Final Report: The Assimilative Capacity of Lake Livingston: Nutrients, Sediments, and High Flow Events

Texas Water Development Board Contract #2000012458

Prepared for:

Texas Water Development Board

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July 31st, 2023

"Pursuant to Senate Bill 1 as approved by the 86th Texas Legislature, this study report was funded for the purpose of studying environmental flow needs for Texas rivers and estuaries as part of the adaptive management phase of the Senate Bill 3 process for environmental flows established by the 80th Texas Legislature. The views and conclusions expressed herein are those of the author(s) and do not necessarily reflect the views of the Texas Water Development Board."

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List of Acronyms

BBEST	Basin and Bay Expert Science Teams
BBASC	Basin and Bay Area Stakeholder Committees
BOD	Biochemical Oxygen Demand
CWA	Clean Water Act
cfs	Cubic Feet per Second
DFW	Dallas-Fort Worth Metroplex
GPS	Global Positing System
HARC	Houston Advanced Research Center
HUC	Hydrologic Unit Code
IQR	Interquartile Range
NWQL	National Water Quality Laboratory
NWIS	National Water Information System
NWS	National Weather Service
NOAA NIDIS	National Oceanic and Atmospheric Administration's National Integrated Drought Information System
QA/QC	Quality assurance/Quality control
SD	Standard Deviation
SWQM	Surface Water Quality Monitoring
SWQMIS	Surface Water Quality Monitoring Information System
TCEQ	Texas Commission on Environmental Quality
TPWD	Texas Parks and Wildlife Department
TWDB	Texas Water Development Board
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total suspended sediment
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
USGS KSL	USGS Kentucky Sediment Laboratory

1 Executive summary

Reservoirs affect downstream flows to coastal waters and often function as nutrient and sediment sinks because they capture and store biological and environmental parameters over time (Vorosmarty et al., 2003; Wang, 2020). Lake Livingston, which is in the Trinity River Basin, has a storage capacity of 1,788,000 acre-feet and a drainage area of 16,616 square miles. The Trinity River headwaters begin north of the Dallas-Fort Worth Metroplex and flow 710 miles south to Trinity Bay, a subbay of the Galveston Bay estuary. Lake Livingston bisects the Trinity River at the southern extent of the river basin, to form two distinct stretches: the Trinity River North and South.

Environmental flow recommendations from Basin and Bay Expert Science Teams and Basin and Bay Area Stakeholder Committees were used to formulize the adoption of environmental flow standards. A provision calling for adaptive management strategies led to the development of Adaptive Management Work Plans. To support the adaptive management process in the Trinity and San Jacinto Rivers and Galveston Bay Basin and Bay Area, the BBASC recommended a study of the assimilative capacity of Lake Livingston. In the spring of 2019, the Houston Advanced Research Center and the United States Geological Survey completed an initial Lake Livingston study (Phase I) funded by the Galveston Bay Estuary Program/Texas Commission on Environmental Quality to assess the assimilative capacity of the reservoir across a variety of flow regimes (Glenn and Bare, 2019).

The goal of this Phase II "The Assimilative Capacity of Lake Livingston: Nutrients, Sediments, and High Flow Events" project was to enhance understanding of how the hydrologic flow regime, biogeochemical cycling, and physical characteristics of the Lake Livingston reservoir influence the regulation of nutrient and sediment delivery from the Upper to Lower reaches of the Trinity River. This project addressed data gaps by increasing the number and temporal resolution of water and sediment samples, performing targeted sample collection during high flow events, and conducting sediment sampling to assess the potential sequestration of nutrients within the reservoir bed. All field sampling was performed by personnel from the USGS Gulf Coast Branch of the Oklahoma-Texas Water Science Center.

The influence of the Trinity River's flow regimes on physiochemical water quality upstream, within, and downstream of the Lake Livingston Reservoir was assessed using historically collected water quality data. The sampling events show higher nutrient concentrations in the bed sediment during high discharge events, and lower nutrient and sediment concentrations at the Trinity Goodrich station downstream of the Lake Livingston Dam compared to the Trinity Riverside station above the reservoir. These results suggest that Lake Livingston, a single-purpose reservoir created in 1969 as an artificial impoundment for water supply, is a nutrient and sediment sink. These data and associated outcomes produced by this project are available to support future studies such as the development of nutrient loading models, use of mass-balance approaches, or further analysis needed to determine patterns of nutrient cycling within the reservoir.

2 Introduction

Reservoirs affect downstream flows to coastal waters and often function as nutrient and sediment sinks because they capture and store biological and environmental parameters over time (Vorosmarty et al., 2003; Wang, 2020). However, these impoundments may eventually reach dynamic equilibrium and become nutrient and sediment sources during high flow events (Palinkas et al., 2019). These source-sink relationships are dependent on dynamic processes influenced by meteorological, hydrological, and biogeochemical factors in combination with the unique physical characteristics of each reservoir (Wellmeyer et al., 2005; Gelca et al., 2016; Maavara et al., 2020; Lei et al., 2021).

Environmental flow recommendations from Basin and Bay Expert Science Teams (BBEST) and Basin and Bay Area Stakeholder Committees (BBASC) served as the basis for the adoption of environmental flow standards by the Texas Commission on Environmental Quality (TCEQ) between 2011 and 2014. A provision calling for adaptive management strategies led to the development of Work Plans for Adaptive Management by the BBASCs that established a periodic review of the environmental flow regime analyses, recommendations, standards, and strategies. To support the adaptive management process in the Trinity and San Jacinto Rivers and Galveston Bay Basin and Bay Area, the BBASC recommended a study of the assimilative capacity of Lake Livingston.

Lake Livingston, which is in the Trinity River Basin, has a storage capacity of 1,788,000 acre-feet and a drainage area of 16,616 square miles (Figure 1). The Trinity River headwaters begin north of the Dallas-Fort Worth Metroplex (DFW) and flow 710 miles south to Trinity Bay, a subbay of the Galveston Bay estuary. Lake Livingston bisects the Trinity River at the southern extent of the river basin, to form two distinct stretches: the Trinity River North and South. The reservoir is in the South-Central Plains ecoregion and is situated amongst mixed pine and hardwood forest habitat. Lake Livingston Dam construction began in 1966 and was completed in 1969, impounding the Trinity River (TRA, 2022).

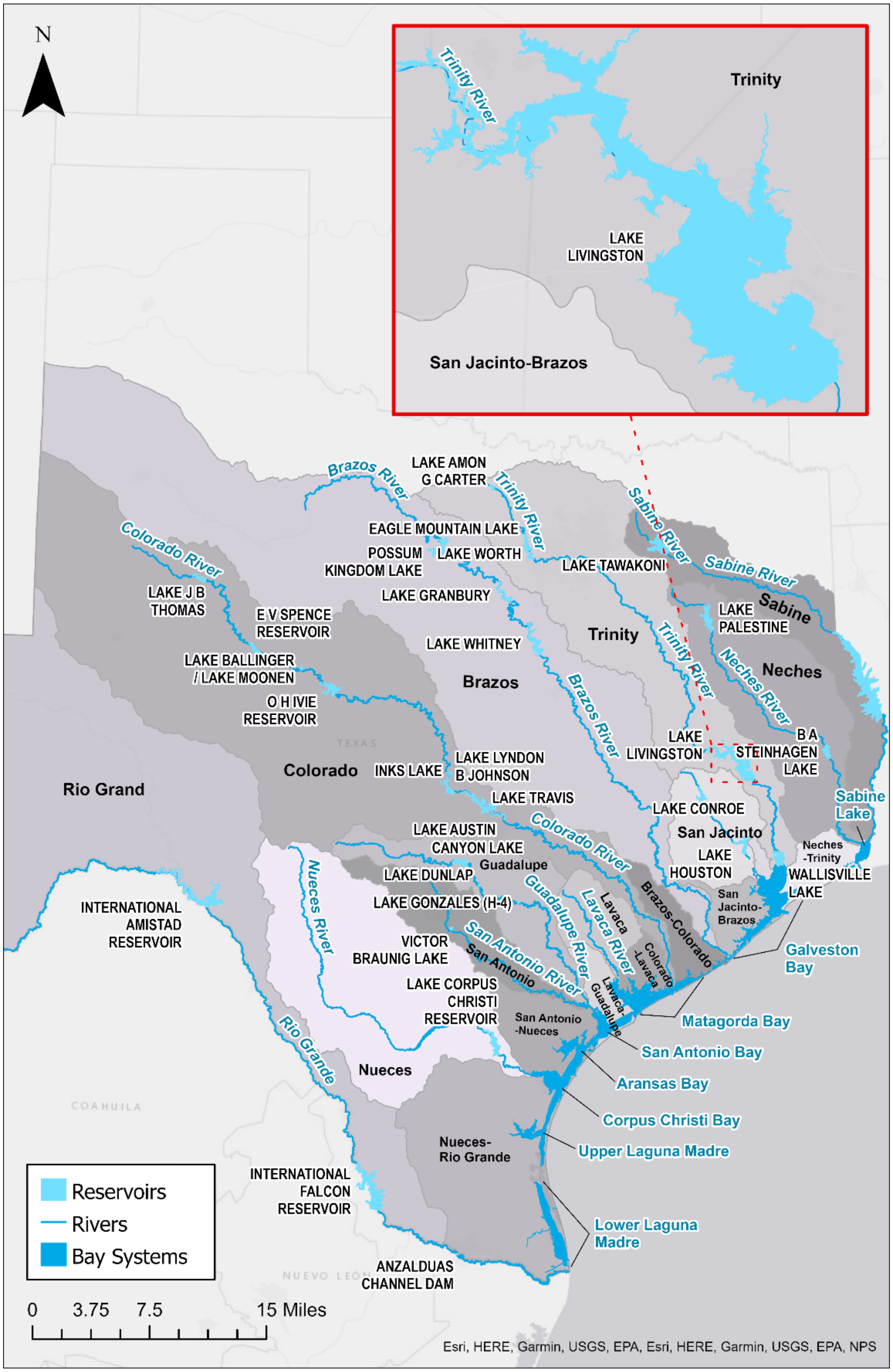


Figure 1. Reservoirs located on major Texas rivers within Texas Water Development Board river and coastal basins, and major Texas bays. Map inset highlights the Lake Livingston reservoir within the Trinity River Basin.

The reservoir reached full capacity on November 3, 1971, over two years post-impoundment (Figure 2). The dam was not designed to manage flood waters during periods of elevated discharge related to intense rain events (TRA, 2022). Twelve tainter gates in a concrete and steel spillway control flow through the dam. As flow entering the reservoir from Trinity River increases, so does flow over the earthen spillway. The dam was not designed to manage flood waters during periods of elevated discharge related to intense rain events (TRA, 2022). Rather, the reservoir was constructed for water supply purposes and is an important source of water for the City of Houston and surrounding municipalities ("HPW," 2022). In fact, 86% of Houston's water supply comes from surface water collected from Lake Livingston, Lake Conroe, and Lake Houston ("HPW," 2022). Secondary uses of the reservoir include water-based recreation, and more recently, the generation of hydroelectric power (TRA, 2022).

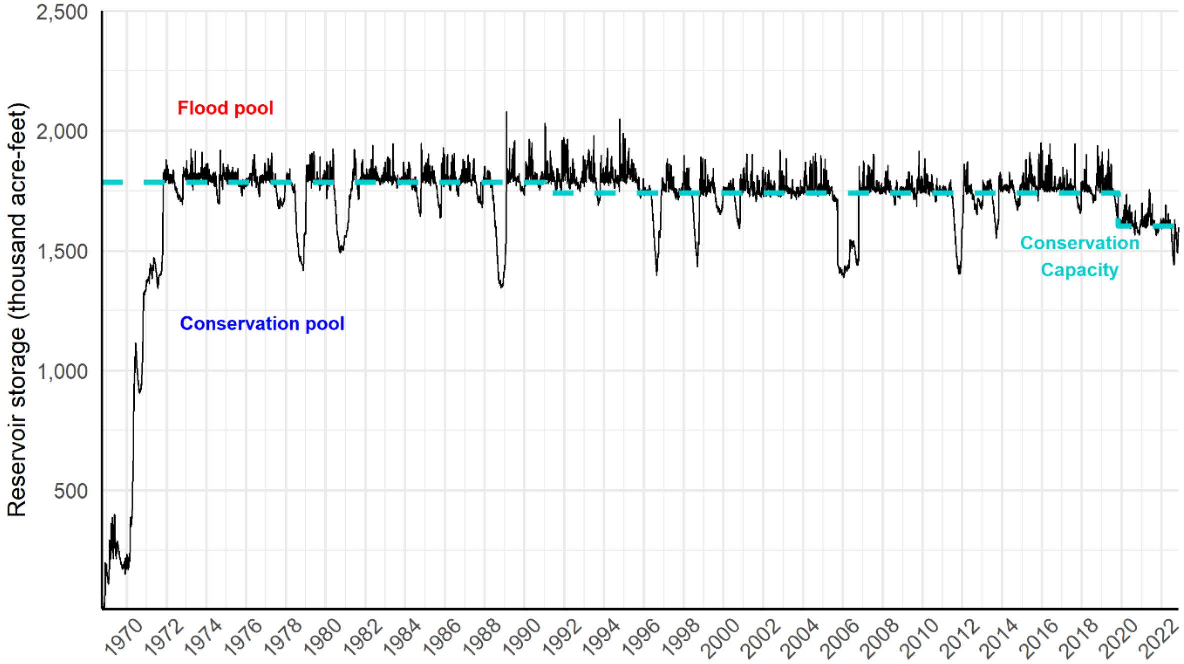


Figure 2. **Lake Livingston reservoir storage (thousand acre-feet) from 10/2/1968 - 11/11/2022. Values below the conservation capacity line are in the conservation pool and those values above are in the flood pool. This storage hydrograph is based on best estimates generated by the Texas Water Development Board methodology: http://waterdatafortexas.org/reservoirs/methodology ("Water Data For Texas," 2022).**

In 2015, the Trinity River Authority and the East Texas Electric Cooperative broke ground on the R.C. Thomas Hydroelectric Project immediately south of the Lake Livingston Dam (TRA, 2022). Construction of the 24-megawatt hydroelectric plant was completed in November 2021 (ETEC, 2021). Power is generated by "run-of-the-river" flows by diverting some of the flow through a pipe or tunnel to the electricity-generating turbines. The diverted water is returned to the Trinity River downstream of the dam. Power generation occurs during periods when water is released from the reservoir and produces an average of 124 million kilowatt-hours of electricity annually (TRA, 2022).

In the spring of 2019, the Houston Advanced Research Center (HARC) and the United States Geological Survey (USGS) completed an initial study (Phase I) funded by the Galveston Bay Estuary Program/TCEQ on Lake Livingston to assess the assimilative capacity of the reservoir across a variety of flow regimes (Glenn and Bare, 2019). The USGS collected water quality samples from four sites to characterize longitudinal differences in sediments and nutrients within and downstream of the reservoir. Water quality sampling was conducted from May 2016 to August 2018 across six sampling events during base, moderate, and high flow conditions (Glenn and Bare, 2019). The initial study deployed a drifter equipped with a Global Positing System (GPS) to track flow patterns and currents and collected water quality depth profiles. Most of the suspended sediments, TP, and nitrate samples results revealed a decreasing gradient of concentrations from north (upstream) to south (downstream). These early results suggest that as nutrients enter Lake Livingston, they are retained in the reservoir (Glenn and Bare, 2019). However, this study was limited to a small sample size and only one high flow event water quality sample.

