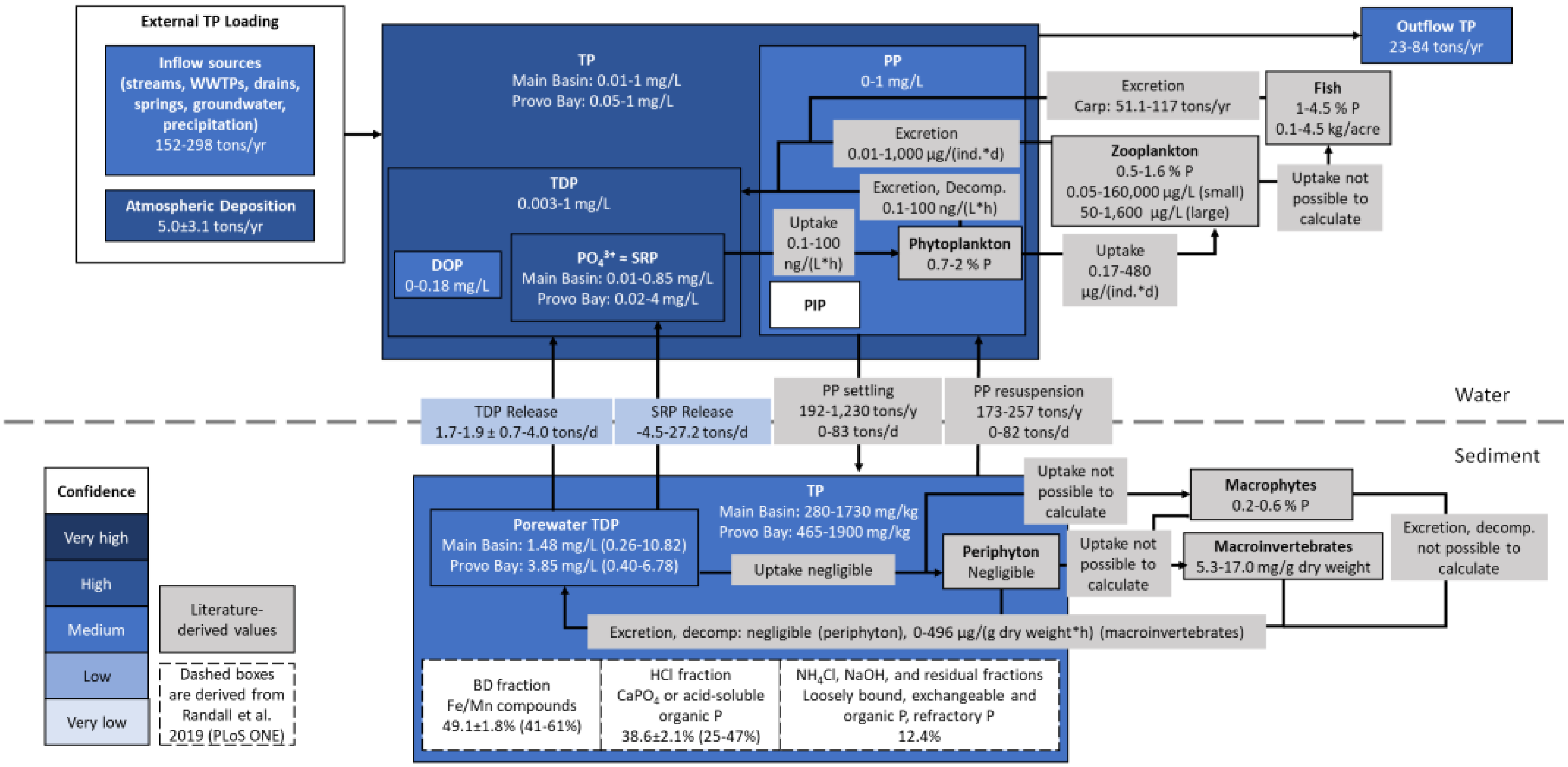


Figure 4. Quantified phosphorus cycle conceptual model for Utah Lake. Items in blue indicate estimates generated from Utah Lake data, with a determination of confidence. Items in gray indicate estimates generated from literature-based measurements in other systems.

EXTERNAL MASS BALANCE MODEL

The goals for the external mass balance portion of this study were to quantify the inputs and outputs of N, P and organic C, to and from Utah Lake. An additional component of this work was to quantify the hydrologic inputs and outputs as well. The hydrologic and nutrient inputs to Utah Lake are comprised of tributary and overland inflows, groundwater, atmospheric deposition, and precipitation. Outputs include outflow to the Jordan River and evaporation.

The Utah Lake watershed consists of 70 sub-catchments characterized by a range of topography, land cover, and flow patterns (i.e., perennial, intermittent, and ephemeral flow; Figure 5). Of these sub-catchments, 16 are monitored by the Utah Division of Water Quality (DWQ) and 13 of those 16 are monitored by the Wasatch Front Water Quality Council (WFWQC). Six of the monitored watersheds contain wastewater treatment plant (WWTP) effluent discharges. Monitoring sites are located in downstream portions of each sub-catchment as near to the lake as practicable.

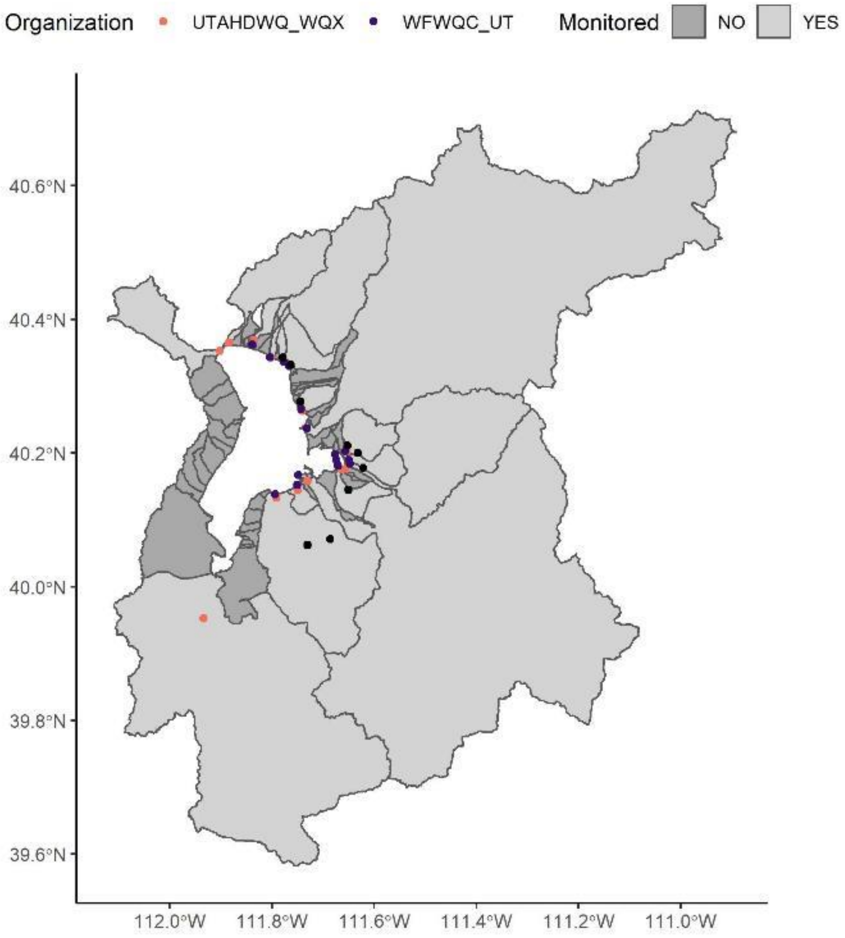


Figure 5. Map of the Utah Lake watershed. Sub-catchments are delineated, with monitored sub-catchments in light gray and unmonitored sub-catchments in dark gray. Tributary monitoring sites are marked in orange (DWQ) and purple (WFWQC). Locations of WWTPs are marked in black.

4.1 MONITORED WATERSHEDS

4.1.1 Methods

Hydrologic and nutrient data for the monitored watersheds from 2015-2020 was obtained through the EPA Water Quality Portal (https://www.waterqualitydata.us/portal/). This time period was chosen because (1) it represents the most recent available data to quantify current conditions and (2) this time period is consistent with the time period analyzed as part of other ULWQS efforts, including the application of the EFDC/WASP mechanistic model, empirical stressor-response analysis, and additional field-based experiments. For each sub-catchment, the most downstream monitoring location that characterized the cumulative tributary flow was identified for each monitoring entity (DWQ and WFWQC; Figure 6, Table 2). In some cases, two monitoring locations represented the total flow due to the presence of two forks that converge further downstream. For Provo River and Hobble Creek, dates when flow was not measured directly were assigned the flow from USGS gage stations 10163000 and 10153100, respectively. For each monitoring location, daily concentrations of total N (TN), total dissolved N (TDN), TP, total dissolved P (TDP), total organic C (TOC), and dissolved organic C (DOC) were multiplied by flows for each monitored day that contained measurements of both variables. Detailed summaries of flows, concentrations, and loads are in the Appendix.

DWQ and WFWQC differed in their nutrient concentration methodology and thus had different detection and reporting limits (Table 1). When nutrient concentrations in a given sub-catchment were below the WFWQC reporting limit but above the DWQ reporting limit, DWQ data only were used to generate loads for that sub-catchment. Those sub-catchments were American Fork River, Provo River, and Spanish Fork River for N; and Lehi Spring Creek, American Fork River, Provo River, and Hobble Creek for P. Flow methodologies also differed; DWQ's method was consistent with USGS methodology that recommends 10 or more partial sections (Turnipseed and Sauer 2010), whereas WFWQC's method used fewer than 10 partial sections. When flow and concentration data were compared between the two entities (Appendix), we determined that measurements were generally consistent between DWQ and WFWQC data, and in discussion with the SP determined that all available flow data should be used to generate load estimates. Two exceptions included Spring Creek – Springville and Lindon Drain. The WFWQC and DWQ sites in Spring Creek – Springville were collected at the same location, and WFWQC flow values exceeded DWQ flow values. We proceeded with using both entities' data for Spring Creek – Springville, noting that an over- or underestimate by either entity would bias the loading estimates. Lindon Drain flow data represented two locations, with DWQ located upstream of the PacifiCorps Energy discharge location which can at least partly explain the higher flow values at the WFWQC site which was located downstream of the PacifiCorps discharge location. Loads from PacifiCorps Energy, as determined from discharge monitoring reports (DMRs), were added to the DWQ loads for Lindon Drain to represent total load for direct comparison to the equivalent WFWQC load. Daily loads were aggregated into monthly average loads across the time period of record (2015-2020). When a given month had no load data available, loads were estimated by linearly interpolating across missing months (i.e., calculating the average load of the two most adjacent months).

Table 1. N and P analytical sensitivity for DWQ and WFWQC protocols.

Constituent	Limit	DWQ	WFWQC
TP & TDP	Lower reporting limit (µg/L)	3	21
	Minimum detection limit (µg/L)	2.8	1
TN & TDN	Lower reporting limit (µg/L)	200	700
	Minimum detection limit (µg/L)	185	317

Table 2. Summary of sampling locations and data availability. N indicates the number of monitoring samples in each year. Unless noted, site IDs between organizations for each sub-catchment represent equivalent sites used to generate total loading.

Sub-Catchment	Site ID	Organization	Start Date	End Date	N 2015	N 2016	N 2017	N 2018	N 2019	N 2020
Tickville Wash	4994792	DWQ	5/16/2017	9/21/2020	0	0	8	12	11	8
Dry Creek – Saratoga	4994804	DWQ	5/16/2017	7/7/2020	0	0	8	12	12	7
Lehi Spring Creek	4994950	DWQ	5/16/2017	9/21/2020	0	0	8	12	12	9
Lehi Spring Creek*	4994948	WFWQC	10/14/2015	12/8/2020	5	12	12	12	12	12
American Fork River	4994960	DWQ	5/16/2017	9/21/2020	0	0	7	11	12	7
American Fork River*+	4994958	WFWQC	10/14/2015	6/16/2020	4	8	12	3	10	6
Timp SSD	4995038	DWQ	5/16/2017	9/21/2020	0	0	8	12	12	9
Timp SSD	4995043	WFWQC	10/14/2015	12/8/2020	5	12	12	13	12	12
Lindon Drain[1]	4995120	DWQ	5/11/2017	9/21/2020	0	0	8	10	12	9
Lindon Drain[1]	4995075	WFWQC	10/14/2015	12/8/2020	5	12	12	13	12	12
Powell Slough Major[2]	4995210	DWQ	8/9/2017	4/19/2019	0	0	4	8	2	0
Powell Slough Major[2]	4995230	DWQ	9/13/2017	9/30/2020	0	0	3	6	2	2
Powell Slough Major[2]	4995210	WFWQC	10/19/2015	12/8/2020	4	2	11	14	12	12
Provo River	4996680	DWQ	5/12/2017	9/21/2020	0	0	8	12	12	9
Provo River*+	4996680	WFWQC	10/14/2015	12/8/2020	6	13	12	13	13	12
Mill Race[3]	4996540	DWQ	5/12/2017	9/21/2020	0	0	8	12	12	9
Mill Race[3]	4996566	DWQ	5/12/2017	9/21/2020	0	0	8	12	12	9
Mill Race[3]	4996536	WFWQC	10/14/2015	6/18/2019	4	8	0	5	3	0
Mill Race[3]	4996540	WFWQC	11/16/2015	12/9/2020	2	13	12	13	12	12
Spring Creek - Springville	4996275	DWQ	9/18/2017	9/21/2020	0	0	4	12	12	9

Sub-Catchment	Site ID	Organization	Start Date	End Date	N 2015	N 2016	N 2017	N 2018	N 2019	N 2020
Spring Creek - Springville	4996275	WFWQC	2/16/2017	12/9/2020	0	0	3	10	12	12
Hobble Creek[4]	4996100	DWQ	5/12/2017	9/21/2020	0	0	8	12	12	9
Hobble Creek*[4]	4996096	WFWQC	4/24/2018	6/18/2019	0	0	0	9	2	0
Hobble Creek*[4]	4996100	WFWQC	10/20/2015	12/9/2020	4	15	12	13	12	12
Dry Creek - Spanish Fork[5]	4996040	DWQ	6/12/2017	9/30/2020	0	0	5	7	11	6
Dry Creek - Spanish Fork[5]	4996042	DWQ	6/12/2017	9/18/2017	0	0	4	0	0	0
Dry Creek - Spanish Fork[5]	4996044	DWQ	10/17/2017	9/21/2020	0	0	3	10	12	9
Dry Creek - Spanish Fork[5]	4996040	WFWQC	5/17/2018	8/6/2018	0	0	0	3	0	0
Spanish Fork River	4995578	DWQ	5/12/2017	9/21/2020	0	0	8	12	12	8
Spanish Fork River[+]	4995575	WFWQC	10/14/2015	12/8/2020	5	12	12	11	12	13
4000 South Drain Spanish Fork	5919910	DWQ	4/19/2018	9/24/2019	0	0	0	9	9	0
4000 South Drain Spanish Fork	4917712	WFWQC	10/14/2015	12/9/2020	5	12	12	13	12	13
Benjamin Slough	4995465	DWQ	5/12/2017	9/21/2020	0	0	8	12	12	9
Benjamin Slough	4995467	WFWQC	10/20/2015	4/14/2020	4	15	12	13	12	4
Currant Creek[6]	4995310	DWQ	5/16/2017	9/21/2020	0	0	8	5	12	8
Currant Creek[6]	4995312	DWQ	10/17/2017	5/16/2018	0	0	3	2	0	0

[1] WFWQC site represents total loading; DWQ site is upstream of PacifiCorps Energy discharge site and was added to PacifiCorps data to represent total loading

[2] Powell Slough has two outfalls, north (4995210) and south (4995230) which were added together to represent total loading

[3] 4996536 is located below compromise elevation and was not used for loading analyses. 4996540 and 4996566 represent separate forks and were added together to represent total loading.

[4] 4996096 and 4996100 are equivalent sites, each representing total load from Hobble Creek.

[5] 4996040 is the primary site in Dry Creek – Spanish Fork and represents total loading. 4996042 and 4996044 represent equivalent sites for the east tributary but do not include the south fork. 4996040 was the only site used to estimate loading.

[6] 4995310 and 4995312 are located at the same location.

*P data not used; P concentrations below reporting limit.

[+] N data not used; N concentrations below reporting limit.

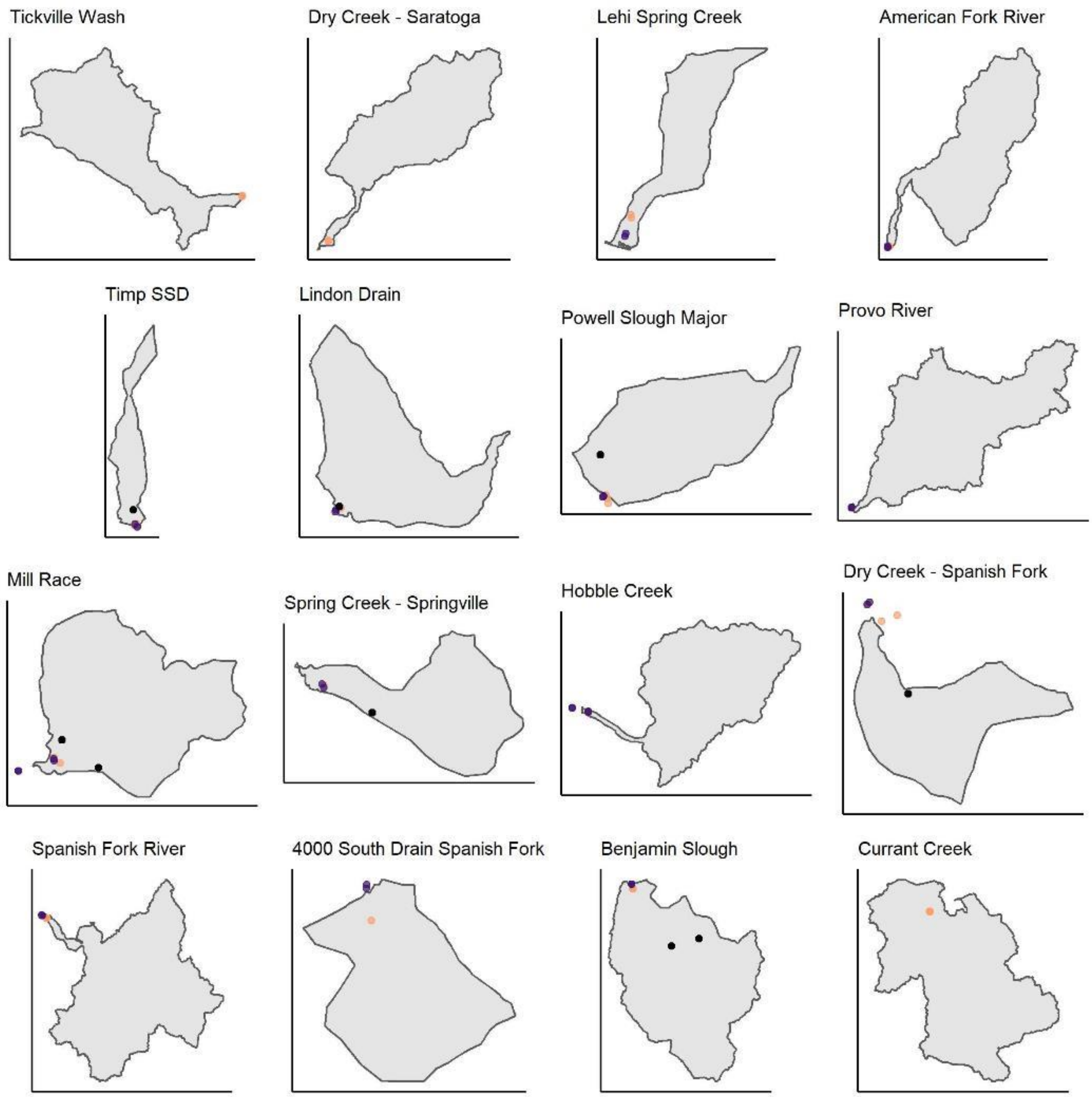


Figure 6. Monitored sub-catchments of Utah Lake, organized in clockwise order from the northwest corner. The most downstream monitoring locations for DWQ (orange) and WFWQC (purple) are displayed, along with the location of WWTPs (black).

Utah Lake experiences substantial changes in elevation; from 2010-2020, the total range in elevation was 10 ft. Other studies and proposals (e.g., the littoral sediment study; Goel et al. 2020) have demonstrated the importance of changing lake level on nutrient cycling. However, external loading estimates are not intended to account for in-lake processes that impact the transformation of nutrients, so accounting for areas that are sometimes inundated poses a challenge. The central consideration is thus to determine a generally agreed lake boundary. Two relevant zones in the lake in this case are Provo Bay and Powell Slough (Figure 7, Figure 8). From 2015-2020, the lake varied from a low maximum elevation of 4,484.94 ft in 2016 to a high maximum elevation of 4,489.05 (compromise elevation) in 2020. Accordingly, sampling sites in the Mill Race and Powell Slough sub-catchments were inundated during portions of the monitored period, and estimates of loading from those watersheds would be limited to low-lake elevation years if the most downstream monitoring sites were used. Two options in this case were to (a) define the lake boundary as the maximum elevation (i.e., compromise elevation) and generate loading estimates from a point above compromise elevation, or (b) to define the lake boundary as the inundated area on any given day and generate loading estimates from downstream sites when they are not inundated. Option (a) would necessitate removal of sampling sites below compromise elevation and would not account for any nutrient transformation occurring during non-inundated periods. Option (b) would rely on limited data, and loading estimates would be biased toward times when the lake is at low elevation. The locations and sampling frequency of monitoring sites prevents an estimate of loading from an intermediate location. Upon discussion with the SP, loads from both options were generated for comparison.

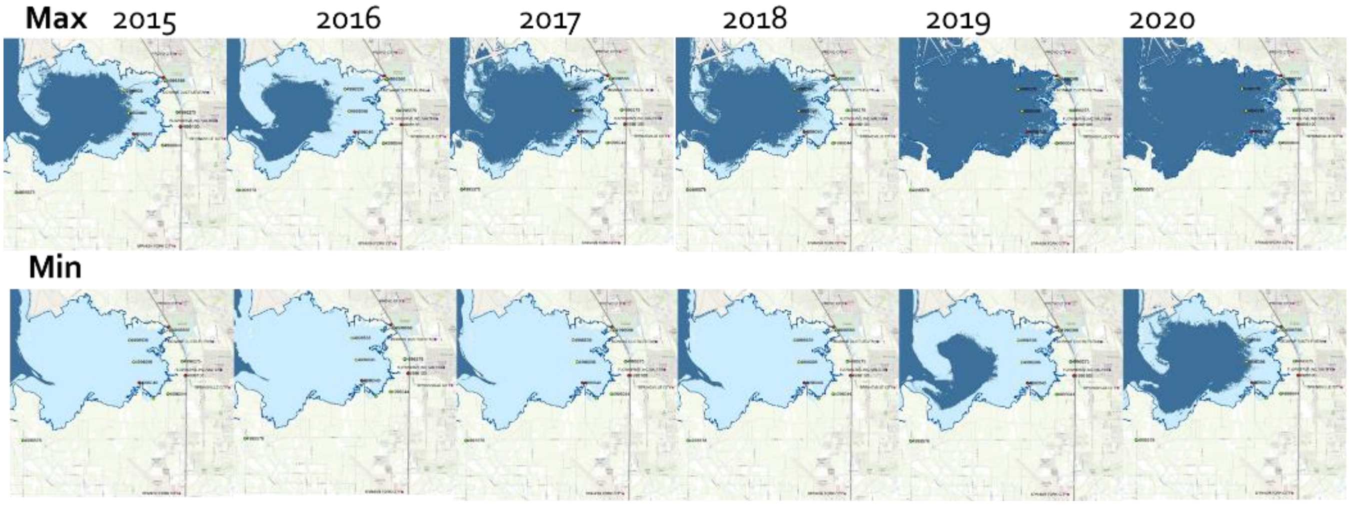


Figure 7. Annual minimum and maximum lake elevation (dark blue) in Provo Bay from 2015-2020.

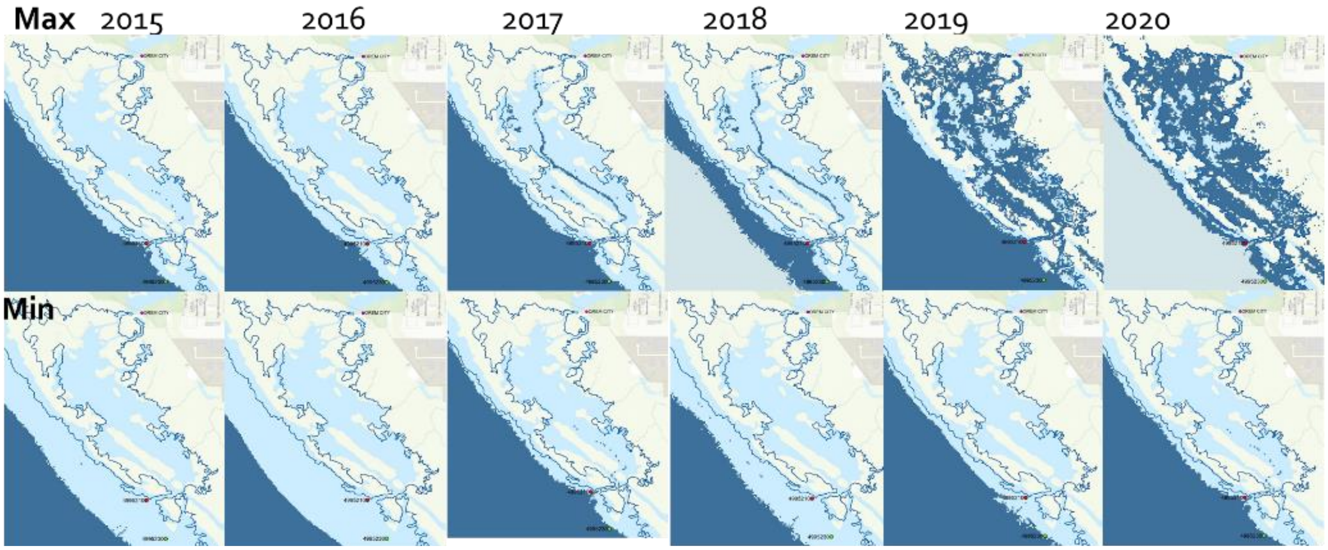


Figure 8. Annual minimum and maximum lake elevation (dark blue) in Powell Slough from 2015-2020.

For the Mill Race sub-catchment specifically, the most downstream sampling site (4996536, monitored by WFWQC) was only sampled three times for TP and once for TN (Figure 9, Figure 10). Thus, we were unable to generate monthly average load estimates from this location and relied on estimates from the most downstream DWQ sites (4996540 and 4996566, sampled 40-41 times each), one of which that was also sampled by WFWQC (4996540, sampled 12-42 times). These monitoring locations represented the north and south forks of the tributary and were summed together to generate the total load.

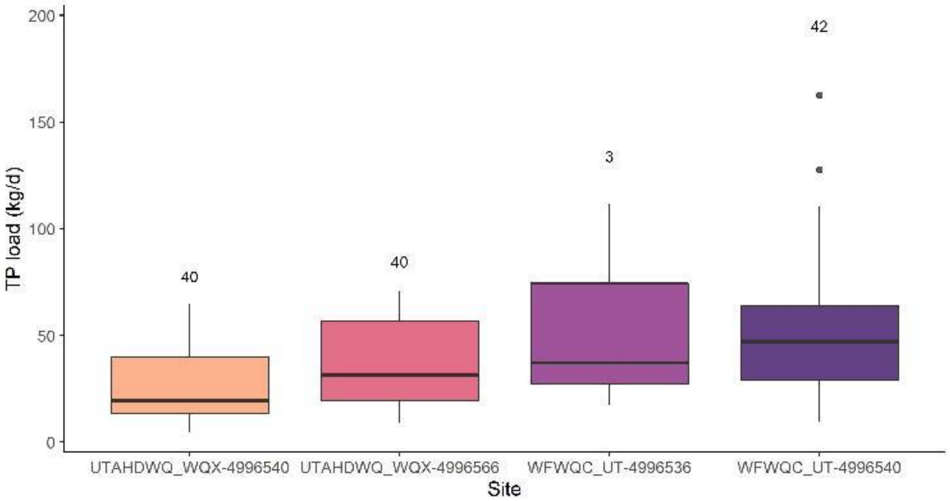


Figure 9. Daily TP loads for the four monitoring locations in the Mill Race sub-catchment. Sample sizes from 2015-2020 are indicated above each box-and-whisker plot.

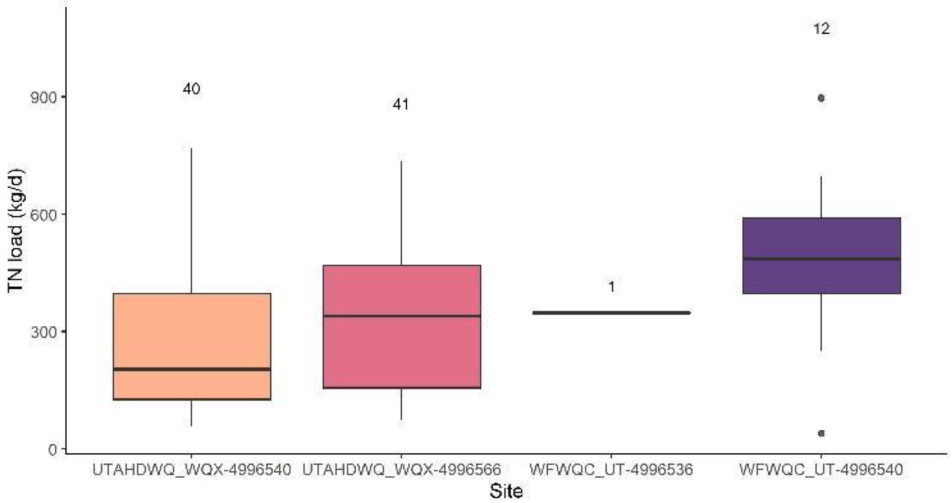


Figure 10. Daily TN loads for the four monitoring locations in the Mill Race sub-catchment. Sample sizes from 2015-2020 are indicated above each box-and-whisker plot.

Finally, point source loads were tracked and reported by WWTPs through discharge monitoring reports (DMRs). Loads from the six sub-catchments containing the WWTPs could be generated from either monitored tributaries or DMR data, if we can assume that watershed loads are negligible and there is no attenuation of nutrient loads from WWTPs before the load reaches the lake. In all cases, loads generated from DMRs were greater than those generated from tributary monitoring, so the assumption that there were no significant nonpoint watershed inputs was deemed valid. Flow reported in DMRs made up a variable proportion of tributary monitoring, with lower proportions generally occurring in sub-catchments where WWTPs were farther from the lake boundary (Table 3). We discussed this topic with the SP and determined together that nutrient loads would be determined by DMRs when the WWTP outflow was adjacent to the lake (Timpanogos SSD and Powell Slough) lake and by tributary monitoring when there was distance between the WWTP(s) outflow and the lake (Mill Race, Spring Creek – Springville, Dry Creek – Spanish Fork and Benjamin Slough).

Table 3. Annual flow estimates for the six sub-catchments containing WWTPs. The WWTP(s) within each sub-catchment is listed along with the flow estimates calculated from tributary monitoring and DMRs.

Sub-Catchment	WWTP	Annual Flow – Monitored (ac*ft/yr)	Annual Flow – DMR (ac*ft/yr)	Percent flow from WWTP
Timp SSD[1]	Timpanogos	22,065	21,116	95.7%
Powell Slough Major	Orem	20,328	9,338	45.9%
Mill Race	Provo	18,405	12,654	68.8%
Spring Creek – Springville	Springville	9,114	3,978	43.6%
Dry Creek – Spanish Fork	Spanish Fork	15,790	4,764	30.2%
Benjamin Slough	Payson Salem	16,156	2,056	12.7%

---

[1] Timp SSD monitored flow and DMR flow are measured at the same location. The differences between these measurements is due to the differences in the reporting period. The monitored flow represents an instantaneous grab sample and the DMR flow represents the 30 day mean.

4.1.2 Results

Hydrology varied substantially in both overall magnitude and seasonality in the monitored sub-catchments (Figure 11). The monitored sub-catchments were characterized by perennial flow were Lehi Spring Creek, Timp SSD, Lindon Drain, Powell Slough Major, Provo River, Mill Race, Spring Creek – Springville, Hobble Creek, Dry Creek – Spanish Fork, Spanish Fork River, 4000 South Drain Spanish Fork, and Benjamin Slough. Sub-catchments characterized by intermittent flow were Tickville Wash, Dry Creek – Saratoga, American Fork River, and Currant Creek. When combined, monitored sub-catchment flows peaked in May at 66,797 ac*ft/mo and remained above 17,000 ac*ft/mo for the remainder of the year (Figure 12). Monitored sub-catchment flow made up an estimated 92.5% of tributary inflow to Utah Lake (Table 5).

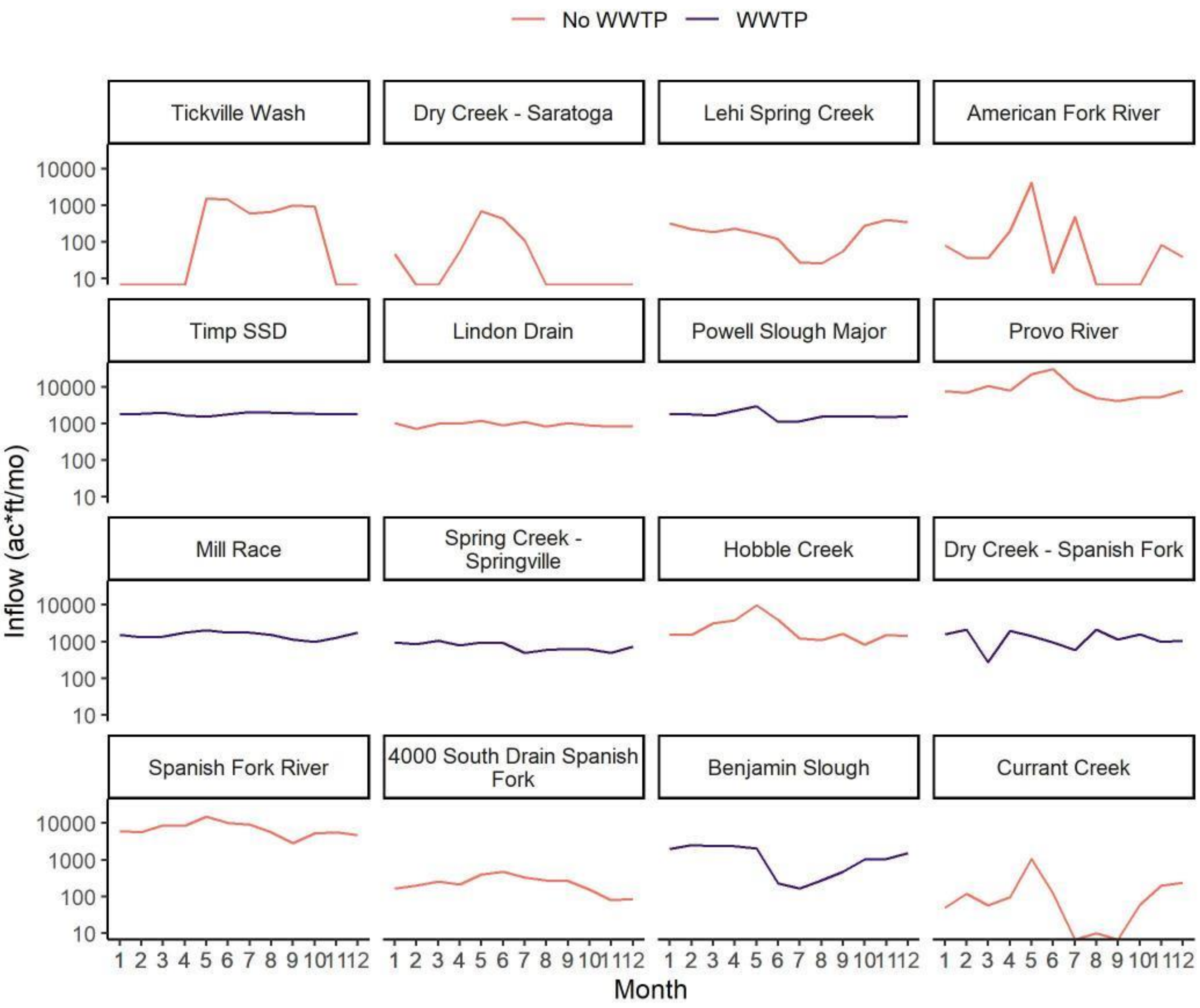


Figure 11. Monthly average tributary flow in the monitored sub-catchments of Utah Lake. Sub-catchments are organized in clockwise order starting at the northwest corner of the lake. Six of the sub-catchments contain WWTPs (noted in purple).

Nutrient loads varied substantially across monitored sub-catchments, with the highest loads generally coming from sub-catchments containing WWTPs. Note that for TN and TP loads, loading was generated from tributary monitoring samples with the exception of Timp SSD and Powell Slough Major, which were generated from DMRs. TN and TP loads were greatest for Timp SSD, Powell Slough Major, and Mill Race, and the Provo River and Spanish Fork River had the greatest load amongst sub-catchments without WWTPs (Figure 13, Figure 14). TOC loads, which were all generated from tributary monitoring data, were greatest for the Provo River and Spanish Fork River, two large catchments with the highest flows (Figure 15). Timp SSD had the greatest load amongst sub-catchments with WWTPs. Loads of TDN, TDP, and DOC were also generated (Table 5). Functionally, dissolved constituents should always make up < 100% of the total loads, but due to methodological differences and analytical variability, dissolved loads were greater than total loads for some sub-catchments.

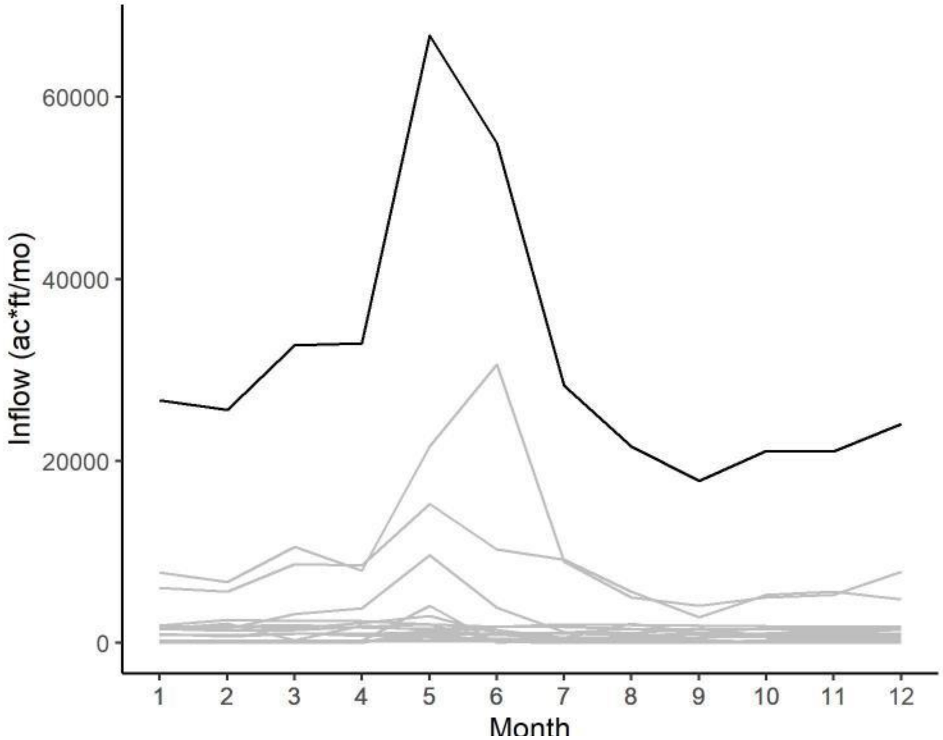


Figure 12. Average monthly flow from the monitored sub-catchments (black). Individual sub-catchments are displayed in gray.

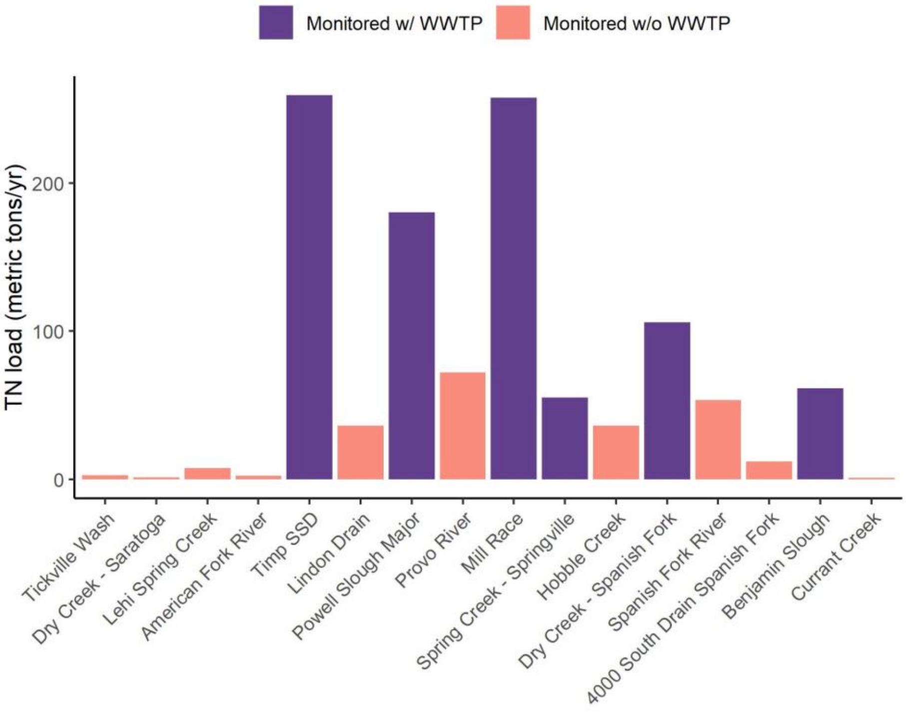


Figure 13. Annual TN loading in monitored sub-catchments. Sub-catchments are organized in clockwise order starting at the northwest corner of the lake. Six of the sub-catchments contain WWTPs (noted in purple).

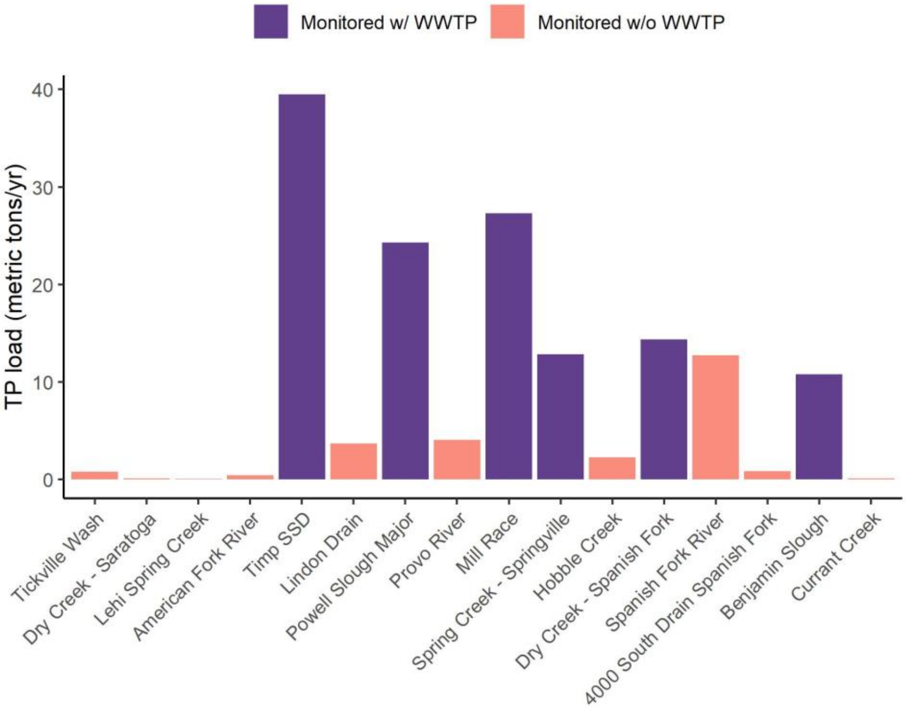


Figure 14. Annual TP loading in monitored sub-catchments. Sub-catchments are organized in clockwise order starting at the northwest corner of the lake. Six of the sub-catchments contain WWTPs (noted in purple).

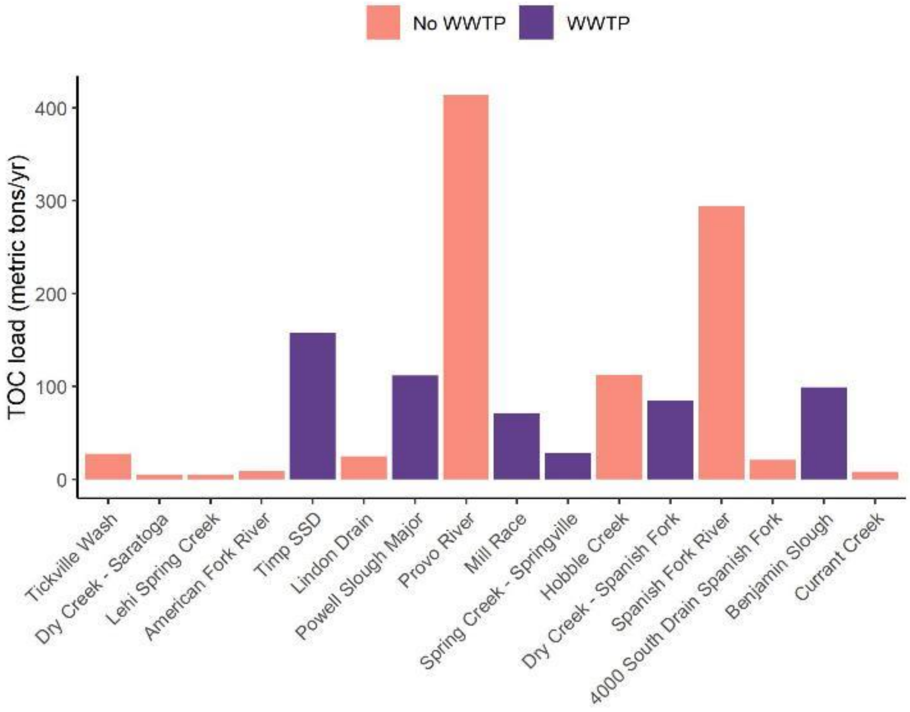


Figure 15. Annual TOC loading in monitored sub-catchments. Sub-catchments are organized in clockwise order starting at the northwest corner of the lake. Six of the sub-catchments contain WWTPs (noted in purple).

4.2 UNMONITORED WATERSHEDS

4.2.1 Methods

The original workplan for this study proposed using a paired watershed approach to estimate hydrologic inputs and nutrient loads from unmonitored watersheds. Upon further evaluation, we determined that due to the prevalence of unmonitored watersheds with ephemeral flow that had no monitored counterpart, a different approach was more appropriate. We explored several options for generating estimates from unmonitored watersheds for a similar amount of effort. The Hydrologic and Water Quality System (HAWQS) and Spreadsheet Tool for Estimating Pollutant Loads (STEPL) models were considered as candidates, but these models are not able to model loading from catchments smaller than the HUC-12 scale. Ultimately we chose Model My Watershed, which was developed by the Stroud Water Research Center to model runoff and water quality impacts, among other things including land use and soil data and development scenario analysis (Stroud Water Research Center 2020).

Model My Watershed offers two models to choose from to predict how water moves through a user’s area of interest and to predict the water quality of water running off from the area of interest. These two options are the Site Storm Model, which simulates a single 24-hour storm, and the Watershed Multi-Year Model, which simulates 30 years of daily water, nutrient and sediment fluxes using the Generalized Watershed Loading Function Enhanced (GWLF-E) model that was developed for a watershed modeling program called MapShed at Penn State University (Evans et al 2016). The “multi-year” model was chosen to estimate hydrology and water quality parameters for Utah Lake sub-catchments, as this is the more comprehensive model of the two options.

For hydrology, NHDplus v2 medium resolution (1:100,000-scale) flow lines are used for the model stream network. Therefore, the model should be suited for perennial, intermittent, and ephemeral flow as NHDplus offers this distinction. For nutrient loading inputs, sources considered are farm animal populations (county level data from USDA), point sources (EPA's Discharge Monitoring Report (DMR) database), land cover data (2011 National Land Cover Database), and estimates of soil N and P concentrations. The initial calibration of the multi-year model was performed using modeled results and observed stream data for 39 test watersheds in specific geographic regions around the country.

For the Utah Lake application, the 54 unmonitored sub-catchments were supplied to the model and output for each sub-catchment was generated by the Watershed Multi-Year Model. The output included monthly hydrology and annual TN and TP loading.

