Final Report: Evaluation of Adopted Flow Standards for the Trinity River, Phase 4

Texas Water Development Board Contract #2000012407




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Texas Water Development Board

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"PURSUANT TO HOUSE 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."

August 31, 2023

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Appendix 3 – Texas Water Development Board Comments on Draft Report

1 Executive Summary

In 2007, the 80th Texas Legislature passed Senate Bill 3 (SB3) which created a stakeholder driven process designed to establish environmental flow standards for all the major river basins in Texas. For the Trinity River, the Trinity and San Jacinto and Galveston Bay Basin and Bay Area Stakeholder Committee (BBASC) and Expert Science Team (BBEST) were created and tasked with recommending environmental flow standards to the Texas Commission on Environmental Quality (TCEQ). On April 20, 2011, the TCEQ adopted flow standards for the Trinity River. Since that time, the Trinity River Authority of Texas (TRA) has performed several studies which have included extensive field work, data analysis, and modeling efforts. This report represents the fourth phase of these studies designed to provide scientific information and data to the BBEST and BBASC that can be used during the adaptive management phase of the SB3 process. It is important to recognize that this work is *not* designed to recommend flows or "validate" existing flows, but to provide a set of tools and information for stakeholders to inform the SB3 process. This phase of the study included long-term channel monitoring and channel bathymetry field surveying, water quality and sediment sampling, sediment transport modeling, and nekton sampling.

<u>Long-term Channel Monitoring and Channel Bathymetry Field Surveying</u>

All of the long-term monitoring cross-sections at four sites were re-surveyed to better understand channel dynamics, and two additional long-term sites were created and surveyed. In general, most of the sites show to be stable, however there is some significant erosion occurring at some sites which can be attributed to the significant flooding events in 2015 and 2016. These are likely due to the extended periods of bankfull flows in the middle reach of the Trinity River between the Dallas/Fort Worth (DFW) area and Lake Livingston created by the controlled releases of flood flows captured in upstream reservoirs.

TRA staff collected over 200 new bathymetric cross-sections for over 70 miles of the Lower Trinity River which were used to update the bathymetry for the Lower Sediment Transport Model.

<u>Water Quality and Sediment Sampling</u>

The USGS collected water quality grab samples, bedload, and suspended sediment data at several sites. None of the water quality grab samples exceeded any TCEQ water quality standards. TRA staff deployed sondes which collected temperature and dissolved oxygen readings at 15-minute intervals for a minimum of 30 days during the hot, dry summer months. Overall, the results from these deployments were as expected: the river gets very hot during the summers and at times, the dissolved oxygen can approach lower limit thresholds. These characteristics are important to understand because there could be potential implications if there are species in the reach that are intolerant to elevated temperatures, like some species of native freshwater mussels.

The suspended sediment samples were used to inform the sediment modeling portion of this project. The bedload samples collected by USGS did not result as expected. It is important to note that collecting bedload requires very specific equipment, methods, and training, and even under perfect conditions, bedload data is highly variable, sometimes by orders of magnitude. While this data was not used specifically for sediment modeling, it is the first step in building a robust dataset for the Trinity River and additional data should be collected whenever possible.

<u>Sediment Transport Modeling</u>

Two sediment transport models were created, or updated, that, when combined, cover the Trinity River between the DFW area and the city of Liberty, near the tidal portion of the river (excluding Lake Livingston). These models investigated the sediment transport dynamics to better understand potential breakpoints in flows that could change the erosional/depositional characteristics of the river. Generally, below Lake Livingston, net depositional processes are more strongly associated with low flows and net erosional processes are more strongly associated with high flows. In the upstream-most reach, however, the lowest flows were actually more strongly-associated with net erosion. Overall, the modeling efforts resulted in a better understanding of the sediment dynamics in the Trinity basin. More importantly, the models provide a tool that the BBASC and BBEST can use, or modify, to test environmental flow scenarios during the adaptive management phase of the SB3 process.

<u>Nekton Sampling</u>

Texas parks and Wildlife Department (TPWD) and TRA staff performed nekton sampling at four sites along the Trinity River above Lake Livingston. This provided new data that was compared to historic data. Overall, a total of 19,668 individuals were collected during this study and the number of taxa identified within the mainstem Trinity River during this project was two lower (38 vs 36) compared to the 2014 sampling event. Interestingly, two new species to the mainstem Trinity River, which were not observed in historic datasets were identified. Of the eight species classified by TPWD as "Species of Greatest Conservation Need," three were found during this project. During this project, species did not seem to be greatly influenced by flows, though additional surveys in the coming years will create larger datasets on which more robust statistical techniques can be used to confirm these assumptions.

2 Background and Methodology

2.1 Background

In 2007, the 80th Texas Legislature passed Senate Bill 3 (SB3) which created a stakeholder driven process designed to establish environmental flow standards for all the major river basins in Texas. For the Trinity River, the Trinity and San Jacinto and Galveston Bay Basin and Bay Area Stakeholder Committee (BBASC) and Expert Science Team (BBEST) were created and tasked with recommending environmental flow standards to the Texas Commission on Environmental Quality (TCEQ). On April 20, 2011, the TCEQ adopted flow standards for the Trinity River at the four measurement points (30 TAC § 298.225, 2011) shown below in Table 1 and in Figure 1. These locations were selected to coincide with United States Geological Survey (USGS) stream gages.

Table 1. Study site locations as described by the Trinity River basin number (08) and river mile and the nearest USGS gage. Sites marked with an * are Senate Bill 3 Measurement Points.

Measurement point USGS gage number	Measurement point USGS gage name	Representative site (Basin number and river mile)
8049500*	West Fork Trinity River near Grand Prairie	080486
8062500*	Trinity River at Dallas	080444
8064570	Trinity River at US 287	080357
8064570	Trinity River at US 287	080344
8065000*	Trinity River near Oakwood	080295
8066500*	Trinity River near Romayor	080075

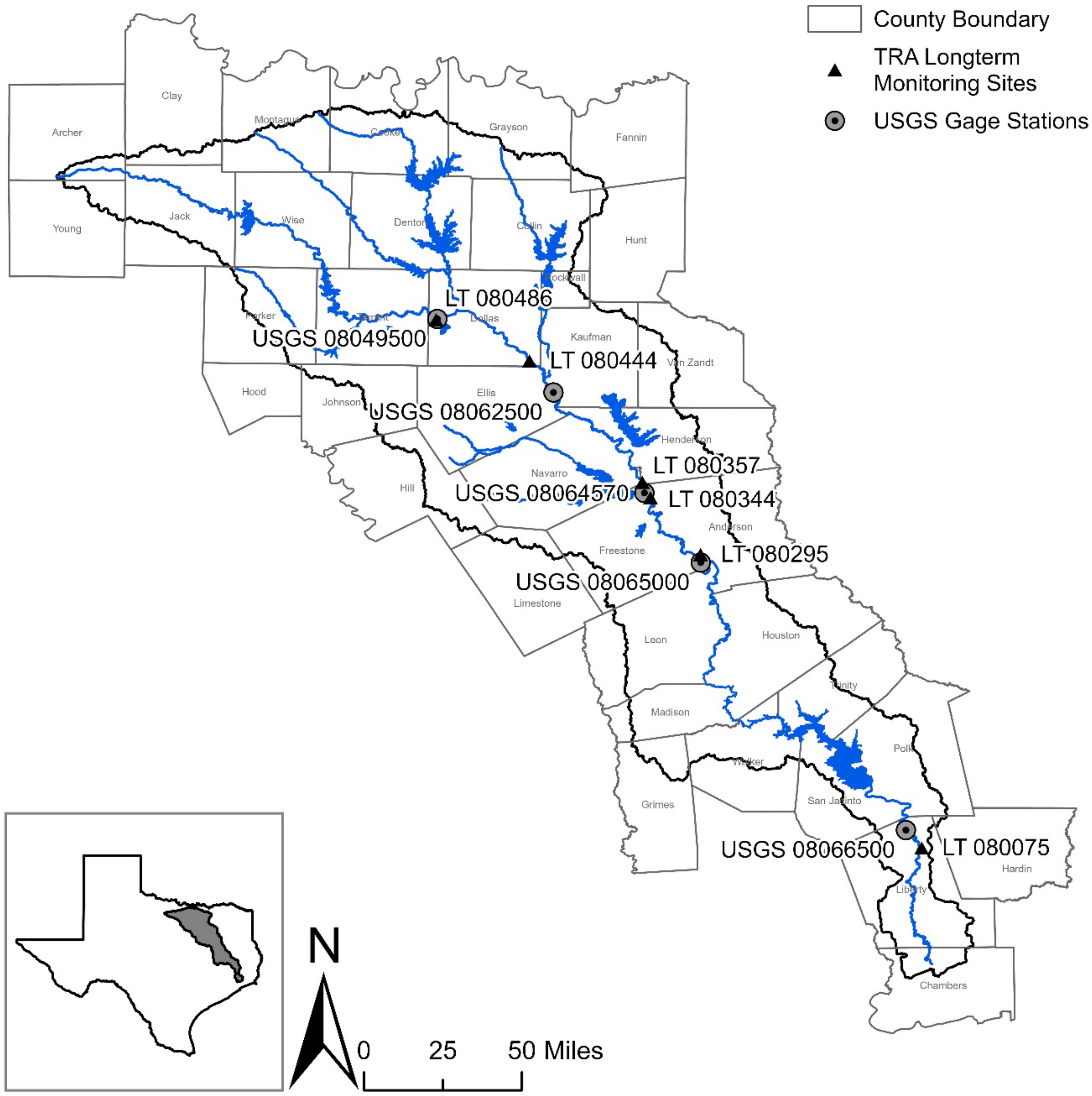

Figure 1. Map of the Trinity River basin, long-term monitoring sites, and USGS gages. Note: Long-term site labels begin with "LT" and USGS gages begin with "08."

During the SB3 process, instream habitat, hydraulics, geomorphology, and ecological data gaps were identified. In response, the BBASC and the BBEST created a Work Plan Report that outlined the additional data needs for the adaptive management provisions of the SB3 legislation (TSJ, 2012). The adaptive management phase is designed to provide for a periodic review of the standards at a maximum interval of every ten years. This is the fourth phase of a project designed to provide data and tools to the BBASC and BBEST to use during this process. It is important to reiterate that this project is designed to provide information and data, *not* to recommend flows or "validate" existing flows. This phase consisted of three tasks:

1. Biological data collection
    a. Complete nekton sampling at four of the six previously sampled sites along the Trinity River mainstem between Dallas and Lake Livingston using modified Texas Instream Flow Program sampling protocols.
    b. Compare data to that collected in the previous study (TRA and TPWD, 2014) and determine if any changes in species composition and/or abundance of fish can be observed.
2. Sediment, hydrologic, and hydraulic assessment
    a. Create or modify a sediment transport HEC-RAS model of the entire Trinity River sub-basin from just below the Dallas/Fort Worth Metropolitan Area to Trinity Bay.
    b. Calibrate the model for sediment transport and run a minimum of three hydrologic scenarios to identify critical, system-wide breakpoints where ecosystem response is acute.
    c. Collect suspended sediment data from published reports and from instream sampling, if required.
3. Long-term monitoring of TCEQ SB3 measurement points for water quality and geomorphic changes
    a. Re-survey cross-sections at each existing TRA long-term monitoring site.
    b. Compare data from this survey to previous surveys and include a review of gage records between previous surveys to attempt to find a relationship between channel change and flow conditions during that time period.
    c. Deploy and collect summer season (June through August) minimum 30-day continuous water quality (sonde) data at each of the measurement points that are not currently represented by a U.S. Geological Survey water quality gage site.

2.2 Previous Work

Based on the SB3 environmental flow designated measurement points, TRA selected four long-term representative study sites. Each site is between 1 and 2 river miles and was selected to best represent that reach and SB3 measurement point. While it is beyond the scope of this report to review the previous studies associate with this report, it is important to note that this project is built on the knowledge gained during five previous studies:

1. [TRA] Trinity River Authority of Texas & [RPS] RPS Espey. (2013.) Trinity River Reconnaissance Survey, 2011. Arlington, Texas.
2. [TRA] Trinity River Authority of Texas. (2015). LiDAR Acquisition and Flow Assessment for the Middle Trinity River. Report produced for: Trinity and San Jacinto Rivers and Galveston Bay Stakeholder Committee through the Texas Water Development Board. Contract No. 1400011696.F
3. [TRA] Trinity River Authority of Texas. (2017a). Evaluation of Adopted Flow Standards for the Trinity River, Phase 2. Texas Water Development Board, Trinity and San Jacinto Rivers and Galveston Bay Stakeholder Committee. Contract No. 1600011940. Austin, Texas: TWDB.
4. [TRA] Trinity River Authority of Texas. (2022). Evaluation of Adopted Flow Standards for the Trinity River, Phase 3. Arlington, Texas.
5. [TRA & TPWD] Trinity River Authority of Texas & Texas Parks and Wildlife Department. (2014). Supplemental Biological Data Collection, Middle Trinity River Priority Instream Flow Study. Final Report. Austin, TX.

3 Methods and Results

Many of the methods used for this project have been developed and described in detail in previous reports (Section 1.2). Only methods that were modified from previous phases of this project are described in detail in this report. Multiple field events were completed during this project (Table 2) and are detailed below.

Table 2. Table describing field data collection events and the date completed. Note: Water Quality (WQ) Grab, Suspended Sediment, and Bedload data were collected under contract by the USGS, Nekton sampling was completed in cooperation with TPWD, and all Survey and Water Quality Sonde work was completed by TRA. WQ-Water Quality

Site name (Basin and river mile)	Site description or access point	Data type	Dates
080486	Beltline Road	Long-term XS Resurvey	4/8/2021
080444	Malloy Bridge Road/USGS Gage #08062500	Long-term XS Resurvey	2/1/2021
080444	Malloy Bridge Road/USGS Gage #08062500	WQ Sonde Deployment	7/29/2021 – 8/31/2021
080425	SH 34	Nekton	8/25/2020, 10/5/2020
080424	USGS Gage #08062500, Trinity River nr Rosser, TX	WQ Grab	3/1/2021, 4/13/2021, 5/5/2021, 7/9/2021
080424	USGS Gage #08062500, Trinity River nr Rosser, TX	Suspended Sediment	3/1/2021, 4/13/2021, 5/5/2021, 7/9/2021
080424	USGS Gage #08062500, Trinity River nr Rosser, TX	Bedload	5/5/2021, 7/9/2021
080357	US 287	New Long-term Install	2/9/2023
080348	US 287	Nekton	8/25/2020, 10/6/2020
080344	US 287	New Long-term Install	2/10/2023
080295	US 79/84	Long-term XS Resurvey	4/4/2022
080295	US 79/84	Nekton	9/19/2022, 4/18/2023
080295	US 79/84	WQ Sonde Deployment	7/29/2021 – 8/28/2021
080244	USGS Gage #08065350, Trinity River nr Crockett, TX	WQ Grab	3/18/2021, 4/27/2021, 5/13/2021

Site name (Basin and river mile)	Site description or access point	Data type	Dates
080244	USGS Gage #08065350, Trinity River nr Crockett, TX	Suspended Sediment	3/18/2021, 4/27/2021, 5/13/2021
080225	Pvt. Ramp RM 221	Pvt. Ramp RM 221	Nekton
080106	USGS Gage #08066250, Trinity River nr Goodrich, TX	WQ Grab	6/16/2021, 6/29/2021, 7/8/2021
080106	USGS Gage #08066250, Trinity River nr Goodrich, TX	Suspended Sediment	6/16/2021, 6/29/2021, 7/8/2021
080085	USGS Gage #08066500, Trinity River nr Romayor, TX	WQ Grab	4/28/2021
080085	USGS Gage #08066500, Trinity River nr Romayor, TX	Suspended Sediment	4/28/2021
080040	USGS Gage #08067000, Trinity River nr Liberty, TX	WQ Grab	3/17/2021, 4/13/2021, 4/27/2021, 5/18/2021
080085	USGS Gage #08067000, Trinity River nr Liberty, TX	Suspended Sediment	3/17/2021, 4/13/2021, 4/27/2021, 5/18/2021
080085	USGS Gage #08067000, Trinity River nr Liberty, TX	Bedload	4/27/2021, 5/18/2021
080075	SH 105	WQ Sonde Deployment	7/5/2022 – 8/19/2022
080075	SH 105	Long-term XS Resurvey	07/6/2022

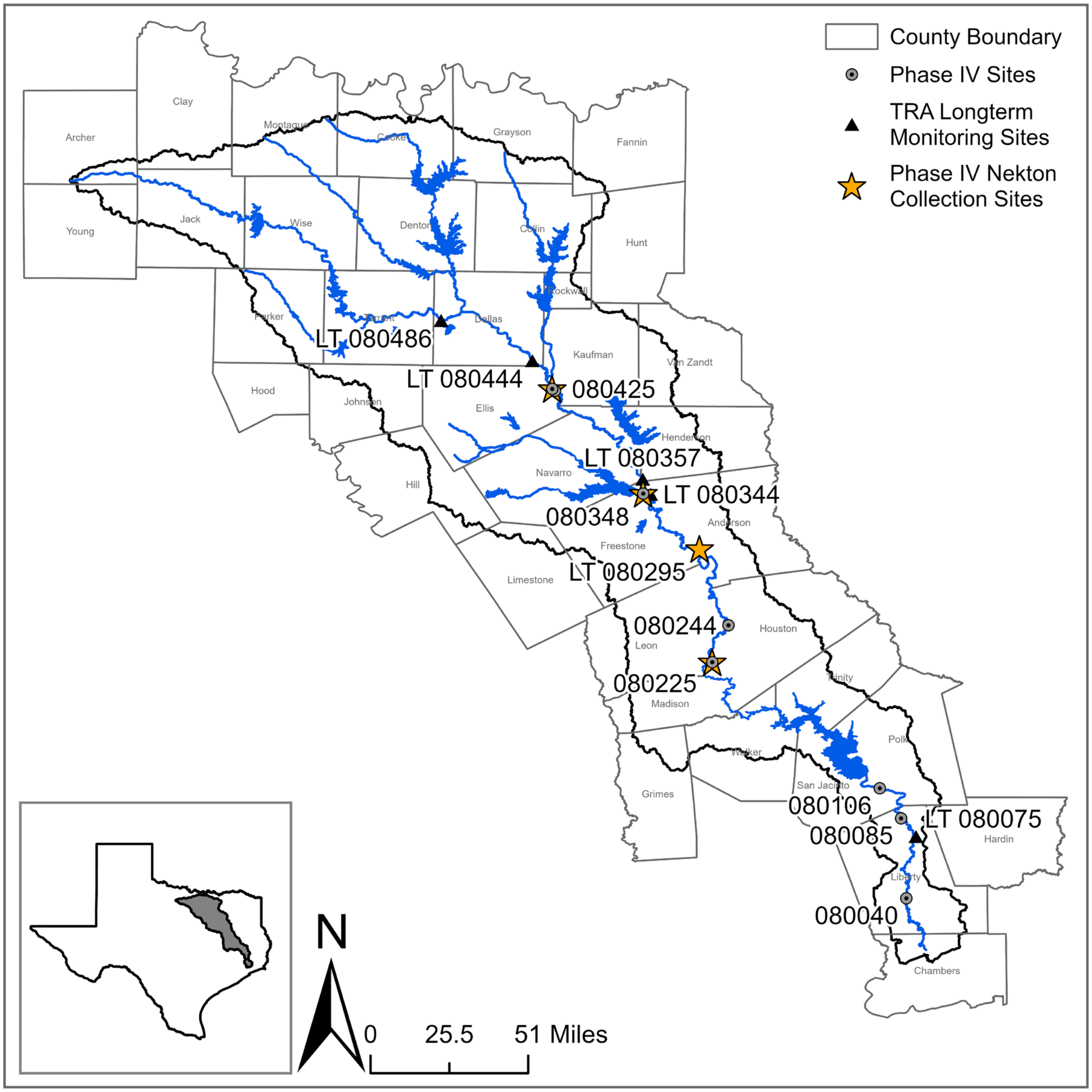

Figure 2. Map showing long-term monitoring sites and nekton collection sites. Phase IV sites are sites that were sampled by USGS for sediment or new long-term cross-section sites. Note: Long-term site labels begin with "LT" and USGS sampling sites begin with "08."

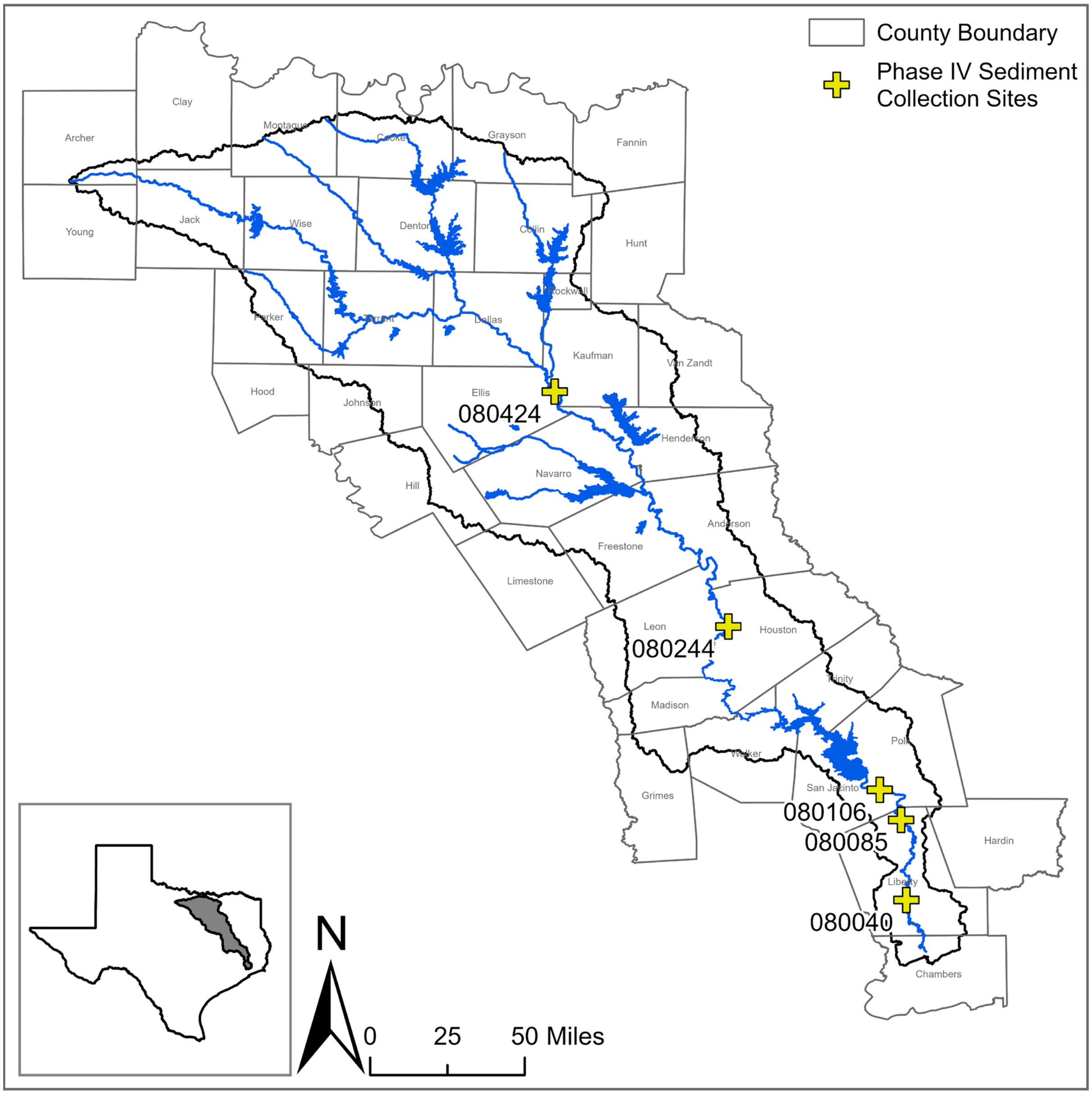

Figure 3. Map showing sites where the USGS collected sediment data.

3.1 Long-term Monitoring Cross-section Resurvey

Each of the four long-term monitoring sites were resurveyed to better understand how the channel changes between surveys. River channels are naturally dynamic, and change based on conditions, e.g. hydrology, drought, development, erosion, etc. Stable river channels are in a state of dynamic equilibrium, meaning that although the river channel changes from event to event, it is stable over time in its pattern, plan, and profile (Rosgen, 1996). Additionally, two new sites, 080344 and 080357, were added to the long-term monitoring project during this phase of the project.

During this resurvey, all topography and bathymetry data were collected with survey-grade, real-time kinematic (RTK) GPS equipment. These methods result in highly accurate northing, easting, and elevation data, far exceeding the minimum < 1.0-foot accuracy goal for this project. All data were collected in United States survey feet in the appropriate Texas State Plane Zone coordinates (4204, 4203, or 4204 depending on location) and reference the North American Vertical Datum 1988 (NAVD88).

Average daily discharge data (cfs) was downloaded from the nearest USGS gage station for each of the original four long-term monitoring sites. The period of record from 1/1/2015 to 12/31/2023 was compared to the channel data gathered from the resurveyed sites, allowing for a fuller picture of the conditions that could cause changes in channel size, location, and/or riparian erosion. A summary of the findings between the resurvey and discharge comparison are below.

Site 080486, Beltline Road, is the most upstream long-term monitoring site located in a very urban environment in the center of the Dallas/Fort Worth metroplex. The highly incised channel has incised to bedrock creating a stable channel that has adjusted and stabilized to the flashy flow regime present in this highly modified, urbanized area. Four cross-sections were surveyed at the Beltline Road site on three occasions by TRA staff over a 4-year period; during Phase 2 on 06/29/17, during Phase 3 on 01/31/19, and during Phase 4 (this report) on 06/29/21 (Figure 5). Discharge through the site, measured at the Beltline Road USGS Gage #08049500, had a median of 328 cfs, the lowest of all four long-term sites (Figure 5). When comparing the channel movement from year to year, the channel appears to be stable and has adapted to existing flow regimes (Figure 9).

Site 080444, Malloy Bridge Road, is the first long-term monitoring site located south of the Dallas/Fort Worth metroplex. The river through this area begins transiting back into to a more natural state, but is still highly impacted by anthropogenic changes upstream. This site contains a relic lock and dam structure at XS4 that the river abandoned when it avulsed to river left between 2017 and 2019. Five cross-sections were surveyed at the Malloy Bridge Road site on three occasions by TRA staff over an 8-year period. Initial surveys, as part of Phase 1a and 1b of this project occurred at cross-sections XS1 and XS5 on 11/15/13 and at XS2 and XS4 on 06/08/15. All five cross-sections were then surveyed on 02/24/17, 02/05/19 and 02/01/21 (Figure 6). Discharge though the site, measured at the Rosser USGS Gage #08062500, had a median of 1,850 cfs, >5 times higher than was seen at the Beltline Road site (Figure 6). Channel variability was seen at XS1 and XS4, between the initial Phase 1 surveys 2013/2015 and the Phase 2 surveys in 2017 (Figure 10). This is not surprising as flooding in 2016 caused elevated peak flows >65,000 cfs and extended releases from upstream flood control reservoirs caused flows at this site to remain above 15,000 cfs for half of 2015 and much of 2016 (Figure 6). XS1 is on a bend with the bank cutbank moving as predicted. After the failure of the lock and dam structure at XS4 due to the 2015-16 floods, the channel became ~75 feet wider (Figure 10). Since then, it appears to have stabilized as seen at both XS4 and XS5 from Phase 2 surveys onward (Figure 10 & Figure 11).

As mentioned earlier, sites 080344 and 080357 were added as new sites to the long-term monitoring plan during Phase 4. Because of this, no channel comparisons can be made to previous surveys, but the baseline data can be found in Figure 12 and Figure 13.

Site 080295, US 79/84 is a middle basin long-term monitoring site flowing through the rural agricultural areas between Dallas/Fort Worth and Lake Livingston. The river in this section of the Trinity is less incised compared to the Beltline and Malloy Bridge stations and exhibits more natural characteristics, though its hydrologic regime is highly modified by elevated wastewater discharges and upstream flood control reservoirs. Three cross-sections were surveyed by TRA staff over a 6-year period on 09/22/16, 01/26/20, and 04/06/22 (Figure 7). Discharge at this site had a median value of 2,870 cfs, from 2015-2023, while being the most impacted by the 2015-2016 flood (Figure 7). Though the channel at the three cross-sections appears to be relatively stable, broader, reach-scale analysis suggests the cross-sections do not capture the changes observed in this reach (Figure 14).

The US 79/84 site was originally scouted as part of the 2011 initial reconnaissance survey. At this time, the banks were stable and vegetated with trees across various age classes suggesting the banks were stable. As a result of the flooding in 2015-16, the riparian areas endured slumps and scours due to the long period of bankfull inundation as upstream flood control reservoirs released captured flood water. Many of the riparian trees were killed, likely due to extended inundation (TRA 2017a). Since then, riparian areas have deteriorated as seen in three satellite photos (Figure 4) from 2014, 2017 and 2022. Multiple entities, both upstream and downstream of this reach, have since dealt with rafts of dead timber floating downstream during high flow events and becoming entangled along the banks and damaging instream infrastructure. TRA staff conducted a tree survey post flooding and found that a quarter of the tree core samples were of too poor quality to analyze due to over saturation and rot (TRA 2017a). With the continued decay and death of trees in the riparian area, channel movement is expected in the following years at this site.

Figure 4. Satellite imagery of site 080295 showing the loss of riparian timber and bank changes between 2014 and 2022.

Site 080075, Romayor, is located below Lake Livingston where the Trinity River becomes a coastal plane ecosystem. Four cross-sections were surveyed by TRA Staff over a four-year period on 07/10/18, 12/03/20, and 07/06/22 (Figure 8). Discharge at this site was the highest of any of the long-term sites with a median value of 4,170 cfs, with multiple periods of elevated discharges between 2015 and 2021 (Figure 8). Cross-sections XS1 and XS4 both showed significant movement between the 2018 and 2020 survey events. At XS1, this movement is expected due to the cross-section being on a tight bend in a sandy, coastal plane ecosystem. Additionally, XS1 is affected by a gully that focuses overland runoff to this cross-section. Movement at XS4 is most likely due to extended periods of high flow during the 2019 floods, which likely caused major channel and bank scour between 2018 and 2020 that has since stabilized (Figure 15).

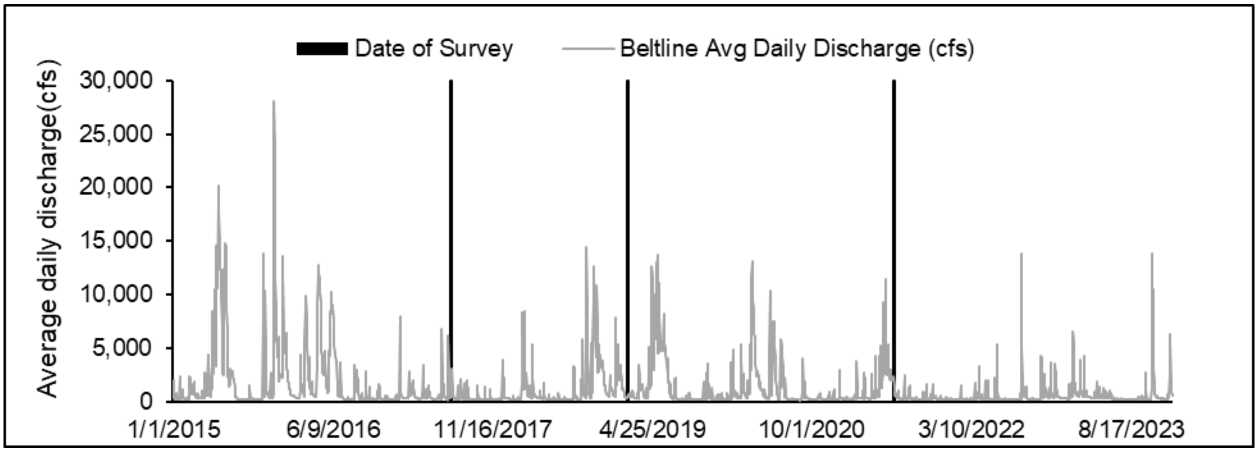

Figure 5. Average daily discharge (cfs) from USGS Gage at Beltline (#08049500) with black bars being centered on the date of channel surveys.

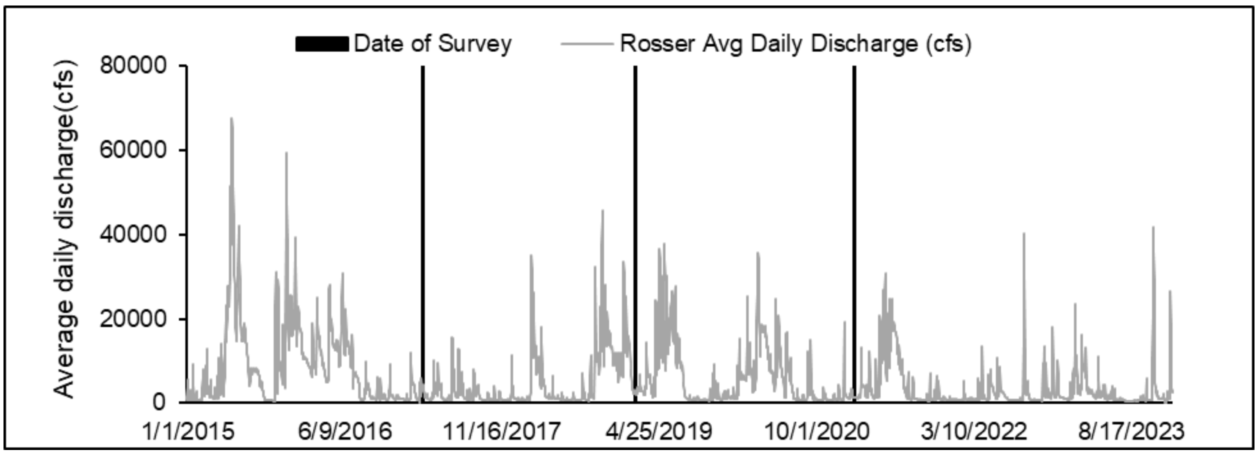

Figure 6. Average daily discharge (cfs) from USGS Gage at Rosser (#08062500) with black bars being centered on the date of channel surveys.

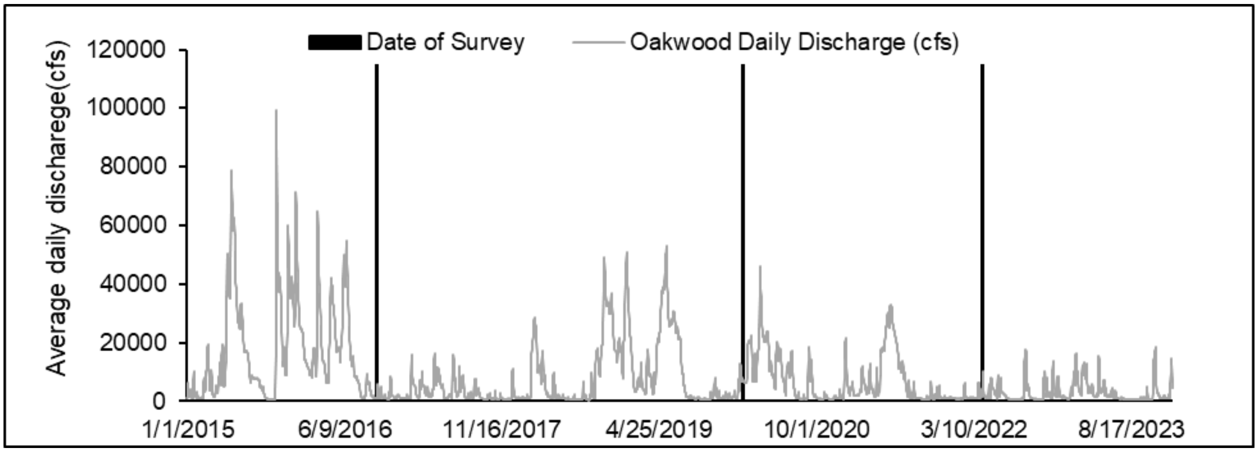

Figure 7. Average daily discharge (cfs) from USGS Gage at Oakwood (#08065000) with black bars being centered on the date of channel surveys.

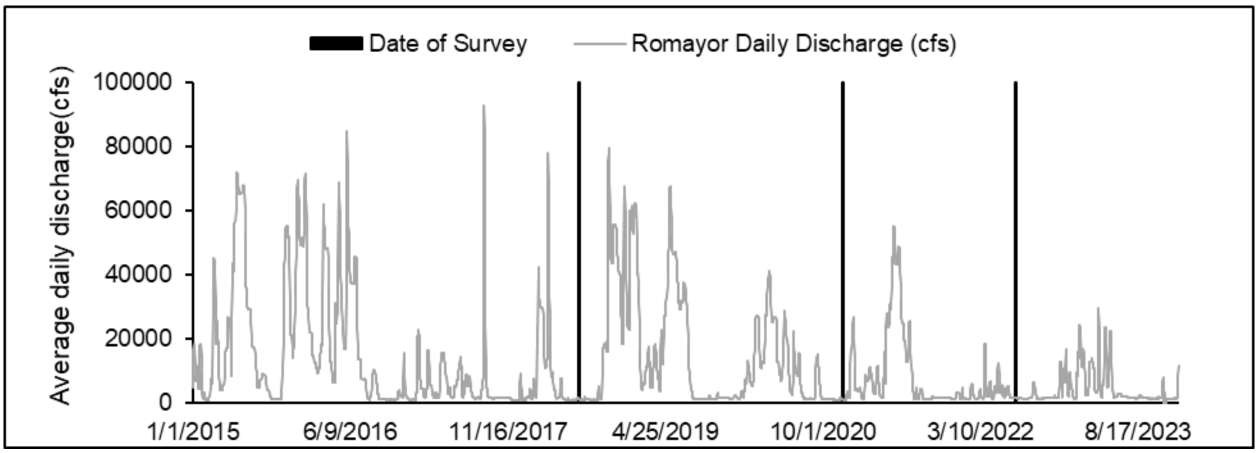

Figure 8. Average daily discharge (cfs) from USGS Gage at Romayor (#08066500) with black bars being centered on the date of channel surveys.

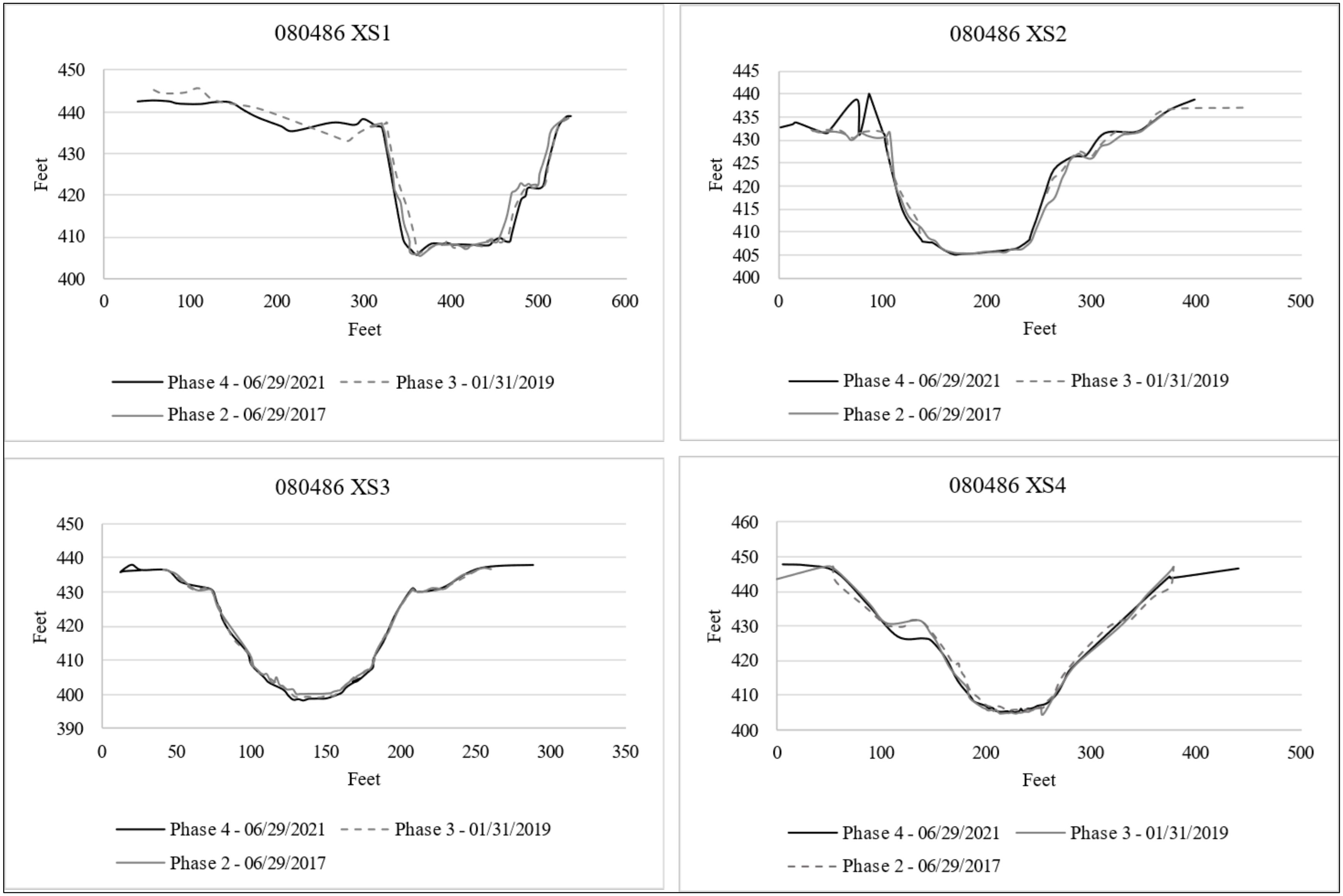

Figure 9. Cross-sections for site 080486.