While the Lake Livingston reservoir is an important water resource, the Trinity River has an ecologically significant role as the primary source of freshwater, nutrients, and sediment inflows to Galveston Bay, the largest Texas estuary. These inflows are spread throughout the Trinity River delta and flow into Trinity Bay which is a subbay of the larger Galveston Bay system (Guthrie et al., 2012). Galveston Bay harbors productive oystering and seafood fisheries that account for one-third of the state's commercial fishing revenue (Lester and Gonzalez, 2011). Understanding the assimilative capacity of the Lake Livingston reservoir and related impacts on freshwater inflows to Galveston Bay is critical in planning for adaptive management.

The goal of the "The Assimilative Capacity of Lake Livingston: Nutrients, Sediments, and High Flow Events" project was to enhance understanding of how the hydrologic flow regime, biogeochemical cycling, and physical characteristics of the Lake Livingston reservoir influence the regulation of nutrient and sediment delivery from the Upper to Lower reaches of the Trinity River. The objectives of the project were to assess the influence of the Trinity River's flow regime on physiochemical water quality upstream, within, and downstream of the Lake Livingston reservoir by 1) quantifying nutrient and total suspended sediment (TSS) concentrations during high flow events above and below the Lake Livingston Dam, 2) assessing nutrient concentrations in the lakebed, and 3) evaluating water quality concentrations at two depth intervals.

3 Methods

3.1 Data management and monitoring plan

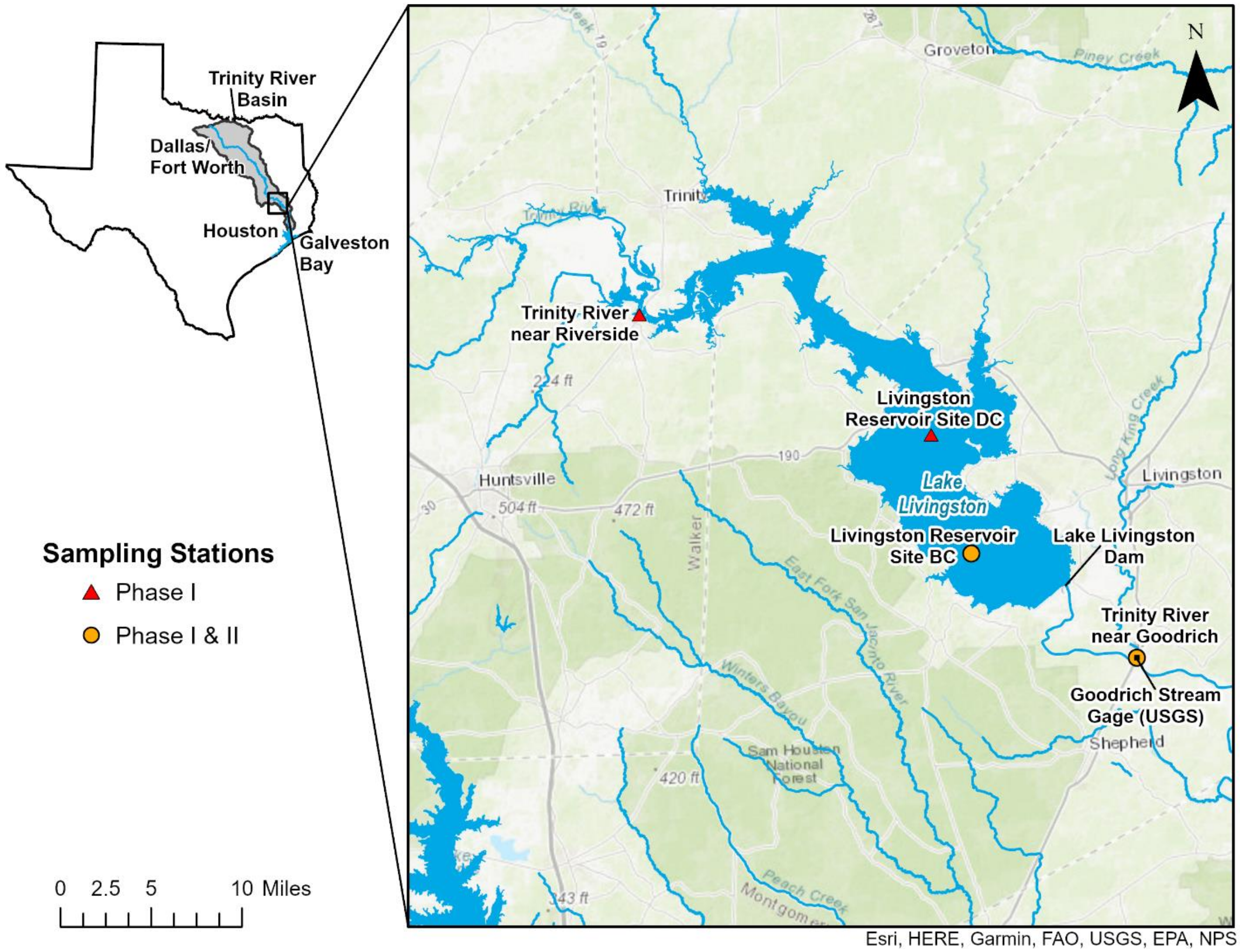
HARC partnered with the USGS to perform water and sediment quality sampling. All field sampling was performed by personnel from the USGS Gulf Coast Branch of the Oklahoma-Texas Water Science Center. Sampling information (e.g., site location, date, time, etc.) and field data were collected and recorded. Monitoring locations for Phase I and Phase II are shown in Table 1 and Figure 3 (Glenn and Bare, 2019). Once samples were collected by field staff, they were transferred to the National Water Quality Laboratory (NWQL) for analysis. Laboratory data produced at the NWQL was uploaded directly to the National Water Information System (NWIS). All field data and lab data results were reviewed and quality assured by USGS. Following data verification and validation, the data were exported from NWIS, and the final distribution-ready data report was electronically sent to the HARC Project/Data Manager. The final data set was further reviewed by the HARC Project/Data Manager for inconstancies and abnormalities prior to analysis.

Table 1. **Sampling station locations for Phases I and II**

Station Name (ID)	Phase	Latitude	Longitude	System Class
Trinity River near Riverside (10914)	I	30.859722	-95.398331	Upper
Livingston Reservoir Site DC (14008)	I	30.755833	-95.131943	Reservoir
Livingston Reservoir Site BC (14005)	I & II	30.659721	-95.098335	Reservoir
Trinity River near Goodrich (10897)	I & II	30.570995	-94.949577	Lower

Before the initiation of sample collection, a monitoring plan was developed by HARC and the USGS. The plan determined the monitoring program design and methods, including sample collection frequency, target flows, specific sampling procedures, and laboratory methods for water and sediment quality analyses. Protocols were outlined to ensure that samples would be representative of the conditions in question and that the objectives aligned with the study goals. An adequate level of quality control and assurance was integrated to ensure that the final data results were robust, of high quality, and could be incorporated into scientific studies. The Water and Sediment Quality Sampling sections provide further details about quality assurance/quality control (QA/QC) protocols.

The USGS Trinity River near Riverside stream gage above the Lake Livingston reservoir was evaluated to determine when high flow event conditions occurred (Figure 3). The USGS Riverside stream gage is a continuous stream gage maintained by USGS (https://waterdata.usgs.gov/monitoring-location/08066000). A review of historical gage heights from the Riverside station indicated that high flow (above 132 ft) occurs approximately four to six times per year, with three events above 134 ft occurring annually. If the minimum thresholds for the flow event were met and the safety of the field crew was ensured, a sampling trip occurred. The USGS Project Chief and HARC Project/Data Manager communicated before a sampling event. In addition to the flow event monitoring, one ambient flow sediment survey was collected in the summer of 2021 to capture sediment nutrient concentrations while the Lake Livingston reservoir was in a summer stratification period.



Esri, HERE, Garmin, FAO, USGS, EPA, NPS

Figure 3. **United States Geological Survey Lake Livingston Phase I and II monitoring site locations. Inset shows sample locations within the Trinity River Basin.**

3.1.2 Sample schedule

The 16-month sampling period began on 03/01/2021 and reached completion on 09/09/2022. The sampling period encompassed two spring seasons and a fall season when high flow events have historically occurred. The monitoring conducted for this project was targeted to capture five high and one ambient flow event water as well as one high and one ambient flow sediment quality sample (Figure 4).

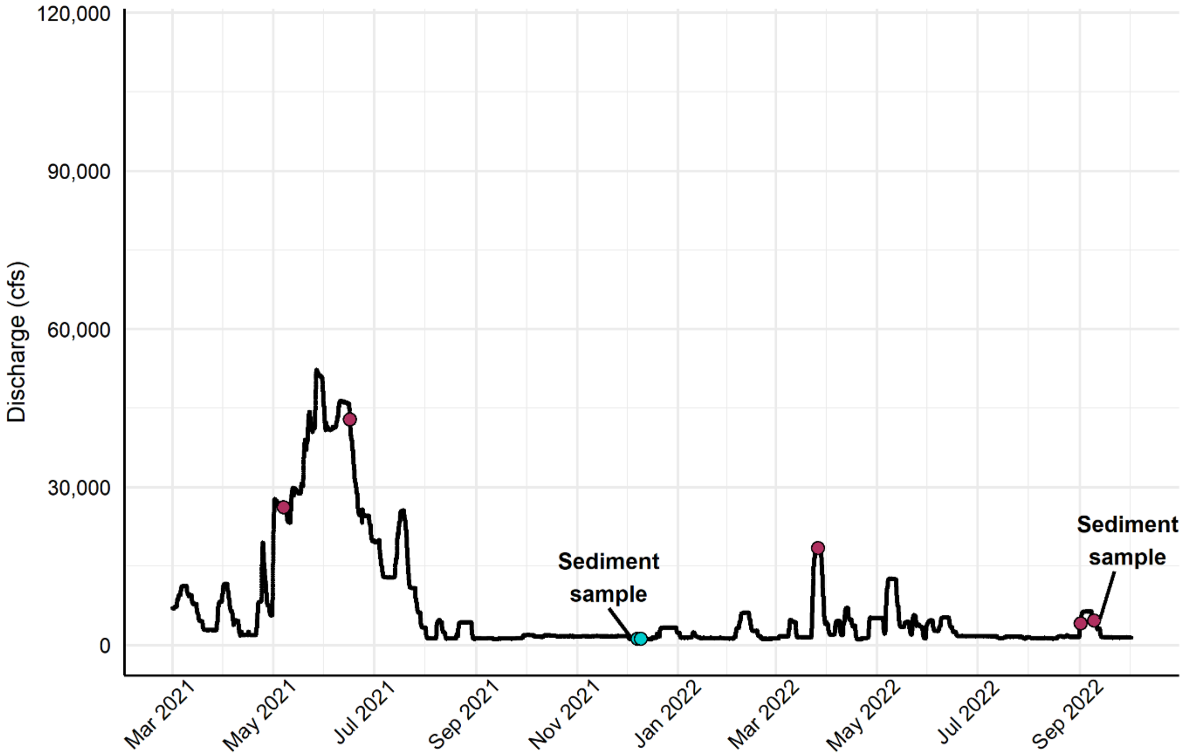


Figure 4. **Discharge measured at the United States Geological Survey Trinity River near Goodrich (08066250) stream gage during the Phase II sampling period from March 2021 through September 2022. Event/high flow (maroon) and ambient/base flow (teal) sample collection dates are shown. Sediment samples were collected on 12/7/2021 (ambient/base flow) and 9/9/2022 (event/high flow). Note that there are seven sample dates because ambient samples were collected from the Livingston Reservoir Site BC on 12/7/2021 and the Trinity River near Goodrich station on 12/9/2021.**

Phase I data were also utilized in this report from the sampling period which began on 05/03/2016 and ended on 08/21/2018 (Glenn and Bare, 2019) (Figure 5). Sediment samples were not collected during the Phase I sampling period. Rainfall from Hurricane Harvey at the end of August 2017 resulted in the largest discharge event (110,000 cfs on 08/29/2017) during both the Phase I and Phase II sampling periods (Glenn and Bare, 2019) (Figure 4 and Figure 5).

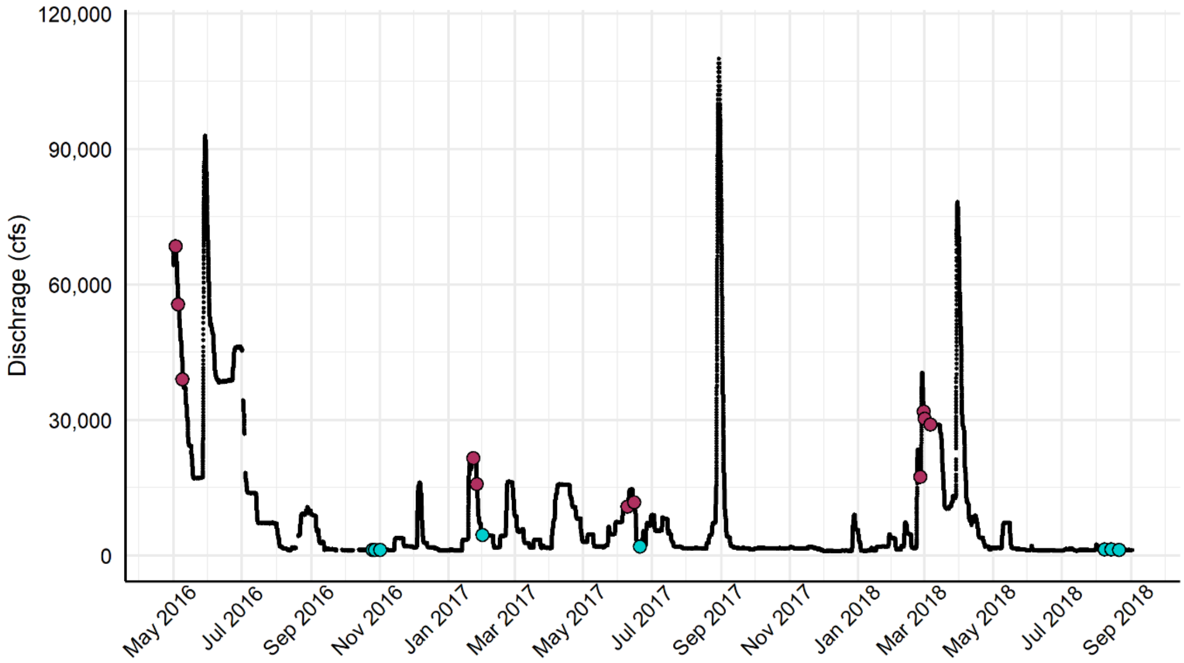


Figure 5. **Discharge measured at the United States Geological Survey Trinity River near Goodrich (08066250) stream gage during the Phase I sampling period from May 2016 through August 2018. Event/high flow (maroon) and ambient/base flow (teal) sample collection dates are shown.**

3.2 Water quality sampling

Water quality sampling consisted of six sets of three sample types for a total of eighteen samples at two monitoring stations (Figure 3). Five water quality sample sets were collected during high flow events while an additional sample was collected during ambient flow (Table 2). Each water quality sampling set collected from the Livingston Reservoir Site BC consisted of one sample collected at site BC near the surface (~10 ft) and one sample collected at site BC at depth (~30 ft).