4.2.2 Results

Hydrology varied substantially in both overall magnitude and seasonality in the monitored sub-catchments (Figure 16). Flow was characterized as perennial, intermittent, and ephemeral across sub-catchments. When combined, unmonitored sub-catchment flows peaked in January and February and were lowest in August and September (Figure 17). Unmonitored sub-catchment flow made up 7.5% of total tributary flow to Utah Lake.

TN and TP loading from unmonitored watersheds was 163.18 and 22.98 metric tons/yr, respectively (Table 5). These nutrient loads made up 9.5% of tributary TN loading to the lake and 8.1% of total TN loading to the lake. For TP loads, unmonitored watersheds made 8.6% of total tributary loading and 8.4% of total loading to the lake.

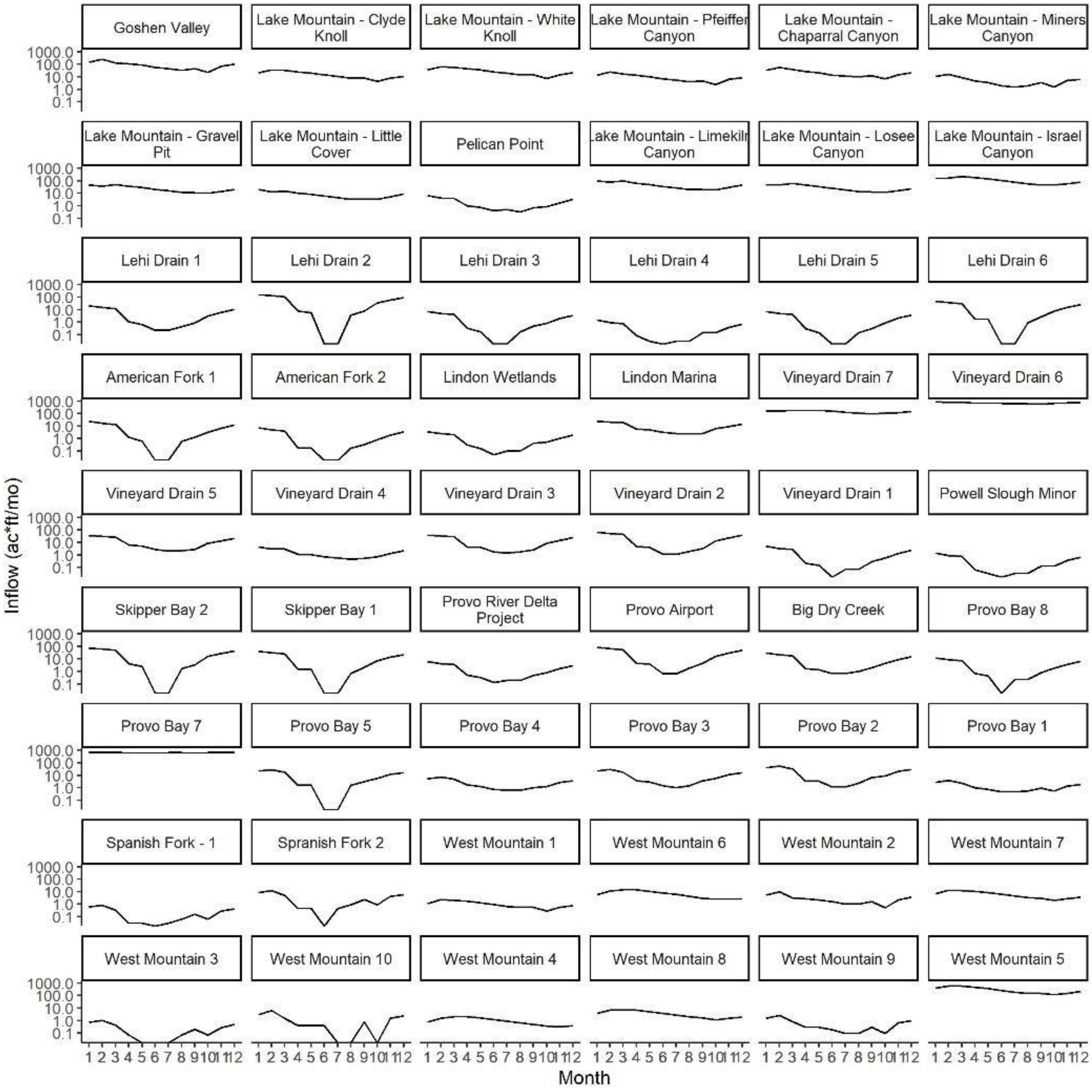


Figure 16. Monthly average tributary flow in the unmonitored sub-catchments of Utah Lake. Sub-catchments are organized in clockwise order starting at the northwest corner of the lake.

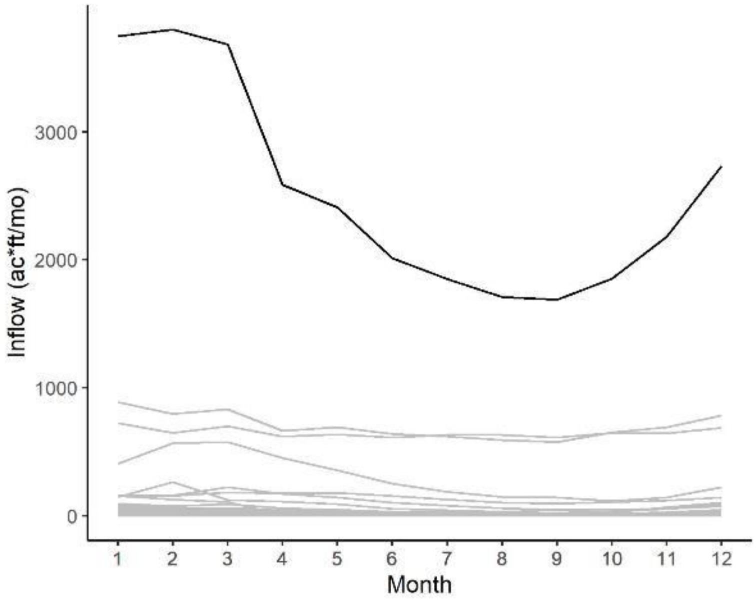


Figure 17. Average monthly flow from the unmonitored sub-catchments (black). Individual sub-catchments are displayed in gray.

4.3 NON-TRIBUTARY INPUTS AND OUTPUTS

Apart from tributary and overland flow from surrounding sub-catchments, inputs of water and nutrients to Utah Lake are made up of groundwater inflow, atmospheric deposition (for nutrients), and precipitation (for water). In general, groundwater can represent either a net input or a net output for a lake, and in the case of Utah Lake has a net input. Annual estimates of groundwater inflow were taken from EFDC/WASP output from Su and von Stackelberg (2020), represented as four zones around the lake. Nutrient concentrations in groundwater measured from 2015-2020 were obtained from the Water Quality Portal, spatially paired with the four zones, and multiplied by the inflow to generate annual load estimates (Table 4). Atmospheric deposition was determined from Brahney (2019), the course of action recommended by the SP until updated measurements of atmospheric deposition become available (ULWQS SP 2019). TN and TP loads from atmospheric deposition were assigned as 170 and 5 metric tons/yr, respectively, with dissolved fractions making up a proportion of total loads (Table 5). Precipitation inputs were taken from EFDC/WASP output from Su and von Stackelbeg (2020) and cross-referenced with daily estimates of the area of Utah Lake to generate input volumes. Daily precipitation was averaged to create monthly averages and annual totals of monthly inputs (Figure 18).

Table 4. Groundwater inputs to Utah Lake.

Zone	Flow (ac*ft/yr)	TN load (metric tons/yr)	TP load (metric tons/yr)
North	25,490	52.82	0.50
South	4,858	10.83	0.12
Goshen Bay	3,605	65.64	0.11
Provo Bay	4,730	4.89	0.07

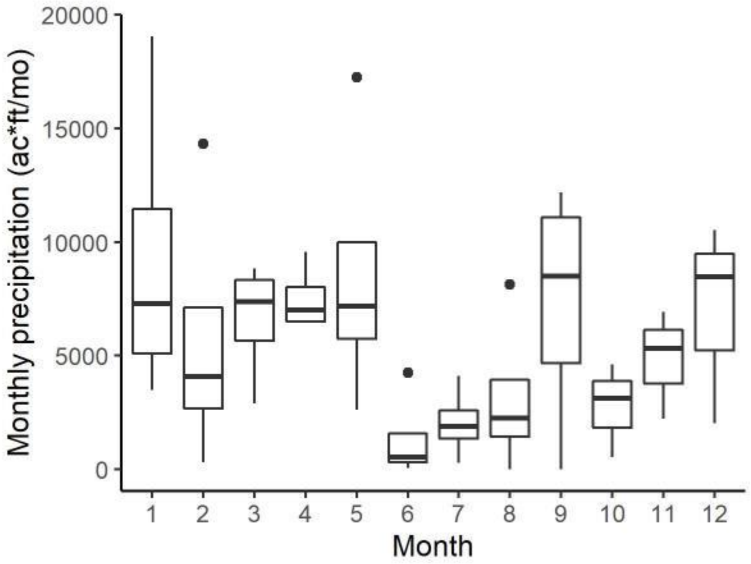


Figure 18. Monthly distributions of precipitation to Utah Lake.

Utah Lake has only one outflow, the Jordan River. Thus, any outputs from Utah Lake are made up of Jordan River flow and evaporation, the latter of which only impacts the hydrologic budget. Jordan River flow was taken from daily measurements at a site downstream of the Utah Lake outlet (the Narrows) by the Utah Division of Water Rights and paired with chemistry measurements collected by the DWQ. The exception to flow data being used from the Narrows was when flows of zero were observed at the outlet during a DWQ sampling outing; these conditions occurred in January and February across the sampling period and flows of zero were assigned rather than the flows observed at the Narrows (Figure 19). Flows were multiplied by nutrient concentrations to generate outflow loads. Evaporation inputs were taken from EFDC/WASP output from Su and von Stackelbeg (2020) and cross-referenced with daily estimates of the area of Utah Lake to generate input volumes. Daily evaporation was averaged to create monthly averages and annual totals of monthly inputs (Figure 20).

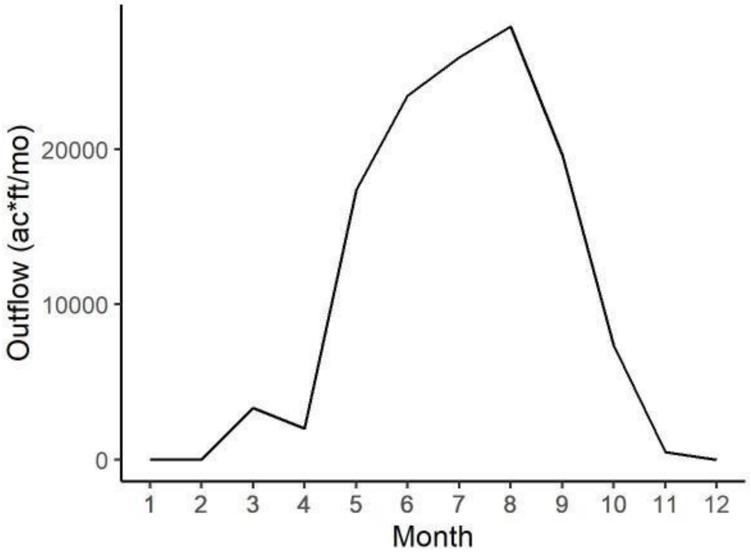


Figure 19. Monthly average outflow for the Jordan River.

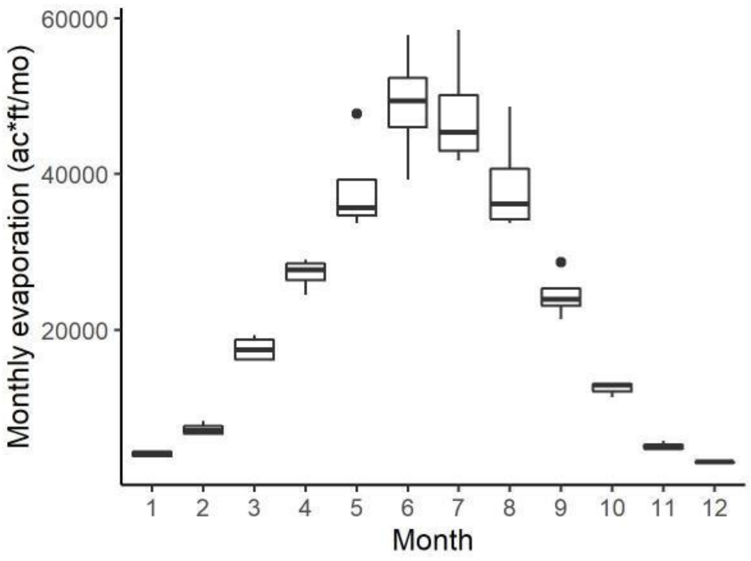


Figure 20. Monthly distributions of evaporation from Utah Lake.

4.4 HYDROLOGIC BUDGET

Tributaries and overland flow made up 79.4% of inputs to Utah Lake, with precipitation and groundwater making up 13.0 and 7.6%, respectively (Figure 21). Evaporation made up 68.3% of outputs, and the Jordan River represented 31.7% of outputs. There was a net positive storage (balance) component of 106,015 ac*ft/yr across the monitored period, representing 20.8% of the total inflow.

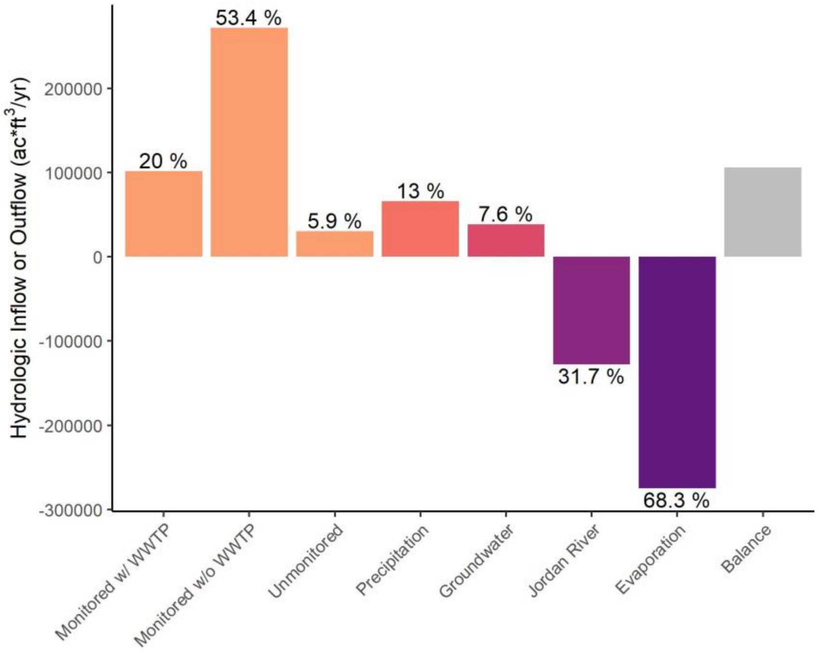


Figure 21. Hydrologic budget of Utah Lake. Percentages represent the percent of total inflows (positive components) and outflows (negative components), respectively.

4.5 NUTRIENT BUDGET

Sub-catchment TN and TP loads were highest on the eastern side of Utah Lake, with monitored sub-catchments and specifically those containing WWTPs representing the highest loads (Figure 22). TOC loads were not available for unmonitored sub-catchments, but the largest loads from monitored sub-catchments were in the Spanish Fork River and Provo River, which do not contain WWTPs but are large watersheds with high tributary flows (Figure 23). For both TN and TP, loading from sub-catchments made up the highest proportions of total loads, in order from monitored sub-catchments containing WWTPs, monitored sub-catchments without WWTPs, and unmonitored sub-catchments (Figure 24, Figure 25). Outflow to the Jordan River represented 6.1 and 10.7% of TN and TP loads to the lake, respectively. Summaries of loading for each source, along with dissolved species, are summarized in Table 5. Functionally, dissolved constituents should make up a proportion of total loads, but due to methodological differences and analytical variability, dissolved loads were greater than total loads for some sub-catchments.

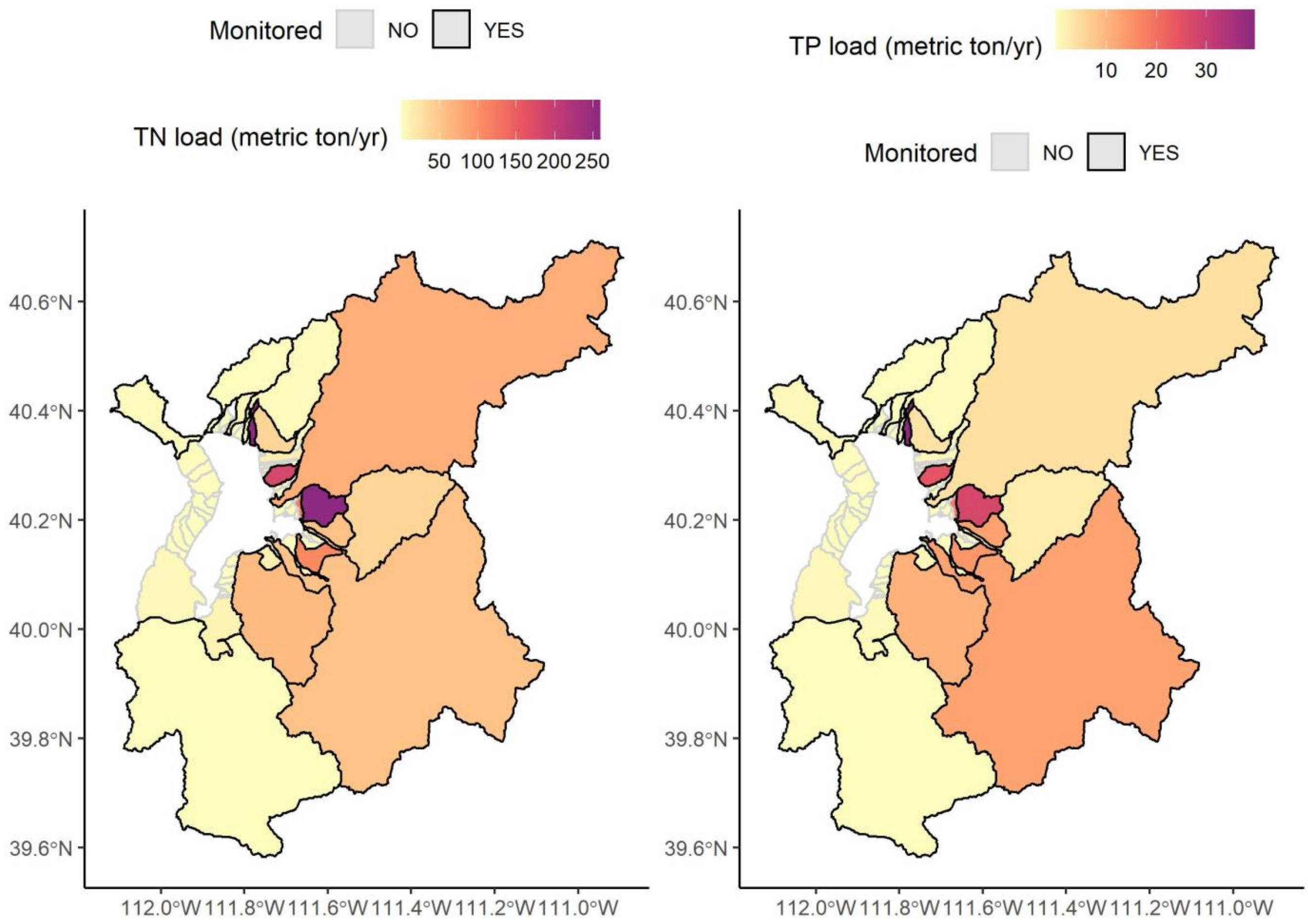


Figure 22. Sub-catchment TN and TP annual loads to Utah Lake. Monitored sub-catchments are outlined in black, and unmonitored sub-catchments are outlined in gray.

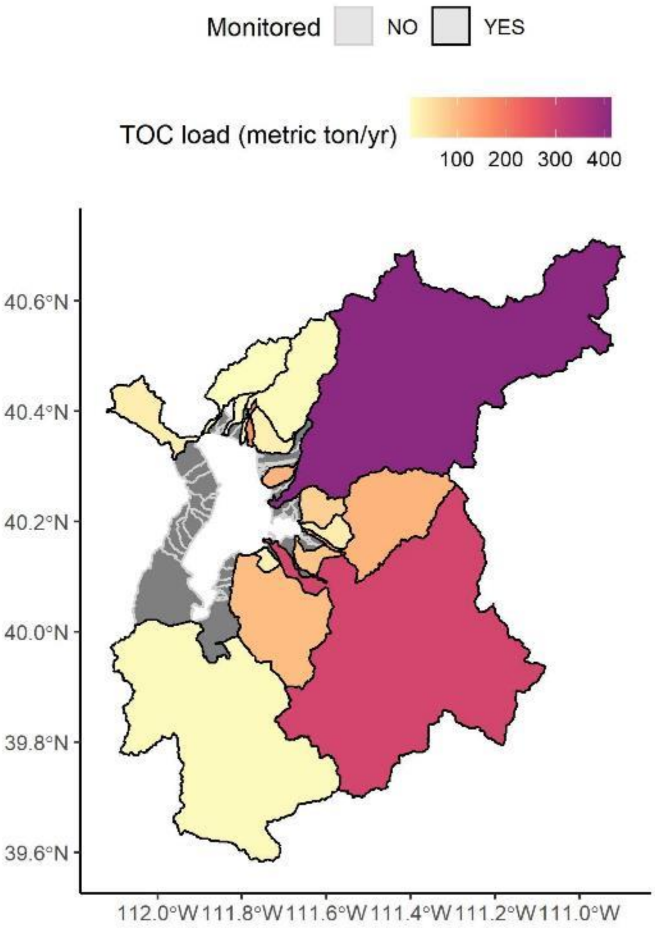


Figure 23. Sub-catchment TOC annual loads to Utah Lake. Monitored sub-catchments are outlined in black. Unmonitored sub-catchments did not have load estimates available and are filled with gray.

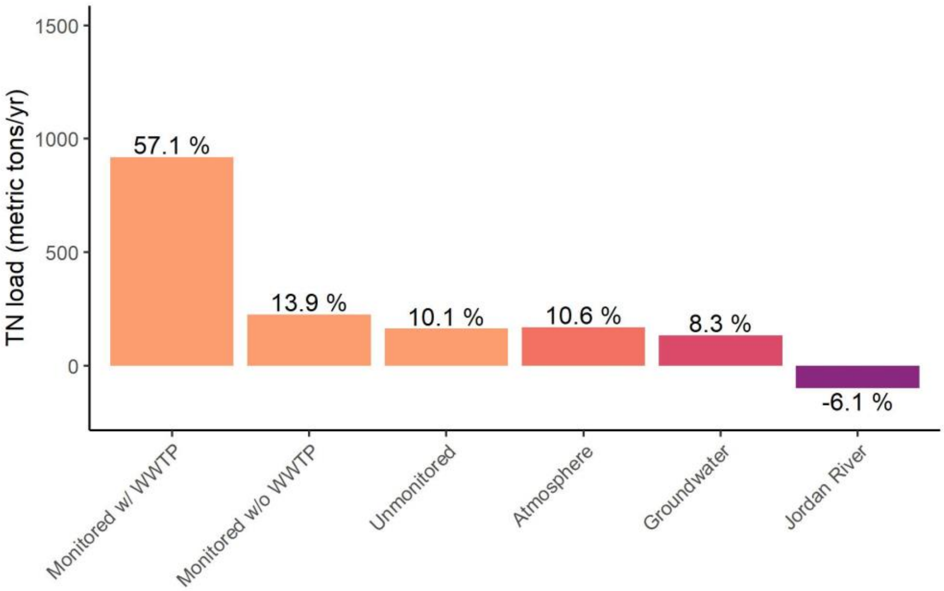


Figure 24. Annual TN loading to and from Utah Lake. Inputs are represented as positive loads and outputs are represented as negative loads. Percentages represent the proportion of the total input.

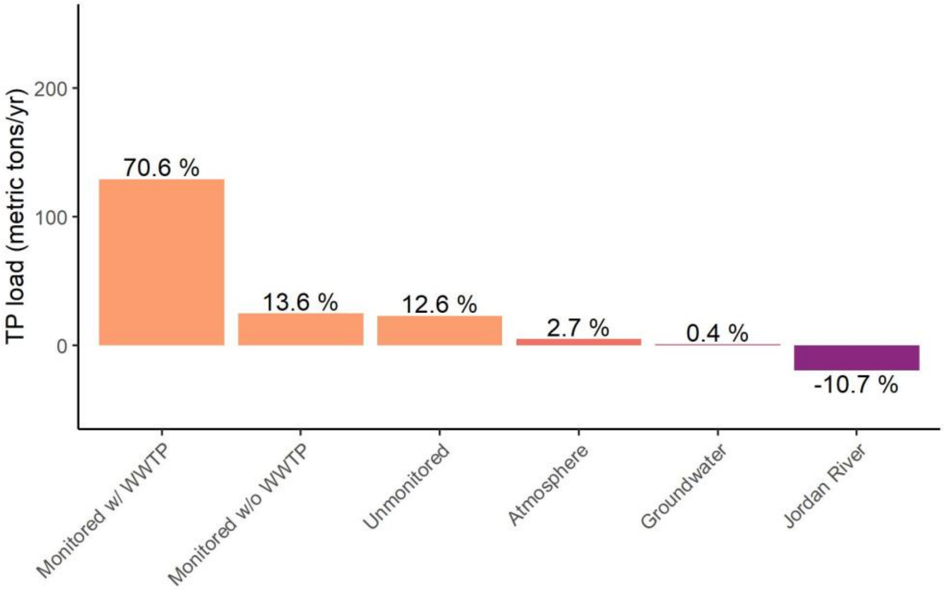


Figure 25. Annual TP loading to and from Utah Lake. Inputs are represented as positive loads and outputs are represented as negative loads. Percentages represent the proportion of the total input.

Table 5. Hydrologic and nutrient loading for Utah Lake inputs and outputs. For monitored watersheds with both tributary and DMR data, the values not used to generate load estimates are noted in gray.

Watershed	Flow	TN load	TDN load	TP load	TDP load	TOC load	DOC load
	ac*ft/yr	metric tons/yr	metric tons/yr	metric tons/yr	metric tons/yr	metric tons/yr	metric tons/yr
INFLOWS							
Tickville Wash	6,151	2.56	3.70	0.78	0.14	27.21	35.70
Dry Creek – Saratoga	1,333	1.21	1.31	0.09	0.02	5.11	6.03
Lehi Spring Creek	2,397	7.60	7.01	0.06	0.03	5.15	7.08
American Fork River	5,058	2.35	2.40	0.41	0.03	8.52	10.71
Timpanogos SSD							
Tributary	22,065	236.97	240.36	28.94	28.22	158.20	193.94
Timpanogos WWTP	21,116	259.21	--	39.49	26.86	--	--
Lindon Drain	11,257	36.09	30.00	3.65	1.96	24.56	38.34
Powell Slough Major							
Tributary	20,328	294.86	272.63	39.22	31.07	111.85	134.68
Orem WWTP	9,338	180.36	--	24.30	25.34	--	--
Provo River	121,454	72.22	90.64	4.07	2.03	413.66	595.08
Mill Race							
Tributary	18,405	257.41	228.82	27.29	24.38	70.84	89.14
Provo WWTP	12,654	414.88	--	42.20	38.10	--	--
Spring Creek – Springville							
Tributary	9,114	55.12	50.42	12.82	11.79	28.41	32.42
Springville WWTP	3,978	116.07	--	18.31	16.16	--	--
Hobble Creek	31,400	36.24	38.52	2.23	1.40	112.19	147.21
Dry Creek – Spanish Fork							
Tributary	15,790	105.89	110.73	14.37	9.28	84.75	107.58
Spanish Fork WWTP	4,764	123.85	--	18.10	13.76	--	--
Spanish Fork River	87,857	53.44	61.02	12.71	3.50	294.19	393.55
4000 South Drain Sp. Fork	2,909	12.12	10.01	0.83	0.62	21.05	22.82
Benjamin Slough							
Tributary	16,156	61.29	55.29	10.78	8.21	98.99	104.95
Payson WWTP	1,821	54.51	--	10.48	9.89	--	--
Salem WWTP	235	5.25	--	0.97	0.71	--	--
Currant Creek	2,036	0.84	1.18	0.08	0.05	8.32	11.36
Unmonitored sub-catchments	30,265	163.18	--	22.98	--	--	--
TOTAL sub-catchments	***403,975***	***1,307.13***	**--**	***176.95***	**--**	**--**	**--**

Precipitation	66,045	--	--	--	--	--	--
Atmospheric Loading	--	170	74.8[1]	5.0	2.5	--	--
Groundwater	38,682	134.18	--	0.80	--	--	--
TOTAL inflows	***508,702***	***1,611.31***	***--***	***182.75***	***--***	***--***	***--***
OUTFLOWS							
Jordan River	127,610	98.83	113.70	19.47	3.68	1,001.29	1,171.07
Evaporation	275,077	--	--	--	--	--	--
TOTAL outflows	***402,687***	***98.83***	***113.70***	***19.47***	***3.68***	***1,001.29***	***1,171.07***

[1] NO_3^- + NH_4^+ wet and dry deposition

4.6 COMPARISONS TO OTHER STUDIES

Several other studies present opportunities to evaluate the budgets generated in this study. Inflow from sub-catchments fell in the middle of estimates from previous studies (Table 6), suggesting that inflows were not biased toward high or low flows and thus nutrient loads are likely to be unbiased as well. Outflow from the Jordan River was lower in this study than in previous studies (Table 7), though it should be noted that the period of interest for each of the studies differs and outflow rate were generated from direct daily measurements. Importantly, Su and von Stackelberg (2020) used the same method as this study, but the period of record in this study was a drier period than 2006-2018. Thus, we do not anticipate outflows are underestimated in this study although they are lower than previous estimates.

Table 6. Comparisons of tributary and overland flow among this and other studies.

Study	Years	Inflow (ac*ft/yr)
This study	**2015-2020**	**403,975**
Su and von Stackelberg (2020)	2006-2018	356,742
Merritt and Miller (2016)	2009-2013	495,092
PSOMAS and SWCA (2007)	1980-2003	421,600
Merritt (unpublished LKSIM)	2015-2020	395,397

Table 7. Comparisons of Jordan River outflow among this study and others.

Study	Years	Streamflow (ac*ft/yr)
This study	**2015-2020**	**127,610**
Su and von Stackelberg (2020)	2006-2018	260,695
Merritt and Miller (2016)	2009-2013	336,045
PSOMAS and SWCA (2007)	1980-2003	428,200

TN and TP loads were compared with two previous studies that have generated loads using LKSIM (PSOMAS and SWCA 2007, Merritt and Miller 2016). TN loads estimated from monitored tributaries tended to be lower than Merrit and Miller (2016) estimates, with the exception of some sub-catchments containing WWTPs (Table 8). N loads from WWTPs tended to be larger than both this study and Merritt and Miller (2016). TP loads varied in how they compared with previous studies, particularly when considering the difference between tributary monitored loads and DMR loads in sub-catchment with WWTPs (Table 9). Overall, this study estimates the TN load to be 1,611 metric tons/yr, compared to 1,946 metric tons/yr in Merritt and Miller (2016). This study estimates total TP loads to Utah Lake are 183 metric tons/yr, compared to 270 and 247 metric tons/yr (PSOMAS and SWCA and Merritt and Miller 2016, respectively). Note that PSOMAS and SWCA (2007) use 1980-2003 as the period of interest and Merritt and Miller (2016) use 2009-2013 as the period of interest, compared to this study which used 2015-2020 as the period of record.

Table 8. Comparison of N loads (metric tons/yr) to Utah Lake between this and other studies. Sub-catchments containing WWTPs are indicated in bold. Note that each study reports a different N species.

Watershed	This Study Tributary data (TN)	DMR data (TN)	Merritt and Miller 2016 (DN)
Tickville Wash	2.56		
Dry Creek – Saratoga	1.21		
Lehi Spring Creek	7.60		10.80
American Fork River	2.35		12.79
Timp SSD	**236.97**	**259.21**	**190.56**
Lindon Drain	36.09		
Powell Slough Major	**294.86**	**180.36**	**88.29**
Provo River	72.22		128.86
Mill Race	**257.41**	**414.88**	**463.70**
Spring Creek – Springville	**55.12**	**116.07**	**92.56**
Hobble Creek	36.24		42.65
Dry Creek – Spanish Fork	**105.89**	**123.85**	**132.49**
Spanish Fork River	53.44		95.28
4000 South Drain Sp. Fork	12.12		
Benjamin Slough	**61.29**	**59.76**	**90.74**
Currant Creek	0.84		

Table 9. Comparison of TP loads (metric tons/yr) to Utah Lake between this and other studies. Sub-catchments containing WWTPs are indicated in bold.

Watershed	This Study Tributary data	This Study DMR data	Merritt and Miller 2016	PSOMAS and SWCA 2007
Tickville Wash	0.78			
Dry Creek – Saratoga	0.09			0.18
Lehi Spring Creek	0.06		0.37	
American Fork River	0.41		0.57	
Timp SSD	**28.94**	**39.49**	**52.90**	**35.39**
Lindon Drain	3.65			
Powell Slough Major	**39.22**	**24.30**	**33.12**	**74.77**
Provo River	4.07		7.50	7.17
Mill Race	**27.29**	**42.20**	**55.72**	**67.51**
Spring Creek - Springville	**12.82**	**18.31**	**16.97**	**13.07**
Hobble Creek	2.23		1.32	1.27
Dry Creek – Spanish Fork	**14.37**	**18.10**	**19.87**	**12.61**
Spanish Fork River	12.71		8.12	19.24
4000 South Drain Sp. Fork	0.83			
Benjamin Slough	**10.78**	**11.45**	**7.85**	**15.06**
Currant Creek	0.08			

SEDFLUX MODEL

5.1 METHODS

To model internal cycling of nutrients, we applied the SedFlux model. Specifically, SedFlux models nutrient fluxes across the sediment-water interface and sediment oxygen demand (SOD). The model is based on DiToro (2001), adapted from original work for QUAL2K by Chapra and Pelletier (2003) and WASP by SP member James Martin. The user-supplied inputs to the model include parameters that mediate the reaction network, sediment conditions at the start of the modeled period, and time series of water column conditions. Parameters were set to the default SedFlux parameters except where otherwise noted in Su and von Stackelberg (2020). Initial sediment conditions were set to the default SedFlux values except dissolved phosphate in the layer 1 porewater, which was set to 1.48 mg/L in the main basin and 3.85 mg/L in Provo Bay. The model was set to the time variable option rather than steady state.

Time series inputs to the water column were obtained from several sources. Buoys were deployed at the “State Park” location (4917390) in the middle of the main basin of Utah Lake from May-October of 2017-2019 and in Provo Bay (4917446) in 2018; this time series formed the period of simulation for the model. Dissolved oxygen (DO) and temperature data were extracted from buoy time series in 6-hour increments. Ammonium (NH_4^+), nitrate (NO_3^-), soluble reactive P (SRP), DOC, and water column depth time series were obtained from routine monitoring data from the Water Quality Portal. When multiple sites across the main basin or Provo Bay were sampled in a given day, the average of all sites was computed. Concentrations for dates when no sampling occurred were estimated via linear interpolation between observations. DOC was converted into oxygen equivalent units using the following equation: mg O_2/L = mg C/L * 32 mg O_2/12 mg C. Salinity and silica, as variables that were not expected to vary over time, were set to the average value across the dataset: 0.8 PSU for salinity and 29 mg/L for silica.

Flux to the sediment from settling particulate organic C, N, and P is also an input to the model, but these rates had to be estimated from the literature rather than from measured values. While several studies (Hogsett et al. 2019, Randall et al. 2019, Brahney et al. pers. comm) have measured sediment nutrient content and accumulation rates, these findings have limited value because (a) they lack estimates of sediment density which is needed to extrapolate to areal input rates for the model, and (b) sediment organic matter (OM) content is typically lower than the organic matter content of sinking phytoplankton and detritus. Similarly, volatile suspended solids are measured in Utah Lake, but sinking rates have not been measured. We used data measured in calcareous Wintergreen Lake, MI by Molongoski and Klug (1980). They noted settling rates were lowest in spring and highest in summer and early fall. This observation mirrored observations in Utah Lake, where phytoplankton biomass is highest in late summer and early fall (Tetra Tech 2020c). When proportions of N and P in phytoplankton biomass were applied to settling organic matter (Figure 3, Figure 4), we computed rates of settling as 0.3-1.8 g m^{-1} d^{-1} for C, 0.084-0.581 g m^{-1} d^{-1} for N, and 0.0168-0.1162 g m^{-1} d^{-1} for P. Four scenarios were run to represent a possible range in Utah Lake:

- Low OM sinking: minimum rate, steady across time series
- Medium OM sinking: mean rate, steady across time series
- High OM sinking: maximum rate, steady across time series
- Seasonal OM sinking: minimum rate at the start of the time series, linear increase to maximum rate on August 1. Maintain high rate for the rest of the time series. Consistent with phytoplankton biomass seasonal trends (Tetra Tech 2020c).

The modeled period for Provo Bay was only from August-October, so the fourth scenario was only run for the main basin.

With the knowledge that Utah Lake changes in elevation, we tested the sensitivity of the model to changing water column depth. Observed depth during the modeled period were 1.95-3.5 m in the main basin, and an alternate scenario of a shallow depth of 2.0 m was tested. Observed depth in Provo Bay during the modeled period was 0.2 m, and an alternate scenario of a deep depth of 1.5 m was tested.

Finally, areal rates were scaled to the area of Utah Lake. Daily LIDAR-generated lake areas were cross-referenced with the modeled dates in SedFlux, and modeled output rates were multiplied by the total lake area for that date.

5.2 SEDFLUX RESULTS & DISCUSSION

All output results are displayed with the four OM sinking rates scenarios, which could be considered a probable range for Utah Lake in the absence of directly measured data. Results for the varying depth scenarios are also displayed, following the seasonal OM sinking scenario for the main basin and the high organic matter sinking scenario for Provo Bay. SOD ranged from 4.90-14.38 g O_2 m^{-2} d^{-1}, peaking from mid-July through August. Rates of SOD were moderately variable based on OM sinking rates, with highest rates occurring under high OM sinking rates (Figure 26). SOD was lower under shallow conditions than under observed conditions (Figure 27). NH_4^+ flux ranged from 0.03-1.23 g N m^{-2} d^{-1} (flux from the sediment to the water column), peaking from mid-July through August. Rates of NH_4^+ flux were quite variable based on OM sinking rates, with highest rates occurring under high OM sinking rates (Figure 28). NH_4^+ flux displayed much greater variability under shallow conditions than under observed conditions (Figure 29). NO_3^- flux ranged from -0.01-0.01 g N m^{-2} d^{-1}, with fluxes to the sediment early and late in the season and fluxes from the sediment to the water column in the mid-summer. Rates of NO_3^- flux were moderately variable based on OM sinking rates, with highest rates occurring under high OM sinking rates (Figure 30). NO_3^- flux displayed greater variability under shallow conditions than under observed conditions (Figure 31). Denitrification rate ranged from 0.0005-0.01 g N m^{-2} d^{-1} and displayed considerable seasonal variability. Rates of denitrification did not vary based on OM sinking rates or changing water column depth (Figure 32, Figure 33). SRP flux ranged from 0.006-0.20 g P m^{-2} d^{-1}, peaking from mid-July through August. The seasonality of OM sinking rates was important for SRP flux, with the seasonal OM sinking scenario displaying distinct seasonal differences compared to constant OM sinking rates (Figure 34). SRP flux displayed much greater variability under shallow conditions than under observed conditions (Figure 35).

Provo Bay displayed generally similar results as the main basin in terms of flux rates, the impact of OM sinking rates, and the impact of depth (Figure 36, Figure 37). Exceptions include that NO_3^- flux was negative (i.e., from the water column to the sediment) across all dates and scenarios, and that SRP flux was lower and sometimes negative under a deeper water column scenario.

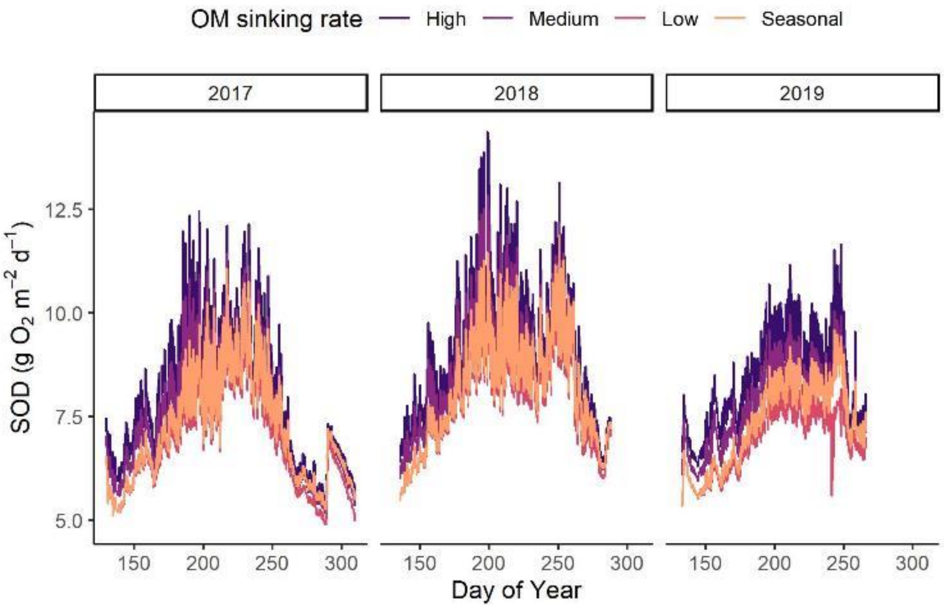


Figure 26. SedFlux SOD rates under variable OM sinking rates.

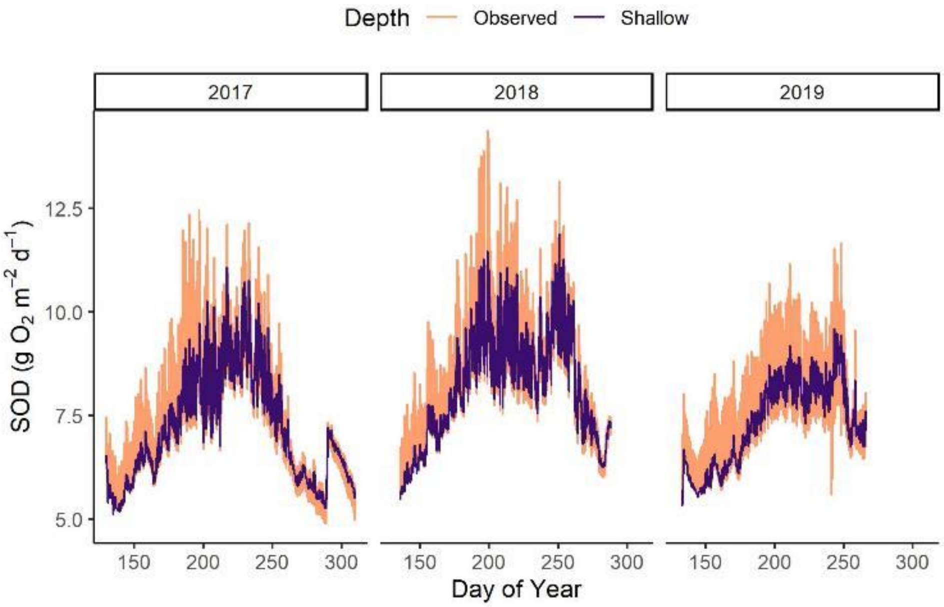


Figure 27. SedFlux SOD rates under two different water column depth scenarios.

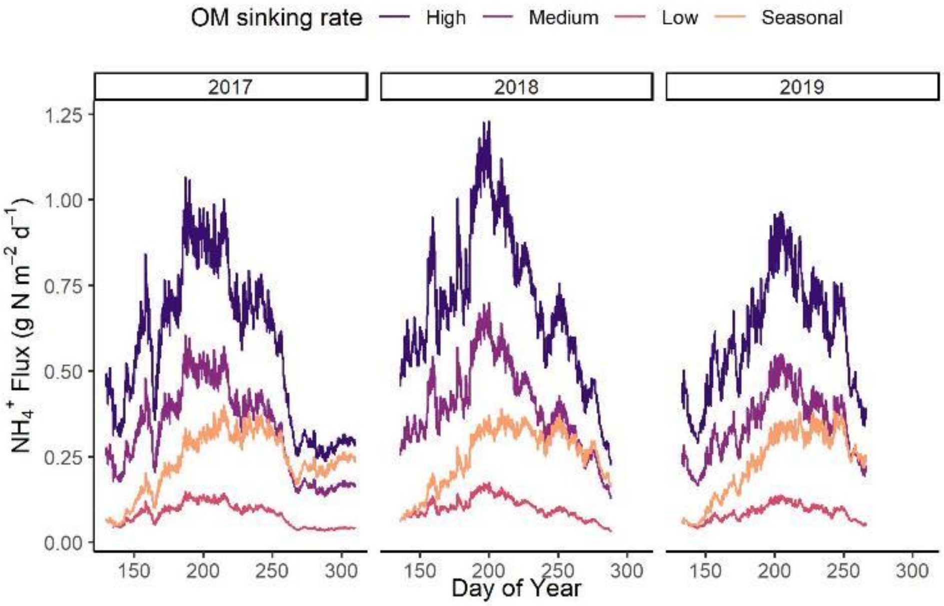


Figure 28. SedFlux NH_4^+ flux rates under variable OM sinking rates.

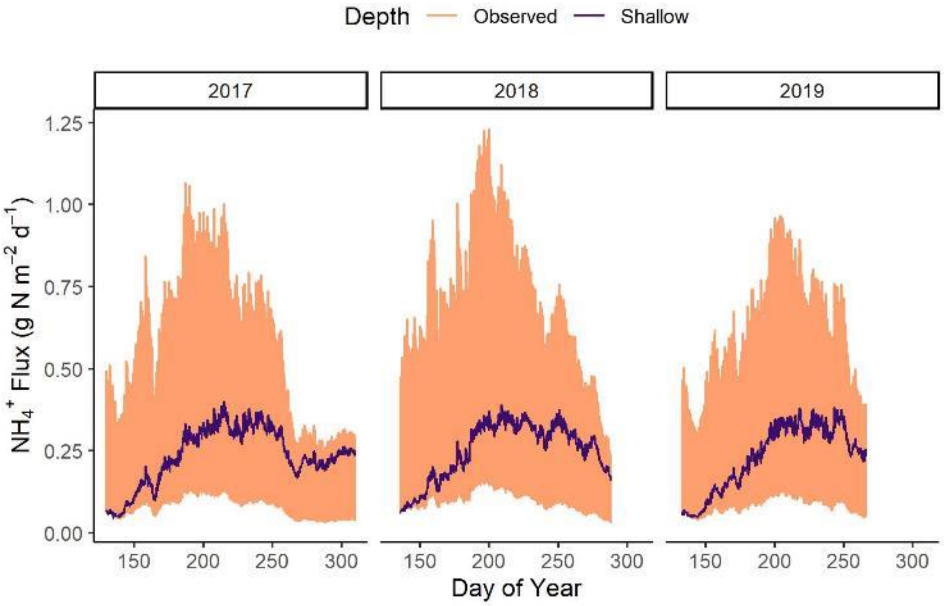


Figure 29. SedFlux NH_4^+ flux rates under two different water column depth scenarios.

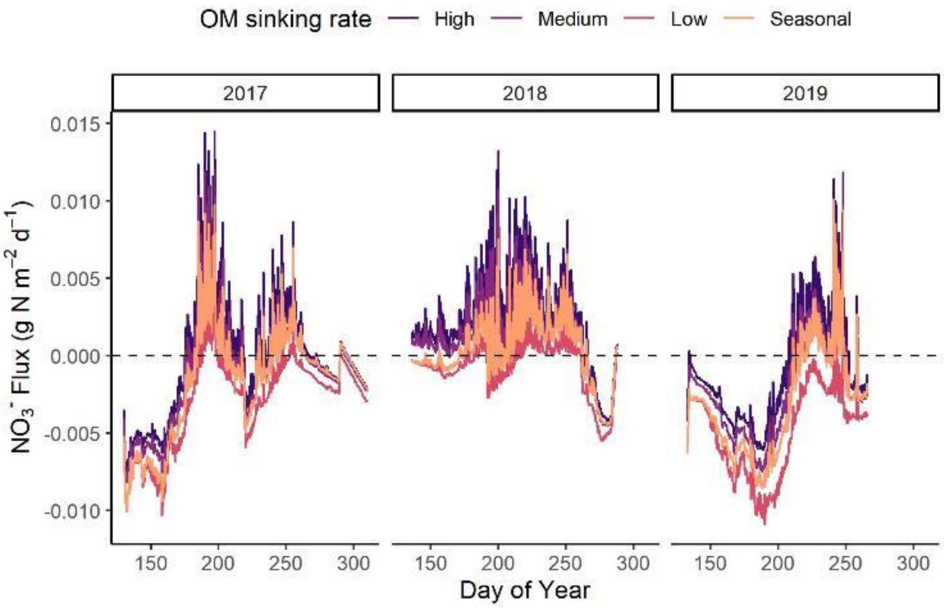


Figure 30. SedFlux NO_3^- flux rates under variable OM sinking rates.