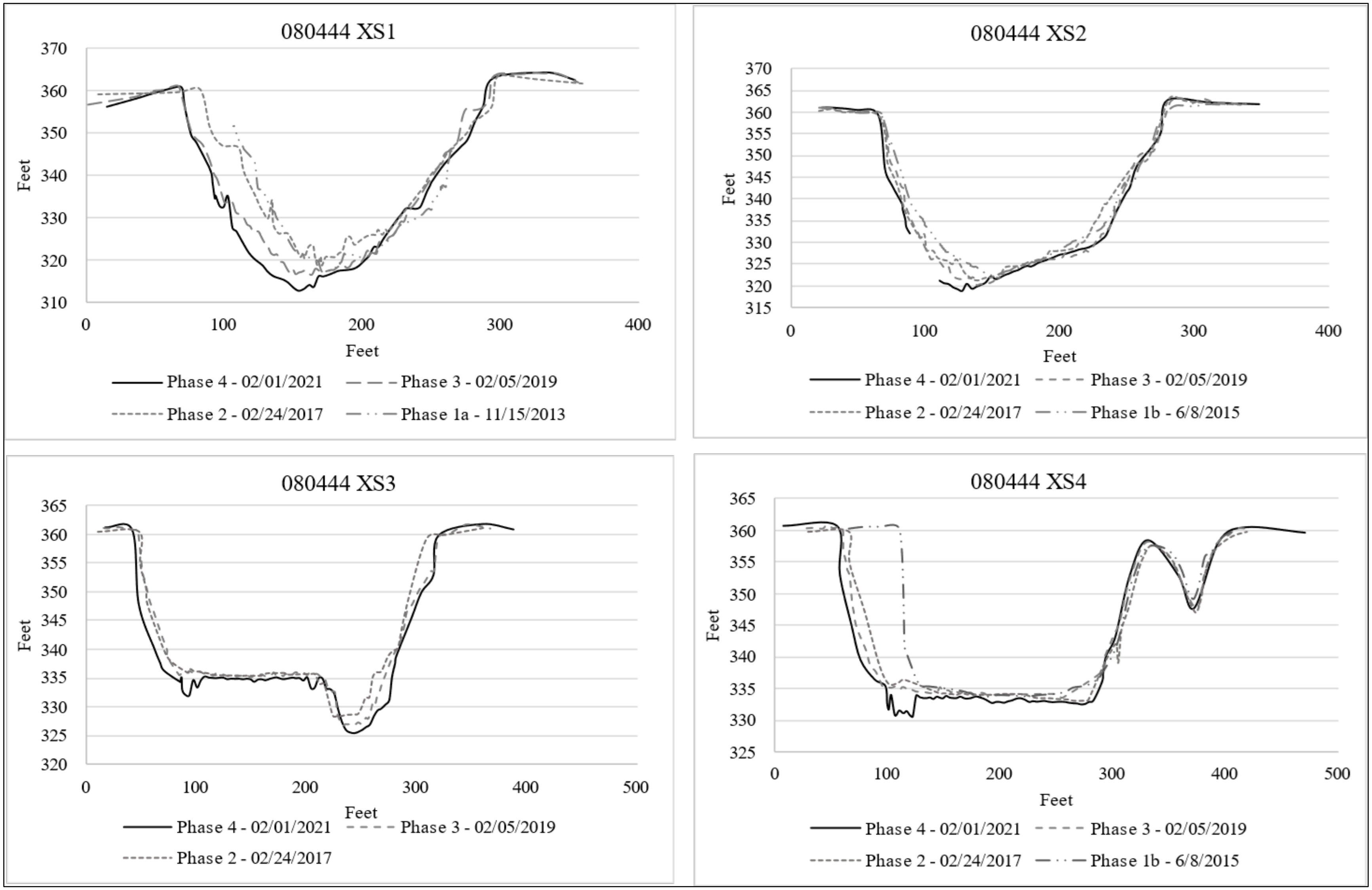

Figure 10. Cross-section comparison for site 080444 XS1-XS4. XS5 is shown in the figure below.

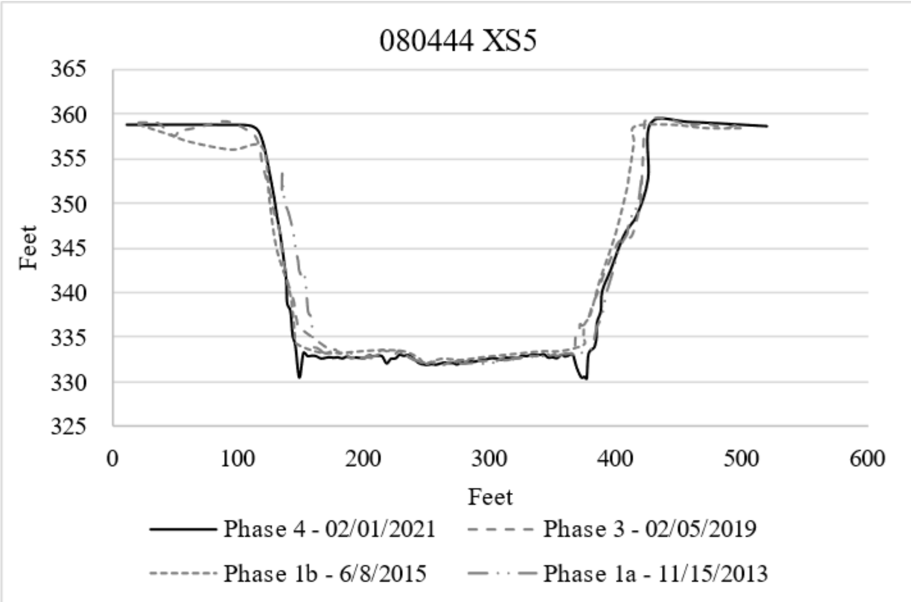

Figure 11. Cross-section comparison for site 080444 XS5. XS1-XS4 are shown in the figure above.

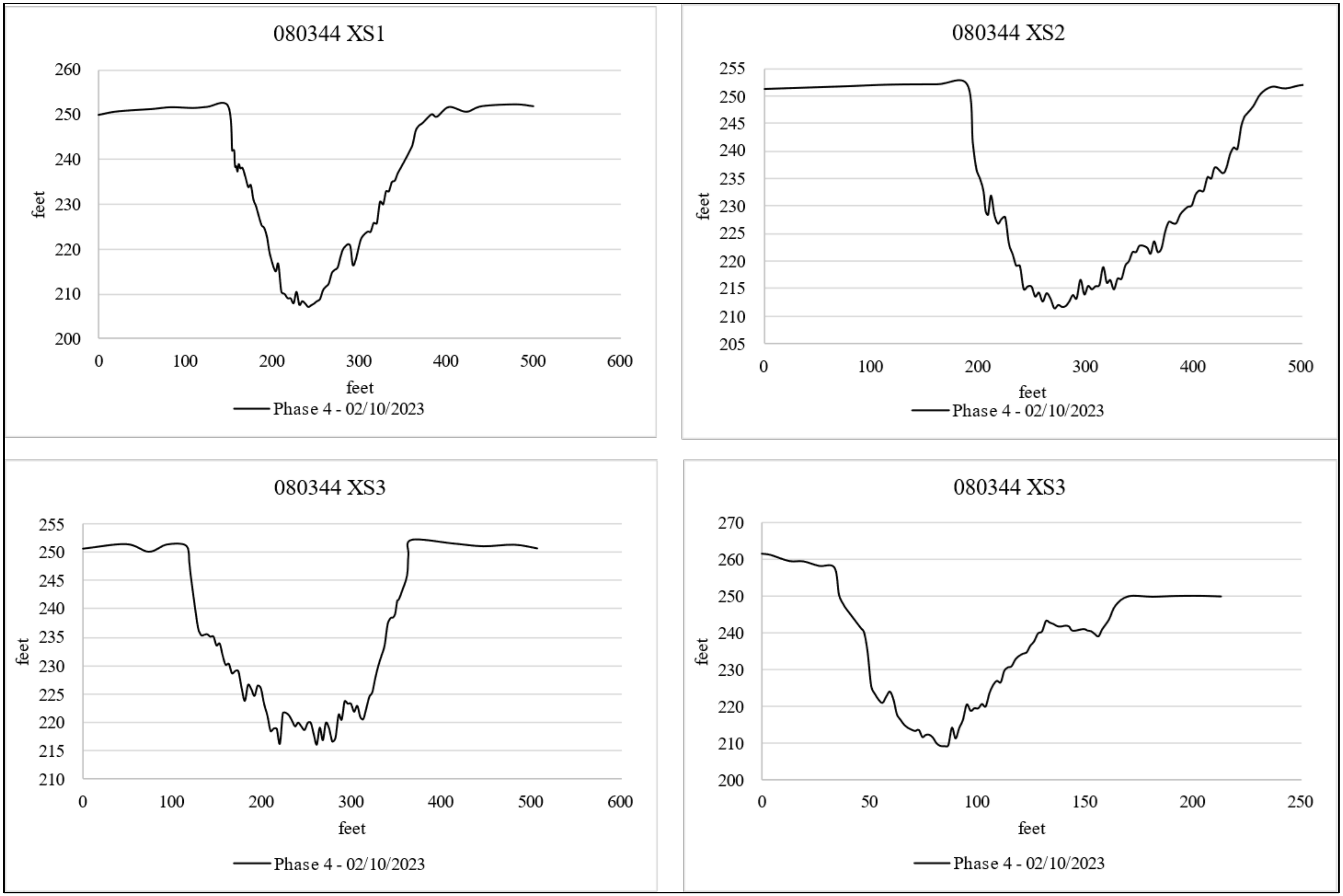

Figure 12. Cross-section comparison for site 080344 XS5.

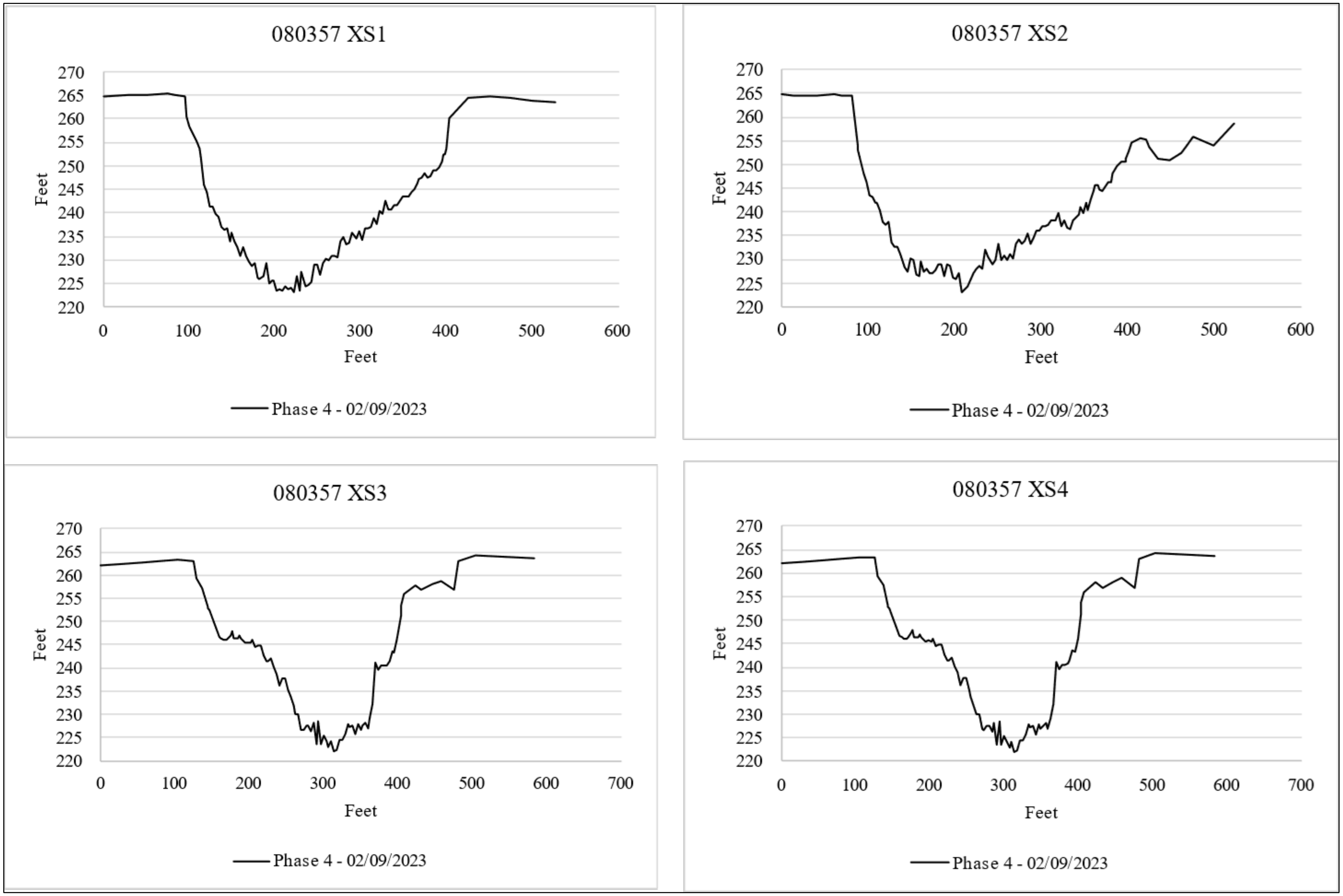

Figure 13. Cross-sections for site 080357.

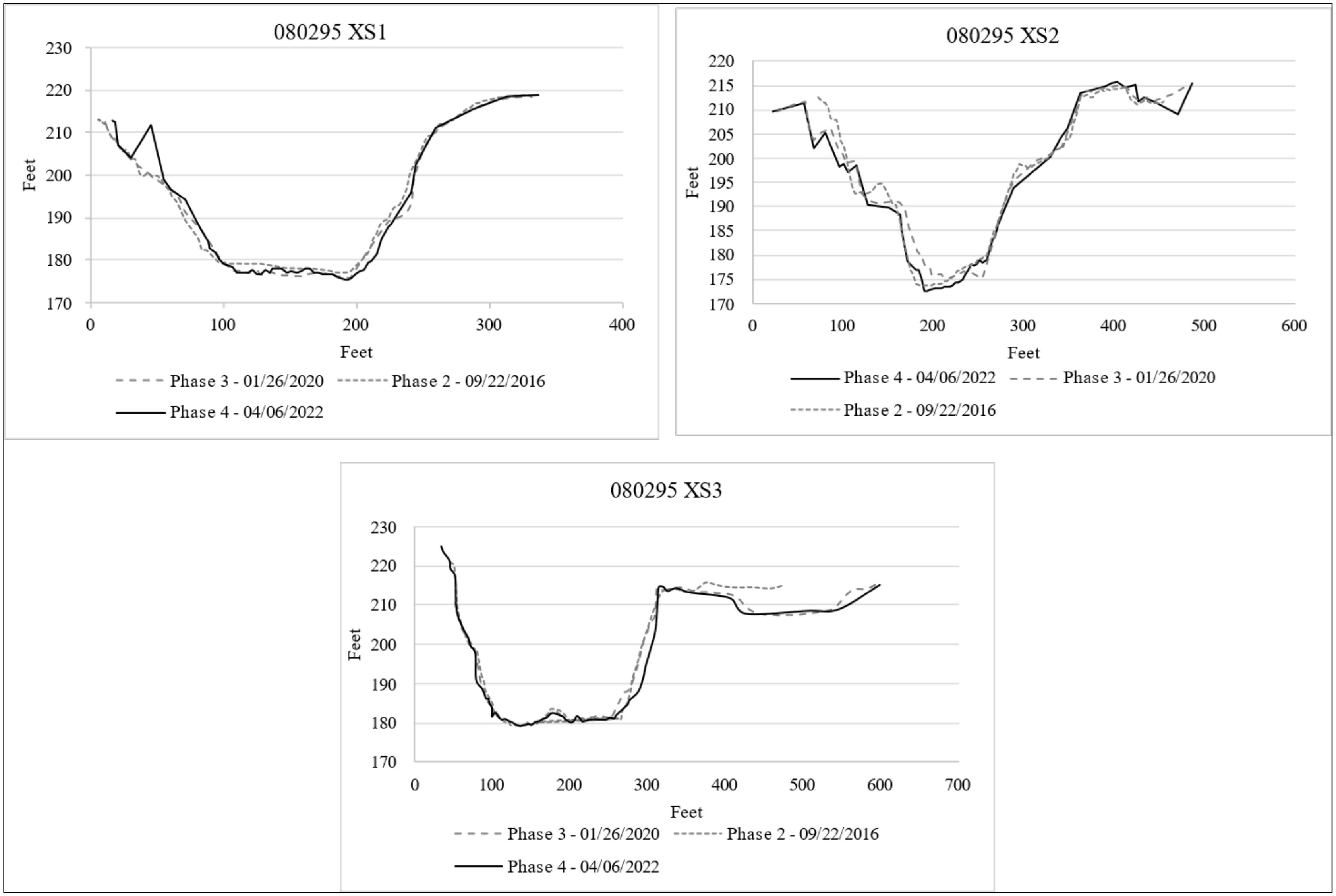

Figure 14. Cross-section comparison for site 080295.

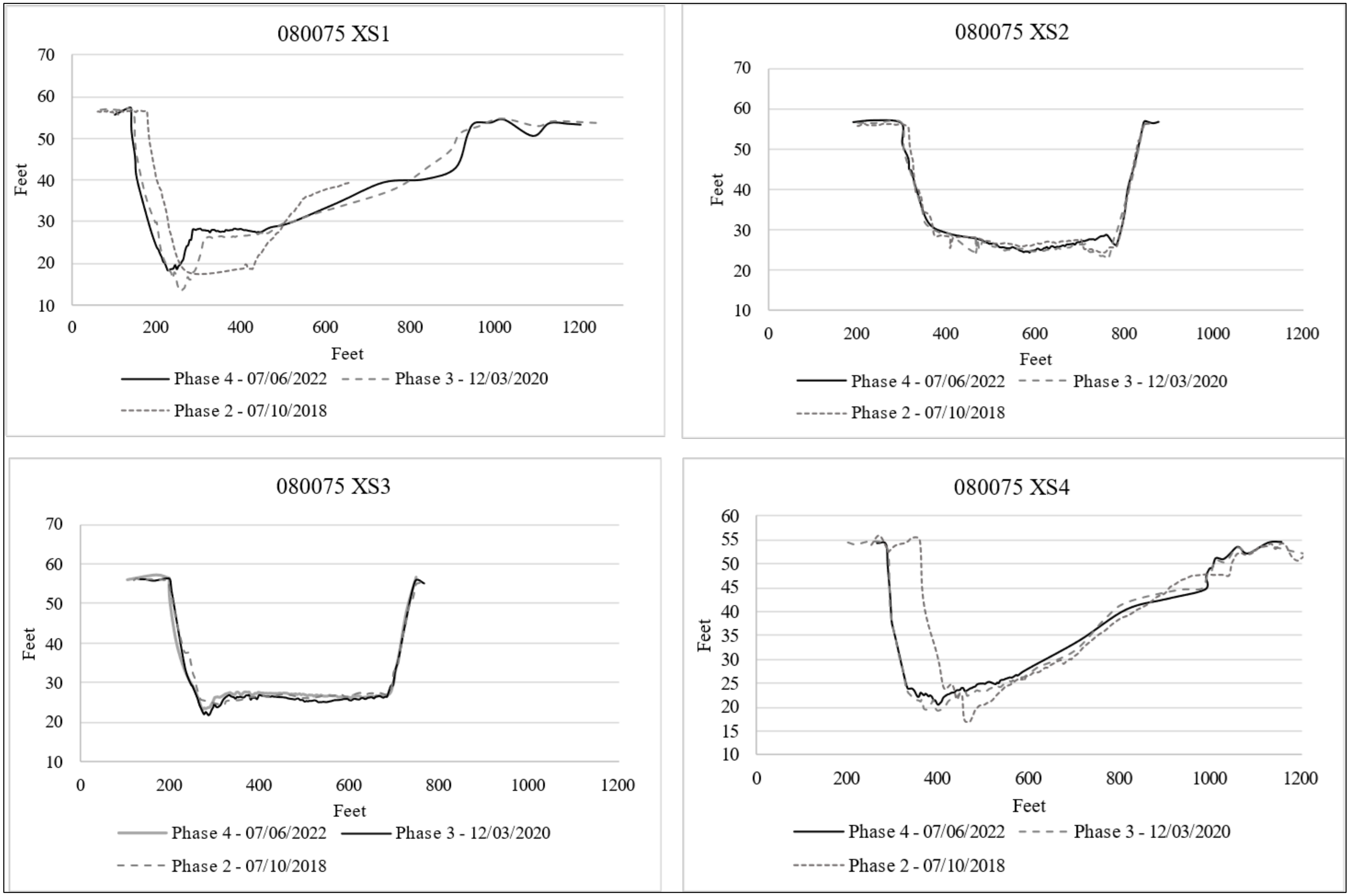

Figure 15. Cross-section comparisons for site 080075.

4 Water Quality

As shown in Table 3, water quality grab samples were taken by the USGS in conjunction with sediment sampling. Additionally, water quality sondes were deployed for a minimum of 30 days at 080444, 080295, and 080075 in order to characterize dissolved oxygen and temperature fluctuations during the hot, dry summer months.

4.1 Water Quality Grab Samples

The USGS performed 17 events across five sites, three were below Lake Livingston and two were above Lake Livingston (Table 3). No violation of any TCEQ water quality standards were observed.

Table 3. Table showing USGS Water Quality grab sample results.

Site	Date	Station name	Time	Flow (cfs)	DO (mg/l)	pH (SU)	Spec. Cond. (ms/cm)	Temp (C)	Turbidity (NTU or FNU)
08062500	20210413	TR nr Rosser	1255	1,424	11.2	8.2	757	21.9	15
08062500	20210311	TR nr Rosser	1205	3,707	10.8	7.5	474	13.8	53
08062500	20210505	TR nr Rosser	1325	11,160	7.5	7.4	473	21.6	170
08062500	20210709	TR nr Rosser	1410	6,997	7.2	7.2	417	28	96
08062500	20210709	TR nr Rosser	1411	6,997	7.2	7.2	417	28	96
08065350	20210317	TR nr Crockett	1200	3,469	8.8	8	475	18.6	--
08065350	20210427	TR nr Crockett	1245	5,046	8.3	7.9	477	21.1	96
08065350	20210513	TR nr Crockett	1141	24,251	7.1	7.7	330	20.7	150
08066250	20210616	TR nr Goodrich	0925	41,938	8.1	7.9	276	29.1	20
08066250	20210629	TR nr Goodrich	0920	20,034	7	7.2	302	28.6	7.4
08066250	20210708	TR nr Goodrich	1725	12,839	7.1	7.3	318	29.6	4.1
08066500	20210428	TR nr Romayor	1015	7,525	9.2	8.3	386	20.5	12
08067000	20210317	TR nr Liberty	1400	6,797	10.5	8.4	351	16.7	19.3
08067000	20210413	TR nr Liberty	1040	2,425	10.3	8.4	393	22.1	14.9
08067000	20210413	TR nr Liberty	1041	2,425	10.3	8.4	393	22.1	14.9
08067000	20210427	TR nr Liberty	1030	12,873	9.3	8.3	380	21.3	26
08067000	20210518	TR nr Liberty	1201	33,540	7.9	7.8	377	23.1	33

4.2 Water Quality Sonde Deployments

SonTek EXO3™ wiped sondes were calibrated per TCEQ Surface Water Quality Monitoring guidelines and deployed on t-posts at stations 080444, 080295, and 080075. The sondes collected temperature and dissolved oxygen readings at 15-minute intervals for a minimum of 30 days. Full deployment details are available in Table 4. Upon retrieval, all instruments were post-calibrated and were within acceptable tolerances. No exceedances of TCEQ Surface Water Quality standards were identified for DO, though at site 080444 was very close to the 3.0 minimum criterion. For temperature, all average temperatures were below the average criterion for water temperature (33.9 C for 080075 and 080295 and 35

C for 080444). It is important to note that the maximum temperature observed at 080075 was above the average criterion, but this is not an exceedance of the criterion because temperature is not assessed based on diurnal maximums. Regardless, it is necessary to understand that these reaches can get very hot in the summer months, which could have potential implications if there are species in the reach that are intolerant to elevated temperatures, like some species of native freshwater mussels. Selected results are shown in Table 4, Figure 16, Figure 17, and Figure 18.

Table 4. Summary of Temperature and Dissolved Oxygen data from 3 sonde deployments.

Site	Temp Min C	Temp Max C	Temp Av. C	DO Min mg/l	DO Max mg/l	DO Av. mg/l
080444	27.0	32.2	30.1	3.08	11.79	7.2
080295	27.52	31.4	29.6	4.32	8.0	6.2
080075	29.3	34.8	31.6	3.4	11.2	6.8

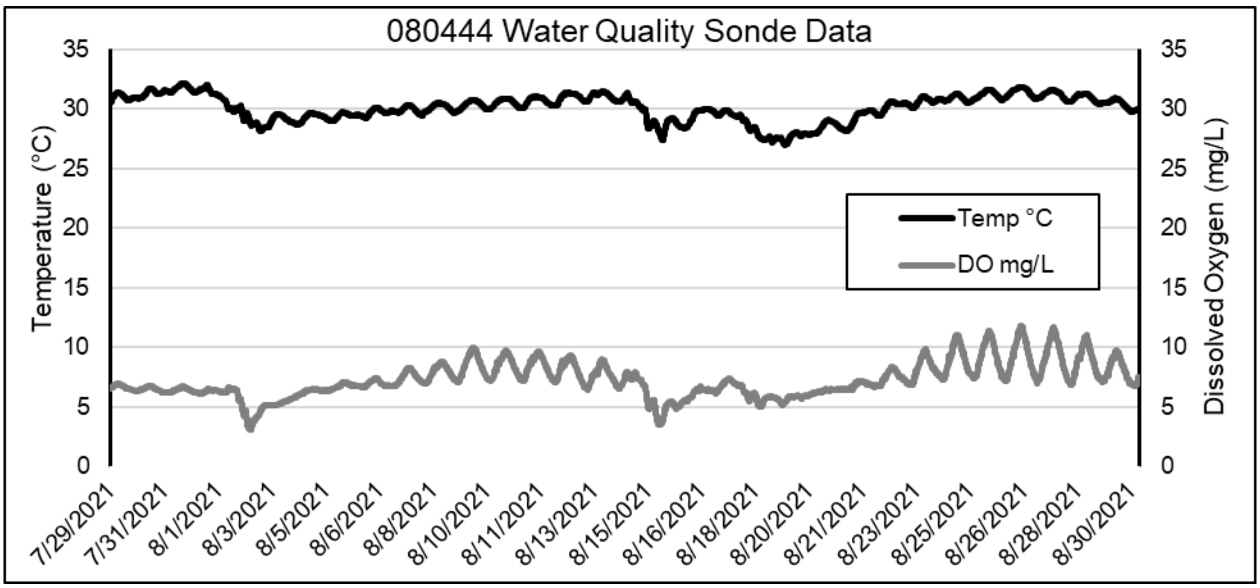

Figure 16. Station 080444 Water quality temperature (°C) and dissolved oxygen (mg/l) data.

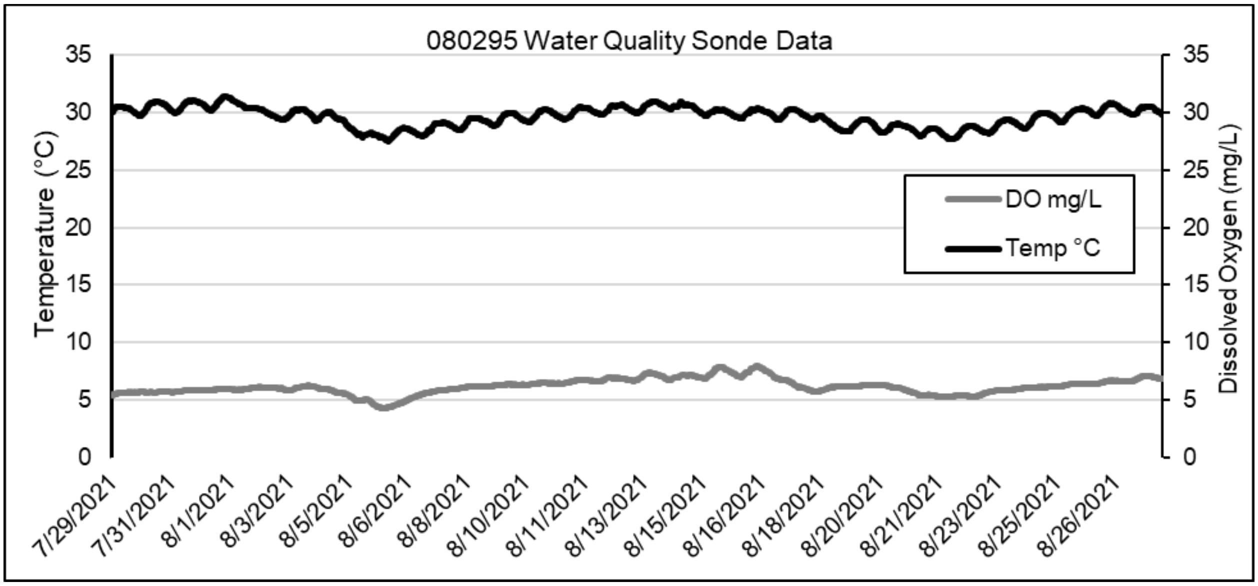

Figure 17. Station 080295 Water quality temperature (°C) and dissolved oxygen (mg/l) data.

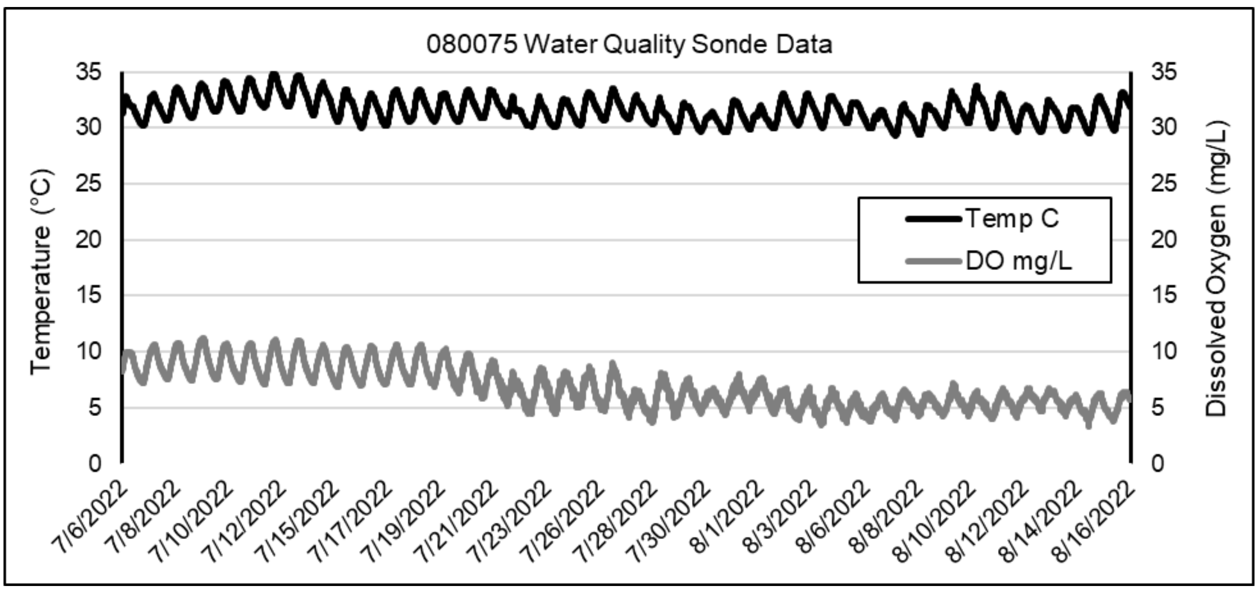

Figure 18. Station 080075 Water quality temperature (°C) and dissolved oxygen (mg/l) data.

5 Sediment Data Collection

The USGS was contracted to collect both suspended sediment and bedload data at two sites above Lake Livingston and three sites below Lake Livingston (Table 2 and Figure 3). Due to safety concerns, the site located at USGS gage 08066500 Trinity River near Romayor was removed after the first event and an additional sampling event was added to site 08067000 Trinity River near Liberty. This data was collected to inform two sediment transport models and is briefly summarized below (Table 5) summarizes the results and selected parameters are discussed in Figure 19 and Figure 20). Sediment data and how it was used during modeling is discussed in detailed in Section 5 of this report and in a technical memo included in the Appendices.

5.1 Bedload

It is important to note that collecting bedload requires very specific equipment, methods, and training, and even under perfect conditions, bedload data is highly variable. In order to best characterize bedload, multiple events should be completed across various hydrologic conditions. This data is only the first step in building a robust dataset for the Trinity River and additional data should be collected whenever possible.

The bedload samples collected by USGS did not result as expected (Figure 19). At the Liberty gage, two replicate samples taken back-to-back showed almost an order of magnitude difference in bedload dry mass, 7.9 grams and 60.7 grams. Additionally, the bedload samples taken at the Rosser gage, located above Lake Livingston just downstream of the Dallas/Fort Worth area, were shown to decrease with flow, which was not entirely unexpected, given the chaotic nature of sediment transport and the difficulties of measuring these processes (72.6 grams at 11,160 cfs and 438.4 grams at 6,997 cfs).

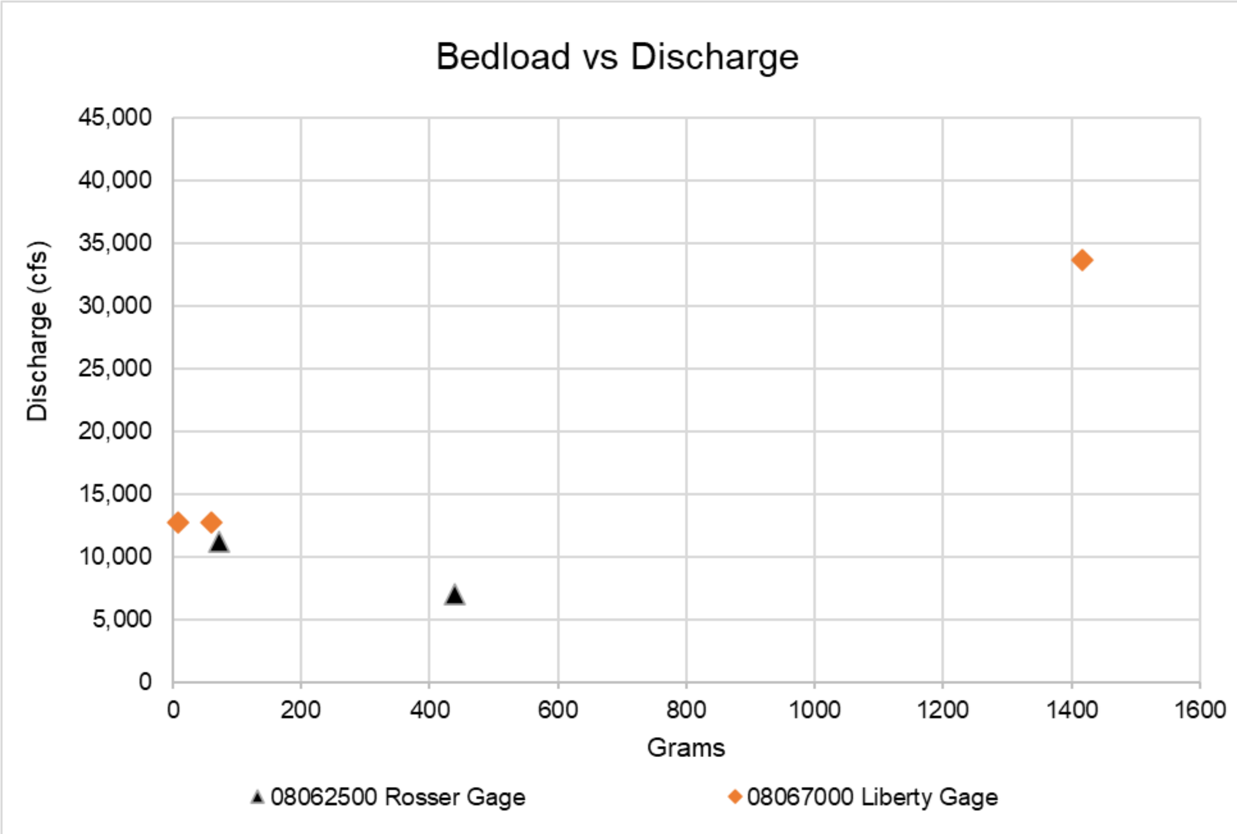

Figure 19. Bedload results from two USGS gages on the Trinity River.

5.2 Suspended Sediment

Suspended sediment results are shown in Table 5. Above Lake Livingston, both sampling sites showed very good agreement between suspended sediment and flow (Figure 19). Below Lake Livingston, the Liberty gage site showed that although suspended sediment concentrations increase more quickly with flow, the water contains far less sediment than either of the two sites above Lake Livingston. On the surface, the Goodrich data appears abnormal because significant increases in flow do not result in increases in suspended sediment. However, it is important to recognize that this site is directly below Lake Livingston which is known to trap sediment and the releases are generally very clear water (Figure 20). As mentioned previously, only one event was completed at the Romayor site due to safety concerns because the bridge is very narrow and cars are traveling at a high rate of speed.