Table 2. **Water quality sample collection dates and types**

Sample Collection Date	Quantity	Sample Type
5/7/2021	1 set	Elevated Flow Water Quality
6/16/2021	1 set	Elevated Flow Water Quality
12/7/2021; 12/9/2021	1 set	Ambient Water Quality
3/26/2022	1 set	Elevated Flow Water Quality
9/1/2022	1 set	Elevated Flow Water Quality
9/9/2022	1 set	Elevated Flow Water Quality

These environmental samples were supported by six QA/QC samples, two blanks, and four replicates. Field quality-control samples are submitted separately to the laboratory and reported accordingly, on the data reports for validation purposes. All water quality parameters, except for the two suspended sediment parameters, were assessed at the NWQL. The two suspended sediment parameters were assessed at the USGS Kentucky Sediment Laboratory (USGS KSL) (Table 3).

Table 3. **Water quality parameters collected. All water quality parameters except for suspended sediment were assessed at the National Water Quality Laboratory (NWQL). Suspended sediment samples were assessed at the USGS Kentucky Sediment Laboratory (USGS KSL).**

Parameter	Units	Method & Citation Link	Storet Code	NWIS Parameter Code	Lab
NH_3-N	mg/L	USGS I-2525-90	00608	00608	NWQL
NO_2-N	mg/L	USGS I-2540-90	00613	00613	NWQL
NO_3-N+NO_2-N	mg/L	USGS I-2547-11	00631	00631	NWQL
Phosphorous, total	mg/L	USGS I-4610-91	00665	00665	NWQL
Phosphorus, orthophosphate	mg/L	USGS I-2601-90	00671	00671	NWQL
Total Organic Carbon	mg/L	Std Methods 5310B	00680	00680	NWQL
Dissolved Organic Carbon	mg/L	Std Methods 5310B	00681	00681	NWQL
Total Suspended Carbon	mg/L	EPA-NERL 440.0		00694	NWQL
Total Suspended Nitrogen	mg/L	EPA-NERL 440.0		49570	NWQL
Absorbance, 254 nm, wf	u/cm	Std Methods 5910B	N/A	50624	NWQL
Absorbance, 280 nm, wf	u/cm	Std Methods 5910B	N/A	61726	NWQL
Total nitrogen, wf	mg/L	USGS I-2650-03		62854	NWQL
Total nitrogen, wu	mg/L	USGS I-4650-03		62855	NWQL
Suspended Sediment % <0.0625mm	%	ASTM D3977-97	80154	70331	USGS KSL
Suspended Sediment Concentration	mg/L	ASTM D3977-97		80154	USGS KSL
Suspended Sediment Mass	g	ASTM D3977-97		91157	USGS KSL
Suspended Sediment Mass <63 um	g	ASTM D3977-97		91158	USGS KSL
Suspended Sediment Mass >63 um	g	ASTM D3977-97		91159	USGS KSL

3.3 Sediment quality sampling

The sediment quality sampling conducted for this study consisted of two sets of five samples collected in a grid pattern around site BC for a total of ten samples. One ambient flow survey and one post high flow event survey were conducted (Table 4). The ten environmental samples were supported by four replicate quality control samples. Each sample was analyzed for select nutrients corresponding to the water quality parameters (suspended sediment and UV absorption were omitted) (Table 5).

Table 4. Sediment sample collection dates

Sample Collection Date	Discharge Category	Quantity
12/7/2021	Ambient Flow	1 set
9/9/2022	Elevated Flow	1 set

Table 5. Sediment parameters collected

Parameter	Units
NH3-N	mg/Kg-dry
NH3-N+organic-N	mg/Kg-dry
Phosphorous, total	mg/Kg-dry
Phosphorous, orthophosphate	mg/Kg-dry
NO2-N	mg/Kg-dry
NO3-N	mg/Kg-dry
Organic-C	mg/Kg-dry
Moisture Content, dry	%

3.4 Field surveys and depth profiles

Each water quality sample was accompanied by a depth profile at site BC. The equal-width-increment method was used to obtain discharge-weighted water samples at the Trinity River Goodrich site (U.S. Geological Survey, 2018). For this sampling method, the river cross-section was divided into a predetermined number of equal-width increments. At the center of each increment, discharge-weighted subsamples were collected across a vertical profile and then combined into a composite sample. The subsample volume collected at each increment was proportional to the discharge. Therefore, the composite sample was proportional to the total streamflow. Each transect survey and depth profile parameters are listed in Table 6.

Table 6. Parameters collected via transect surveys and depth profiles

Parameter	Units
pH	pH units
Temperature	°C
Conductivity	uS/cm
Dissolved Oxygen	mg/L
Turbidity	FNU
Nitrate	mg/L

The instrumentation used to conduct the field surveys and depth profiles consisted of a YSI 6920 multi-parameter sonde equipped with sensors to measure temperature, specific conductance, pH, dissolved oxygen, and turbidity. The sondes used were calibrated in the lab immediately before each field data collection event and verified again after the field event was conducted. Each sensor calibration was carried out and documented according to the USGS National Field Manual (U.S. Geological Survey, 2018).

In addition to the multi-parameter sonde, a Trios Nico nitrate sensor was used to record Nitrate in mg/L as N. This instrument is set to a 10 mm pathlength, giving it an effective operating range of 0 to 6.0 mg/L as N, with a detection limit of 0.05 mg/L. This is a relatively new technology not often used for field surveys in the manner of a multi-parameter sonde, so published procedural guidance is not available beyond that provided by the manufacturer. The calibration of the Nico was checked prior to each field event using 1 mg/L nitrate standard and verified after the field data collection event.

3.5 External data acquisition

In addition to the field monitoring data collected by the USGS, several other non-direct sources of data were incorporated. The Phase I study dataset collected by the USGS was utilized to bolster the number of samples available for analysis (Glenn and Bare, 2019). Historical physicochemical field water quality, suspended sediment, and nutrient data were obtained from the TCEQ's Surface Water Quality Monitoring Information System (SWQMIS) (TCEQ, 2022). To support the analyses, historical discharge and gage height (ft) were acquired from the USGS Trinity River near Goodrich (08066250; https://waterdata.usgs.gov/monitoring-location/08066250) (Figure 4 and Figure 5). Lastly, monthly precipitation data was exported from Texas Water Development Board's

(TWDB) Water Data for Texas Lake Evaporation and Precipitation data page ("TWDB," 2022). Rainfall data from Quad ID 712, which includes Lake Livingston, was incorporated for analysis (to view the TWDB Quad map, see https://waterdatafortexas.org/lake-evaporation-rainfall).

To further support the historical rainfall data evaluation, historical crest and drought period data were obtained. Historical crest data recorded as gage height (ft) above major flood state (41 ft) at the USGS Trinity River near Goodrich (08066250) stream gage station were obtained from the Advanced Hydrologic Prediction Service of the National Weather Service (NWS). Drought data were obtained from the National Oceanic and Atmospheric Administration's National Integrated Drought Information System (NOAA NIDIS) to identify abnormally dry seasons.

3.6 Analysis

All analysis and data processing were performed using the software tools JMP Pro 15.2.0, ArcGIS Pro 2.9.2, Program R version 4.2.1, and SQL.

3.6.1 Data processing

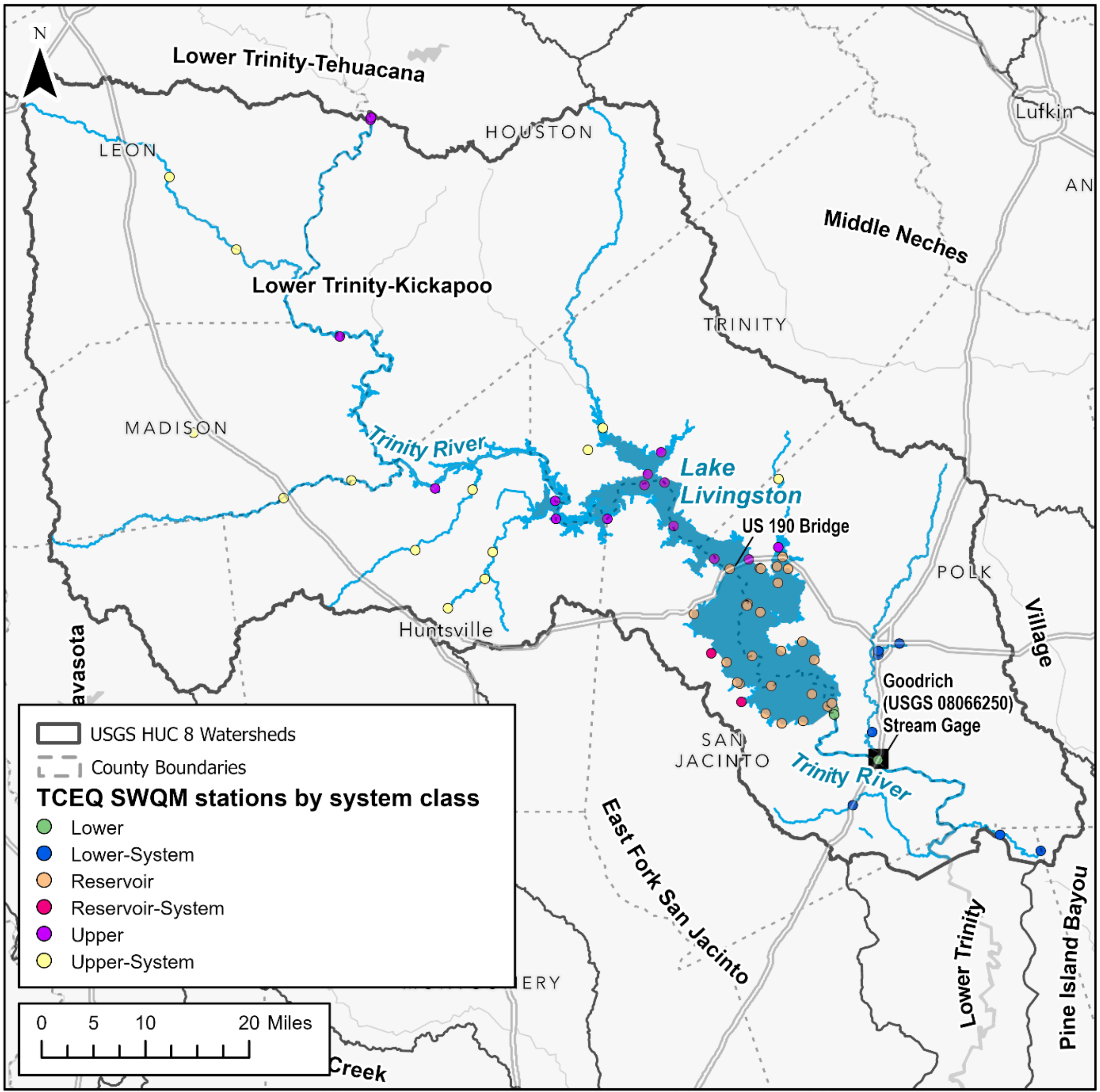
For this study, the USGS Hydrologic Unit Code (HUC) 8 Lower Trinity-Kickapoo Watershed was utilized as a spatial analysis unit. A historical database was developed for analysis by creating a systems classification attribute to spatially associate water quality monitoring stations with the Upper (Trinity River upstream of the US-190 bridge), Reservoir, and Lower (Trinity River downstream of Lake Livingston Dam) as representatives of the main Lake Livingston system components. Based on the drifter results and the previous Phase I study, the US 190 causeway was used as a boundary for the Phase II study's Lake Livingston Upper Trinty River and Reservoir systems classification boundaries (Glenn and Bare, 2019) (Figure 6). Second-order classes (Upper-System, Reservoir-System, and Lower-System) were assigned to categorize the remaining water quality monitoring stations not located in the main system classes. The secondary station classifications are representative of tributaries that drain directly to the waterways of the main system. Some streams flow directly into the Lake Livingston Reservoir and are classified as part of the Reservoir-System (Figure 6).

In addition to the spatial classifications, a temporal attribute was created to represent the seasonal influence of meteorological conditions by grouping months into seasonal periods for Winter (December from the previous year, January, and February), Spring (March, April, and May), Summer (June, July, and August), and Fall (September, October, and November). The seasonal attribute was assigned to each coordinated historical water quality record. A second field was created to associate Goodrich discharge values with related water quality records based on the nearest 15-minute discharge value at the time of water quality sample collection. The Goodrich gage station was utilized as an overall proxy for flow through the Lake Livingston system and is representative of the volume of water flowing downstream towards Trinity Bay.

Additionally, historical discharge data from the Goodrich gage station was used to create an attribute representing three seasonally adjusted discharge classifications (Base, Moderate, and High) (Table 7). Thresholds were established for each discharge class by sorting the historical discharge data by season and evaluating breaks at predetermined percentiles. Water quality records were then grouped into one of the three seasonally adjusted discharge classifications based on the discharge at the time of sample collection. This approach was based on the TCEQ Environmental Flow Standards for Surface Water which accounts for seasonal and interannual variations of precipitation by assigning defined measurement points to discharge data (TCEQ, 2011).

Table 7. **Seasonally adjusted discharge categories and streamflow range in cubic feet per second (cfs)**

Season	Base (cfs)	Moderate (cfs)	High (cfs)
Spring	324 - 2,210	2,211 - 19,100	> 19,101
Summer	617 – 1,230	1,231 – 6,890	>6,891
Fall	365 – 1,050	1,051 – 3,280	>3,281
Winter	589 – 1,590	1,591 – 14,400	>14,401



Baylor University, Texas Parks & Wildlife, CONANP, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS

Figure 6. **Texas Commission on Environmental Quality (TCEQ) Surface Water Quality Monitoring (SWQM) stations on the main Lake Livingston system (Upper, Reservoir, and Lower) and tributaries (Upper-System, Reservoir-System, and Lower-System) by class. The Upper-System SWQM station located southwest of the Upper Trinity River in the Lower Trinity Kickapoo watershed is located on Madisonville Lake (reservoir) and is hydrologically connected (not shown) to the Trinity River via Town Branch, a tributary of Caney Creek which flows into Bedias Creek, a tributary of the Upper Trinity River.**

The three physiochemical water and quality parameters of focus for the historical analysis were total suspended sediment (TSS)(mg/L) (n=5,851), total phosphorus (TP) (mg/L) (n=5,682), and total nitrate (TN) (mg/L as nitrogen) (n=4,015). The period of record selected for the water quality data was 1972-2020, as there were no data for all three parameters for 1971 and the reservoir did not reach full capacity until November 1st, 1971 ("Water Data For Texas," 2022). One outlier (95 mg/L, Record Number: 2600980) was excluded from the TP (Parameter Code: 00665) dataset. One outlier (500,000,000 mg/L, Record Number: 3155659) that was likely due to a reporting error in the Surface Water Quality Monitoring (SWQM) data was excluded from the TSS (Parameter Code: 00530) dataset.