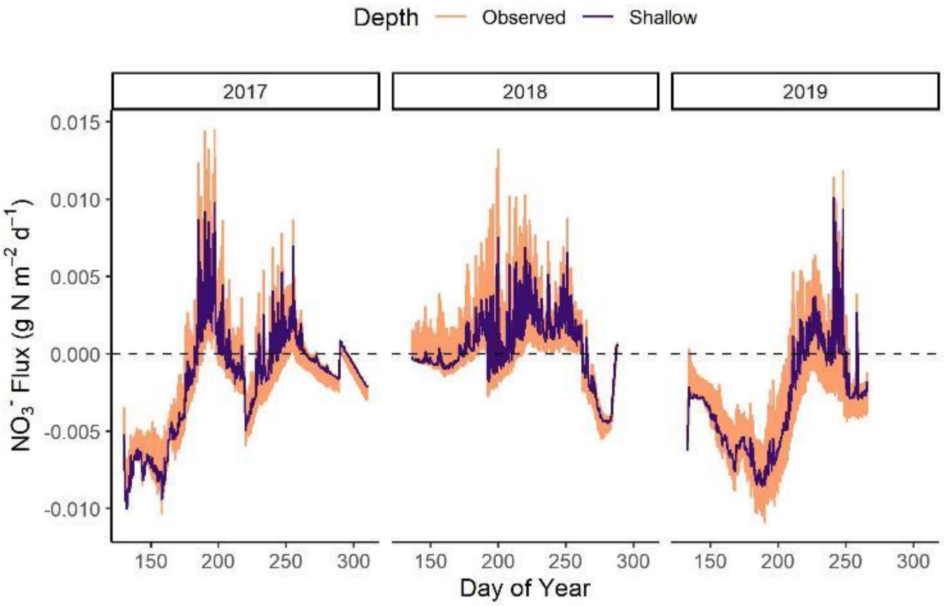


Figure 31. SedFlux NO_3^- flux rates under two different water column depth scenarios.

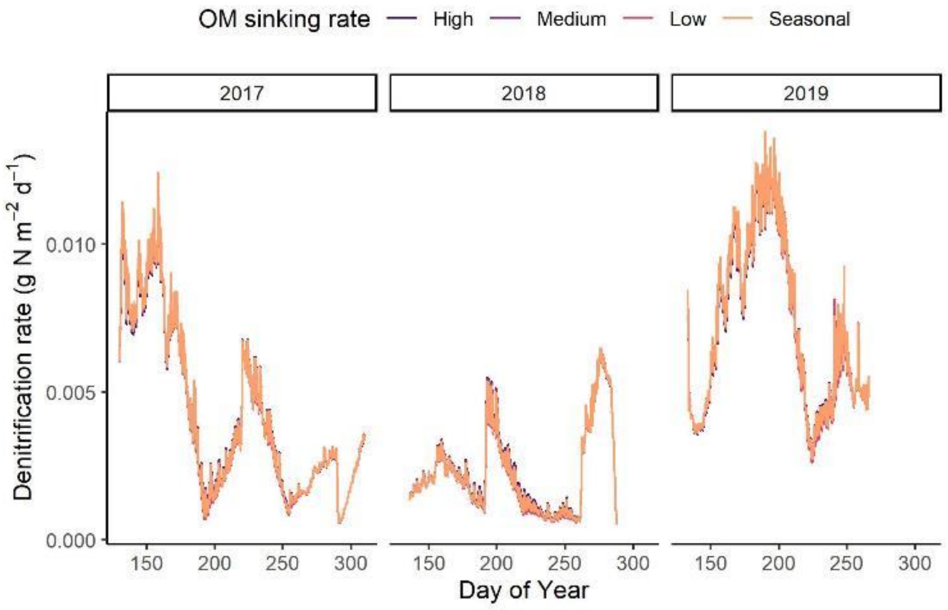


Figure 32. SedFlux denitrification rates under variable OM sinking rates.

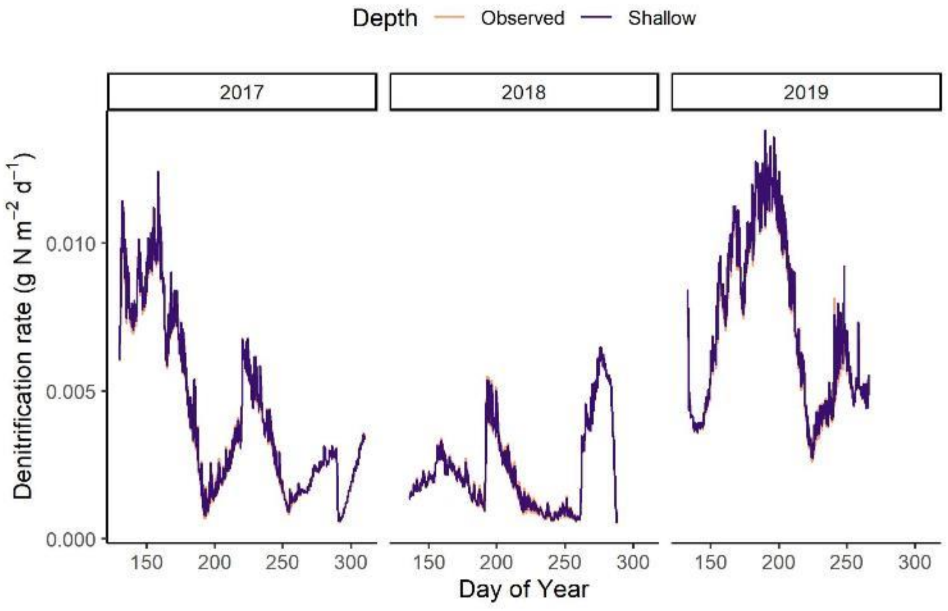


Figure 33. SedFlux denitrification rates under two different water column depth scenarios.

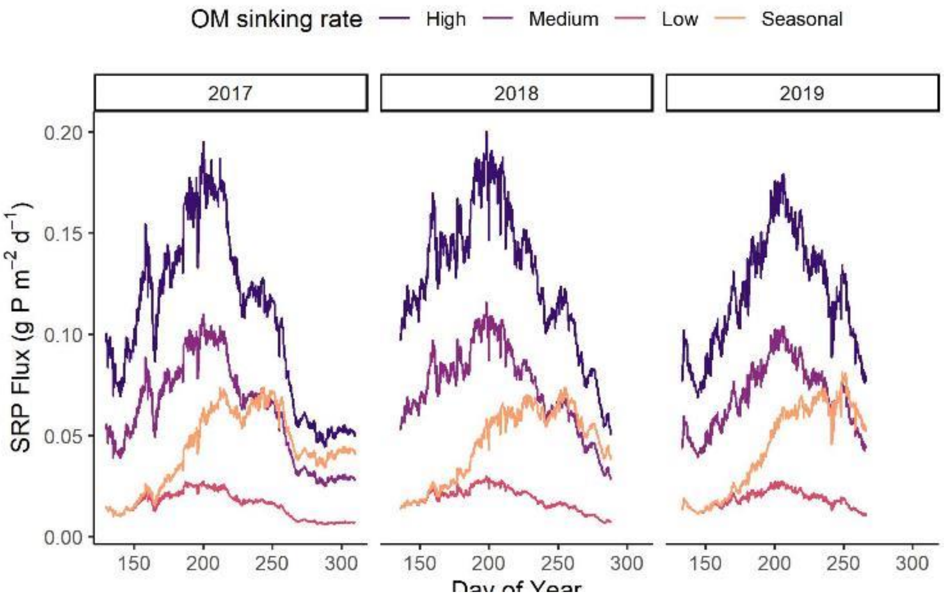


Figure 34. SedFlux SRP flux rates under variable OM sinking rates.

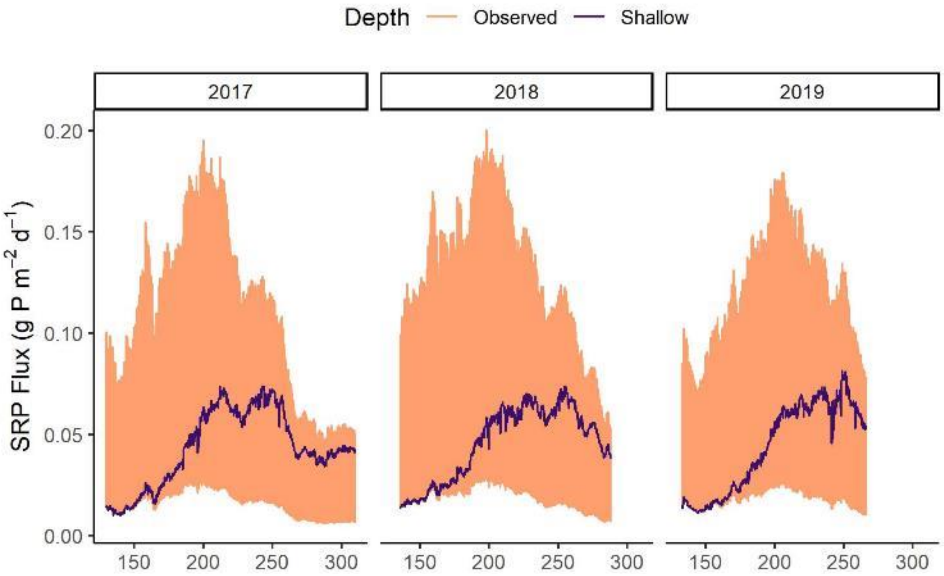


Figure 35. SedFlux SRP flux rates under two different water column depth scenarios.

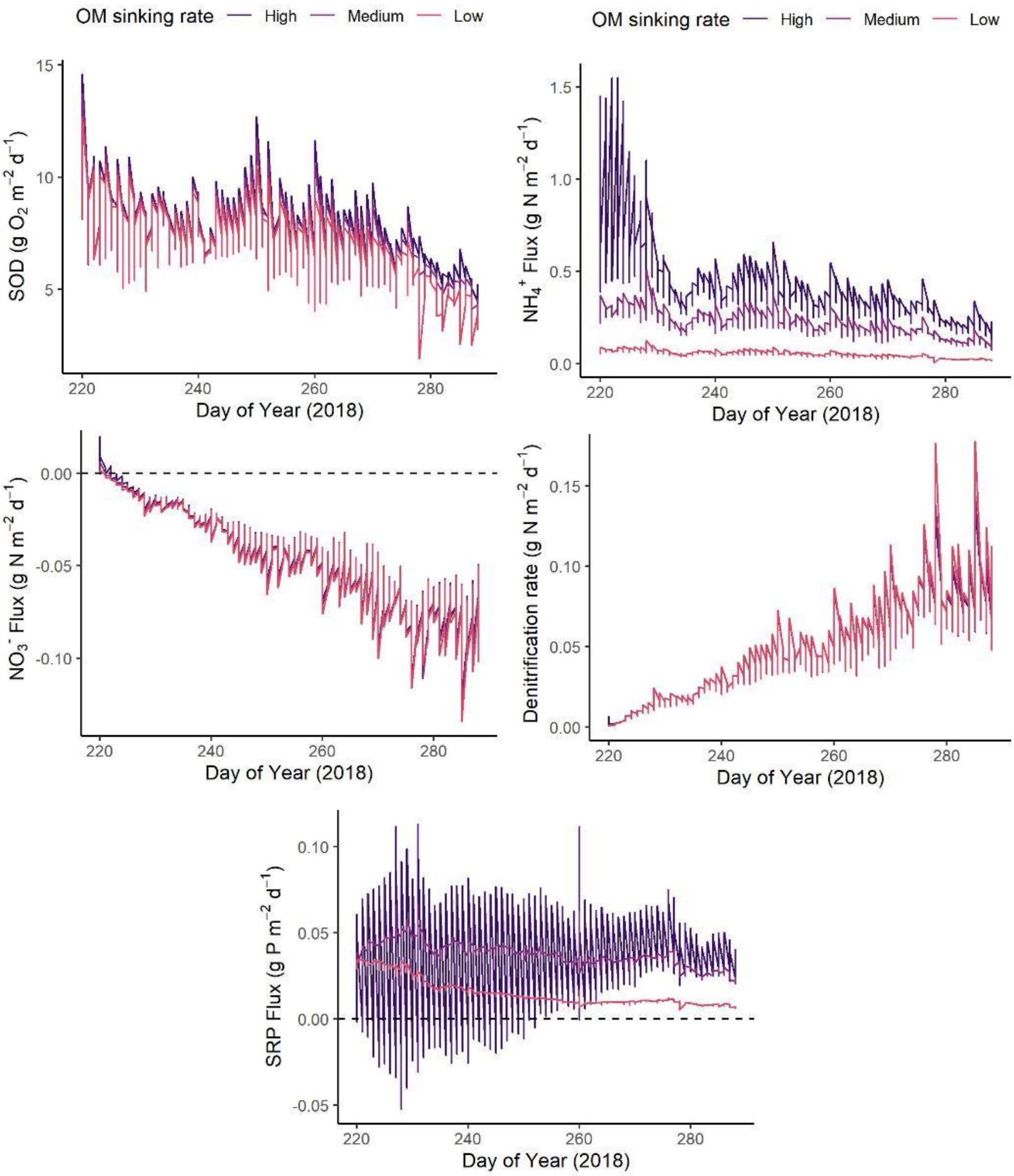


Figure 36. SedFlux rates under varying OM sinking rates.

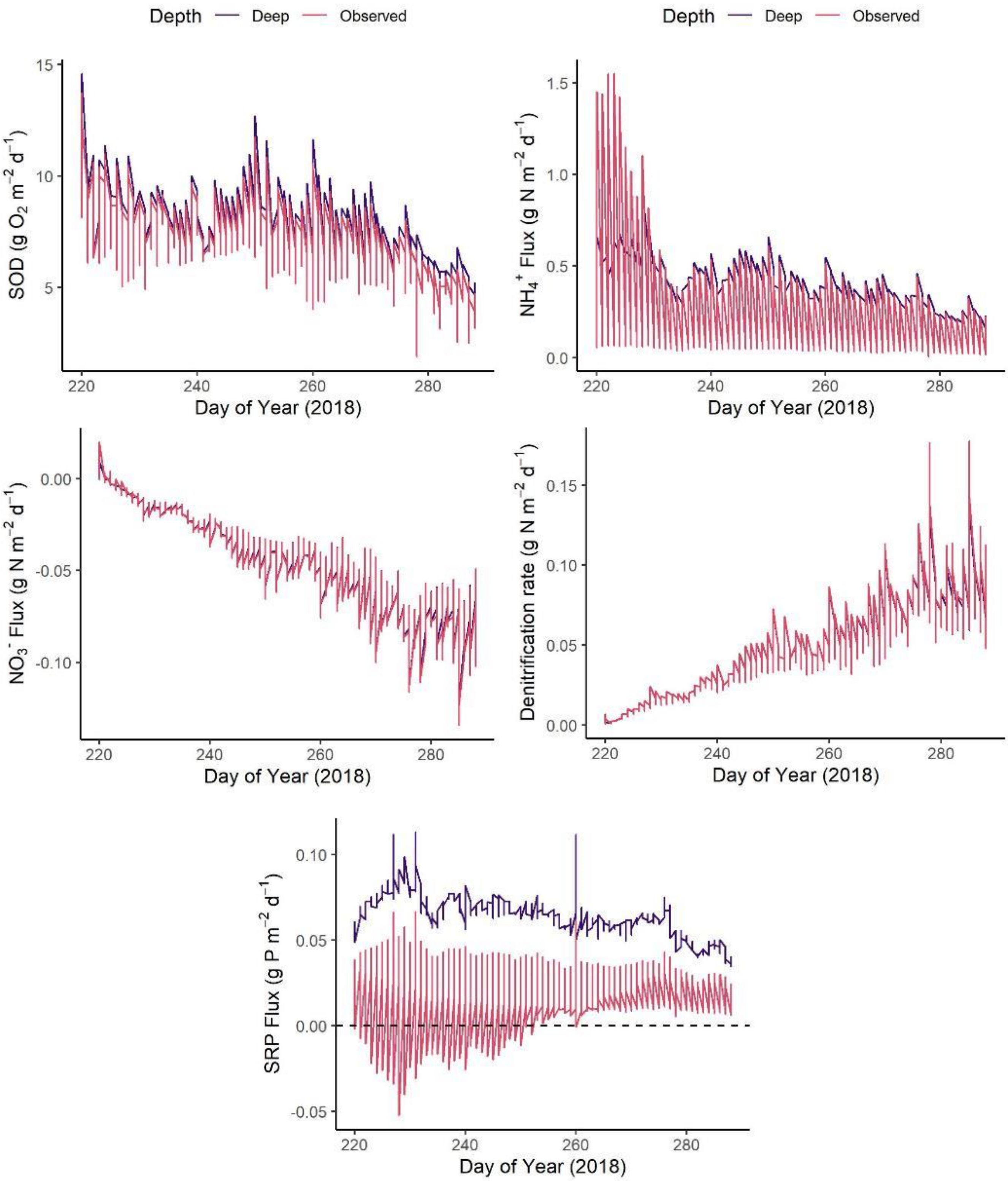


Figure 37. SedFlux rates under two different water column depth scenarios.

5.3 LAKEWIDE ESTIMATES

Lakewide estimates based on observed water column depth data varied based on the OM sinking rate (Figure 38, Figure 39, Figure 40, Figure 41, Figure 42). Rates were consistent with the ranges estimated in the conceptual models (Figure 3, Figure 4). However, these results should be interpreted with caution given the assumptions inherent in extrapolating the results from one site to a lakewide estimate. In addition, the results presented as daily rates were not able to be upscaled to annual rates due to the absence of monitoring data in the late fall, winter, and spring (i.e., outside the May-October monitoring window).

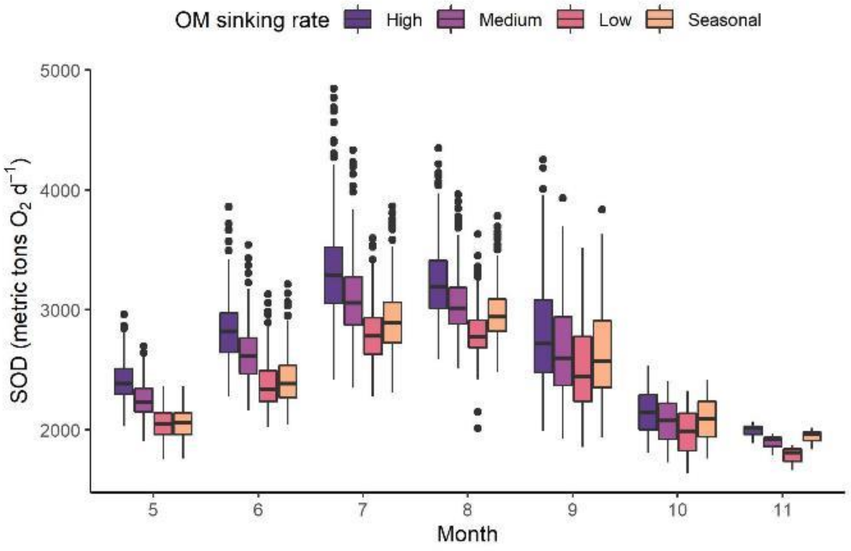


Figure 38. Lakewide SedFlux-derived SOD estimates under varying OM sinking rates.

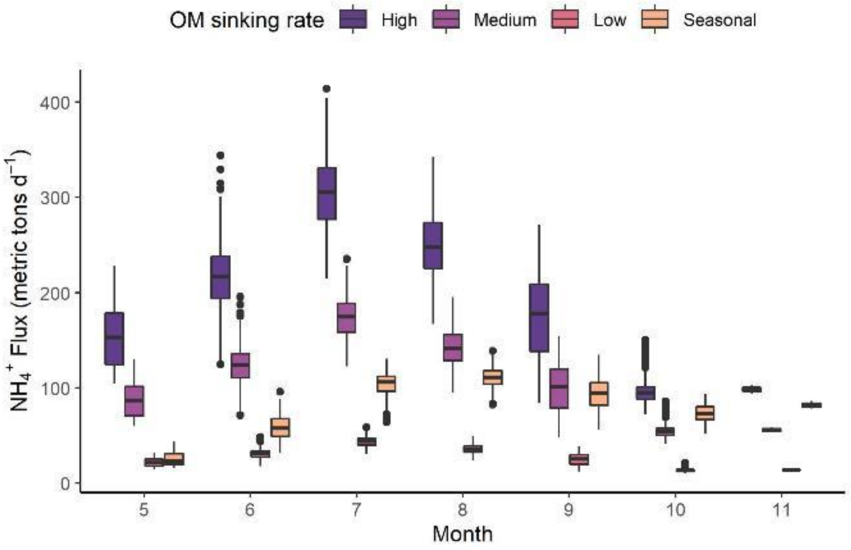


Figure 39. Lakewide SedFlux-derived NH_4^+ flux estimates under varying OM sinking rates.

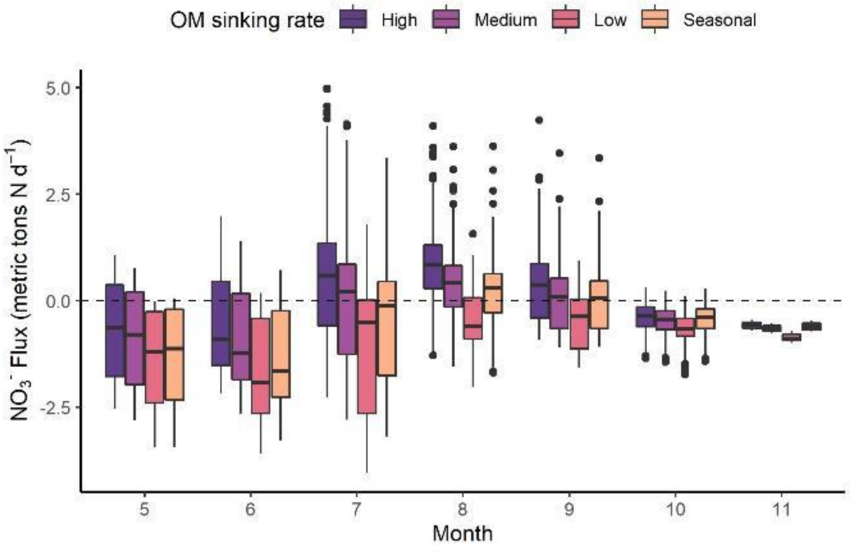


Figure 40. Lakewide SedFlux-derived NO_3^- flux estimates under varying OM sinking rates.

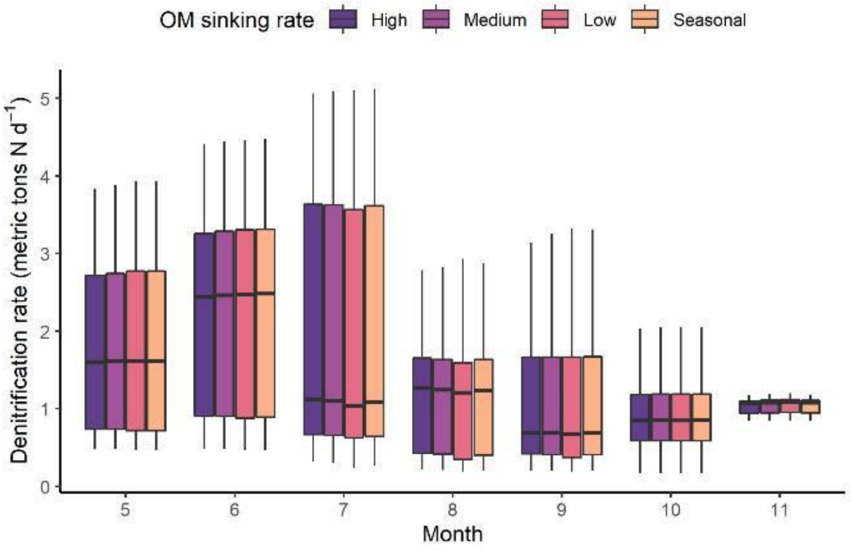


Figure 41. Lakewide SedFlux-derived denitrification estimates under varying OM sinking rates.

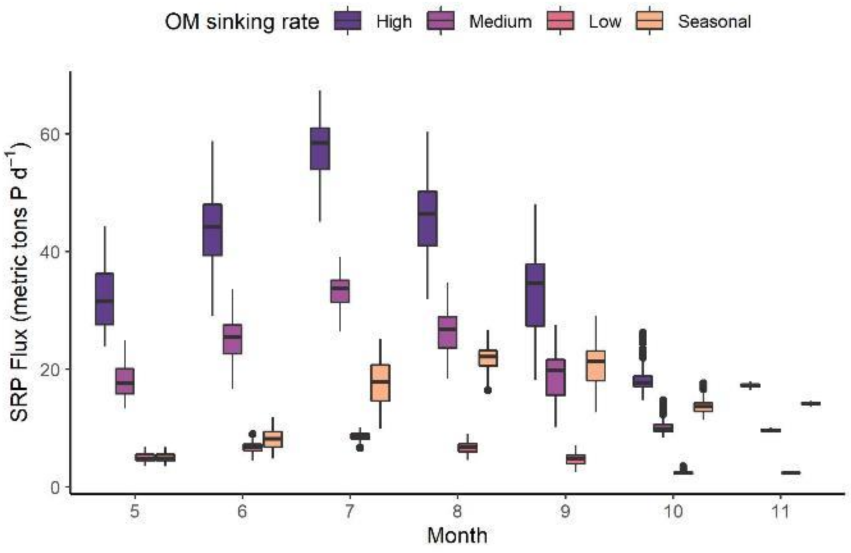


Figure 42. Lakewide SedFlux-derived SRP flux estimates under varying OM sinking rates.

5.4 COMPARISONS TO OTHER STUDIES

Sediment nutrient fluxes modeled by SedFlux were generally comparable to observed rates in Utah Lake (Table 10). Modeled NH_4^+ and SRP fluxes were positive (to the water column) and fell within a similar range as reported by Hogsett et al. (2019), who observed positive fluxes in all locations except two for NH_4^+ and one for SRP. Goel et al. (2020) observed negative fluxes of these constituents, albeit with a good deal of variability across replicate sediment cores. TDP fluxes in that study were positive (0.00432 ± 0.00190 g m^{-2} d^{-1} in the main basin and 0.00504 ± 0.01038 g m^{-2} d^{-1} in Provo Bay). Modeled NO_3^- flux rates spanned positive and negative fluxes and were in the same range as Hogsett et al. (2019). In all cases, flux rates under the “high” OM sinking rate scenario exceeded observed estimates, suggesting this scenario is likely not realistic for Utah Lake.

Modeled SOD rates were higher than measured SOD by an order of magnitude or more (Table 10). We attempted to determine the potential drivers of unusually high model outputs for SOD. First, we found that SOD was not sensitive to large adjustments in SOD-relevant model parameters. SOD rates were responsive to the OM sinking rate, as illustrated in Figure 26 and Figure 36, but not enough to fully explain the unusually high rates. Further study of OM sinking rates in Utah Lake would increase our certainty for that input rate in the future. Finally, SOD is sensitive to the DO concentrations in the water column, which in this case were accurate as measured by the deployed buoys on a sub-daily timescale. One potential explanation for the overestimate of SOD by SedFlux is the large influence of sediment resuspension in Utah Lake. When sediment resuspension occurs, labile organic matter stored in the sediments is transferred into the water column, where the potential source of SOD would become a source for water column respiration. The addition of sediment to the water column may also dilute the incoming source of sinking OM with inorganic particles (e.g., $CaCO_3$), thus further decreasing SOD. This examination suggests that SedFlux, and by extension the WASP model, may not be accounting for important factors driving SOD in Utah Lake, including the impacts of sediment resuspension and OM sinking rates.

Table 10. Comparison of nutrient fluxes and SOD between SedFlux and observed studies.

Rate (g m^{-2} d^{-1})	Main Basin This Study	Hogsett et al. 2019	Goel et al. 2020	Provo Bay This Study	Hogsett et al. 2019	Goel et al. 2020
SRP Flux	0.006-0.20	-0.004-0.071	-0.0024 ± 0.0042	0.005-0.17	0.01	-0.012 ± 0.0097
NH_4^+ Flux	0.03-1.23	-0.033-0.141	-0.0098 ± 0.0034	0.005-0.89	1.442	-0.017 ± 0.01
NO_3^- Flux	-0.01-0.01	-0.008-0.08	Not measured	-0.13-0.009	0	Not measured
SOD	4.90-14.38	0.9-2.04	2.97	1.91-14.58	4.61	0.05

5.5 CONCLUSIONS

Model outputs from SedFlux suggest that the sediments are a net source of SRP and NH_4^+ to the water column in the summer months. Importantly, this result does not suggest that the sediments are an overall net source of N or P to the water column, but rather that labile forms of N and P are released to the water column where they may be taken up by phytoplankton while at the same time the sediments represent a large sink for nutrients (as evidenced by the external mass balance). There was a net sink of NO_3^- to the sediment, which was consistent with the positive modeled denitrification rates, and denitrification may thus represent an important removal mechanism for N in Utah Lake. Nutrient flux rates were sensitive to OM sinking rates, with a higher flux to the water column at higher OM sinking rate scenarios. Rates were also sensitive to water depth, where in the main basin rates were more variable at deeper depths and in Provo Bay were higher at deeper depths.

While SedFlux produced nutrient flux estimates that were consistent with observed studies, modeled SOD appeared to be overestimated by an order of magnitude. This result highlights the need to better characterize processes driving SOD in Utah Lake, including the delivery of OM to the sediments and the impacts of sediment resuspension on water column and sediment respiration.

DATA GAPS

6.1 CONCEPTUAL MODEL

Conceptual models for N and P cycles in Utah Lake were quantified, where possible, with data from Utah Lake studies. When data for a specific stock or process was not available for Utah Lake, we searched the literature for established values. As much as was possible, data were compiled from systems anticipated to act similarly to Utah Lake (e.g., eutrophic, shallow, and/or high alkalinity lakes) or from reviews that included data from multiple systems. In many cases, quantities of stocks or fluxes gathered from the literature were reported as a fairly wide range because the site-specific variables that would constrain these estimates were not available for Utah Lake.

The chemical fractions of water column and sediment P in Utah Lake are known to a certain extent, but specific species are not fully quantified. Specifically, particulate P has been measured in Utah Lake, but the relative fractions of particulate inorganic and particulate organic P are unknown. Dissolved organic P was estimated by subtraction as the difference between total dissolved P and orthophosphare or soluble reactive P. Similarly, chemical fractions of water column N, dissolved organic N and particulate N, were estimated by difference following quantification of total, total dissolved, and dissolved inorganic fractions.These data gaps may not be considered crucial, as the total and dissolved inorganic fractions of N and P are typically the fractions of interest.

However, the importance of calcite scavenging and other processes that bind and release P have been identified for Utah Lake, and a forthcoming study will quantify P partitioning kinetics to address this knowledge gap.

The food web components of the N and P conceptual modeling were generated largely from literature values for Utah Lake. In several cases, the general abundance of a given component of the food web was known for Utah Lake, but the body content of N and P and/or the N and P uptake and release rates had to be generated from the literature. N and P content, on a per unit mass or per individual level, is generally well-known and well-constrained in the literature, so we have a high degree of confidence in the N and P content for specific food web components. In general, the total biomass for various groups of organisms is not well-constrained in Utah Lake:

- Phytoplankton: biovolume and cell count is known, but a conversion to mass is needed. Volatile suspended solids may provide a reasonable estimate of biomass but includes detritus as well.
- Fish
- Macrophytes
- Periphyton: assumed negligible but likely nonzero
- Macroinvertebrates: conversion from wet to dry mass is needed

Because N and P uptake and release rates of fish are taxa-dependent, specific information on the biomass of individual taxa, their food sources, and feeding rates are needed.

The N budget for any given lake encompasses inflows, outflows, atmospheric deposition, groundwater exchange, and microbial N uptake or release via N fixation and denitrification (and potentially anammox), respectively. Previous bugets (Merritt and Miller 2016) and the current external mass balance work have quantified the hydrologic fluxes and atmospheric deposition but do not consider N fixation and denitrification. In the conceptual model, literature values for these rates were provided. Water column N fixation rates were generated from a study in Lake Mendota (Beversdorf et al. 2013), and benthic N fixation rates were generated from a study in Lake Champlain (McCarthy et al. 2016). Note these lakes are not necessarily similar to Utah Lake in terms of morphometry or chemistry, but N cycling rates in other eutrophic lakes may provide a useful comparison considering the connection between trophic state and nutrient cycling. Denitrification rates were estimated from a global review of lakes (Seitzinger et al. 2006). Aanderud et al. (2021) provided the first measurements of water column N fixation in Utah Lake, which could be used to fill in the literature-based N fixation rates developed for the conceptual model. No known estimates of denitrification or anammox exist for Utah Lake, with the exception of modeled SedFlux rates.

Finally, extrapolating hourly or daily rates to annual rates can be difficult for many processes, given the considerable variation that can occur at the sub-daily and seasonal timescales. In Utah Lake and in lakes in general, there is a dearth of winter measurements that would enable accurate scaling-up to annual rates.

6.2 EXTERNAL MASS BALANCE MODEL

6.2.1 Monitored Watersheds

In monitored watersheds, the major data limitation for quantifying nutrient loading is the incorporation of grab samples that were collected approximately monthly. Monthly sampling may miss period of high or low flows, resulting in a potential over- or underestimation of nutrient loads. However, this study also uses a five year dataset which partially amelerates the monthly sampling limitation. Comparisons of stream discharge estimates with previous efforts (PSOMAS and SWCA 2007, Merritt and Miller 2016, Su and von Stackelberg 2020) indicated there was not a systematic over- or underestimation of flows, suggesting nutrient load estimates are likely to be accurate as well. Nonetheless, quantifying discharge more frequently will help to bolster confidence in nutrient load estimates. Several watersheds are now equipped with pressure transducer data, pointing to the possibility of developing stage-discharge, C-Q, and load duration curves from daily data.

Another data uncertainty involves the location of tributary monitoring sites. Utah Lake experiences intra- and interannual changes in elevation, with resulting changes in the extent of the shoreline. As part of the tributary monitoring effort, monitoring locations were chosen with the goal of representing the most downstream portion of tributaries to most closely track the inputs to the lake. However, some of these sites are located in areas that are sometimes inundated by lake water, or conversely are located in areas that are upland from the high water mark. A true accounting of nutrient loads to the lake is complicated by (a) whether the lake boundary is determined as the high water mark or the inundated area at the time of sampling, and (b) placement of monitoring sites as close as possible to the lake boundary. Because the lake level of Utah lake varies both intra- and interannually there is not one universal lake boundary that is always correct. The current estimates represent the current best possible approximation of tributary loads, but the nature of the placement of monitoring sites is a limitation nonetheless.

6.2.2 Unmonitored Watersheds

Estimates of flow and loading from unmonitored watersheds were generated from the Model My Watershed tool which incorporated the Watershed Multi-Year Model. While this model was developed for nationwide applications, calibration efforts were not conducted for watersheds in Utah and thus output from this model should be interpreted with caution. A more customized watershed model will be developed through the forthcoming ULWQS watershed modeling project, which will involve a detailed calibration and validation routine that will improve the accuracy of loading estimates from unmonitored watersheds.

6.2.3 Non-Tributary Components

Atmospheric deposition was estimated according to Brahney (2019). Previous direct monitoring of atmospheric deposition (Olsen et al. 2018) may not be accurate due to contamination concerns (Gay 2019), so the estimates used by this study would be improved by using direct measurements. Atmospheric deposition data will be improved by direct monitoring efforts that incorporate NADP methodology (Miller and Barrus 2020).

Groundwater quality data are limited for Utah Lake. While inflow volumes were estimated according to the most up-to-date estimates from EFDC/WASP model outputs (Su and von Stackelberg 2020), the nutrient concentrations associated with these flows have not been as rigorously monitored as tributary and in-lake water quality.

6.3 SEDFLUX MODEL

The SedFlux model depends on inputs of (a) initial water column and sediment conditions, (b) sub-daily inputs of water column conditions, and (c) site-specific adjustments to rate parameters that drive the reaction network.

The available Utah Lake data for SedFlux were sufficient in many aspects. In particular, the inputs of temperature and dissolved oxygen measurements by the buoys provided the necessary sub-daily timescales crucial for driving redox-sensitive processes at the sediment-water interface. However, assumptions had to be made for other aspects of the input data, including:

- *Sedimentation rates of organic matter-associated C, N, and P.* While several studies (Hogsett et al. 2019, Randall et al. 2019, Brahney et al. pers. comm) have measured sediment nutrient content and accumulation rates, these findings have limited value because (a) they lack estimates of sediment density which are needed to extrapolate to areal input rates for the model, and (b) sediment organic matter content is typically lower than the organic matter content of sinking phytoplankton and detritus. Assessing the proportion of volatile suspended solids in total suspended solids would provide a more accurate assessment of sinking organic matter, but this value would still lack Utah Lake-specific information about sinking rate and C, N, and P content.

- *Detailed tracking of seasonal variation in depth at specific sites.* We estimated depth based on a linear interpolation between approximately monthly monitoring dates, but sub-monthly changes in depth could have an impact on rates that is not captured in the current model application.
- *Rate parameterization.* When available, parameter values from the EFDC/WASP application for Utah Lake were applied (Su and von Stackelberg 2020). Very little calibration data for the modeled rates is available, so adjustments to the parameterization would constitute only a sensitivity analysis rather than a calibration-validation routine.

Finally, the SedFlux model estimates sediment-water column exchange of nutrients at a given location supplied by the model and outputs rates in areal units of m^2. We extrapolated these rates to lakewide estmates based on LIDAR-generated daily lake area. However, extrapolation to lakewise estimates relies on an assumption that all sites in the lake behave similarly. This assumption is likely not accurate for the littoral zone that is periodically inundated and dried; in fact, the biogeochemical cycling in these zones may be of higher magnitude due to rapidly changing redox conditions (Baldwin and Mitchell 2000). The littoral sediment study will help to fill these gaps.

FUTURE STUDIES RECOMMENDATIONS

Many of the limitations and data gaps related to this study will be addressed, at least in part, by ongoing and forthcoming studies as part of the Strategic Research Plan for the ULWQS. For in-lake stocks and processes, the P binding study and the paleolimnological study will better quantify the chemical speciation of P in the water column and sediment, and the littoral sediment study will quantify additional sediment nutrient cycling rates and fluxes across the sediment-water interface. The littoral sediment study will also provide greater spatial resolution of processes, particularly in zones that are periodically inundated and dried. For external loading estimates, several ongoing studies will serve to improve the resolution and confidence in current estimates. DWQ currently has pressure transducers deployed in several sub-catchments, which will enable the calculation of daily loading estimates through the development of load-duration curves. The watershed modeling study will better calibrate and validate loading estimates from unmonitored watersheds. Finally, the atmospheric deposition study will provide updated empirical estimates of atmospheric deposition of N and P, including assessment of bioavailability.

Additional data gaps that will not be addressed by ongoing or forthcoming studies may merit future study. The need and prioritization of these studies could be evaluated in relation to the ULWQS management goals and nutrient criteria development process; some may not be necessary or could be deprioritized based on the tradeoff of level of effort vs. improved knowledge. First, the stocks and transfer of C, N, and P among food web components (phytoplankton, zooplankton, fish, periphyton, macrophytes) are not well-defined in Utah Lake, so a study quantifying these stocks and fluxes would improve certainty about the amount of C, N, and P stored in those stocks and the movement between them. Denitrification, anammox, and nitrous oxide production rates have also not been measured in Utah Lake, so a future study assessing these processes would quantify this N removal process from the lake. Finally, most measurements of stocks and fluxes in Utah Lake have been focused on summer months and shoulder seasons, so we would recommend an evaluation of winter biogeochemistry for stocks and processes deemed the most key for the nutrient criteria development process.

CONCLUSIONS AND RESPONSE TO STRATEGIC RESEARCH PLAN

This study sought to characterize the current state of knowledge of C, N, and P in Utah Lake and use this information in combination with new internal and external loading efforts to quantify the budgets of C, N, and P in Utah Lake. External N and P loads were similar to previous estimates, at 1,611 metric tons of N and 183 metric tons of P. Sub-catchments with WWTPs dominated tributary input, making up 57 and 71% of N and P inputs, respectively. Remaining sources of tributary input were divided roughly equally between monitored and unmonitored sub-catchments. Organic C loading was only calculated for monitored watersheds, with highest loads attributed to sub-catchments draining larger areas (Provo River and Spanish Fork River). Output volume and nutrient loads were lower than previous estimates due to lower flow exiting through the Jordan River than in previous years. Outflow via the Jordan River represented 6 and 11% of N and P loads to the lake, indicating that Utah Lake retains 94% and 89% of incoming N and P loads, respectively. Note that estimates of N retention are incomplete due to the lack of quantification of N fixation and denitrification as inputs and outputs of N, respectively. Overall, sediments in Utah Lake are a large sink for nutrients, though they are a source of bioavailable N and P to the water column in the summer months which could fuel phytoplankton growth.

The ULWQS Strategic Research Plan (Tetra Tech 2020a) identified two priority research ideas that were addressed as part of this study: (1) How large is internal vs. external loading, and (2) sediment budgets. These research topics relate to several of the identified charge questions:

- What is the current state of the lake with respect to nutrients and ecology? (Science Panel charge 2)
- What are current sediment equilibrium P concentrations (EPC) throughout the lake? What effect will reducing inputs have on water column concentrations? If so, what is the expected lag time for lake recovery after nutrient inputs have been reduced? (Science Panel charge 2.4.i)
- What is the sediment oxygen demand of, and nutrient releases from, sediments in Utah Lake under current conditions? (Science Panel charge 2.4.ii)
- What would be the current nutrient regime of Utah Lake assuming no nutrient inputs from human sources? (Science Panel charge High Level Questions 4.1.)

The internal and external mass balances conducted here directly address the first and third charge question bullets above and will help to inform mechanistic modeling efforts that will address the second and fourth charge question bullets. Future efforts by the SP will collect the information from this and other studies to develop answers and uncertainty for each charge question.

REFERENCES

Aanderud ZT, Abbott BW, Baker MA, Lawson GM, Jones EF, Bratsman SP, Buck R. 2021. Utah Lake bioassay final report – nutrient limitation of total phytoplankton, cyanobacteria and cyanotoxins. Final Report. Prepared for Utah Department of Environmental Quality.

Baldwin DS and Mitchell AM. 2000. The effects of drying and re-flooding on the sediment and soil nutrient dynamics of lowland river-floodplain systems: a synthesis. Regulated Rivers: Research & Management 16: 457-467.

Beversdorf LJ, Miller TR, McMahon KD. 2013. The role of nitrogen fixation in cyanobacterial bloom toxicity in a temperate, eutrophic lake. PLoSONE 8(2): e56103.

Brahney J. 2019. Estimating total and bioavailable nutrient loading to Utah Lake from the atmosphere. Final Report. Prepared for Utah Department of Environmental Quality.

Brett M. 2019. Analysis fo the Merritt and Miller (2016) “Nutrient loadings to Utah Lake” report. Prepared for Utah Department of Environmental Quality.

Chapra SC. and Pelletier GJ. 2003. QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality (Beta Version): Documentation and Users Manual. Civil and Environmental Engineering Dept., Tufts University, Medford, MA.

DiToro DM. 2001. Sediment Flux Modeling. Wiley-Interscience. New York, NY.

Evans BM and Corradini KJ. 2016. MapShed Users Guide (Version 1.5), Penn State Institutes of Energy and the Environment, Penn State University, 140 pp.

Gaeta JW, Walsworth TE, Landom K. 2019. An age-structured common carp population model and standardized seining to support common carp removal in Utah Lake, UT. Draft Report. Prepared for the June Sucker Recovery Implementation Program.

Goel R, Carling G, Li H, Smithson S. 2020. Utah Lake sediment-water nutrient interactions. Final Report. Prepared for Utah Department of Environmental Quality.

Hogsett M, Li H, Goel R. 2019. The role of internal nutrient cycling in a freshwater shallow alkaline lake. Environmental Engineering Science 36(5): 551-563.

Liljenquist GK. 2012. Study of Water Quality of Utah Lake Tributaries and the Jordan River Outlet for the Calibration of the Utah Lake Water Salinity Model (LKSIM). Theses and Dissertations. 3104.

McCarthy MJ, Gardner WS, Lehmann MF, Guindon A, Bird DF. 2016. Benthic nitrogen regeneration, fixation, and denitrification in a temperate, eutrophic lake: Effects on the nitrogen budget and cyanobacteria blooms. Limnology and Oceanography 61: 1406-1423.

Merritt LB and Miller AW. 2016. Nutrient loadings to Utah Lake. Interim Report. Prepared for Jordan River, Farmington Bay & Utah Lake Water Quality Council.

Molongoski JJ and Klug MJ. 1980. Quantification and characterization of sedimenting particulate organic matter in a shallow hypereutrophic lake. Freshwater Biology 10: 497-506.

PSOMAS and SWCA. 2007. Utah Lake TMDL: Pollutant loading assessment & designated beneficial use impairment assessment. Final Report. Prepared for Utah Division of Water Quality.

Randall MC, Carling GT, Dastrup DB, Miller T, Nelton ST, Rey KA, Hansen NC, Bickmore BR, Aanderud ZT. 2019. Sediment potentially controls in-lake phosphorus cycling and harmful cyanobacteria in shallow, eutrophic Utah Lake. PLoS ONE 14(2): e0212238.

Seitzinger S, Harrison JA, Bohlke JK, Bouwman AF, Lowrance R, Peterson B, Tobias C, Van Drecht G. 2006. Denitrification across landscapes and waterscapes: a synthesis. Ecological Applications 16(6): 2064-2090.

Stroud Water Research Center. 2020. Model My Watershed Technical Documentation. Retrieved from https://wikiwatershed.org/help/model-help/mmw-tech/#water-quantity-and-quality-models

Su J-Y and von Stackelberg N. 2020. Utah Lake hydrodynamic (EFDC) and water quality (WASP) model report. Final Report.

Tetra Tech 2020a. Utah Lake Water Quality Study Strategic Research Plan. Final Report. Prepared for Utah Department of Environmental Quality.

Tetra Tech 2020b. Utah Lake Water Quality Study Uncertainty Guidance. Final Report. Prepared for Utah Department of Environmental Quality.

Tetra Tech 2020c. Utah Lake Water Quality Study Analysis Update. Draft Report. Prepared for Utah Department of Environmental Quality.

Tetra Tech 2021a. Utah Lake C, N, and P Data Compilation Spreadsheet. Prepared for Utah Department of Environmental Quality.

Tetra Tech 2021b. Literature Review and Data Compilation Memo. Prepared for Utah Department of Environmental Quality.

Tetra Tech 2021c. Conceptual Model Memo. Prepared for Utah Department of Environmental Quality.

Turnipseed DP and Sauer VB. 2010. Discharge measurements at gaging stations: U.S. Geological Survey Techniques and Methods book 3, chap. A8, 87 p.

ULWQS SP. 2019. ULWQS atmospheric deposition loading recommendation. Final Report.

APPENDIX

10.1 SUMMARY TABLES

Table 11. Total Nitrogen (TN) concentrations (µg/L) in tributary monitoring locations. P = percentile.