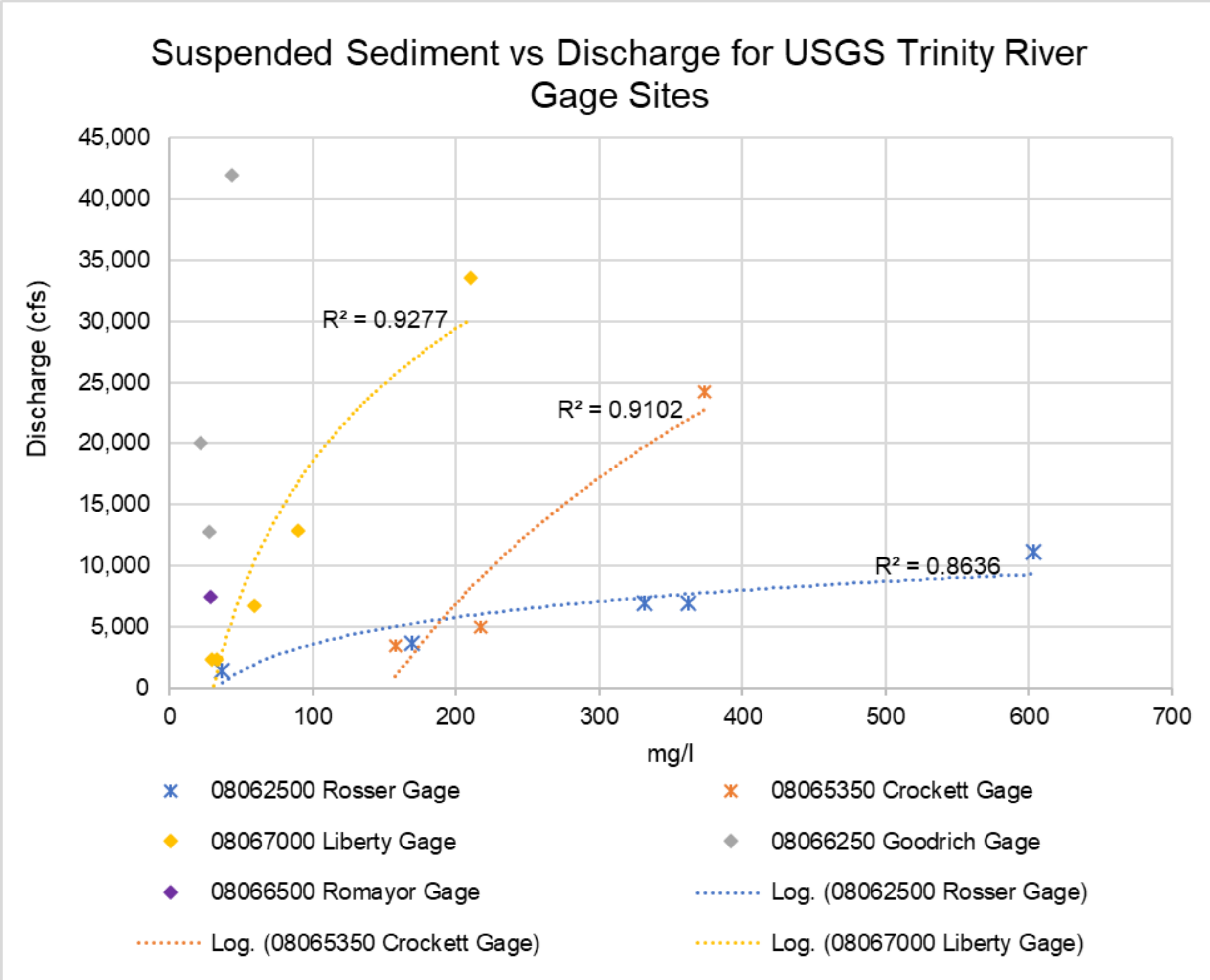

Figure 20. Figure showing suspended sediment concentrations compared to flow.

Table 5. Table of suspended and bedload collected by USGS for this project.

Station number	Date	Station name	Suspended sediment, between 0.063 and 4 mm, grams	Suspended sediment, mass dry weight, grams	Total solids, mg/l	Suspended sediment, <0.0625 mm, percent	Suspended sediment, <.25 mm, percent	Suspended sediment concentration, mg/l	Bedload sediment, <0.0625 mm, percent	Bedload sediment, <0.125 mm, percent	Bedload sediment, <0.25 mm, percent	Bedload sediment, <0.5 mm, percent	Bedload sediment, <1 mm, percent	Bedload sediment, between 0.063 and 4 mm grams	Bedload sediment, total sample mass, dry weight, grams
08062500	20210413	Trinity Rv nr Rosser	0.0204	0.24	502	92	100	37	--	--	--	--	--	--	--
08062500	20210311	Trinity Rv nr Rosser	0.2436	1.0765	409	77	86	169	--	--	--	--	--	--	--
08062500	20210505	Trinity Rv nr Rosser	0.7037	2.5561	698	72	98	603	--	--	--	--	--	--	--
08062500	20210709	Trinity Rv nr Rosser	0.6284	2.3505	498	73	97	362	--	--	--	--	--	--	--
08062500	20210709	Trinity Rv nr Rosser	0.4576	2.1487	498	79	99	332	--	--	--	--	--	--	--
08062500	20210505	Trinity Rv nr Rosser	--	--	--	--	--	--	7	9	13	61	85	67.5	72.6
08062500	20210709	Trinity Rv nr Rosser	--	--	--	--	--	--	4	4	6	65	71	422.9	438.4
08065350	20210317	Trinity Rv nr Crockett	0.0479	0.5926	--	92	99	158	--	--	--	--	--	--	--
08065350	20210427	Trinity Rv nr Crockett	0.0672	0.7808	--	91	95	217	--	--	--	--	--	--	--
08065350	20210513	Trinity Rv nr Crockett	0.3819	2.2746	--	83	99	374	--	--	--	--	--	--	--
08066250	20210616	Trinity Rv nr Goodrich	0.0944	0.1879	16	50	94	44	--	--	--	--	--	--	--
08066250	20210629	Trinity Rv nr Goodrich	0.0533	0.1455	195	63	94	22	--	--	--	--	--	--	--
08066250	20210708	Trinity Rv nr Goodrich	0.0398	0.1871	214	79	97	28	--	--	--	--	--	--	--
08066500	20210428	Trinity Rv nr Romayor	0.0176	0.1181	21	85	97	29	--	--	--	--	--	--	--
08067000	20210317	Trinity Rv nr Liberty	0.0431	0.2523	--	83	100	59	--	--	--	--	--	--	--
08067000	20210413	Trinity Rv nr Liberty	0.0109	0.1321	--	92	98	30	--	--	--	--	--	--	--
08067000	20210413	Trinity Rv nr Liberty	0.0162	0.1483	--	89	95	33	--	--	--	--	--	--	--
08067000	20210427	Trinity Rv nr Liberty	0.0829	0.3288	--	75	99	90	--	--	--	--	--	--	--
08067000	20210518	Trinity Rv nr Liberty	0.8331	1.4767	--	44	91	210	--	--	--	--	--	--	--
08067000	20210427	Trinity Rv nr Liberty	--	--	--	--	--	--	21	22	25	99	100	6.3	7.9
08067000	20210427	Trinity Rv nr Liberty	--	--	--	--	--	--	2	2	5	100		59.7	60.7
08067000	20210518	Trinity Rv nr Liberty	--	--	--	--	--	--	1	1	20	95	100	273.8	1417.7

6 Sediment Transport Modeling

This chapter provides a summary of the work completed, complications encountered, results, conclusions, and next steps. A technical memo is included in the Appendix of this report which provides full details related to model construction, hydraulic and sediment calibration, and scenario development. The goal for this modeling effort was to:

1. Create a tool that the Trinity and San Jacinto BBASC and BBEST groups could use during future adaptive management studies to better understand the sediment transport characteristics of the Trinity River mainstem,
2. Attempt to identify critical, system-wide sediment transport breakpoints where ecosystem response is acute, and
3. Identify breakpoints in flow where sediment transport processes change.

While identifying breakpoints in flow where sediment transport processes change is useful for management purposes across all flows, investigating lower flows, in the range of the SB3 flows, was the main priority in this project due to their relevance to the SB3 adaptive management process. Because of the size and scale of this system, the complicated processes and natural variability inherent in sediment transport modeling, and previous modeling efforts, HEC-RAS 1D was chosen for this task.

To make this effort more manageable, two models were created with Lake Livingston as the natural dividing point. The two study areas for this project are approximately 1) the Upper Model Study Region (Upper Model) from USGS Rosser streamgage to Lake Livingston and 2) the Lower Model Study Region (Lower Model) from Lake Livingston to just below the USGS Liberty streamgage. The Upper Model Study Region includes the Oakwood SB3 environmental flow standards measurement point, which is near USGS gage number 08065000 and River Mile 295 of the Trinity River. The Lower Model Study Region includes the Romayor SB3 environmental flow standards measurement point, which is near USGS gage number 08066500 and River Mile 75 of the Trinity River.

The Upper Model Study Region flows were based around the SB3 measurement point at the Oakwood USGS streamgage which has subsistence flow standards ranging from 75-160 cfs and base flow standards ranging from 250-450 cfs. The Lower Model Study Region flows were based around the environmental flow standards from the Romayor USGS streamgage which has subsistence flow standards ranging from 200-700 cfs and base flow standards ranging from 575-1,150 cfs (Table 6).

Table 6. SB3 flow standards from 08065000, Trinity River near Oakwood and 08066500, Trinity River at Romayor.

SB3 measurement point/USGS gage	Season	Subsistence (cfs)	Base (cfs)	Pulse trigger (cfs)	Pulse volume (af)	Pulse duration (days)
08065000, Trinity River near Oakwood	Winter	120	340	3,000	18,000	5
08065000, Trinity River near Oakwood	Spring	160	450	7,000	130,000	11
08065000, Trinity River near Oakwood	Summer	75	250	2,500	23,000	5
08065000, Trinity River near Oakwood	Fall	100	260	2,500	23,000	5
08066500, Trinity River at Romayor	Winter	495	875	8,000	80,000	7
08066500, Trinity River at Romayor	Spring	700	1,150	10,000	10,000	9
08066500, Trinity River at Romayor	Summer	200	575	4,000	4,000	5
08066500, Trinity River at Romayor	Fall	230	625	4,000	4,000	5

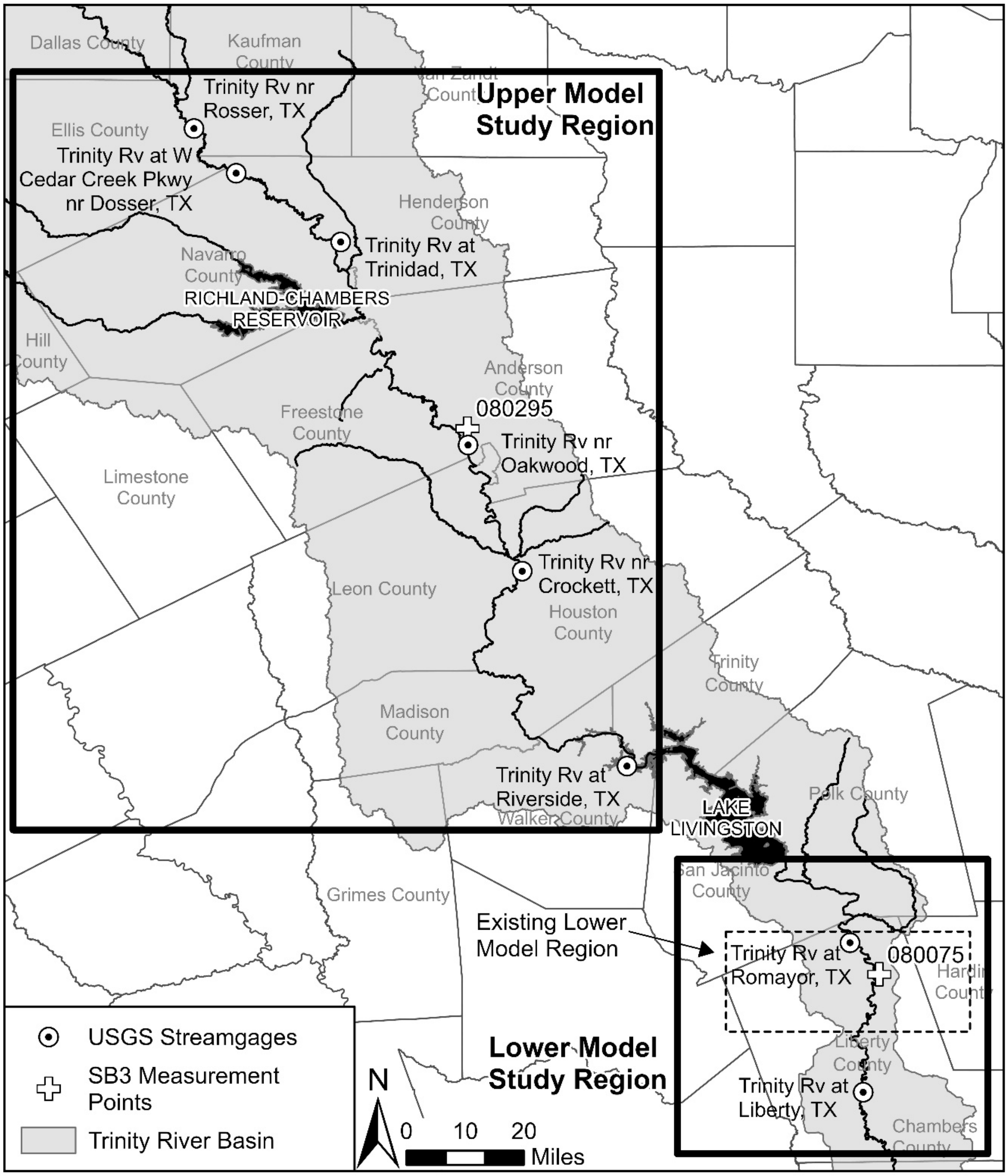

Figure 21. Map showing Upper and Lower Model Study Regions.

6.1 Model Construction

The Upper Model was constructed and calibrated for low flows in the last phase of TRA's SB3-related work.

During the previous phase of this project, a HEC-RAS model was created and calibrated for low flows for a portion of the Lower Trinity River near long-term site 080075 which spanned from the Romayor USGS streamgage to the State Highway 105 bridge near Franklin, TX. To expand this model for this project, TRA collected approximately 220 additional bathymetric cross-sections for most of the Lower Trinity River between river miles 116 and 35 at predetermined, model-derived cross-sections. This new channel data was complied with LiDAR DEM's for overbank elevation to extend the Lower Model upstream to Lake Livingston dam and downstream to approximately 6 river miles below the USGS gage at Liberty. This task resulted in the completion of HEC-RAS 1D hydraulic model geometries for a large portion of the Middle and Lower Trinity River and, importantly, sections around environmental flow standards measuring points.

6.2 Model Hydraulic Calibration

To extend the hydraulic calibration to very high flows and facilitate the creation of 1D sediment models using these model geometries, a full re-calibration of hydraulics was performed for both models. This process included phases of steady and unsteady model calibration, and a reasonable calibration of flows and stages for a 5-year unsteady flow series was achieved by modifying cross-sections where justified, adding levees and ineffective flow areas, and adjusting channel roughness. Intervening inflows from sizeable, ungaged tributaries were also developed and added into the model using HEC-RAS's internal Ungaged Lateral Inflow estimation techniques to improve the sediment models. The flow series timeframes for each model were chosen based on the availability of continuous flow and stage data from USGS gages.

The Upper Model utilized a flow series constructed entirely from USGS flow and stage data that spanned the period of 2008-2013. The model consisted of an upstream inflow boundary, set using time-adjusted Rosser gage flows, 12 intervening inflows (2 of which were gaged, 10 of which were ungaged), 2 diversions informed by historical data (TRWD Wetlands and Huntsville) and a downstream stage series boundary representing Lake Livingston's elevation (Figure 22). Flows at the upstream boundary ranged from 600-40,000 cfs, with a median flow of about 1,000 cfs. Flows at the Crockett gage location ranged from 900-60,000 cfs, with a median flow of about 1,600 cfs. Lake Livingston elevation ranged from 127 to 135 ft during this time period.

The Lower Model also utilized USGS flow series data and spanned the period of June 2018 – December 2023 – this was the longest continuous period across all of the available streamgages. The model consisted of an upstream inflow boundary, set using time-adjusted Goodrich gage flows, 5 intervening inflows (2 of which were gaged, 3 of which were ungaged), and 1 diversion informed by historical data (Luce Bayou starting 2022). Flows at the upstream boundary ranged from 1,000-80,000 cfs, with a median flow of about 3,000 cfs. The downstream boundary was between the Liberty and Moss Bluff gage locations, and was informed by a flow-stage rating curve created using data from both gages.

The difference in calibration period occurred because data set availability differed between the upstream and downstream models. The Upper Model had been calibrated to some degree during prior modeling phases and datasets were available from those efforts that included the most complete set of contiguous flow records at upstream and downstream boundaries, and plus intervening locations to incorporate ungaged flows. The Lower Model lacked discharge data at the downstream boundary (Liberty gage) prior to 2018, so the best complete set of contiguous flow records for calibration for the Lower Model were for a post-2018 period.

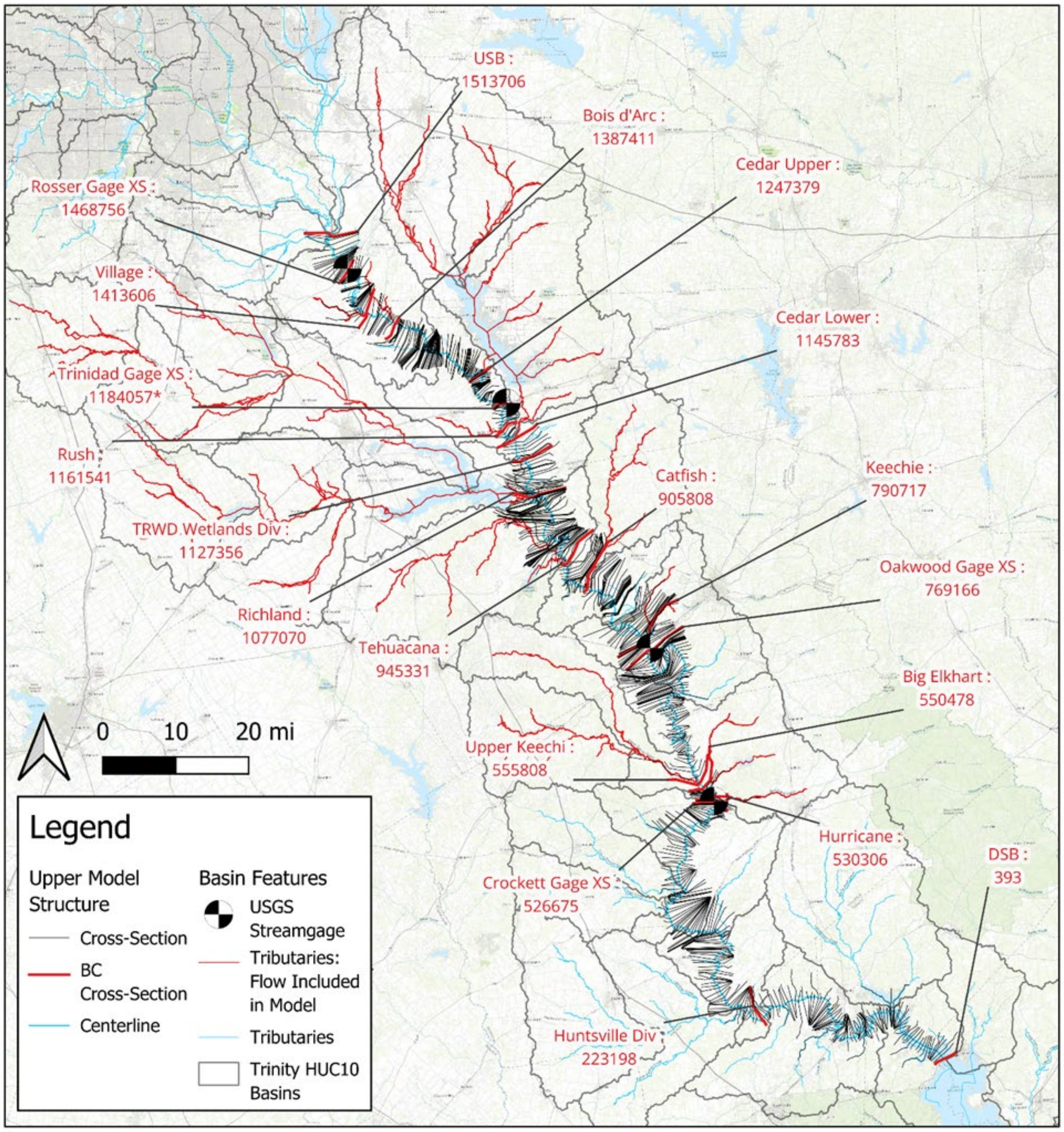

Figure 22. Map detailing basin features and model configuration for Upper Model area. Labels indicate features that were represented in the model with their name and cross-section number. Tributaries labeled as red are not explicitly modeled as streams in HEC-RAS.

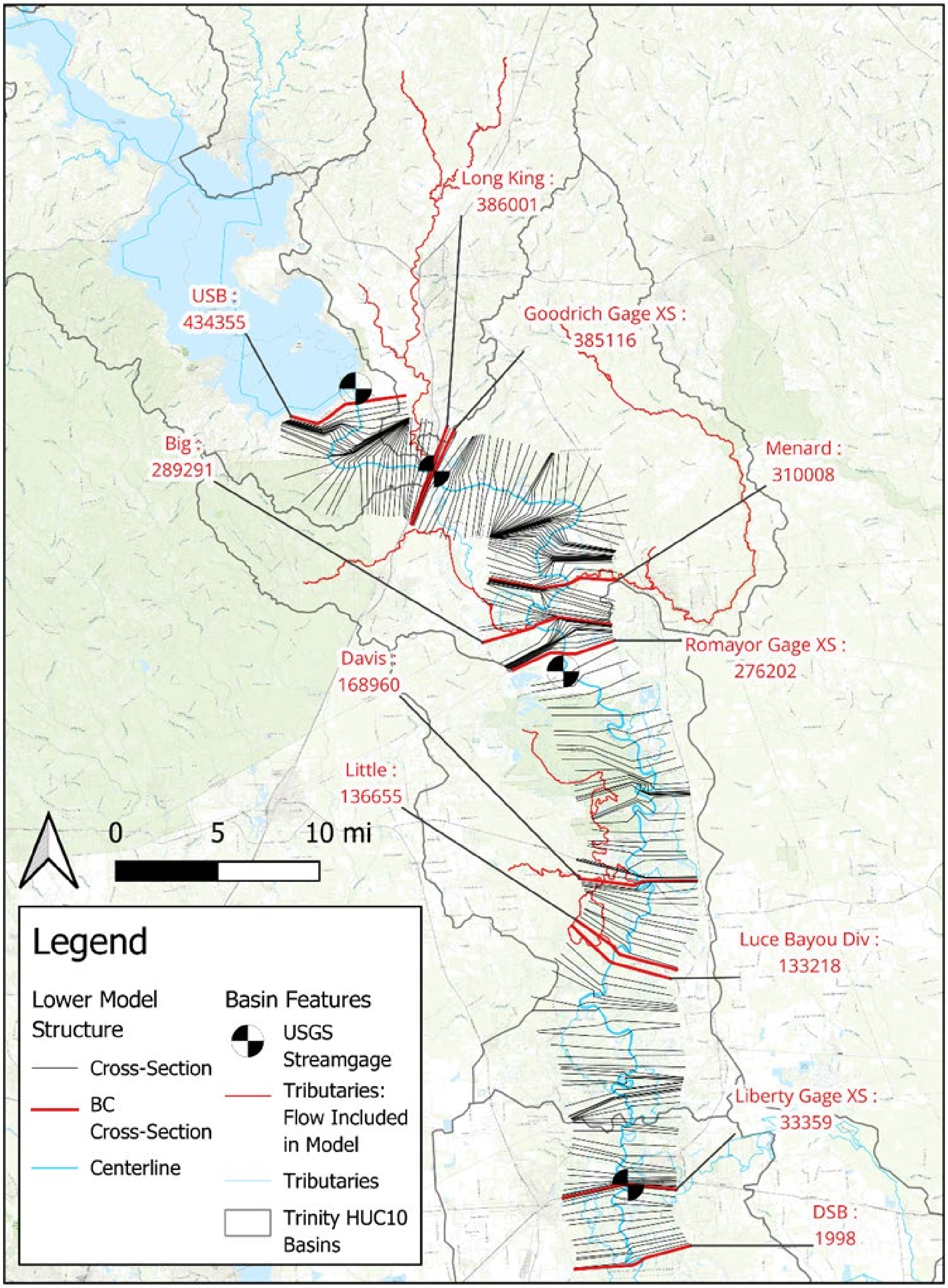

Figure 23. Map detailing basin features and model configuration for Lower Model area. Labels indicate features that were represented in the model with their name and cross-section number. Tributaries labeled as red are not explicitly modeled as streams in HEC-RAS.

The hydraulic calibration of the Upper and Lower Models was deemed suitable for sediment models. The, timing of flows in the Upper Model is close to that shown in the observed dataset, and flow magnitudes are quite closely-matched for all but high flows (Figure 24). High flows are very closely matched at Trinidad (within ~5% of the observed value) and are off by between ~5-10% for Oakwood and Crockett. We examined single flood events during the calibration period and identified that times where high flow magnitudes were off by the greatest amount were during periods where intervening inflows were high relative to flow coming from the upstream boundary, and that the relatively close match shown here represents the best that the HEC-RAS ungaged lateral inflows estimation tool was able to achieve with our simplified representation of tributaries. Predicted stage similarly matched closely (within ~1 ft) for most low to medium flows. During some high flows, stages could be off by as much as 5 ft, but this often simply reflected the mismatch in flow translating to lower stages. Overall, the hydraulic calibration of the Upper Model is demonstrated to be quite good considering the size of the model and the range of flows that need to be run for sediment model calibration. It was deemed acceptable for the sediment modeling tasks of 1) sediment calibration and 2) running sediment model scenarios.

The Lower Model's hydraulic calibration was also deemed good for low flows, with the exception that it was as much as 3 ft too low at the Romayor gage location. Predicted and observed flow values at USGS Goodrich, Romayor and Liberty streamgage locations for the Lower Model for one of the five simulated years are shown in Figure 25. The other four years of the five-year period show similarly well-calibrated hydraulics. As shown in Figure 24, timing of flows in the Lower Model is close to that shown in the observed dataset, and flow magnitudes are quite closely matched for all flows at Romayor and for all but high flows at Liberty. The relatively-worse flow calibration at Liberty is likely due to difficulties associated with setting ineffective flow areas and levees in the low-gradient downstream portion of the river. Predicted stage matched closely (within ~1 ft) for most medium flows. During some high flows, stages could be off by as much as 2.5 ft, with some of this effect likely reflecting a mismatch in flow translating to lower stages. Stage calibration for low flows was quite good at Liberty but was consistently off by ~3 feet at the Romayor gage. This stage mismatch at the Romayor gage was difficult to diagnose but is likely due to there being somewhat of a gap in available bathymetric data at this location and the absence of the bridge from the model[1]. Overall, the hydraulic calibration of the Lower Model is demonstrated to be good considering the size of the model and the range of flows that need to be run for sediment model calibration. It was deemed acceptable for the sediment modeling tasks of 1) sediment calibration and 2) running sediment model scenarios.

[1] Bridges were removed from this model to reduce instability.

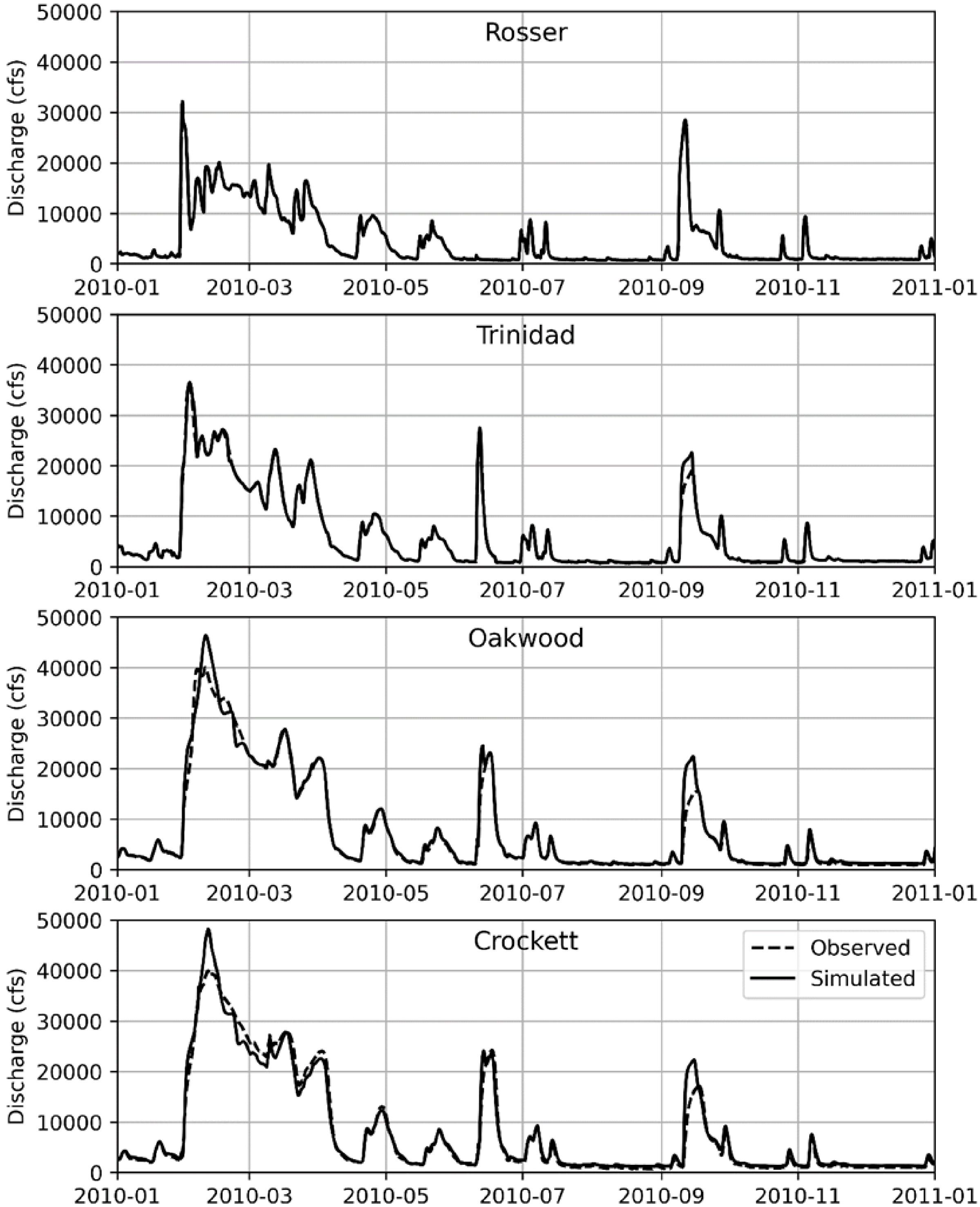

Figure 24. Comparison of observed and predicted discharge for 2010 at four streamgage locations in Upper Model, shown in order from upstream to downstream. This represents 1 year of results from the 5-year calibration period (2007-2011).

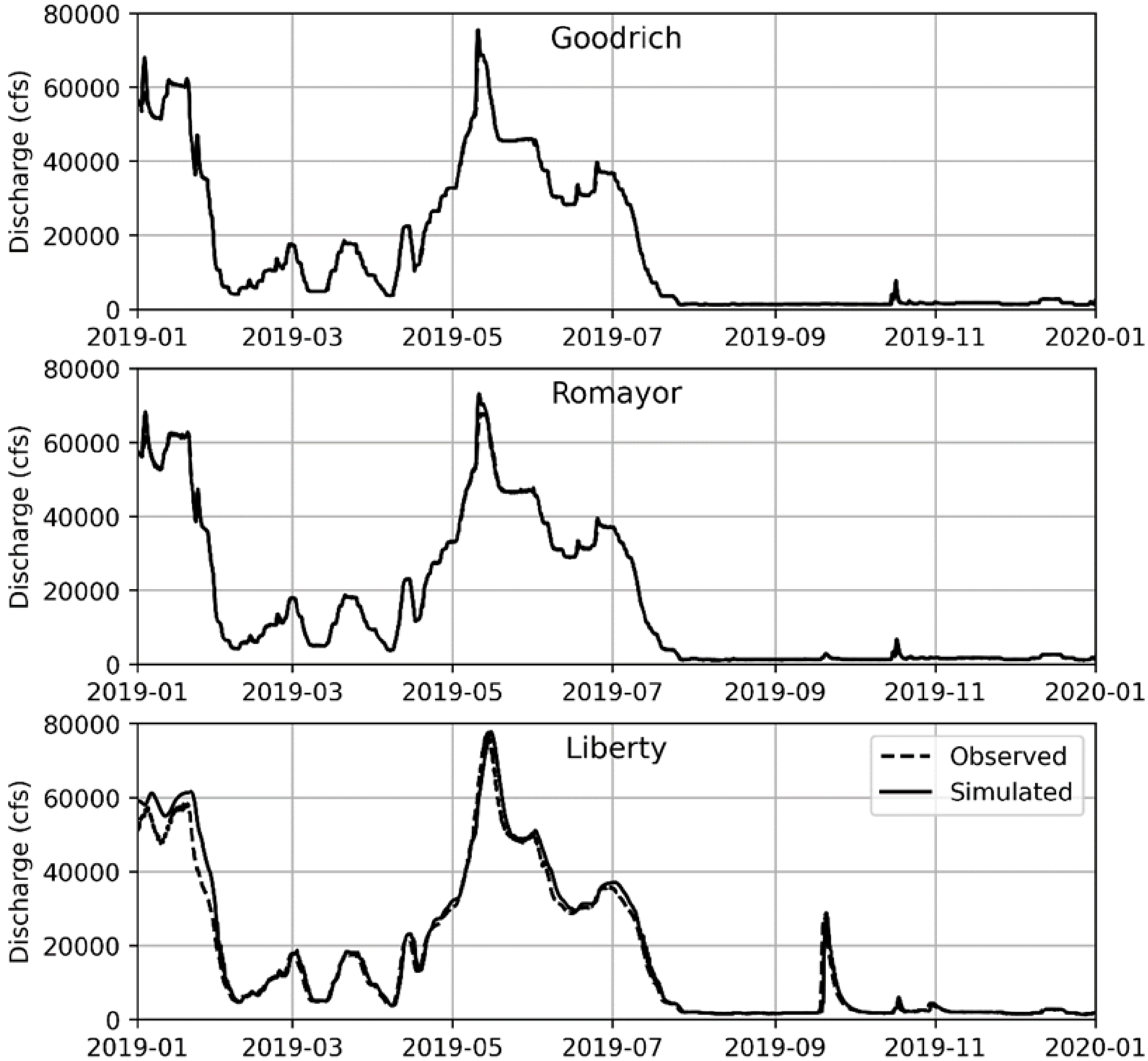

Figure 25. Comparison of observed and predicted discharge for 2019 at three streamgage locations in Lower Model, shown in order from upstream to downstream. This represents 1 year of results from the 4.5-year calibration period (2013-2018).

6.3 Model Sediment Calibration

After the hydraulic calibration was complete, 1D sediment models were developed and calibrated to simulate bedload transport. 1D sediment models leveraged available information from USGS sediment data collection and, in the case of the Upper Model, a detailed technical report on sediment characteristics. Sediment calibration models were run for the same 5-year flow series with intervening inflows that was developed for the hydraulic calibration. The hot-start models utilized outputs from a 3-year spin-up model with flows approximating the effective discharge of the channel to set the initial sediment conditions. Boundary conditions all utilized a sediment load-flow rating curve that was initially set from data sources and later adjusted as part of the model calibration process.

No information was available for sediment inputs from tributaries, so the modeling team made assumptions about sediment load-flow rating curves for tributaries based on information about observed loads at the upstream boundary and at streamgage locations in the model domain and adjusted them as part of the calibration process.

While flow-load rating curves in the model domain suggest that the sediment models could achieve a better match with reality, the main calibration target for the sediment models was to achieve a model that had a stable bed at the end of the 5-year flow series and that was capable of eroding and depositing. This was achieved in both models, with a few caveats described in the full technical report included in the Appendix. It is recommended that the calibration of each be revisited in any future work using these models, and that significant changes to the model's structure be considered as part of this revisitation to make them more appropriate for decadal-scale sediment runs with widely-ranging flows. Paring down the number of model cross-sections would likely have an impact of shortening model runtimes, reducing the computational burden of the calibration process, and improving the quality of the model calibration. A summary of the calibration process is included in Sections 5.4 and 5.5 below and a full description is included in the full technical report included in the Appendix.

6.4 Upper Model Calibration

For the Upper Model, sediment inflows were set at the upstream boundary and at all intervening inflows, due to their generally high flow contributions (Figure 26). USGS historical sediment load data indicated that load did not change significantly in the downstream direction in this stretch of the river, so the upstream boundary flow-load rating curve was used for all intervening inflows.

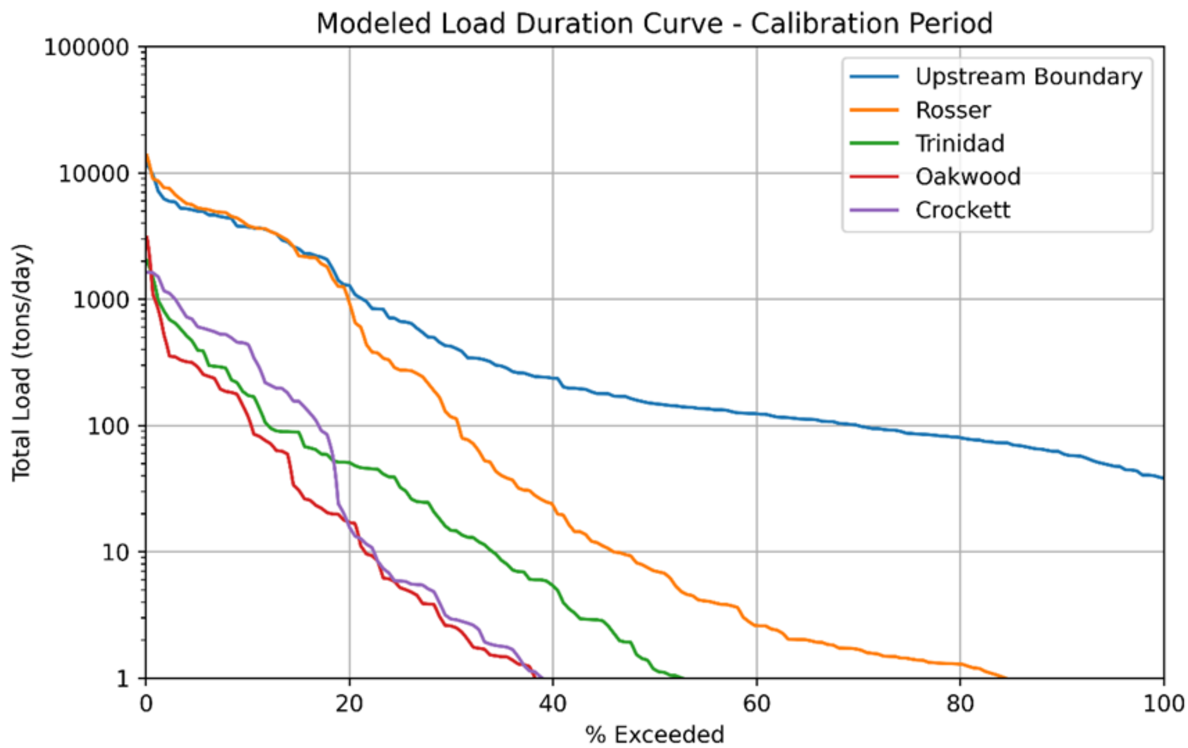

Figure 26. Modeled load duration curves at Upstream boundary and streamgage locations for the Upper Calibration Period Model.

Net invert change results for the Upper Calibration Period Model show net aggradation in the reach between the upstream boundary and the Trinidad location as shown in the first panel of (Figure 27). Net erosion greater than 0.1 ft was only observed at 6 out of 193 cross-sections. The average net deposition in this reach was 0.54 ft and 157 out of 194 cross-sections showed net deposition of more than 0.1 ft. Several cross-sections in this reach showed more than 2 ft of net deposition, one of which was the upstream-most cross-section where flows and sediment loads enter the model. Invert changes are fairly continuous at the very upstream end of this reach, indicating that some load is still present in low flows, but this effect decreases in the downstream direction. By the Rosser location, much of the load at low flows has clearly been deposited out, and the time series plots of invert change have become more stepped with invert changes primarily occurring only at higher flows.

Net invert change results show progressively more net erosion moving downstream in the two reaches below the Trinidad location, shown in the second and third panel of Figure 27. The average net invert change was -0.06 ft in the Trinidad – Crockett Reach and -0.24 ft in the Crockett – downstream boundary reach. In the Trinidad – Crockett reach, 105 out of 288 cross-sections showed net deposition of more than 0.1 ft, compared to only 31 showing net erosion of more than 0.1 ft. However, several cross-sections in this reach showed more than 2 ft of erosion, leading to net erosion in the reach. The erosion signal was stronger in the Crockett – downstream boundary reach, with 69 out of 208 cross-sections showing more than 0.1 ft of net erosion and only 17 showing more than 0.1 ft of net deposition. Time series plots of invert change in the Trinidad – Crockett reach are mostly stepped, and only a few cross-sections have a smooth profile that indicates any invert change occurring at low flows. For the Crocket – downstream boundary reach, invert change is clearly only happening during periods of high flow.