3.6.2 Analysis methods

The annual average concentrations for the three physiochemical parameters (see section 4.1.2 Water quality trends) were compared visually to total annual precipitation levels (see section 4.1.1 Precipitation and discharge events) to represent how these parameters have changed over time between 1972 and 2020. Only water quality data collected from the main Lake Livingston system (Upper, Reservoir, and Lower) were included in the annual average concentration plots. Annual averages were not calculated for years when there were fewer than 10 water quality samples for each parameter of interest because there weren't enough data points to represent the annual period. Flux was not calculated for the historical data because not all concentrations have an associated discharge measurement.

Boxplots further investigate the relationship between the concentrations of the three physiochemical parameters of all system classifications (Upper, Upper-System, Reservoir, Reservoir-System, Lower, Lower-System). All data above the 90th percentile were excluded from the plots to facilitate comparisons between system classes due to the large number of values above this threshold. However, all concentration values except for the outliers previously discussed were included in the calculation of the mean, median, Interquartile Range (IQR), and sample size, as well as in all analyses and results. The ranges and the count of values above the 90th percentile by system class and water quality parameter are shown in 8 Appendix, Table 11.

4 Results

4.1 Historical analysis

4.1.1 Precipitation and discharge events

The annual average precipitation between 1972 and 2020 for Quad ID 712 was 47.9 inches. There were eight years (1973, 1979, 1991, 2001, 2004, 2015, 2017, 2018) with above average (+1 Standard Deviation (SD) above the mean) precipitation for the area surrounding the reservoir. Most of the above-average total precipitation occurred in the last 20 years (Figure 7). Tropical Storm Claudette impacted eastern Texas in July of 1979, which was the only year with total rainfall exceeding +1SD above the mean that did not correspond to a historic crest at the Goodrich station (Figure 7). In October of 1994, record high levels were reported for Lake Livingston and a release of 110,000 ft^3/s resulted in the highest crest on record (48.97 ft recorded on 10/18/1994). The second highest crest on record (48.34 ft) occurred because of Hurricane Harvey on 8/30/2017. In 2018, three different historic crests were recorded in the spring, fall, and winter.

Table 8. **Historic crests on the Trinity River as measured at the Goodrich station**

Date	Gage Height (ft)
6/14/1973	46.36
1/16/1991	38.63
10/18/1994	48.97
6/10/2001	41.41
7/2/2004	35.33
5/28/2015	39.53
8/30/2017	48.34
10/20/2018	40.81
3/20/2018	37.48
12/9/2018	37.48

There were 45 crests recorded at the Goodrich station as reported by the NWS. Four of these crests occurred before 1972 (1966, 1968, 1969, 1971). However, the remaining 41 crests that occurred during the period of record (1972-2020) were utilized to develop the historical water quality data set. Only 10 years with total rainfall greater than one SD above the mean (57.7 inches) corresponded with dates of the historic crests at the Goodrich station (USGS 08066250) (Table 8).

The lowest total annual precipitation (22.4 inches) was recorded in 2011, which was during the peak of the 2010-2015 drought. All years with total precipitation one SD below the mean (38.1 inches) occurred in years that were abnormally dry or under drought conditions as reported by the (NOAA NIDIS). These years were 1977, 1978 (slightly above -1SD), 1980, 1988, 1996, 1999, 2005, 2010 and 2011 (Figure 7).

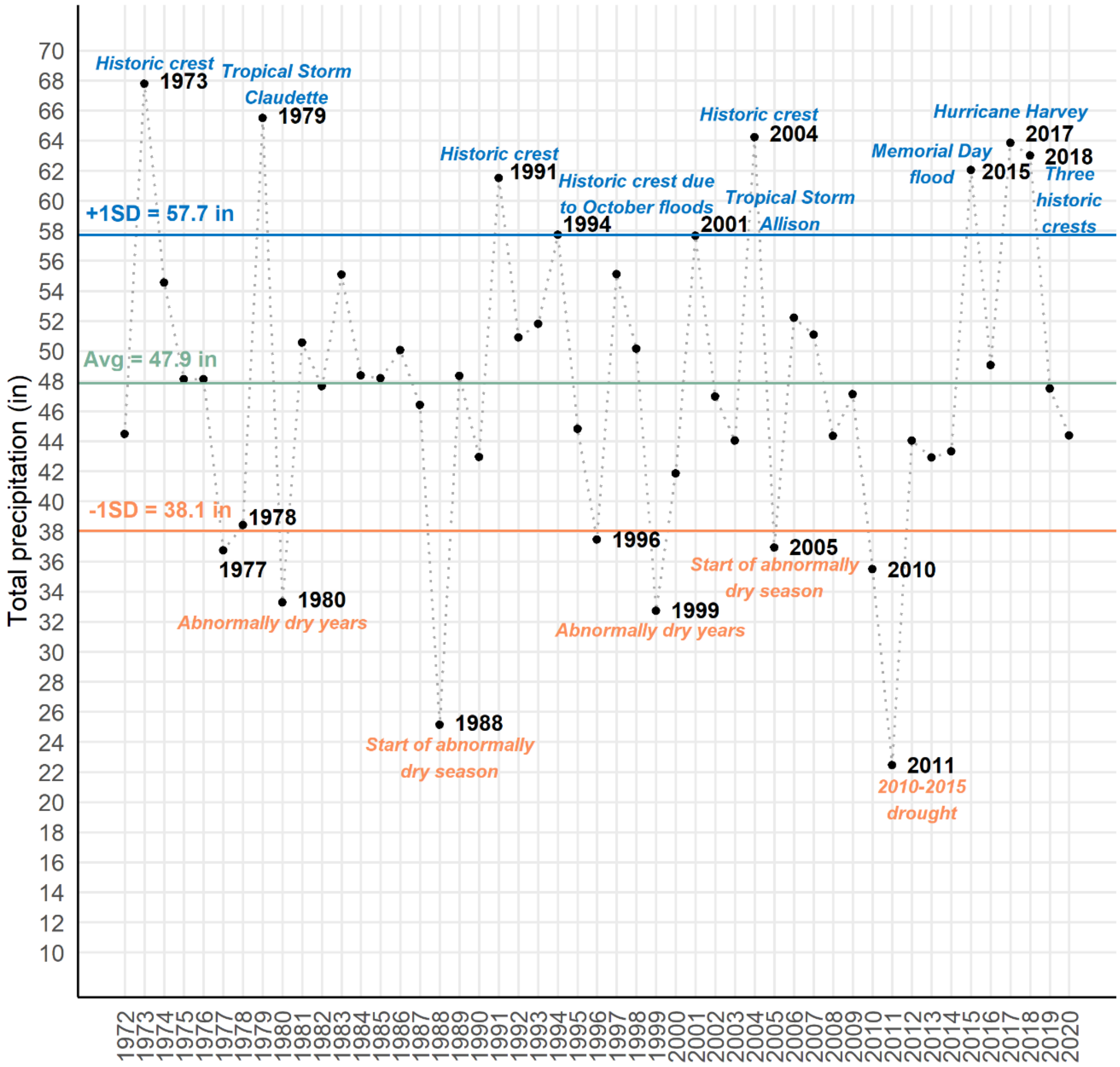


Figure 7. **Total precipitation by year (1972-2020) Texas Water Development Board Quad ID 712 (see [https://waterdatafortexas.org/lake-evaporation-rainfall for TWDB Quad map](https://waterdatafortexas.org/lake-evaporation-rainfall)). Historic crests reflect gage height (ft) data above major flood stage (41 ft) recorded at the Goodrich Station (USGS 08066250) and reported by the Advanced Hydrologic Prediction Service of the National Weather Service. Total rainfall +1SD above the mean is annotated in blue. Abnormally dry seasons were identified with data from National Oceanic and Atmospheric Administration's National Integrated Drought Information System (orange). Major flood, storm, and drought events are identified. Average precipitation is shown in green.**

4.1.2 Water quality trends

The highest annual average TP concentration (1.75 mg/L) occurred early in the historical record in 1972 (Figure 8). However, most of the 1972 samples (15 out of 21) were collected from the Upper part of the Lake Livingston system which was known to have degraded water quality at the State Highway 21 station (SWQM Station ID: 10917). Also, many of the 1972 samples were collected just after the reservoir reached 100% storage capacity on 11/1/1971 while sample collection first occurred on 1/12/1972. The lowest annual average TP concentration (0.23 mg/L) occurred in 2020, with the five lowest annual average concentrations occurring in the last 5 years of the period of record except for 2018 (2019: 0.24 mg/L, 2017: 0.31 mg/L, 2016:0.24 mg/L, 2015: 0.32 mg/L). Although variable in the early part of the record, overall, the annual average TP concentrations have declined in the main Lake Livingston System (Upper, Reservoir, Lower) after the peak concentrations recorded in the 70s and 80s. There is no apparent pattern in average TP concentrations and total annual rainfall.

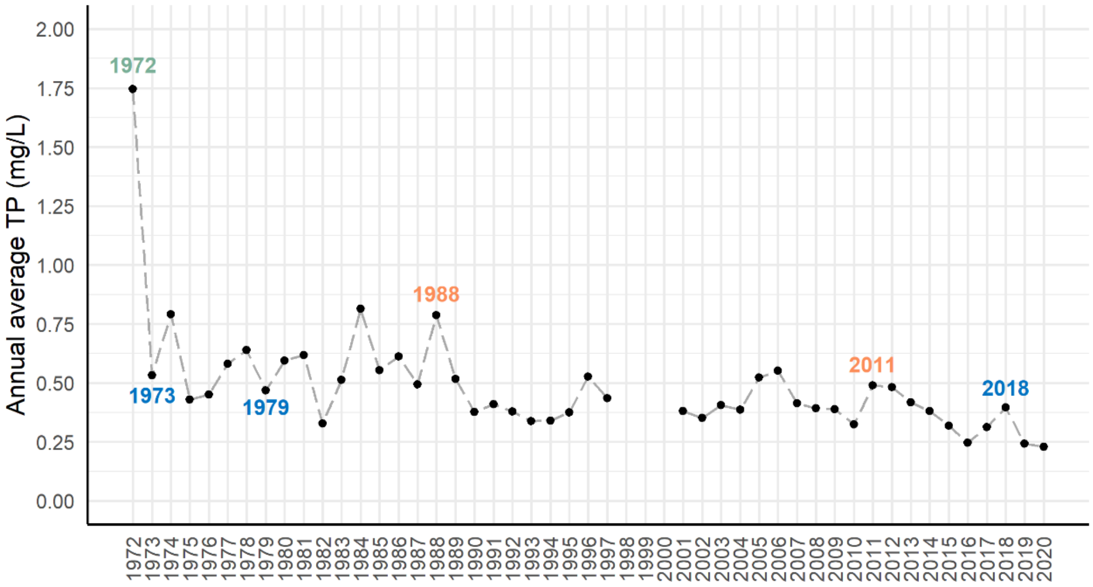


Figure 8. **Annual average total phosphorus (TP) concentrations (mg/L) in the main Lake Livingston system (Upper, Reservoir, Lower) from 1972-2020. Years corresponding with total precipitation values that are ±1SD above or below the mean or with years of high or low annual average TP concentrations are labeled. Years labeled in green have total precipitation near the mean (47.9 inches). Years labeled in orange have total precipitation -1SD below the mean (38.1 inches). Years labeled in blue have total precipitation +1SD above the mean (57.7 inches).**

The annual average TN concentration in 1972 was the second highest (2.97 mg/L) in the period of record (Figure 9). The highest annual average TN concentration (3.58 mg/L) occurred in 2012 and the lowest annual average TN concentration (0.30 mg/L) occurred in 1989. There are two distinct temporal clusters of mean TN concentrations separated by a seven-year data gap. Annual average TN concentrations in the main Lake Livingston system (Upper, Reservoir, Lower) from the early decades (1970s and 1980s) to the later decades (1990s, 2000s, 2010s) rose slightly. No apparent relationship was observed between the historical annual average TN concentrations and total annual rainfall.

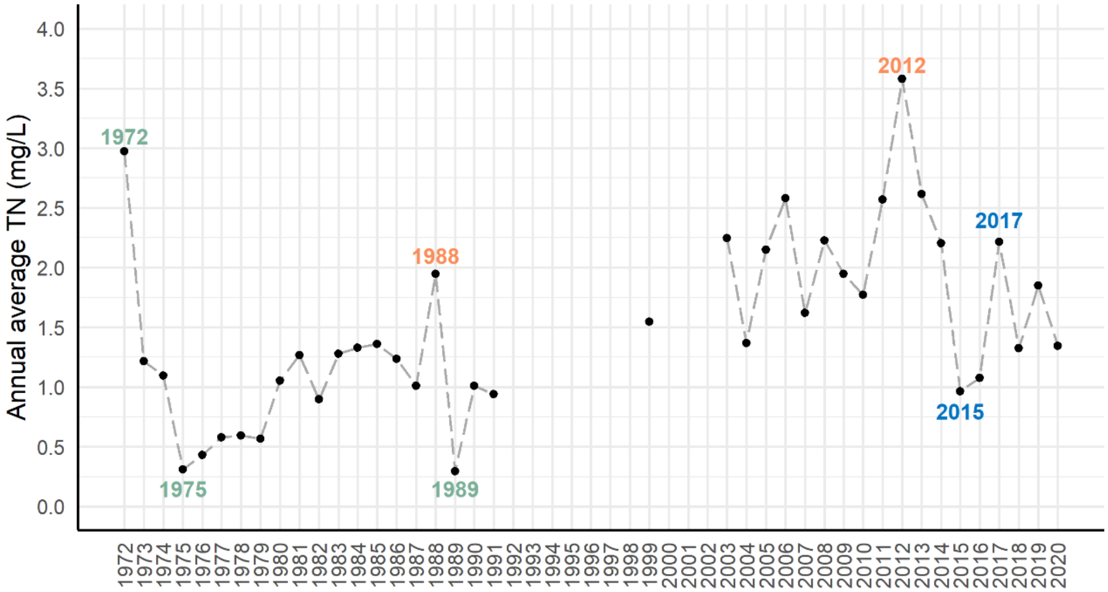


Figure 9. **Annual average total nitrate (TN) concentrations (mg/L) in the main Lake Livingston system of (Upper, Reservoir, Lower) from 1972-2020. Years corresponding with total precipitation values that are ±1SD above or below the mean or with years of high or low annual average TN concentrations are labeled. Years labeled in red have total precipitation near the mean (47.9 inches). Years labeled in gold have total precipitation -1SD below the mean (38.1 inches). Years labeled in blue have total precipitation +1SD above the mean (57.7 inches).**

The lowest mean TSS concentration (28.3 mg/L) in the main Lake Livingston system for the period of record was measured in 1977. The lowest average TSS concentrations were observed primarily in drought years, with peaks occurring in years with average or above average (+1SD above the mean) rainfall. The highest mean TSS concentration (173.8 mg/L) occurred in 2015 (Figure 10). In recent decades higher average concentrations were observed compared to historical concentrations observed in the 1970s, 1980s, 1990s, and 2000s. Overall, annual average TSS concentrations in the main Lake Livingston system (Upper, Reservoir, Lower) have been highly variable.