Sub-Catchment	Site ID	Organization	Start Date	End Date	n	Min	P10	P25	Median	Mean	P75	P90	Max
Tickville Wash	4994792	DWQ	5/16/2017	9/21/2020	24	75	208	270	370	639	497	1935	2580
Dry Creek - Saratoga	4994804	DWQ	5/16/2017	7/7/2020	13	329	542	675	792	1027	1180	1646	2590
Lehi Spring Creek	4994950	DWQ	5/16/2017	9/21/2020	41	825	1270	1530	2150	2371	3140	3600	5210
Lehi Spring Creek	4994948	WFWQC	8/30/2016	7/17/2018	13	534	1214	2070	3080	2842	3710	3814	5000
American Fork River	4994960	DWQ	5/16/2017	6/16/2020	16	202	257	430	635	914	1390	1865	2080
American Fork River	4994958	WFWQC	12/21/2016	12/12/2017	5	513	522	535	777	829	1080	1176	1240
Timp SSD	4995038	DWQ	5/16/2017	9/21/2020	41	5230	6700	7670	8450	8665	9260	11100	14800
Timp SSD	4995041	DWQ	5/16/2017	6/19/2019	23	4500	6630	7020	7830	7822	8455	9082	11300
Timp SSD	4995043	WFWQC	8/30/2016	8/14/2018	14	5540	7454	8115	9365	9404	10850	11570	12800
Lindon Drain	4995120	DWQ	5/11/2017	9/21/2020	38	1370	2377	2723	3075	3047	3483	3733	4530
Lindon Drain	4995075	WFWQC	8/31/2016	8/14/2018	12	2610	2869	3063	3520	3570	4113	4450	4540
Powell Slough Major	4995210	DWQ	8/9/2017	4/19/2019	14	9750	10725	13825	15050	15250	16625	19780	20000
Powell Slough Major	4995230	DWQ	9/13/2017	4/19/2019	11	160	173	209	352	381	476	711	731
Powell Slough Major	4995210	WFWQC	1/23/2017	7/17/2018	8	4700	5267	8338	9570	10604	11825	15980	21300
Provo River	4996680	DWQ	5/12/2017	9/21/2020	41	153	387	413	478	500	584	675	865
Provo River	4996680	WFWQC	8/31/2016	8/14/2018	12	605	647	764	956	1038	1148	1371	2180
Mill Race	4996540	DWQ	5/12/2017	9/21/2020	40	6930	9561	10055	13750	13070	15100	16710	18900
Mill Race	4996566	DWQ	5/12/2017	9/21/2020	41	4190	6180	7630	10000	10720	14200	15700	17300
Mill Race	4996536	WFWQC	8/4/2016	6/20/2018	5	10900	10900	10900	12300	12000	12800	12980	13100

Sub-Catchment	Site ID	Organization	Start Date	End Date	n	Min	P10	P25	Median	Mean	P75	P90	Max
Mill Race	4996540	WFWQC	8/31/2016	8/15/2018	14	1550	7787	12075	14050	12961	14475	15690	22800
Spring Creek - Springville	4996275	DWQ	9/18/2017	9/21/2020	37	1260	5254	5630	6760	7040	8130	9468	13400
Spring Creek - Springville	4996275	WFWQC	2/16/2017	8/15/2018	5	4390	5466	7080	7840	7180	8100	8334	8490
Hobble Creek	4996100	DWQ	5/12/2017	9/21/2020	41	396	501	577	634	1039	927	1260	12300
Hobble Creek	4996096	WFWQC	5/16/2018	8/15/2018	5	440	503	597	841	810	942	1115	1230
Hobble Creek	4996100	WFWQC	8/18/2016	12/13/2017	11	1020	1140	1390	1930	3020	2640	7890	9490
Dry Creek - Spanish Fork	4996040	DWQ	6/12/2017	9/30/2020	29	2090	2458	3320	4130	4787	6290	7198	7670
Dry Creek - Spanish Fork	4996042	DWQ	6/12/2017	9/18/2017	4	1900	2128	2470	2760	2598	2888	2937	2970
Dry Creek - Spanish Fork	4996044	DWQ	10/17/2017	9/21/2020	33	1240	1994	2260	2780	2705	3160	3410	4350
Dry Creek - Spanish Fork	4996040	WFWQC	6/20/2018	6/20/2018	1	3260	3260	3260	3260	3260	3260	3260	3260
Spanish Fork River	4995578	DWQ	5/12/2017	9/21/2020	39	75	386	494	571	620	686	903	1560
Spanish Fork River	4995575	WFWQC	8/31/2016	6/12/2018	10	410	635	702	790	2043	1112	2426	13100
4000 South Drain Spanish Fork	5919910	DWQ	4/19/2018	9/24/2019	18	1490	2649	3340	4190	3959	4448	5328	6250
4000 South Drain Spanish Fork	4917712	WFWQC	8/31/2016	8/14/2018	11	840	974	2045	3820	3383	4700	5120	6150
Benjamin Slough	4995465	DWQ	5/12/2017	8/11/2020	38	509	1012	1328	3175	3010	3945	5293	6420
Benjamin Slough	4995467	WFWQC	7/28/2016	8/14/2018	15	518	1204	1525	2340	3413	4955	6762	8860
Currant Creek	4995310	DWQ	5/16/2017	8/11/2020	19	43	171	342	437	428	512	563	1040
Currant Creek	4995312	DWQ	10/17/2017	3/7/2018	4	103	137	187	236	240	289	348	387

Table 12. Total Dissolved Nitrogen (TDN) concentrations (µg/L) in tributary monitoring locations. P = percentile.

Sub-Catchment	Site ID	Organization	Start Date	End Date	n	Min	P10	P25	Median	Mean	P75	P90	Max
Tickville Wash	4994792	DWQ	5/16/2017	9/21/2020	24	258	386	430	521	786	684	2025	2590
Dry Creek - Saratoga	4994804	DWQ	5/16/2017	7/7/2020	13	484	526	695	886	1077	1240	1756	2590
Lehi Spring Creek	4994950	DWQ	5/16/2017	9/21/2020	41	1110	1370	1570	2280	2413	3010	3520	5630
American Fork River	4994960	DWQ	5/16/2017	6/16/2020	16	233	303	391	685	965	1443	1990	2170
Timp SSD	4995038	DWQ	5/16/2017	9/21/2020	41	4690	6860	7430	8460	8832	9390	11700	16500
Timp SSD	4995041	DWQ	5/16/2017	6/19/2019	24	4160	6513	7003	7970	7921	8370	9603	12700
Lindon Drain	4995120	DWQ	5/11/2017	9/21/2020	38	1440	2569	2935	3240	3159	3485	3616	4600
Powell Slough Major	4995210	DWQ	8/9/2017	4/19/2019	14	9190	11210	12575	15200	14849	16675	18560	20900
Powell Slough Major	4995230	DWQ	9/13/2017	4/19/2019	11	193	278	382	445	463	600	617	659
Provo River	4996680	DWQ	5/12/2017	9/21/2020	41	272	374	483	592	615	701	905	1250
Mill Race	4996540	DWQ	5/12/2017	9/21/2020	40	6950	9637	10900	13700	13101	14825	15620	18900
Mill Race	4996566	DWQ	5/12/2017	9/21/2020	40	4210	6477	7990	10750	10802	13450	15230	17000
Spring Creek - Springville	4996275	DWQ	9/18/2017	9/21/2020	37	1200	5188	5610	6820	7142	8280	9554	14500
Hobble Creek	4996100	DWQ	5/12/2017	9/21/2020	41	367	575	619	811	1152	1050	1350	13000
Dry Creek - Spanish Fork	4996040	DWQ	6/12/2017	9/30/2020	29	2320	2606	3310	4730	4988	6740	7134	8020
Dry Creek - Spanish Fork	4996042	DWQ	6/12/2017	9/18/2017	4	2810	2852	2915	3085	3840	4010	5432	6380
Dry Creek - Spanish Fork	4996044	DWQ	10/17/2017	9/21/2020	34	1630	1962	2360	2760	2773	3265	3432	4390
Spanish Fork River	4995578	DWQ	5/12/2017	9/21/2020	39	75	444	540	668	706	843	1040	1590
4000 South Drain Spanish Fork	5919910	DWQ	4/19/2018	9/24/2019	18	1720	2980	3223	4000	3996	4518	5364	6390
Benjamin Slough	4995465	DWQ	5/12/2017	8/11/2020	38	675	997	1465	3045	3015	4303	5114	6040
Currant Creek	4995310	DWQ	5/16/2017	8/11/2020	20	185	264	404	503	529	648	876	901
Currant Creek	4995312	DWQ	10/17/2017	5/16/2018	5	202	230	272	311	336	404	456	490

Table 13. Total Phosphorus (TP) concentrations (µg/L) in tributary monitoring locations. P = percentile

Sub-Catchment	Site ID	Organization	Start Date	End Date	n	Min	P10	P25	Median	Mean	P75	P90	Max
Tickville Wash	4994792	DWQ	5/16/2017	9/21/2020	24	16	25	42	59	82	98	168	266
Dry Creek - Saratoga	4994804	DWQ	5/16/2017	7/7/2020	13	21	24	27	39	66	67	110	282
Lehi Spring Creek	4994950	DWQ	5/16/2017	9/21/2020	41	10	14	21	30	31	42	48	57
Lehi Spring Creek	4994948	WFWQC	3/15/2016	8/13/2019	16	10	13	18	28	33	42	66	76
American Fork River	4994960	DWQ	5/16/2017	6/16/2020	16	5	5	5	9	22	32	59	79
American Fork River	4994958	WFWQC	10/28/2015	6/11/2019	8	21	22	22	30	71	88	195	199
Timp SSD	4995038	DWQ	5/16/2017	9/21/2020	41	171	287	491	910	1129	1610	2190	3170
Timp SSD	4995041	DWQ	5/16/2017	6/19/2019	23	163	289	365	700	988	1430	2122	2790
Timp SSD	4995043	WFWQC	10/14/2015	12/8/2020	44	57	245	575	1090	1121	1639	1855	3060
Lindon Drain	4995120	DWQ	5/11/2017	9/21/2020	38	21	33	38	48	79	60	121	555
Lindon Drain	4995075	WFWQC	10/14/2015	12/8/2020	40	29	58	115	206	210	313	374	444
Powell Slough Major	4995210	DWQ	8/9/2017	4/19/2019	14	619	1067	1343	1675	1749	1875	2328	3850
Powell Slough Major	4995230	DWQ	9/13/2017	4/19/2019	11	38	46	51	117	103	127	140	204
Powell Slough Major	4995210	WFWQC	10/27/2015	12/8/2020	36	111	411	982	1440	1651	1875	2655	9550
Provo River	4996680	DWQ	5/12/2017	9/21/2020	41	7	11	13	21	27	35	48	76
Provo River	4996680	WFWQC	10/14/2015	9/11/2019	20	10	12	16	26	34	32	58	131
Mill Race	4996540	DWQ	5/12/2017	9/21/2020	40	706	906	1118	1275	1280	1440	1671	1890
Mill Race	4996566	DWQ	5/12/2017	9/21/2020	40	667	774	902	1125	1140	1370	1494	1670
Mill Race	4996536	WFWQC	10/14/2015	6/18/2019	13	278	1022	1160	1250	1221	1320	1626	1720

Sub-Catchment	Site ID	Organization	Start Date	End Date	n	Min	P10	P25	Median	Mean	P75	P90	Max
Mill Race	4996540	WFWQC	11/16/2015	12/9/2020	44	388	996	1115	1410	1387	1608	1778	2140
Spring Creek - Springville	4996275	DWQ	9/18/2017	9/21/2020	37	10	776	899	1010	1099	1270	1736	1950
Spring Creek - Springville	4996275	WFWQC	2/16/2017	12/9/2020	29	262	680	951	1190	1247	1670	1860	2660
Hobble Creek	4996100	DWQ	5/12/2017	9/21/2020	41	5	8	9	25	68	36	70	1710
Hobble Creek	4996096	WFWQC	5/16/2018	6/18/2019	8	30	34	36	38	50	57	76	103
Hobble Creek	4996100	WFWQC	2/17/2016	9/11/2019	16	5	20	33	45	118	65	195	977
Dry Creek - Spanish Fork	4996040	DWQ	6/12/2017	9/30/2020	29	74	220	455	661	677	803	977	2820
Dry Creek - Spanish Fork	4996042	DWQ	6/12/2017	9/18/2017	4	85	90	96	101	151	156	254	319
Dry Creek - Spanish Fork	4996044	DWQ	10/17/2017	9/21/2020	33	26	35	46	60	67	74	105	186
Dry Creek - Spanish Fork	4996040	WFWQC	5/17/2018	6/20/2018	2	252	311	399	546	546	693	781	840
Spanish Fork River	4995578	DWQ	5/12/2017	9/21/2020	39	12	18	40	63	135	158	286	825
Spanish Fork River	4995575	WFWQC	10/14/2015	11/10/2020	33	14	32	52	89	119	122	193	739
4000 South Drain Spanish Fork	5919910	DWQ	4/19/2018	9/24/2019	18	56	85	94	196	251	349	440	902
4000 South Drain Spanish Fork	4917712	WFWQC	10/14/2015	12/9/2020	45	12	56	92	127	180	201	402	628
Benjamin Slough	4995465	DWQ	5/12/2017	8/11/2020	38	150	212	336	486	499	676	812	864
Benjamin Slough	4995467	WFWQC	10/27/2015	4/14/2020	40	43	103	258	530	516	758	880	1030
Currant Creek	4995310	DWQ	5/16/2017	8/11/2020	18	16	17	26	33	43	51	83	116
Currant Creek	4995312	DWQ	10/17/2017	3/7/2018	4	17	17	17	18	18	19	20	21

Table 14. Total Dissolved Phosphorus (TDP) concentrations (µg/L) in tributary monitoring locations. P = percentile

Sub-Catchment	Site ID	Organization	Start Date	End Date	n	Min	P10	P25	Median	Mean	P75	P90	Max
Tickville Wash	4994792	DWQ	5/16/2017	9/21/2020	24	5	7	11	22	21	25	38	54
Dry Creek - Saratoga	4994804	DWQ	5/16/2017	7/7/2020	13	5	5	8	12	13	15	18	42
Lehi Spring Creek	4994950	DWQ	5/16/2017	9/21/2020	41	4	5	7	12	16	22	26	71
Lehi Spring Creek	4994948	WFWQC	5/16/2016	6/11/2019	11	13	18	19	36	38	49	63	95
American Fork River	4994960	DWQ	5/16/2017	6/16/2020	16	3	4	4	5	7	7	13	16
American Fork River	4994958	WFWQC	3/15/2016	4/2/2019	4	11	14	18	21	19	22	23	24
Timp SSD	4995038	DWQ	5/16/2017	9/21/2020	41	19	215	441	872	1067	1570	2050	3280
Timp SSD	4995041	DWQ	5/16/2017	6/19/2019	24	90	105	159	454	806	1258	1967	2770
Timp SSD	4995043	WFWQC	10/27/2015	12/8/2020	43	141	258	466	1070	1077	1535	1890	2880
Lindon Drain	4995120	DWQ	5/11/2017	9/21/2020	38	9	16	19	25	86	32	142	1340
Lindon Drain	4995075	WFWQC	10/27/2015	12/8/2020	37	23	48	92	159	181	249	365	402
Powell Slough Major	4995210	DWQ	8/9/2017	4/19/2019	14	534	1011	1270	1575	1635	1755	2230	3680
Powell Slough Major	4995230	DWQ	9/13/2017	4/19/2019	11	24	37	46	65	67	91	94	97
Powell Slough Major	4995210	WFWQC	10/27/2015	12/8/2020	37	58	181	753	1250	1263	1750	2268	2830
Provo River	4996680	DWQ	5/12/2017	9/21/2020	41	1	6	8	12	15	22	27	35
Provo River	4996680	WFWQC	5/16/2016	7/14/2020	13	14	20	27	43	52	58	92	142
Mill Race	4996540	DWQ	5/12/2017	9/21/2020	40	528	827	917	1185	1157	1370	1467	2010
Mill Race	4996566	DWQ	5/12/2017	9/21/2020	40	1	611	775	1015	995	1195	1374	1660
Mill Race	4996536	WFWQC	11/17/2015	6/18/2019	12	222	508	861	1150	986	1170	1188	1430

Sub-Catchment	Site ID	Organization	Start Date	End Date	n	Min	P10	P25	Median	Mean	P75	P90	Max
Mill Race	4996540	WFWQC	11/16/2015	12/9/2020	44	336	786	1028	1275	1230	1450	1587	1980
Spring Creek - Springville	4996275	DWQ	9/18/2017	9/21/2020	37	9	665	852	969	1042	1310	1592	1900
Spring Creek - Springville	4996275	WFWQC	2/16/2017	12/9/2020	29	106	378	854	1120	1151	1270	1818	3040
Hobble Creek	4996100	DWQ	5/12/2017	9/21/2020	41	1	5	6	14	56	22	30	1580
Hobble Creek	4996096	WFWQC	5/16/2018	6/18/2019	8	30	42	54	70	73	96	104	114
Hobble Creek	4996100	WFWQC	2/17/2016	8/19/2020	24	11	16	28	45	86	60	143	818
Dry Creek - Spanish Fork	4996040	DWQ	6/12/2017	9/30/2020	28	39	145	370	562	535	661	834	1480
Dry Creek - Spanish Fork	4996042	DWQ	6/12/2017	9/18/2017	4	31	33	37	48	103	114	215	283
Dry Creek - Spanish Fork	4996044	DWQ	10/17/2017	9/21/2020	34	18	22	26	34	37	42	53	100
Dry Creek - Spanish Fork	4996040	WFWQC	5/17/2018	6/20/2018	2	344	383	441	538	538	635	693	732
Spanish Fork River	4995578	DWQ	5/12/2017	9/21/2020	39	5	6	12	24	27	41	52	85
Spanish Fork River	4995575	WFWQC	11/17/2015	11/10/2020	27	12	17	31	51	52	64	87	111
4000 South Drain Spanish Fork	5919910	DWQ	4/19/2018	9/24/2019	18	21	57	61	109	186	247	350	785
4000 South Drain Spanish Fork	4917712	WFWQC	11/17/2015	12/9/2020	40	12	28	68	95	144	197	286	550
Benjamin Slough	4995465	DWQ	5/12/2017	8/11/2020	38	24	90	133	294	328	482	679	766
Benjamin Slough	4995467	WFWQC	10/27/2015	4/14/2020	40	14	39	123	440	403	600	731	914
Currant Creek	4995310	DWQ	5/16/2017	8/11/2020	20	5	7	10	13	20	23	43	57
Currant Creek	4995312	DWQ	10/17/2017	5/16/2018	5	7	7	8	10	10	11	14	16

Table 15. Total Organic Carbon (TOC) concentrations (µg/L) in tributary monitoring locations. P = percentile

Sub-Catchment	Site ID	Organization	Start Date	End Date	n	Min	P10	P25	Median	Mean	P75	P90	Max
Tickville Wash	4994792	DWQ	5/16/2017	9/21/2020	24	1050	1441	2718	3330	3391	4248	4623	5960
Dry Creek - Saratoga	4994804	DWQ	5/16/2017	7/7/2020	13	583	1520	1880	2090	2836	3650	4584	7930
Lehi Spring Creek	4994950	DWQ	5/16/2017	9/21/2020	41	1190	1530	1760	2050	2284	2610	3000	5900
American Fork River	4994960	DWQ	5/16/2017	6/16/2020	16	832	924	1068	1350	1454	1810	1935	2840
Timp SSD	4995038	DWQ	5/16/2017	9/21/2020	41	4480	4980	5180	5990	5988	6710	7030	7760
Timp SSD	4995041	DWQ	5/16/2017	6/19/2019	23	4560	4824	5295	6080	6156	7185	7616	7990
Lindon Drain	4995120	DWQ	5/11/2017	9/21/2020	28	1630	1796	2218	2420	2580	2685	3483	4610
Powell Slough Major	4995210	DWQ	8/9/2017	4/19/2019	14	3710	3958	4248	4795	4826	5198	5497	6690
Powell Slough Major	4995230	DWQ	9/13/2017	4/19/2019	11	2780	2830	3705	4800	4564	5250	5730	6370
Provo River	4996680	DWQ	5/12/2017	9/21/2020	41	1800	2070	2290	2640	2857	2990	3370	11300
Mill Race	4996540	DWQ	5/12/2017	9/21/2020	40	2760	3240	3468	3980	4030	4368	4951	6110
Mill Race	4996566	DWQ	5/12/2017	9/21/2020	41	2830	3160	3310	3780	3797	4140	4740	5190
Spring Creek - Springville	4996275	DWQ	9/18/2017	9/21/2020	37	1130	2786	3130	3550	3613	4230	4562	5250
Hobble Creek	4996100	DWQ	5/12/2017	9/21/2020	41	709	948	1140	2660	2386	3430	3680	4410
Dry Creek - Spanish Fork	4996040	DWQ	6/12/2017	9/30/2020	29	2740	3252	3400	4280	4427	4880	6198	6710
Dry Creek - Spanish Fork	4996042	DWQ	6/12/2017	9/18/2017	4	2570	2618	2690	2735	3105	3150	3888	4380
Dry Creek - Spanish Fork	4996044	DWQ	10/9/2018	9/21/2020	24	1500	1902	2280	2510	2550	2923	3161	3860
Spanish Fork River	4995578	DWQ	5/12/2017	9/21/2020	39	1600	1958	2065	3210	3356	4370	5082	6260
4000 South Drain Spanish Fork	5919910	DWQ	4/19/2018	9/24/2019	18	5520	5960	6538	7475	8283	8745	10310	19100
Benjamin Slough	4995465	DWQ	5/12/2017	8/11/2020	38	3440	4271	5175	6670	7226	8993	10790	12300
Currant Creek	4995310	DWQ	5/16/2017	8/11/2020	14	1890	2790	3505	4265	4636	6053	6745	7310
Currant Creek	4995312	DWQ	3/7/2018	3/7/2018	1	3440	3440	3440	3440	3440	3440	3440	3440

Table 16. Dissolved Organic Carbon (DOC) concentrations (µg/L) in tributary monitoring locations. P = percentile

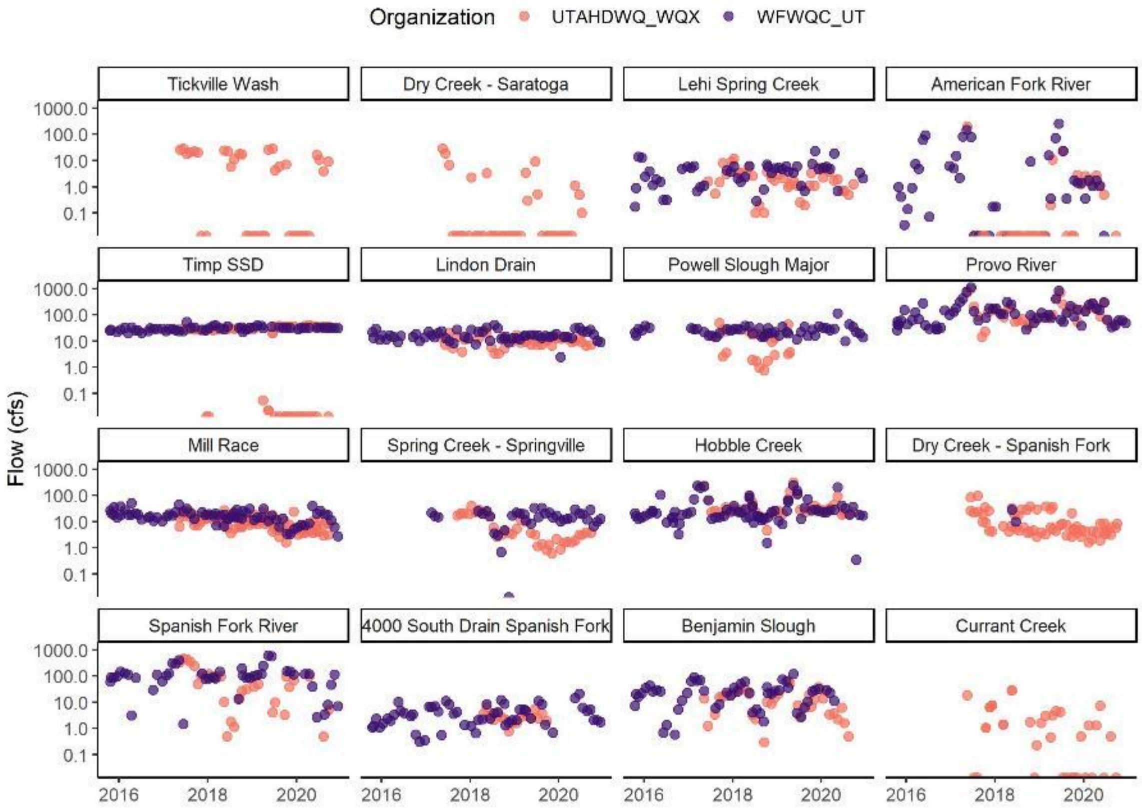
Sub-Catchment	Site ID	Organization	Start Date	End Date	n	Min	P10	P25	Median	Mean	P75	P90	Max
Tickville Wash	4994792	DWQ	5/16/2017	9/21/2020	24	1390	1994	3228	4485	4615	5933	7392	8410
Dry Creek - Saratoga	4994804	DWQ	5/16/2017	7/7/2020	13	1200	2048	2370	3560	3592	4400	4598	7470
Lehi Spring Creek	4994950	DWQ	5/16/2017	9/21/2020	41	1680	1960	2070	2860	3273	3790	4780	7380
American Fork River	4994960	DWQ	5/16/2017	6/16/2020	16	927	1260	1368	1850	2244	2378	3530	6470
Timp SSD	4995038	DWQ	5/16/2017	9/21/2020	41	4380	5090	5780	6520	7200	8160	9370	16000
Timp SSD	4995041	DWQ	5/16/2017	6/19/2019	24	4440	4823	5200	5885	6194	6898	8353	9040
Lindon Drain	4995120	DWQ	5/11/2017	9/21/2020	28	1700	2482	2895	3440	3956	4338	5998	9120
Powell Slough Major	4995210	DWQ	8/9/2017	4/19/2019	14	3690	4694	5025	6465	6454	7090	8146	11800
Powell Slough Major	4995230	DWQ	9/13/2017	4/19/2019	11	3070	3460	4460	5390	5522	6895	7550	7620
Provo River	4996680	DWQ	5/12/2017	9/21/2020	41	2130	2550	2860	3710	4184	5130	5690	14200
Mill Race	4996540	DWQ	5/12/2017	9/21/2020	40	2970	3567	3960	4500	5144	6075	7420	10200
Mill Race	4996566	DWQ	5/12/2017	9/21/2020	40	3100	3187	3905	4310	5003	5583	7088	10200
Spring Creek - Springville	4996275	DWQ	9/18/2017	9/21/2020	37	1560	3080	3550	4270	4911	6160	7494	12300
Hobble Creek	4996100	DWQ	5/12/2017	9/21/2020	41	913	1460	1950	3580	3456	4380	5800	7670
Dry Creek - Spanish Fork	4996040	DWQ	6/12/2017	9/30/2020	29	3210	3964	4600	5460	5548	5920	7182	10300
Dry Creek - Spanish Fork	4996042	DWQ	6/12/2017	9/18/2017	4	3570	3981	4598	5315	5353	6070	6754	7210
Dry Creek - Spanish Fork	4996044	DWQ	10/9/2018	9/21/2020	24	1860	2341	2723	3205	3793	4968	5814	6920
Spanish Fork River	4995578	DWQ	5/12/2017	9/21/2020	39	1960	2170	2495	4080	4351	5195	7496	8820
4000 South Drain Spanish Fork	5919910	DWQ	4/19/2018	9/24/2019	18	5730	6807	7313	8560	9134	9420	12180	17800
Benjamin Slough	4995465	DWQ	5/12/2017	8/11/2020	38	3360	4818	5920	7610	8127	9598	12830	18000
Currant Creek	4995310	DWQ	5/16/2017	8/11/2020	14	2380	3208	3433	6705	6396	8040	9863	12100
Currant Creek	4995312	DWQ	3/7/2018	3/7/2018	1	4090	4090	4090	4090	4090	4090	4090	4090

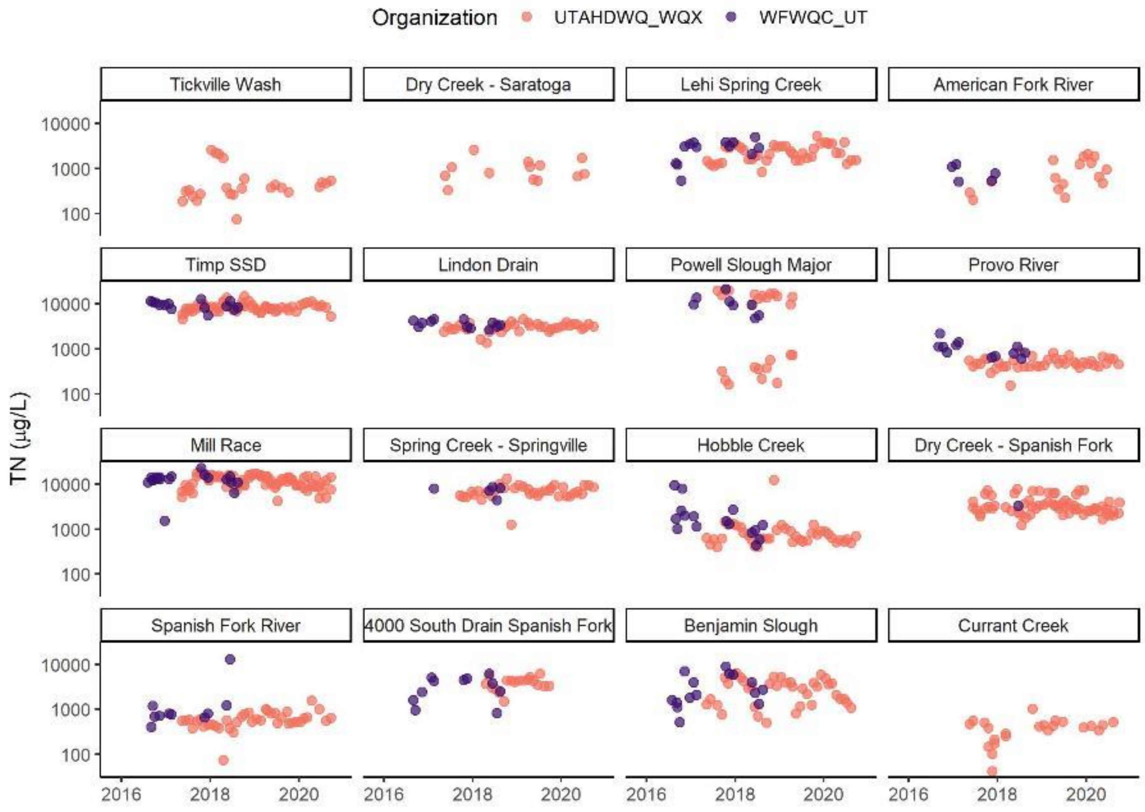
Table 17. Flow (cfs) measured in tributary monitoring locations. P = percentile

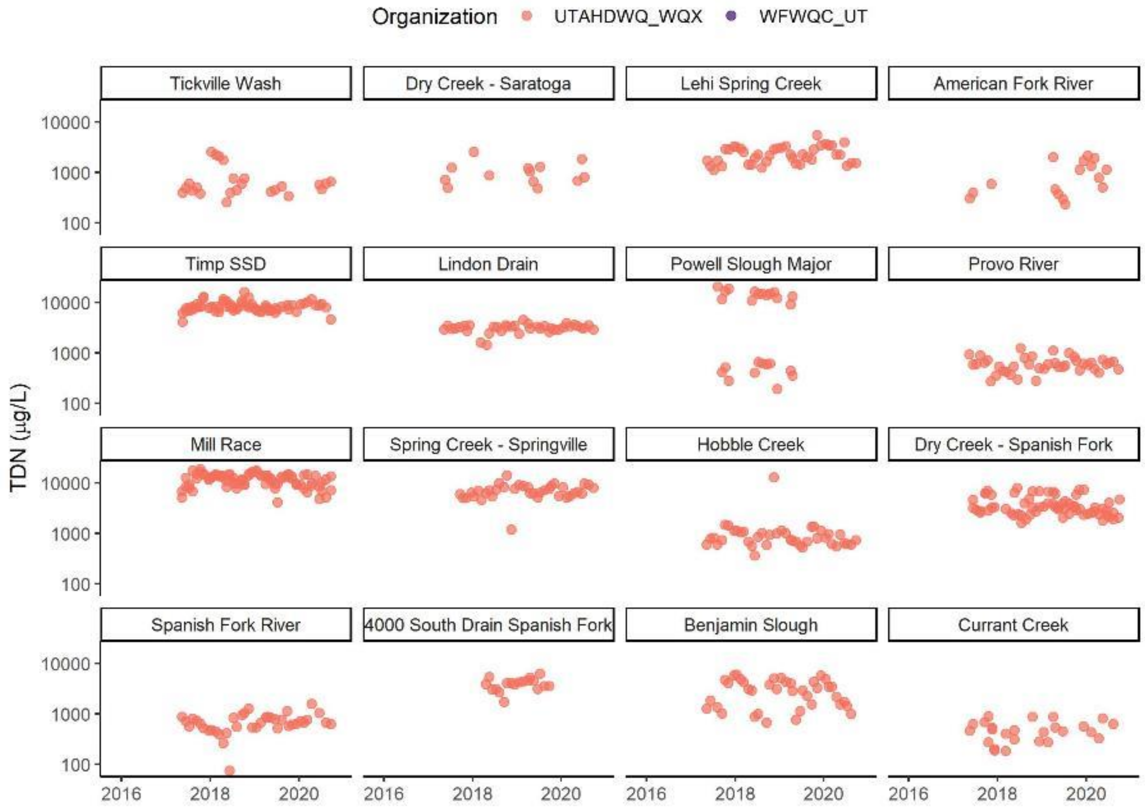
Sub-Catchment	Site ID	Organization	Start Date	End Date	n	Min	P10	P25	Median	Mean	P75	P90	Max
Tickville Wash	4994792	DWQ	5/16/2017	9/21/2020	35	0.0	0.0	0.0	6.1	10.0	19.2	25.3	28.6
Dry Creek - Saratoga	4994804	DWQ	5/16/2017	7/7/2020	38	0.0	0.0	0.0	0.0	2.0	0.5	4.5	29.1
Lehi Spring Creek	4994950	DWQ	6/12/2017	9/21/2020	39	0.1	0.2	1.0	1.8	2.6	3.4	5.3	11.9
Lehi Spring Creek	4994948	WFWQC	10/19/2015	12/8/2020	49	0.2	0.7	1.2	3.9	4.5	5.7	7.2	23.7
American Fork River	4994960	DWQ	5/16/2017	9/21/2020	33	0.0	0.0	0.0	0.0	7.5	1.2	2.8	198.0
American Fork River	4994958	WFWQC	10/28/2015	6/16/2020	41	0.0	0.0	0.2	1.4	21.9	9.2	77.5	260.3
Timp SSD	4995038	DWQ	5/16/2017	9/21/2020	38	0.0	26.3	28.5	29.9	30.0	35.5	37.4	41.3
Timp SSD	4995041	DWQ	12/20/2017	9/21/2020	17	0.0	0.0	0.0	0.0	1.2	0.0	0.0	20.3
Timp SSD	4995043	WFWQC	10/19/2015	12/8/2020	57	20.5	24.0	26.9	31.4	30.7	32.8	35.8	54.6
Lindon Drain	4995120	DWQ	5/11/2017	9/21/2020	39	3.5	5.5	7.2	9.9	10.7	12.6	15.7	24.8
Lindon Drain	4995075	WFWQC	10/19/2015	12/8/2020	62	2.5	9.9	12.9	15.3	17.2	21.7	27.7	42.4
Powell Slough Major	4995210	DWQ	8/9/2017	4/1/2019	13	9.4	13.1	14.6	19.4	22.7	23.9	41.4	48.5
Powell Slough Major	4995230	DWQ	10/10/2017	4/19/2019	10	0.8	1.0	1.8	2.2	2.3	3.1	3.7	3.8
Powell Slough Major	4995210	WFWQC	10/19/2015	12/8/2020	51	9.9	15.2	19.5	25.8	26.8	31.3	36.7	113.0
Provo River	4996680	DWQ	5/12/2017	9/21/2020	41	14.8	43.5	69.4	104.0	174.7	180.0	297.0	997.0
Provo River	4996680	WFWQC	10/14/2015	12/8/2020	65	26.0	35.1	53.3	102.4	158.4	172.3	312.1	1123.9
Mill Race	4996540	DWQ	5/12/2017	9/21/2020	40	1.6	3.6	4.3	6.5	8.2	11.9	15.1	21.1
Mill Race	4996566	DWQ	5/12/2017	9/21/2020	41	3.2	5.2	7.7	10.2	13.0	17.9	23.6	27.3
Mill Race	4996536	WFWQC	10/20/2015	8/28/2018	10	6.8	7.0	15.0	24.5	25.0	33.9	39.4	50.5

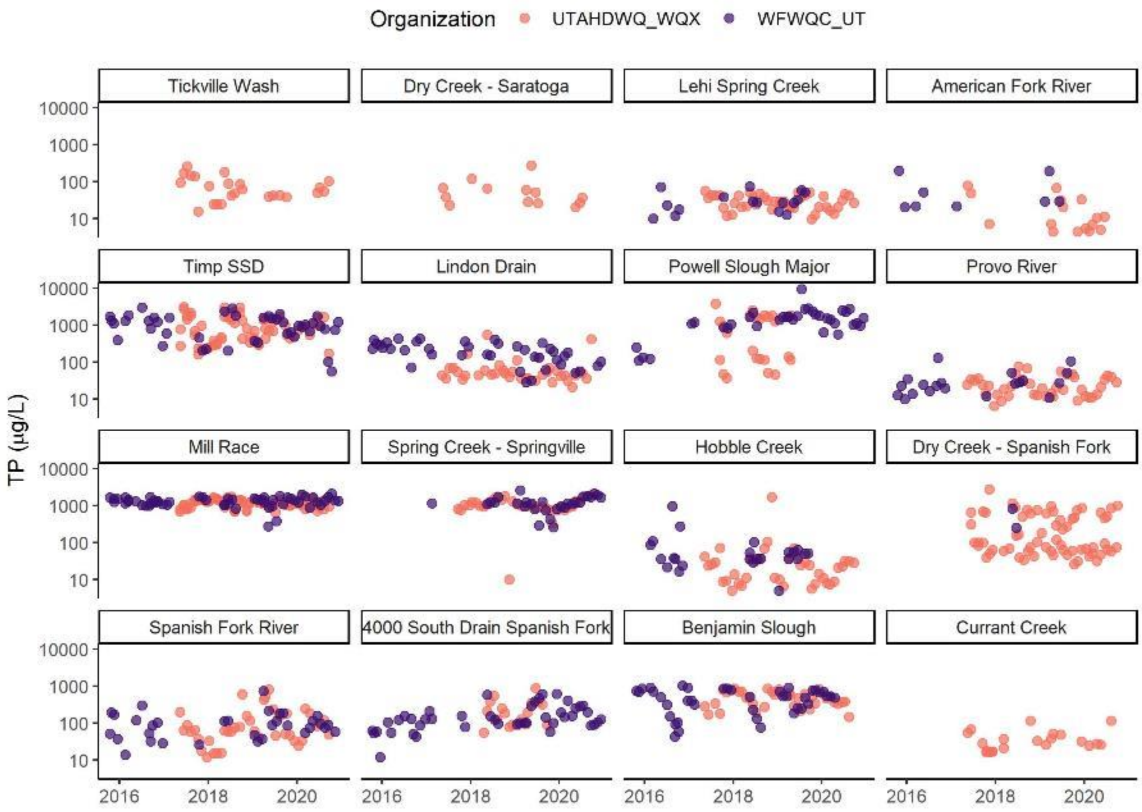
Sub-Catchment	Site ID	Organization	Start Date	End Date	n	Min	P10	P25	Median	Mean	P75	P90	Max
Mill Race	4996540	WFWQC	11/16/2015	12/9/2020	62	2.8	6.4	12.4	16.5	16.8	20.1	26.3	44.5
Spring Creek - Springville	4996275	DWQ	9/18/2017	9/21/2020	36	0.6	1.2	1.9	3.7	8.8	16.3	21.9	39.6
Spring Creek - Springville	4996275	WFWQC	2/16/2017	12/9/2020	37	0.0	4.2	11.3	15.6	16.2	21.2	26.7	34.3
Hobble Creek	4996100	DWQ	5/12/2017	9/21/2020	41	4.7	18.9	22.3	27.5	49.2	40.7	99.8	322.0
Hobble Creek	4996096	WFWQC	4/24/2018	6/18/2019	10	9.2	11.1	14.0	16.1	39.6	58.5	98.4	117.0
Hobble Creek	4996100	WFWQC	10/20/2015	12/9/2020	68	0.4	10.3	15.0	23.0	42.1	33.2	90.2	242.3
Dry Creek - Spanish Fork	4996040	DWQ	6/12/2017	9/30/2020	27	3.2	4.6	8.0	19.4	21.9	30.0	36.8	97.5
Dry Creek - Spanish Fork	4996042	DWQ	6/12/2017	9/18/2017	4	10.0	13.6	19.1	23.0	35.1	39.0	66.4	84.6
Dry Creek - Spanish Fork	4996044	DWQ	10/17/2017	9/21/2020	33	1.6	2.7	3.7	4.3	4.5	5.4	6.7	9.0
Dry Creek - Spanish Fork	4996040	WFWQC	5/17/2018	6/20/2018	2	10.1	11.9	14.6	19.2	19.2	23.7	26.5	28.3
Spanish Fork River	4995578	DWQ	5/12/2017	9/21/2020	31	0.5	1.8	10.3	50.3	99.5	101.1	326.8	458.0
Spanish Fork River	4995575	WFWQC	10/20/2015	12/8/2020	47	1.5	7.7	70.6	104.9	127.9	131.0	267.4	632.8
4000 South Drain Spanish Fork	5919910	DWQ	4/19/2018	9/24/2019	18	0.8	1.6	2.1	2.8	3.0	3.7	4.6	6.5
4000 South Drain Spanish Fork	4917712	WFWQC	10/20/2015	12/9/2020	56	0.3	0.9	1.7	3.1	4.4	5.6	9.5	21.2
Benjamin Slough	4995465	DWQ	5/12/2017	8/11/2020	36	0.3	1.9	3.5	13.6	15.8	21.1	34.8	65.4
Benjamin Slough	4995467	WFWQC	10/20/2015	4/14/2020	52	0.6	3.8	8.1	23.4	28.2	34.7	64.5	120.4
Currant Creek	4995310	DWQ	5/16/2017	9/21/2020	31	0.0	0.0	0.0	0.5	3.0	3.1	7.5	28.3
Currant Creek	4995312	DWQ	10/17/2017	5/16/2018	5	1.1	1.2	1.4	6.6	9.0	7.6	20.0	28.3

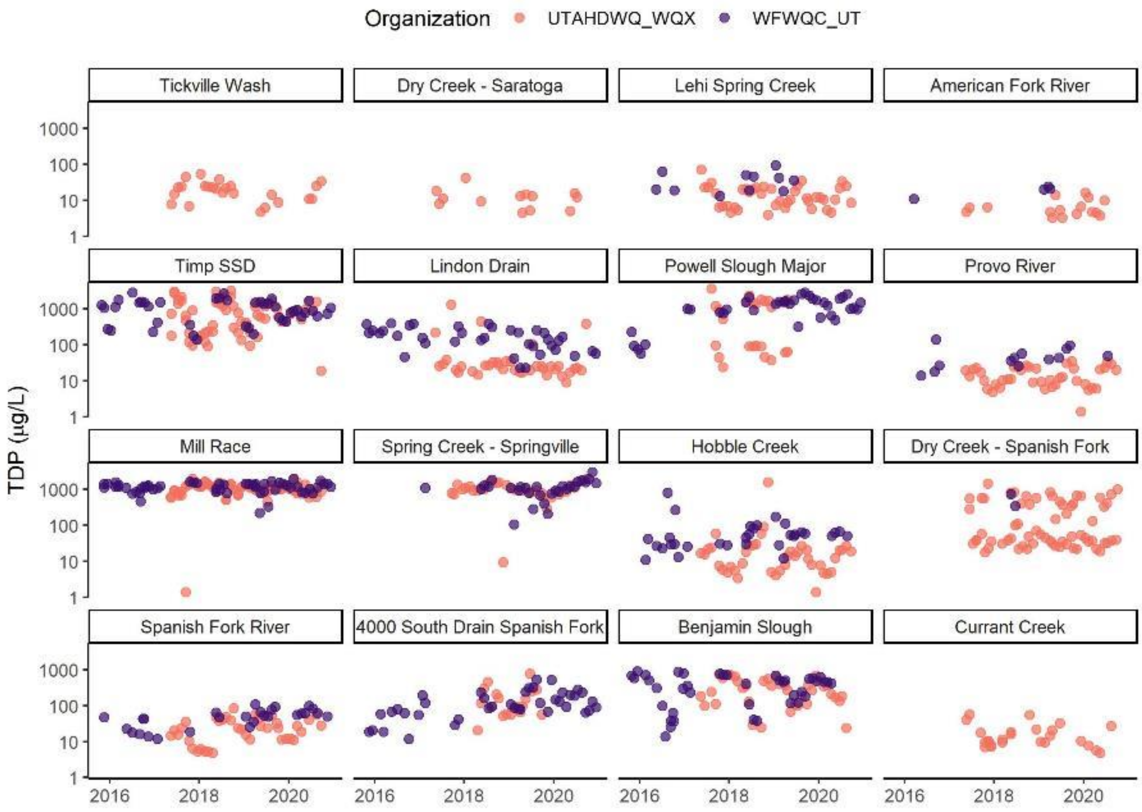
10.2 TIME SERIES OF TRIBUTARY MONITORING LOCATIONS



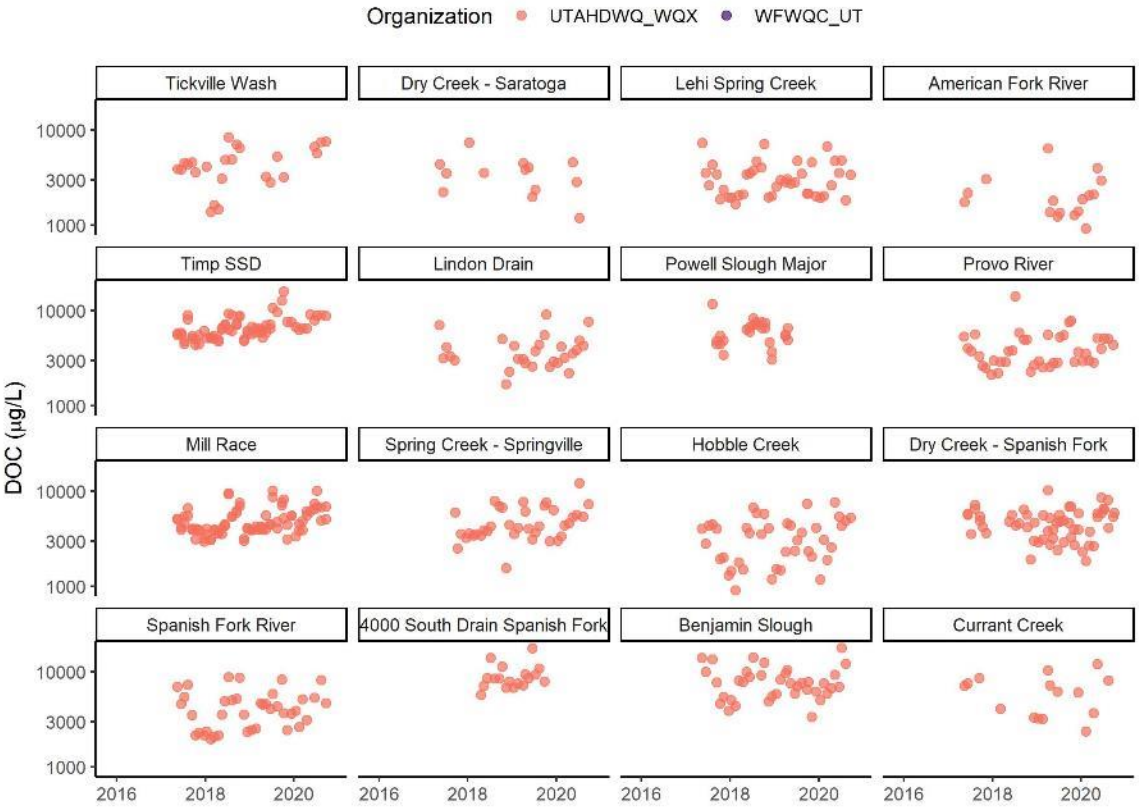

Organization
● UTAHDWQ_WQX
● WFWQC_UT
Tickville Wash
Dry Creek - Saratoga
Lehi Spring Creek
American Fork River
Timp SSD
Lindon Drain
Powell Slough Major
Provo River
Mill Race
Spring Creek - Springville
Hobble Creek
Dry Creek - Spanish Fork
Spanish Fork River
4000 South Drain Spanish Fork
Benjamin Slough
Currant Creek
TN (µg/L)
10000
1000
100
2016
2018
2020


Organization
● UTAHDWQ_WQX
● WFWQC_UT
Tickville Wash
Dry Creek - Saratoga
Lehi Spring Creek
American Fork River
Timp SSD
Lindon Drain
Powell Slough Major
Provo River
Mill Race
Spring Creek - Springville
Hobble Creek
Dry Creek - Spanish Fork
Spanish Fork River
4000 South Drain Spanish Fork
Benjamin Slough
Currant Creek
TDN (µg/L)
10000
1000
100
2016
2018
2020