Sediment transport is generally shown to be more active in the reach between the upstream boundary and the Rosser location, with both net erosion and net deposition occurring for flows below about 20,000 cfs and mostly net erosion occurring for flows above that (Figure 28). The reach between the Rosser and Trinidad locations shows mostly net deposition, but there are some periods of net erosion during flows greater than 20,000 cfs. In the reach between the Trinidad and Oakwood locations, flows below about 20,000 cfs generally cause negligible change or, in some cases, some net deposition, and higher flows cause net erosion. For the reaches between the Oakwood location and the downstream boundary of the model, low flows generally cause negligible invert change and flows above 20,000 cfs cause significant net erosion (Figure 28).

In summary, model results showed 0.5 ft of reach-averaged net deposition upstream of the Trinidad cross-section and <0.25 ft of net erosion downstream of the Trinidad cross-section. Downstream of Trinidad, significant bed change primarily occurred only at high flows.

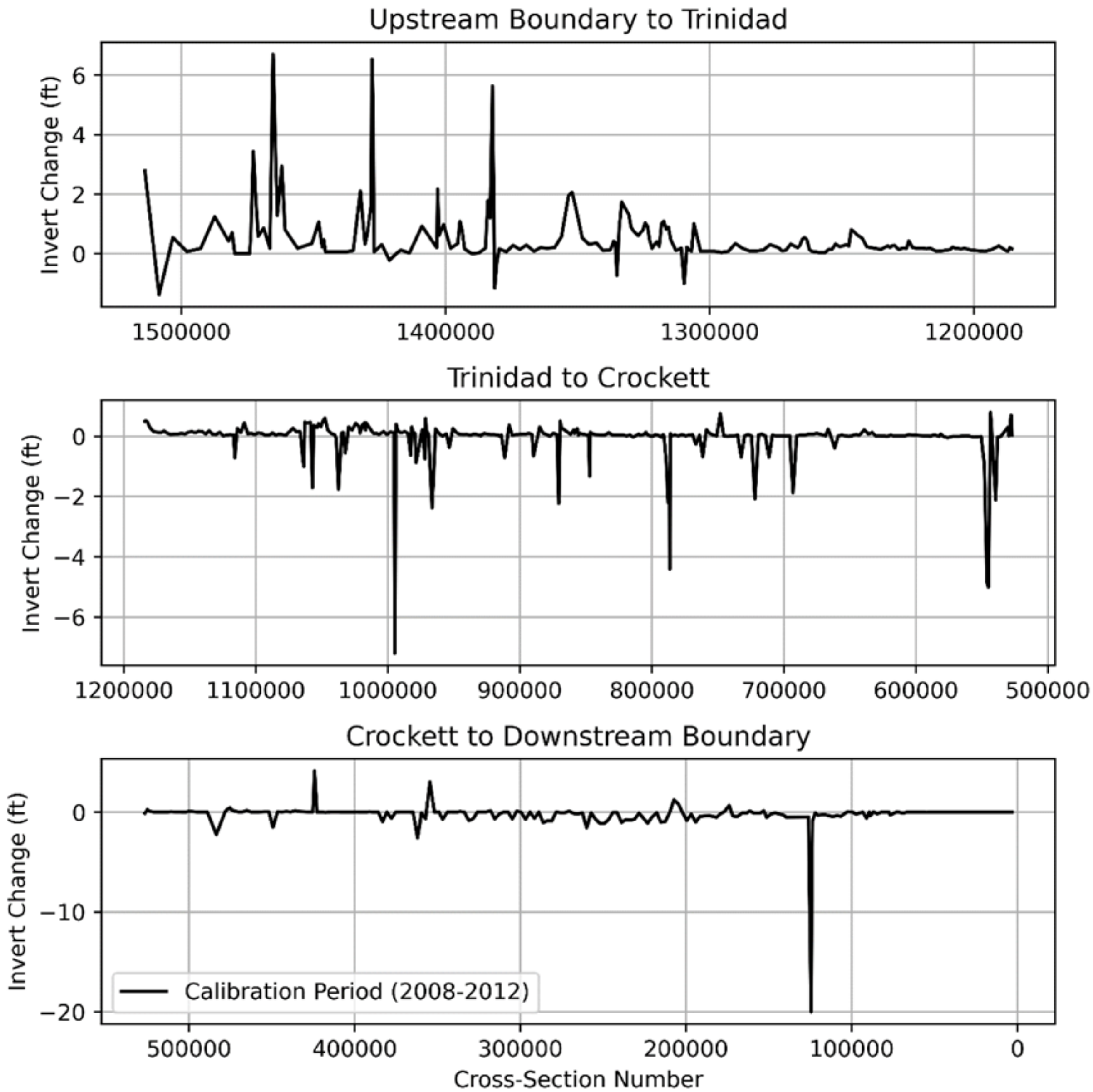

Figure 27. Modeled net invert change (ft) for the Upper Calibration Period Model.

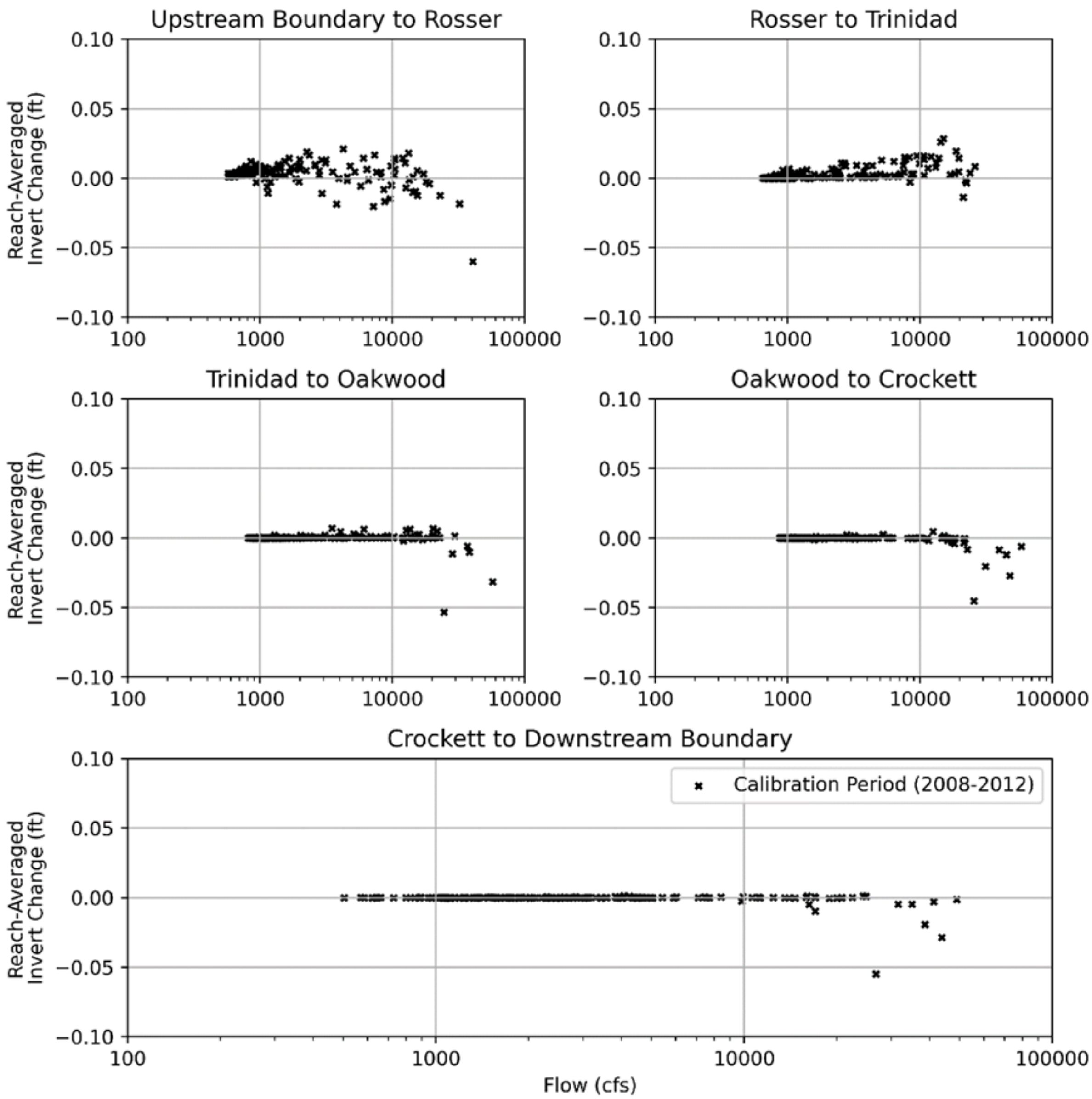

Figure 28. Reach-averaged invert change (ft) vs. Flow in reaches between boundary/streamgage locations for Upper Calibration Period Model. Invert change was output at every computational increment, and is accordingly presented as a rate of ft of invert change per 10 days.

6.5 Lower Model Calibration

For the Lower Model, a clear water inflow (no sediment load) was set at the upstream boundary due to the Lake Livingston dam. Because of this, intervening sediment inflows were especially important to supply sediment to the model, and the three upstream-most intervening inflows were assigned a flow-load duration curve (Figure 29). These were based on the flow-load relationship at Romayor established from USGS historical sediment observations, and the flows associated with each load-gradation point were adjusted iteratively as a part of model calibration.

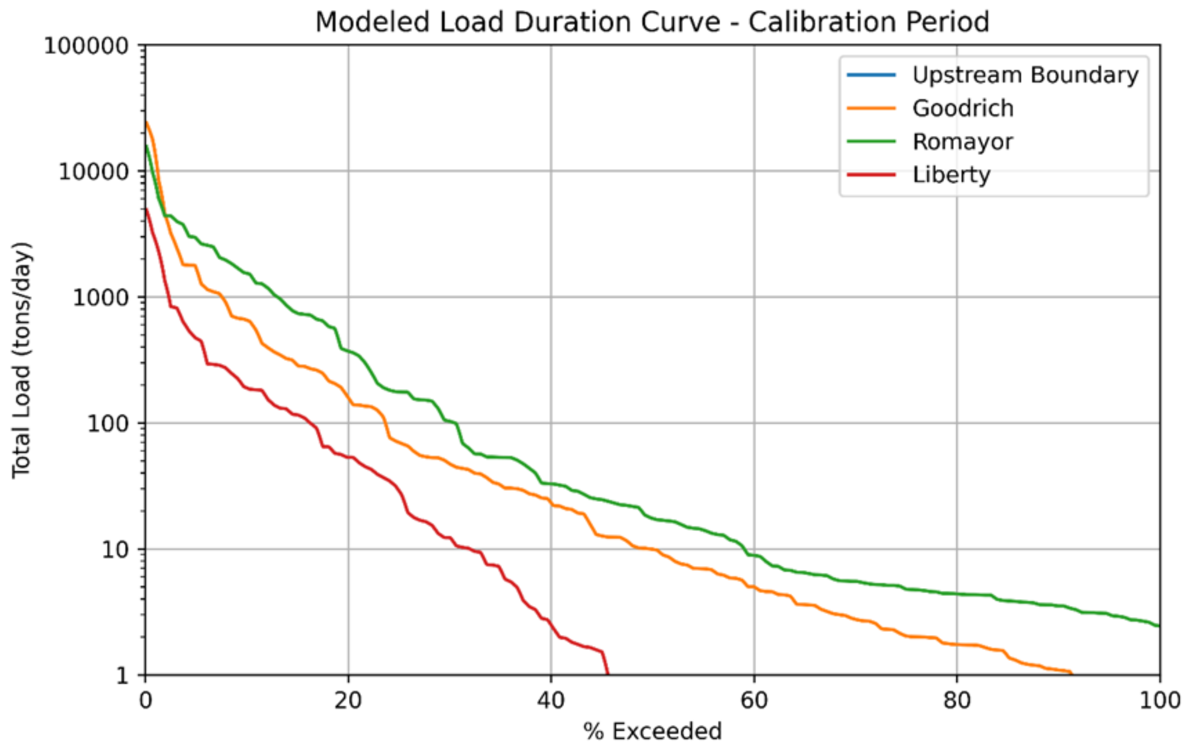

Figure 29. Modeled load duration curves at streamgage locations for the Lower Calibration Period Model. Note that upstream boundary is a clear water boundary condition due to the presence of the dam.

Net invert change results for the Lower Calibration Period Model show net erosion throughout the model reach, as shown in Figure 30. For the reach between the upstream boundary and the Romayor location, net deposition greater than 0.1 ft was only observed at 13 out of 122 cross-sections. The average net invert change in this reach was -0.24 ft and 43 out of 122 cross-sections showed net deposition of more than 0.1 ft. Several cross-sections in this reach showed more than 1 ft of net deposition. The reach between the Romayor location and the downstream boundary was similar, with an average net invert change of -0.22 ft. In this reach, more cross-sections experienced net deposition of more than 0.1 ft than experienced net erosion of more than 0.1 ft, but several cross-sections eroded more than 1 ft. Invert changes are fairly stepped at the upstream end of the model, indicating that sediment transport is only occurring at high flows. This makes sense given the clear water upstream boundary.

Reach-averaged invert changes shown that the majority of the erosion occurred above ~25,000 cfs between the Upstream Boundary – Goodrich and Goodrich – Romayor reaches, and above ~40,000 cfs at the Romayor – Liberty and Liberty – Downstream Boundary reaches (Figure 31).

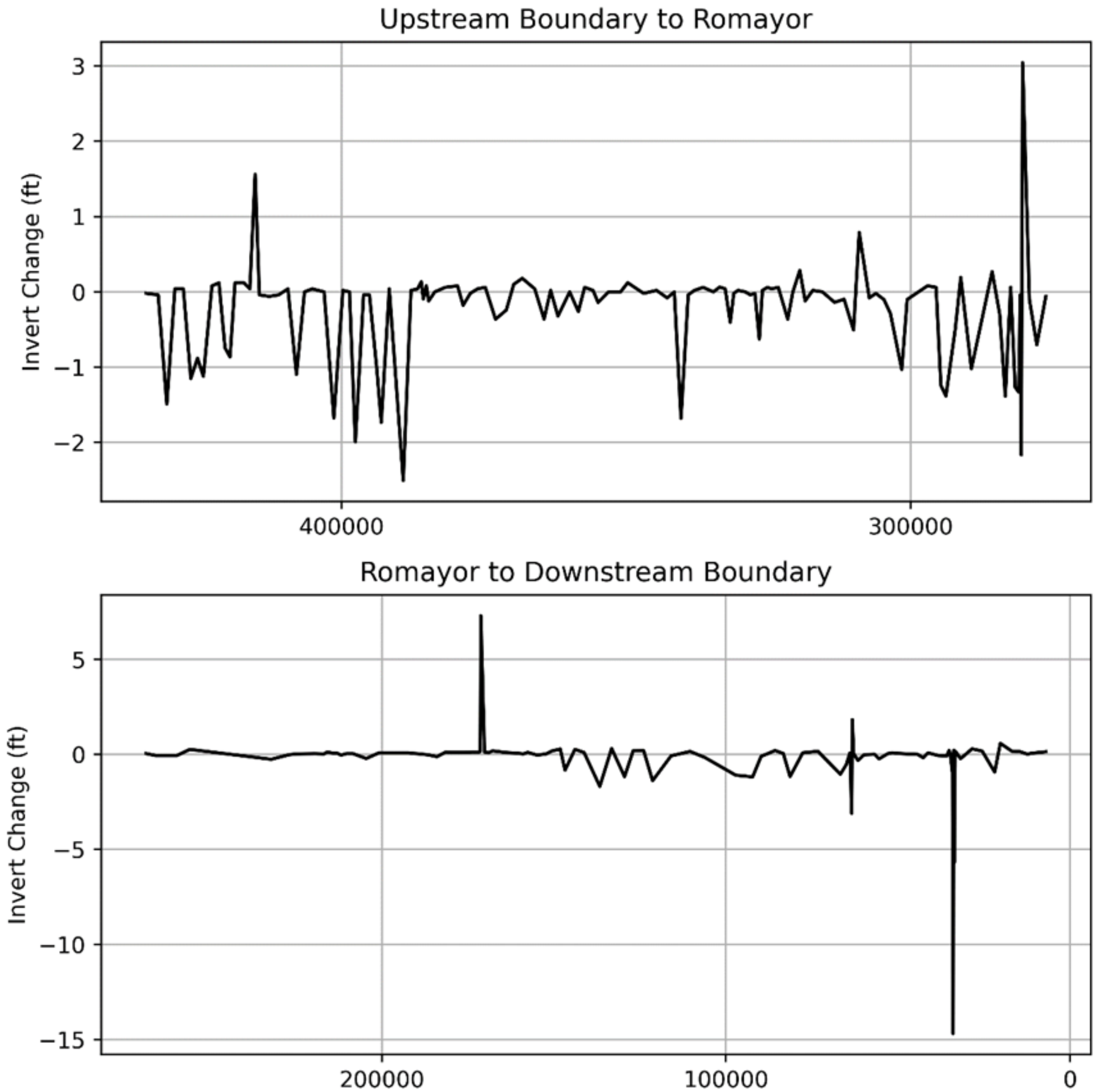

Figure 30. Modeled net invert change (ft) for the Lower Calibration Period Model.

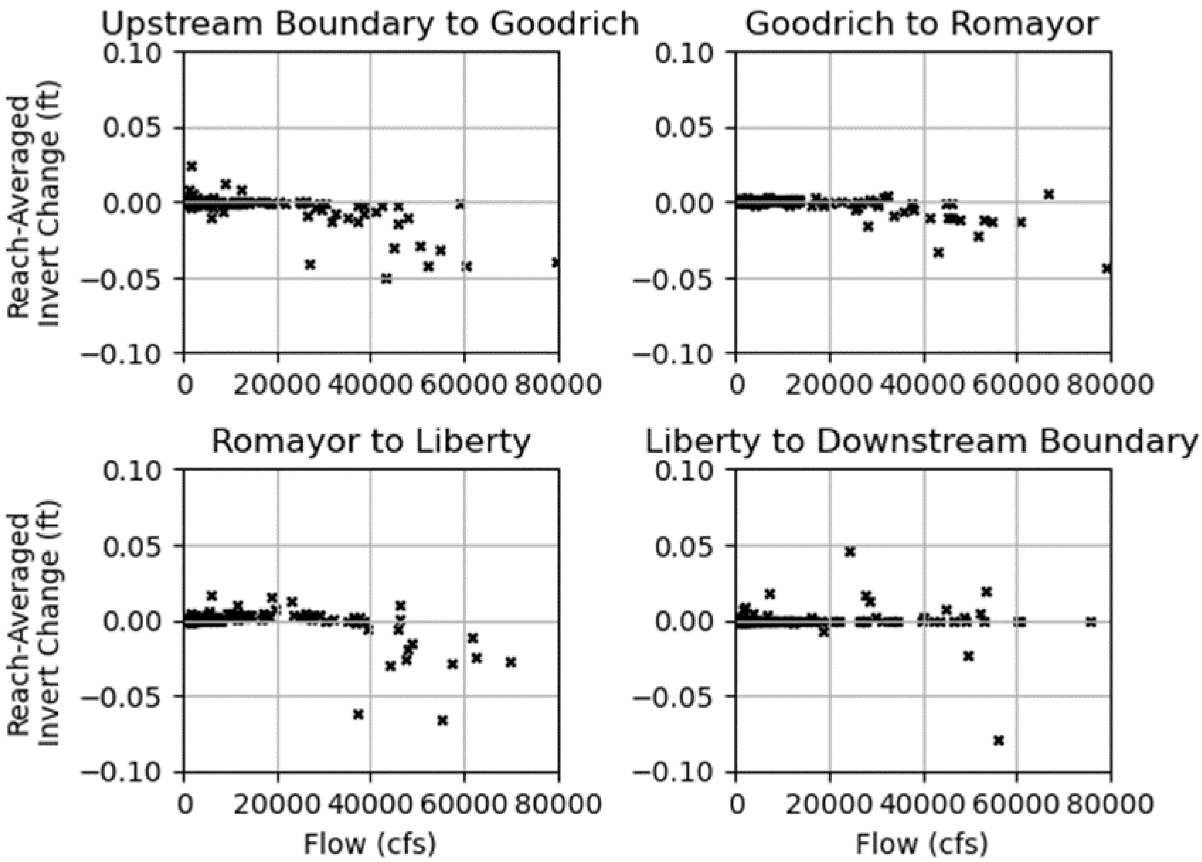

Figure 31. Reach-averaged invert change (ft) vs. Flow in reaches between boundary/streamgage locations for Lower Calibration Period Model. Invert change value is incremental between timesteps, and represents the change in invert elevation over a 10-day period.

6.6 Results and Discussion

Three long-term hydraulic scenarios were developed and run and their results were used to determine breakpoints in flow where sediment processes change. TRA's "Run 3 Compact Mod[2] of the Trinity River Monthly Water Availability Model (WAM) was used as a baseline model ("WAM Flows") and "High WAM Flows" and "Low WAM Flows" were developed by running the same model with +50% and -50% return flows, respectively. WAM regulated flows for each scenario were spatially disaggregated based on drainage area to the same representation of intervening inflows and diversions used in the calibration models. Then, monthly flows were disaggregated to daily flows using the unregulated flow series at the Rosser gage location and the Goodrich gage location from the daily version of the Trinity

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[2] Run 3 Compact Mod is described in detail in a report from a previous report (Mangham, Osting, & Flores, 2017). This model represents full utilization of water rights at their priority dates, a "worst case scenario," from a water availability and instream flows standpoint where all return flows are utilized except for those obligated to remain in the river to support Houston's rights in Lake Livingston.

River WAM. Due to difficulties in timing during low flow events, achieving very low flows with this disaggregation scheme and the sediment model turned on without the model going unstable was extremely difficult. At times where this scheme tried to divert water that was not there and caused the model to go unstable, all diversions were set to 0 and low flows were forced by setting the flows at the upstream end of the model to 100 cfs for the Upper Model and 200 cfs for the Lower Model. Several low flow values were tested to find the limits of what the model could achieve in terms of low flows before arriving on these numbers. Although the WAM runs stretch from 1940-1996, we opted to run a fifty-year period starting on 1/1/1940 and ending on 12/31/1989. At the lowest computational timesteps that we were able to achieve, this still represented multiple days of computer runtime for each model, and this time period was deemed sufficiently long to achieve the research goals of this project.

Adding sediment transport processes makes the models significantly less stable, and it was a major challenge to balance 1) using the WAM scenario hydraulics, 2) including very low flow periods in the model, and 3) making sure the models ran to completion without crashing. The target low flow value for the Upper Model to achieve this balance was 100 cfs, and we were able to run all the models using this as the minimum flow.

The creation scheme yielded flow series scenarios with sufficient differences in the frequency of low flows to assess how changes in flow affect sediment transport processes. For the Upper Model, there was a 5-15% difference in the duration of flows between the scenarios for flows in the range of 100-2,000 cfs. This difference in flows between scenarios was visible at many of the model gage locations. For the Lower Model, there was a 5-10% difference in the duration of flows between the scenarios for flows in the range of 100-2,000 cfs at the upstream boundary. This difference, however, quickly dissipated in the downstream direction, and was only about 1-2% at locations further downstream. The creation scheme yielded flow series scenarios with sufficient differences in the frequency of low flows to assess how changes in flow affect sediment transport processes.

It is also important to note that during the 1940-1989 timeframe of these model runs, the Trinity basin experienced significant urbanization, land use changes, levee and dam construction, and significantly increased water supply diversions. Reservoirs significantly impact the sediment dynamics of a river system by trapping downstream sediment supply and changing hydrologic patterns. In the early 1900s a series of lock and dam structures were constructed ensuring grade control at many locations. Between 1950 and 1990, 22 reservoirs were built in the Trinity basin which added 14,080 square miles of controlled watershed. This significant increase in reservoirs makes it impossible for the models to reproduce historic channel changes without a digitized comprehensive initial condition bathymetric dataset. A future study could be to digitize cross-section data from the lock and dam construction period, then to model long-term scour and deposition patterns using available flow records. However, in their present state, these models are useful to better understand the sediment dynamics of the Trinity River basin.

6.7 Upper Model Results

All three Upper Model WAM Flows scenarios were run as sediment models for the 1940-1989 time period with the calibrated sediment model inputs in the same hot-start configuration. There was a 5-15% difference in the duration of flows between the scenarios for flows in the range of 100-2,000 cfs. This difference in flows between scenarios was visible at many of the model gage locations.

Significant differences in modeled load duration between the High WAM Flows and Low WAM Flows scenario were mostly observed at the upstream boundary and Rosser gage location, with differences in modeled load between the two scenarios dissipating in the downstream direction (Figure 32).

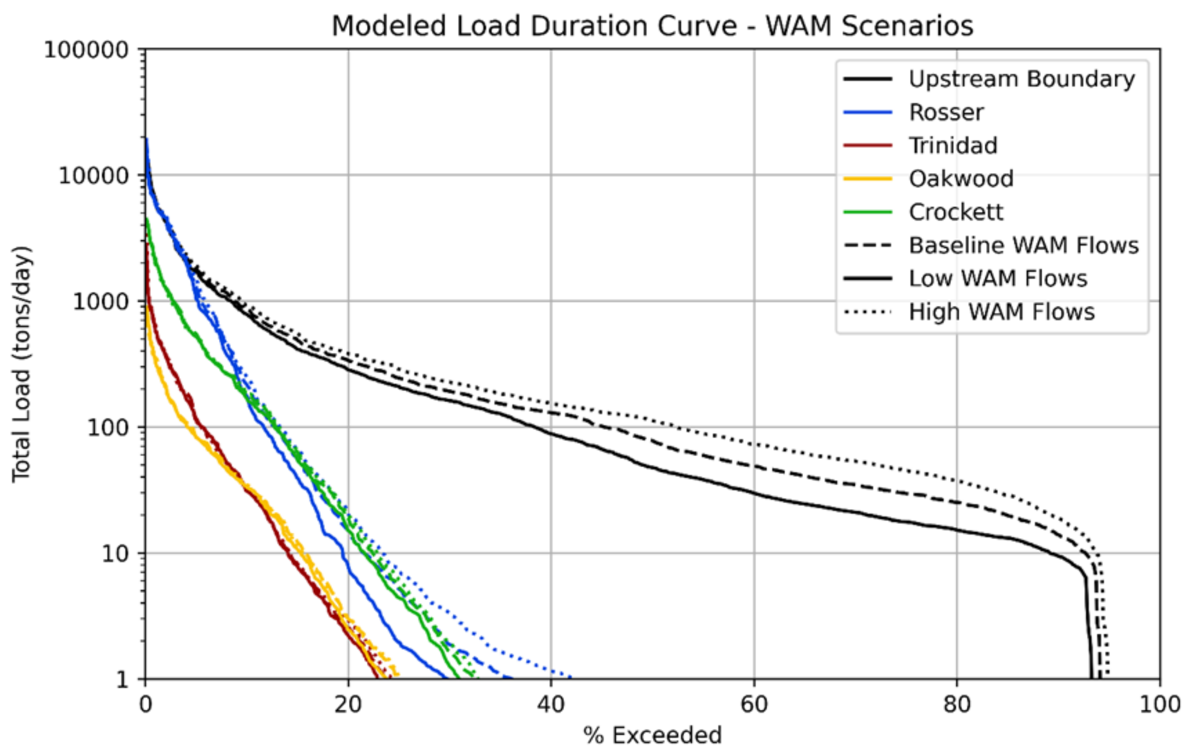

Figure 32. Modeled load duration curves at Upstream boundary and streamgage locations for the Upper WAM Scenario Models.

Net invert change results for the three WAM Flow scenario models are shown in Figure 33 . Due to the longer time period of this model, net invert change magnitudes were larger than in the Calibration Period model. A handful of cross-sections spread throughout the model domain saw net erosion or deposition of 10-25 ft. Major differences in net invert change between WAM Flow scenarios were largely confined to the reach between the upstream boundary and the Trinidad location, and particularly to cross-sections upstream of the Rosser location (Figure 33). This indicates that much of the difference in incoming sediment load for the WAM Flow scenarios is at the upstream boundary, and that much of the additional sediment load that flows in for the higher flow scenarios is deposited in the upper reaches of the model.

Reach-averaged invert change values for the whole period are shown in Table 7. The most significant difference is, again, seen in the upstream-most reach, where almost 0.25 ft more net deposition occurred in the High WAM Flows scenario than in the Low WAM Flows scenario. In the WAM Flow scenario models, the net invert change in the reach between the Trinidad and Crockett locations is actually positive, while it was negative in the Calibration Period model. Additionally, the net erosion in the reach between Crockett and the downstream boundary for the WAM Flow scenario models is equal to or slightly more than the change observed in the Calibration Period model, despite the much longer time-period. These results generally show that the lower flows of the WAM Flow scenarios cause less sediment transport. In the depositional upper portion of the model, this means that more of the incoming load is deposited, and in the erosional lower portion of the model, this means that less sediment is eroded.

The methodology used here comprises a set of statistical summaries of the model results to make analysis and interpretation possible. The summaries present a comparison of erosion/deposition characteristics across flows that, although aggregated spatially and temporally, accurately reflects trends observed in model results. Model results were available for several hundred cross-sections at ten-day intervals for 50 years of simulation across several scenario runs, and thus some summary was needed to address questions posed to the model. The methods also allowed use of the same set of simulations to look at impacts from changing basin hydrology (differences between WAM runs) and to investigate flow breakpoints, while retaining a model complexity that keeps model geometries useful for other HEC-RAS hydraulic and water quality analyses that TRA may wish to run. A suggestion for future work in the conclusion of the report identifies that different flow boundary conditions that more specifically test particular flows would be better suited to address this question.

From a brief literature review, no peer-reviewed references could be identified for methodologies having the same goal of using 1D model results to identify flow breakpoints where sediment dynamics with respect to erosion and deposition change. A TWDB contracted report from 2012 discusses using much simpler HEC-RAS 1D sediment transport models to assess prescribed instream flows impact on sediment dynamics, and does so by comparing time series of invert change at each cross-section to a time series of flow. The approach presented herein is a similar comparison, with summarizing assumptions made to deal with the complexity of our modeled results dataset.

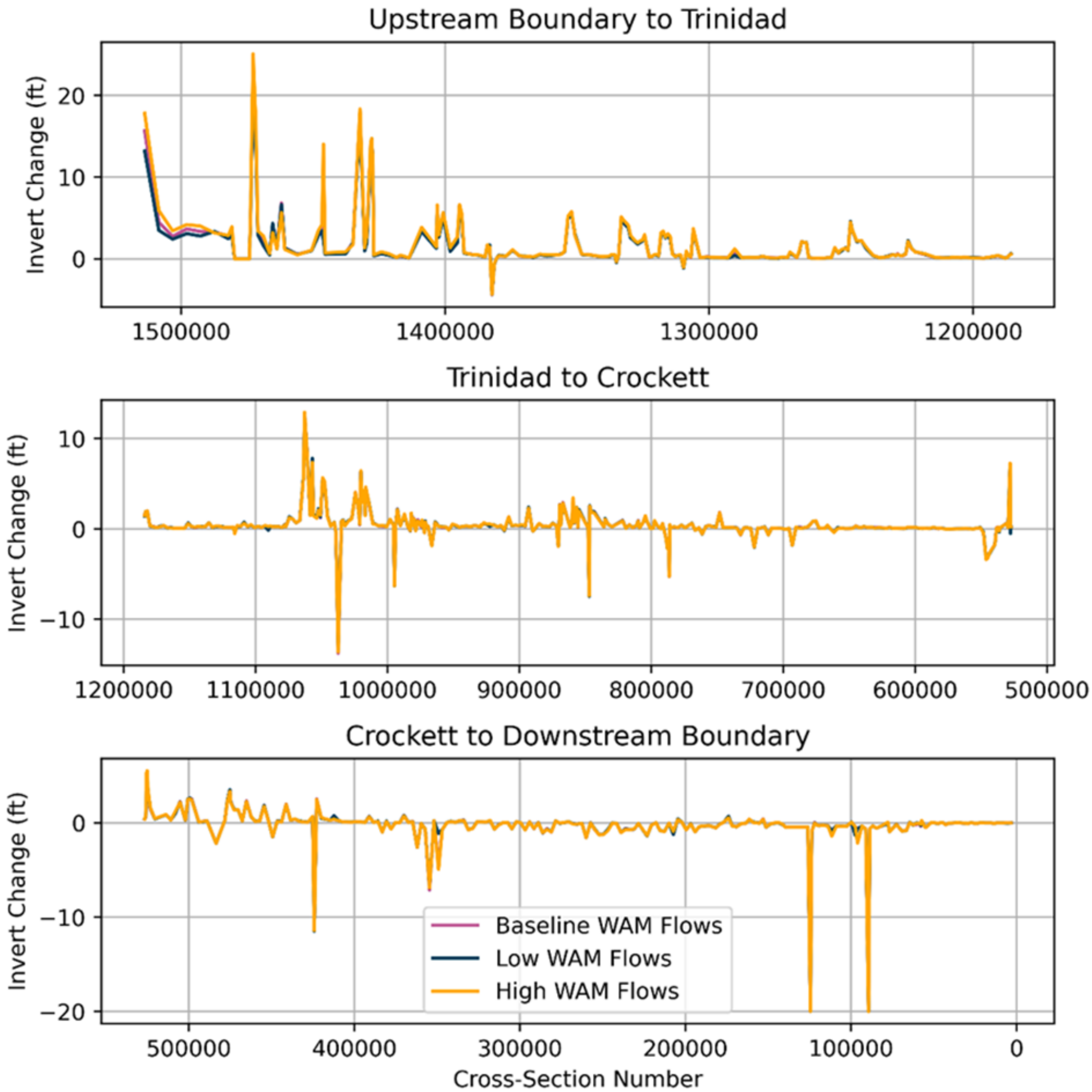

Figure 33. Modeled net invert change (ft) for the Upper WAM Scenario Models. Note, when one solid line appears, the values from all three scenarios shows very little difference.

Table 7. Reach-averaged invert change (ft) for Upper WAM scenario model.

Reach	Reach-Averaged Invert Change (ft) Low WAM Flows	Reach-Averaged Invert Change (ft) Baseline WAM Flows	Reach-Averaged Invert Change (ft) High WAM Flows
Upstream Boundary to Trinidad	1.67	1.78	1.91
Trinidad to Crockett	0.5	0.51	0.51
Crockett to Downstream Boundary	-0.21	-0.23	-0.24

In order to examine flow breakpoints where sediment processes change with respect to erosion and deposition, we compared reach-averaged invert change to flow between streamgage/boundary locations for the Baseline WAM Flows model in Figure 33. This plot is very useful for identifying flow breakpoints where the sediment regime of the channel transitions between erosion and deposition and where these breakpoints are pertinent. A detailed breakdown of the flow breakpoints identified in this plot is shown in Table 8. Results suggest that seemingly small changes to basin hydrology can impact low flow duration in a way that leads to changes in sediment transport in the channel.

Table 8. Flow breakpoints for Upper Model where sediment regime changes.

Reach	Approximate Flow Range (cfs)	10-day points (%)	Stable (%)	Depositing (%)	Eroding (%)	Depositing Magnitude	Eroding Magnitude
Upstream Boundary to Rosser	100-1,000	67.3	56	11.2	.1	Low / Medium	Medium
Upstream Boundary to Rosser	1,000-5,000	25.3	7	17.1	1.2	Low / Medium / High	Low / Medium / High
Upstream Boundary to Rosser	5,000-50,000	5.3	1.5	2.4	1.4	Low / Medium / High	Low / Medium / High
Rosser to Trinidad	100-1,000	67.4	67.2	0.2	0.0	Low	None
Rosser to Trinidad	1,000-5,000	25.2	22.5	2.7	0.0	Low / Medium	None
Rosser to Trinidad	5,000-50,000	7.6	4.5	2.6	0.5	None	Low / Medium / High
Trinidad to Oakwood	100-1,000	60.1	60.1	0.0	0.0	None	None
Trinidad to Oakwood	1,000-20,000	37.3	34.4	2.8	0.1	Low / Medium	Low
Trinidad to Oakwood	20,000-100,000	2.1	1.4	0.1	0.6	Low	Low / Medium / High
Oakwood to Crockett	100-10,000	81.3	81.2	0.1	0.0	Low	None
Oakwood to Crockett	10,000-100,000	16.9	15.8	0.2	0.9	Low	Low / Medium / High
Crockett to Downstream Boundary	100-100,000	98.3	98	0.0	0.3	None	Low

6.8 Lower Model Results

The calibrated Lower sediment transport Model was run with WAM scenario hydraulics for the fifty-year period 1/1/1940 – 12/31/1989. All of the models were run as hot-start models to set the same initial gradations that were used in the calibration model. Adding sediment transport processes makes the models significantly less stable, and similar challenges were faced in this model as in the Upper Model (see Section 1.1.1). The target low flow value for the Lower Model to achieve this balance was 200 cfs, and we were able to run all the models using this as the minimum flow.

Modeled load duration curves for all three WAM Flow scenarios at the upstream boundary and streamgage locations are shown in Figure 34. Significant differences in modeled load duration between the High WAM Flows and Low WAM Flows scenario were only observed at the Goodrich gage location. The load duration curves for Goodrich and Romayor are somewhat different from those for the calibration period, primarily because of the lower and differently spatially-distributed flows in the WAM Flow scenarios. The rating curve at the Goodrich location was quite different in the WAM Flow scenarios model than in the calibration period model, with a load greater than 1 ton/day occurring 7.50-10% less frequently, but generally more frequent higher loads.

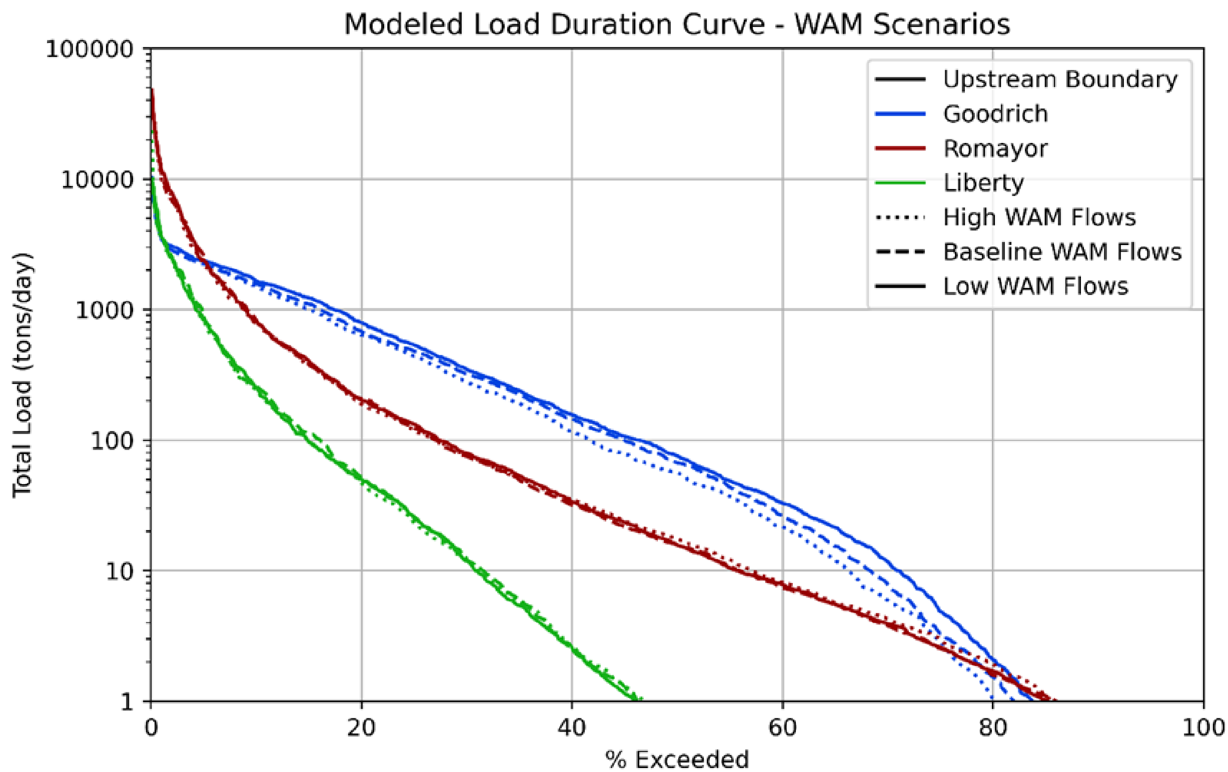

Figure 34. Modeled load duration curves at Upstream boundary and streamgage locations for the Lower WAM Scenario Models. Note that the Upstream boundary is from the dam and has a load of zero, so it does not show on the plot.