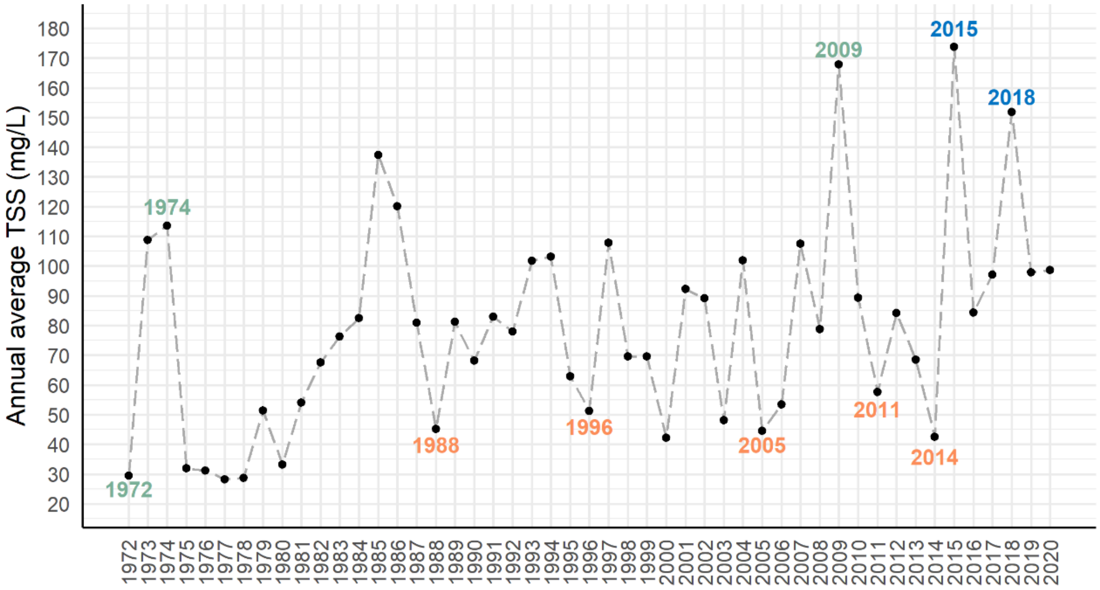


Figure 10. **Annual average total suspended sediment (TSS) concentrations (mg/L) in the main Lake Livingston system (Upper, Reservoir, Lower) from 1972-2020. Years corresponding with total precipitation values that are ±1SD above or below the mean or with years of high or low annual average TSS concentrations are labeled. Years labeled in red have total precipitation near the mean (47.9 inches). Years labeled in gold have total precipitation -1SD below the mean (38.1 inches). Years labeled in blue have total precipitation +1SD above the mean (57.7 inches).**

4.1.3 Spatial assessment of historical trends

The highest median TP concentration (0.53 mg/L) was from the Upper Lake Livingston system. However, the greatest TP concentrations were observed in the Upper-System, which had a high amount of variability (IQR=1.36) when compared to the other system classes. There was a decreasing pattern along a longitudinal gradient from the Upper Lake Livingston system to the Lower-System tributaries in median TP concentrations. In general, the main Lake Livingston system (Upper, Reservoir, Lower) had higher median TP concentrations compared to the tributaries (Upper-System, Reservoir-System, Lower-System). The mean values showed a similar trend, except for the Upper-System, which had a higher mean (1.22 mg/L) than the Upper Lake Livingston system (0.78 mg/L). Sample sizes were small for the Reservoir-System (n=95), Lower (n=696), and Lower-System (n=239) classes.

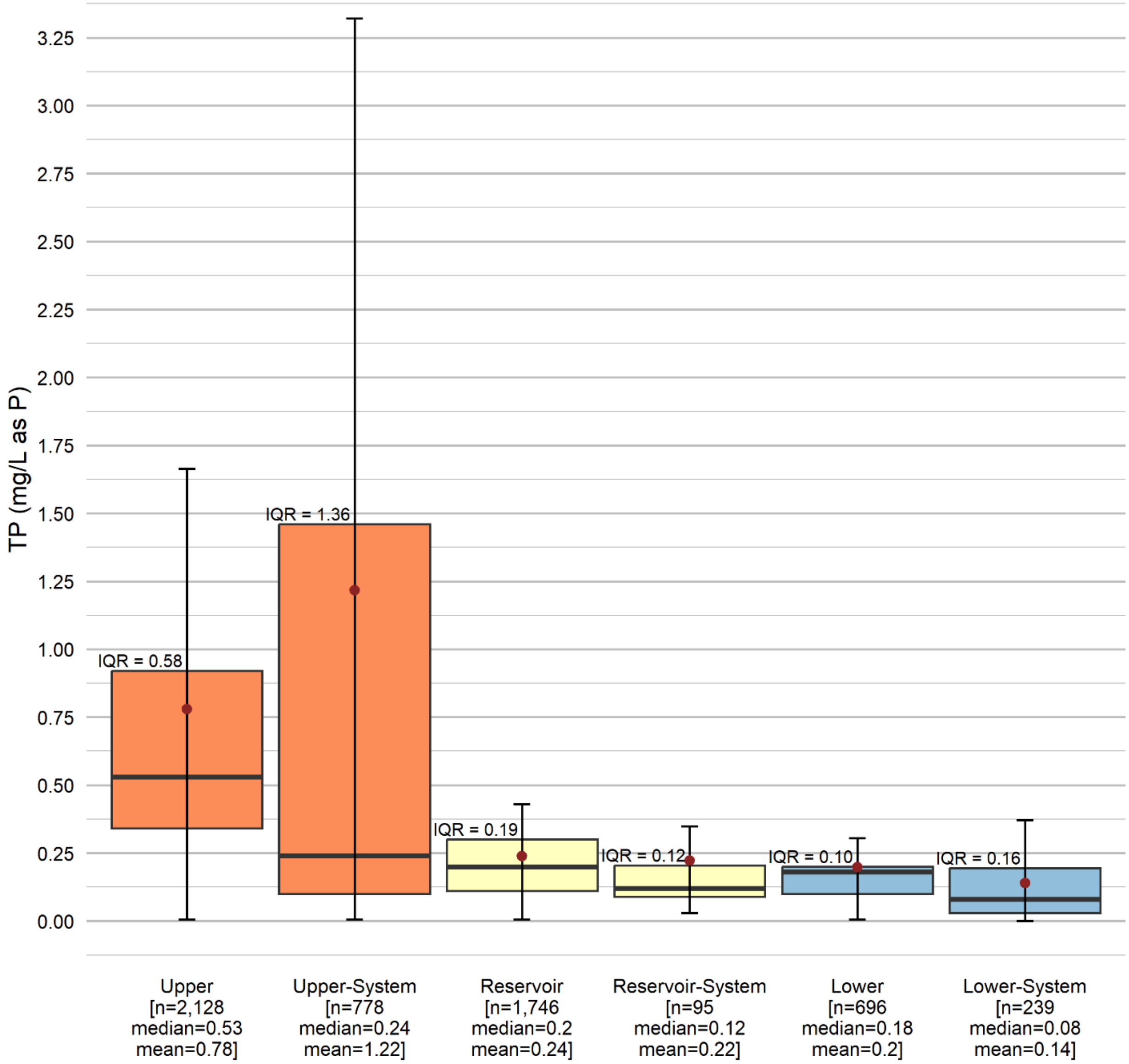


Figure 11. **Boxplots of total phosphorus (TP) (mg/L as P) by system class (see Section 2.6.1 for system class description) from 1972-2020. Mean concentrations are represented by the maroon point. Median concentrations are represented by the center line of each boxplot. Concentrations greater than the 90th percentile for each system class are not shown but were included in all analyses and results. The range and count of the values not depicted are shown in 8 Appendix, Table 11. Therefore, the lower whisker represents the minimum and the higher whisker is the 90th percentile.**

The highest median TN concentration (1.45 mg/L) was from the Upper Lake Livingston system (Figure 12). All other median concentrations for this parameter were similar and much lower (0.2-0.08 mg/L). While there were higher median TN concentrations for the main Lake Livingston system versus the tributaries, the Reservoir had a lower median concentration (0.11 mg/L) than the Lower section of the main Lake Livingston system (0.2 mg/L). The Upper Trinity River had the greatest variability in TN concentrations (IQR=2.2 mg/L), while the Reservoir-System had the least variability (IQR=0.07) and the smallest sample size (n=95). The highest mean (2.17 mg/L) TN concentration was present in the Upper Trinity River.

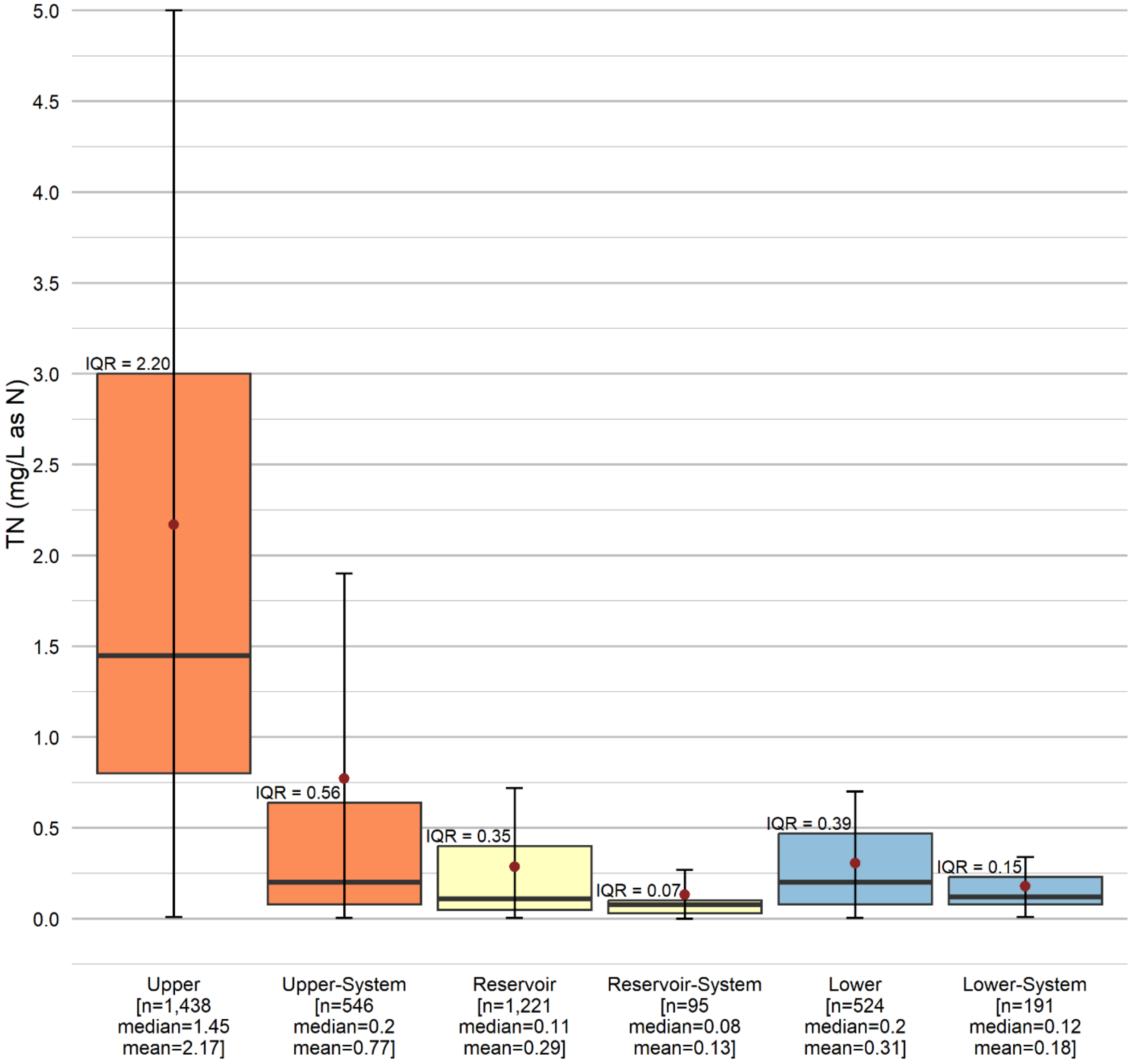


Figure 12. **Boxplots of total nitrate (TN) (mg/L as N) by system class (see Section 2.6.1 for system class description) from 1972-2020. Mean concentrations are represented by the maroon point. Median concentrations are represented by the center line of each boxplot. Concentrations greater than the 90th percentile for each system class are not shown but were included in all analyses and results. The range and count of the values not depicted are shown in Appendix, Table 11. Therefore, the lower whisker represents the minimum and the higher whisker is the 90th percentile.**

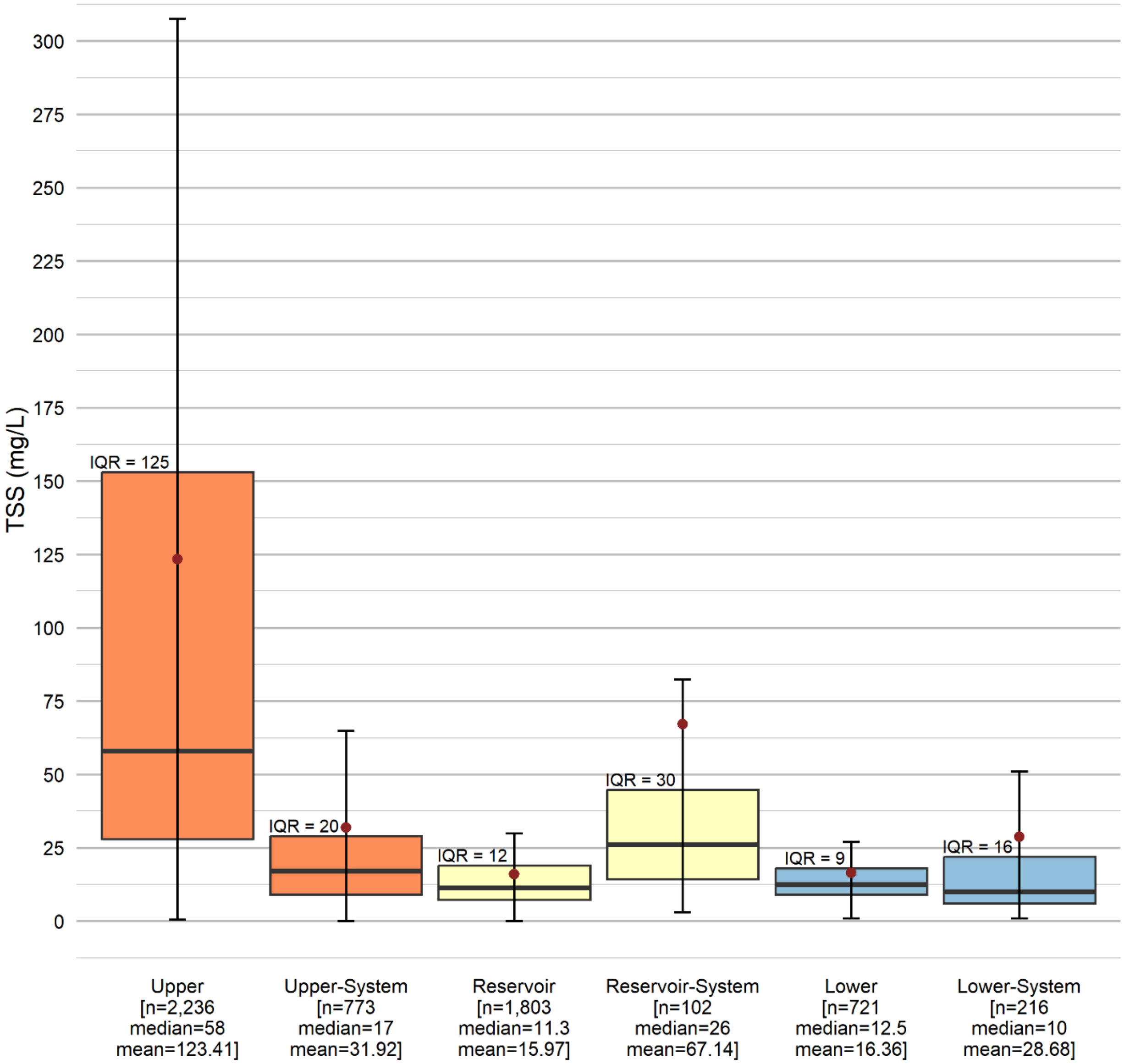


Figure 13. **Boxplots of total suspended sediment (TSS) (mg/L) by system class (see Section 2.6.1 for system class description) from 1972-2020. Mean concentrations are represented by the maroon point. Median concentrations are represented by the center line of each boxplot. Concentrations greater than the 90th percentile for each system class are not shown but were included in all analyses and results. The range and count of the values not depicted are shown in Appendix, Table 11. Therefore, the lower whisker represents the minimum and the higher whisker is the 90th percentile.**