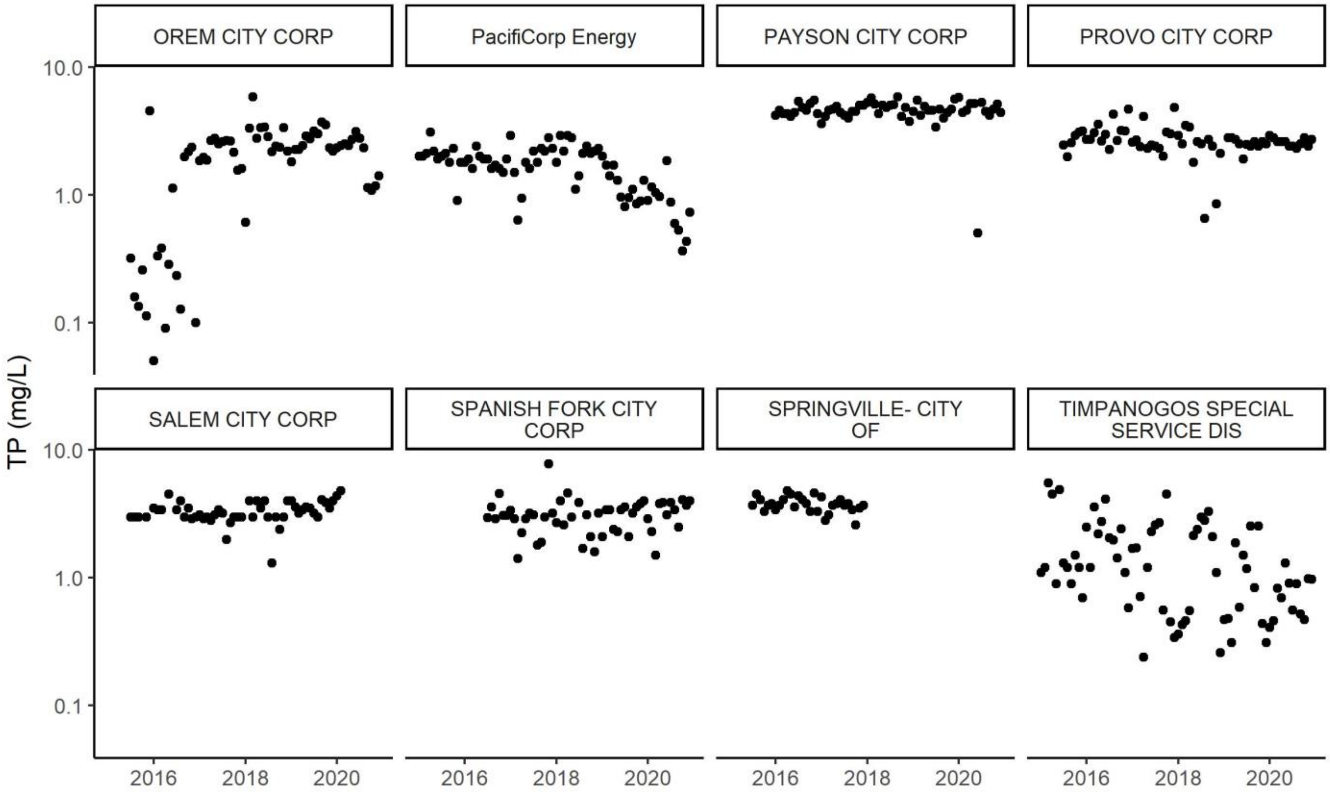

Organization
UTAHDWQ_WQX
WFWQC_UT
TP (µg/L)
Tickville Wash
Dry Creek - Saratoga
Lehi Spring Creek
American Fork River
Timp SSD
Lindon Drain
Powell Slough Major
Provo River
Mill Race
Spring Creek - Springville
Hobble Creek
Dry Creek - Spanish Fork
Spanish Fork River
4000 South Drain Spanish Fork
Benjamin Slough
Currant Creek
10000
1000
100
10
2016
2018
2020

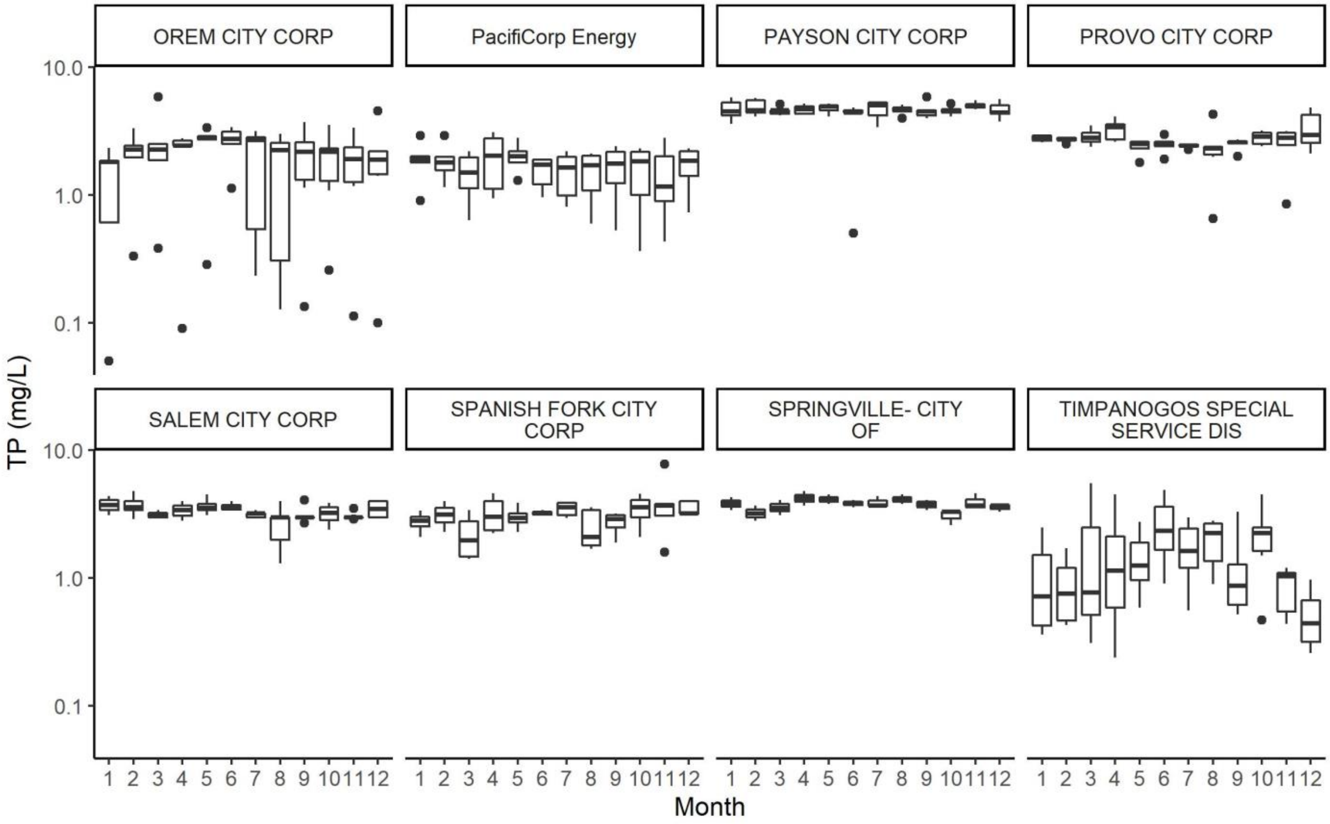

Organization
UTAHDWQ_WQX
WFWQC_UT
TDP (µg/L)
Tickville Wash
Dry Creek - Saratoga
Lehi Spring Creek
American Fork River
Timp SSD
Lindon Drain
Powell Slough Major
Provo River
Mill Race
Spring Creek - Springville
Hobble Creek
Dry Creek - Spanish Fork
Spanish Fork River
4000 South Drain Spanish Fork
Benjamin Slough
Currant Creek
1000
100
10
1
2016
2018
2020

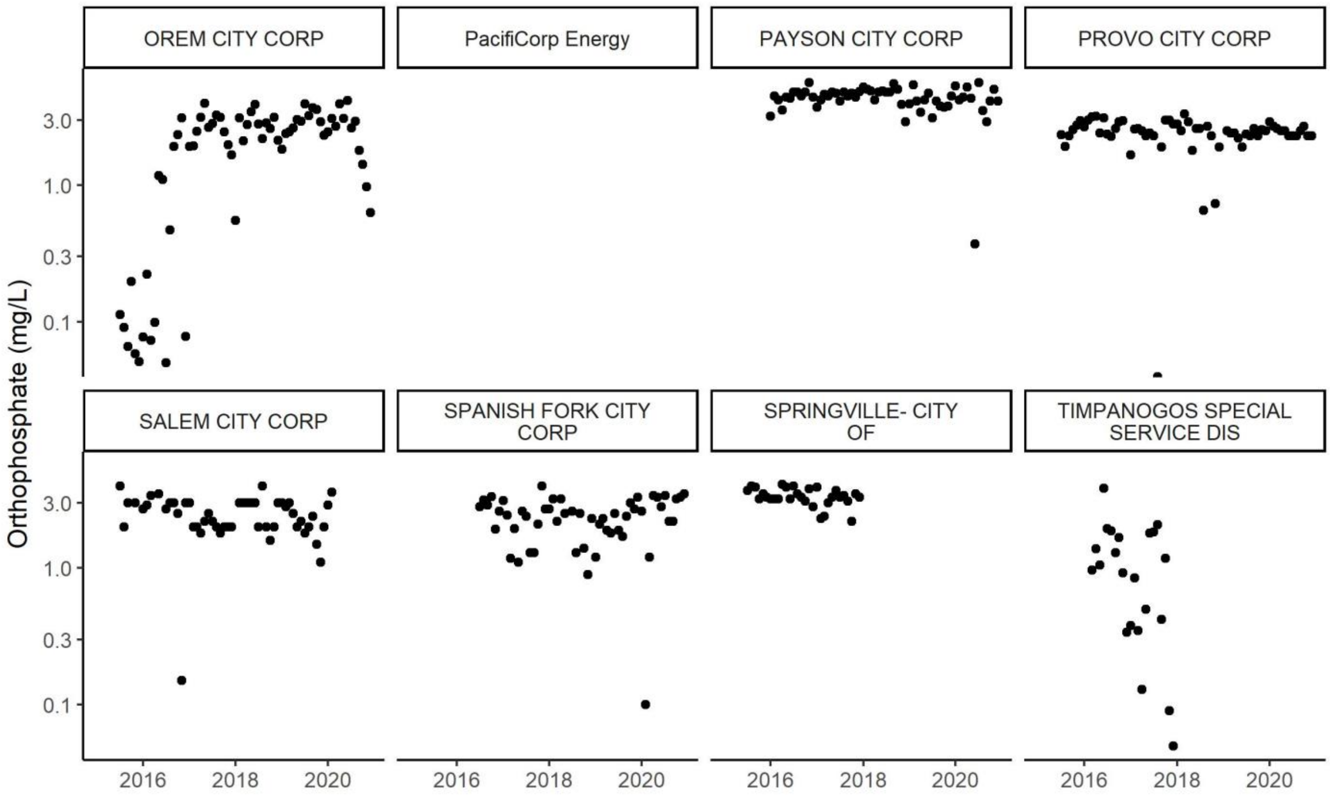

Organization
● UTAHDWQ_WQX
● WFWQC_UT
Tickville Wash
Dry Creek - Saratoga
Lehi Spring Creek
American Fork River
Timp SSD
Lindon Drain
Powell Slough Major
Provo River
Mill Race
Spring Creek - Springville
Hobble Creek
Dry Creek - Spanish Fork
Spanish Fork River
4000 South Drain Spanish Fork
Benjamin Slough
Currant Creek
TOC (µg/L)
10000
3000
1000
2016
2018
2020

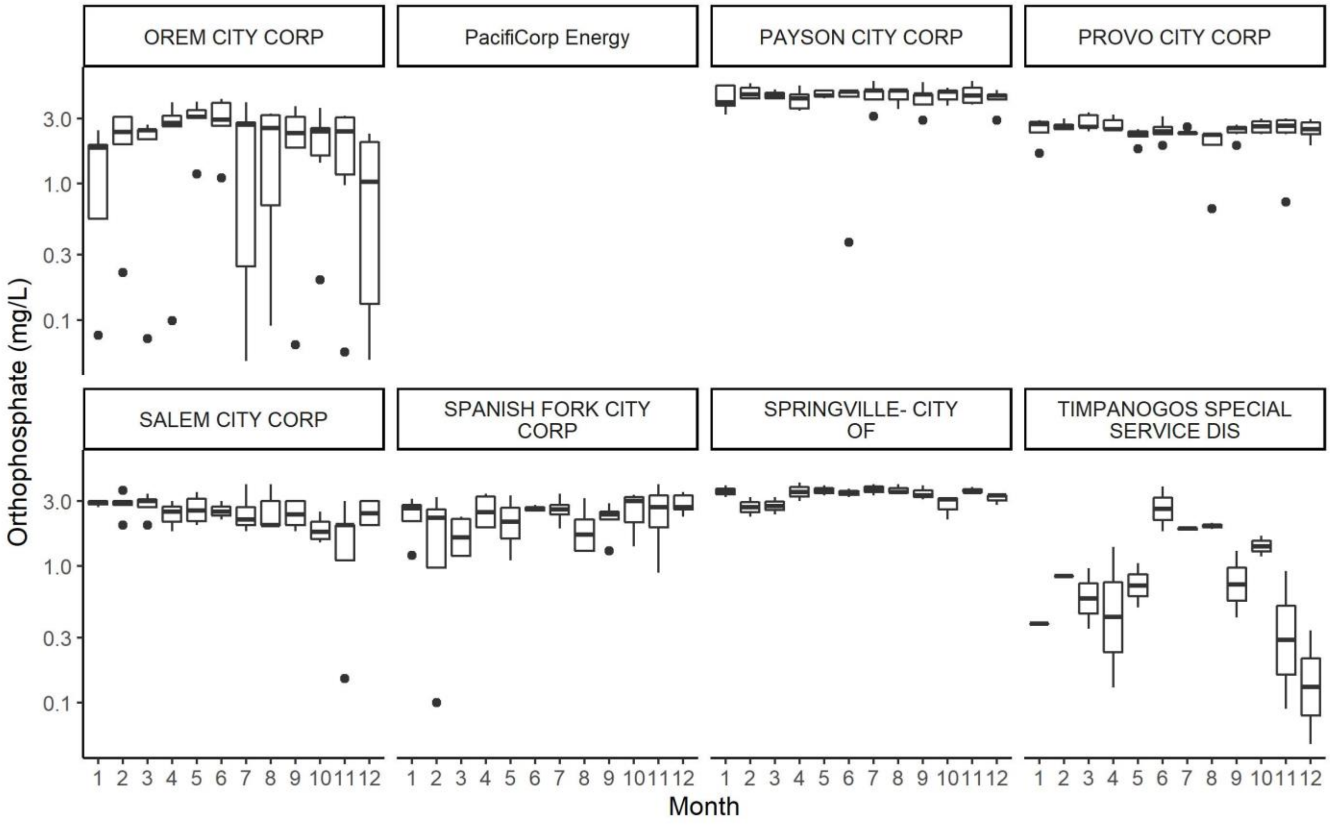

Organization
● UTAHDWQ_WQX
● WFWQC_UT
Tickville Wash
Dry Creek - Saratoga
Lehi Spring Creek
American Fork River
Timp SSD
Lindon Drain
Powell Slough Major
Provo River
Mill Race
Spring Creek - Springville
Hobble Creek
Dry Creek - Spanish Fork
Spanish Fork River
4000 South Drain Spanish Fork
Benjamin Slough
Currant Creek
DOC (µg/L)
10000
3000
1000
2016
2018
2020

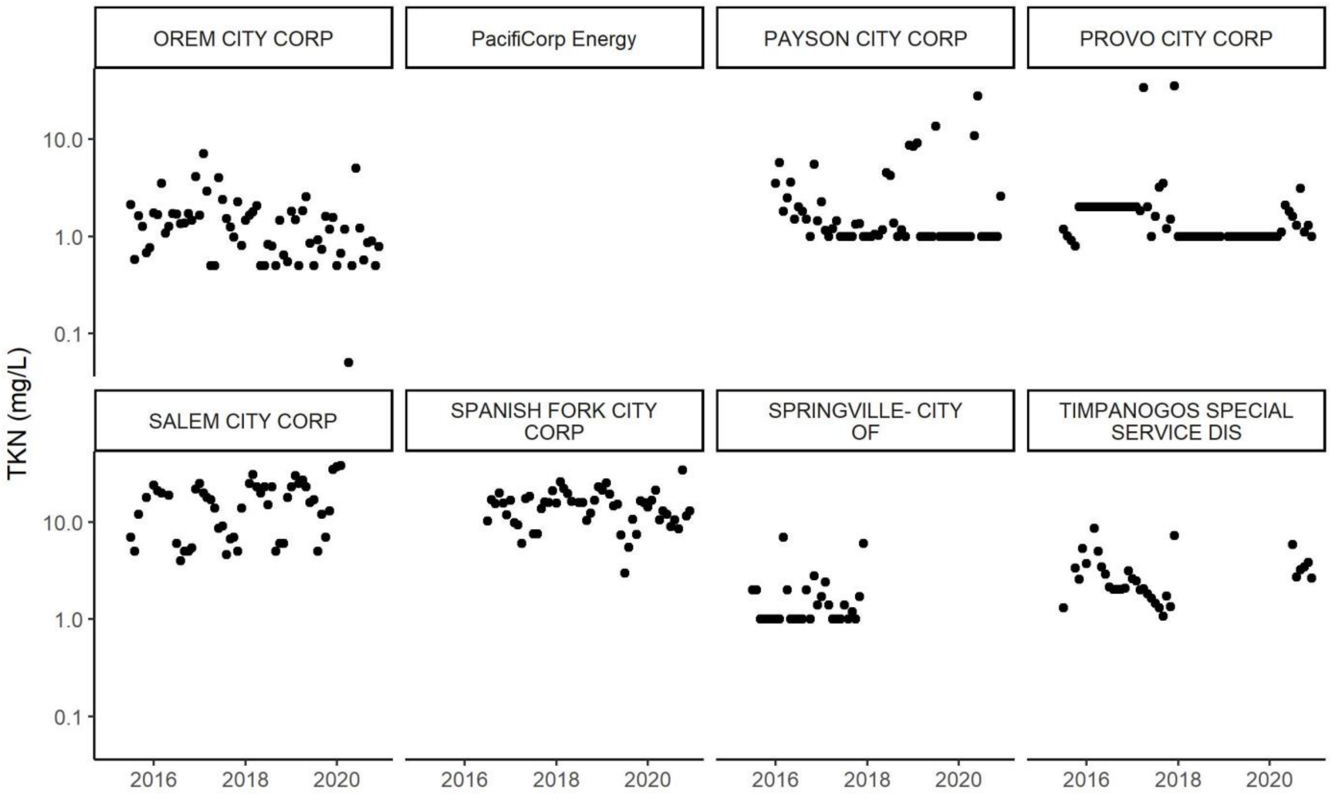
10.3 TIME SERIES AND MONTHLY DMR FLOW AND CONCENTRATIONS

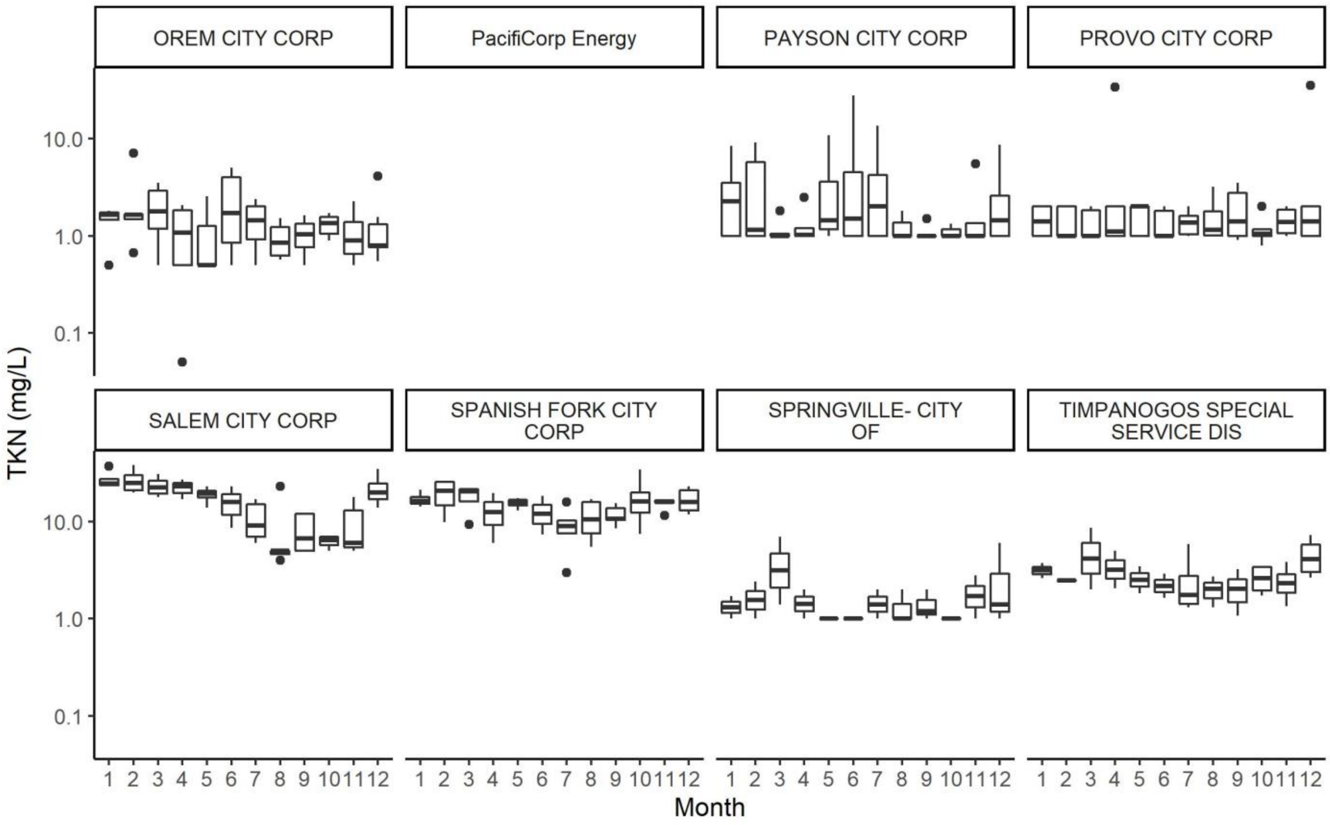


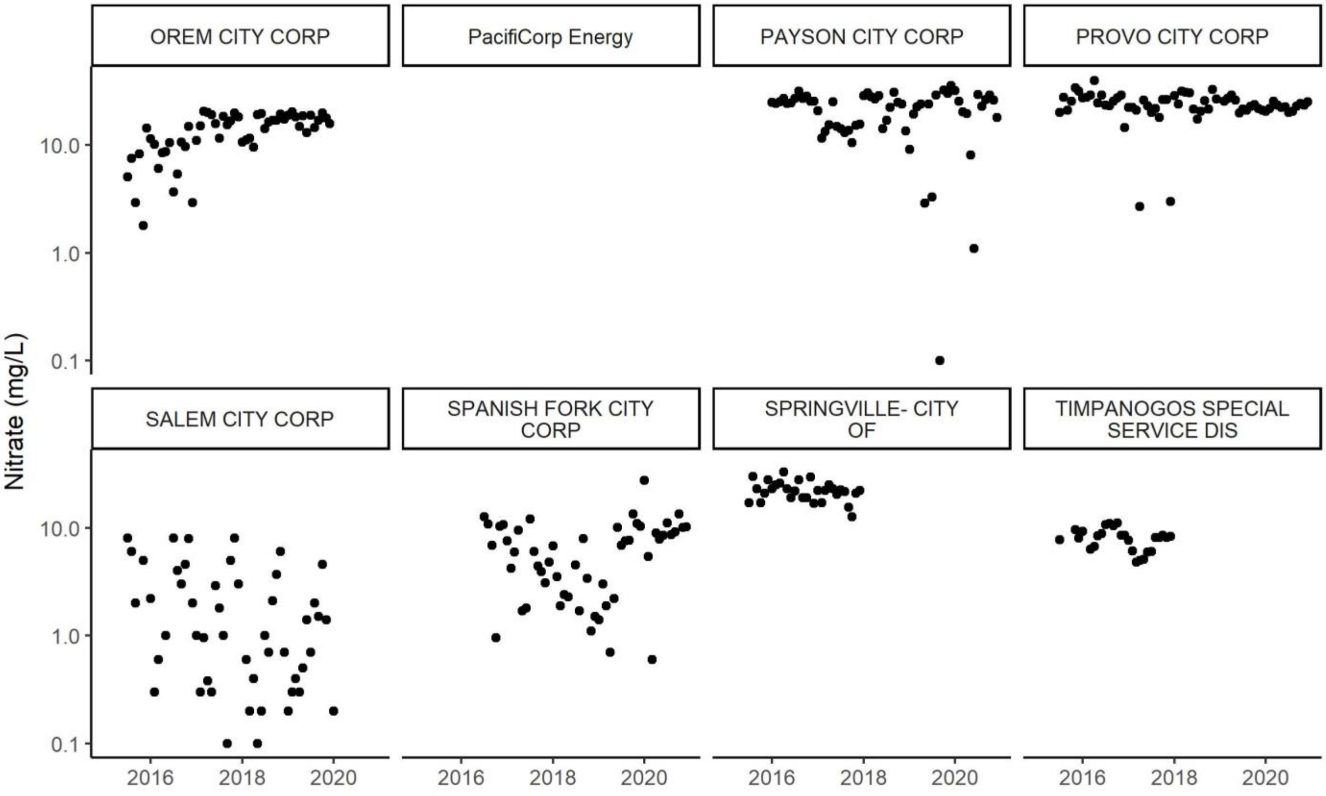


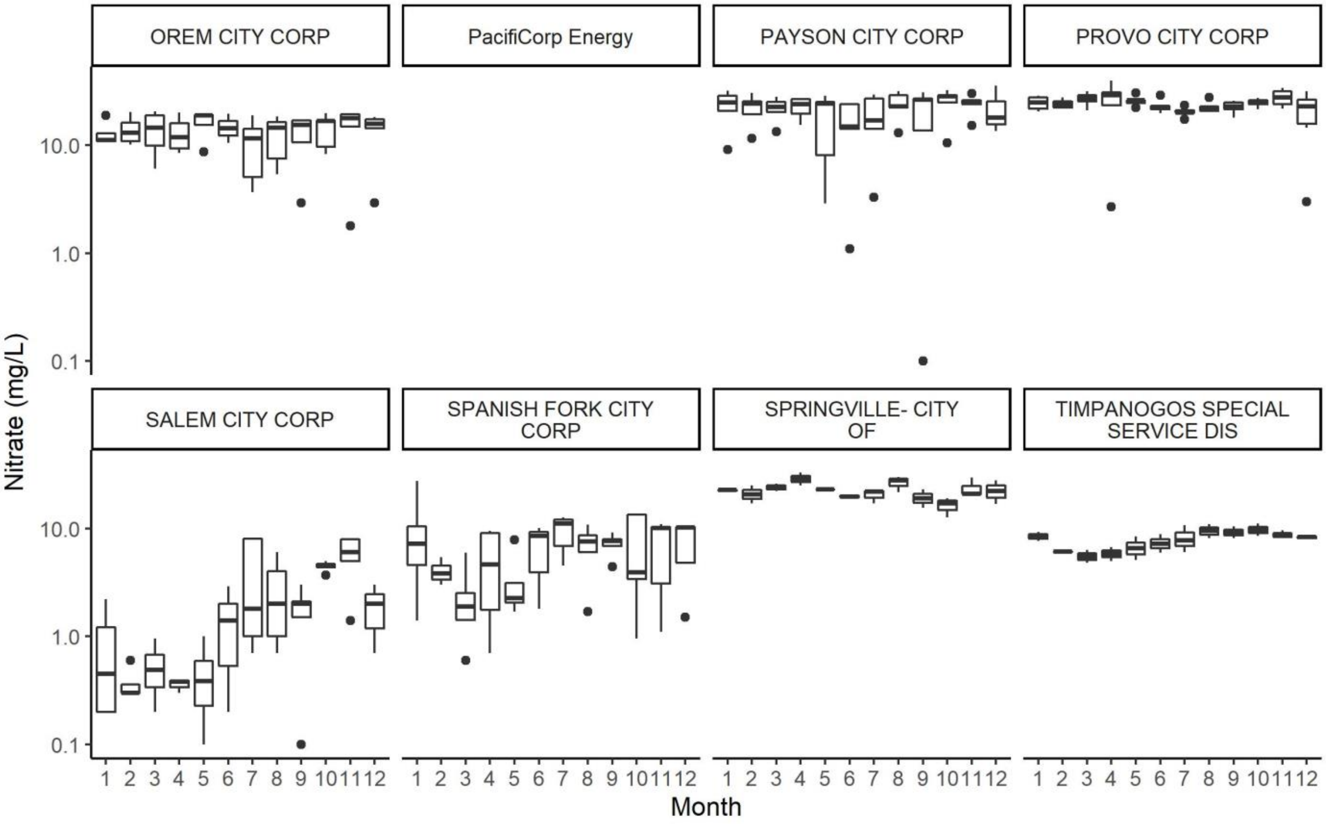

OREM CITY CORP
PacifiCorp Energy
PAYSON CITY CORP
PROVO CITY CORP
SALEM CITY CORP
SPANISH FORK CITY CORP
SPRINGVILLE- CITY OF
TIMPANOGOS SPECIAL SERVICE DIS
Orthophosphate (mg/L)
3.0
1.0
0.3
0.1
2016
2018
2020

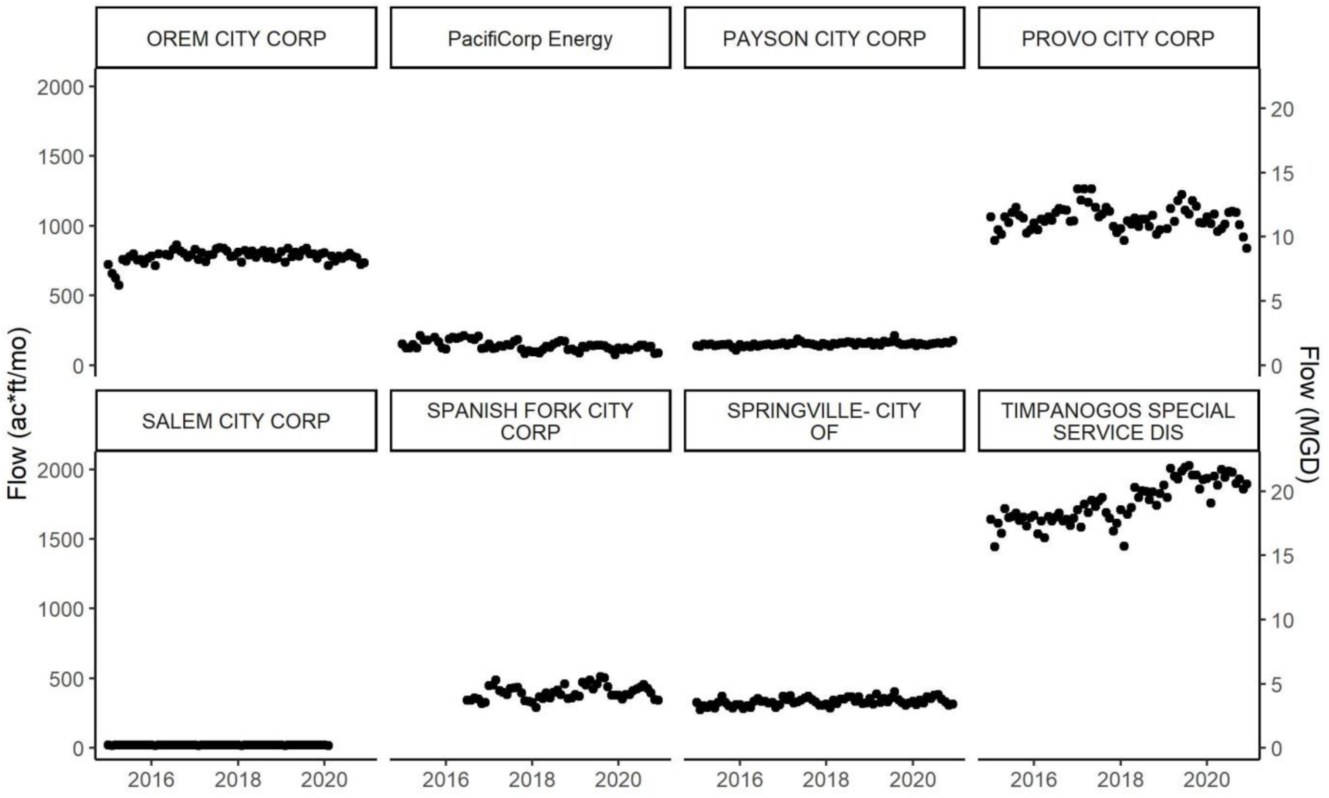

OREM CITY CORP
PacifiCorp Energy
PAYSON CITY CORP
PROVO CITY CORP
SALEM CITY CORP
SPANISH FORK CITY CORP
SPRINGVILLE- CITY OF
TIMPANOGOS SPECIAL SERVICE DIS
Orthophosphate (mg/L)
3.0
1.0
0.3
0.1
1 2 3 4 5 6 7 8 9 10 11 12
Month

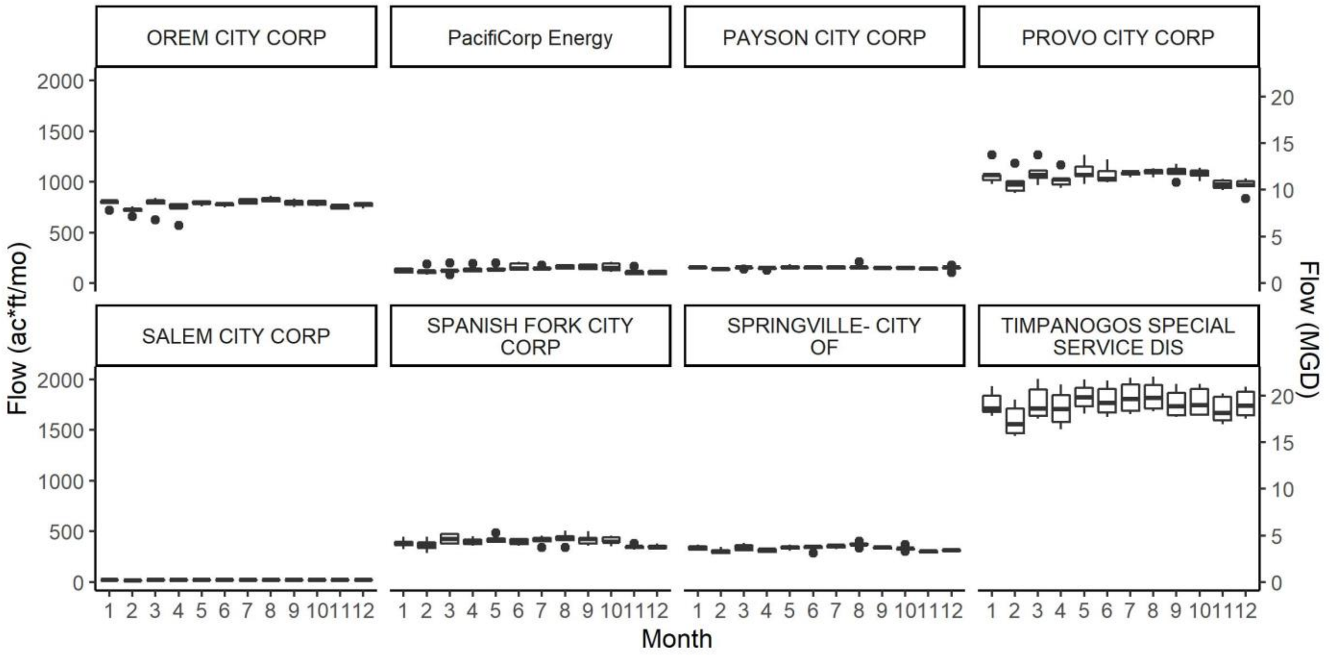

OREM CITY CORP
PacifiCorp Energy
PAYSON CITY CORP
PROVO CITY CORP
SALEM CITY CORP
SPANISH FORK CITY CORP
SPRINGVILLE- CITY OF
TIMPANOGOS SPECIAL SERVICE DIS
TKN (mg/L)
10.0
1.0
0.1
2016
2018
2020


OREM CITY CORP
PacifiCorp Energy
PAYSON CITY CORP
PROVO CITY CORP
SALEM CITY CORP
SPANISH FORK CITY CORP
SPRINGVILLE- CITY OF
TIMPANOGOS SPECIAL SERVICE DIS
TKN (mg/L)
10.0
1.0
0.1
1 2 3 4 5 6 7 8 9 10 11 12
Month

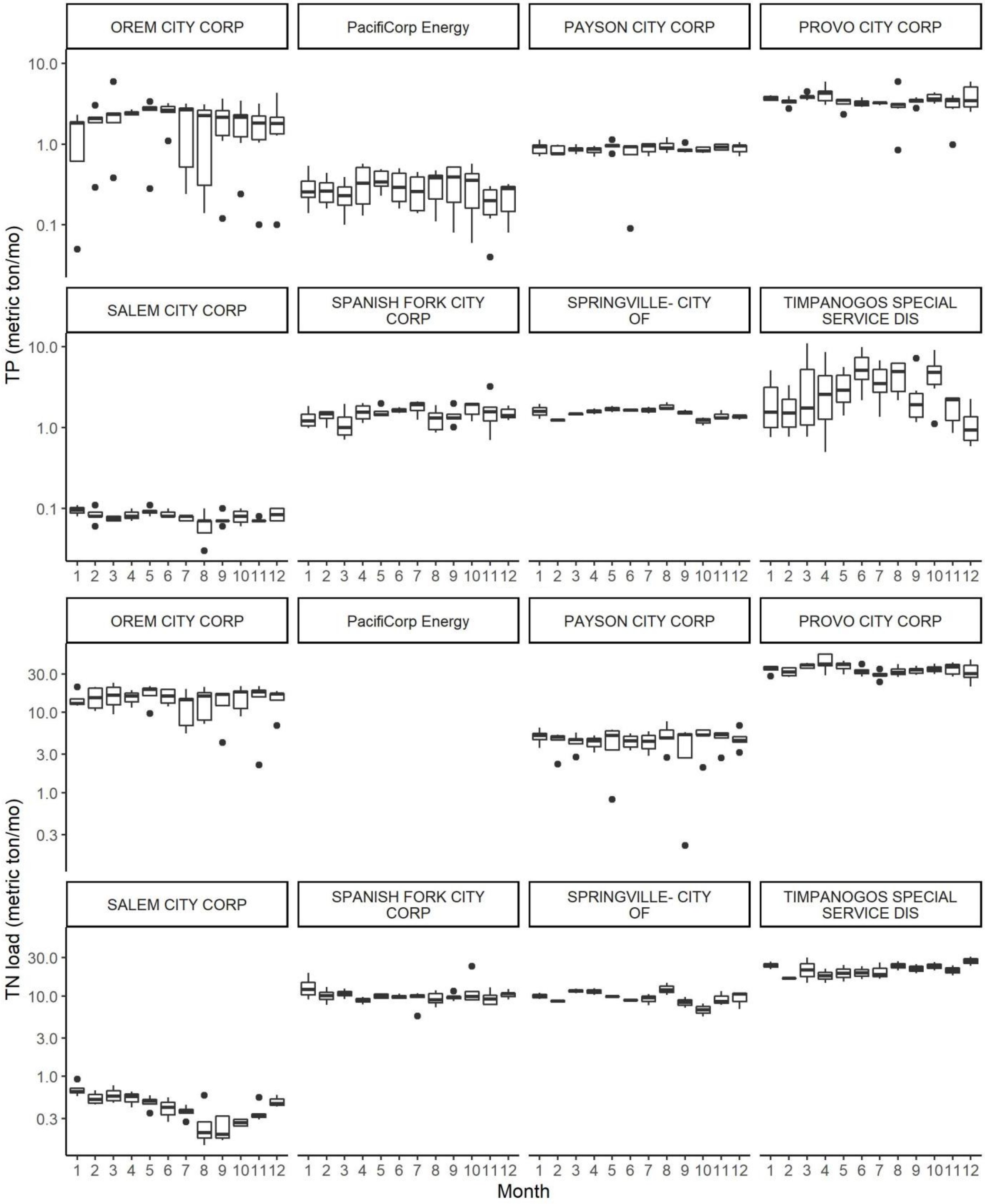

OREM CITY CORP
PacifiCorp Energy
PAYSON CITY CORP
PROVO CITY CORP
SALEM CITY CORP
SPANISH FORK CITY CORP
SPRINGVILLE- CITY OF
TIMPANOGOS SPECIAL SERVICE DIS
Nitrate (mg/L)
10.0
1.0
0.1
2016
2018
2020


OREM CITY CORP
PacifiCorp Energy
PAYSON CITY CORP
PROVO CITY CORP
SALEM CITY CORP
SPANISH FORK CITY CORP
SPRINGVILLE- CITY OF
TIMPANOGOS SPECIAL SERVICE DIS
Nitrate (mg/L)
10.0
1.0
0.1
1 2 3 4 5 6 7 8 9 10 11 12
Month

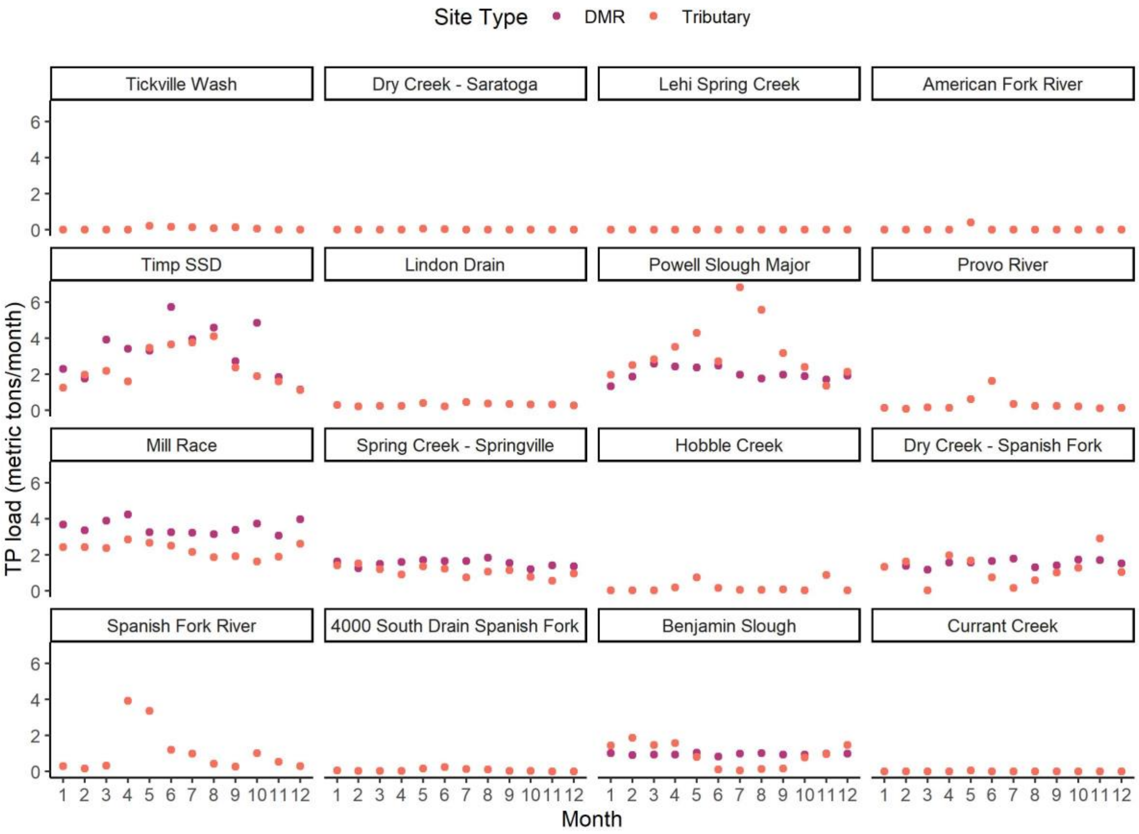

OREM CITY CORP
PacifiCorp Energy
PAYSON CITY CORP
PROVO CITY CORP
SALEM CITY CORP
SPANISH FORK CITY CORP
SPRINGVILLE- CITY OF
TIMPANOGOS SPECIAL SERVICE DIS
Flow (ac*ft/mo)
Flow (MGD)
0
500
1000
1500
2000
0
5
10
15
20
2016
2018
2020

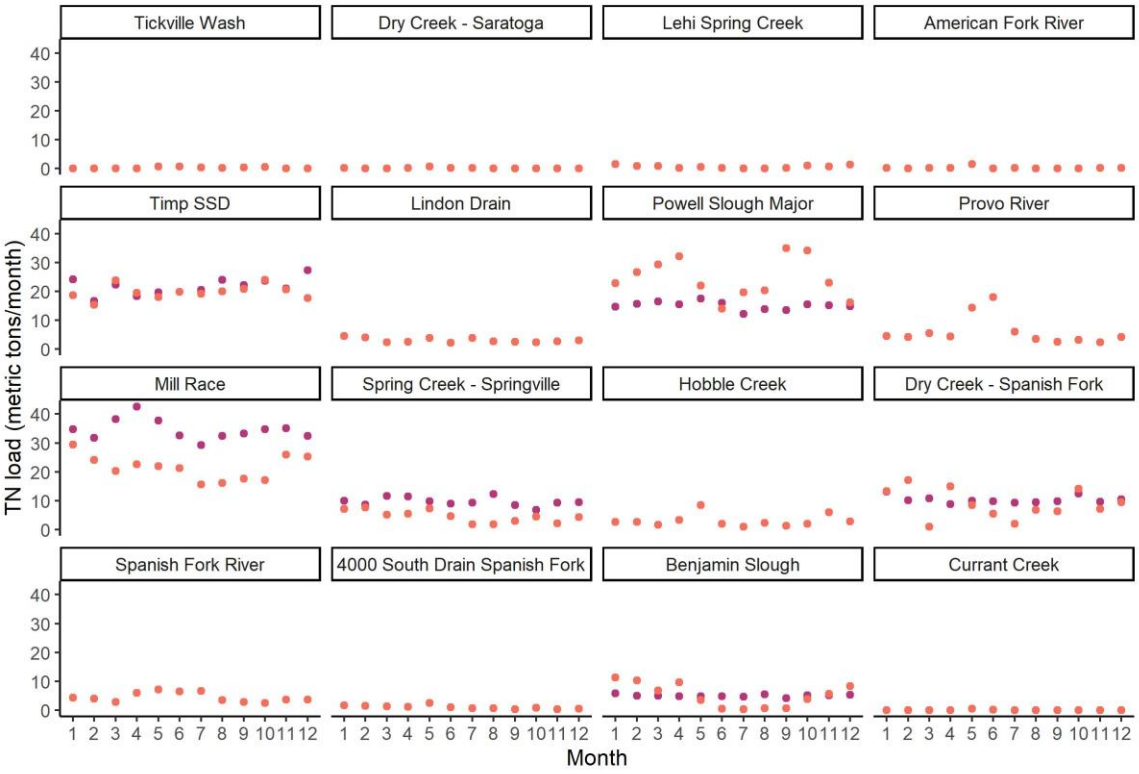

OREM CITY CORP
PacifiCorp Energy
PAYSON CITY CORP
PROVO CITY CORP
SALEM CITY CORP
SPANISH FORK CITY CORP
SPRINGVILLE- CITY OF
TIMPANOGOS SPECIAL SERVICE DIS
Flow (ac*ft/mo)
Flow (MGD)
0
500
1000
1500
2000
0
5
10
15
20
1 2 3 4 5 6 7 8 9 10 11 12
Month