Net invert change results for the three WAM Flow scenario models are shown in Figure 35. Due to the longer time period of this model, net invert change magnitudes were larger than in the Calibration Period model. A few cross-sections spread throughout the model domain saw net erosion or deposition of 10-20 ft, although there were fewer cross-sections showing changes of these magnitudes than in the Upper Model. Major differences in net invert change between WAM Flow scenarios were largely confined to the reach between the upstream boundary and the Romayor location. This indicates that much of the difference in sediment dynamics between the WAM Flow scenarios has to do with different inflows from tributaries upstream of the Romayor gage.

Reach-averaged invert change values for the whole period are shown in Table 9. In the Lower Model, there were significant differences in net invert change between WAM Flows scenarios for both the reach between the upstream boundary and the Romayor location and the reach between the Romayor location and the downstream boundary. In the downstream portion of the model, 0.16 ft more net deposition occurred in the Low WAM Flows scenario than in the High WAM Flows scenario. This result indicates that higher flows in this model translate to less erosion in erosional locations and less deposition in depositional locations as compared to the Upper Model. In the WAM Flow scenario models, the net invert change in the reach between the Romayor location and the downstream boundary of the model is actually positive, while it was negative in the Calibration Period model.

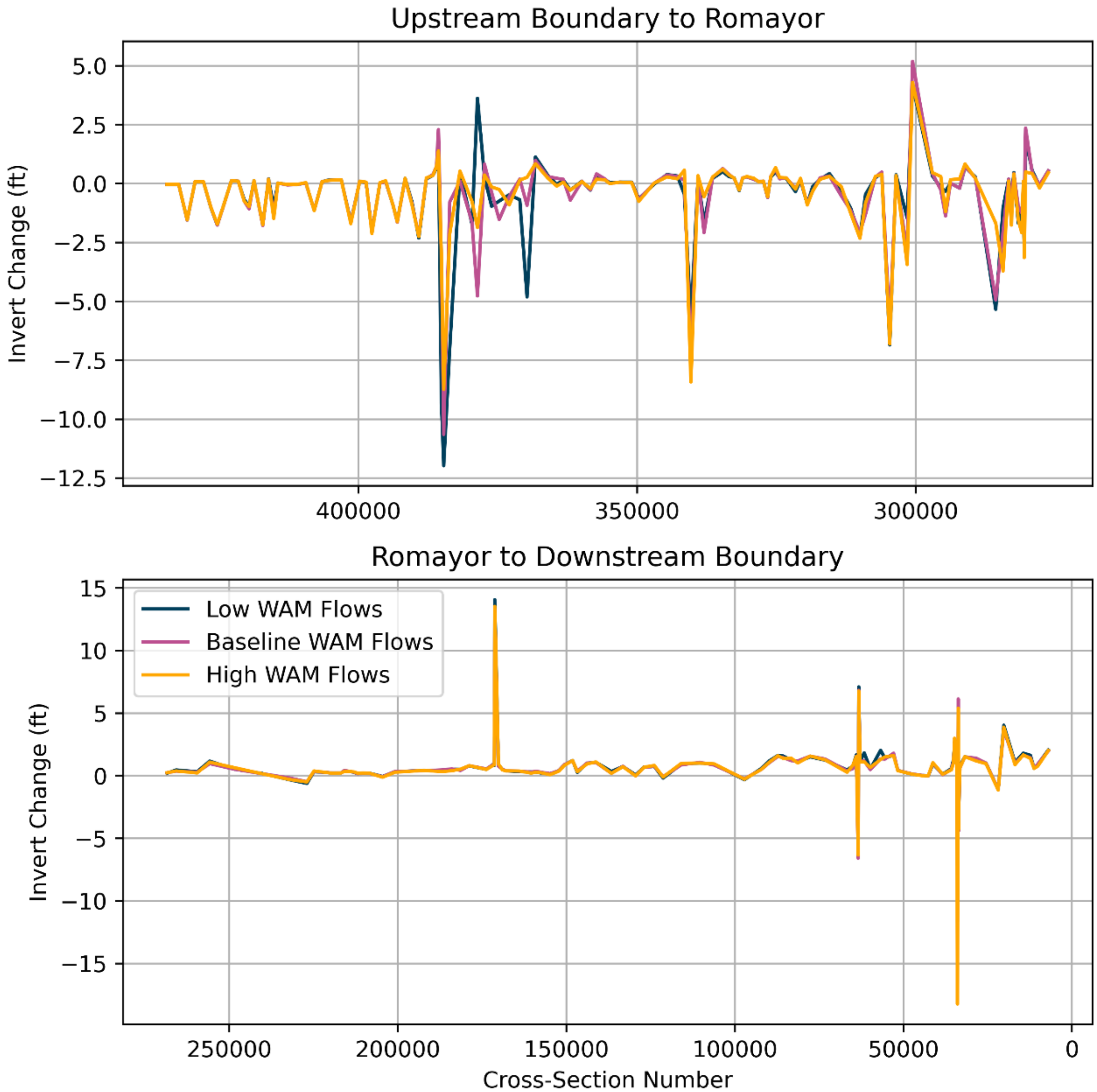

Figure 35. Modeled net invert change (ft) for the Lower WAM Scenario Models.

Table 9. Reach-averaged net invert change (ft) for Lower WAM Scenario Models.

Reach	Reach-Averaged Invert Change (ft) Low WAM Flows	Reach-Averaged Invert Change (ft) Baseline WAM Flows	Reach-Averaged Invert Change (ft) High WAM Flows
Upstream Boundary to Romayor	-0.57	-0.49	-0.48
Romayor to Downstream Boundary	0.78	0.7	0.62

Broadly, in the Lower Model, net depositional processes are more strongly associated with low flows and net erosional processes are more strongly associated with high flows in this model. In the upstream-most reach, however, the lowest flows were actually more strongly-associated with net erosion. Breakpoints in flow where sediment processes change were present in the Lower Model and varied considerably with flow just as they did in the Upper Model. In approximately the upper half of the model, breakpoints are in the range of 1,000-5,000 cfs. In the lower end of the model there is a consistent breakpoint of 1,000 cfs that acts as a threshold above which net invert change occurs, and in the reach between the Romayor and Liberty gage locations the channel transitions from primarily deposition to primarily erosion at a breakpoint of 5,000 cfs. Comparison of results from the three WAM Flows scenarios in the reach between the upstream boundary and the Romayor gage location for a sustained low flow period identifies that differences in reach-averaged net invert change between the scenarios often arise during times when High WAM Flows scenario flows were in the range of 1,000-5,000 cfs and Low WAM Flows scenario flows were in the range of 500-5,000 cfs, identifying that there is a breakpoint in sediment processes exist in this range of flows such that a small difference in flow translates to markedly different sediment transport characteristics. Results suggest that seemingly small changes to basin hydrology can impact low flow duration in a way that leads to changes in sediment transport in the channel.

Table 10. Flow breakpoints for Lower Model where sediment regime changes.

Reach	Approximate Flow Range (cfs)	10-day points (%)	Stable (%)	Depositing (%)	Eroding (%)	Depositing Magnitude	Eroding Magnitude
Upstream Boundary to Goodrich	100-200	9.9	9.4	0.2	0.3	Low	Low
Upstream Boundary to Goodrich	200-1,000	29.5	23	4.9	1.6	Low / High	Low
Upstream Boundary to Goodrich	1,000-5,000	31.9	27.2	2.4	2.3	Low / High	Low
Upstream Boundary to Goodrich	5,000-20,000	23.4	19.4	0.9	3.1	Low	Low / High
Upstream Boundary to Goodrich	20,000-100,000	4.7	2.3	0.0	2.4	None	Low / High
Goodrich to Romayor	100-500	13.9	13.3	0.4	0.2	Low	Low / High
Goodrich to Romayor	500-5,000	58	48.1	9.7	0.2	Low / High	Low
Goodrich to Romayor	5,000-100,000	27.6	22.3	0.4	4.9	Low	Low / High
Romayor to Liberty	100-1,000	16.3	16.1	0.2	0.0	Low	None
Romayor to Liberty	1,000-10,000	66.2	65.4	0.6	0.2	Low	Low
Romayor to Liberty	10,000-50,000	16.7	14.3	1.2	1.2	Low	Low / High
Romayor to Liberty	50,000-100,000	0.7	0.3	0.0	0.4	None	Low
Goodrich to Romayor	100-500	13.9	13.3	0.4	0.2	Low	Low / High
Goodrich to Romayor	500-5,000	58	48.1	9.7	0.2	Low / High	Low

Reach	Approximate Flow Range (cfs)	10-day points (%)	Stable (%)	Depositing (%)	Eroding (%)	Depositing Magnitude	Eroding Magnitude
Goodrich to Romayor	5,000-100,000	27.6	22.3	0.4	4.9	Low	Low / High
Liberty to Downstream Boundary	100-1,000	12.2	12.2	0.0	0.0	None	None
Liberty to Downstream Boundary	1,000-5,000	52.5	52.1	0.4	0.0	Low / High	None
Liberty to Downstream Boundary	5,000-100,000	36	34.6	1.1	0.3	Low / High	Low

6.9 Discussion

As previously stated, a full technical memo detailing the modeling process is included in the Appendix 1. Calibrated model and scenario model results indicate that refinements should be made to the models before results regarding predictions of channel response to a given change in basin hydrology can be taken at face value. Several refinements are suggested that would help to enable use of the models in this manner, taking the lessons learned from this project to make them better suited to answering the questions posed to them. Despite this, the results from the models in their present state and discussion in this report 1) provide an excellent framework for how to interpret results of the sediment models with respect to breakpoints in flow, and 2) clearly indicate that there are breakpoints in flow where sediment processes change that are in the range of environmental flow standards such that they are relevant to discussion of environmental flow standards. Note that while this 1D HEC- RAS model can show scour and deposition locations between different proposed alternatives, and can predict changes to cross-sectional area, sediment grainsize distribution, grade changes, slope, and longitudinal velocity changes, this sediment model cannot predict detailed lateral changes to cross-section shapes as may be desired for conducting spatially explicit aquatic habitat studies.

The large size, dense cross-section spacing and widely-varying flows of these sediment models present numerous hurdles for calibration efforts, and the calibration that was achieved in this project could be improved in further work. If pursued, several possible avenues could be taken. Cross-section density could be reduced in such a way that only the most representative cross-sections are retained, strengthening the model's ability to reproduce the conceptual sediment dynamics of the system and making short runtimes and larger computational increments possible. If more detailed results are wanted in a specific section of the channel, submodels could be cut out of the larger model to make smaller models that can be run at a smaller computational increment. Finally, if low flows are the highest priority target of future studies, simulations that exclude very high flows could be created that could likely be run at a higher computational increment without issue.

The WAM Flows scenarios developed for this project were reasonable in that they provided long hydrologic scenario time series and were flexible enough to be adapted to the calibrated sediment model configuration. Ideally, in a future version of this model, they would be modified to use regulated flows as opposed to unregulated flows for the Lower Model to better represent the dam's impact on flows. This would require the appropriate Trinity River daily WAM model to be run. It was difficult to run low flows with the WAM Flows scenario creation scheme because of the complexity of the representation of the basin hydrology. In future work, it would be ideal to modify the creation scheme or use a different flow series to attain flows as low as or lower than the lowest environmental flow standards in these reaches (75 cfs for the Upper Model and 200 cfs for the Lower Model). Future work with this model should also give additional thought to where flow reductions occur – with regards to sediment dynamics, it makes a considerable difference if changes in flows are implemented upstream in the river, at tributaries to the river, or at diversions from the river.

The Low, Baseline and High WAM Flows scenarios provided time series for similar basin hydrologies with differences at low flows that were a target of this study and allowed for comparisons of sediment dynamics to see the impact of the decrease in return flows. In future work, a more useful approach might be to create long-term “normal conditions” time series and drop in more regularized, sustained periods of suspected flow breakpoints to better quantify their long-term impacts. This could, for example, be done with environmental flow standard flows, if desired. If future projects used these models to answer questions about more targeted ranges of flows, sediment rating curves should also be revisited to be constrained at a higher resolution (smaller magnitudes of flow between flow-load-gradation points) in the range of targeted study flows. This step could utilize information about approximate locations of breakpoints determined in this project. Additionally, the models would benefit from a more robust sediment data collection at varying flows along the mainstem and large tributaries.

7 Nekton Sampling and Analysis

In late 2012, the TRA and TPWD began work on a reconnaissance and information evaluation project to fill large biological data gaps on the middle Trinity River identified during SB2. This project resulted in a report titled, "Supplemental Biological Data Collection, Middle Trinity River Priority Instream Flow Study" (TRA and TPWD, 2014), detailing the nekton community at six sites along the mainstem Trinity River, sampled between August and November 2012. In the report, 38 nekton species were identified, and the community data was compared to historic Trinity River nekton occurrences.
Since the completion of the TRA and TPWD (2014) study, several years of elevated flows and flood events have occurred within the middle Trinity. In response to these increased flow conditions, TRA and TPWD agreed to resample the nekton communities at four of the six previously sampled TRA and TPWD (2014) sampling sites between the years of 2014-2023. The objective of this follow-up study was to determine if any differences in nekton composition and/or abundance could be observed between the initial 2012 sampling event and the resample events.

The resampling of the four TRA and TPWD (2014) stations can be grouped within two 4-year timeframes. (Table 11) The first timeframe occurred between September 2014 to August 2018 (2014-18 Events), and the second timeframe occurred between August 2020 to April 2023 (2020-23 Events). Collection methods included boat electrofishing and seine netting as many different habitat types as possible within each reach. The intent was to sample each site twice within the TCEQ designated Index Period (March 15 – October 15), with one sample event occurring within the Critical Period (July 1 – Sept 30). At times however, weather conditions necessitated pushing the sampling outside of these periods to allow species to recover after flood pulses.

Table 11. Sample site locations and the date nekton sampling events took place.

Site number	Site description	2012	2014	2017	2018	2020	2022	2023
80423	Trinity River at SH 34	9/13, 11/1		10/11 -12		8/25, 10/5		
80354	Trinity River upstream of US 287	9/11, 10/30		5/16, 9/12		8/25, 10/6		
80295	Trinity River upstream of US 79	8/16, 10/29		5/17	8/7		9/19	4/18
80214	Trinity River upstream of SH 21	8/14, 10/17	9/30				9/20	4/19

A total of 19,668 individuals were collected during this study. 4,994 individuals were sampled across 36 taxa between 2014-2018, whereas 14,672 individuals were sampled across 36 taxa between 2020-2023. (Table 12) 14 individuals were dropped from the following analysis (>0.02% of all individuals sampled) due to unconfirmed species identification (young-of-year or hybrid species).

Overall, the number of taxa found within the mainstem Trinity River was lower (36 taxa during both timeframes) compared to the 38 taxa found in the TRA and TPWD (2014) study. (Table 12) Though, in both 2014-2018 and 2020-2023, 34/38 taxa (89%) were repeat species collected during the initial TRA and TPWD (2014) study. Additionally, two new species to the mainstem Trinity River, which were not observed in historic datasets (Perkins & Bonner 2014) were identified. These species were the Fathead Minnow (*Pimephales promelas*, sampled at US 79/84) identified in 2018 and the Pallid Shiner (*Hybopsis aminis*, sampled at SH 34) identified in 2020.

Table 12. Fish species collected in the middle Trinity River from 1970s to 2000s (Perkins & Bonner 2014), 2012 Events (TRA and TPWD 2014), the 2014-2018 Events, and the 2020-2023 Events.

Species	Common name	Historic	2012 Events	2014-18 Events	2020-23 Events
Ameiurus melas	black bullhead	X	.	.	.
Ameiurus natalis	yellow bullhead	X	X	.	X
Amia calva	bowfin	X	.	.	.
Aplodinotus grunniens	freshwater drum	X	X	X	X
Atractosteus spatula	alligator gar	X	X	X	X
Campostoma anomalum	central stoneroller	X	.	.	.
Carpiodes carpio	river carpsucker	X	X	X	X
Ctenopharyngodon idella	grass carp	X	.	.	X
Cyprinella lutrensis	red shiner	X	X	X	X
Cyprinella venusta	blacktail shiner	X	X	X	X
Cyprinus carpio	common carp	X	X	X	X
Dorosoma cepedianum	gizzard shad	X	X	X	X
Dorosoma petenense	threadfin shad	X	X	X	X
Etheostoma chlorosoma	bluntnose darter	X	X	X	X
Etheostoma gracile	slough darter	X	X	.	X
Etheostoma proeliare	cypress darter	X	.	.	.
Fundulus notatus	blackstripe topminnow	X	X	X	X
Gambusia affinis	western mosquitofish	X	X	X	X
Ictalurus furcatus	blue catfish	X	X	X	X
Ictalurus punctatus	channel catfish	X	X	X	X
Ictiobus bubalus	smallmouth buffalo	X	X	X	X
Labidesthes sicculus	brook silverside	X	.	.	.
Lepisosteus oculatus	spotted gar	X	X	X	X
Lepisosteus osseus	longnose gar	X	X	X	X
Lepomis auritus	redbreast sunfish	X	.	.	.
Lepomis cyanellus	green sunfish	X	X	X	X

Species	Common name	Historic	2012 Events	2014-18 Events	2020-23 Events
Lepomis gulosus	warmouth	X	X	X	X
Lepomis humilis	orangespotted sunfish	X	X	X	X
Lepomis macrochirus	bluegill	X	X	X	X
Lepomis marginatus	dollar sunfish	X	.	.	
Lepomis megalotis	longear sunfish	X	X	X	X
Lepomis microlophus	redear sunfish	X		X	
Lepomis miniatus	redspotted sunfish	X	.	.	.
Lythrurus fumeus	ribbon shiner	X	.	.	.
Lythrurus umbratilis	redfin shiner	X	.	.	.
Menidia beryllina	inland silverside	X	X	X	X
Micropterus punctulatus	spotted bass	X	X	X	
Micropterus salmoides	largemouth bass	X	X	X	X
Minytrema melanops	spotted sucker	X			
Morone chrysops	white bass	X	X	X	X
Morone mississippiensis	yellow bass	X	.	.	.
Morone saxatilis	striped bass	X	.	.	.
Notemigonus crysoleucas	golden shiner	X	.	.	.
Notropis buchanani	ghost shiner	X	X	X	X
Notropis shumardi	silverband shiner	X	X	X	X
Notropis texanus	weed shiner	X	X	.	X
Notropis volucellus	mimic shiner	X	X	.	.
Noturus gyrinus	tadpole madtom	X	.	.	.
Noturus nocturnus	freckled madtom	X	*X*	X	X
Opsopoeodus emiliae	pugnose minnow	X	X	X	X
Percina macrolepida	bigscale logperch	X	X	X	.
Percina sciera	dusky darter	X	X	X	.
Pimephales promelas	Fathead Minnow	.	.	X	.
Pimephales vigilax	bullhead minnow	X	X	X	X
Pomoxis annularis	white crappie	X	X	X	X
Pomoxis nigromaculatus	black crappie	X	.	.	.
Pylodictis olivaris	flathead catfish	X	X	X	X
Hybopsis amnis	pallid shiner	.	.	.	X
. **Total Number of Species**		**56**	**38**	**36**	**36**

Eight species classified as "TPWD Species of Greatest Conservation Need" are found within the Trinity River Basin (Table 13). Two of those species, Alligator Gar (*A. spatula*) and Silverband Shiner (*N. shumardi*) were identified during all sampling timeframes. The Pallid Shiner (*H. amnis*) was identified at one event at SH 34 in August 2020. The Spotted Sucker (*M. melanops*), though listed as historically present within the mainstem Trinity River, was never collected during any of the recent surveys. Four species including, Chub Shiner *(N. potteri*), Suckermouth Minnow (*P. mirabilis*), Blackside Darter (*P. macalata*) and Paddlefish (*P. spathula*), have ranges that overlap with the Trinity River, but were not found during either the historical and current studies.

Table 13. Species of Greatest Conservation Need (TPWD 2023) collected in the middle Trinity River by sampling timeframe. State conservation rank (S1=Critically Imperiled, S2=Imperiled, S3=Vulnerable, S4=Apparently Secure)

Scientific name	Common name	State conservation rank and status	Historic	2012	2014-18	2020-23
Atractosteus spatula	alligator gar	S4 (not listed)	X	X	X	X
Minytrema melanops	spotted sucker	S3 (not listed)	X	.	.	.
Notropis shumardi	silverband shiner	S4 (not listed)	X	X	X	X
Hybopsis amnis	pallid shiner	S4 (not listed)	.	.	.	X
Notropis potteri	chub shiner	S2 (threatened)	.	.	.	.
Phenacobius mirabilis	suckermouth minnow	S4 (not listed)	.	.	.	.
Percina maculata	blackside darter	S1 (threatened)	.	.	.	.
Polyodon spathula	paddlefish	S3 (threatened)	.	.	.	.

The TCEQ defines the Critical Period as spanning from "July 1st to September 30th, when minimum streamflows, maximum temperatures and minimum DO concentrations typically occur in Texas Streams" (SWQM Procedures Manual, Vol 1 2012). Temporal changes between Critical Period and Non-Critical Period (Oct 1-June 30th) samples were evaluated for the Average Number of Individuals, Average Number of Taxa, and Average Discharge (cfs) at time of sampling event, by sampling timeframe. Average daily discharge values from the day of sampling event were acquired from the nearest USGS Gage Station located on the mainstem Trinity River to the sample site from August 1st, 2012 to April 30, 2023. (Table 14, Figure 37, Figure 38, Figure 39, Figure 40) Due to small samples sizes (maximum 4 samples per period timeframe), formal statistics were not run but the trends were visualized in Figure 36.

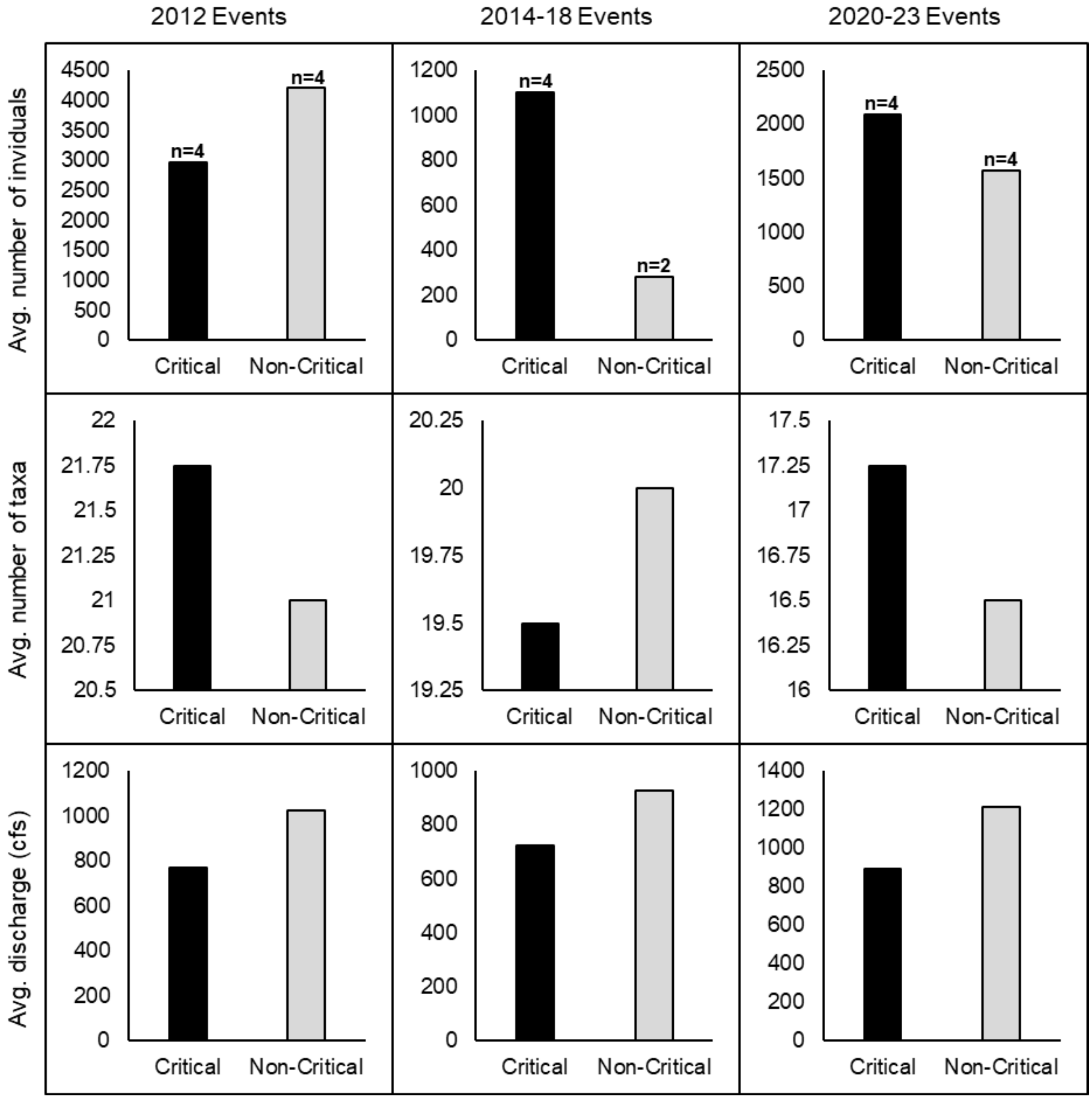

Figure 36. Temporal changes in Average Number of Individuals, Average Number of Taxa, and Average Discharge (cfs) at time of sample between Critical (July 1-Sept. 30) and Non-Critical (Oct. 1-June 30) Periods for the mainstem Trinity River. The number of sampling events (n=) for each period's timeframe above the bars in the top row of charts is the same for all charts below.

The Average Number of Individuals captured was not consistent by timeframe, as more individuals were captured in the non-critical period in 2012, but not in the 2014-18 and 2020-23 events. The Average Number of Taxa identified were similar between Critical and Non-Critical period samples, with <1 taxa on average difference being observed. Again, no timeframe trends were evident for the Average Number of Taxa. Average Discharge was lower during Critical Period samples compared to Non-Critical Period samples in all three sampling timeframes. These results are consistent with the assumptions described in the SWQM Procedures Manual, Vol 1 (2012).

7.1 Discussion

Overall, the nekton community of the mainstem Trinity River seems to be anchored by a core assemblage of ~34 taxa which is evident from both current and historic sampling. The composition of percent of taxa within each feeding guild by site stayed relatively the same throughout this study (Figure 41, Figure 42, Figure 43, Figure 44). Invertivores were the most common type of species all at sites and during all sampling events except for 2012 survey at SH 34 (Figure 41). Species within the Trinity River seem to not be greatly influenced by flow from the results of this most recent round of sampling, though additional surveys in coming years and more powerful analyses are needed to confirm these general conclusions.

Table 14. Summary of Sampling Events, Period abbreviations: C= Critical Period (July 1-Sept. 30) and N= Non-Critical Period (Oct. 1- June 30).

Location	Event	Period	Number of individuals	Number of taxa	USGS Gage	Daily Discharge (cfs)
SH 21	8/14/2012	C	5,780	26	Crockett Station #08065350	731
US 79	8/16/2012	C	1,524	21	Oakwood Station #08065000	653
US 287	9/11/2012	C	1,420	18	Trinidad Station #08062700	1,060
SH 34	9/13/2012	C	3,150	22	Rosser Station #08062500	630
SH 21	10/17/2012	N	8,764	20	Crockett Station #08065350	1,940
US 79	10/29/2012	N	3,214	24	Oakwood Station #08065000	806
US 287	10/30/2012	N	1,702	18	Trinidad Station #08062700	728
SH 34	11/1/2012	N	3,168	22	Rosser Station #08062500	617
SH 21	9/30/2014	C	735	25	Crockett Station #08065350	411
US 287	5/16/2017	N	345	21	Trinidad Station #08062700	828
US 79	5/17/2017	N	224	19	Oakwood Station #08065000	1,030
US 287	9/12/2017	C	233	16	Trinidad Station #08062700	894
SH 34	10/11/2017	C	2,148	14	Rosser Station #08062500	1,000
US 79	8/7/2018	C	1,300	23	Oakwood Station #08065000	585
SH 34	8/25/2020	C	5,128	18	Rosser Station #08062500	672
US 287	8/25/2020	C	1,461	20	Trinidad Station #08062700	788
SH 34	10/5/2020	N	977	14	Rosser Station #08062500	672
US 287	10/6/2020	N	281	18	Trinidad Station #08062700	712
US 79	9/19/2022	C	859	18	Oakwood Station #08065000	992
SH 21	9/20/2022	C	912	13	Crockett Station #08065350	1,120
US 79	4/18/2023	N	2,202	14	Oakwood Station #08065000	1,310
SH 21	4/19/2023	N	2,849	20	Crockett Station #08065350	2,160

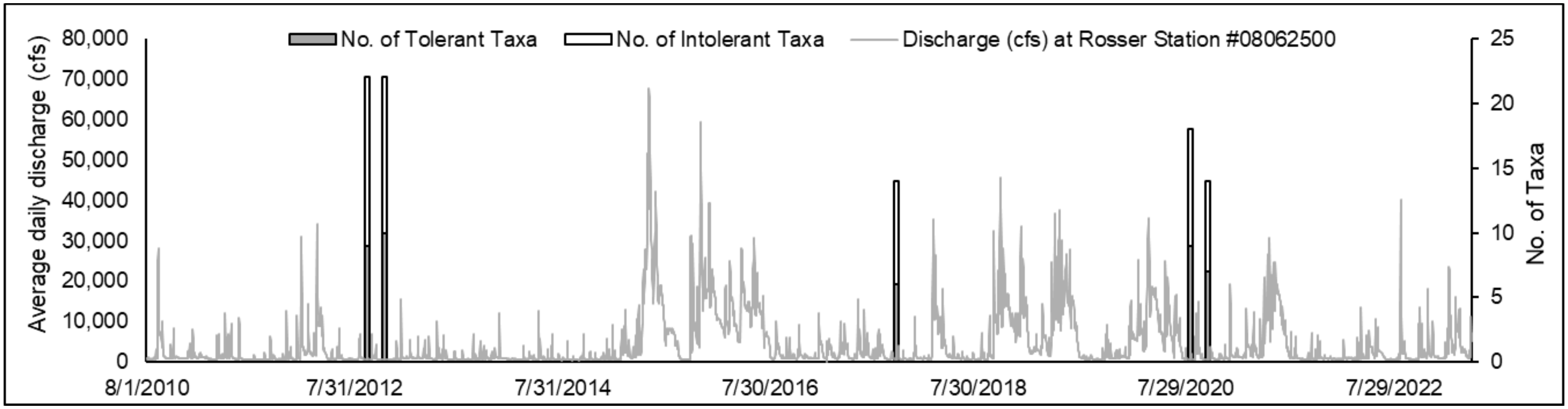

Figure 37. Average daily discharge (cfs) at USGS Gage #08062500 (Rosser Station). Vertical bars are the centered on the date of nekton sampling at SH 34. With bar height being the total number of taxa and shading showing number of tolerant (grey) and intolerant (white) taxa.

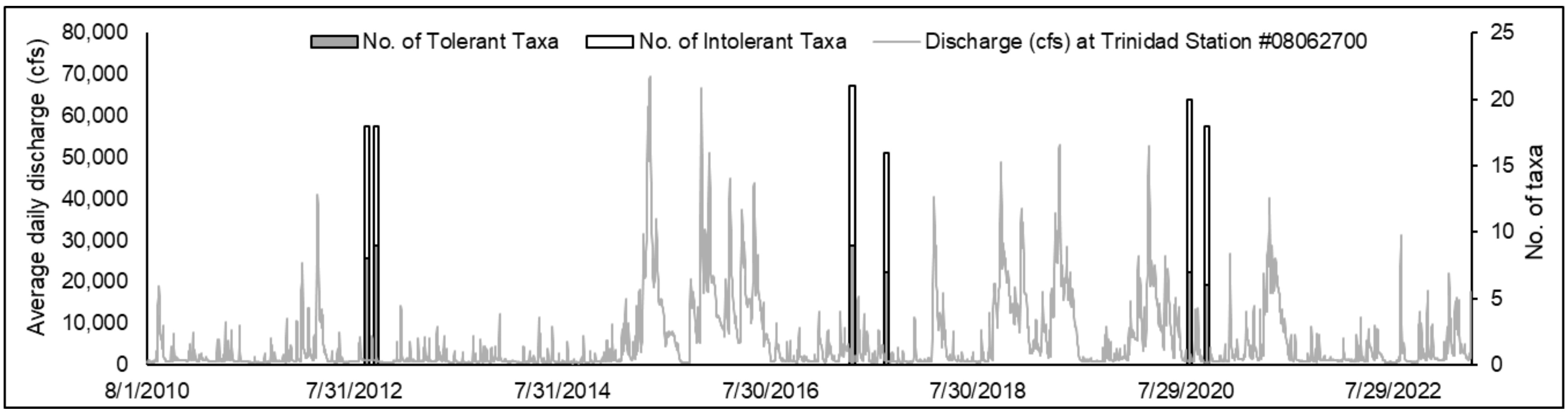

Figure 38. Daily discharge (cfs) at USGS Gage #08062700 (Trinidad Station). Vertical bars are the centered on the date of nekton sampling at US 287. With bar height being the total number of taxa and shading showing number of tolerant (grey) and intolerant (white) taxa.

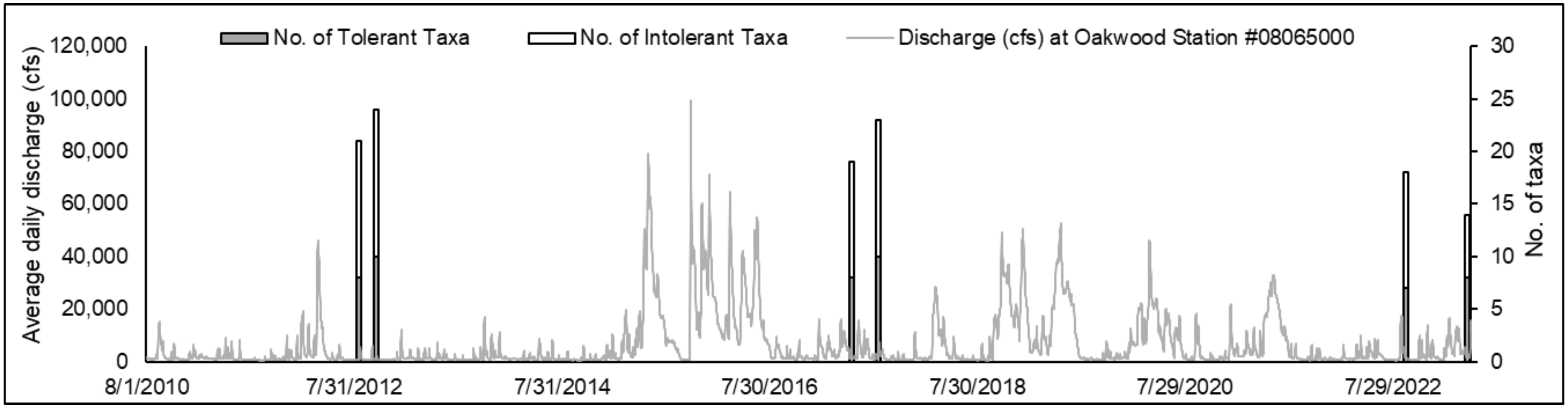

Figure 39. Daily discharge (cfs) at USGS Gage #08065000 (Oakwood Station). Vertical bars are the centered on the date of nekton sampling at US 79. With bar height being the total number of taxa and shading showing number of tolerant (grey) and intolerant (white) taxa.

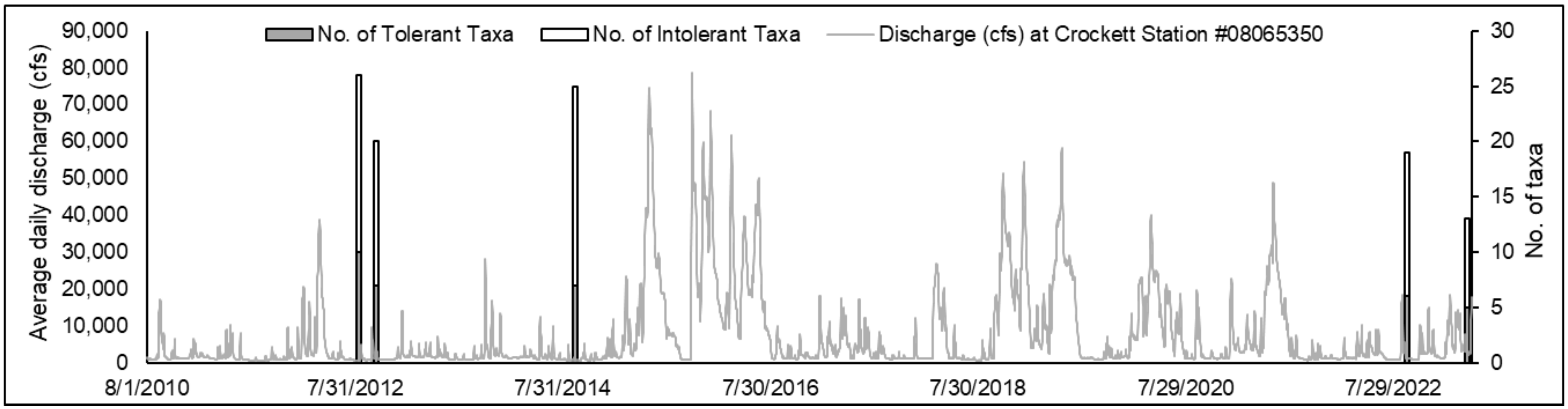

Figure 40. Daily discharge (cfs) at USGS Gage #08065350 (Crockett Station). Vertical bars are the centered on the date of nekton sampling at SH 21. With bar height being the total number of taxa and shading showing number of tolerant (grey) and intolerant (white) taxa.

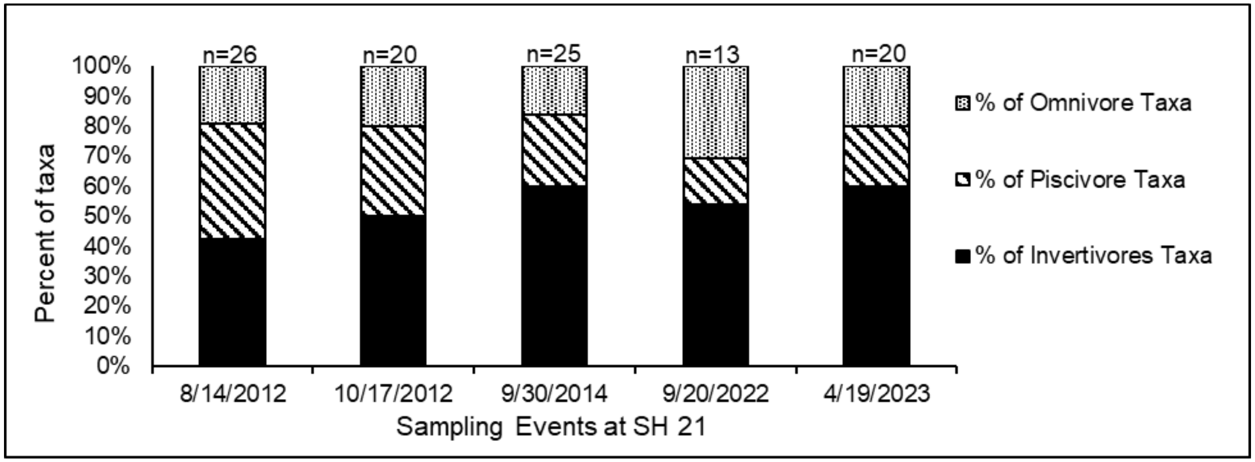

Figure 41. The percentage of taxa by Trophic Classification collected during each sampling event at SH 21. The total number of taxa collected at the event is shown above the bars.