The greatest variability (IQR=125) and highest median TSS concentration occurred in the Upper portion of the Lake Livingston system (58 mg/L). The median for the Reservoir (11 mg/L) was slightly lower than that of the lower Trinity River (12 mg/L). The Reservoir-System had a higher median (26 mg/L) than the Upper-System (17 mg/L) and the

Reservoir (11.3 mg/L) and the Lower Trinity River had a lower median (12.5 mg/L) than the Reservoir-System (26 mg/L) (Figure 13).

4.1.4 Discharge and water quality

Figure 14 shows an inverse relationship between the degree of discharge and average TN concentrations for the Upper Lake Livingston system across seasons. Average TP concentrations and the magnitude of discharge also have an inverse relationship for the Upper Lake Livingston system across seasons. Base flow conditions have the highest average concentrations of nutrients followed by moderate and high throughout the system across seasons. The highest average TN (5.4 mg/L) and TP (0.95 mg/L) concentrations were observed in the Fall during base flow conditions in the Upper Lake Livingston system. The Fall is also when some of the lowest base flow conditions were recorded between 1972 and 2020 ranging from 679 to 1,050 cfs (Figure 14).

A similar trend was observed in the Upper-System (tributaries above US 190). However, there was a slight decline in average TP concentrations at base flow in Summer and a decline in average TN concentrations at base flow in Winter for this system class. There was a slight increase in average TP in base flows compared to moderate flows in the lower tributaries (Lower-System) in Fall. The Reservoir showed an increase in average TN at moderate flows in the Spring.

Figure 15 shows a decreasing trend in average TSS as flow decreases across seasons in the Upper Lake Livingston system. There was one exception, which was a decrease in average TSS from high to moderate flows followed by an increase in average TSS at base flow for the Lower Lake Livingston system in the Fall. However, the Lower-System (tributaries below US 190) showed a decline from high to base flows like that observed for the Upper-System, except that the decline was steeper going from moderate to base flows in the Fall. The Lower-System tributaries had higher average TSS than the Lower Trinity River at high and moderate flows in the Fall and at high flows in the Winter. The average TSS load from the Upper Trinity River is greatly reduced in the Reservoir across discharge levels and seasons.

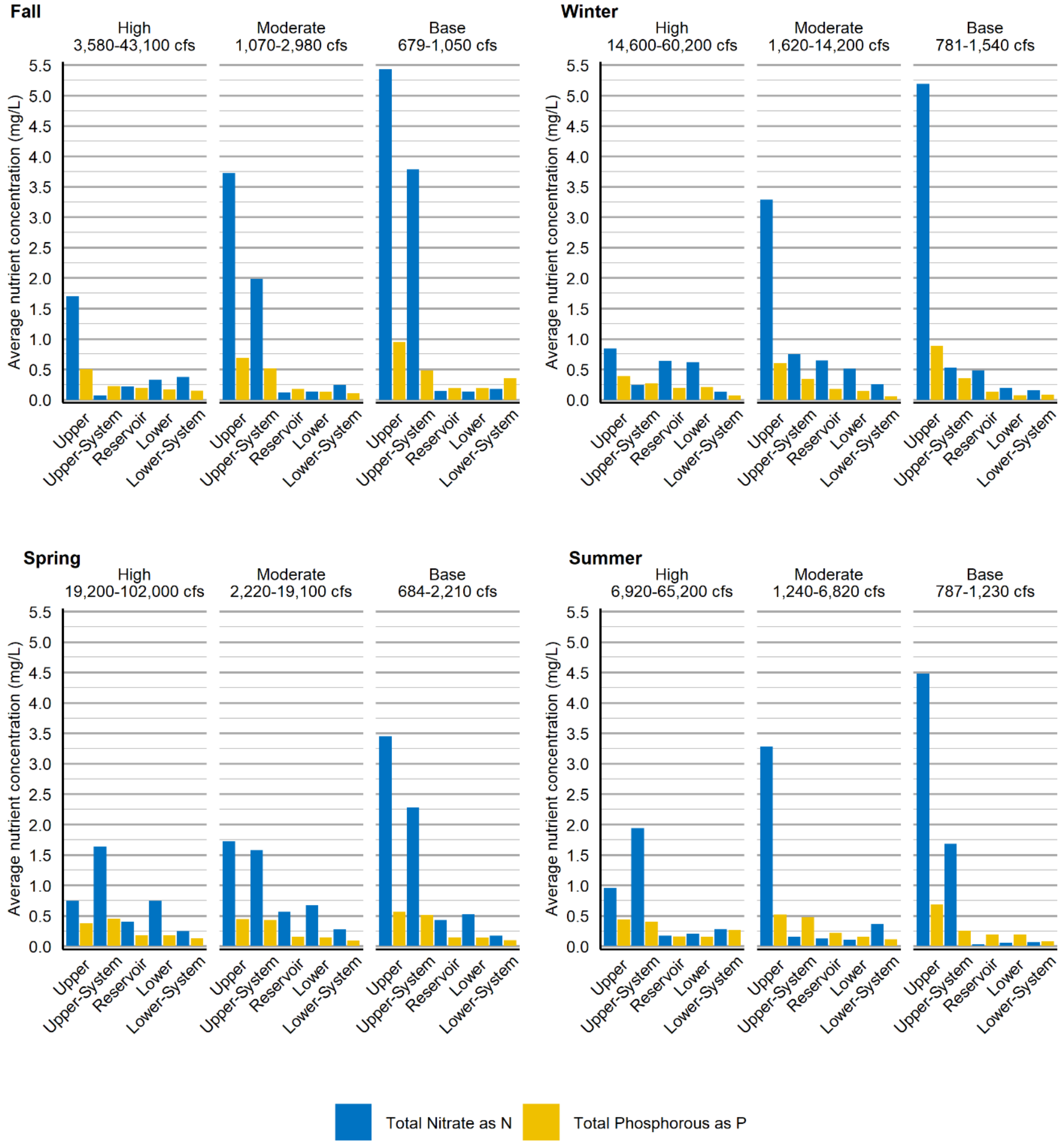


Figure 14. **Average nutrient concentrations by seasonally adjusted discharge (high, moderate, or base) and system class (see Section 2.6.1 for system class description) from 1972-2020. Discharge measured at the United States Geological Survey Trinity River near Goodrich (08066250) stream gage was used as a proxy to assign seasonally adjusted discharge classifications throughout the Lake Livingston system.**

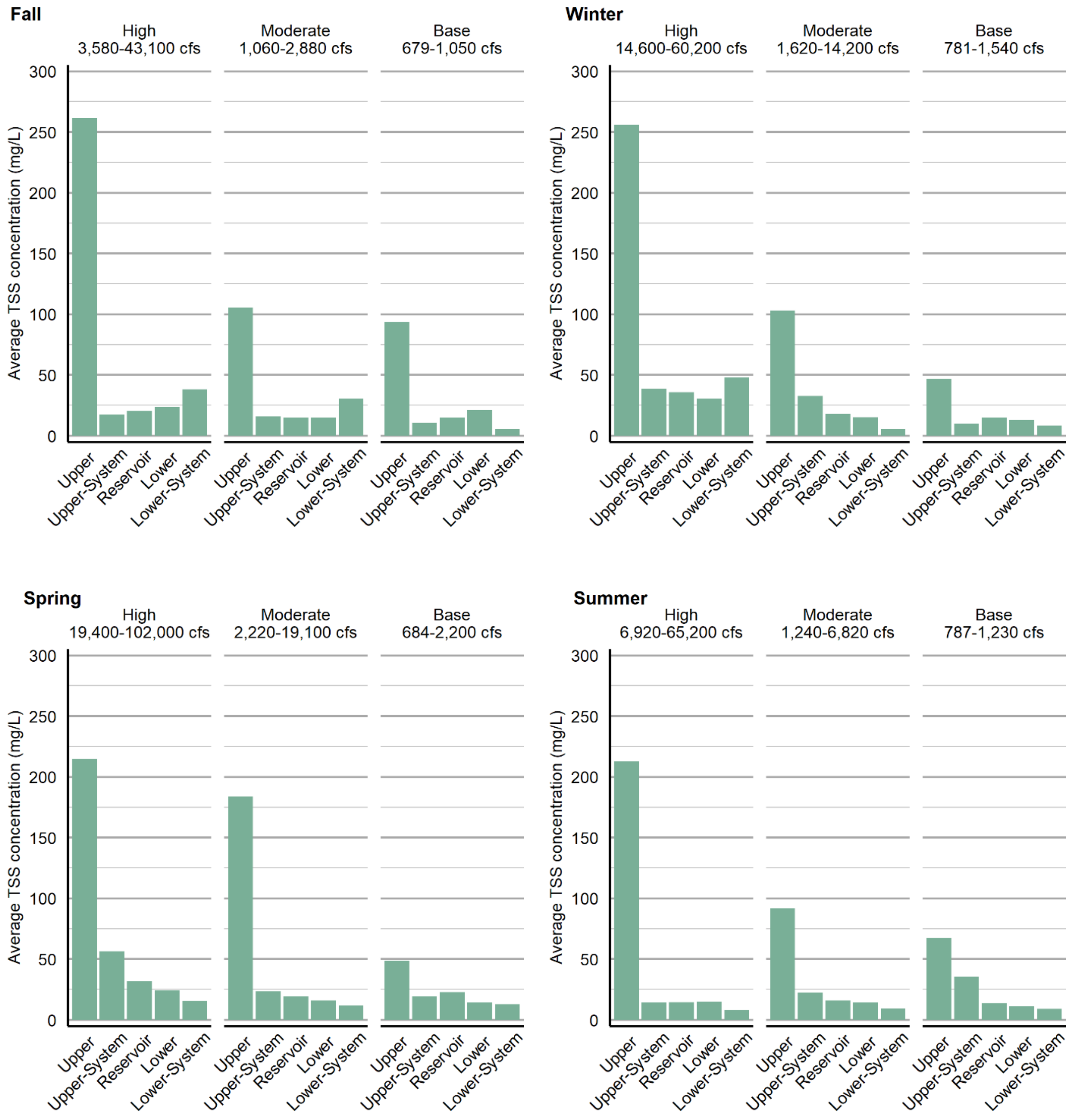


Figure 15. **Average total suspended sediment (TSS) concentrations by seasonally adjusted discharge (high, moderate, or base) and system class (see Section 2.6.1 for system class description) from 1972-2020. Discharge measured at the United States Geological Survey Trinity River near Goodrich (08066250) stream gage was used as a proxy to assign seasonally adjusted discharge classifications throughout the Lake Livingston system.**

4.3 Phase II Study results for nutrient, sediments, and discharge

The maximum discharge measured at the Goodrich station (USGS 08066250) during the Phase II sampling period was 52,300 cfs while the minimum was 1,080 cfs. The highest flow occurred on 05/27/2021 starting at 7:15 AM (Figure 4). The discharge recorded for the two highest nitrate water column samples was 26,200 cfs on 05/7/2021 during the highest discharge event during the study period (Figure 4). The three highest TP concentrations were recorded during two separate sampling dates (06/16/2021 and 09/1/2022). The sample with the highest TP concentration was collected on 06/16/2021 at 30ft with a discharge of 42,900 cfs. This was during the same discharge event that the highest nitrate concentrations were recorded. The other two highest TP concentrations were collected at 10 ft and 30 ft on 09/1/2022 during a recorded discharge of 4,020 cfs (Figure 16 A and B).