10.4 MONTHLY DMR LOAD

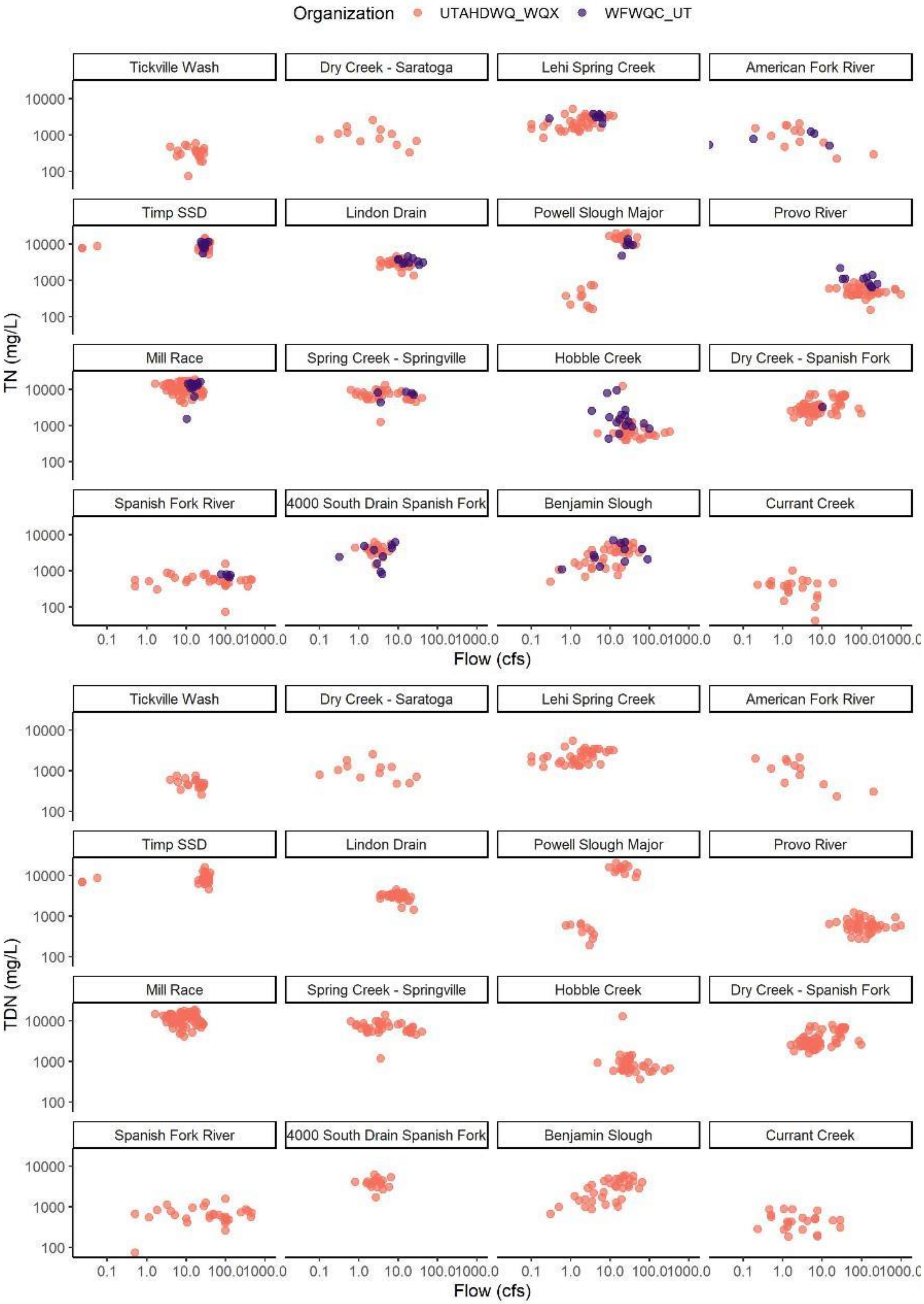


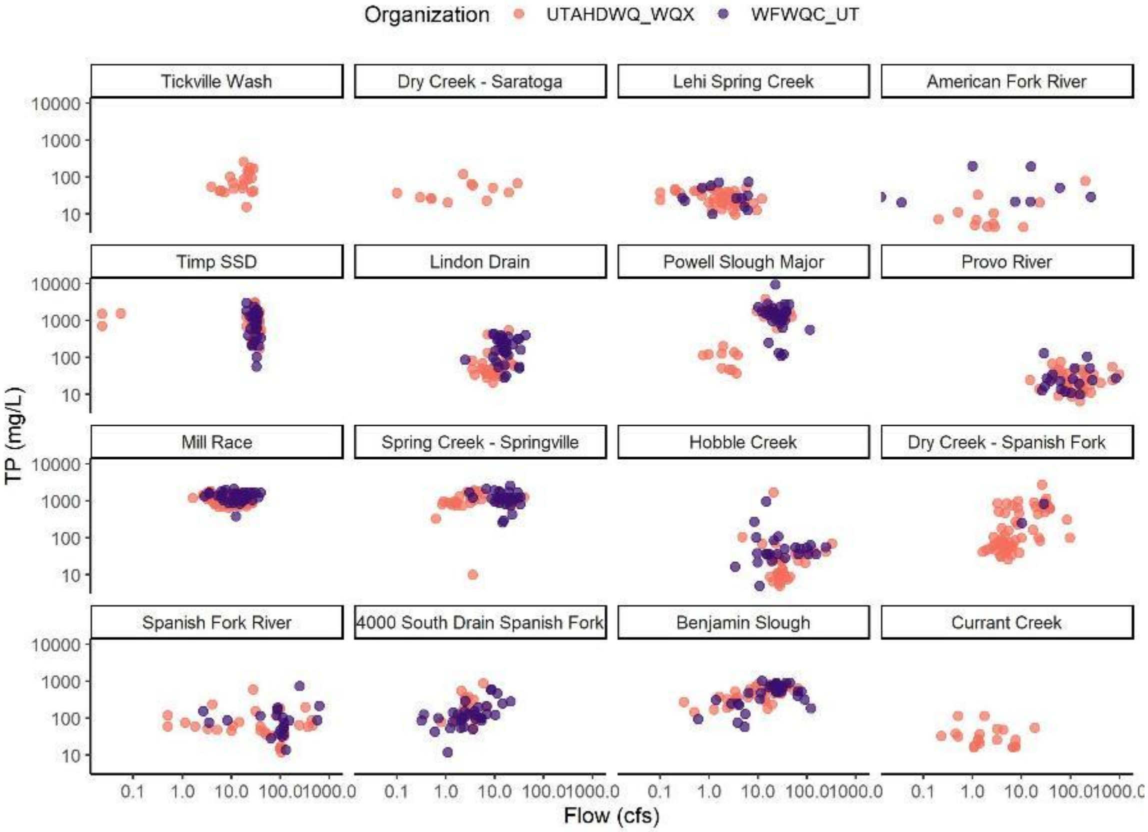
10.5 DMR AND TRIBUTARY LOAD COMPARISONS

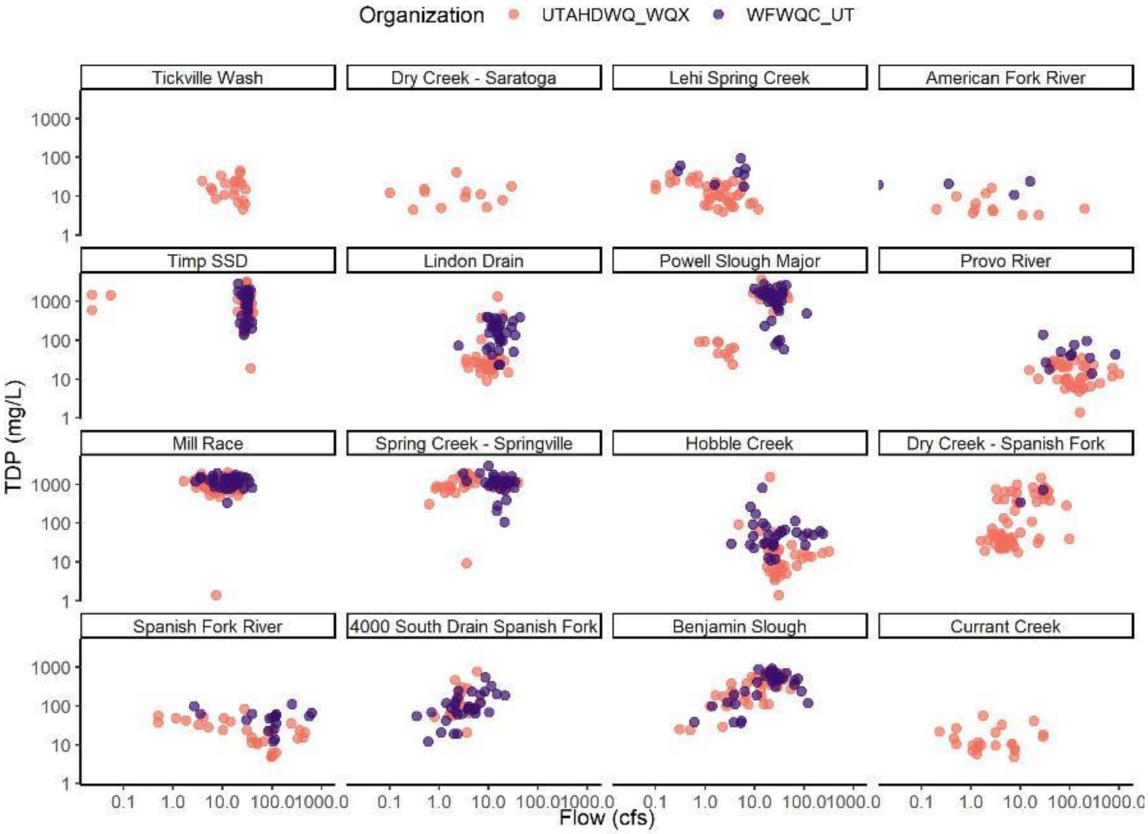


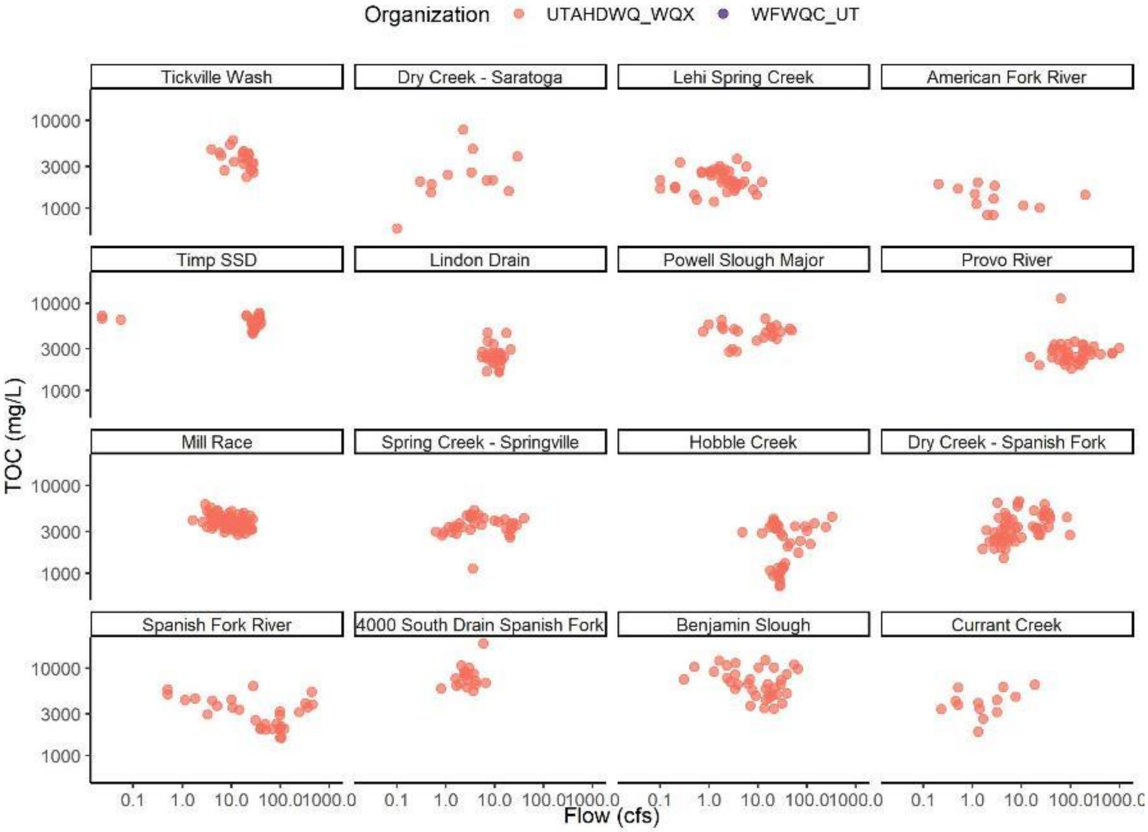


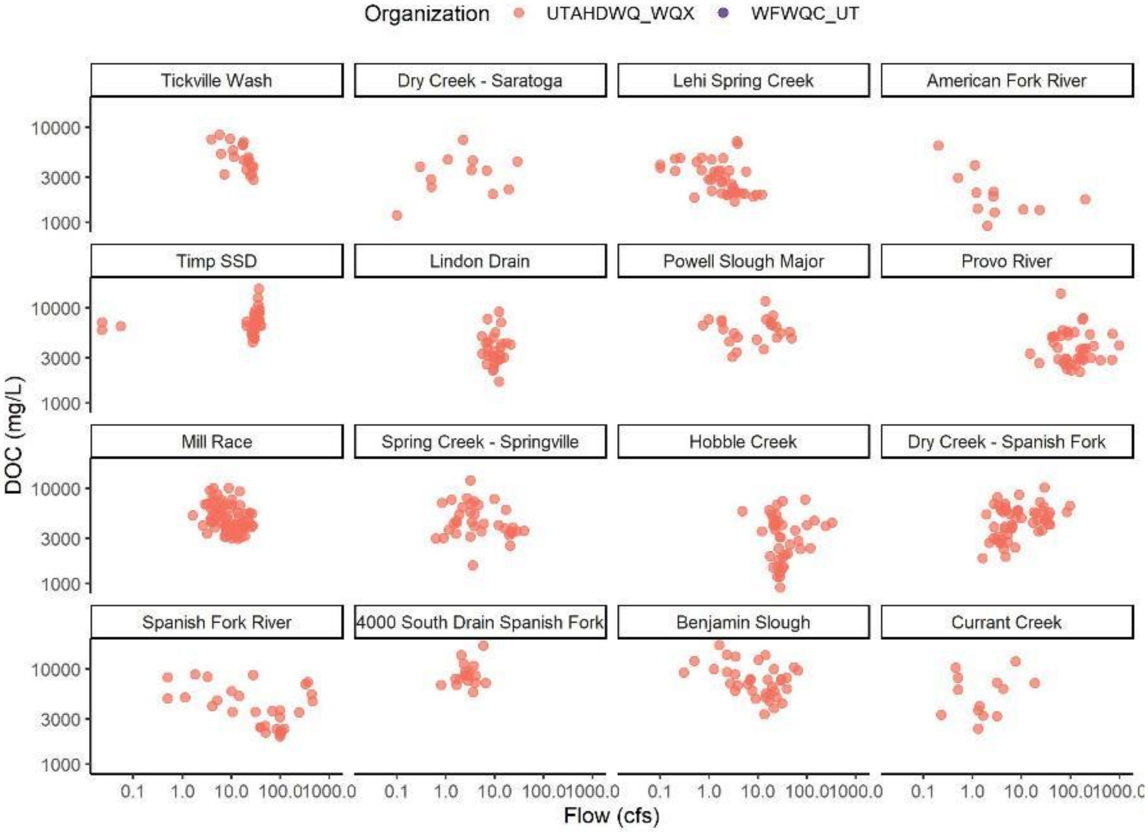
10.6 CONCENTRATION-FLOW RELATIONSHIPS




Organization
UTAHDWQ_WQX
WFWQC_UT
Tickville Wash
Dry Creek - Saratoga
Lehi Spring Creek
American Fork River
Timp SSD
Lindon Drain
Powell Slough Major
Provo River
Mill Race
Spring Creek - Springville
Hobble Creek
Dry Creek - Spanish Fork
Spanish Fork River
4000 South Drain Spanish Fork
Benjamin Slough
Currant Creek
TP (mg/L)
10000
1000
100
10
0.1
1.0
10.0
100.0
1000.0
Flow (cfs)

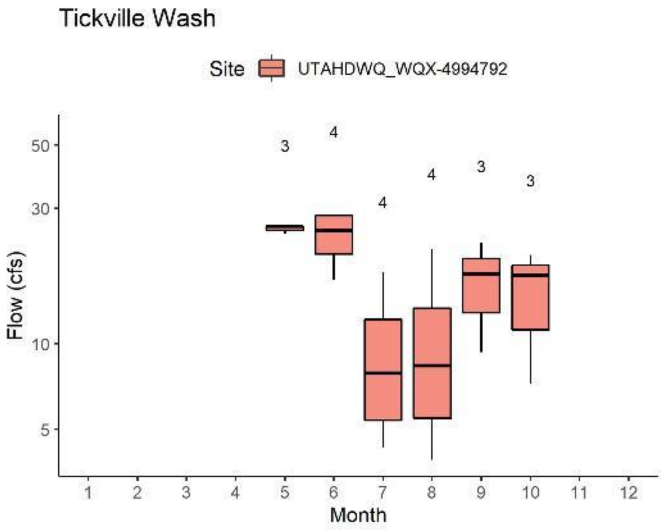

Organization
UTAHDWQ_WQX
WFWQC_UT
Tickville Wash
Dry Creek - Saratoga
Lehi Spring Creek
American Fork River
Timp SSD
Lindon Drain
Powell Slough Major
Provo River
Mill Race
Spring Creek - Springville
Hobble Creek
Dry Creek - Spanish Fork
Spanish Fork River
4000 South Drain Spanish Fork
Benjamin Slough
Currant Creek
TDP (mg/L)
1000
100
10
1
0.1
1.0
10.0
100.0
1000.0
Flow (cfs)

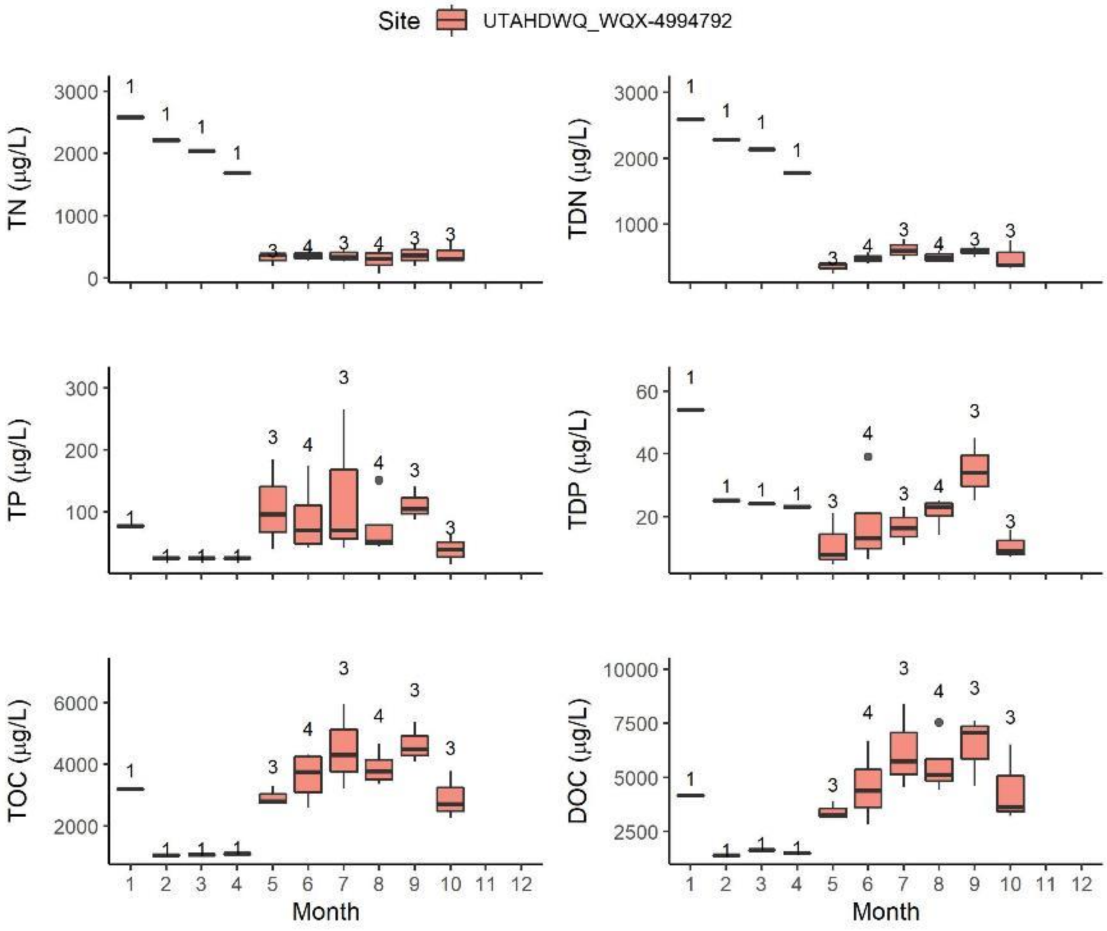

Organization
● UTAHDWQ_WQX
● WFWQC_UT
Tickville Wash
Dry Creek - Saratoga
Lehi Spring Creek
American Fork River
Timp SSD
Lindon Drain
Powell Slough Major
Provo River
Mill Race
Spring Creek - Springville
Hobble Creek
Dry Creek - Spanish Fork
Spanish Fork River
4000 South Drain Spanish Fork
Benjamin Slough
Currant Creek
TOC (mg/L)
10000
3000
1000
0.1
1.0
10.0
100.0
1000.0
Flow (cfs)

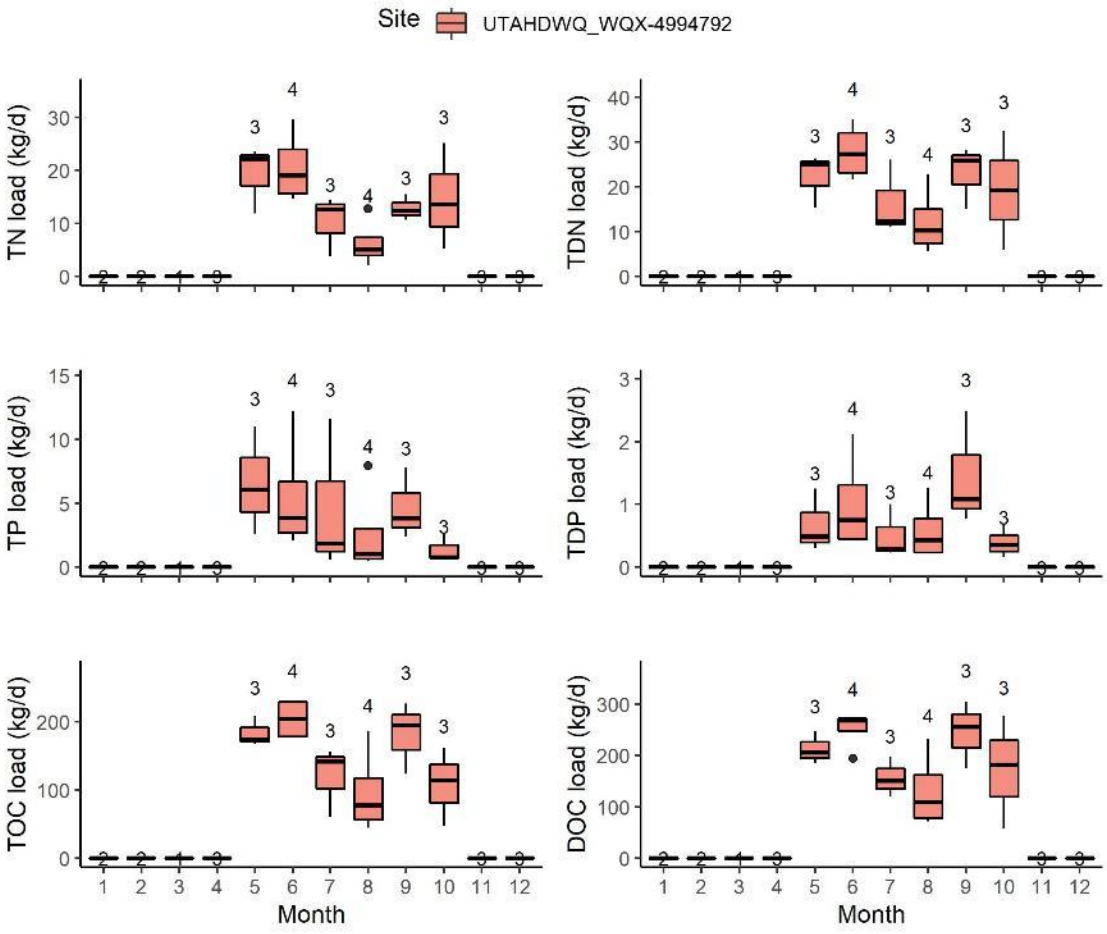

Organization
● UTAHDWQ_WQX
● WFWQC_UT
Tickville Wash
Dry Creek - Saratoga
Lehi Spring Creek
American Fork River
Timp SSD
Lindon Drain
Powell Slough Major
Provo River
Mill Race
Spring Creek - Springville
Hobble Creek
Dry Creek - Spanish Fork
Spanish Fork River
4000 South Drain Spanish Fork
Benjamin Slough
Currant Creek
DOC (mg/L)
10000
3000
1000
0.1
1.0
10.0
100.0
1000.0
Flow (cfs)

10.7 INVIDUAL SUB-CATCHMENTS

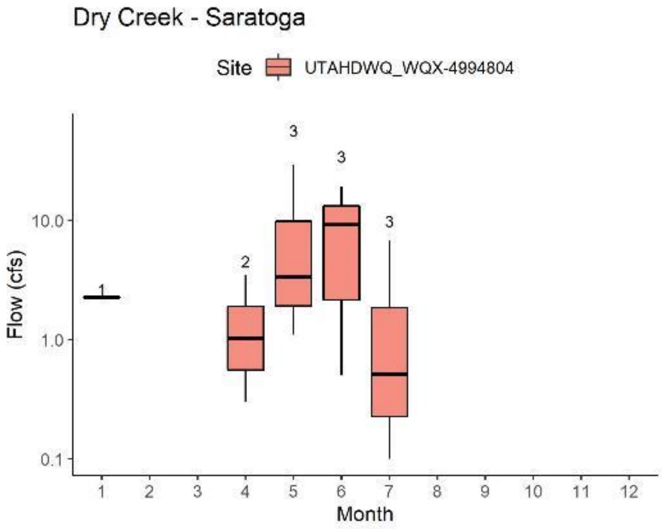
10.7.1 Tickville Wash

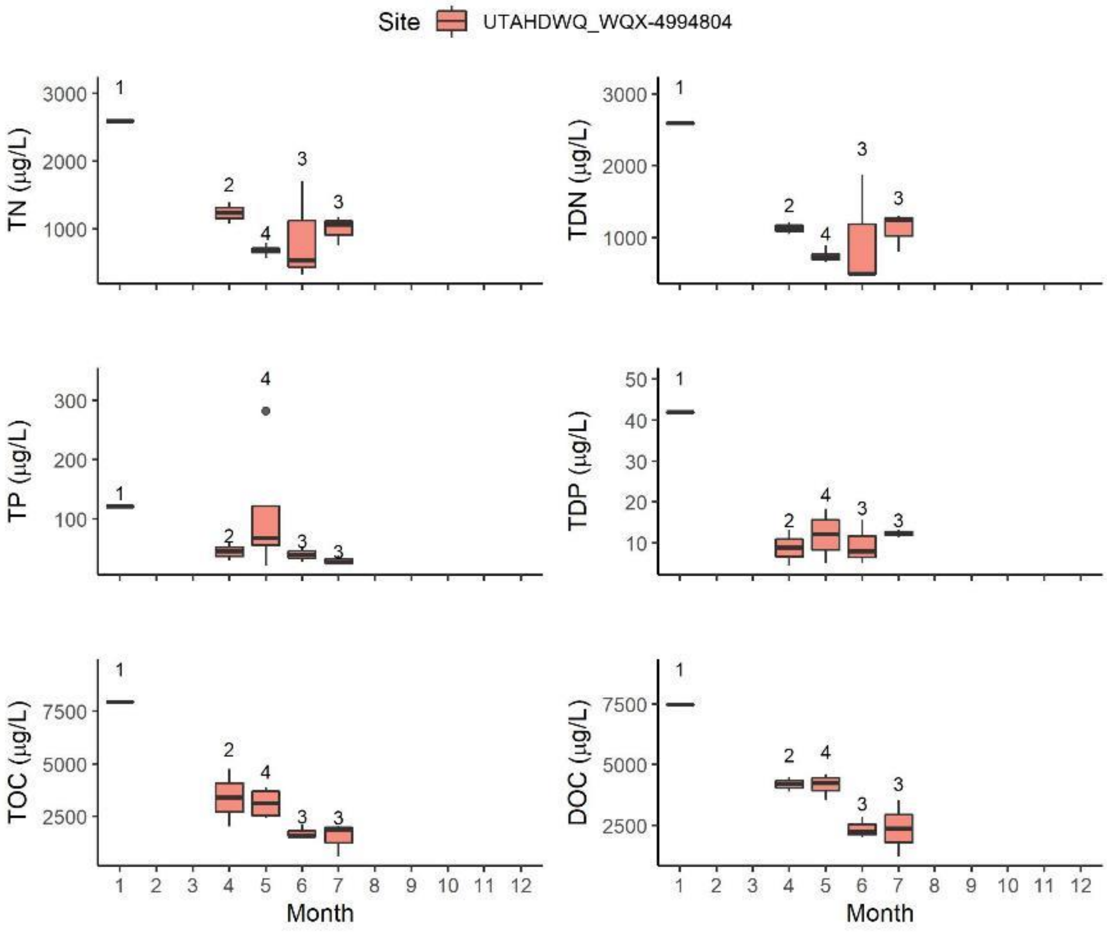


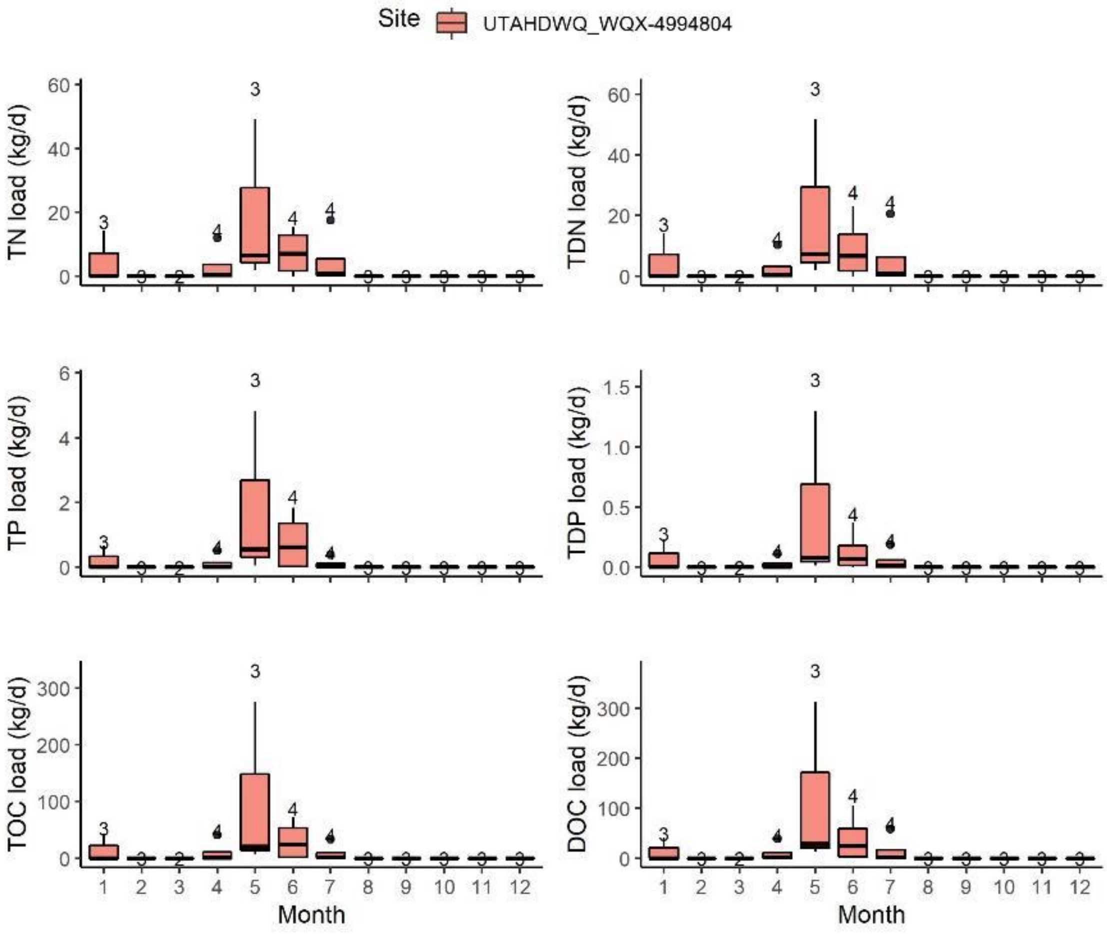



Site
UTAHDWQ_WQX-4994792
TN load (kg/d)
TDN load (kg/d)
TP load (kg/d)
TDP load (kg/d)
TOC load (kg/d)
DOC load (kg/d)
Month
Month
1
2
3
4
5
6
7
8
9
10
11
12

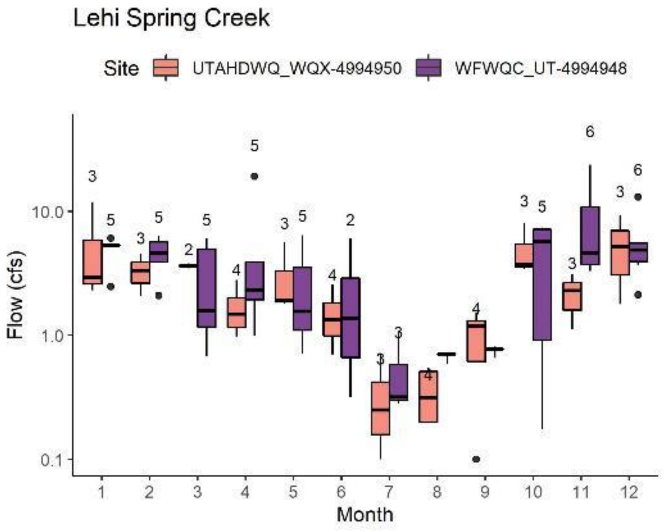
10.7.2 Dry Creek – Saratoga

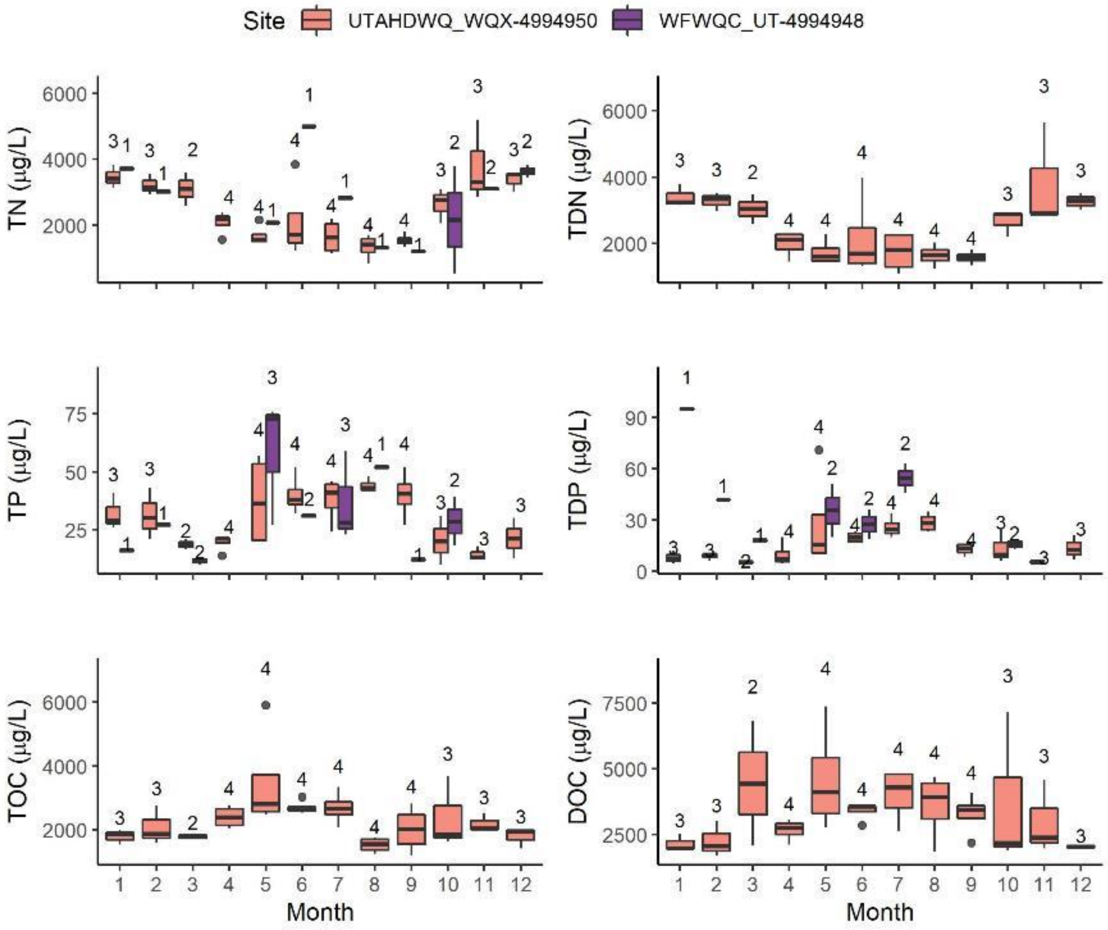


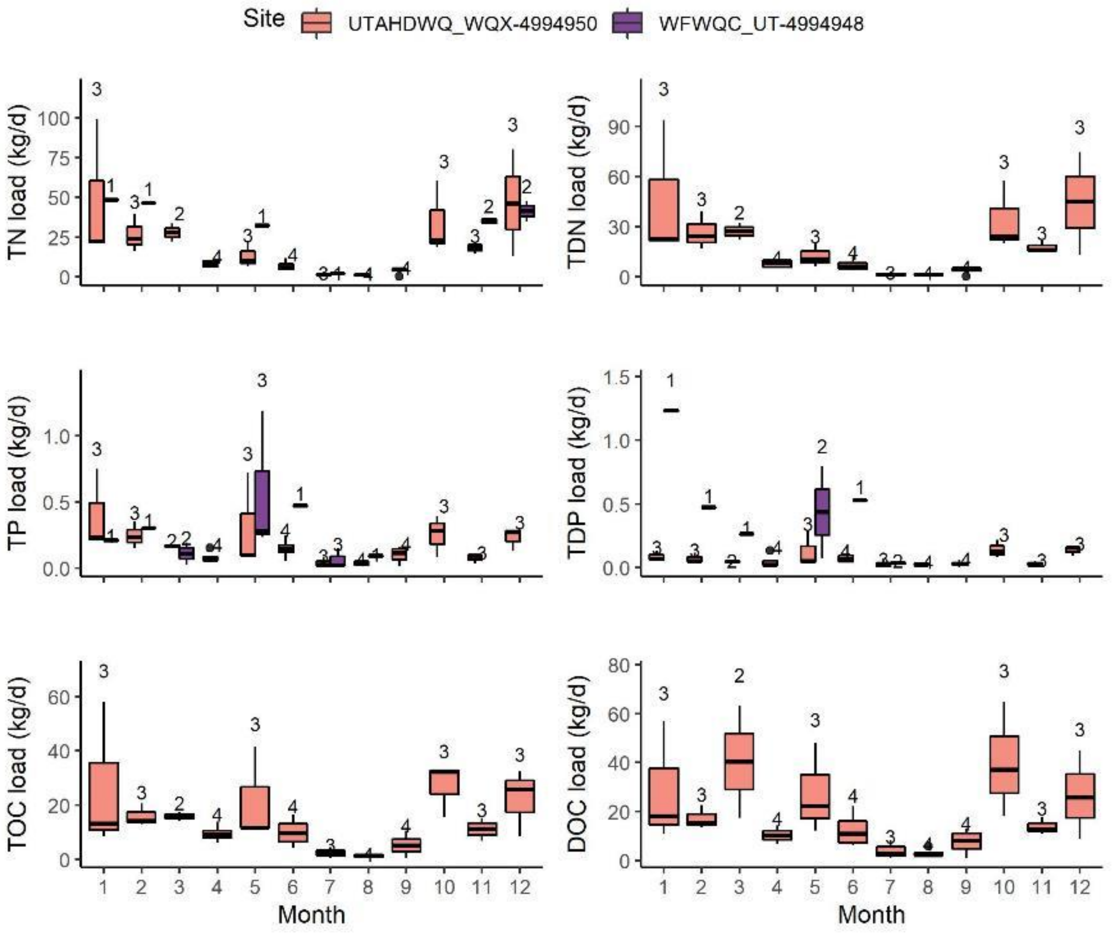



Site
UTAHDWQ_WQX-4994804
TN load (kg/d)
TDN load (kg/d)
TP load (kg/d)
TDP load (kg/d)
TOC load (kg/d)
DOC load (kg/d)
Month
Month
1
2
3
4
5
6
7
8
9
10
11
12

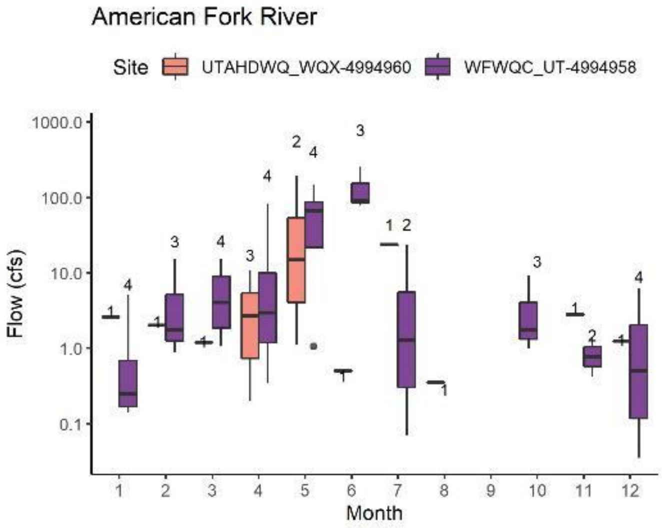
10.7.3 Lehi Spring Creek

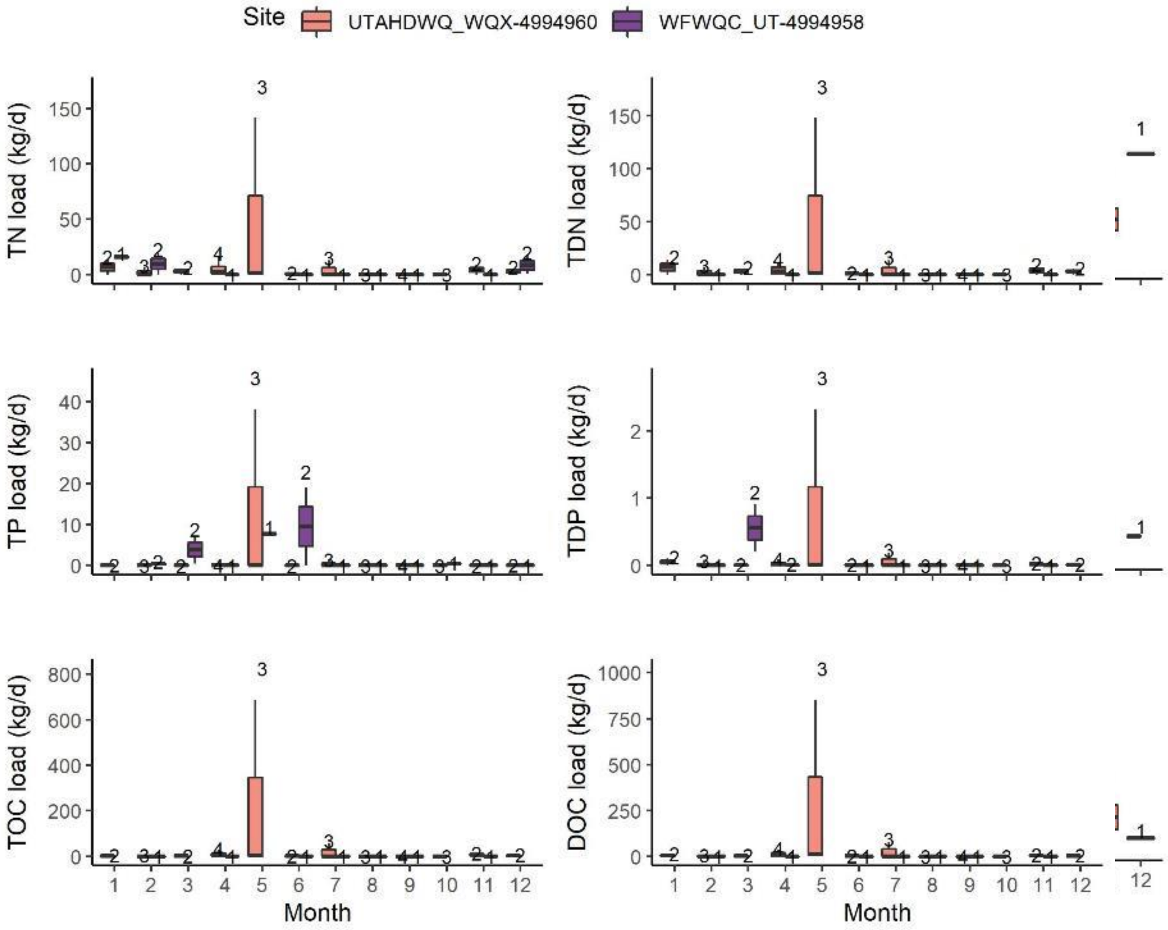


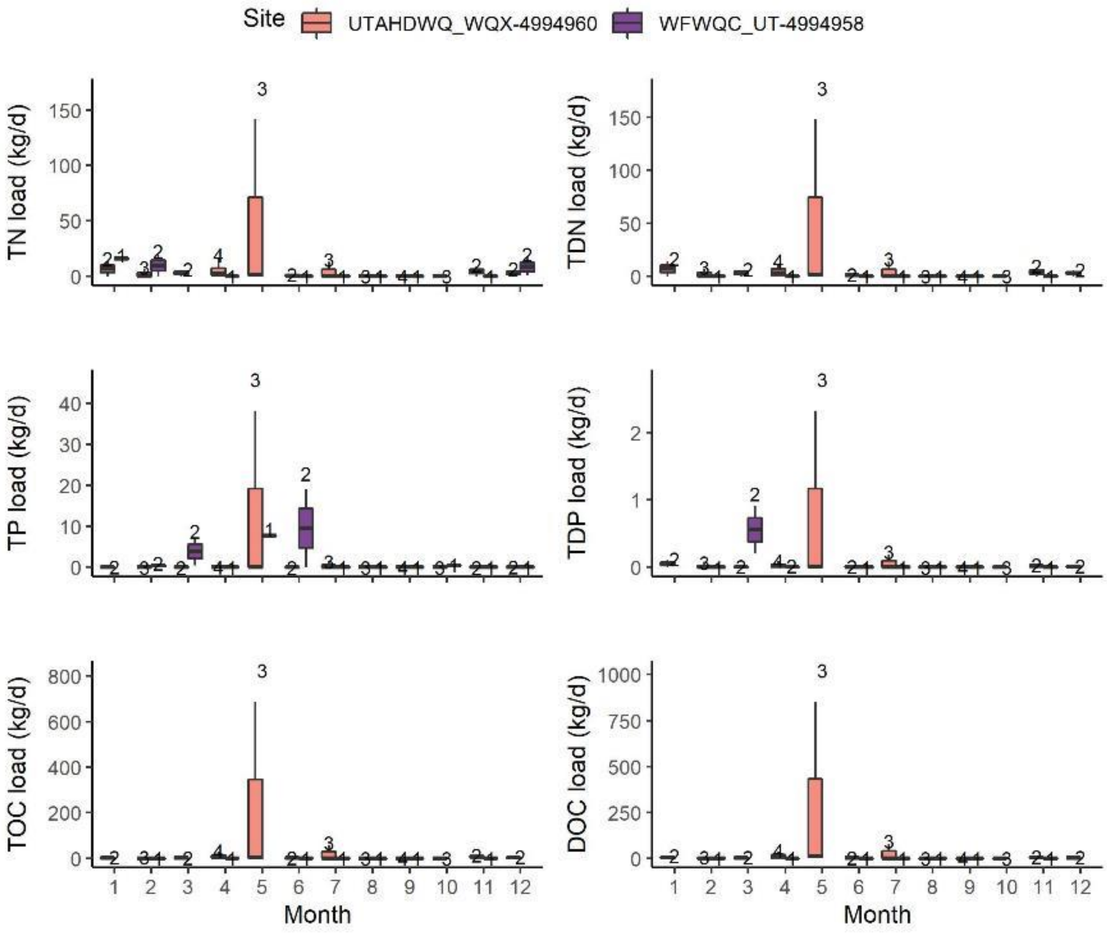



Site
UTAHDWQ_WQX-4994950
WFWQC_UT-4994948
TN load (kg/d)
0
25
50
75
100
TDN load (kg/d)
0
30
60
90
TP load (kg/d)
0.0
0.5
1.0
TDP load (kg/d)
0.0
0.5
1.0
1.5
TOC load (kg/d)
0
20
40
60
DOC load (kg/d)
0
20
40
60
80
1
2
3
4
5
6
7
8
9
10
11
12
Month
Month