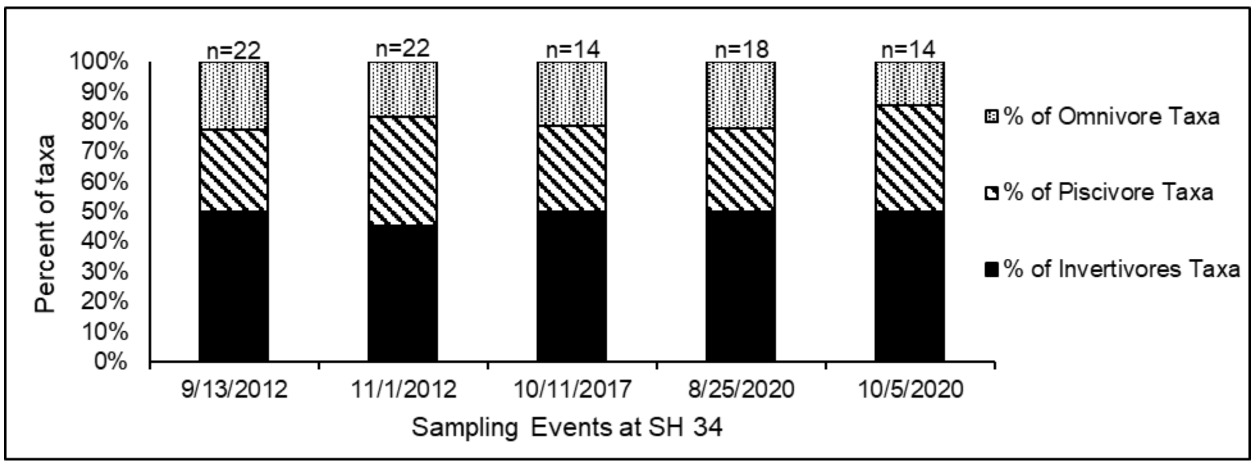

Figure 42. The percentage of taxa by Trophic Classification collected during each sampling event at SH 34. The total number of taxa collected at the event is shown above the bars.

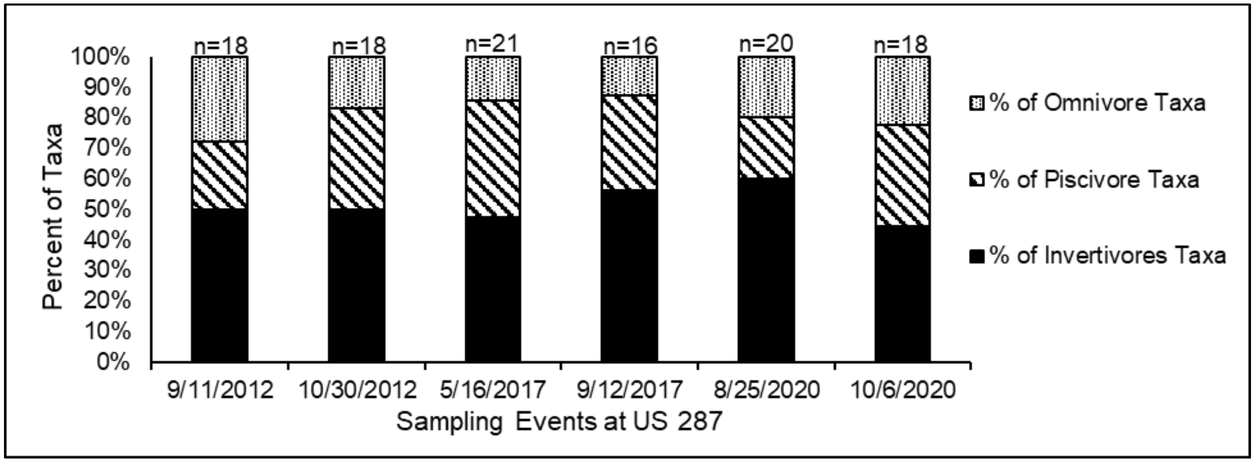

Figure 43. The percentage of taxa by Trophic Classification collected during each sampling event at US 287. The total number of taxa collected at the event is shown above the bars.

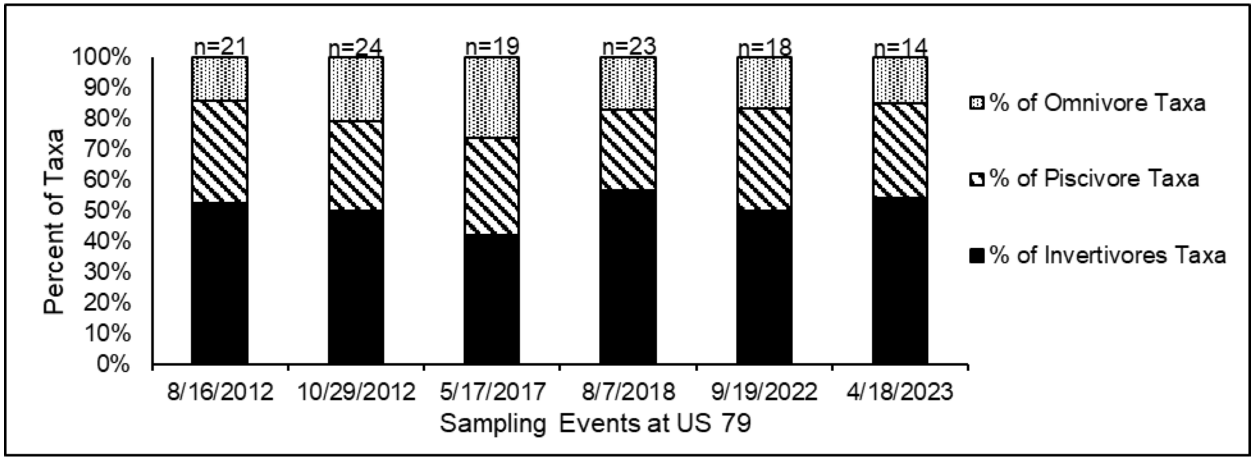

Figure 44. The percentage of taxa by Trophic Classification collected during each sampling event at US 79. The total number of taxa collected at the event is shown above the bars.

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9 Appendices

Appendix 1 – FINAL Technical Sediment Modeling Memorandum: Trinity River Phase IV, Environmental Flows Assessment: Task 1 – HEC-RAS Sediment Transport

Appendix 2 – Response to comments for Final Report: Evaluation of Adopted Flow Standards for the Trinity River, Phase 4

Appendix 1 - FINAL Technical Sediment Modeling Memorandum: Trinity River Phase IV, Environmental Flows Assessment: Task 1 – HEC-RAS Sediment Transport 1

Final Technical Sediment Modeling Memorandum

TO: Web Mangham, Trinity River Authority of Texas

FROM: Paul Southard, PG - (339) 364-4492
Tim Osting, PE – 512-627-1563

DATE: 01/10/2024

RE: Trinity River Phase IV, Environmental Flows Assessment: Task 1 – HEC-RAS Sediment Transport Modeling

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Executive Summary

In 2007, the Texas Senate Bill 3 (SB3) process led to the establishment of environmental flow standards for the Trinity River Basin by a stakeholder committee. As a regional conservation and reclamation district within the Trinity River Basin, the Trinity River Authority has a desire to better understand environmental characteristics of the basin, and to collect scientific information that will be informative in the event that instream flow standards are adjusted during the adaptive management phase of the Senate Bill 3 process.

The goal of this project is to utilize large HEC-RAS 1D hydraulic and sediment transport models to identify breakpoints in flow where sediment transport processes change. The Middle Trinity River environmental flow standard measurement point at the Oakwood USGS streamgage has subsistence flow standards ranging from 75-160 cfs and base flow standards ranging from 250-450 cfs, and the Lower Trinity River environmental flow standard measurement point at the Romayor USGS streamgage has subsistence flow standards ranging from 200-700 cfs and base flow standards ranging from 575-1,150 cfs. While identifying breakpoints in flow where sediment transport processes change is useful for management purposes across all flows, investigating these low flow ranges was the main priority in this project due to their relevance to the SB3 adaptive management process.

Model Construction

An Upper Model spanning a portion of the Middle Trinity River from upstream of the Rosser USGS streamgage to the northern-most part of Lake Livingston was constructed and calibrated for low flows in the last phase of TRA's SB3-related work. This model includes the reach around the Oakwood environmental flow standards measurement point.

In the prior phase of TRA's SB3-related work, a Lower Model spanning a portion of the Lower Trinity River from the Romayor USGS streamgage to the Rt. 105 bridge near Franklin, TX was also constructed and calibrated for low flows. In this project, TRA collected additional bathymetry data for other portions of the Lower Trinity River that were complied with LiDAR DEM's for overbank elevation to extend the Lower Model to span a portion of the Lower Trinity River from Lake Livingston Dam to just downstream of the Liberty USGS streamgage. This extended Lower Model includes the reach around the Romayor environmental flow standards measurement point. This task resulted in the completion of HEC-RAS 1D hydraulic model geometries for a large portion of the Middle and Lower Trinity River and, importantly, sections around environmental flow standards measuring points.

Calibration

To extend the hydraulic calibration to very high flows and facilitate the creation of 1D sediment models using these model geometries, a full re-calibration of hydraulics was performed for both models as part of this project. This process included phases of steady and unsteady model calibration, and a reasonable calibration of flows and stages for a 5-year unsteady flow series was achieved by modifying cross-sections where justified, adding levees and ineffective flow areas, and adjusting channel roughness. Intervening inflows from sizeable, ungaged tributaries were also developed and added into the model using HEC-RAS's internal Ungaged Lateral Inflow estimation techniques to improve the sediment models.

The Upper Model utilized a flow series constructed entirely from USGS flow and stage data that spanned the period of 2008-2013. The model consisted of an upstream inflow boundary, set using time-adjusted Rosser gage flows, 12 intervening inflows (2 of which were gaged, 10 of which were ungaged), 2 diversions informed by historical data (TRWD Wetlands and Huntsville) and a downstream stage series boundary representing Lake Livingston's elevation. Flows at the upstream boundary ranged from 600-40,000 cfs, with a median flow of about 1,000 cfs. Flows at the Crockett gage location ranged from 900-60,000 cfs, with a median flow of about 1,600 cfs. Lake Livingston elevation ranged from 127 to 135 ft during this time period.

The Lower Model also utilized USGS flow series data and spanned the period of June 2018 – December 2023 – this was the longest continuous period across all of the streamgages used. The model consisted of an upstream inflow boundary, set using time-adjusted Goodrich gage flows, 5 intervening inflows (2 of which were gaged, 3 of which were ungaged), 1 diversion informed by historical data (Luce Bayou starting 2022). Flows were similar throughout the model and intervening inflows were relatively small. Flows at the upstream boundary ranged from 1,000-80,000 cfs, with a median flow of about 3,000 cfs. The downstream boundary was between the Liberty and Moss Bluff gage locations, and was informed by a flow-stage rating curve created using data from both gages.

The hydraulic calibration of the Upper and Lower Models was deemed suitable for the purposes of their use in sediment models. The Upper Model's hydraulic calibration was good for low flows and usually only off by more than 2 ft for very high flows. The Lower Model's hydraulic calibration was also good for low flows, with the exception that it was as much as 3 ft too low at the Romayor gage location. For very high flows, the stage was only ever more than 2 ft too low at the Liberty and Goodrich gage locations. Generally, for areas where the stage calibration was poor, it was likely due to 1) the exclusion of bridges from the model geometries for the sake of sediment modeling efforts and 2) the coarse scale at which levees and ineffective flow areas were set due to the model size and the manual effort involved in doing so. The calibration that was achieved provided reasonable stages for the majority of flows that would be experienced in the sediment models, despite having bridges removed for stability.

After the hydraulic calibration was complete, 1D sediment models were developed and calibrated to simulate bed load transport. 1D sediment models leveraged available information from USGS sediment data collection and, in the case of the Upper Model, a detailed technical report on sediment characteristics. Sediment calibration models were run for the same 5-year flow series with intervening inflows that was developed for the hydraulic calibration. The hot-start models utilized outputs from a 3-year spin-up model with flows approximating the effective discharge of the channel to set the initial sediment conditions. Boundary conditions all utilized a sediment load-flow rating curve that was initially set from data sources and later adjusted as part of the model calibration process. No information was available for sediment inputs from tributaries, so the modeling team made assumptions about sediment load-flow rating curves for tributaries based on information about observed loads at the upstream boundary and at streamgage locations in the model domain and adjusted them as part of the calibration process.

For the Upper Model, sediment inflows were set at the upstream boundary and at all intervening inflows, due to their generally high flow contributions. USGS historical sediment load data indicated that load did not change significantly in the downstream direction in this stretch of the river, so the upstream boundary flow-load rating curve was used for all intervening inflows. Model results showed 0.5 ft of reach-averaged net deposition upstream of the Trinidad cross-section and <0.25 ft of net erosion downstream of the Trinidad cross-section. Downstream of Trinidad, significant bed change primarily occurred only at high flows.

For the Lower Model, a clear water inflow (no sediment load) was set at the upstream boundary due to the dam. Because of this, intervening sediment inflows were especially important to supply sediment to the model, and the three upstream-most intervening inflows were assigned a flow-load duration curve. These were based on the flow-load relationship at Romayor established from USGS historical sediment observations, and the flows associated with each load-gradation point were adjusted iteratively as a part of model calibration. Modeled invert change results showed reach-averaged net erosion of 0.2-0.25 ft throughout most of the modeled reaches. Upstream of the Romayor location, bed change mostly only occurred at high flows. Downstream of Romayor net bed change occurred at all flows.

While flow-load rating curves in the model domain suggest that the sediment models could achieve a better match with reality, the main calibration target for the sediment models was to achieve a model that had a stable bed at the end of the 5-year flow series and that was capable of eroding and depositing. This was achieved in both models, with a few caveats described in the report. It is recommended that the calibration of each be revisited in any future work using these models, and that significant changes to the model's structure be considered as part of this revisitation to make them more appropriate for decadal-scale sediment runs with widely-ranging flows. Paring down the number of model cross-sections would likely have an impact of shortening model runtimes, reducing the computational burden of the calibration process, and improving the quality of the model calibration.

Sediment Scenarios + Findings

Three long-term hydraulic scenarios were run and their results were used to determine breakpoints in flow where sediment processes change. TRA's Run 3 of the Trinity River Monthly Water Availability Model (WAM) was used as a baseline model ("WAM Flows") and "High WAM Flows" and "Low WAM Flows" were developed by running the same model with +50% and -50% return flows, respectively. WAM regulated flows for each scenario were spatially disaggregated based on drainage area to the same representation of intervening inflows and diversions used in the calibration models. Then, monthly flows were disaggregated to daily flows using the unregulated flow series at the Rosser gage location and the Goodrich gage location from the daily version of the Trinity River WAM. Due to difficulties in timing during low flow events, achieving very low flows with this disaggregation scheme and the sediment model turned on without the model going unstable was extremely difficult. At times where this scheme tried to divert water that was not there and caused the model to go unstable, all diversions were set to 0 and low flows were forced by setting the flows at the upstream end of the model to 100 cfs for the Upper Model and 200 cfs for the Lower Model. Several low flow values were tested to find the limits of what the model could achieve in terms of low flows before arriving on these numbers. The calibrated sediment model was run with each of the three resulting hydraulic scenarios for the period of 1940-1989 to achieve a 50-year run.

The creation scheme yielded flow series scenarios with sufficient differences in the frequency of low flows to assess how changes in flow affect sediment transport processes. For the Upper Model, there was a 5-15% difference in the duration of flows between the scenarios for flows in the range of 100-2,000 cfs. This difference in flows between scenarios was visible at many of the model gage locations. For the Lower Model, there was a 5-10% difference in the duration of flows between the scenarios for flows in the range of 100-2,000 cfs at the upstream boundary. This difference, however, quickly dissipated in the downstream direction, and was only about 1-2% at locations further downstream.

All three Upper Model WAM Flows scenarios were run as sediment models for the 1940-1989 time period with the calibrated sediment model inputs in the same hot-start configuration. Significant differences in modeled load duration between the High WAM Flows and Low WAM Flows scenario were mostly observed at the upstream boundary and Rosser gage location, with differences in modeled load between the two scenarios dissipating in the downstream direction. Similarly, significant differences in the reach-averaged net invert change were only observed in the reach between the upstream boundary and the Trinidad gage location, where net deposition at the end of the simulation was about 15% greater in the High WAM Flows scenario. Additionally, for the WAM Flows scenarios, net deposition was observed for the reach between the Trinidad and Crockett gage locations, which was different from the result seen during the 5-year sediment calibration period. Net erosion was observed for the WAM Flows scenarios in the reach between the Crockett gage location and the downstream boundary, which is in line with 5-year calibration period results.

Results from the Baseline WAM Flows scenario were used to determine breakpoints in flow where sediment processes change by comparing reach-averaged invert change over a 10-day period to the flow during that 10-day period. This analysis acts as a kind of meta-analysis, using the large dataset generated by the 50-year run period to identify broad trends in sediment dynamics. Classifications made to quantify amount or frequency of net invert change are presented in a relative sense: What manner of invert change occurs relatively more frequently in this reach? Relatively how much net invert change occurs in this flow range in this reach relative to other flow ranges? Characteristic sediment dynamics associated with flow ranges are identified in Table 11 of this report. Breakpoints in flow are the upper and lower ends of each range.

Broadly, in the Upper Model, net depositional processes are more strongly associated with low flows and net erosional processes are more strongly associated with high flows in this model. Breakpoints in flow where sediment processes change vary by reach, but in many reaches there are identifiable points where the channel switches between net deposition and net erosion, one of these processes intensifies in magnitude or frequency noticeably, or the channel begins to experience net erosion or deposition only above some flow. In approximately the upper half of the model, breakpoints are in the range of 100-5,000 cfs, whereas in the lower end of the model they are for flows of at least 10,000 cfs. Comparison of results from the three WAM Flows scenarios in the reach between the upstream boundary and the Trinidad gage location for a sustained low flow period identifies that differences in reach-averaged net invert change between the scenarios often arise during times when High WAM Flows scenario flows were in the range of 1,000-5,000 cfs and differences in flow were on the order of 1,000-1,500 cfs, identifying that breakpoints in sediment processes exist in this range of flows such that a small difference in flow translates to markedly different sediment transport characteristics.

All three Lower Model WAM Flows scenarios were run in the same manner as the Upper Model scenarios. Significant differences in modeled load duration between the High WAM Flows and Low WAM Flows scenario were only observed at the Goodrich gage location. Significant differences in the reach-averaged net invert change were observed in the reach between the upstream boundary and the Romayor gage location, where net erosion at the end of the simulation was about 15% less in the High WAM Flows scenario, and in the reach between the Romayor gage location and the downstream boundary, where the net deposition at the end of the simulation was about 20% less in the High WAM Flows scenario. For the WAM Flows scenarios, net deposition was observed for the reach between the Romayor gage location and the downstream boundary, which was different from the result seen during the 5-year sediment calibration period.

Results from the Baseline WAM Flows scenario were used in the same way as they were for the Upper Model to determine breakpoints in flow where sediment processes change. Characteristic sediment dynamics associated with flow ranges are identified in Table 13 of this report. Breakpoints in flow are the upper and lower ends of each range. Broadly, in the Lower Model, net depositional processes are more strongly associated with low flows and net erosional processes are more strongly associated with high flows in this model. In the upstream-most reach, however, the lowest flows were actually more strongly-associated with net erosion. Breakpoints in flow where sediment processes change were present in the Lower Model and varied considerably with flow just as they did in the Upper Model. In approximately the upper half of the model, breakpoints are in the range of 1,000-5,000 cfs. In the lower end of the model there is a consistent breakpoint of 1,000 cfs that acts as a threshold above which net invert change occurs, and in the reach between the Romayor and Liberty gage locations the channel transitions from primarily deposition to primarily erosion at a breakpoint of 5,000 cfs. Comparison of results from the three WAM Flows scenarios in the reach between the upstream boundary and the Romayor gage location for a sustained low flow period identifies that differences in reach-averaged net invert change between the scenarios often arise during times when High WAM Flows scenario flows were in the range of 1,000-5,000 cfs and Low WAM Flows scenario flows were in the range of 500-5,000 cfs, identifying that there is a breakpoint in sediment processes exist in this range of flows such that a small difference in flow translates to markedly different sediment transport characteristics.

Scenario model results indicate that breakpoints in flow where sediment processes change in the Middle and Lower Trinity River exist across at a variety of flows in the range of 100-100,000 cfs. Many of these breakpoints are at flow magnitudes less than 5,000 cfs, which is relevant to resource management for two reasons. First of all, some of these breakpoints are less than 1,000 cfs, such that they are relevant to the discussion of environmental flow standards magnitudes. Additionally, results suggest that seemingly small changes to basin hydrology on a scale that can be accomplished by resource management activities (like those accomplished in the scenarios by changing return flows) can impact low flow duration in a way that leads to changes in sediment transport in the channel.

Conclusions and Recommendations

Calibrated model and scenario model results indicate that refinements should be made to the models before results regarding predictions of channel response to a given change in basin hydrology can be taken at face value. Several refinements are suggested that would help to enable use of the models in this manner, taking the lessons learned from this project to make them better suited to answering the questions posed to them. Despite this, the results from the models in their present state and discussion in this report 1) provide an excellent framework for how to interpret results of the sediment models with respect to breakpoints in flow, and 2) clearly indicate that there are breakpoints in flow where sediment processes change that are in the range of environmental flow standards such that they are relevant to discussion of environmental flow standards.

The large size, dense cross-section spacing and widely-varying flows of these sediment models present numerous hurdles for calibration efforts, and the calibration that was achieved in this project could be improved in further work. If TRA pursues this, several possible avenues could be taken. Cross-section density could be reduced in such a way that only the most representative cross-sections are retained, strengthening the model's ability to reproduce the conceptual sediment dynamics of the system and making short runtimes and larger computational increments possible. If more detailed results are wanted in a specific section of the channel, submodels could be cut out of the larger model to make smaller models that can be run at a smaller computational increment. Finally, if low flows are the highest priority target of future studies, simulations that exclude very high flows could be created that could likely be run at a higher computational increment without issue.

The WAM Flows scenarios developed for this project were reasonable in that they provided long hydrologic scenario time series and were flexible enough to be adapted to the calibrated sediment model configuration. Ideally, in a future version of this model, they would be modified to use regulated flows as opposed to unregulated flows for the Lower Model to better represent the dam's impact on flows. This would require the appropriate Trinity River daily WAM model to be run. It was difficult to run low flows with the WAM Flows scenario creation scheme because of the complexity of the representation of the basin hydrology. In future work, it would be ideal to modify the creation scheme or use a different flow series to attain flows as low as or lower than the lowest environmental flow standards in these reaches (75 cfs for the Upper Model and 200 cfs for the Lower Model). Future work with this model should also give additional thought to where flow reductions occur – with regards to sediment dynamics, it makes a considerable difference if changes in flows are implemented upstream in the river, at tributaries to the river, or at diversions from the river.

The Low, baseline and High WAM Flows scenarios provided time series for similar basin hydrologies with differences at low flows that were a target of this study and allowed for comparisons of sediment dynamics to see the impact of the decrease in return flows. In future work, a more useful approach might be to create long-term "normal conditions" time series and drop in more regularized, sustained periods of suspected flow breakpoints to better quantify their long-term impacts. This could, for example, be done with environmental flow standard flows if desired. If future projects used these models to answer questions about more targeted ranges of flows, sediment rating curves should also be revisited to be constrained at a higher resolution (smaller magnitudes of flow between flow-load-gradation points) in the range of targeted study flows. This step could utilize information about approximate locations of breakpoints determined in this project.

1 Introduction

The 80th Texas Legislature passed Senate Bill 3 in 2007 and triggered a process to establish environmental flow standards for all major river basins in Texas, including the Trinity River. Environmental flow standards were created by a stakeholder committee consisting of the Trinity and San Jacinto and Galveston Bay Basin and Bay Area Stakeholder Committee (BBASC) and Expert Science Team (BBEST). The Texas Commission on Environmental Quality (TCEQ) adopted recommended flow standards for the Trinity River at four measurement points that align with United States Geological Survey (USGS) streamgages.

The Trinity River Authority (TRA) is a regional conservation and reclamation district within the Trinity River Basin and has a desire to better understand the river's biology, hydrology, water quality and sediment transport characteristics. TRA also desires to collect scientific information that will be informative when instream flow standards are potentially adjusted during the adaptive management phase of the SB3 process. The goal of this project was to utilize large, existing and newly-created hydraulic models to identify breakpoints in flow where sediment processes change at a spectrum of locations. Subtasks defined in the scope of work that dovetail into this larger task included:

- Extending the footprint of the Lower Model to extend from Livingston Dam to the USGS Liberty streamgage;
- Develop full-reach sediment models and calibrate sediment processes; and
- Run calibrated sediment models with three hydrologic scenarios to look at how hypothetical changes to basin hydrology impact sediment transport processes.

The two study areas for this project are approximately 1) the "Upper Model Study Region" from USGS Rosser streamgage to Lake Livingston and 2) the "Lower Model Study Region" from Lake Livingston to the USGS Liberty streamgage. A map of the approximate combined study area is shown in Figure 1. The Upper Model Study Region includes the Oakwood SB3 environmental flow standards measurement point, which is near USGS gage number 08065000 and River Mile 295 of the Trinity River. The Lower Model Study Region includes the Romayor SB3 environmental flow standards measurement point, which is near USGS gage number 08066500 and River Mile 75 of the Trinity River.

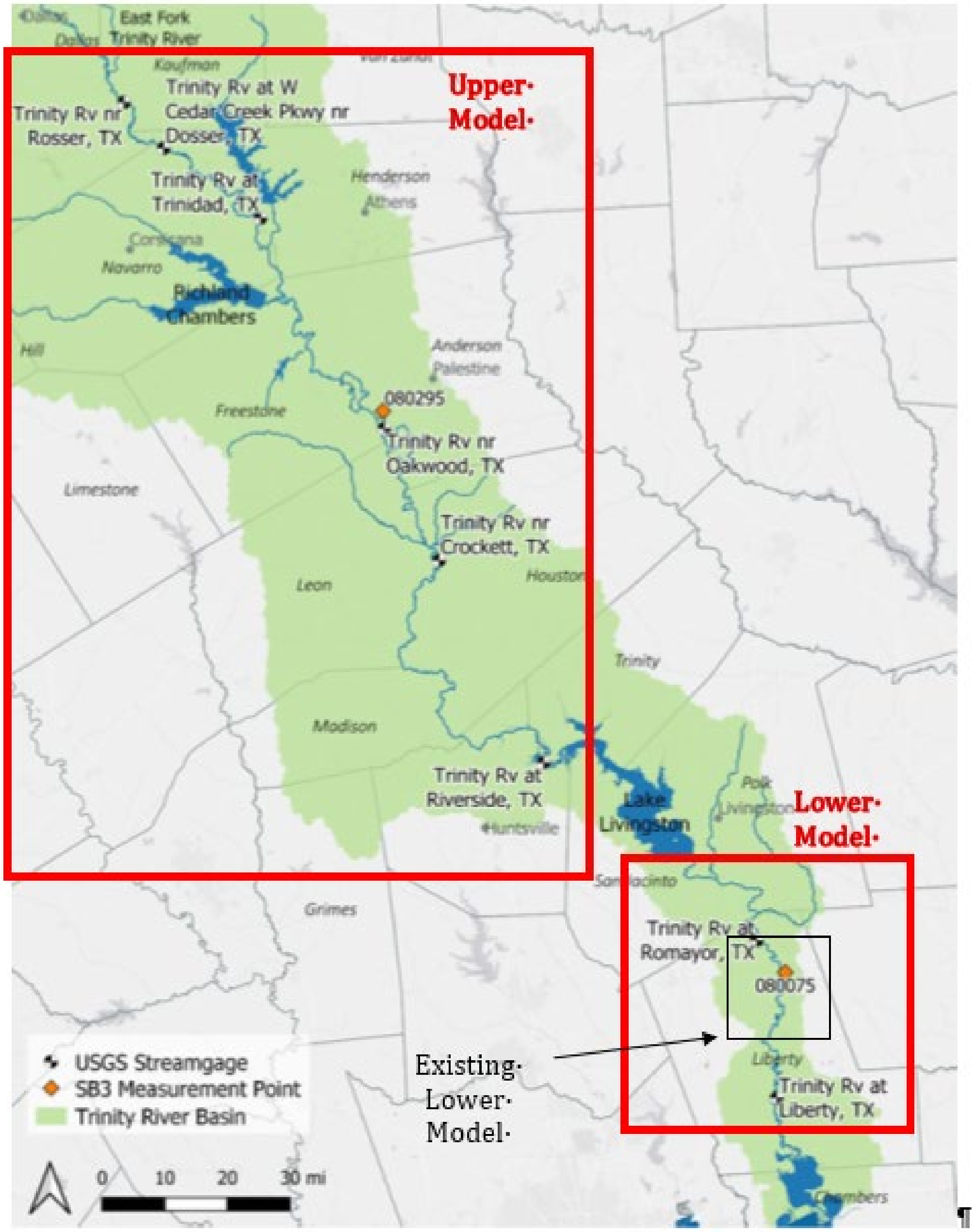

Figure 1: Project study site, including major USGS streamgages and SB3 measurement points, from (Mangham, McKnight, Osting, Southard, & Flores, 2020). Upper and Lower Model Study Regions highlighted by red boxes.

Hydrologic scenarios designed for this project aimed to investigate the sediment transport impacts of sustained periods of low flows. Environmental flow standards for the Oakwood measurement point are shown in Table 1, and environmental flow standards for the Romayor measurement point are shown in Table 2. Note that:

- The lowest flow for the Upper Model Study Region is the summer subsistence flow of 75 cfs and the highest flow is the spring base flow of 450 cfs; and
- The lowest flow for the Lower Model Study Region is the summer subsistence flow of 200 cfs and the highest flow is the spring base flow of 1,150 cfs.

Table 1: Environmental flow standards for Oakwood measurement point, from (Mangham, Osting, & Flores, 2017).

USGS Gage 08065000, Trinity River near Oakwood

Season	Subsistence	Base	Pulse
Winter	120 cfs	340 cfs	Trigger: 3,000 cfs Volume: 18,000 af Duration: 5 days
Spring	160 cfs	450 cfs	Trigger: 7,000 cfs Volume: 130,000 af Duration: 11 days
Summer	75 cfs	250 cfs	Trigger: 2,500 cfs Volume: 23,000 af Duration: 5 days
Fall	100 cfs	260 cfs	Trigger: 2,500 cfs Volume: 23,000 af Duration: 5 days

cfs = cubic feet per second
af = acre-feet

Table 2: Environmental flow standards for Romayor measurement point, from (Mangham, Osting, & Flores, 2017).

Season	Subsistence	Base	Pulse
Winter	495 cfs	875 cfs	Trigger: 8,000 cfs Volume: 80,000 af Duration: 7 days
Spring	700 cfs	1150 cfs	Trigger: 10,000 cfs Volume: 150,000 af Duration: 9 days
Summer	200 cfs	575 cfs	Trigger: 4,000 cfs Volume: 60,000 af Duration: 5 days
Fall	230 cfs	625 cfs	Trigger: 4,000 cfs Volume: 60,000 af Duration: 5 days

cfs = cubic feet per second
af = acre-feet

This project is not explicitly aimed at investigating sediment transport impacts of environmental flows standards, but a goal is to begin to identify ranges of flows where sediment processes change to see if that information is pertinent to discussions of environmental flow standards.

2 Subtask 1A & B: Updating the Lower Model Geographic Footprint

A major subtask of this project was to extend the geographic footprint of the Lower Trinity HEC-RAS model. The existing Lower Model extended approximately from the USGS gage 08066500 at Romayor, TX on the Farm to Market Road (FM) 787 bridge to the State Highway (SH) 105 bridge at Franklin, TX. This model was completed in a previous project and calibrated for low flows in the last phase of this project. Overbank elevation in the model is based on a Digital Elevation Model (DEM) made using 2011 LiDAR data, detailed in Table 3. In this project, the geographic footprint of the Lower Model was extended to cover the entire length of the mainstem from the outlet of Lake Livingston to the USGS gage 08067000 at Liberty, TX.

The HEC-RAS model developed for this project incorporated a new LiDAR-derived DEM terrain as well as Trinity River in-channel bathymetric survey data collected by TRA. The new DEM terrain, covering the full extent of the Lower Model, was composed of available LiDAR-derived DEM tiles obtained from the Texas Geographic Information Office (TxGIO). If DEM data overlapped, the most recent dataset was prioritized. This DEM was available from the last phase of the project (Mangham, McKnight, Osting, Southard, & Flores, 2020). In this project, we extended the existing DEM by adding tiles from the same LiDAR sources when needed, but we did not add additional LiDAR data sources. Data sources used to generate this DEM are detailed in Table 3. A map of the LiDAR availability is shown in Figure 2. No new LiDAR was available since the completion of the last phase of the project, therefore overbank geometry was not updated.

Table 3: LiDAR datasets used in the creation of 1) the existing available HEC-RAS geometry for a portion of the Lower Model below Romayor gage detailed in (Mangham, Osting, & Flores, 2017), and 2) the existing DEM, detailed in (Mangham, McKnight, Osting, Southard, & Flores, 2020), that was used to create overbank portions of the new Lower Model HEC-RAS geometry.

Model Status	Name	Citation
Existing Lower Model	Liberty County Lidar 2011	Federal Emergency Management Agency (FEMA). Liberty County Lidar, 2011-01-01. Web.
New Lower Model	Upper Coast Lidar 2018	Strategic Mapping Program (StratMap). Upper Coast Lidar, 2018-03-22. Web. 2020-06-22.
New Lower Model	Jefferson, Liberty, & Chambers Counties Lidar 2017	Strategic Mapping Program (StratMap). Jefferson, Liberty, & Chambers Counties Lidar, 2017-03-23. Web. 2020-06-25.
New Lower Model	East Texas Lidar 2017	Strategic Mapping Program (StratMap). East Texas Lidar, 2017-04-14. Web. 2020-06-25.
New Lower Model	Neches River Basin Lidar 2017	United States Geological Survey (USGS). Neches River Basin Lidar, 2017-02-22. Web. 2020-06-22.

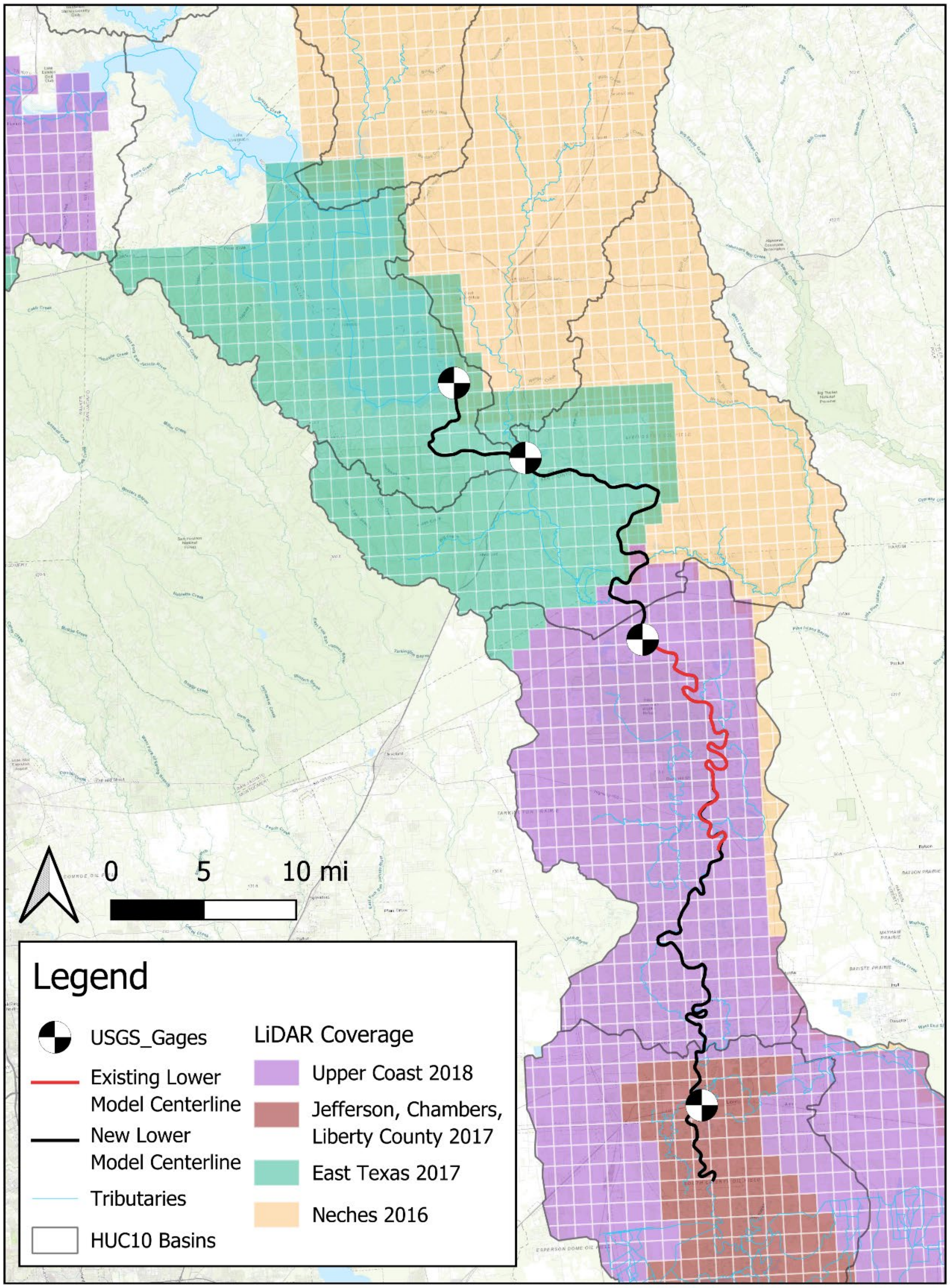

Figure 2: Map detailing LiDAR sources for Lower Model. Note that the smaller Existing Lower Model used older LiDAR, as detailed in Table 3.

TRA collected bathymetry data for approximately the upper and lower thirds of the channel during two field excursions. TRA collected bathymetry data for the Lower Model Study Region on August 17 and 18, 2021 and December 20 and 21, 2023 along pre-determined cross-section lines developed in GIS based on information available from LiDAR DEM's and aerial imagery. New HEC-RAS model geometry files were made using LiDAR elevation in the overbanks and TRA bathymetry data in the channel using a RiverGIS workflow described below. Then, the two new geometries for the upper and lower thirds of the reach were combined with the existing geometry for the middle third of the reach in HEC-RAS to create one Lower Model Study Region HEC-RAS geometry that extends from Lake Livingston Pool to the Liberty USGS gage and covers much of the Lower Trinity River. To avoid having negative river station numbers in HEC-RAS, river station numbers for the middle reach were changed and a note was included in the model geometry file "Description" box indicating which of the old river stations they correspond to.

RiverGIS is a QGIS plugin that generates HEC-RAS input files from spatial data such as DEM's and shapefiles. TRA provided bathymetry information as a shapefile of processed bathymetry points that had already been snapped to HEC-RAS cross-section lines. A RiverGIS workflow that was used to create HEC-RAS input files is described below. This task utilized LiDAR terrain files for elevation of banks and overbanks and TRA bathymetry shapefiles for elevation in the channel. The RiverGIS workflow was:

1. Load shapefiles that define HEC-RAS model structure, TRA bathymetry points and raster DEM files into QGIS. An extended stream centerline for the Lower Model (that aligns exactly with the old stream centerline where they overlap) and new cross-sections for the new portions of the model were created before bathymetry data collection. Bank lines were created after bathymetry data collection, and were based on information available from LiDAR DEM's and recent aerial imagery.
2. Create left and right flowpath lines and copy the stream channel geometry to the channel flowline. Left and right flow path lines were drawn to follow the expected center of mass of flow down in the left and right overbanks, respectively.
3. Import centerlines, cross-sections, banklines and flowlines into RiverGIS River Database Tables.
4. Update elevations for cross-section cut lines based on LiDAR-derived DEM data.
5. Update cross-section cut line elevations with bathymetry data using all bathymetry points located between bank lines.
6. Export HEC-RAS geometry from RiverGIS/QGIS to HEC-RAS.