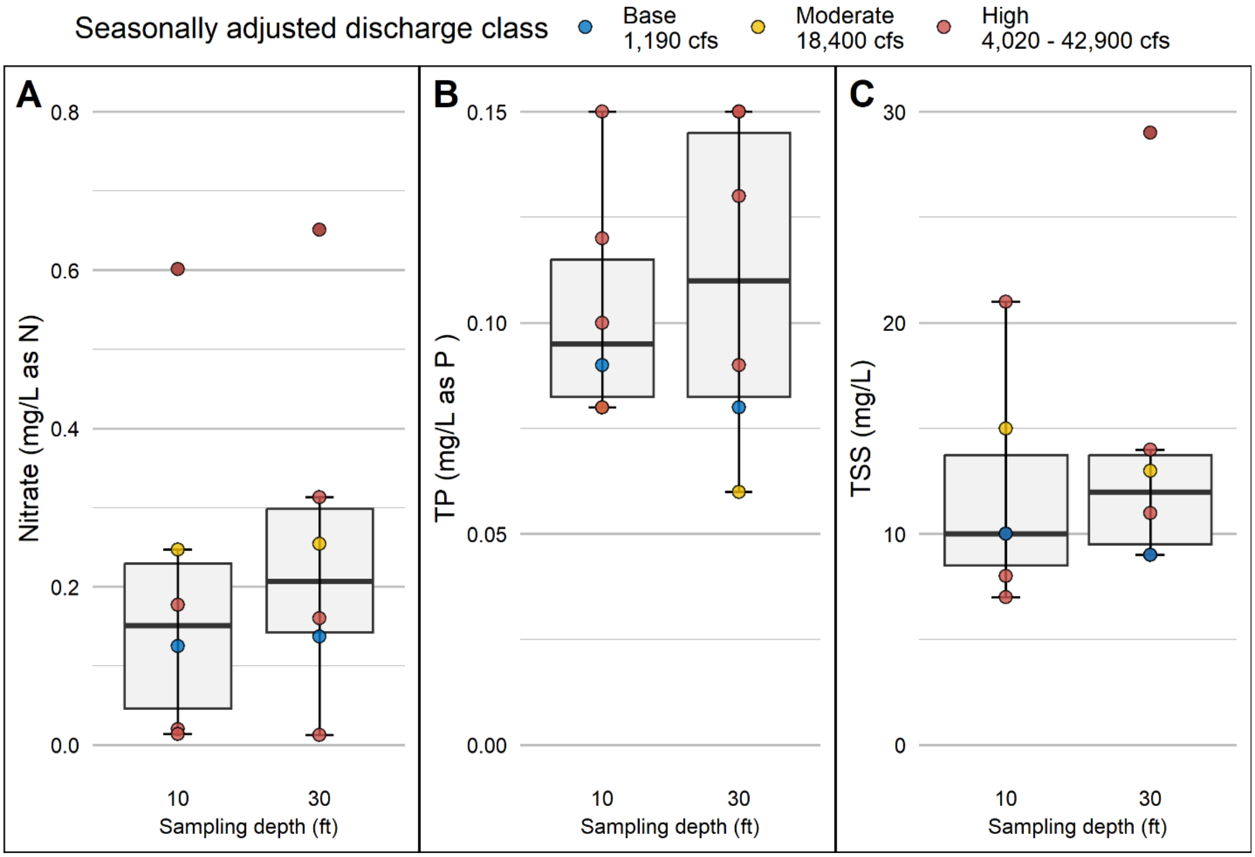


Figure 16. **Boxplots of nitrate, total phosphorus (TP), and total suspended sediment (TSS) concentrations collected at 10 ft and 30 ft below the surface at Livingston Reservoir Site BC (Phase II). Sample concentrations are shown as points color coded by seasonally adjusted discharge class (Boxplots A-C have different Y-axis scales). A) Nitrate, B) TP, and C) TSS concentrations measured at 10 ft and 30 ft below the surface by seasonally adjusted discharge class.**

The lowest nitrate (0.01 mg/L at 10 ft and 30 ft, n=2) and TP (0.08 mg/L at 10 ft and 0.06 mg/L at 30 ft, n=3) concentrations in the water column were collected during high and moderate flow events (Figure 16 A and B). The nitrate samples were collected on 9/1/2022 and 9/9/2022 during a discharge of 4,020 cfs and 4,690 cfs, respectively. These discharges are at the lower threshold for the range of high seasonally adjusted discharge values recorded during the study period. Two of the lowest TP concentrations (0.08 mg/L at 10 ft and 0.06 mg/L at 30 ft) were collected on 3/26/2022 during the moderate seasonally adjusted discharge of 18,400 cfs. The third low TP concentration (0.08 mg/L at 10 ft) was collected on 5/7/2021 during a discharge of 26,200 cfs. This was the largest discharge event during the study period. All TP concentrations measured at base flow were below the median (54.8 mg/L). This pattern was also observed for nitrate (Figure 16 A and B).

Overall, the nitrate, TP, and TSS concentrations measured from samples collected at 10 ft and 30 ft below the surface of the reservoir had similar ranges and medians. However, the median concentrations for all three parameters were slightly higher for samples collected at 30 ft (Figure 16 and Table 9). The maximum TSS concentrations were recorded during high discharge events at 10 ft and 30 ft sampling depths (10 ft: 21 mg/L, 30 ft: 29 mg/L). The median concentration of TSS collected at 10ft is less than the results from the deeper in the water column. However, the shallower samples exhibited higher variability (IQRs) despite the maximum TSS concentration being detected at 30 ft (Figure 16 C).

Table 9. **IQR, median, and mean for nitrate, total phosphorus (TP), and total suspended sediment (TSS) concentrations collected at Site BC at 10 ft and 30 ft below the surface during Phase II**

Parameter	IQR		Median		Mean	
	10 ft	30 ft	10 ft	30 ft	10 ft	30 ft
Nitrate	0.18	0.16	0.15	0.21	0.20	0.26
TP	0.03	0.06	0.01	0.11	0.10	0.11
TSS	5.3	4.3	10	12	12	14

The high discharge recorded for the nitrate and TP bed sediment samples was 4,680 cfs, which is at the lower threshold for the range of high seasonally adjusted discharge values (Figure 17). This was lower than the moderate seasonally adjusted discharge sample (18,400 cfs) (Figure 17). The bed sediment samples collected during high seasonally adjusted discharge had more variability in the nitrate (IQR=32) and TP concentrations (IQR=300) than the samples collected during base flow (nitrate: IQR=6.1, TP: IQR=80). The highest nitrate (59 mg/kg-dry) and the highest TP (790 mg/kg-dry) concentrations were recorded during a high flow event (4,680 cfs) (Figure 17). The highest TP concentration collected at base flow (1,190 cfs) was equivalent to the median (210 mg/kg-dry).

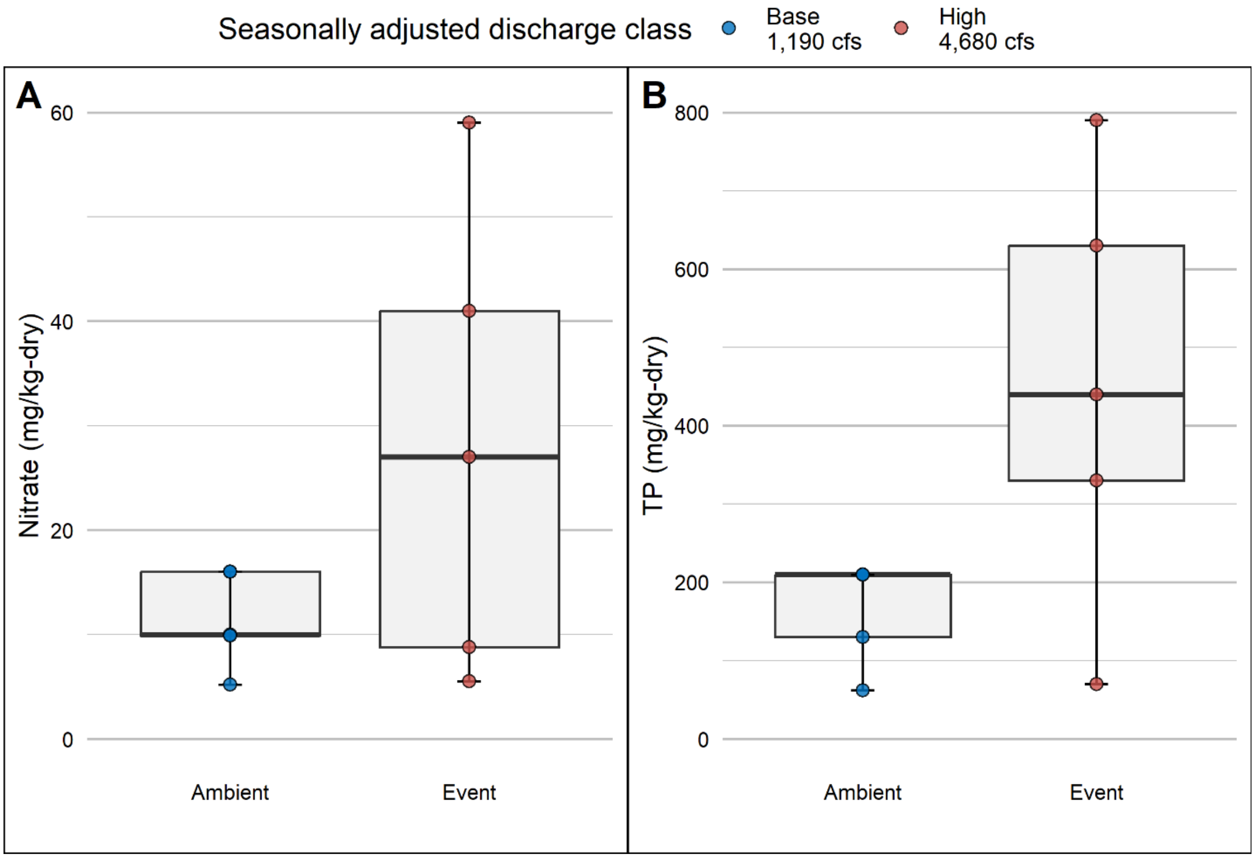


Figure 17. **Nutrient concentrations in bed sediment at Livingston Reservoir Site BC by sample type and seasonally adjusted discharge class (Phase II). A) Nitrate and B) Total Phosphorus (TP) concentrations in bed sediment.**

There is a wide range of flux values observed for the Trinity Riverside station for all three parameters. The highest nitrate flux (7,668 kg/hr) occurred at Riverside at a discharge of 17,700 cfs (high), which was collected in February of 2018 after a long period of base flow following Hurricane Harvey, which was the highest discharge event during the Phase I study period (Glenn and Bare, 2019) (Figure 5). The lowest nitrate flux (6 kg/hr) occurred at Goodrich at a discharge of 1,170 cfs (base). The highest TP flux (2,761 kg/hr) occurred at Riverside at a discharge of 17,700 cfs (high). The lowest TP flux (11 kg/hr) occurred at Goodrich at a discharge of 1,170 cfs (base). While the nitrate flux was also variable at the Trinity Goodrich station, this was not the case for TP and TSS. At the Trinity Goodrich station, the highest TP (482 kg/hr) and TSS (232,322 kg/hr) fluxes were observed at the highest discharge (43,000 cfs) (Figure 18B and C).

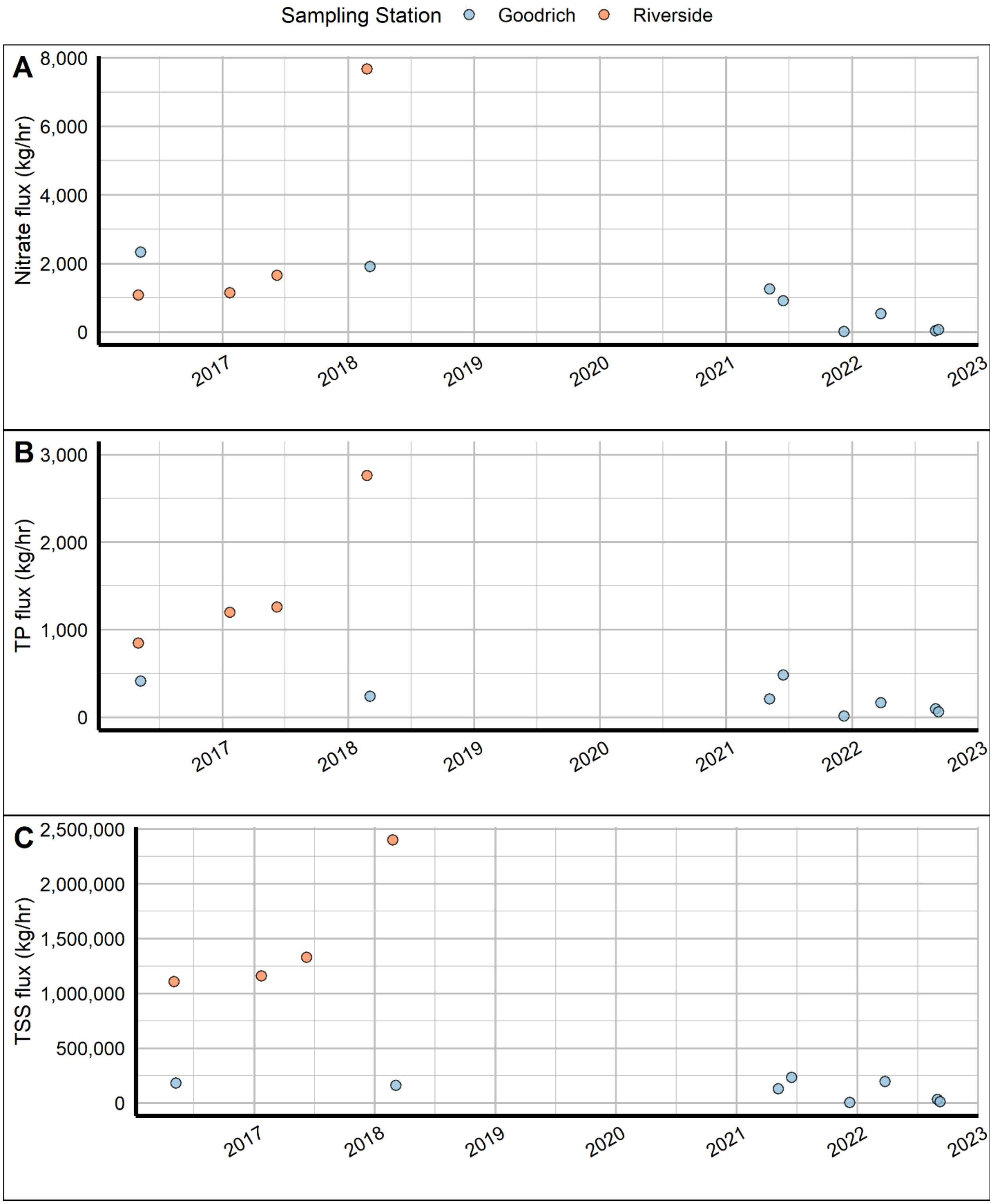


Figure 18. **Nitrate (A), total phosphorus (TP) (B), and total suspended sediment (TSS) (C) flux at the Trinity Goodrich and Trinity Riverside gage stations using Phase I and Phase II discharge weighted data. Flux was calculated by multiplying the discharge-weighted sample by the discharge measured at the time of sample collection.**

The discharge-weighted water quality samples collected from the Trinity Riverside station in the Upper Lake Livingston system (Figure 19) had greater variability (larger IQRs) and higher median and mean concentrations for all three parameters than those collected at the Trinity Goodrich station in the Lower Trinity River (

Table 10). The highest nitrate concentration (6.3 mg/L) was recorded at the Trinity Riverside station during a discharge of 1,200 cfs measured during the Phase I sampling period. The maximum concentrations measured for TP and TSS at the Trinity Riverside and Trinity Goodrich stations were recorded during discharges ranging from 4,680 – 43,600 cfs.