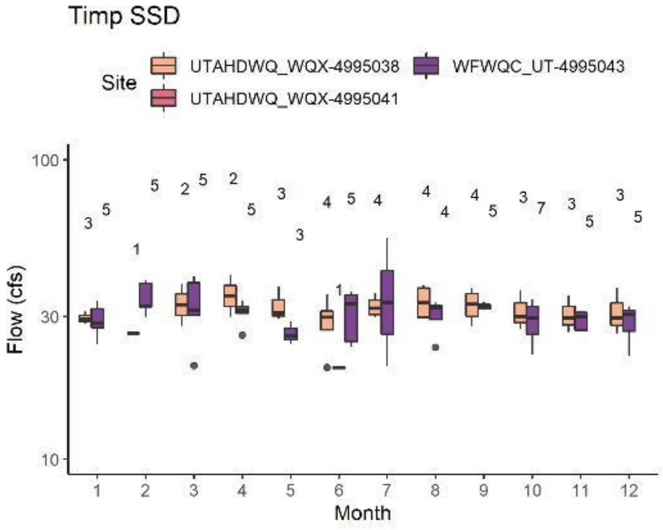
10.7.4 American Fork River

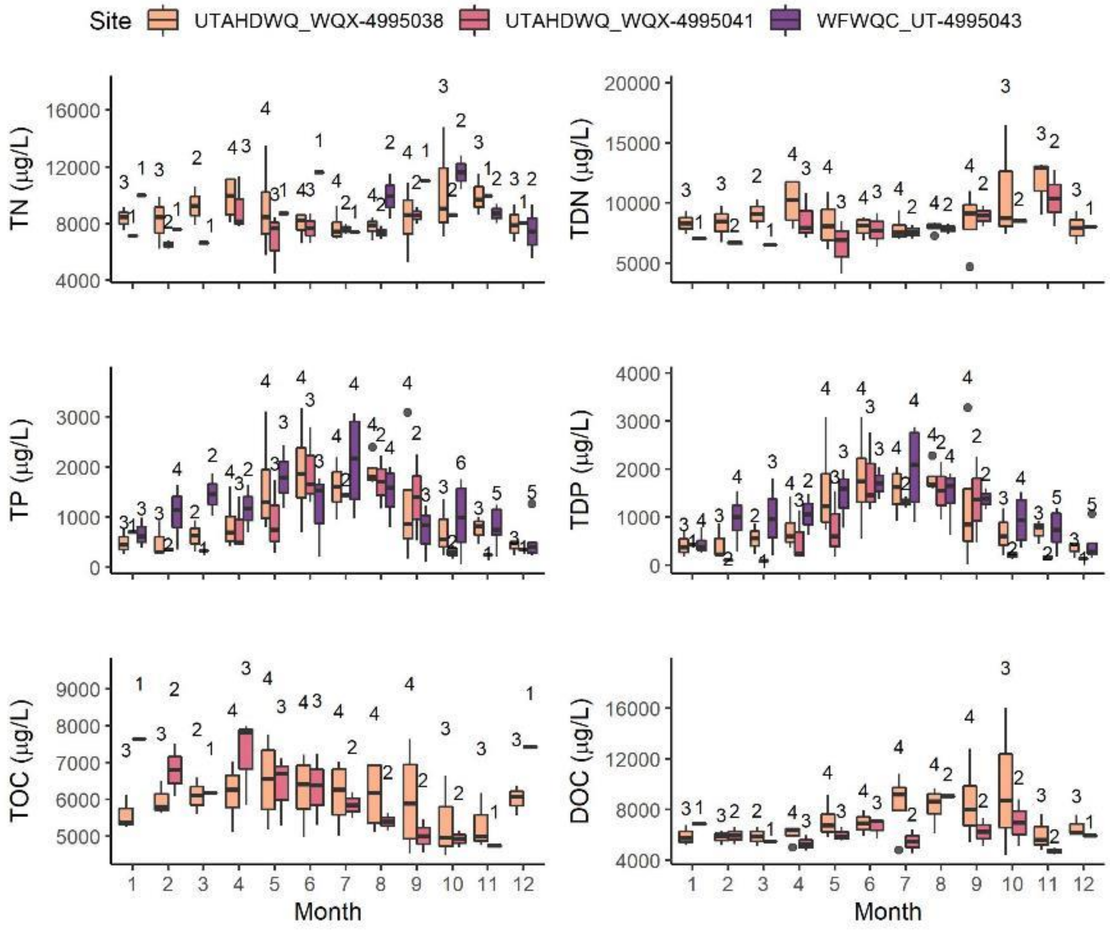


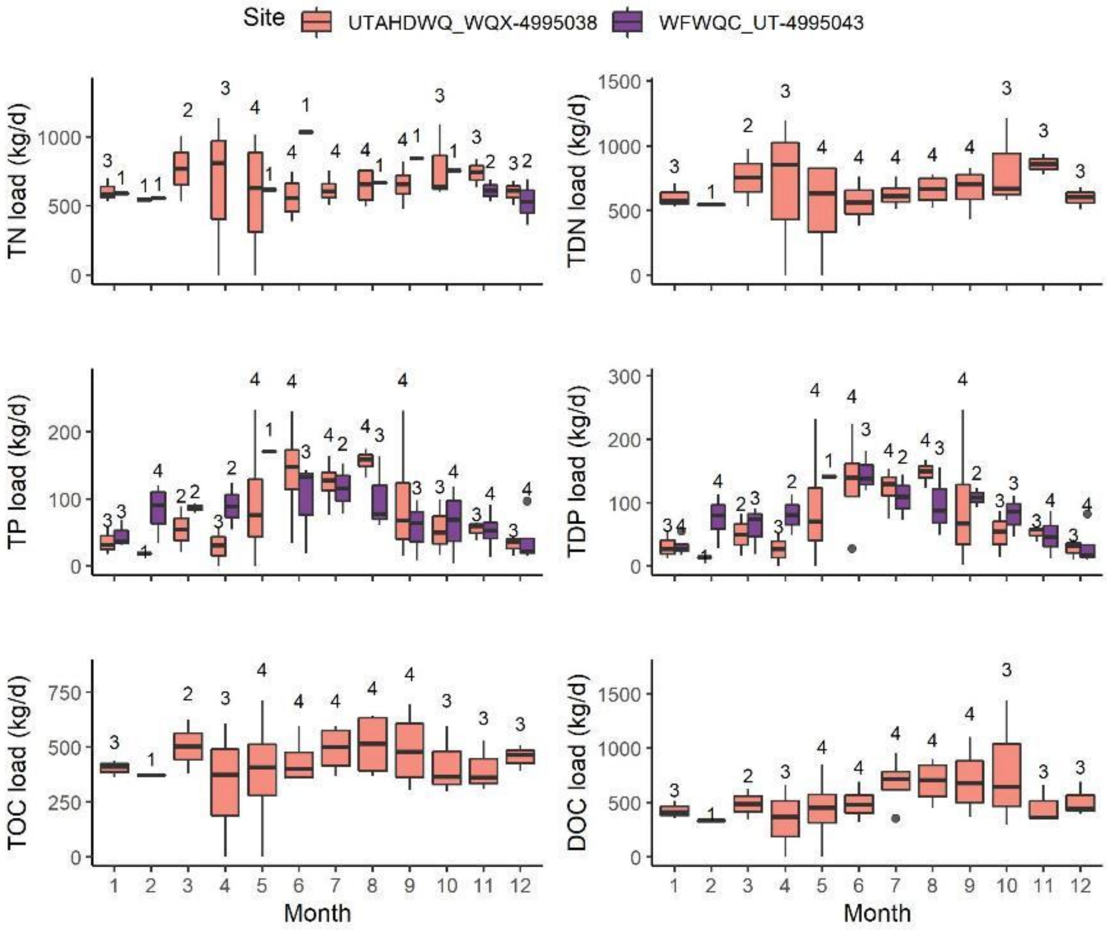



Site
UTAHDWQ_WQX-4994960
WFWQC_UT-4994958
TN load (kg/d)
0
50
100
150
TDN load (kg/d)
0
50
100
150
TP load (kg/d)
0
10
20
30
40
TDP load (kg/d)
0
1
2
TOC load (kg/d)
0
200
400
600
800
DOC load (kg/d)
0
250
500
750
1000
1 2 3 4 5 6 7 8 9 10 11 12
Month
1 2 3 4 5 6 7 8 9 10 11 12
Month

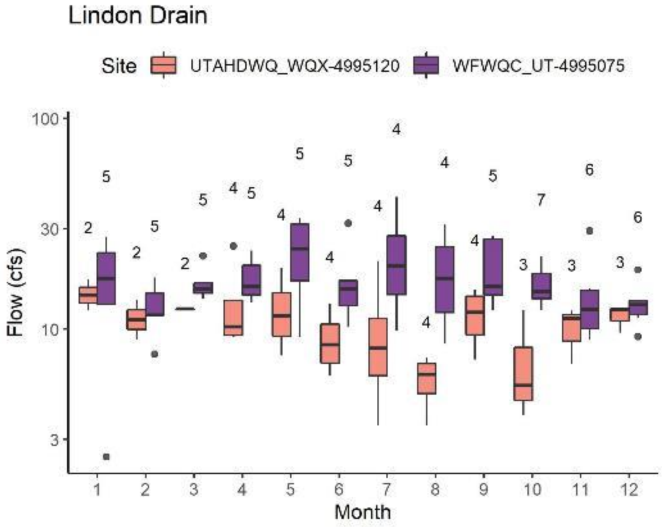
10.7.5 Timp SSD

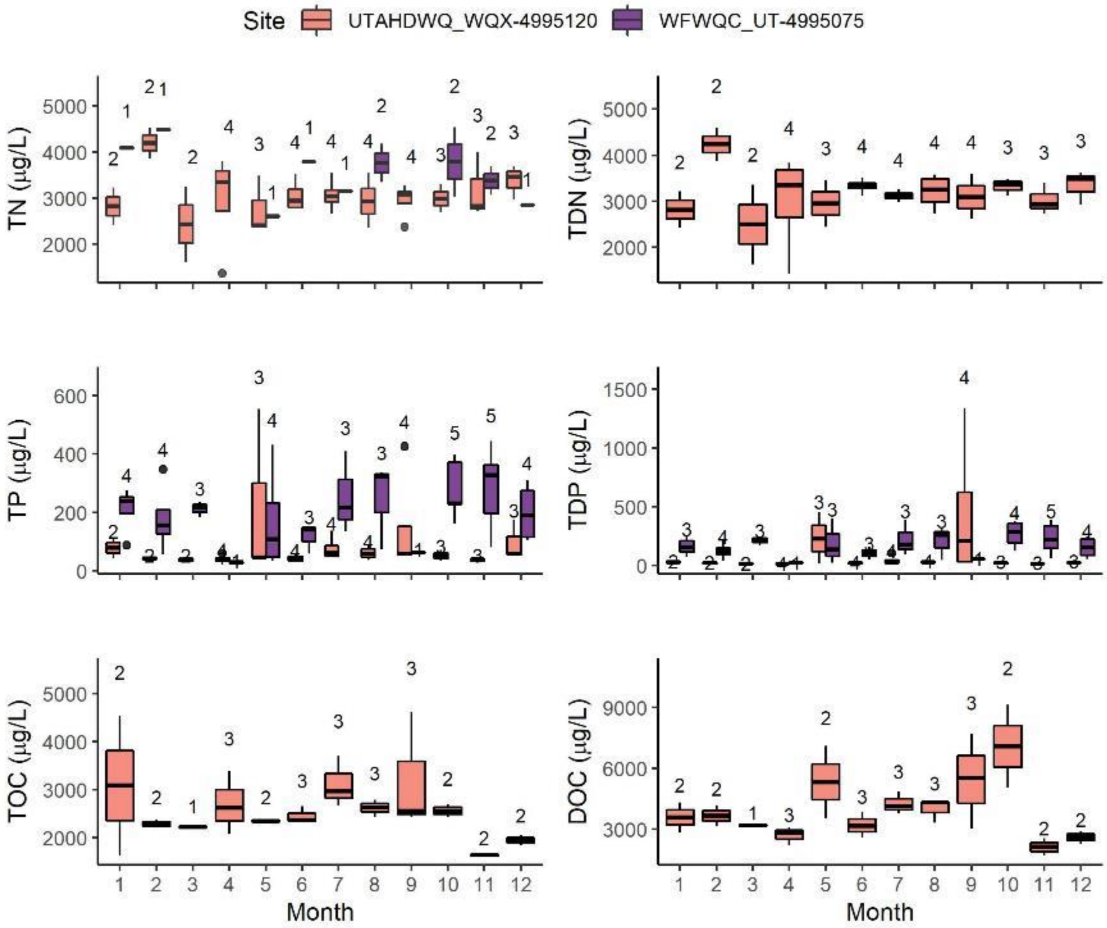


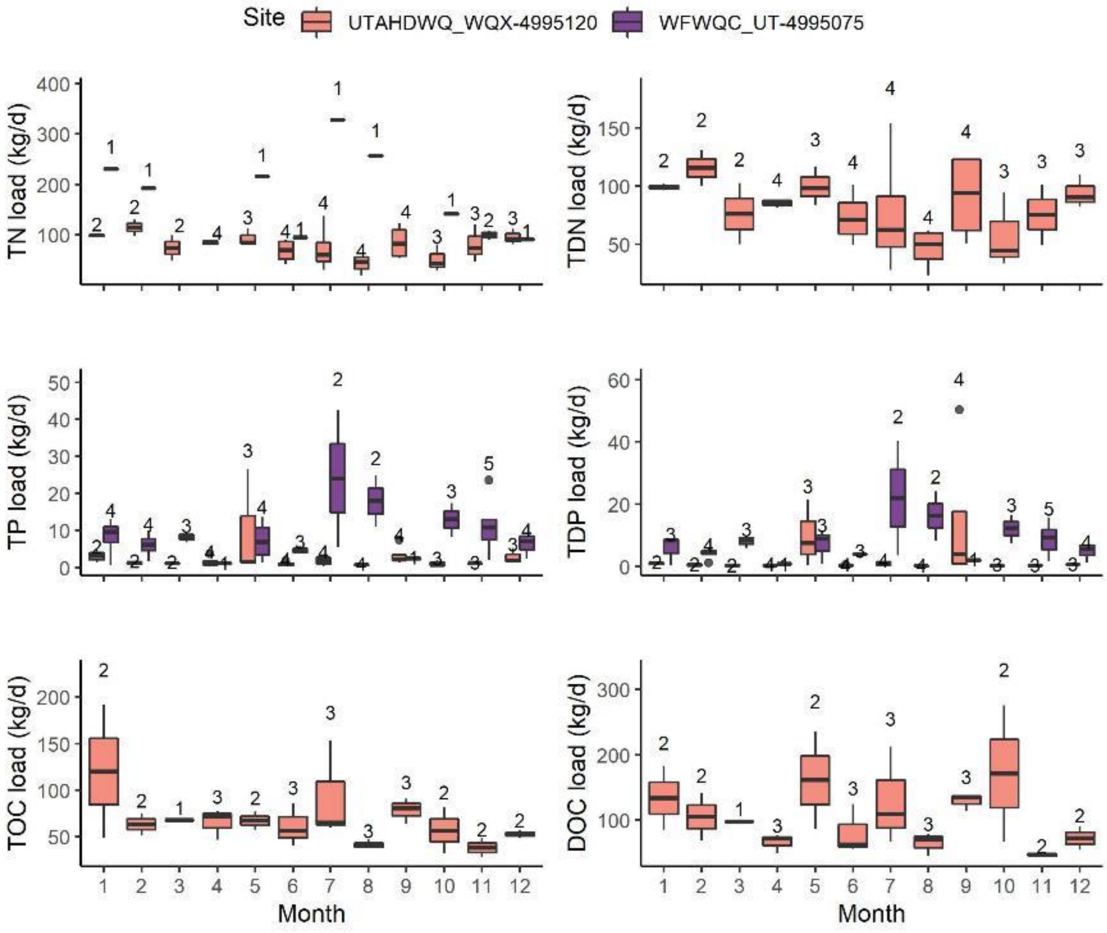



Site
UTAHDWQ_WQX-4995038
WFWQC_UT-4995043
TN load (kg/d)
TDN load (kg/d)
TP load (kg/d)
TDP load (kg/d)
TOC load (kg/d)
DOC load (kg/d)
0
500
1000
1500
100
200
300
250
750
1
2
3
4
5
6
7
8
9
10
11
12
Month
Month

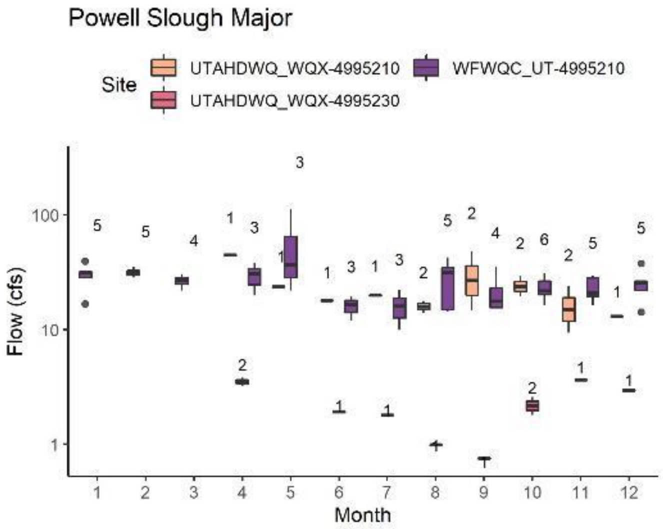
10.7.6 Lindon Drain

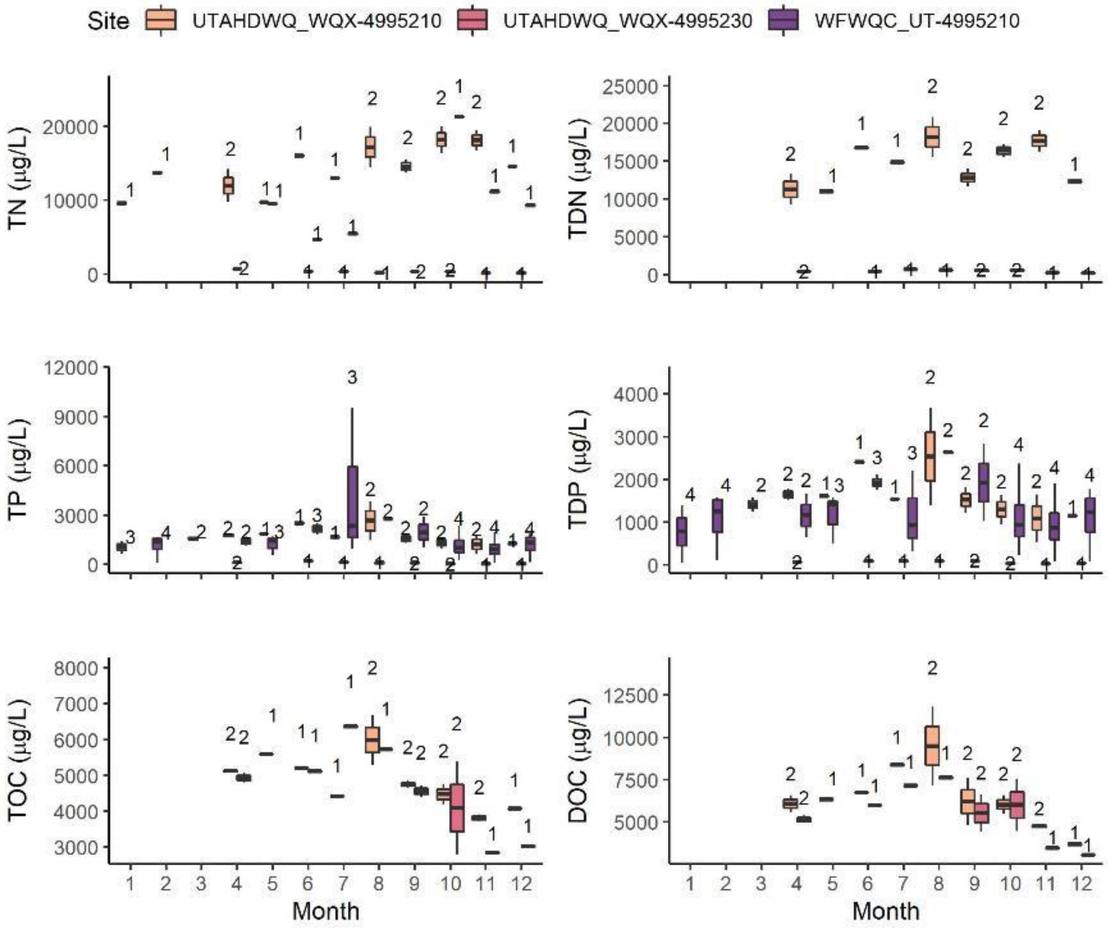


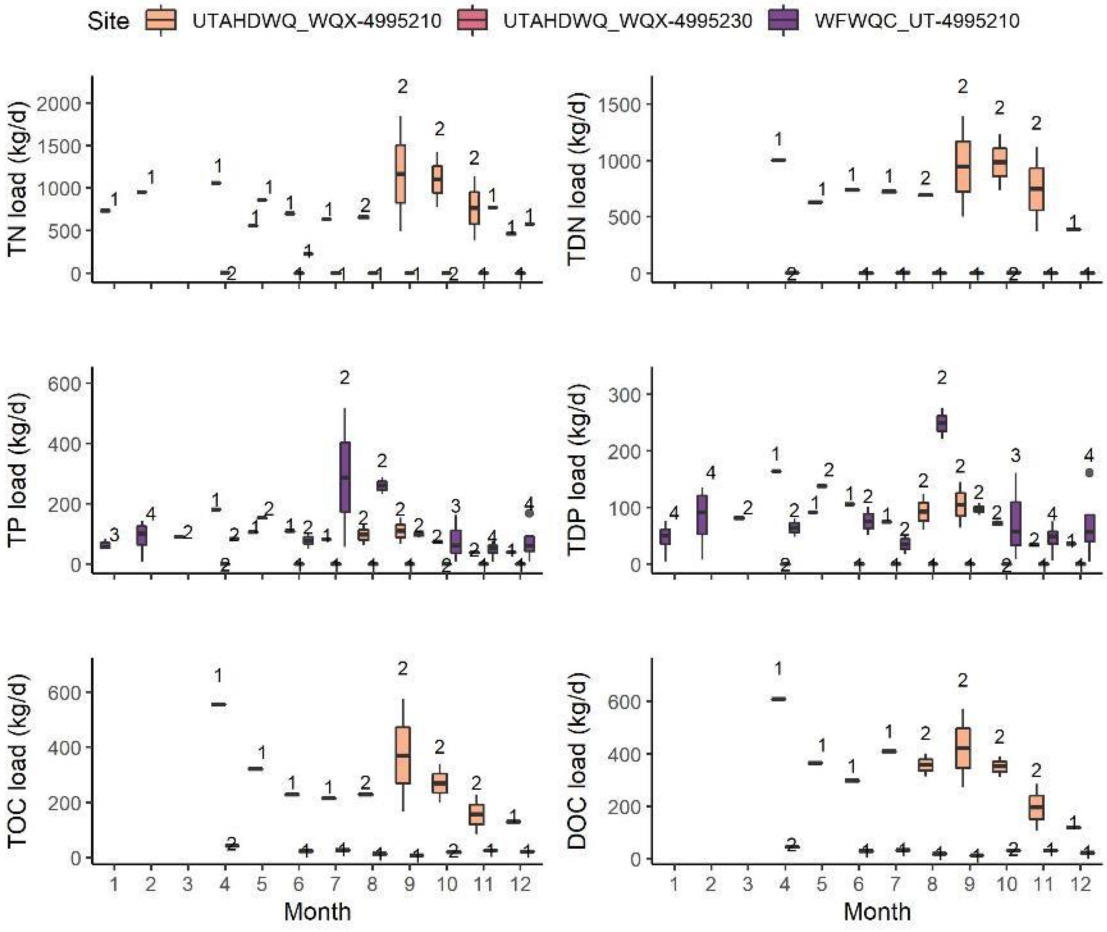



Site
UTAHDWQ_WQX-4995120
WFWQC_UT-4995075
TN load (kg/d)
TDN load (kg/d)
TP load (kg/d)
TDP load (kg/d)
TOC load (kg/d)
DOC load (kg/d)
Month
Month
1 2 3 4 5 6 7 8 9 10 11 12

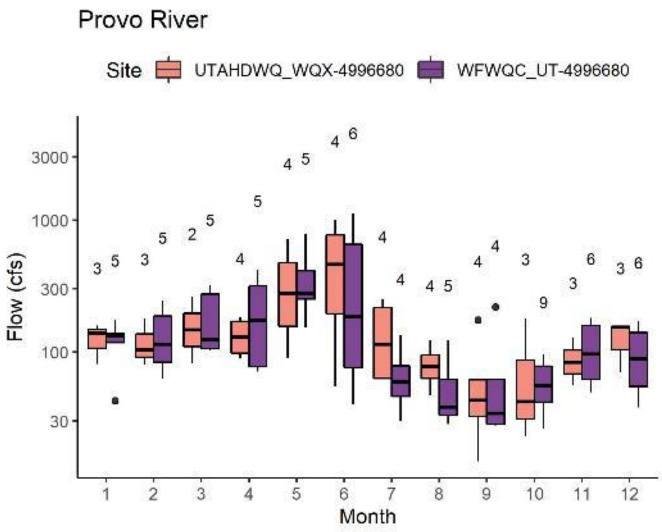
10.7.7 Powell Slough Major

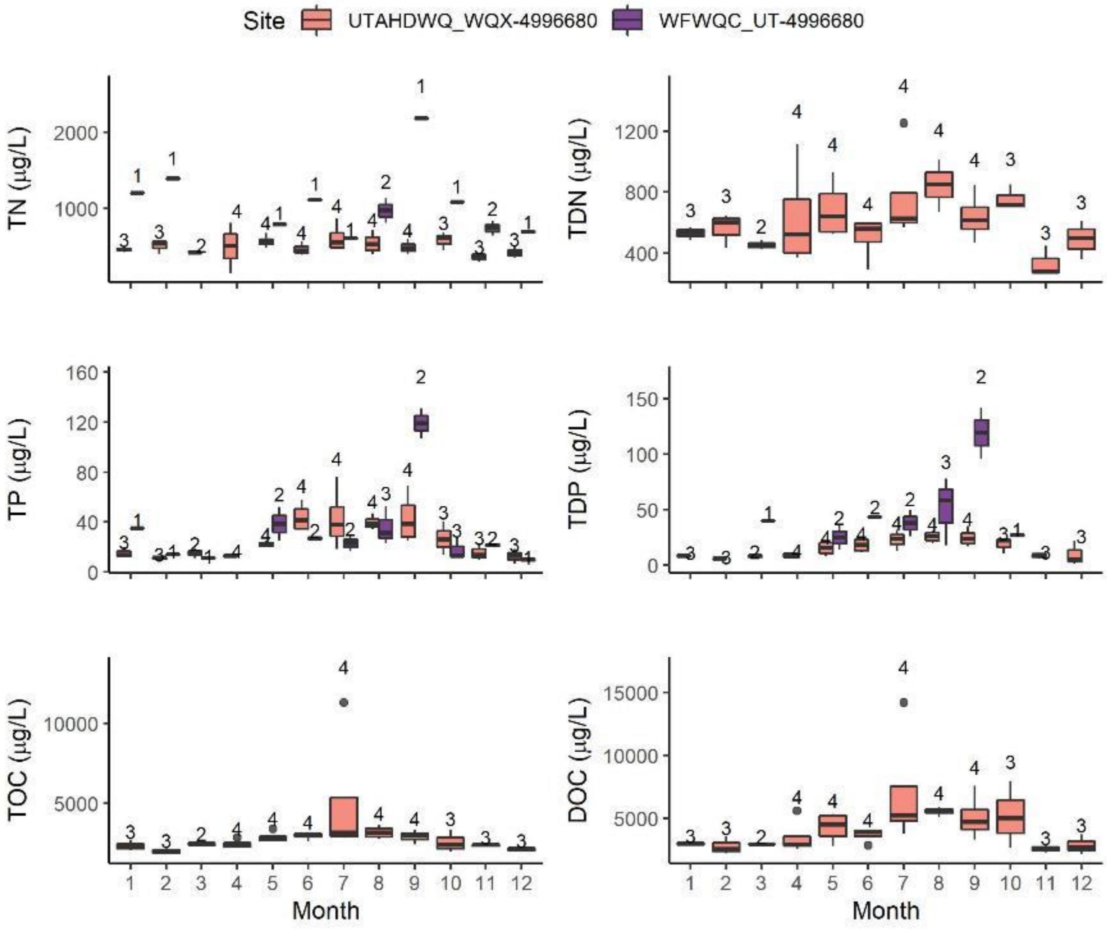


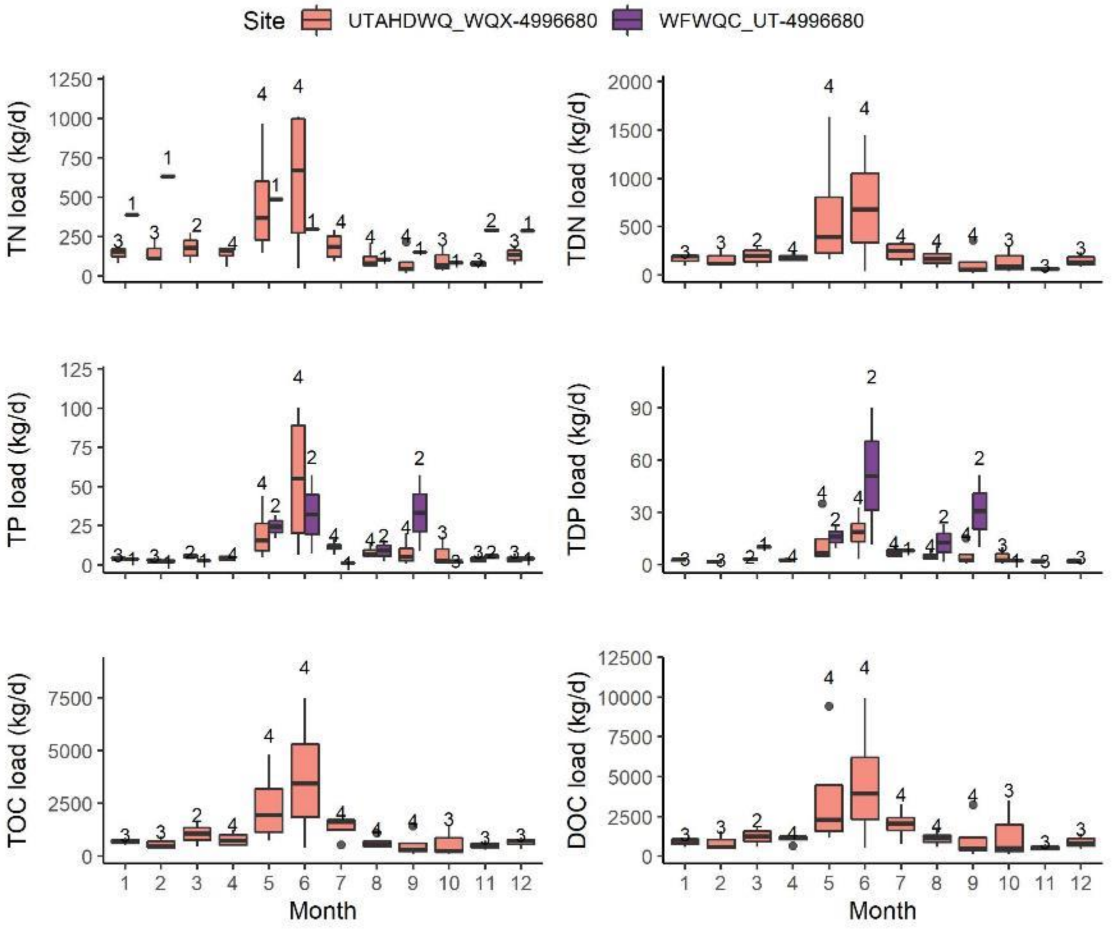



Site
UTAHDWQ_WQX-4995210
UTAHDWQ_WQX-4995230
WFWQC_UT-4995210
TN load (kg/d)
TDN load (kg/d)
TP load (kg/d)
TDP load (kg/d)
TOC load (kg/d)
DOC load (kg/d)
Month
1 2 3 4 5 6 7 8 9 10 11 12

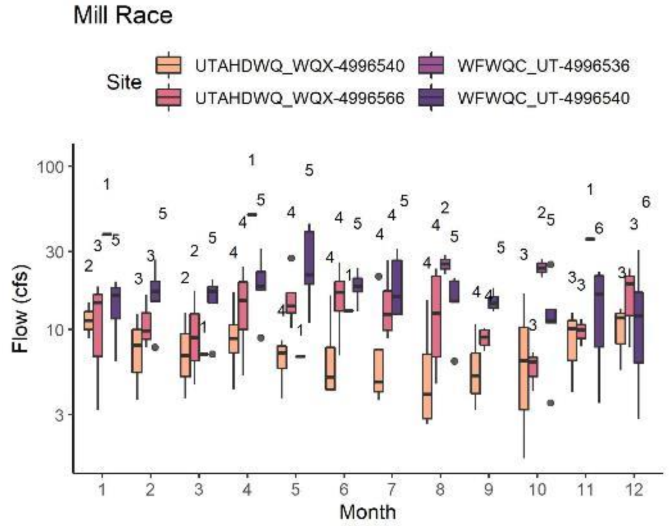
10.7.8 Provo River

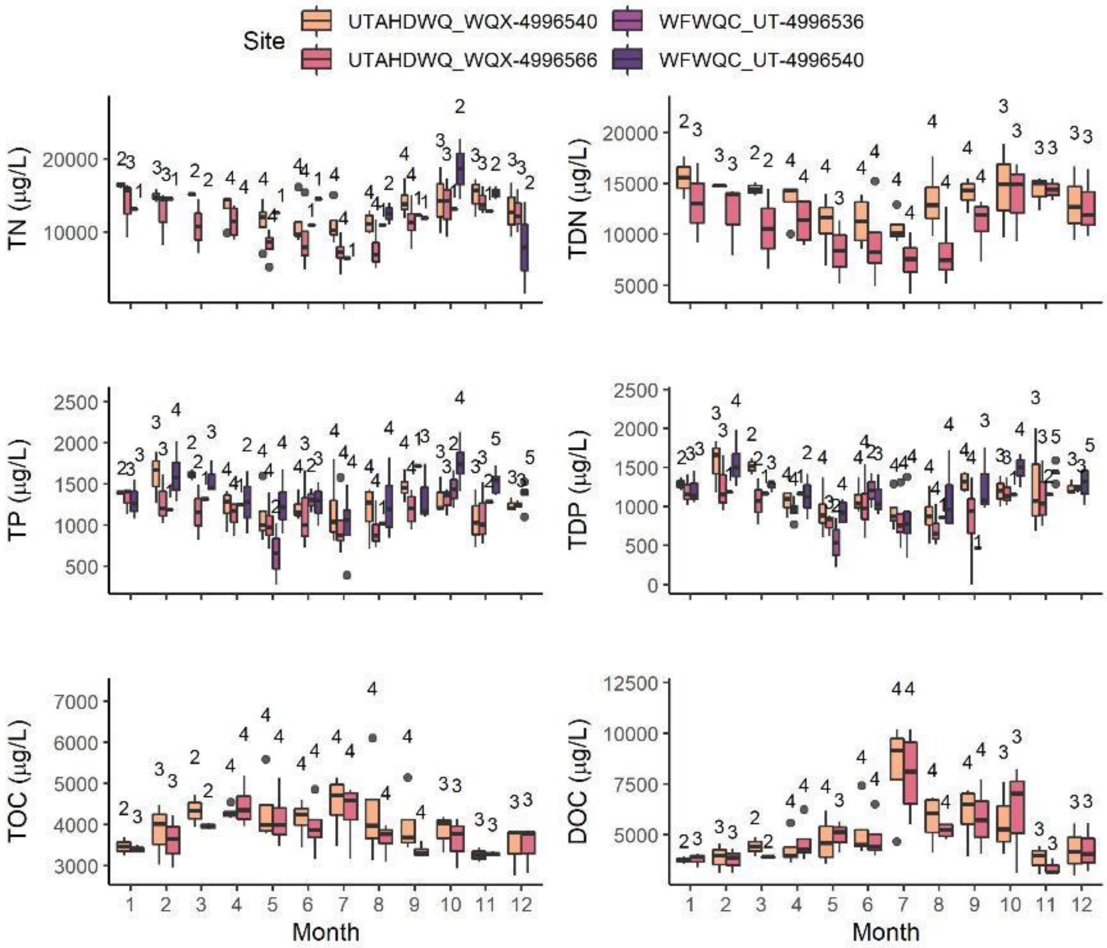


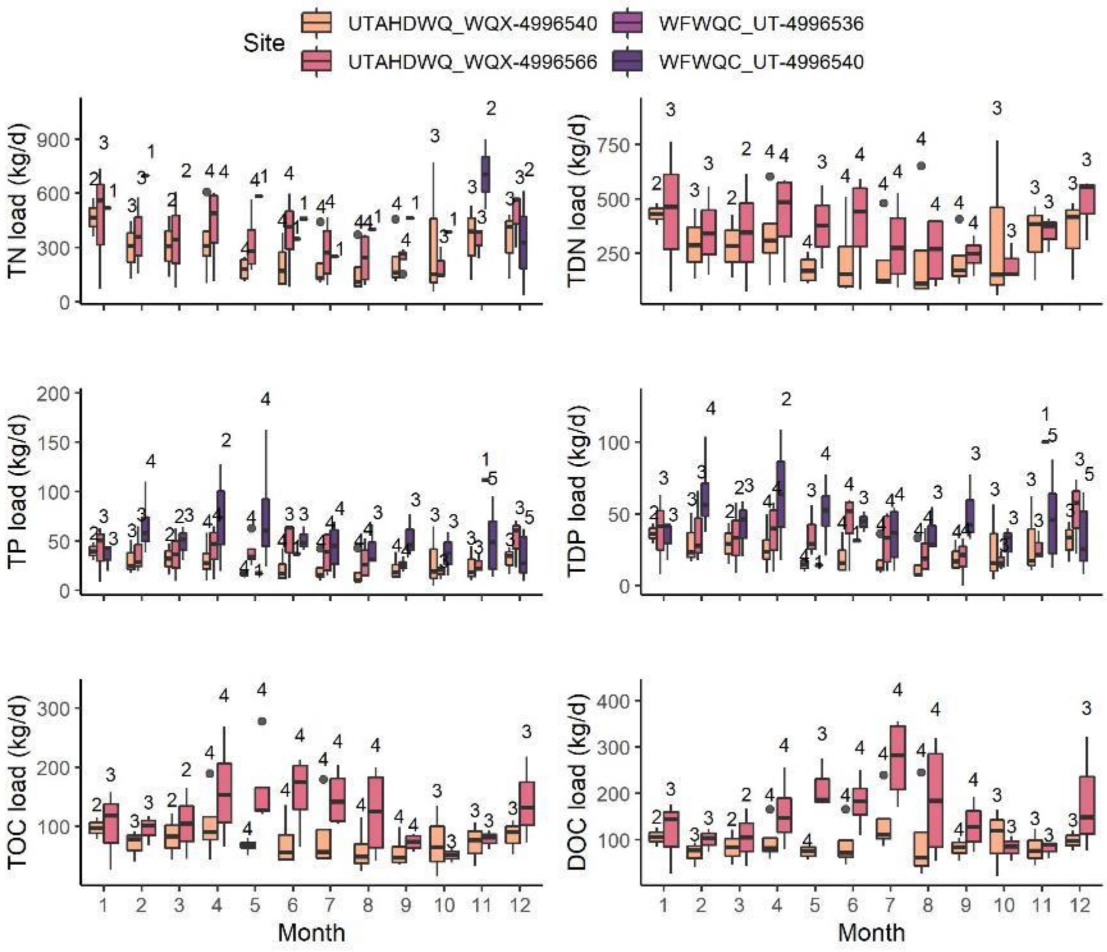



Site
UTAHDWQ_WQX-4996680
WFWQC_UT-4996680
TN load (kg/d)
0
250
500
750
1000
1250
TDN load (kg/d)
0
500
1000
1500
2000
TP load (kg/d)
0
25
50
75
100
125
TDP load (kg/d)
0
30
60
90
TOC load (kg/d)
0
2500
5000
7500
DOC load (kg/d)
0
2500
5000
7500
10000
12500
1
2
3
4
5
6
7
8
9
10
11
12
Month

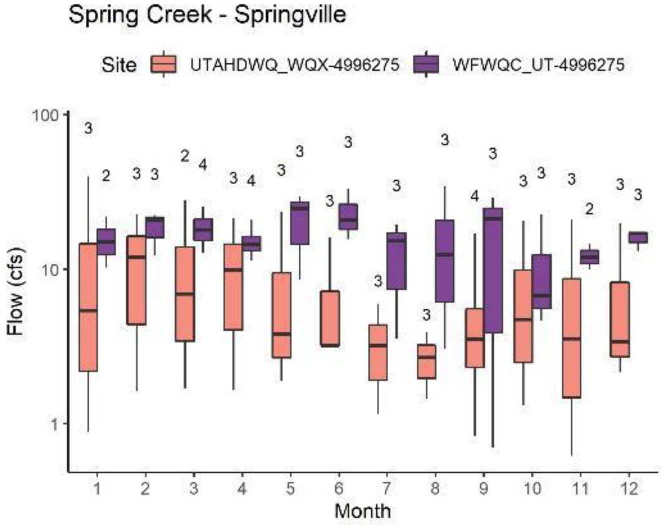
10.7.9 Mill Race

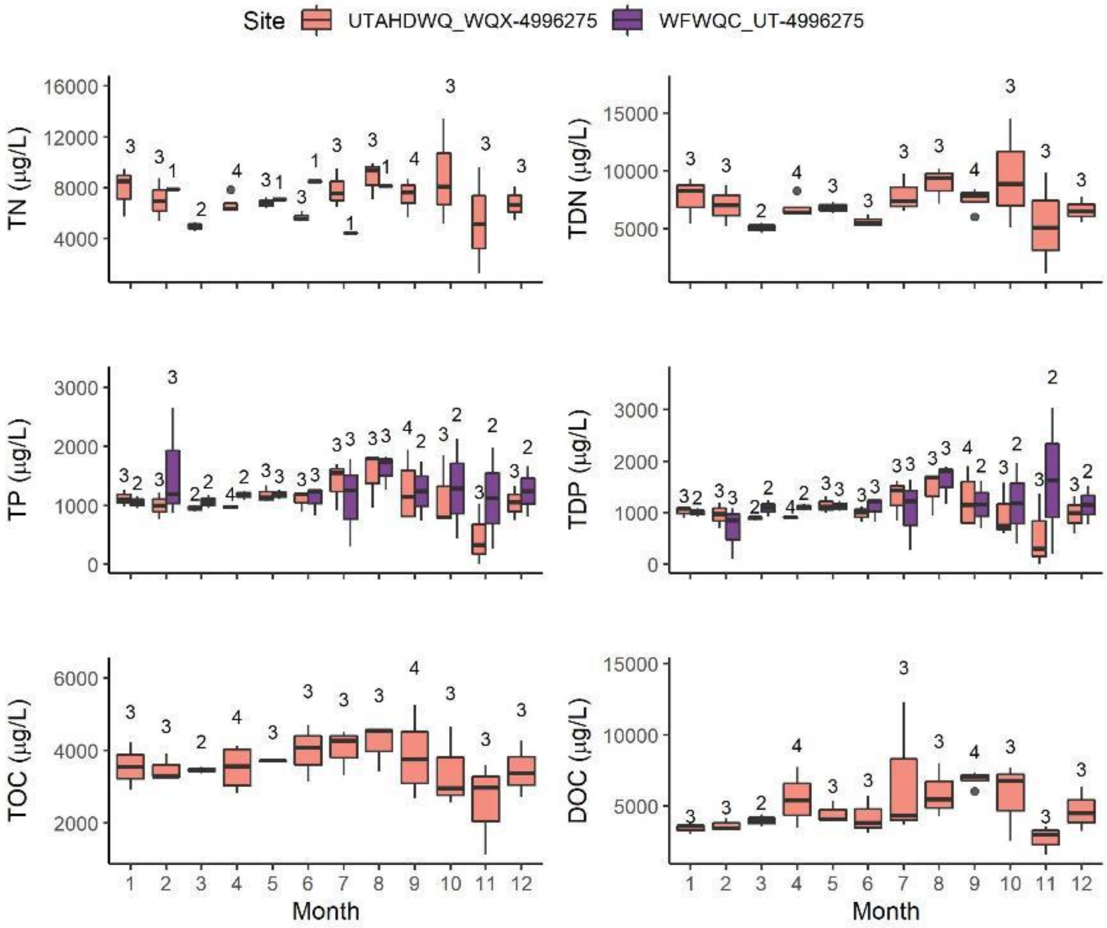


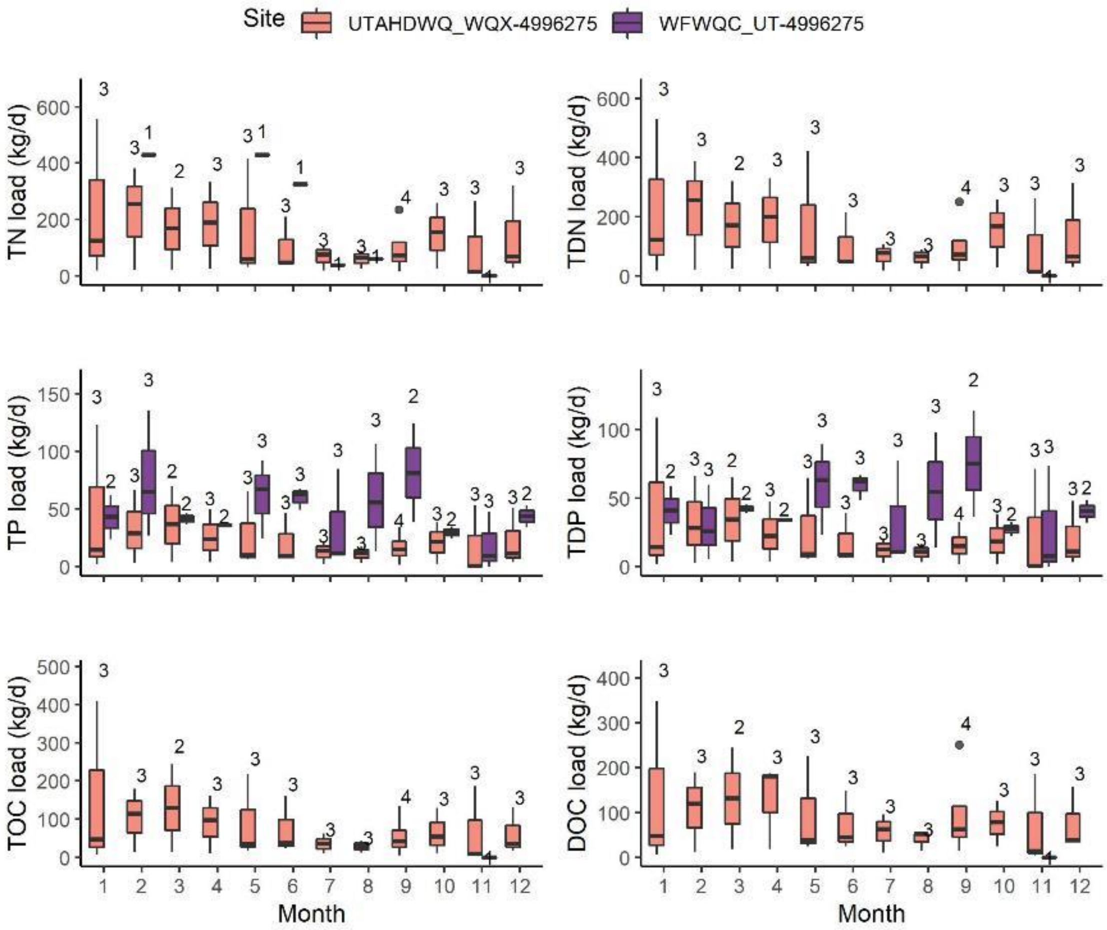



Site
UTAHDWQ_WQX-4996540
UTAHDWQ_WQX-4996566
WFWQC_UT-4996536
WFWQC_UT-4996540
TN load (kg/d)
0
300
600
900
TDN load (kg/d)
250
500
750
TP load (kg/d)
0
50
100
150
200
TDP load (kg/d)
0
50
100
TOC load (kg/d)
100
200
300
DOC load (kg/d)
100
200
300
400
1
2
3
4
5
6
7
8
9
10
11
12
Month