3 Subtask 1C: Calibrating Sediment Processes in the Upper and Lower Model

The HEC-RAS 1D sediment model is appropriate for modelling decadal-scale sediment dynamics in rivers. As a 1D model, it calculates a single sediment transport value for an entire cross-section and is not intended to identify where in a given cross-section erosion or deposition occurs. For this reason, it is not appropriate for modeling bank migration, localized scour, or any other processes that are 2D/3D in nature (Gibson & Sanchez, 2020). This project spanned multiple years and multiple HEC-RAS versions, but the final model results were produced in HEC-RAS 6.4.1.

The goal of this study was to use hydraulic models of the Trinity River with the HEC-RAS sediment capabilities to calibrate a sediment model that could be used to characterize decadal-scale sediment dynamics. The calibrated sediment model would then enable examination of breakpoints in flow where sediment processes change and evaluation of scenarios associated with increased or decreased flow from return flows to see how they affect sediment regime. We consulted with TWDB staff who specialize in sediment transport modeling to arrive at a reasonable goal for sediment model calibration. This goal was to calibrate model sediment dynamics such that flows of given magnitudes produced expected responses of aggradation or erosion, and such that the bed was stable in the long-term for a historical flow series of sufficient length.

3.1 Hydraulic Calibration

Model hydraulics are an important control on sediment dynamics, and a well-calibrated hydraulic model is a crucially important first step to a calibrated sediment model. Prior to the onset of this project, calibrated hydraulic models for the entire Upper Model Study Region and the middle portion of the Lower Model Study Region had been prepared. These calibrated hydraulic models, however, were primarily prepared for low-flow water quality scenarios, and were not calibrated for high flows, which are a necessary component of any decadal-scale sediment model (Mangham, McKnight, Osting, Southard, & Flores, 2020). New portions of the Lower Model prepared as part of this project also needed to undergo hydraulic calibration before sediment calibration was possible.

The existing Upper Model from Phase 3 of the project included a small tributary from Cedar Creek Reservoir that was removed from the model geometry as an initial step, because we did not want to model sediment transport in this reach.

Another early decision in the sediment modelling process was to remove bridges from the sediment model versions of the HEC-RAS geometry. Bridges, especially those with multiple openings, can cause model stability issues and a common recommendation to improve model stability is to remove them entirely (Gibson & Sanchez, 2020). The following bridge cross-sections were removed from the model, along with the cross-sections immediately upstream and downstream of the bridges, which often reflect the multiple openings of the bridge in their configuration. Cross-sections that were removed from the model as part of this step include:

- Highway bridge for Route 34 near Rosser – XSs 1469980, 1469926 & 1469804
- Highway bridge for Route 85 near Kemp – XSs 1389308, 1389246, 1389142
- Highway bridge for Route 31 near Trinidad – XSs 1184915, 1184879, 1184695
- Railroad bridge near Trinidad – XSs 1182782, 1182754, 1182689
- Highway bridge for US Hwy 287 near Richland Chambers Reservoir – XSs 1088652, 1088551, 1088336
- Dual highway bridge for US Hwy 79 near Oakwood – XSs 771494, 771411, 771200
- Railroad bridge near Oakwood – XSs 763229, 763202, 763137
- Highway bridge for Route 7 near Crockett – XSs 526590, 526525, 526366
- Highway bridge for Hwy 21 near Antioch – XSs 358056, 357991, 357832
- Highway bridge for Route 3478 – XSs 206058, 206039, 205977
- Dual highway bridge for Route 19 near Riverside – XSs 121230, 121124, 120980

When we created the Lower Model geometry, we didn't create any bridge cross-sections. Bridges at the following locations should be included in any standalone hydraulic modelling that uses this geometry:

- Railroad bridge and two highway bridges for US Hwy 59 near Goodrich – Between XSs 386001 & 385116
- Railroad bridge – Between XSs 280697 & 280522
- Highway bridge for Route 787 near Romayor – Between XSs 276202 & 268494
- Highway bridge for Route 105 near Moss Hill – Between XSs 171651 & 171374
- Railroad bridge – Between XSs 63430 & 63242
- Railroad bridge and highway bridge for US Hwy 90 near Liberty – Between XSs 33962 & 33359

The bridge for SH 105 near Moss Hill was already included in the model geometry "ASI_2020_Final_with_bridge" from Phase 3 of the project, so that can be used to include that bridge in the new geometry if the need arises.

For the hydraulic and sediment calibration, we exclusively used USGS streamgages and the USGS lake elevation gage on Lake Livingston to inform model boundary condition inflows. We identified USGS streamgages with overlapping periods of record on the mainstem of each of these streams and acquired 15-minute flow and gage height observations at each. We processed the data, linearly interpolating to fill small gaps, converting gage height to stage using each gage's datum, resampling all time-series to 1-hour intervals, and applying time offsets to create new time series of flow at critical model cross-sections that were not gaged (e.g. the upstream boundary of each model). For any significant tributaries that had a USGS streamgage, we acquired this data and multiplied flows by the ratio of the drainage area (DAR) at the confluence of the tributary and the Trinity mainstem to the drainage area at the streamgage location. We used the USGS Lake Livingston gage stage time-series as the downstream boundary of the Upper Model. For the Lower Model, we used rating curve information from the Liberty streamgage and the Moss Bluff streamgage to develop a reasonable rating curve at the model's downstream boundary. Some of this information is detailed further in Table 4 and Table 5.

For both full models, we employed a hydraulic calibration strategy recommended in the HEC-RAS 1D Flow User Manual (Gibson & Sanchez, 2020). For the first step in hydraulic calibration, we prepared rating curves for each gage location by binning flow observations and finding the average stage within each flow range bin. For both models, we ran steady simulations for a range of flows and compared rating curve results to the rating curves prepared using observations at streamgages. We performed this process iteratively, updating the in-channel and overbank Mannings n values and the representation of levees and ineffective flow areas at each cross-section to achieve stages for given flows at each gage station that resembled observed data as closely as possible. For the second step in hydraulic calibration, we identified short (<1 year) periods with single or multiple distinct flood pulses of varying size where it was apparent that intervening inflows were not significant. We iteratively ran unsteady flow simulations for these periods, comparing stage and flow hydrographs from results to observed stage and flow hydrographs at each streamgage and updating in-channel and overbank Mannings n values and the representation of levees and ineffective flow areas at each cross-section to achieve the correct timing, flow magnitude and maximum stage for flood peaks at each gage station. For the final step in the hydraulic calibration, we prepared a ~5-year unsteady flow simulation covering a wide range of flows and including floods with significant intervening inflows. We ran these simulations and again compared flow and stage hydrographs from results to observations at streamgages to ensure that the calibration of model hydraulics was reasonable outside of floods where there was a clear influence of intervening inflows.

It is also important to represent intervening inflows from tributaries and diversions by water users in a sediment model, because 1) inflows from tributaries can deliver sediment to the river, and 2) addition or removal of flow that is not transporting sediment can impact the sediment capacity of river flows and cause erosion and deposition. We decided to include intervening inflows from any tributary with a drainage area greater than 125 km^2. This threshold was selected to ensure that the representation of tributary inflows was as simple as possible while still containing at least one tributary between each pairing of streamgages to deliver intervening flows to the river. Where possible, we used DAR-adjusted USGS streamgage data collected on these tributaries to inform their flow values. Most of the tributaries, however, were ungaged, and a HEC-RAS Ungaged Lateral Inflows (ULI) Analysis was used to inform their flow values. This analysis uses stage and flow observations at the USGS streamgage locations as well as the drainage area and estimated lag time for each selected tributary location to estimate ungaged intervening inflows. To calculate lag time, we assumed a water velocity of 3 ft/s. This method was found to be very effective for estimating intervening inflows, as evidenced by a marked improvement in the similarity of predicted to observed stage and flow hydrographs in runs with ungaged inflows implemented. When their operation overlapped with the 5-year hydraulic and sediment calibration period, we also included diversions from large diverters on the river informed by historical diversion data that TRA obtained from water providers.

We detail the configuration of inflows to the hydraulic models in Table 4 and Table 5.

Table 4: Inflow Configuration for Upper Model Calibration Run. Fill color indicates whether boundary condition at each location is an upstream boundary flow series (yellow), internal boundary used for HEC-RAS Ungaged Lateral Inflow Analysis (no fill), lateral inflow (green), lateral diversion (brown) or downstream boundary stage series (gray). Data column indicates whether source was USGS streamgage data, lag-adjusted USGS streamgage data, HEC-RAS Ungaged Inflows Analysis series, or disaggregated reported monthly diversions provided by TRA. DAR Adjustment factor details ratio of drainage area at tributary mouth to drainage area at gage, which was multiplied by the USGS streamgage flow series data. Drainage Area for ULI was assessed using the NHDPlus HR dataset. Lag Time for ULI was assessed by dividing mainstem channel distances by an average speed of 3 ft/s.

Upper Model	XS	Data Source	DAR Adjustment Factor	Drainage Area for ULI (mi2)	Lag Time for ULI (Hrs)
Upstream Boundary	1513706	**Rosser Gage Series with 4 Hr Time Lag**	-	-	-
Rosser Gage	1468756	**USGS 08062500: Trinity Rv nr Rosser, TX**	-	-	-
Village Creek	1413606	ULI	-	62	21.3
Bois d'Arc Creek	1387411	ULI	-	73.3	18.8
Cedar Creek Upper	1247379	ULI	-	253.6	5.9
Trinidad Gage	1184057*	**USGS 08062700: Trinity Rv at Trinidad, TX**	-	-	-
Rush Creek	1161541	ULI	-	79.3	36.3
Cedar Creek Lower	1145783	ULI	-	253.6	34.9
TRWD Wetlands Diversion	1127356	**Reported Monthly Diversions** (Mangham, Personal Communication: Historical TRWD Wetlands Diversion Data, 2023)	-	-	-
Richland Creek	1077070	ULI	-	1,975.4	28.5

Upper Model	XS	Data Source	DAR Adjustment Factor	Drainage Area for ULI (mi2)	Lag Time for ULI (Hrs)
Tehuacana Creek	945331	**Goodrich 08064700: Tehuacana Ck nr Streetman, TX**	2.99	-	-
Catfish Creek	905808	ULI	-	288.5	12.7
Keechie Creek	790717	ULI	-	93.5	2
Oakwood Gage	769166	**USGS 08065000: Trinity Rv nr Oakwood, TX**	-	-	-
Upper Keechi Creek	555808	**USGS 08065200 Upper Keechi Ck nr Oakwood, TX**	3.33	-	-
Big Elkhart Creek	550478	ULI	-	141.4	2.2
Hurricane Bayou	530306	ULI	-	104.6	0.3
Crockett Gage	526675	**USGS 08065350: Trinity Rv nr Crockett, TX**	-	-	-
Huntsville Diversion	223198	**Reported Monthly Diversions** (Mangham, Personal Communication: Huntsville Historical Diversion Data, 2023)	-	-	-
Lake Livingston	393	**USGS 08066190: Livingston Res nr Goodrich, TX**	-	-	-

Table 5: Inflow Configuration for Lower Model Calibration Run. Fill color indicates whether boundary condition at each location is an upstream boundary flow series (yellow), internal boundary used for HEC-RAS Ungaged Lateral Inflow Analysis (no fill), lateral inflow (green), lateral diversion (brown) or downstream boundary stage series (gray). Data column indicates whether source was USGS streamgage data, lag-adjusted USGS streamgage data, HEC-RAS Ungaged Inflows Analysis series, or disaggregated reported monthly diversions provided by TRA. DAR Adjustment factor details ratio of drainage area at tributary mouth to drainage area at gage, which was multiplied by the USGS treamgage flow series data. Drainage Area for ULI was assessed using the NHDPlus HR dataset. Lag Time for ULI was assessed by dividing mainstem channel distances by an average speed of 3 ft/s.

Lower Model	XS	Data Source	DAR Adjustment Factor	Drainage Area for ULI (mi2)	Lag Time for ULI (Hrs)
Upstream Boundary	434355	**Goodrich Minus Long King Creek with 4 Hr Time Lag**	-	-	-
Long King Creek	386001	**USGS 08066200: Long King Ck at Livingston, TX**	1.59	-	-
Goodrich Gage	385116	**USGS 08066250: Trinity Rv nr Goodrich, TX**	-	-	-
Menard Creek	310008	**USGS 08066300: Menard Ck nr Rye, TX**	1.05	-	-
Big Creek	289291	ULI	-	200	1.9
Romayor Gage	276202	**USGS 08066500: Trinity Rv at Romayor, TX**	-	-	-
Davis Bayou	168960	ULI	-	193.4	12.6
Little Bayou	136655	ULI	-	134	9.6
Luce Bayou Diversion	133218	**Reported Daily Diversions** (Mangham, Personal Communication: Historical Luce Bayou Diversion Data, 2023)	-	-	-
Liberty Gage	33359	**USGS 08067000: Trinity Rv at Liberty, TX**	-	-	-
Downstream Boundary	1998	**Rating Curve Developed Using Liberty Series and USGS 08067100: Trinity Rv nr Moss Bluff, TX**	-	-	-

A detailed hydraulic calibration was not the primary objective of this project, nor was it provided for in the level of effort assigned to this task in the project scope and budget. The goals of the hydraulic calibration for each phase were, in order of priority:

- Achieve reasonable wetted cross-sections that would not cause instability in the sediment model. We chose to employ overbank veneer deposition methods in the sediment model, which means that overbank flows and their frequency can have a significant impact on the sediment results.
- Achieve a close match on the timing and magnitude of flood peaks. Flooding events typically cause a lot more sediment transport than low flow events.
- Achieve a good match between predicted and observed flows and stages at USGS gage stations. For flows, it was typically easy to get within 1% of the correct value with ungaged inflows analysis methods. For stages, we tried to achieve a predicted stage within 1 ft of the observed stage.

We made the following modifications to the model geometry file to calibrate model hydraulics:

- Varied overbank and in-channel Mannings N numbers within reasonable limits.
- Added levees or ineffective flow areas.
- Adjusted cross-section bathymetry when necessary or when there was evidence that it was appropriate.
- Removed model cross-sections when they were clearly causing model stability issues.

The configuration of the Upper and Lower Model geometry and their boundary conditions are detailed in Figure 3 and Figure 4.

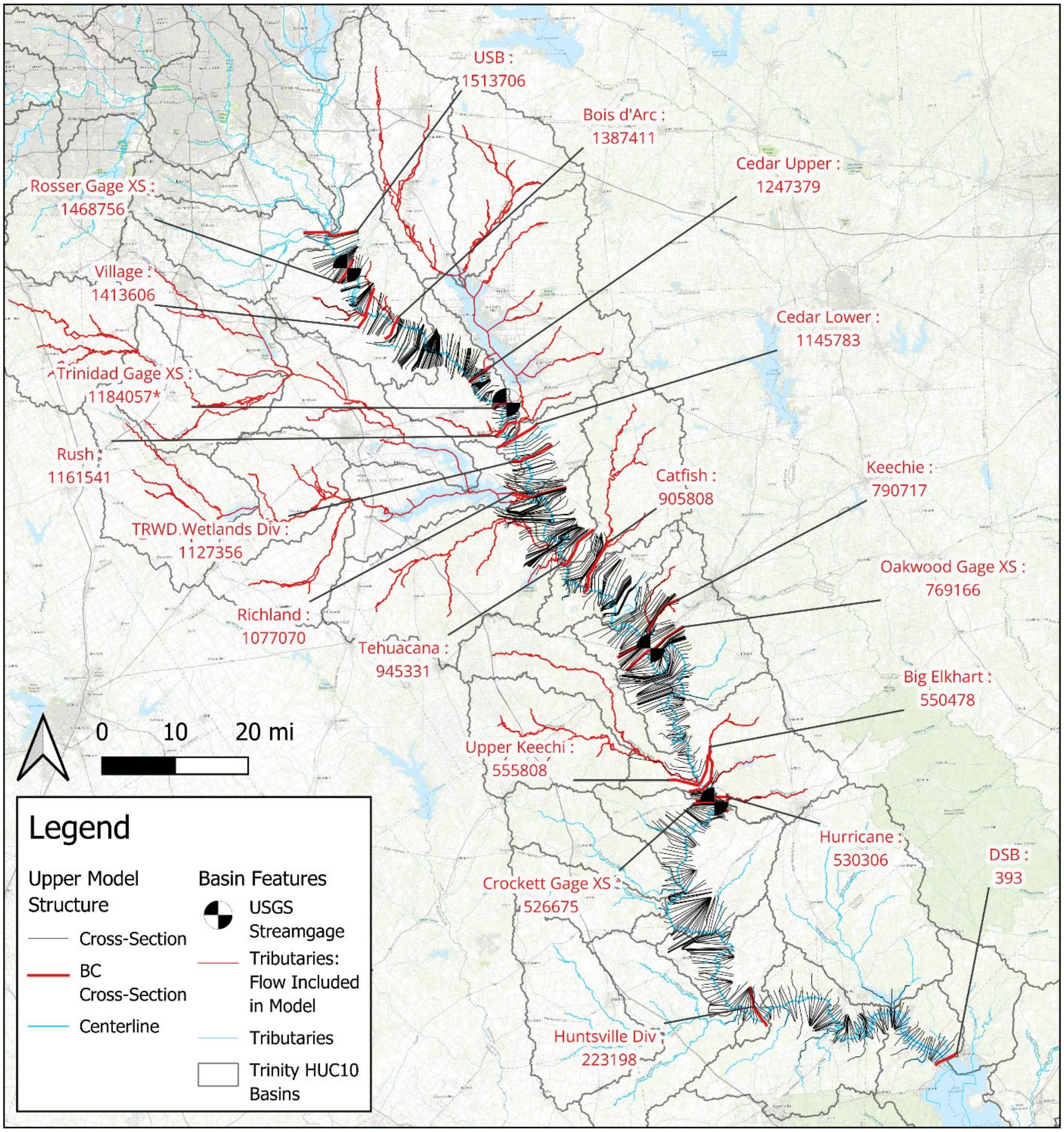

Figure 3: Map detailing basin features and model configuration for Upper Model area. Labels indicate features that were represented in the model with their name and cross-section number. Tributaries labeled as red are not explicitly modeled as streams in HEC-RAS, but are represented in the model hydraulics with a lateral inflow boundary condition.

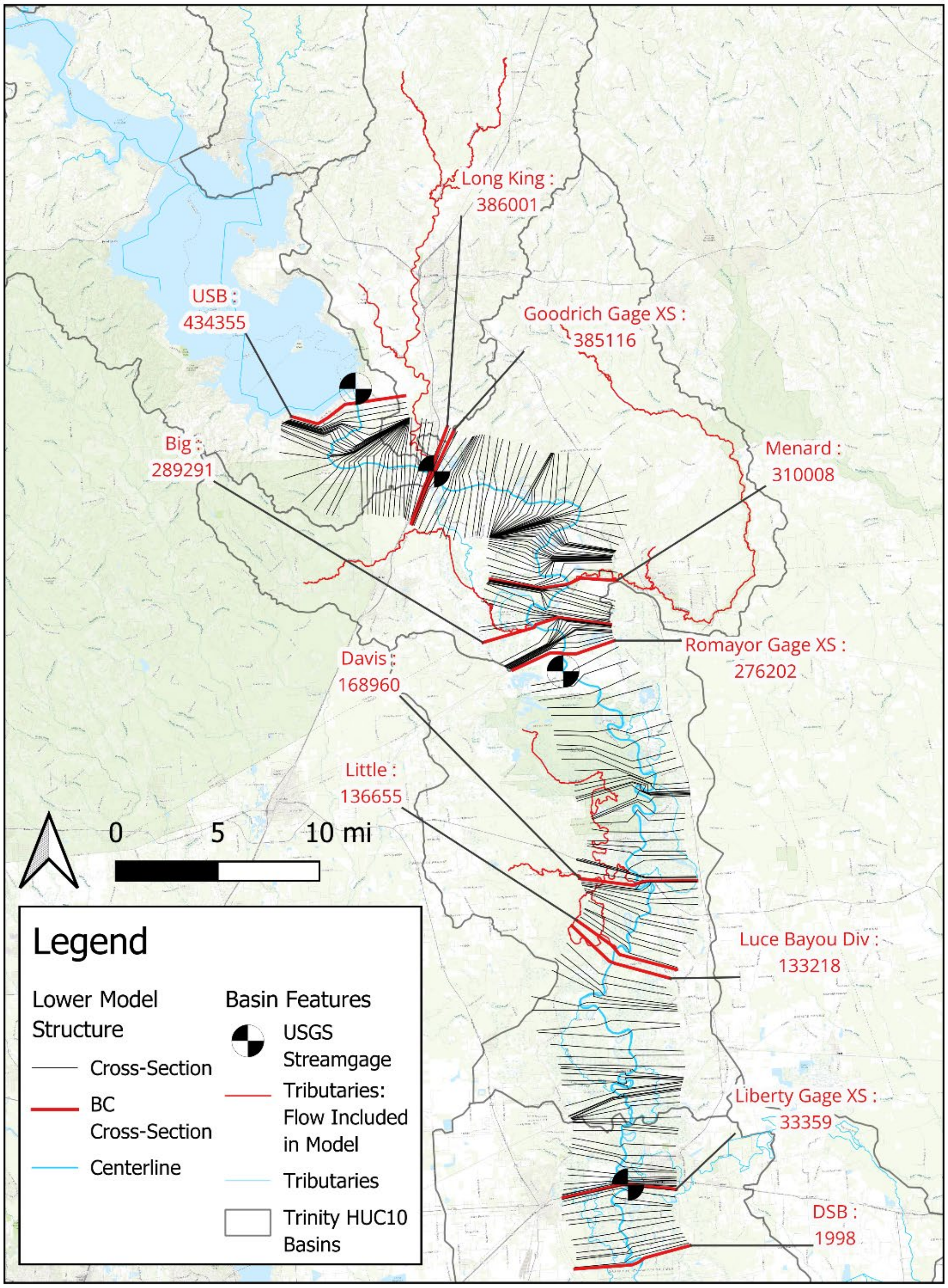

Figure 4: Map detailing basin features and model configuration for Lower Model area. Labels indicate features that were represented in the model with their name and cross-section number. Tributaries labeled as red are not explicitly modeled as streams in HEC-RAS, but are represented in the model hydraulics with a lateral inflow boundary condition.

3.1.1 Upper Model Hydraulic Calibration Results

Boundary condition inputs for the Upper Model are visualized in time-series in Figure 5. Flows originating upstream during this time period vary from a minimum of about 600 cfs to a maximum of about 40,000 cfs. Intervening inflows (from drainage-area adjusted USGS gage data and estimated ungaged inflows) are dynamic during this time period, making total intervening flow contributions ranging from hundreds to tens of thousands of cfs. Observed diversions were fairly low during this time period, usually in the tens of cfs. Lake Livingston stage hovered around 130 ft during this time period, but did show months-long periods of significant increases or decreases in stage, which were important to include in the calibration to examine model stability during these conditions.

Figure 6 shows flow duration curves for the Upper Model calibration time period at each of the gage locations. A wide range of flow conditions were experienced during this time period, indicating that it is suitable for a hydraulic and sediment calibration. Flow frequencies are shown to increase significantly in the downstream direction, which indicates the relative importance of incorporating intervening inflows into the model. The median flow for this time period is shown to range from about 1,000 – 1,500 cfs. Flows greater than 10,000 cfs occur for about 10-15% of this time period.

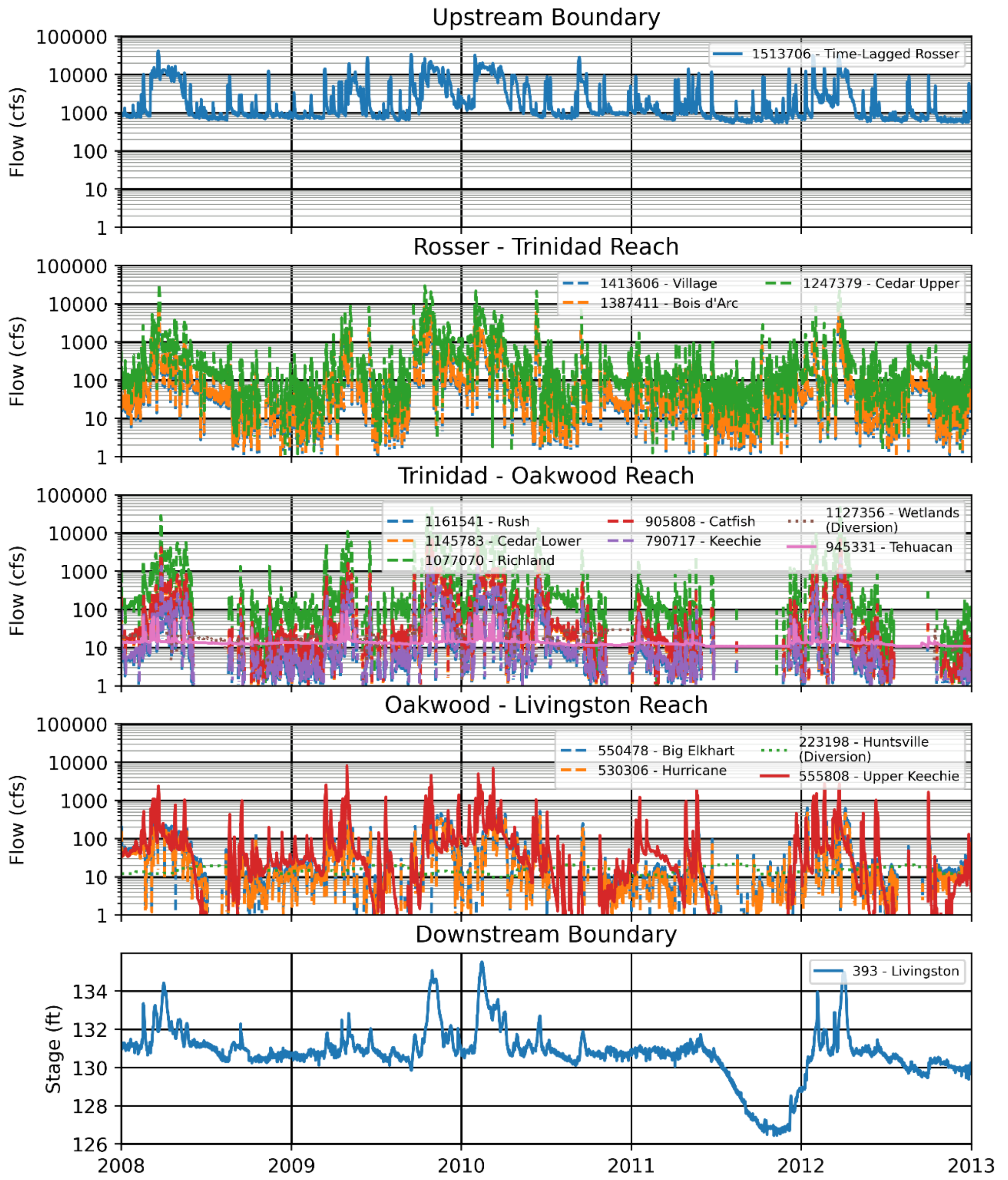

Figure 5: Model boundary condition inputs for Upper Model, grouped by model region. Upstream and tributary flows calculated from USGS flow series with time-lags and drainage area adjustments implemented are shown as solid lines. Estimated ungaged lateral inflows are shown as dashed lines. Diversions are shown as dotted lines and are informed by observation data provided by diverters or assumed. Downstream boundary condition is a stage boundary informed by a USGS lake gage on Lake Livingston.

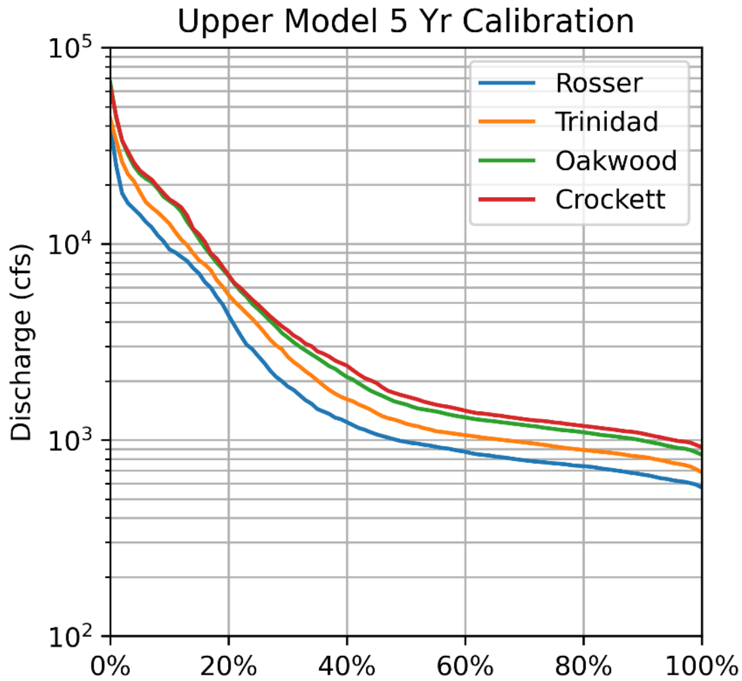

Figure 6: Flow duration curves at gage locations for Upper Model 5-year calibration period (2008-2012). Note that the Rosser location essentially represents incoming flows at the upstream boundary of the model.

We were able to satisfactorily calibrate the Upper Model hydraulics for the purposes of creating a reasonable sediment model. Predicted and observed stage and flow values at USGS Rosser, Trinidad, Oakwood, and Crockett streamgage locations for the Upper Model for one of the five simulated years are shown in Figure 7 and Figure 8. The other four years of the five-year period show similarly well-calibrated hydraulics. As shown in Figure 7, timing of flows in the Upper Model is close to that shown in the observed dataset, and flow magnitudes are quite closely-matched for all but high flows. High flows are very closely matched at Trinidad (within ~5% of the observed value) and are off by between ~5-10% for Oakwood and Crockett. We examined single flood events during the calibration period and identified that times where high flow magnitudes were off by the greatest amount were during periods where intervening inflows were high relative to flow coming from the upstream boundary, and that the relatively close match shown here represents the best that the HEC-RAS ungaged lateral inflows estimation tool was able to achieve with our simplified representation of tributaries. Predicted stage similarly matched closely (within ~1 ft) for most low to medium flows. During some high flows, stages could be off by as much as 5 ft, but this often simply reflected the mismatch in flow translating to lower stages. Stage calibration results are summarized in Table 6. Overall, the hydraulic calibration of the Upper Model is demonstrated to be quite good considering the size of the model and the range of flows that need to be run for sediment model calibration. It was deemed acceptable for the sediment modeling tasks of 1) sediment calibration and 2) running sediment model scenarios.

Table 6: Approximate average difference in ft between observed and simulated stage for approximate ranges of flows at gage locations in Lower Model. Low = 0-5,000 cfs; Medium = 5,000-10,000 cfs, High = 10,000-50,000 cfs.

Flow Range	Rosser	Trinidad	Oakwood	Crockett
Low	+/-1	+1	-	+1
Medium	-	+1	-	+2
High	-3	-3	+4	-3

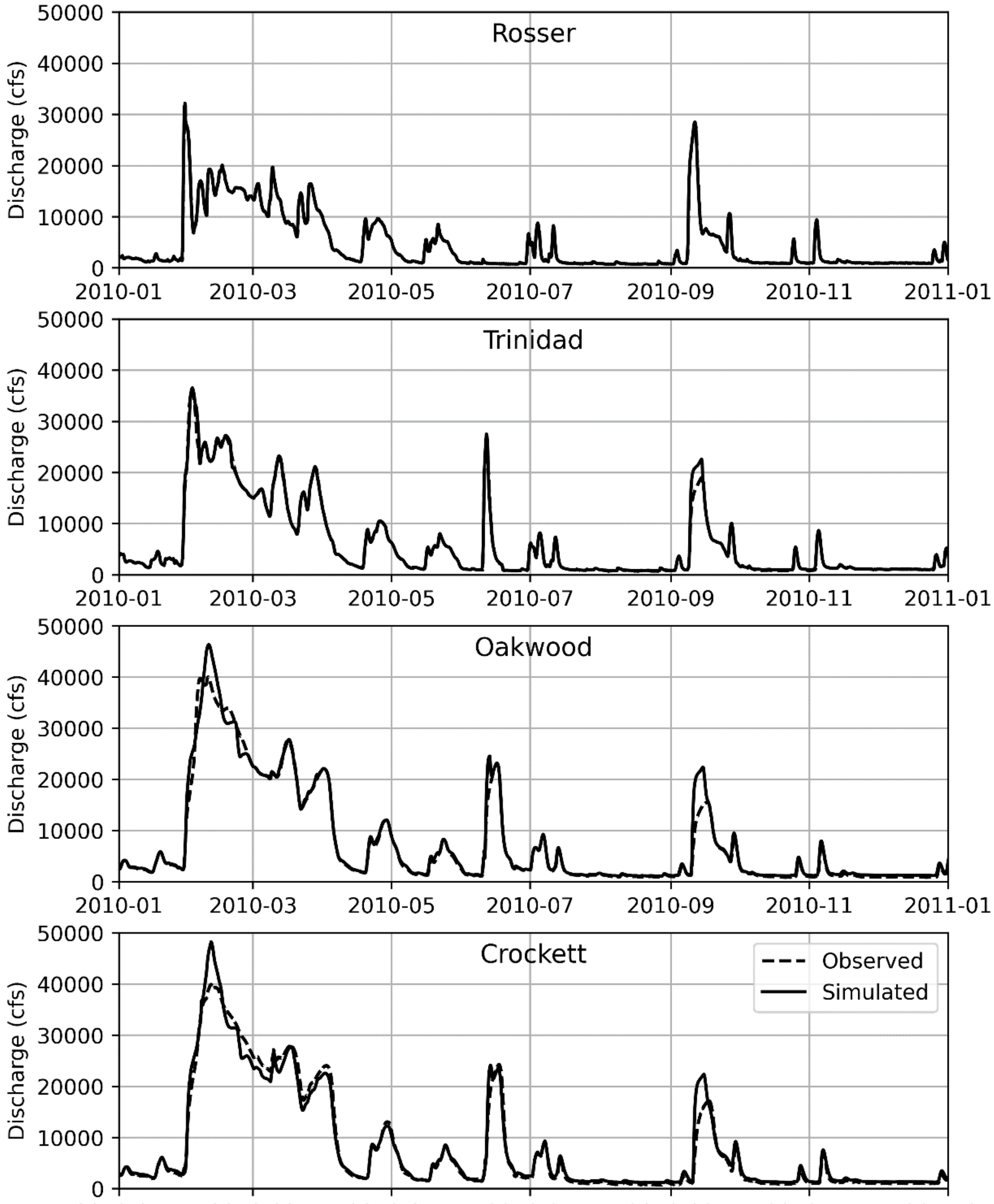

Figure 7: Comparison of observed and predicted discharge for 2010 at four streamgage locations in Upper Model, shown in order from upstream to downstream. This represents 1 year of results from the 5-year calibration period (2007-2011).

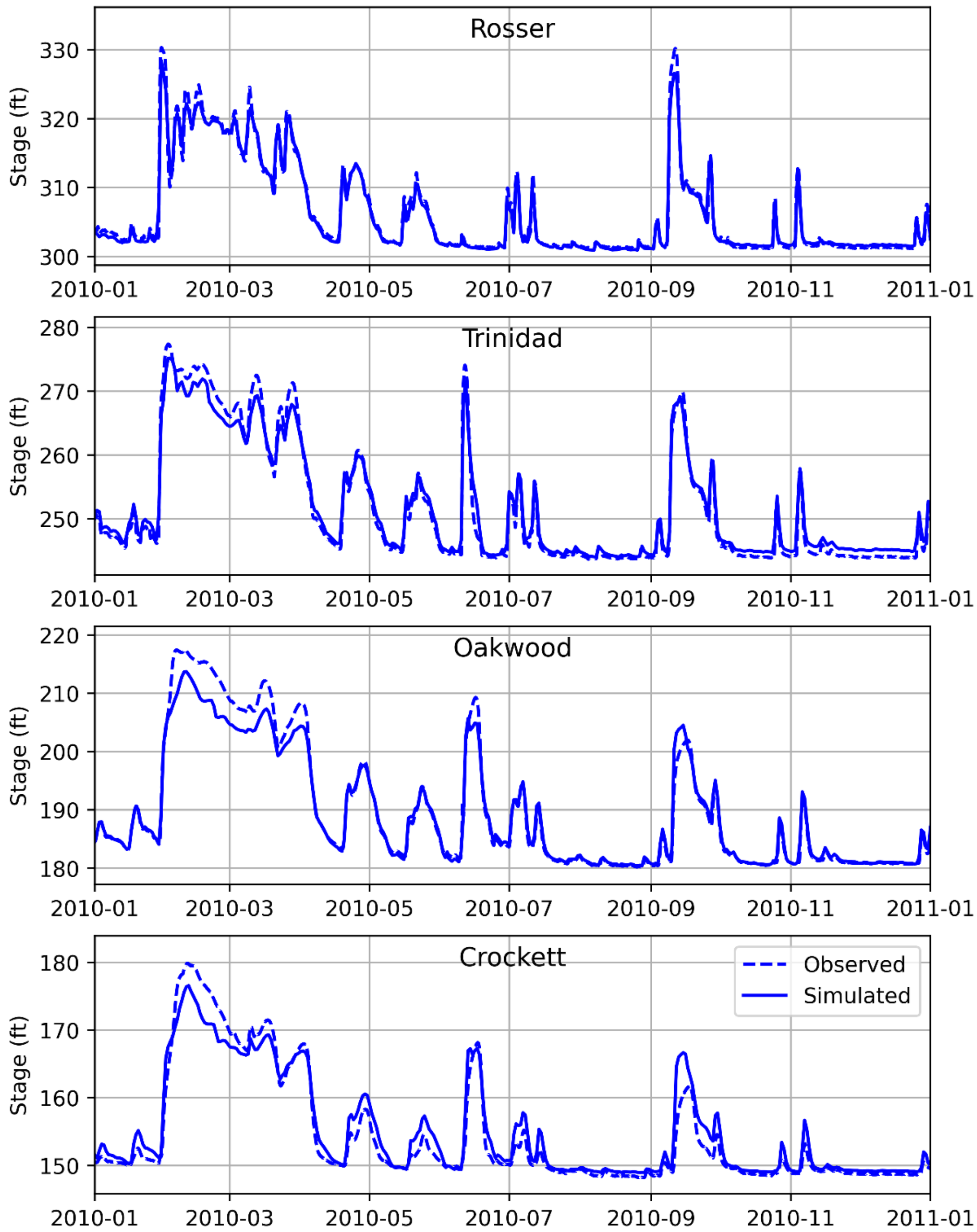

Figure 8: Comparison of observed and predicted stage for 2010 at four streamgage locations in Upper Model, shown in order from upstream to downstream. This represents 1 year of results from the 5-year calibration period (2007-2011).

3.1.2 Lower Model Hydraulic Calibration Results

Boundary condition inputs for the Lower Model are visualized in time-series in Figure 9. Flows originating upstream during this time period vary from a minimum of about 1,000 cfs to a maximum of about 90,000 cfs. Intervening inflows (from drainage-area adjusted USGS gage data and estimated ungaged inflows) are dynamic during this time period, showing a range of flows similar to those in the Upper Model. Observed diversions at Luce Bayou were only made during the last two years of this period, and were usually about 100 cfs.

Figure 10 shows flow duration curves for the Lower Model calibration time period at each of the gage locations. A wide range of flow conditions are experienced during this time period, indicating that it is suitable for a hydraulic and sediment calibration. The median flow for this time period is shown to range from about 3,000-4,000 cfs. Flows greater than 10,000 cfs occur for about 30% of this time period. Flow duration curves for this reach are considerably different from those for the Upper Model calibration period, likely because of flow regulation occurring at Lake Livingston dam.