Table 10. **IQR, median, and mean for nitrate, total phosphorus (TP), and total suspended sediment (TSS) concentrations (mg/L) at Trinity Riverside and Trinity Goodrich stations for discharge-weighted samples collected during Phase I and Phase II.**

Station	Parameter	IQR (mg/L)	Median (mg/L)	Mean (mg/L)
Trinity Riverside	Nitrate	3.2	2.1	2.6
	TP	0.41	0.6	0.65
	TSS	694	449	513
Trinity Goodrich	Nitrate	0.4	0.23	0.31
	TP	0.04	0.1	0.12
	TSS	14.2	51	50.2

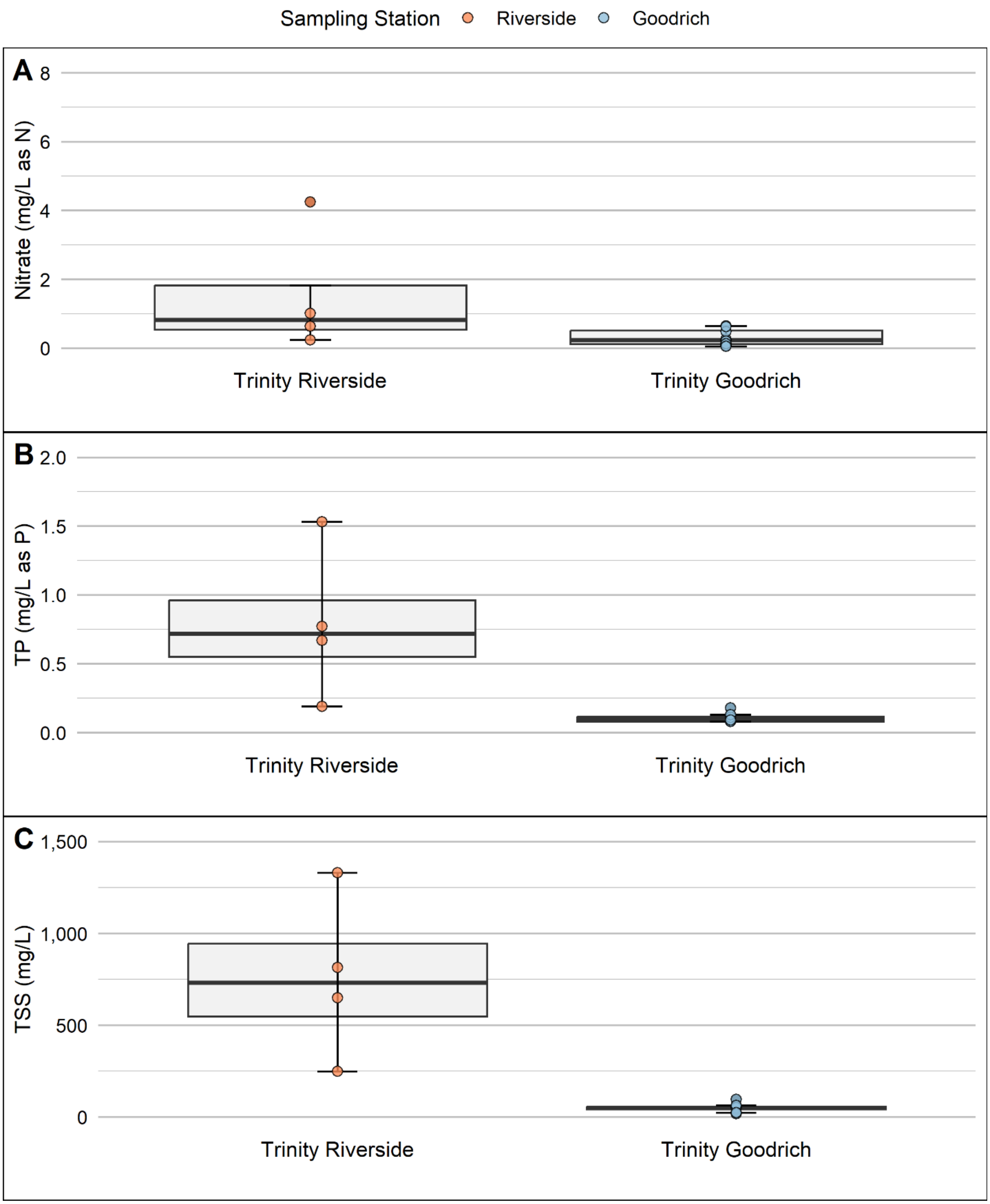


Figure 19. **Boxplots of nitrate (A), total phosphorus (TP) (B), and total suspended sediment (TSS) (C) concentrations at Trinity Riverside (Upper Trinity River) and Trinity Goodrich (Lower Trinity River) gage stations using Phase I and Phase II discharge weighted data.**

5 Discussion

During the Phase I study, six sampling events over base (two samples), moderate (three samples), and high flows (one sample) were conducted between May 2016 and August 2018 (Glenn and Bare, 2019). USGS collected water quality samples from one station on the Upper Trinity, two stations within the reservoir, and one station on the Lower Trinity south of the Lake Livingston Dam. The study quantified nutrient and suspended sediment concentrations, deployed a GPS drifter to track flow patterns and currents, and collected depth profiles to determine the degree of stratification in the reservoir. Most of the TSS, TP, and nitrate sample results revealed a longitudinal gradient of decreasing concentrations from north (upstream) to south (downstream). These early results suggest that as nutrients enter Lake Livingston, they are retained in the reservoir (Glenn and Bare, 2019). However, this study was limited by a small sample size and only one high flow (event) water quality sample.

The objectives of the Phase II project were to assess the Trinity River's flow regime influence on physiochemical water quality upstream, within, and downstream of the Lake Livingston reservoir by quantifying 1) nutrient and total suspended sediment concentrations during high flow events above and below the Lake Livingston Dam, 2) nutrient concentrations in the lakebed for the potential of sequestration, and 3) water quality concentrations at two depth intervals. Six sets of eighteen samples at two monitoring stations were collected between March 2021 and September 2022 (Figure 3). Five water quality samples were collected during high flow events while an additional sample was collected during ambient flow. The sampling period encompassed two spring seasons and a fall season, which is when high flow events have historically occurred. Historical water quality data were also analyzed.

5.1 Historic nutrients, sediment, and precipitation trends

Over time, the concentrations of TN, TP, and TSS in the Trinity River have been influenced by policy, meteorological, biological, and land use changes. Two significant policy changes at the state and federal levels that may have affected water quality in the river were the Upper Trinity River Basin Comprehensive Sewerage Plan of 1971 and the signing of the Clean Water Act (CWA) in October 1972. This was shortly after the Lake Livingston Reservoir reached full capacity in November of 1971 (Figure 2). While decreases in annual average TN and TP concentrations were observed following the passage of these statutes and after impoundment (Figure 8 and Figure 9), elevated nutrient and sediment concentrations remained an issue for the Trinity River (Davis, 1997). Flow pulses from the DFW metroplex led to decreased dissolved oxygen and increased biological oxygen demand (BOD) downstream and resulted in 13 major fish kills between 1970 and 1985 (Mirochna, 1988; Land et al., 1998). This may explain some of the variability in the annual average TN, TP, and TSS concentrations observed in the 1970s and 1980s (Figure 8-Figure 10).

Rainfall patterns may have also affected TP concentrations. A reduction in the annual average TP concentrations was observed in 1973 (Figure 8). The highest total annual precipitation (67.77 inches) between 1972 and 2020 occurred in the same year (Figure 7 and Figure 8). The lowest annual average TP concentrations were not observed until 2020

(0.23 mg/L) (Figure 8). Therefore, this reduction in average annual TP over time could have been influenced by the high total annual rainfall. However, total annual rainfall is not likely the only factor influencing the changes in average TP concentrations in the Trinity River, as abnormally dry years did not always correspond with elevated concentrations. For example, there was a peak in average TP concentrations in 1984, which was a year with close to average total annual precipitation (Figure 7Figure 8). Also, the second lowest total yearly precipitation (25.15 inches) for the reported period occurred in 1988, while the lowest total annual precipitation levels (22.44 inches) were recorded in 2011 during the peak of the 2010-2015 drought. There were higher observed annual average phosphorous concentrations in these drought years. However, these average concentrations were not much higher than in other years with more rainfall, such as in 2018.

Like TP, years with above-average rainfall do not appear to have a consistent impact on average TN concentrations. For example, the total precipitation recorded for 2015 was (62.04 inches), which is greater than +1SD above the mean and corresponded with the lowest annual average nitrate concentration (0.96 mg/L) for the last 20 years. But, in 2017 when the state was impacted by Hurricane Harvey, the total precipitation amount was 63.85 in, which corresponded with a slight peak in the average nitrate concentration (2.22 mg/L) (Figure 7 and Figure 9). In contrast, the highest mean nitrate concentration occurred in 2012 (3.58 mg/L), during the 2010-2015 drought (Figure 7 Figure 7 and Figure 9). In addition, there are two distinct groupings of annual average nitrate concentrations: 1972-1991 and 2003-2020. It is possible that these observations could also be due to the complex nature of biogeochemical cycles rather than a result of policy changes or fluctuations in annual rainfall totals.

In contrast to the annual average TP and TN concentrations, the annual average TSS concentrations appear to follow a similar pattern to the total annual precipitation measurements, with several of the peaks in average TSS concentrations corresponding with above-average rainfall years and lower average TSS concentrations occurring in abnormally dry years in many cases. Specifically, all of the years with low mean TSS concentrations (1988, 1996, 2005, 2011, 2014) occurred in years with below-average total precipitation, and most occurred in abnormally dry or drought years (greater than -1SD below the mean, or less than 38.1 in of total annual rainfall) (Figure 7 and Figure 10). In addition, two of the years with higher-than-average total precipitation (2015 and 2018) also had some of the highest annual average TSS concentrations (173.8 mg/L and 151.8 mg/L, respectively) (Figure 7 and Figure 10). Liu et al. (2020) observed that sediment concentrations in a watershed increase with increasing rainfall intensities. While this study did not focus on rainfall intensity, it is probable that years with higher annual rainfall totals also had storm events with greater rainfall intensities, such as in 2017 when Hurricane Harvey impacted the Texas coast.

Low annual average TSS concentrations were recorded in 1972, which was the opposite of the trend observed in the annual average TP and TN concentrations. However, a peak in annual average TSS concentrations occurred between 1973 and 1974. This delay in elevated average TSS concentrations in the years just after the Lake Livingston reservoir reached full capacity may be an artifact of the water levels increasing over time in the reservoir when the samples were collected (Figure 10). Therefore, urbanization in the Trinity River Basin may have influenced the average TSS concentrations over time through increased sediment deposition in the Trinity River during storm events (Murphy, 2020).

5.2 Influences on reservoir retention

Lake Livingston characteristically operates as a river in the northern portion, while south of the causeway it behaves as a reservoir (PBS&J, 2003). The Phase I study employed a GPS-equipped drifter to study flow patterns throughout the reservoir system (Glenn and Bare, 2019). During a high discharge event, the velocity of the drifter slowed after it traveled past the US 190 causeway substantiating the results from PBS&J (2003). As the flow from the Trinity River slackens, winds likely become the dominant driving force controlling surface water currents in the reservoir. These findings support the Phase II observations and suggest that as sediments and nutrients flow into the reservoir, deposition begins to increase as flow and mixing decrease (Figures 11-13 and Figure 19).

Another possible explanation for the reduction of nutrients and TSS between the Upper and Reservoir Lake Livingston segments is the dilution affect that occurs when the constituent mass is reduced by the water volume contained within the main reservoir (Figures 11, 12, and 13). In future studies discharge data should be collected with water quality constituents to enable the use of a mass-balance approach such as the calculation of flux to compare concentration and across various flow scenarios. As a result of these physical properties, much of the inflowing TSS and nutrients are likely retained within the reservoir, limiting downstream release. This finding is supported by a previous study that found the Lower Trinity River downstream of the Lake Livingston Dam had the lowest nutrient concentrations when compared to upstream reaches of the river above the Lake Livingston Reservoir (Perkin and Bonner, 2016).

Not only was there evidence of a longitudinal gradient of decreasing TSS and nutrient concentrations from the Upper part of the main Lake Livingston system to the Lower, but higher median TSS and nutrient concentrations were observed at depth within the reservoir (Figure 2). However, the ranges of the concentrations collected at either depth were similar and the sample size was limited. Despite these limitations, these results are supported by an earlier study that found higher nutrient concentrations near the bottom of Lake Livingston during the summer (Rawson, 1979). Elevated concentrations of nitrate and TP were also found in the Lake Livingston bed sediment samples collected during the high discharge event when compared to ambient conditions (Figure 17). This indicates that the nutrients are immobilized and may be less likely to be transported downstream during periods of elevated flow. This is supported by the findings of another study in a subtropical reservoir system which concluded that the settling of sediments leads to the accumulation of nutrients (Wang, 2020). In addition, Rawson (1979) concluded that seasonal temperature differences and dissolved oxygen cycles have resulted in significant recycling of nutrients within the reservoir, which would further reduce downstream nutrient availability.

The retention of sediment and nutrients within the reservoir has important ecological implications because the amount of water flowing downstream from Lake Livingston plays a role in regulating the delivery of these constituents to the Galveston Bay system (Lucena and Lee, 2017, 2022). However, sediment delivery to the bay may occur from second-order waterways and downstream hydrodynamic processes. The Lower Trinity is a coastal sand-bed river susceptible to channel erosion due to a highly erodible substratum. The dam is affecting downstream incision within the river channel (Smith and Mohrig, 2017). As flow increases below the dam, sediment is lifted into the water column as the channel re-establishes transport capacity. Persistent bed erosion of the Lower Trinity River increases the bed-material load with increasing distance downstream (Smith and Mohrig, 2017). This bed and bank erosion from the Lower Trinity River may contribute to offsetting the sediment load lost to deposition within the reservoir. Another potential source of sediment downstream of the dam may occur during intense precipitation events that correspond with periods of high flow, which are likely to increase the mobilization of sediment particles from tributaries that feed into the Lower Trinity River.

6 Conclusion

Reservoirs can function as nutrient and sediment sinks because they capture and store nutrient and sediment constituent over time, interrupting downstream flows into coastal waters. This project addressed data gaps by increasing the number and temporal resolution of water and sediment samples, performing targeted sample collection during high flow events, and conducting sediment sampling to assess the potential sequestration of nutrients within the reservoir bed. The influence of the Trinity River's flow regimes on physiochemical water quality upstream, within, and downstream of the Lake Livingston Reservoir was assessed using historically collected water quality data. The sampling events show higher nutrient concentrations in the bed sediment during high discharge events, and lower nutrient and sediment concentrations at the Trinity Goodrich station downstream of the Lake Livingston Dam compared to the Trinity Riverside station above the reservoir. These results suggest that Lake Livingston, a single-purpose reservoir created in 1969 as an artificial impoundment for water supply, is a nutrient and sediment sink. These data and associated outcomes produced by this project are available to support future studies such as the development of nutrient loading models, use of mass-balance approaches, or further analysis needed to determine patterns of nutrient cycling within the reservoir.

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8 Appendix

Table 11. Range and count of concentration values above the 90th percentile by parameter and system class

Parameter (Code)	System Class	Concentration range (mg/L)	Count of values above the 90th percentile
Total Suspended Sediment (00530)	Upper	310-1,770	223
	Upper-System	65-1,130	78
	Reservoir	30-344	181
	Reservoir-System	83-2,060	11
	Lower	28-452	66
	Lower-System	53-780	22
Total Phosphorous (00665)	Upper	1.7-10	213
	Upper-System	3.4-19	78
	Reservoir	0.44-3.9	169
	Reservoir-System	0.36-3.5	10
	Lower	0.31-2.6	70
	Lower-System	0.38-0.97	24
Total Nitrate (00620)	Upper	5-15	142
	Upper-System	2-14	54
	Reservoir	0.74-8.5	121
	Reservoir-System	0.29-1.4	10
	Lower	0.72-3.7	52
	Lower-System	0.35-1.1	19