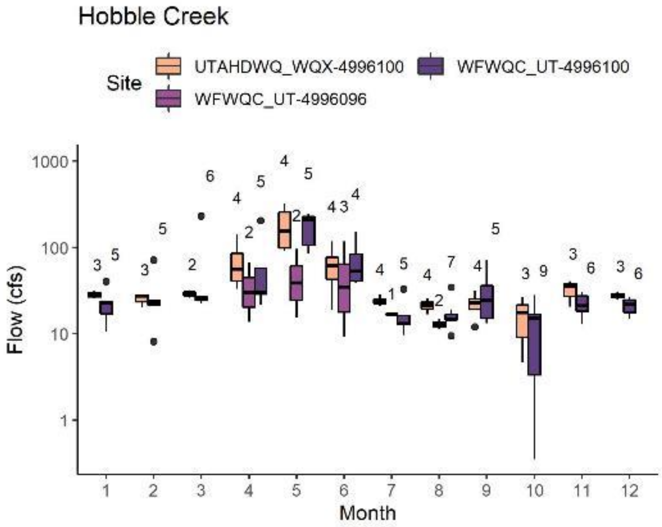
10.7.10 Spring Creek – Springville

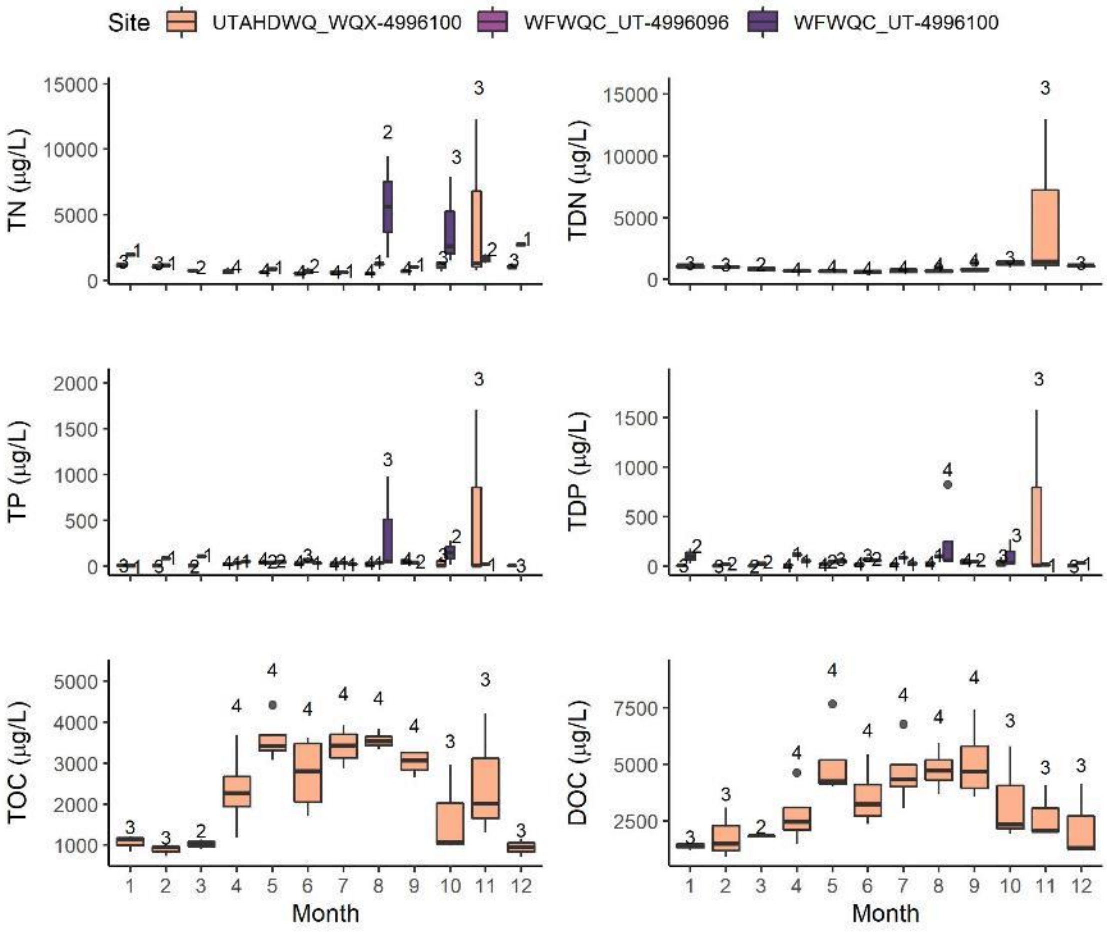


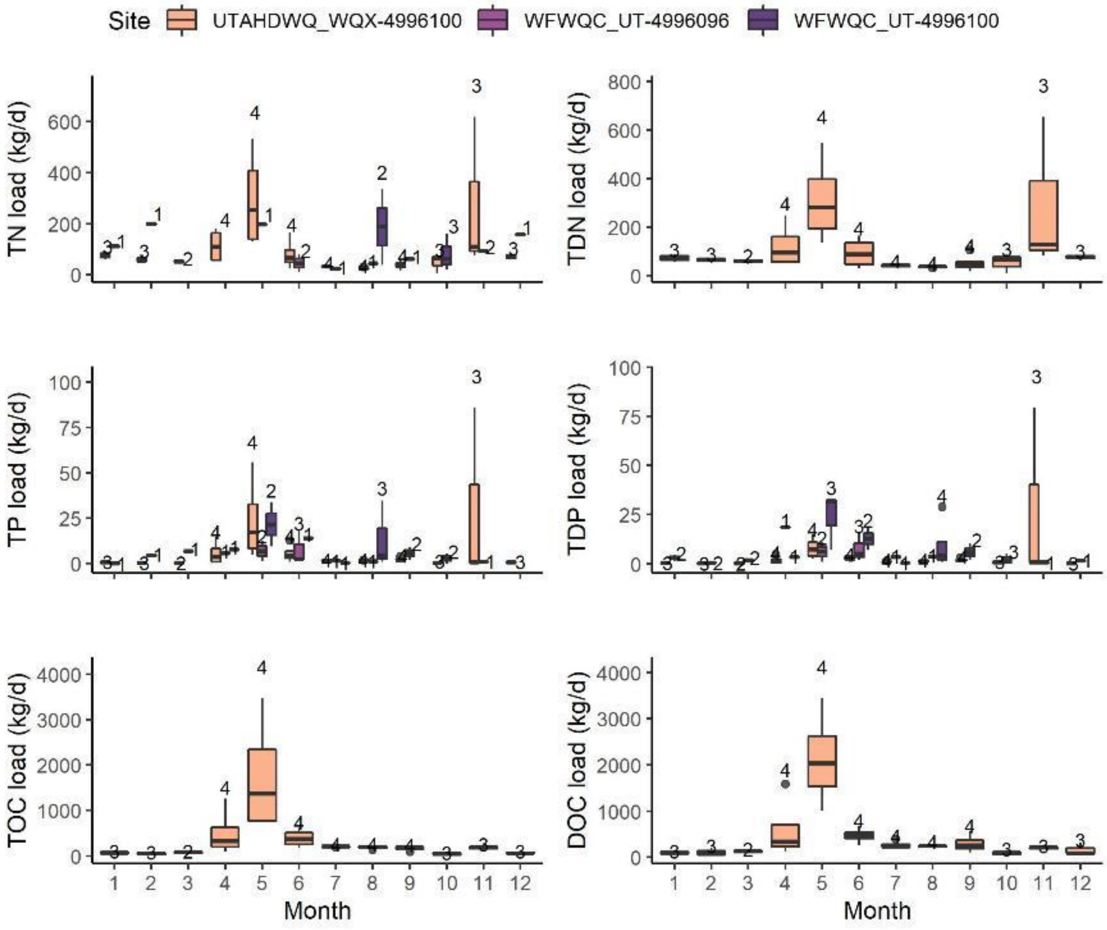



Site
UTAHDWQ_WQX-4996275
WFWQC_UT-4996275
TN load (kg/d)
0
200
400
600
TDN load (kg/d)
0
200
400
600
TP load (kg/d)
0
50
100
150
TDP load (kg/d)
0
50
100
TOC load (kg/d)
0
100
200
300
400
500
DOC load (kg/d)
0
100
200
300
400
1
2
3
4
5
6
7
8
9
10
11
12
Month

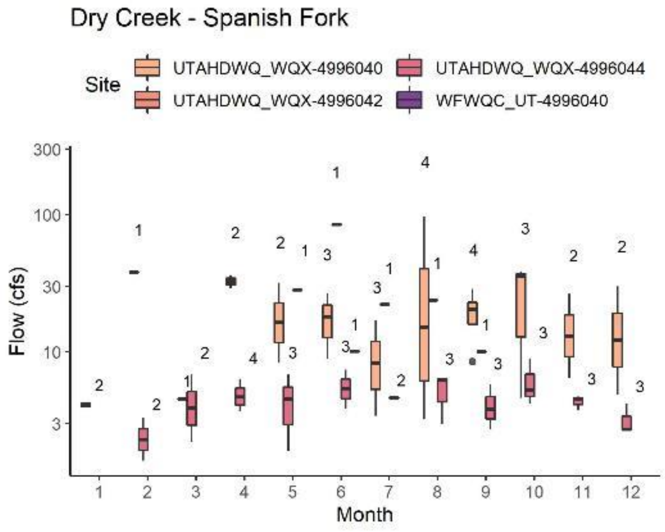
10.7.11 Hobble Creek

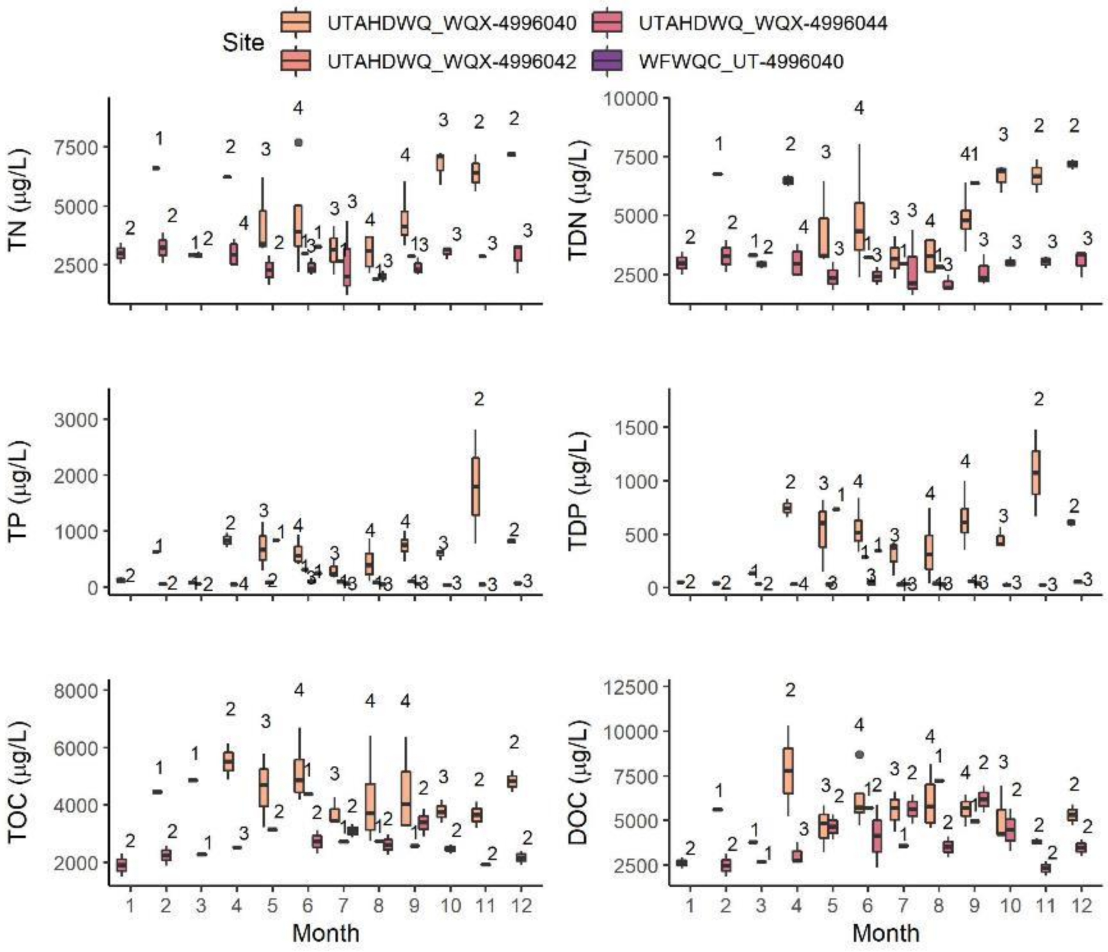


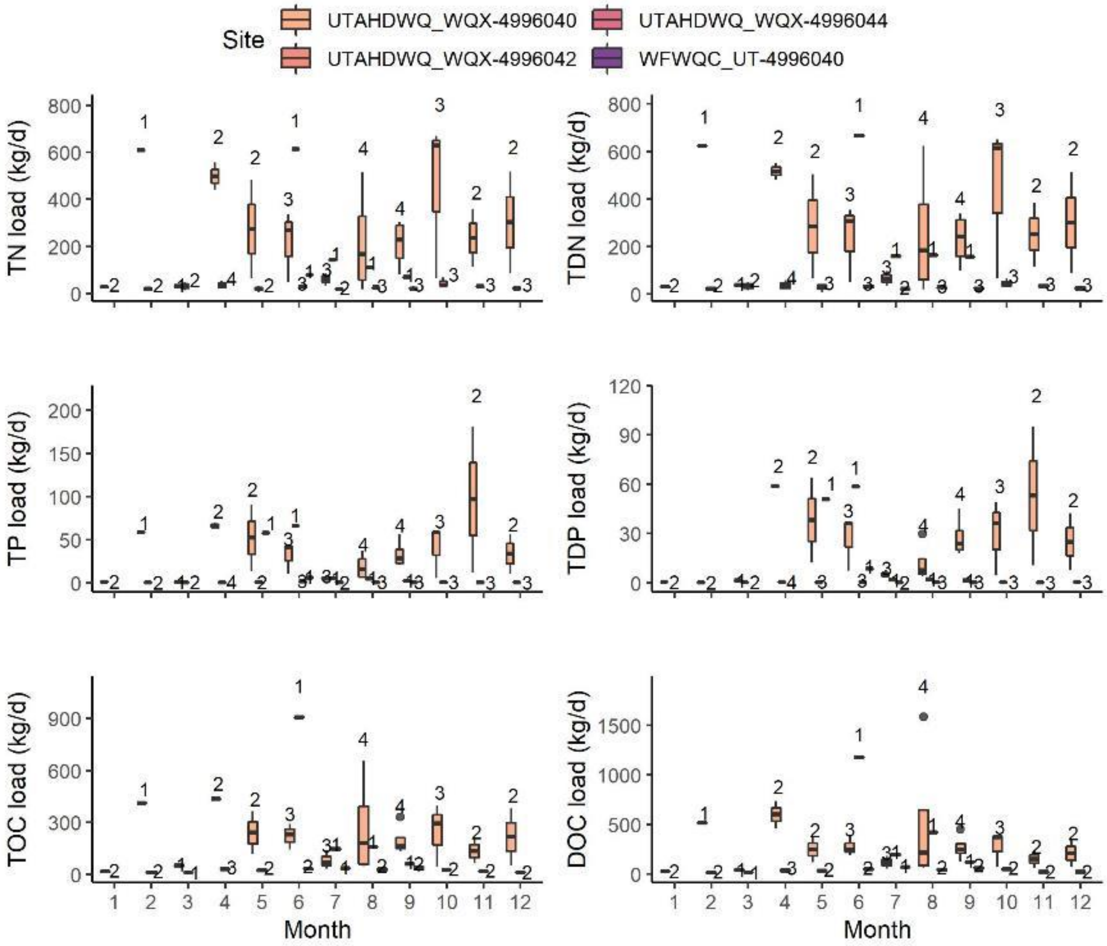



Site
UTAHDWQ_WQX-4996100
WFWQC_UT-4996096
WFWQC_UT-4996100
TN load (kg/d)
0
200
400
600
TDN load (kg/d)
0
200
400
600
800
TP load (kg/d)
0
25
50
75
100
TDP load (kg/d)
0
25
50
75
100
TOC load (kg/d)
0
1000
2000
3000
4000
DOC load (kg/d)
0
1000
2000
3000
4000
1 2 3 4 5 6 7 8 9 10 11 12
Month
1 2 3 4 5 6 7 8 9 10 11 12
Month

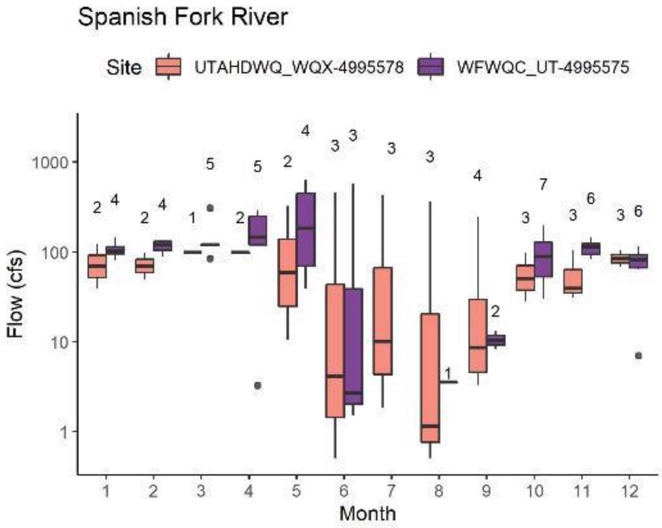
10.7.12 Dry Creek – Spanish Fork

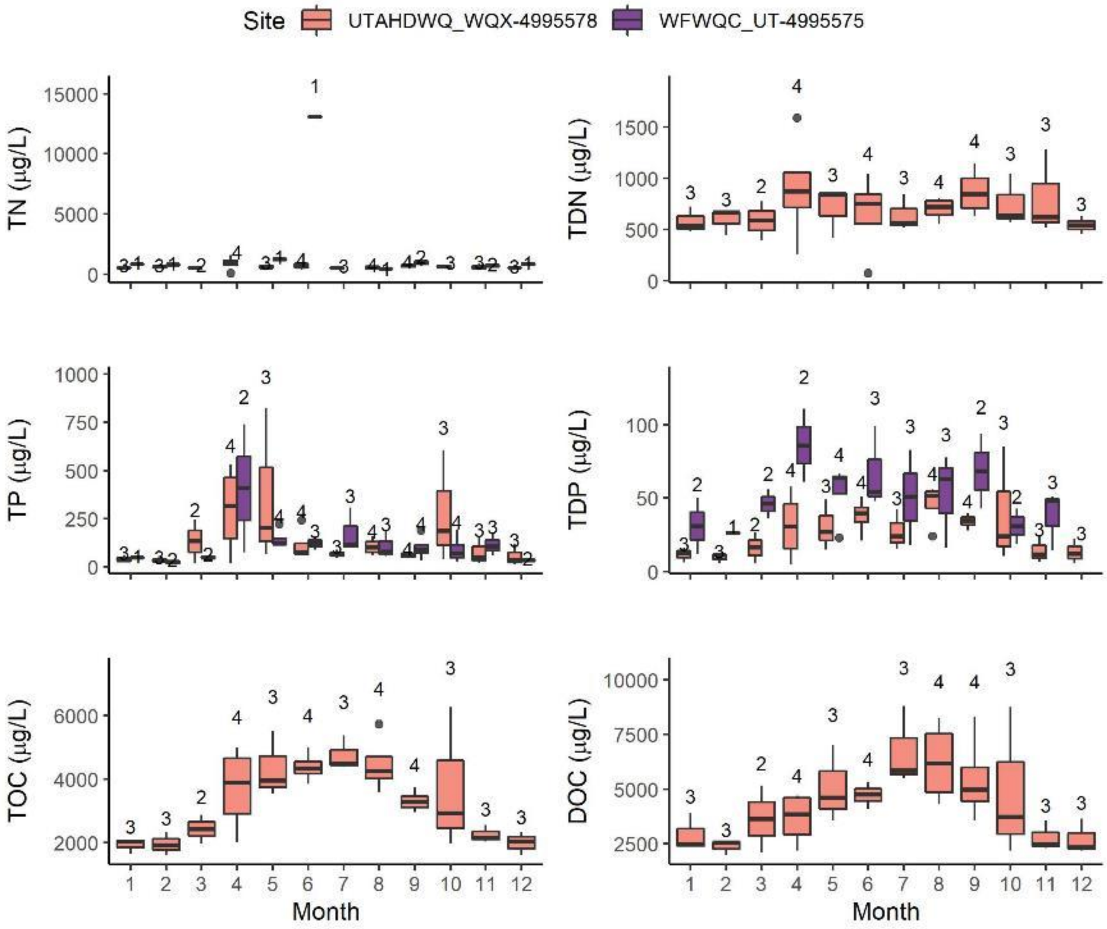


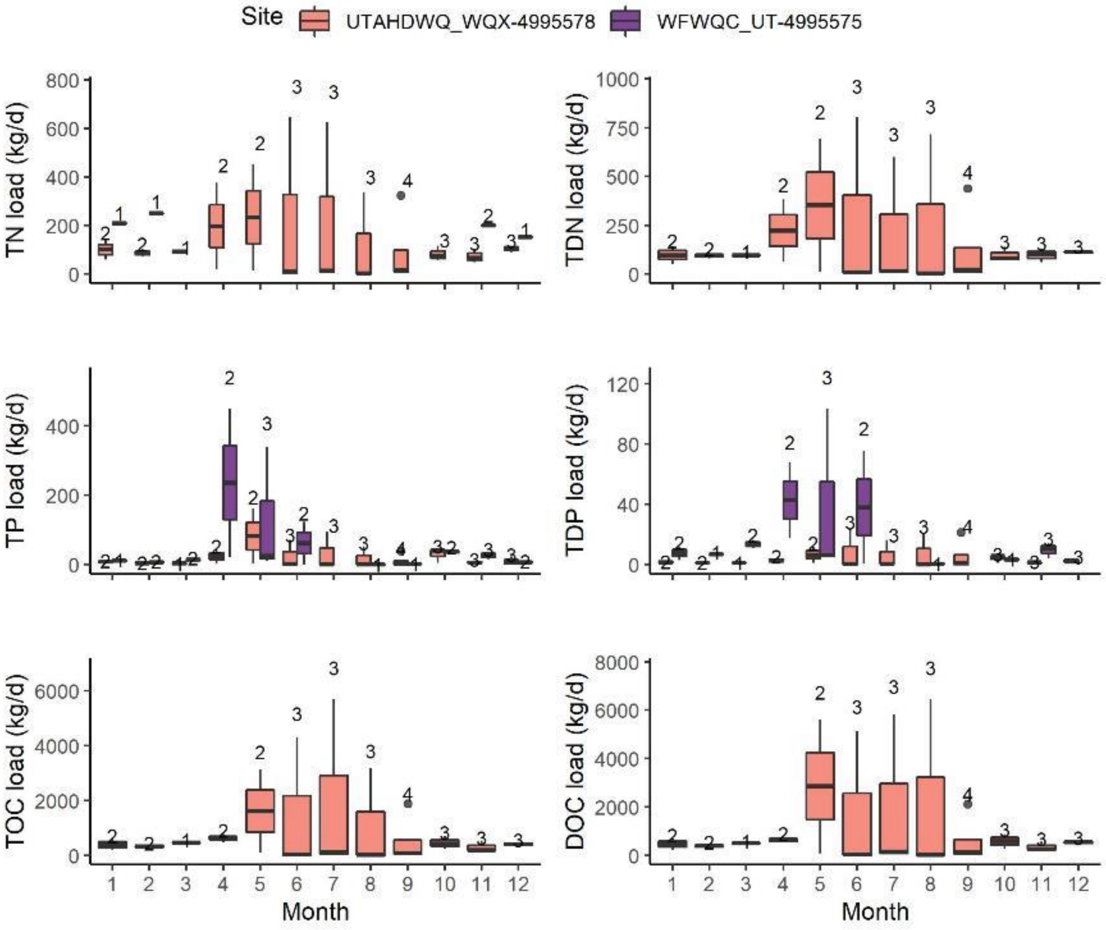



Site
UTAHDWQ_WQX-4996040
UTAHDWQ_WQX-4996042
UTAHDWQ_WQX-4996044
WFWQC_UT-4996040
TN load (kg/d)
0
200
400
600
800
TDN load (kg/d)
0
200
400
600
800
TP load (kg/d)
0
50
100
150
200
TDP load (kg/d)
0
30
60
90
120
TOC load (kg/d)
0
300
600
900
DOC load (kg/d)
0
500
1000
1500
1
2
3
4
5
6
7
8
9
10
11
12
Month

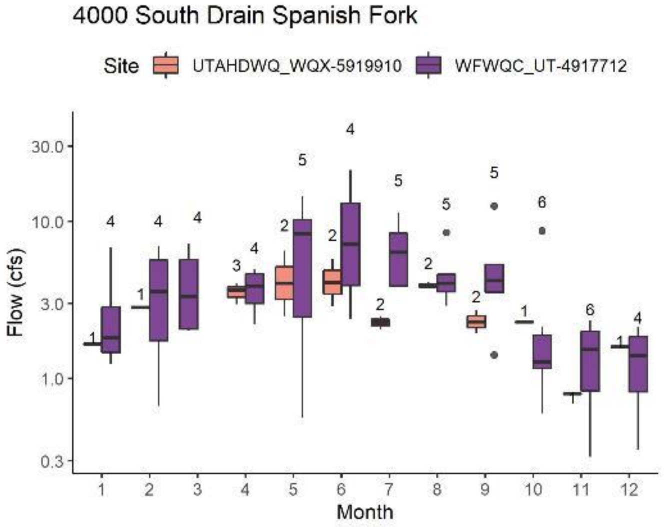
10.7.13 Spanish Fork River

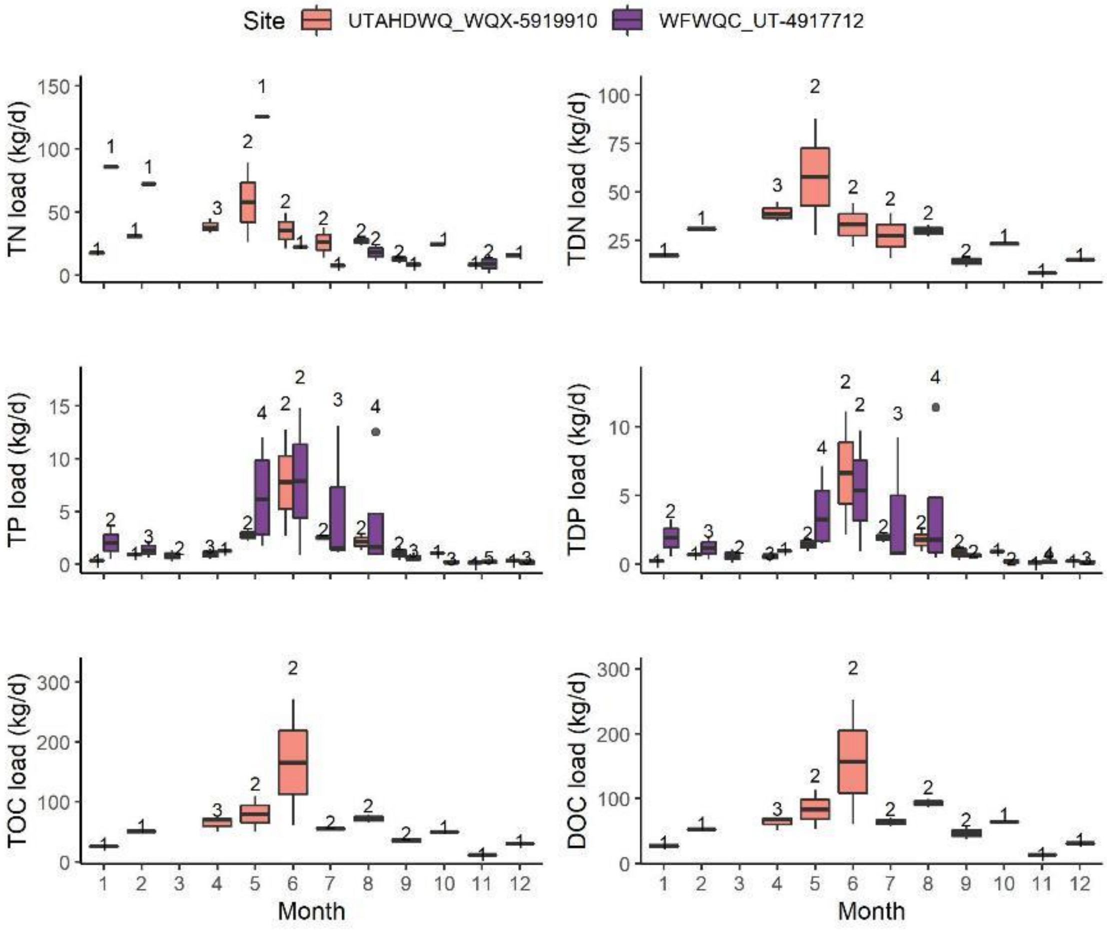


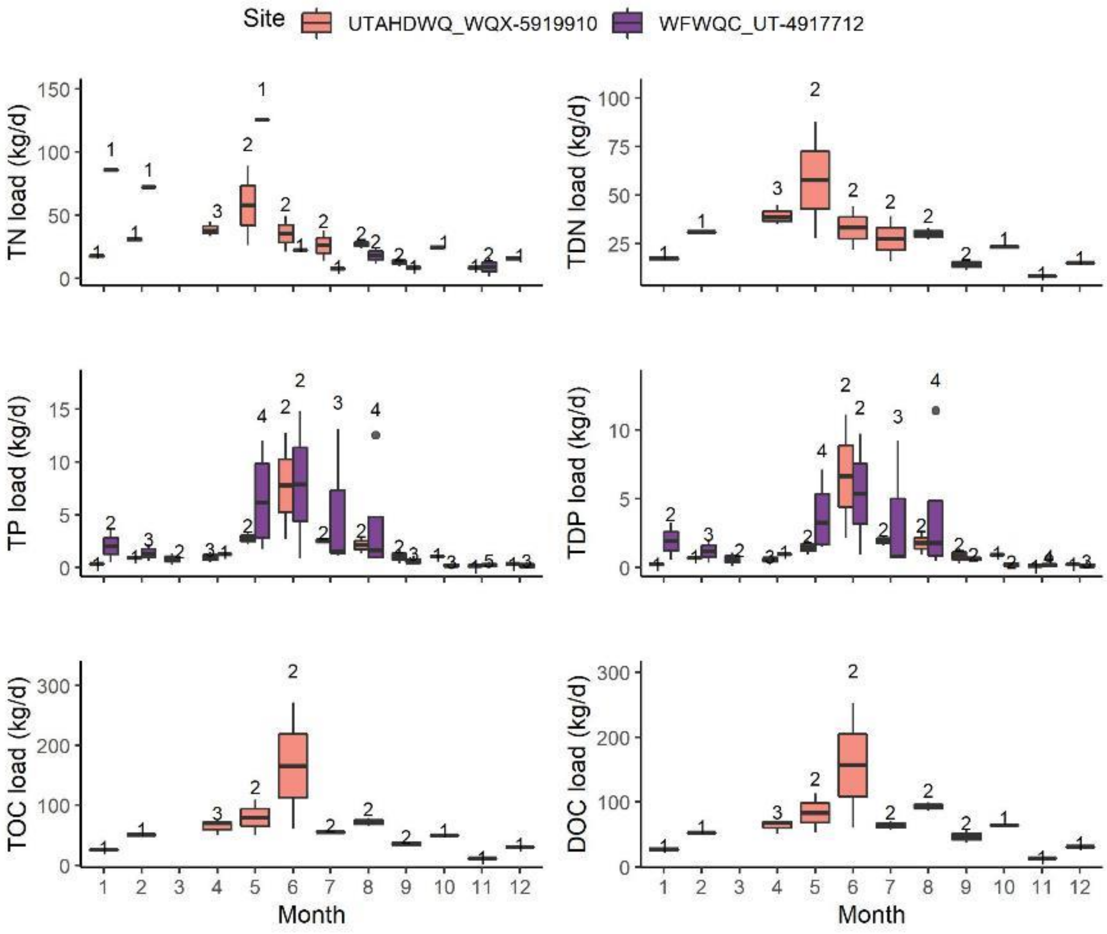



Site
UTAHDWQ_WQX-4995578
WFWQC_UT-4995575
TN load (kg/d)
TDN load (kg/d)
TP load (kg/d)
TDP load (kg/d)
TOC load (kg/d)
DOC load (kg/d)
Month
Month

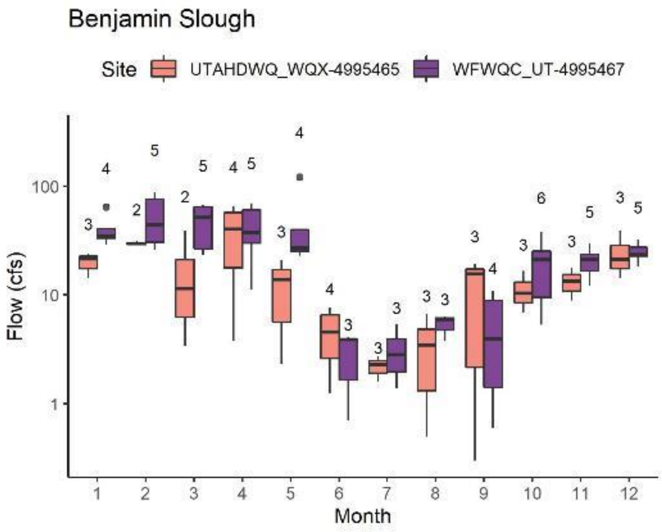
10.7.14 4000 South Drain Spanish Fork

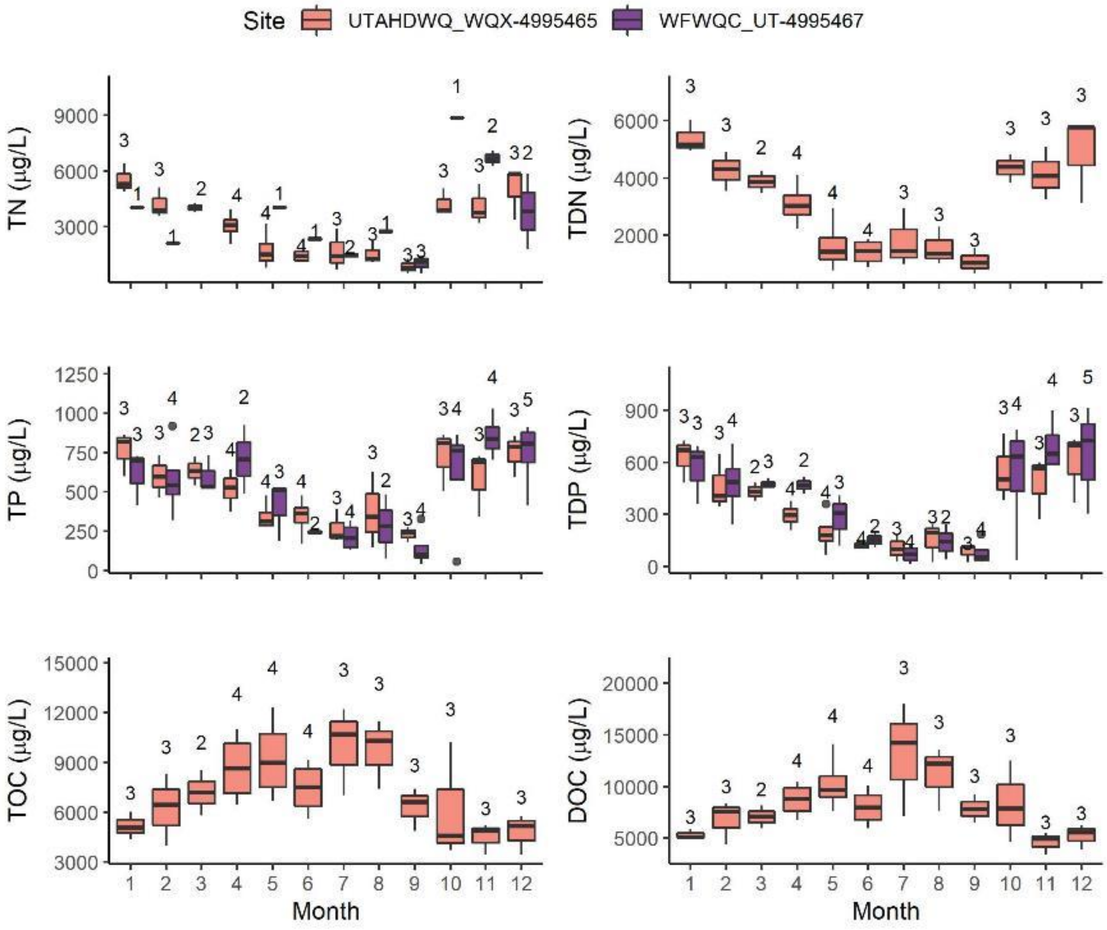


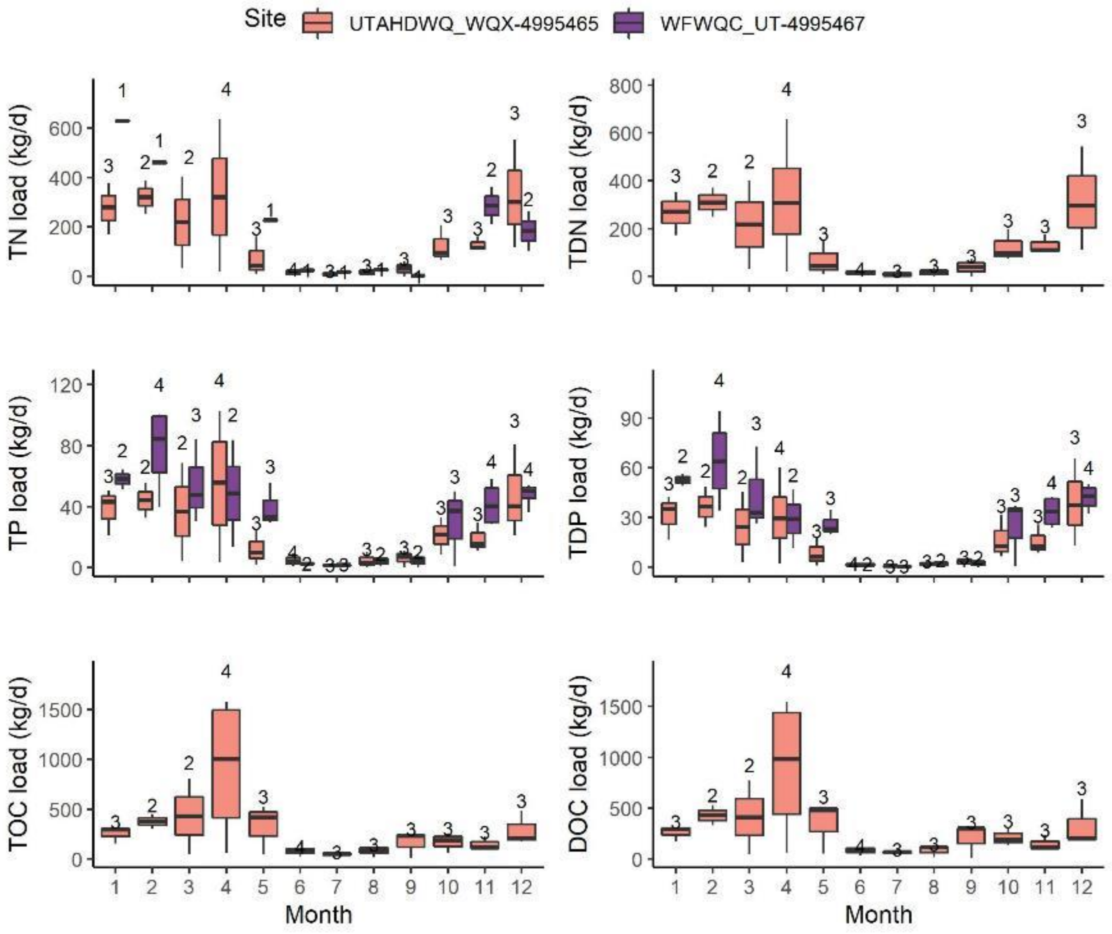



Site
UTAHDWQ_WQX-5919910
WFWQC_UT-4917712
TN load (kg/d)
0
50
100
150
1
1
1
1
3
2
1
2
1
2
1
2
2
2
1
1
2
1
TDN load (kg/d)
25
50
75
100
1
1
3
2
2
2
2
2
1
1
1
TP load (kg/d)
0
5
10
15
1
2
1
3
2
3
1
2
4
2
2
2
3
4
2
3
1
3
1
5
1
3
TDP load (kg/d)
0
5
10
1
2
1
3
2
3
1
2
4
2
2
2
3
2
4
2
2
1
2
1
4
1
3
TOC load (kg/d)
0
100
200
300
1
1
3
2
2
2
2
2
1
1
1
DOC load (kg/d)
0
100
200
300
1
1
3
2
2
2
2
2
1
1
1
1
2
3
4
5
6
7
8
9
10
11
12
Month

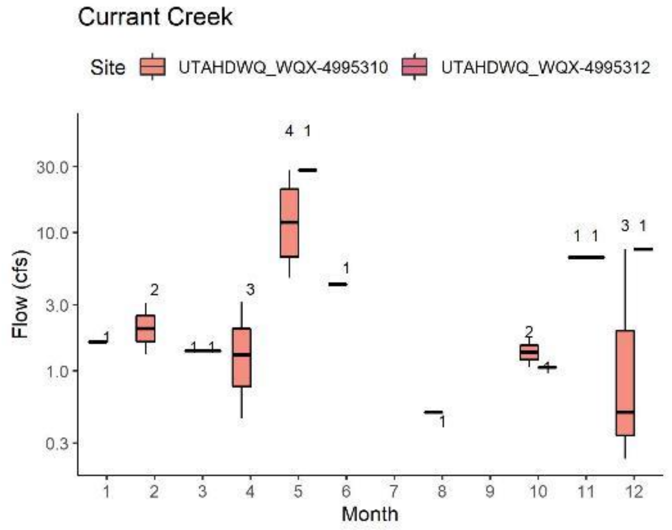
10.7.15 Benjamin Slough

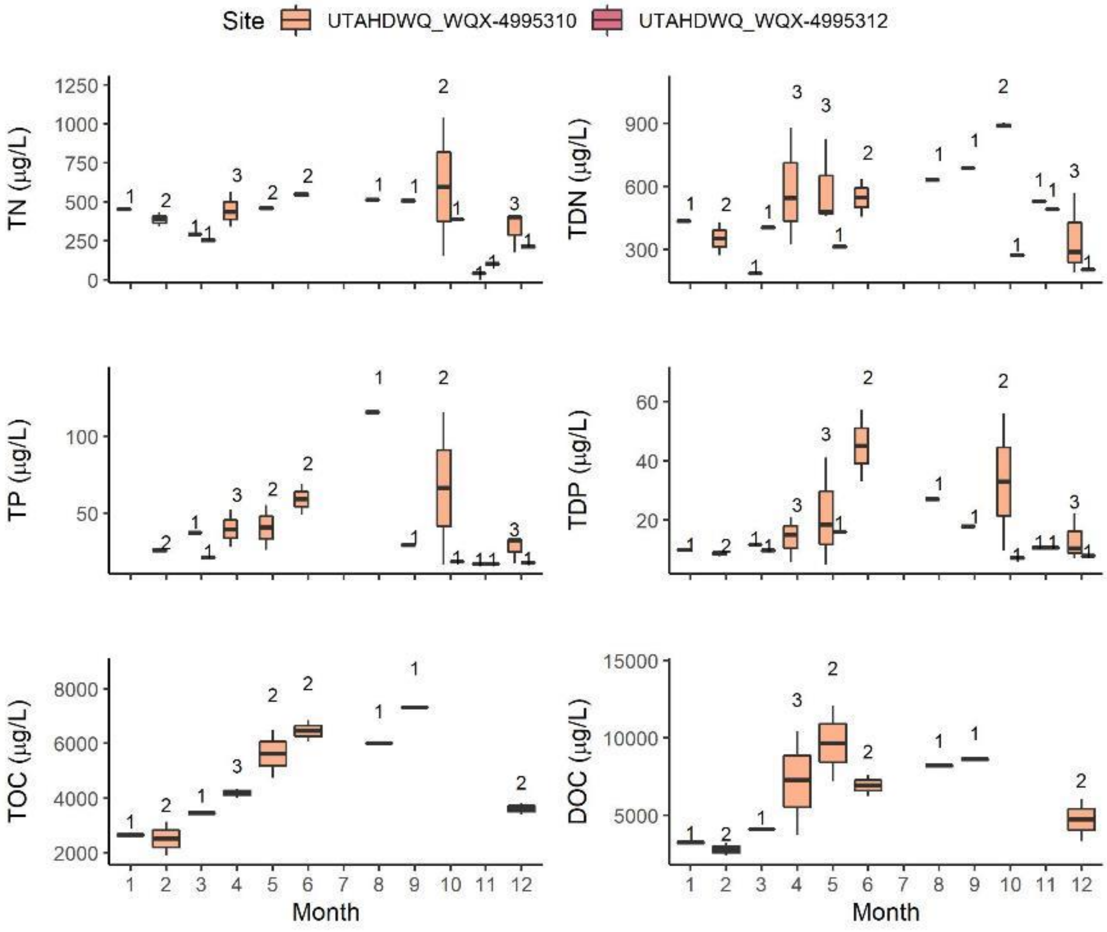


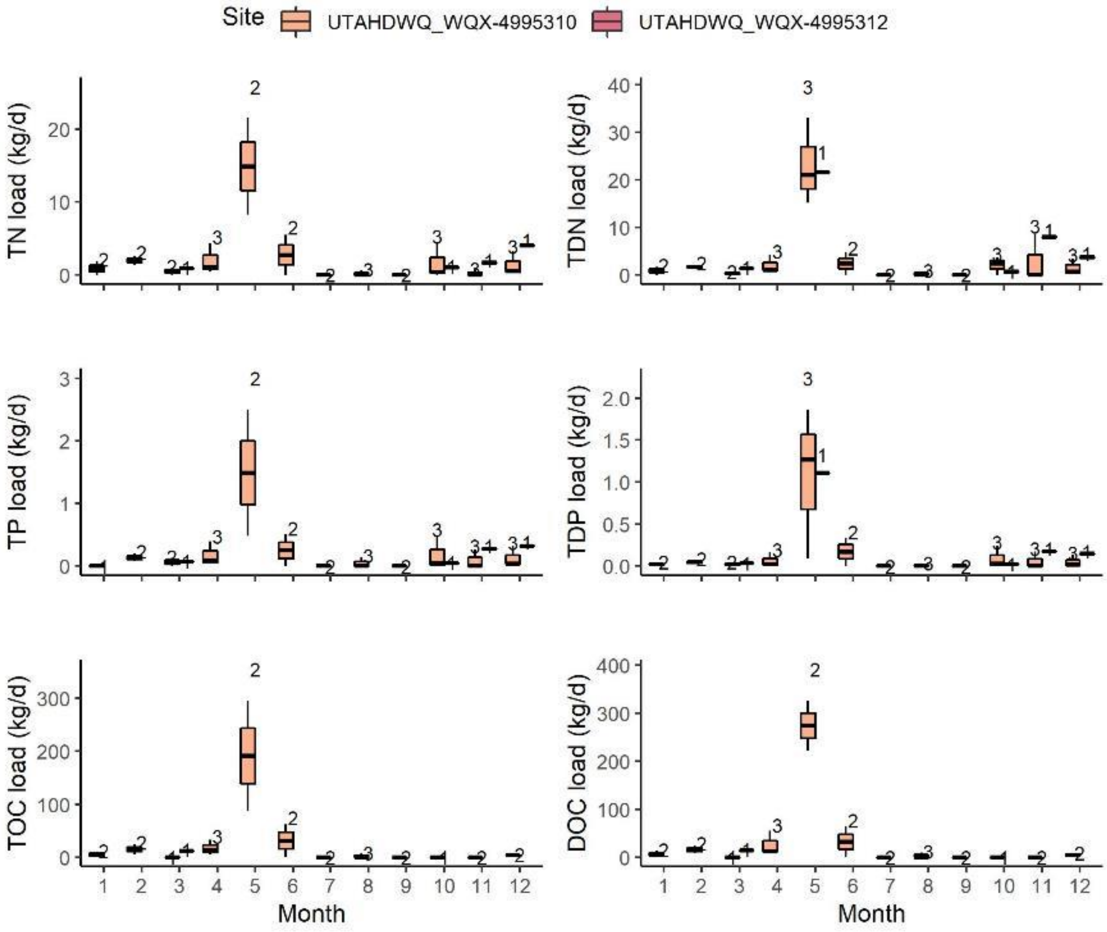



Site
UTAHDWQ_WQX-4995465
WFWQC_UT-4995467
TN load (kg/d)
0
200
400
600
TDN load (kg/d)
0
200
400
600
800
TP load (kg/d)
0
40
80
120
TDP load (kg/d)
0
30
60
90
TOC load (kg/d)
0
500
1000
1500
DOC load (kg/d)
0
500
1000
1500
1 2 3 4 5 6 7 8 9 10 11 12
Month

10.7.16 Currant Creek






Site
UTAHDWQ_WQX-4995310
UTAHDWQ_WQX-4995312
TN load (kg/d)
TDN load (kg/d)
TP load (kg/d)
TDP load (kg/d)
TOC load (kg/d)
DOC load (kg/d)
Month
Month
1 2 3 4 5 6 7 8 9 10 11 12