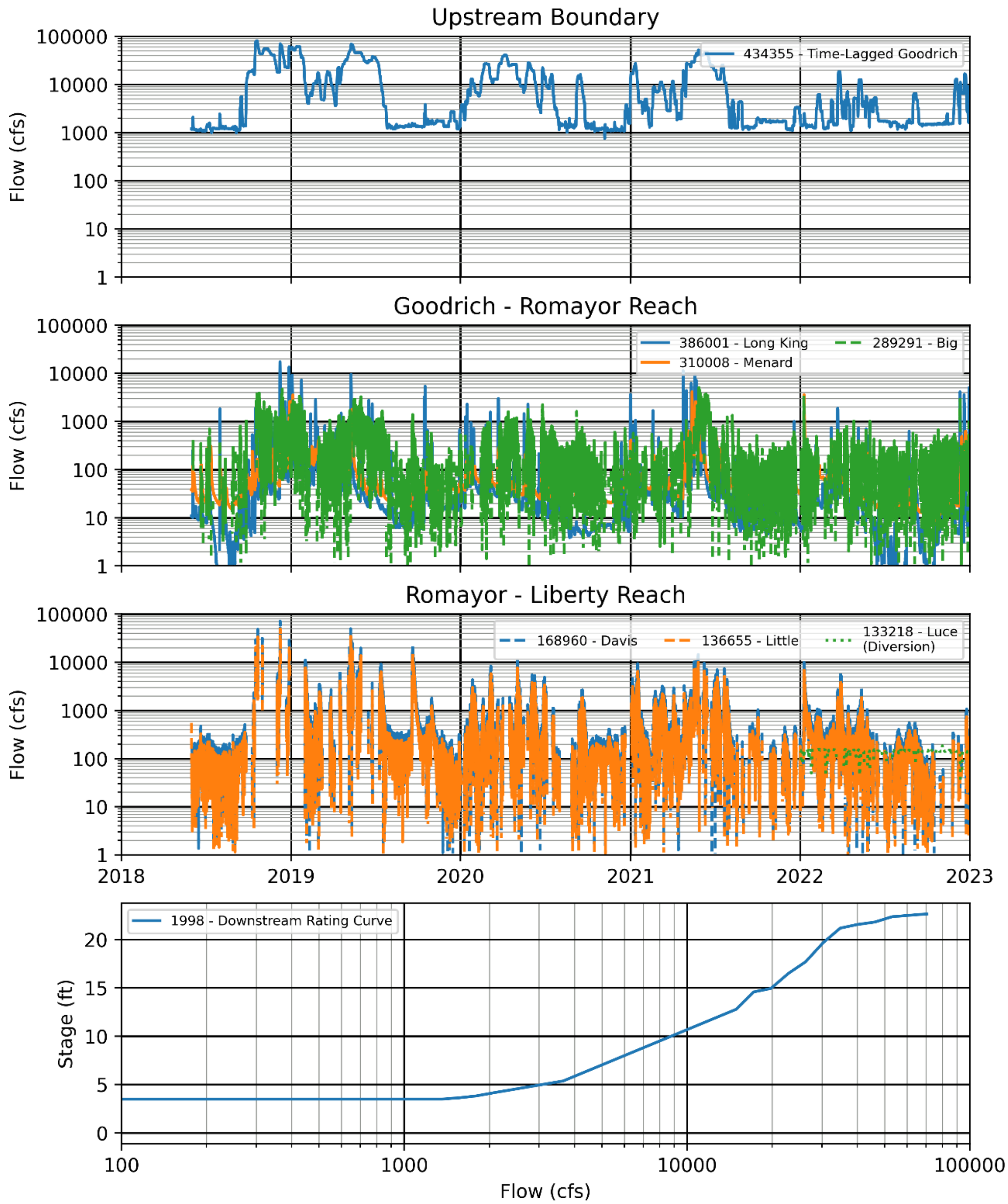

Figure 9: Model boundary condition inputs for Lower Model, grouped by model region. Upstream and tributary flows calculated from USGS flow series with time-lags and drainage area adjustments implemented are shown as solid lines. Estimated ungaged lateral inflows are shown as dashed lines. Diversions are shown as dotted lines and are informed by observation data provided by diverter. Downstream boundary condition is a rating curve boundary informed by USGS Liberty and Moss Bluff gage observations.

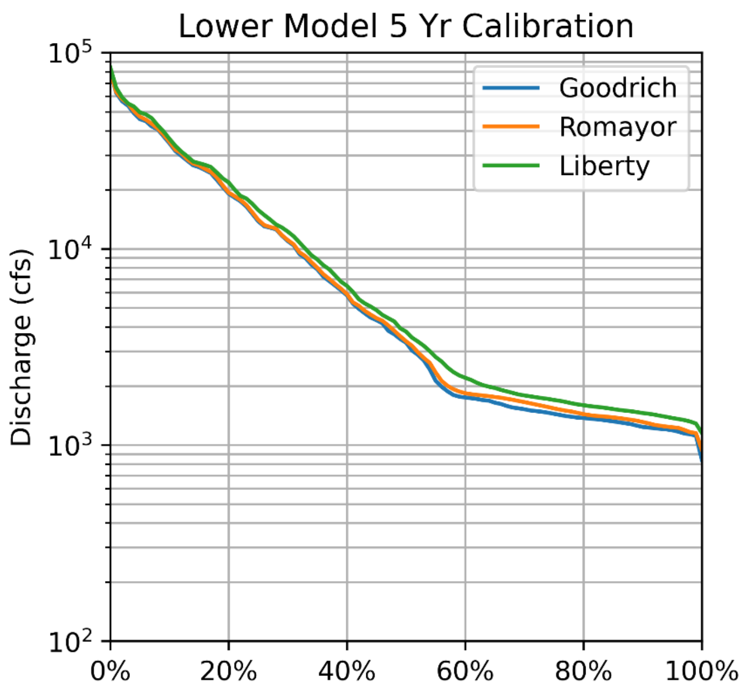

Figure 10: Flow duration curves at gage locations for Lower Model 5-year calibration period (mid-2018-2022). Note that the Goodrich location essentially represents incoming flows at the upstream boundary of the model.

We were also able to satisfactorily calibrate the Lower Model hydraulics for the purposes of creating a reasonable sediment model. Predicted and observed stage and flow values at USGS Goodrich, Romayor and Liberty streamgage locations for the Lower Model for one of the five simulated years are shown in Figure 11 and Figure 12. The other four years of the five-year period show similarly well-calibrated hydraulics. As shown in Figure 11, timing of flows in the Lower Model is close to that shown in the observed dataset, and flow magnitudes are quite closely matched for all flows at Romayor and for all but high flows at Liberty. The relatively-worse flow calibration at Liberty is likely due to difficulties associated with setting ineffective flow areas and levees in the low-gradient downstream portion of the river. Predicted stage matched closely (within ~1 ft) for most medium flows. During some high flows, stages could be off by as much as 2.5 ft, with some of this effect likely reflecting a mismatch in flow translating to lower stages. Stage calibration for low flows was quite good at Liberty, but was consistently off by ~3 feet at the Romayor gage. This stage mismatch at the Romayor gage was difficult to diagnose, but is likely due to there being somewhat of a gap in available bathymetric data at this location and the absence of the bridge from the model. Stage calibration results are summarized in Table 6. Overall, the hydraulic calibration of the Lower Model is demonstrated to be good considering the size of the model and the range of flows that need to be run for sediment model calibration. It was deemed acceptable for the sediment modeling tasks of 1) sediment calibration and 2) running sediment model scenarios.

Table 7: Approximate average difference in ft between observed and simulated stage for approximate ranges of flows at gage locations in LowerModel. Low = 0-5,000 cfs; Medium = 5,000-10,000 cfs, High = 10,000-50,000 cfs.

Flow Range	Goodrich	Romayor	Liberty
Low	-	-3	-.5
Medium	-	+1	-1
High	-3	-1	-2

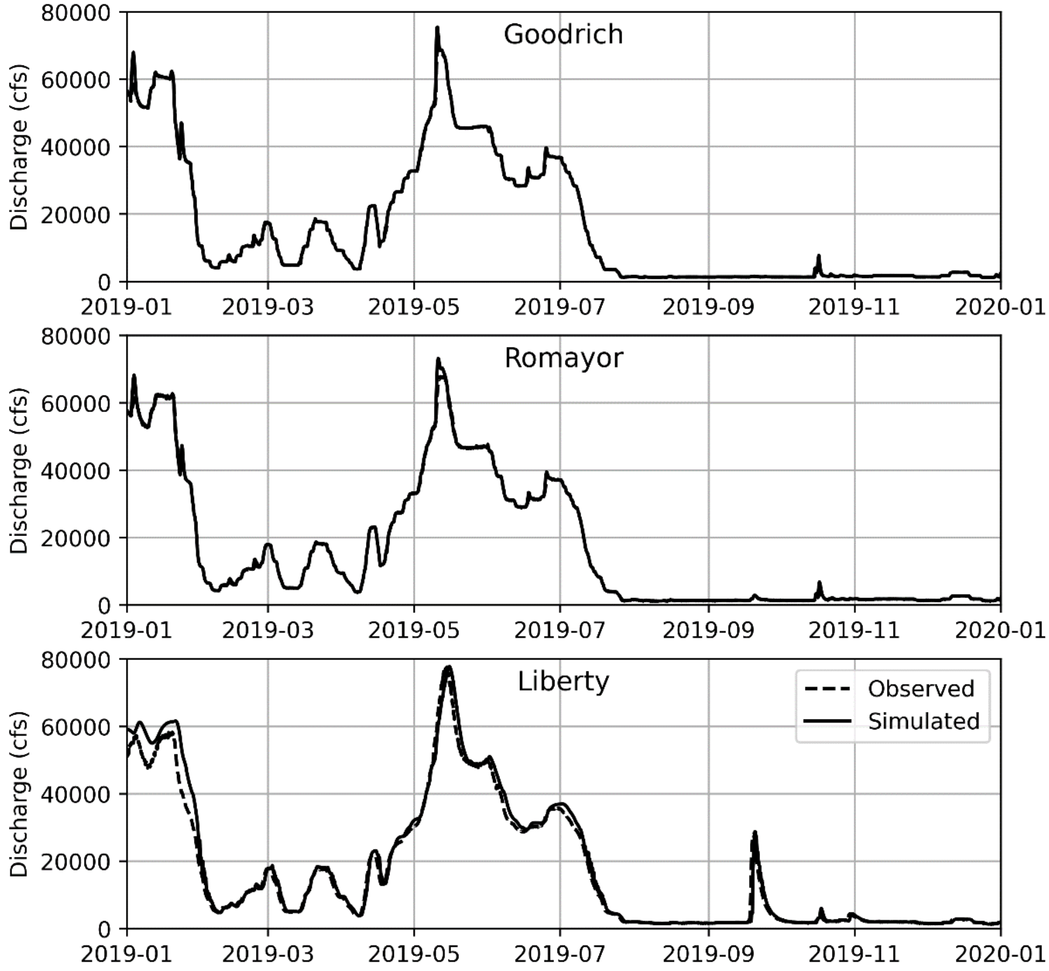

Figure 11: Comparison of observed and predicted discharge for 2019 at three streamgage locations in Lower Model, shown in order from upstream to downstream. This represents 1 year of results from the 4.5-year calibration period (2013-2018).

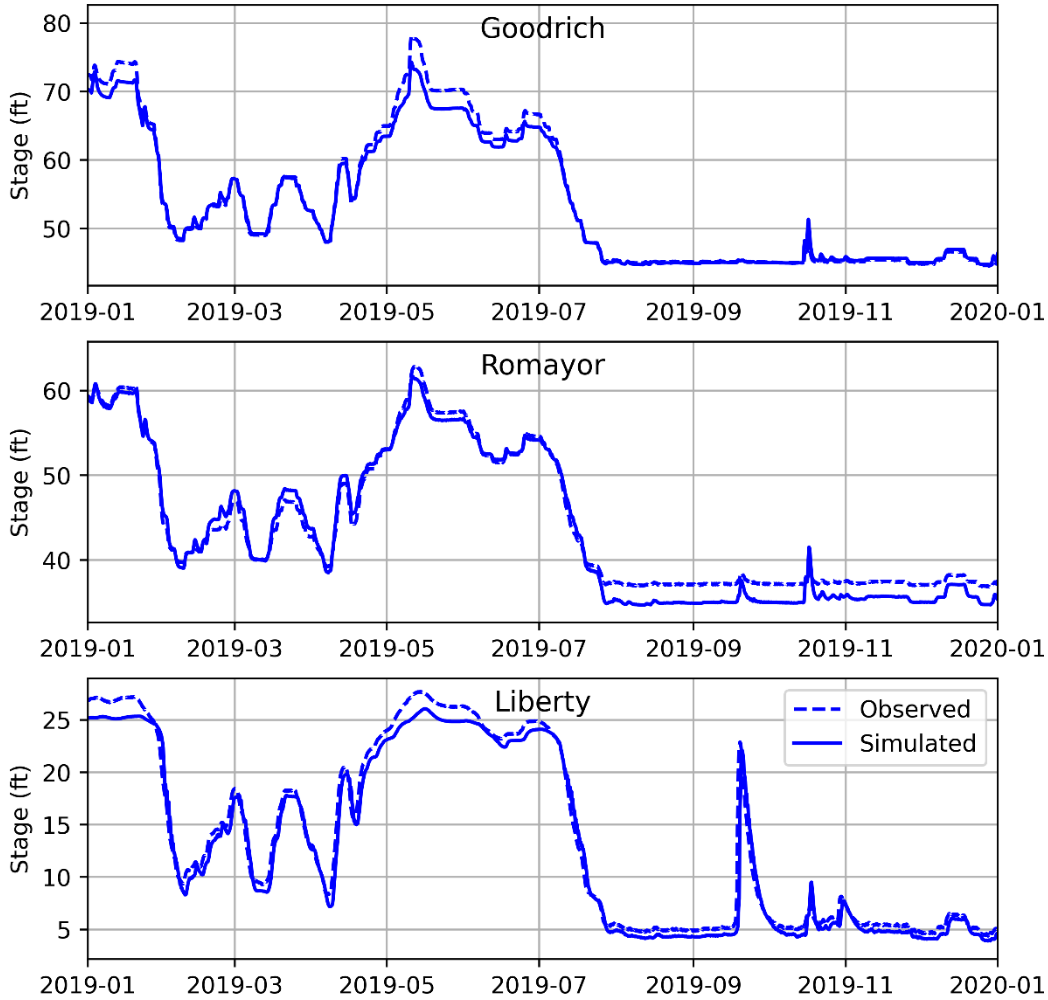

Figure 12: Comparison of observed and predicted stage for 2019 at three streamgage locations in Lower Model, shown in order from upstream to downstream. This represents 1 year of results from the 4.5-year calibration period (2013-2018).

3.2 Sediment Calibration

Approximately the same process was used to develop and calibrate both sediment transport models. Required sediment model inputs include:

- Modeled processes and functions used to represent processes
- Sediment inputs
- Bed gradation
- Mobile bed extent

Since the models are portions of the same river and represent systems that are not all that different, the Upper and Lower sediment Models shared many similar features, including the representation of sediment processes in the model and the methods used to initialize the model. Due to the relatively large size and high flows of the Trinity River, sediment in the clay and silt size range were assumed to be washload. Accordingly, sediment smaller than the Very Fine Sand bin (0.0625 – 0.125 mm) was not represented in either model for the sake of simplicity and model speed (by reducing the number of calculations).

Modeled sediment processes were represented the same way in both models. The Laursen-Copeland transport function was used because it is widely applicable over a wide range of sediment sizes and outperforms other transport functions down to the Very Fine Sand size (Gibson & Sanchez, 2020). The Thomas (Ex5) sorting method was used in both models, which is the default bed sorting method. The Rubey fall velocity method was also used in both models, which was the default method in the version of HEC-RAS that was used at the beginning of this project. The Continuity sediment routing method was used in both models. Global bed change was set to allow veneer deposition on the mobile bed and the wetted portion of the channel outside of the mobile bed and to allow erosion only on the mobile bed. This is a common global bed change representation for 1D models of large rivers that experience overbank flow with deposition in the floodplain like the Trinity.

The initial bed gradation for both the upper and Lower Models was established using a spin-up model. The spin-up model ran hydraulics representing the effective discharge of the channel for three years. The sediment model inputs were specified for this spin-up model such that:

1. A minimum elevation 1 ft below the existing channel bathymetry was used to define the lower extent of the erodible bed sediment. This was done in an attempt to fix the existing channel bathymetry and force gradations to adjust themselves to the existing channel bathymetry.
2. A uniform initial gradation was set for every cross-section in the model as a starting point for the bed gradation. This uniform initial gradation, shown in Figure 13, needed to be varied for the Upper and Lower Models to aid in calibration and model stability. The Upper Model initial gradation consists of more than 90% sand-sized particles and was taken from a representative bed sample collected in an earlier phase of this work and used in smaller Phase 3 sediment models of the Upper Model

Study Region (Mangham, McKnight, Osting, Southard, & Flores, 2020). The Lower Model initial gradation was made systematically coarser until the 3-year spin-up model yielded a set of initial gradations that could run all the way through the scenarios.

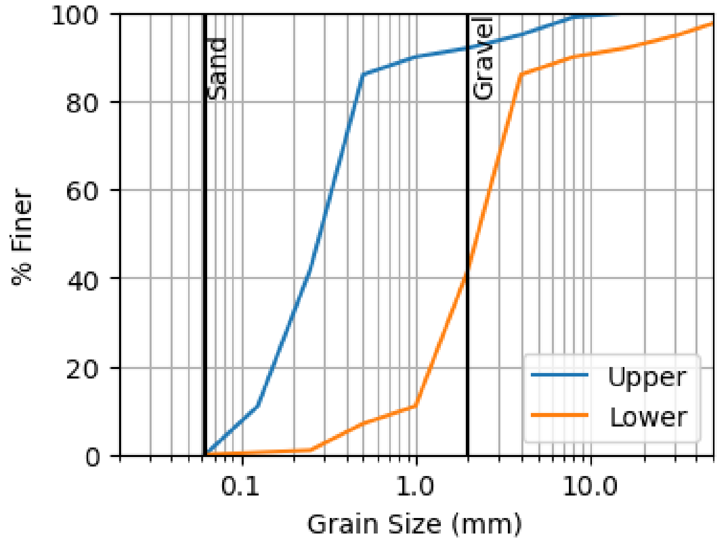

Figure 13: Initial gradation used in Upper and Lower sediment spin-up models.

For the Upper Model, where the majority of flow and sediment came from the upstream boundary, the effective discharge hydraulics was represented as the following:

- 1513706 (Upstream Boundary) – 11,102 cfs

For the Lower Model, where the upstream boundary has no bed load due to the presence of the dam, it was important to include tributary flows from some of the larger tributaries in order to introduce some sediment to the model. Here, the effective discharge hydraulics were represented as the following:

- 434355 (Upstream Boundary) – 11,000 cfs
- 386001 (Long King) – 1,500 cfs
- 310008 (Menard) – 1,500 cfs
- 289291 (Big) – 1,000 cfs

Another important parameter that must be specified for every cross-section is the mobile bed extent. Due to the fact that erosion is only allowed in the channel, per the global bed change settings, the mobile bed extent controls what portion of the cross-section can erode and is an important parameter. For both models, the mobile bed extent was manually specified to be well within the channel bank stations from the geometry file, according to the recommendations in the 1D Sediment Transport User Manual (Gibson & Sanchez, 2020).

3.2.1 Upper Model Sediment Transport Calibration

The Upper sediment transport Model was created for the period 1/1/2008 – 12/31/2012 so that it encompassed five years of flows, including high and low flow events. The model was run as a hot-start model that utilized bed sediment gradation outputs from the spin-up model as its bed sediment gradation inputs. This step was necessary because of the large size of the model domain and relative lack of high-resolution bed grain size distribution data.

Extensive sediment data was available for the Upper Model from four USGS streamgages:
1. USGS 08062500 – Rosser
2. USGS 08062700 – Trinidad
3. USGS 08065000 – Oakwood
4. USGS 08065350 – Crockett

A sediment sampling study from University of Houston (UH) that was mostly focused on suspended sediment was also available (Strom & Hosseiny, 2015). The sediment transport model was calibrated iteratively by choosing values from these data sources to define the incoming sediment load rating curve and gradations, running the combination of the 3-year effective discharge spin-up model and the 5-year hot-start model, viewing results, and accordingly adjusting the incoming sediment load rating curve and gradations. Various boundary condition implementations were tried in this process that combined:
1. USGS total and suspended load rating curve data;
2. USGS bed gradation data;
3. UH bed material load data; and
4. Equilibrium load and gradation data calculated in HEC-RAS

It is often necessary to define sediment loads associated with intervening inflows to achieve a reasonable and stable sediment transport model – introducing significant flows without also introducing sediment can cause erosion of the mainstem bed by increasing transport capacity without adding sediment to fill that capacity. Although incoming sediment loads were thought to be a less important source of sediment in the Upper Model Study Region than in the Lower Model Study Region, we did include sediment inflows at all intervening inflows. Comparison of USGS streamgage and UH sediment observations at the four streamgage locations along the length of the river, shown in Figure 14, did not indicate any major changes in transported sediment load along the length of the mainstem before the river enters Lake Livingston. Additionally, no data was available to help identify sediment loads from tributaries in this reach. For this reason, we decided that an appropriate assumption would be to simply apply the same upstream boundary rating curve and gradations at each of the tributaries, in an effort to retain the flow/load relationship that is represented at the upstream boundary as more flow is introduced into the system from tributaries.

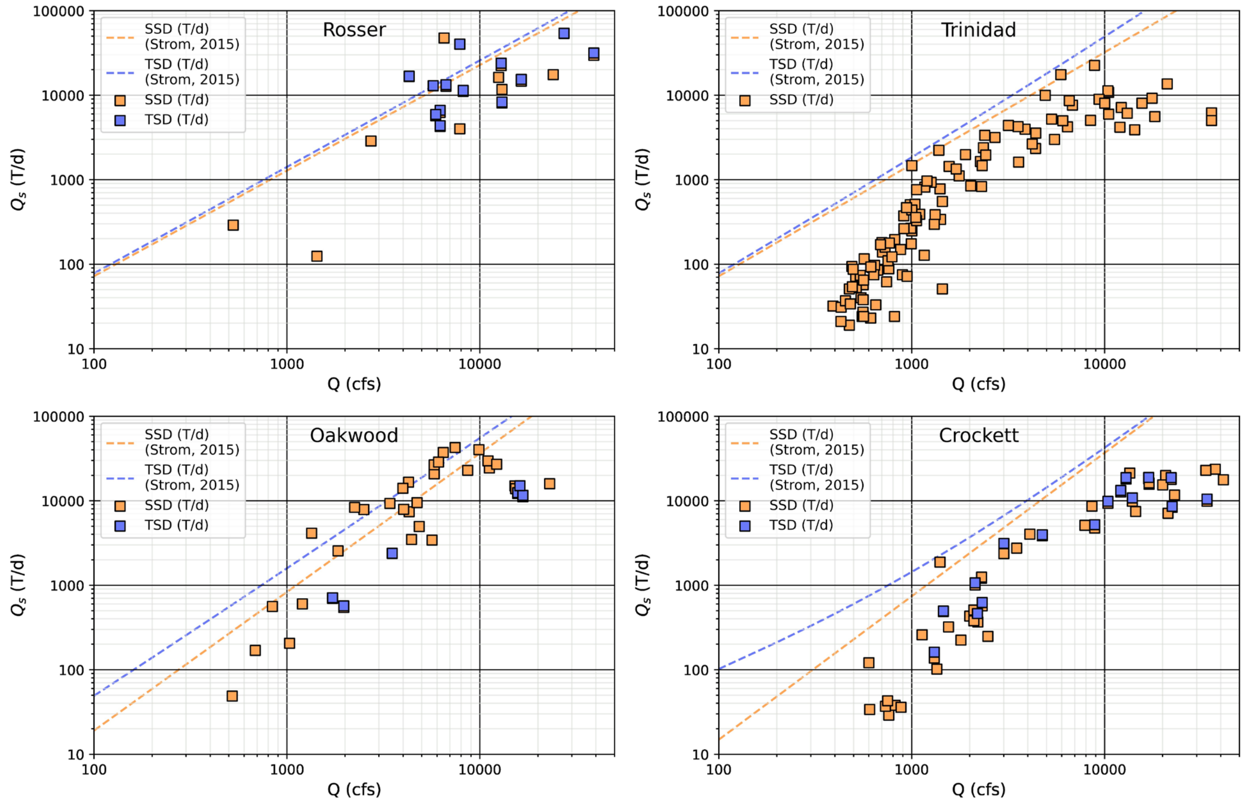

Figure 14: Comparison of 1) UH-calculated (Strom & Hosseiny, 2015) suspended sediment discharge (SSD) rating curve, 2) UH-calculated (Strom & Hosseiny, 2015) total sediment discharge (TSD) rating curve, 3) USGS SSD observations, and 4) USGS TSD observations at four Trinity River streamgage locations in Upper Model reach.

Ultimately, the configuration that achieved the most stable bed at the end of the calibration period was a combination of an adjusted UH bed sediment load rating curve equation and gradations determined from equilibrium load calculations in HEC-RAS. This rating curve and gradation is shown in Figure 15, and zero load is specified for 100 cfs. To determine the load for any flow, HEC-RAS interpolates between the flow-load-gradation points provided as the boundary condition. Almost all of the sediment inputs defined by this rating curve are in the sand-sized range.

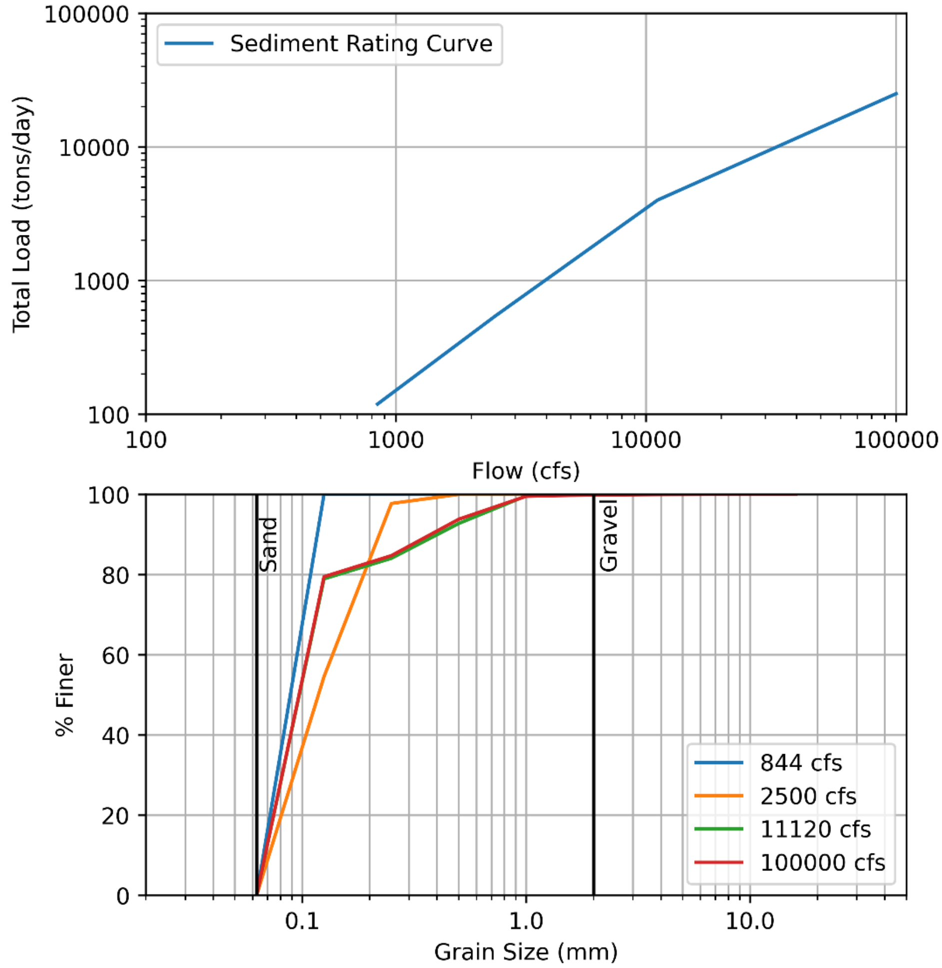

Figure 15: Upper Model incoming sediment load boundary condition applied at all model inflows. Top: Rating curve defining relationship of bed load to flow for incoming flows. Bottom: Gradations defining grain size distributions of incoming sediments at various flows.

Modeled sediment rating curve results for the Upper Calibration Period Model are shown in Figure 16. Results indicate that the load being supplied at the upstream boundary is quickly deposited out at the upstream end and is not replenished by lateral inflows of sediment. For flows below 5,000 cfs, the modeled sediment load decreases significantly by the Rosser cross-section and continues to decrease in the downstream direction. Modeled sediment load is similar to the upstream boundary condition for flows above 5,000 cfs at Rosser, but decreases by about 80% at the Trinidad cross-section and by at least an order of magnitude at the Oakwood and Crockett cross-sections. Below the Trinidad cross-section, peak loads during this period are only about 1,500-3,000 tons/day, compared to the 15,000 tons/day that is observed at the upstream boundary and the Rosser location.

These observations are supported by load duration curves, shown in Figure 17. The minimum load at the upstream boundary was about 40 tons/day, but loads are shown to be essentially negligible (<1 ton/day) with a frequency of about 15% at Rosser, 50% at Trinidad, and 60% at both Oakwood and Crockett locations. Modeled loads greater than 1,000 tons/day occurred about 20% of the time at the upstream boundary and the Rosser location, but less than 5% of the time at all the other streamgage locations. Loads greater than 100 tons/day were also observed less than 20% of the time at the Trinidad, Oakwood and Crockett locations.

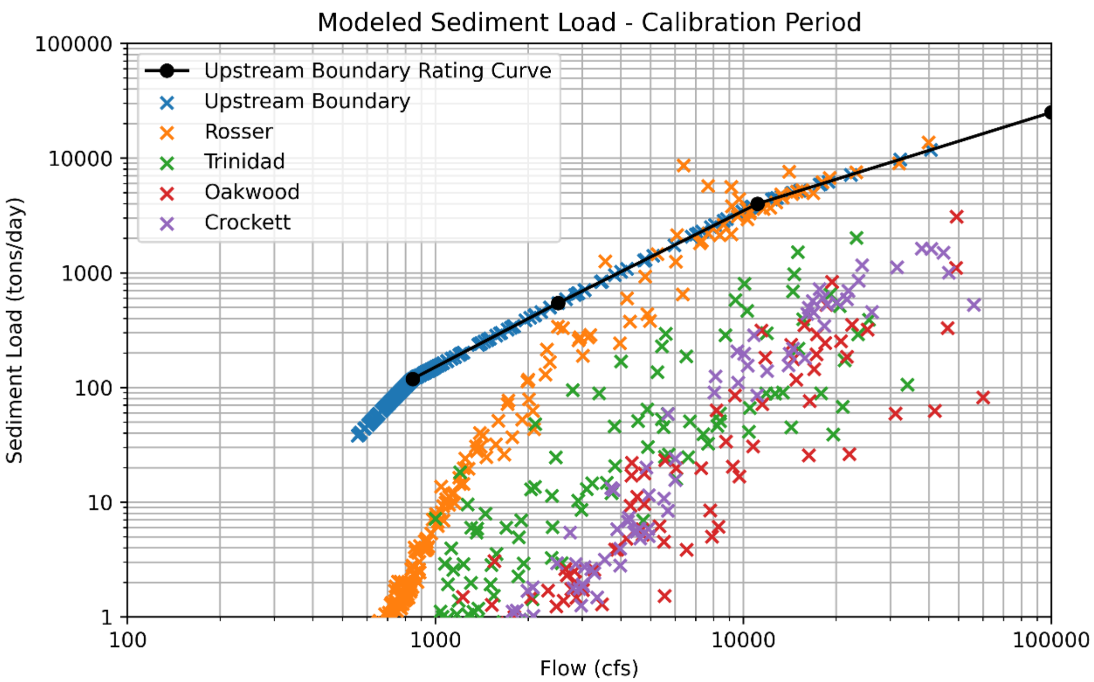

Figure 16: Modeled sediment load at Upstream boundary and streamgage locations compared to imposed upstream boundary/lateral inflow sediment rating curve for the Upper Calibration Period Model.

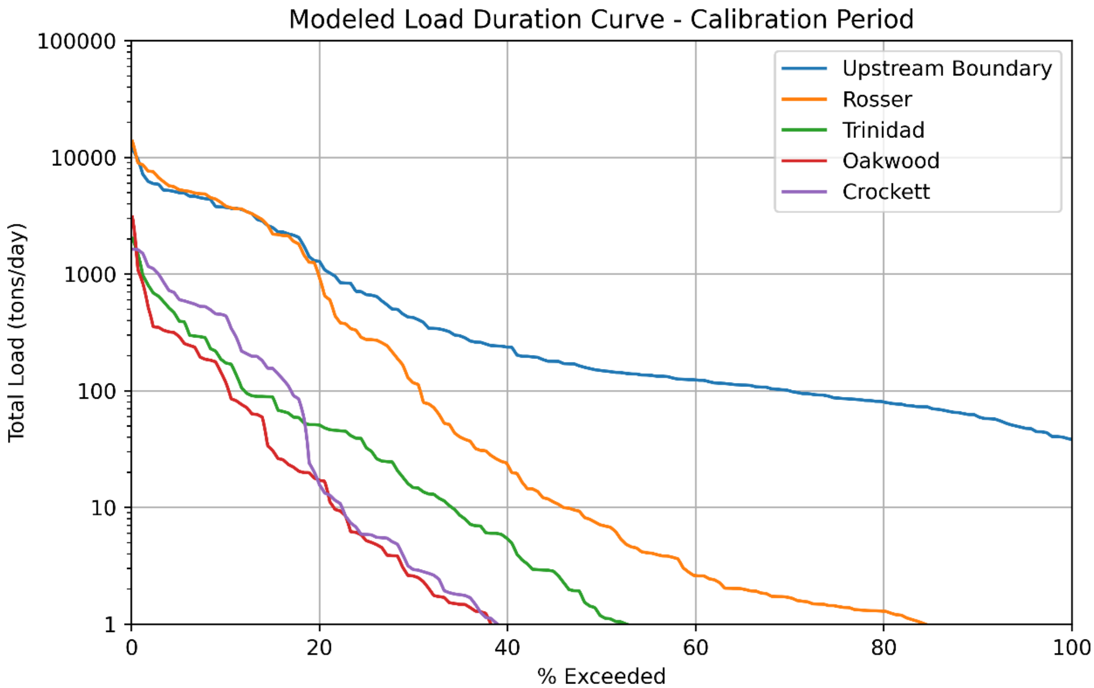

Figure 17: Associated Flows are provided in Figure 6.

Net invert change results for the Upper Calibration Period Model show net aggradation in the reach between the upstream boundary and the Trinidad location as shown in the first panel of Figure 18. Net erosion greater than 0.1 ft was only observed at 6 out of 193 cross-sections. The average net deposition in this reach was 0.54 ft and 157 out of 194 cross-sections showed net deposition of more than 0.1 ft. Several cross-sections in this reach showed more than 2 ft of net deposition, one of which was the upstream-most cross-section where flows and sediment loads enter the model. Invert changes are fairly continuous at the very upstream end of this reach, indicating that some load is still present in low flows, but this effect decreases in the downstream direction. By the Rosser location, much of the load at low flows has clearly been deposited out, and the time series plots of invert change have become more stepped with invert changes primarily occurring only at higher flows.

Net invert change results show progressively more net erosion moving downstream in the two reaches below the Trinidad location, shown in the second and third panel of Figure 18. The average net invert change was -0.06 ft in the Trinidad – Crockett Reach and -0.24 ft in the Crockett – downstream boundary reach. In the Trinidad – Crockett reach, 105 out of 288 cross-sections showed net deposition of more than 0.1 ft, compared to only 31 showing net erosion of more than 0.1 ft. However, several cross-sections in this reach showed more than 2 ft of erosion, leading to net erosion in the reach. The erosion signal was stronger in the Crockett – downstream boundary reach, with 69 out of 208 cross-sections showing more than 0.1 ft of net erosion and only 17 showing more than 0.1 ft of net deposition. Time series plots of invert change in the Trinidad – Crockett reach are mostly stepped, and only a few cross-sections have a smooth profile that indicates any invert change occurring at low flows. For the Crocket – downstream boundary reach, invert change is clearly only happening during periods of high flow.

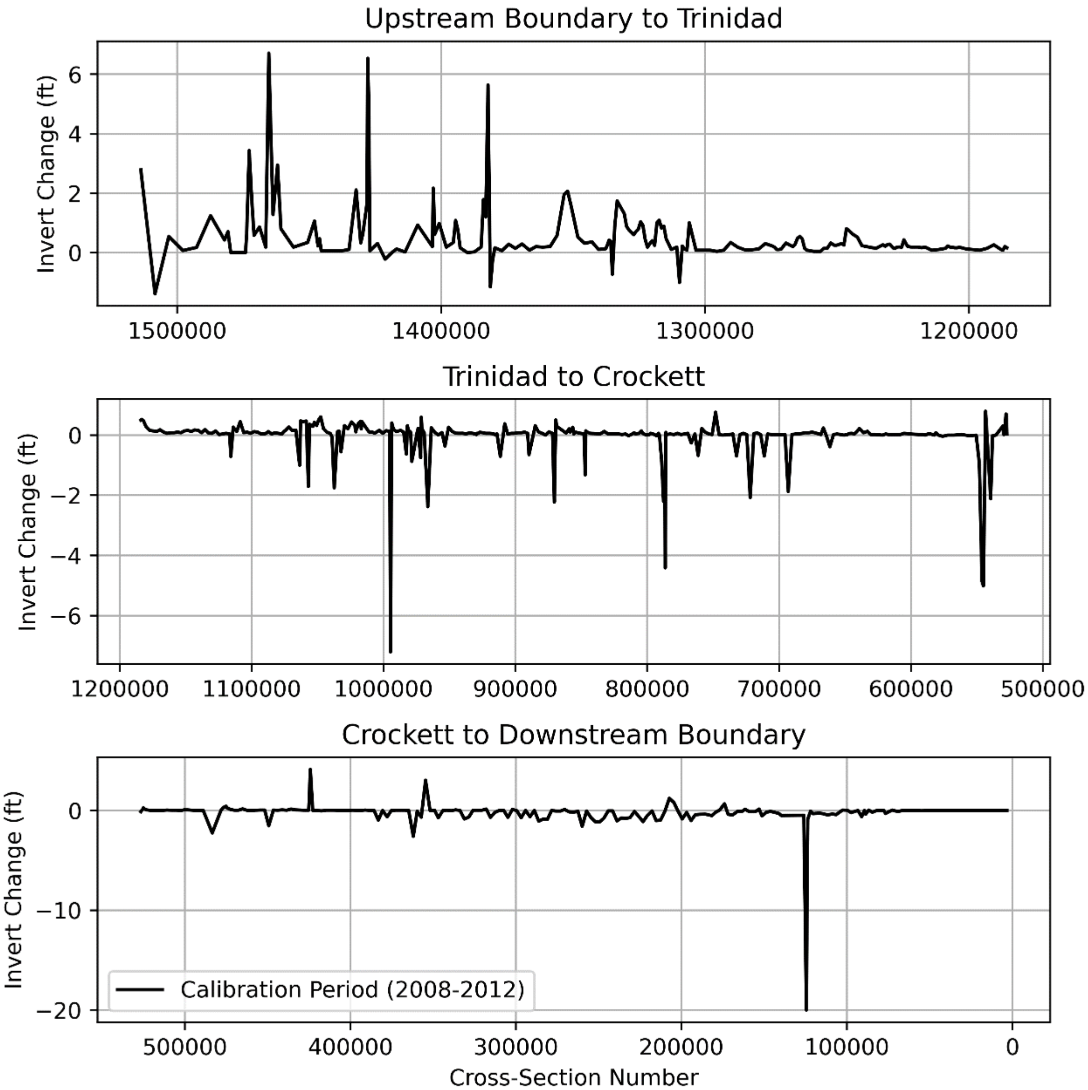

Figure 18: Modeled net invert change (ft) for the Upper Calibration Period Model.

These results are also shown in the reach-averaged invert change vs. flow results in Figure 19. Sediment transport is generally shown to be more active in the reach between the upstream boundary and the Rosser location, with both net erosion and net deposition occurring for flows below about 20,000 cfs and mostly net erosion occurring for flows above that. The reach between the Rosser and Trinidad locations shows mostly net deposition, but there are some periods of net erosion during flows greater than 20,000 cfs. In the reach between the Trinidad and Oakwood locations, flows below about 20,000 cfs generally cause negligible change or, in some cases, some net deposition, and higher flows cause net erosion. For the reaches between the Oakwood location and the downstream boundary of the model, low flows generally cause negligible invert change and flows above 20,000 cfs cause significant net erosion.

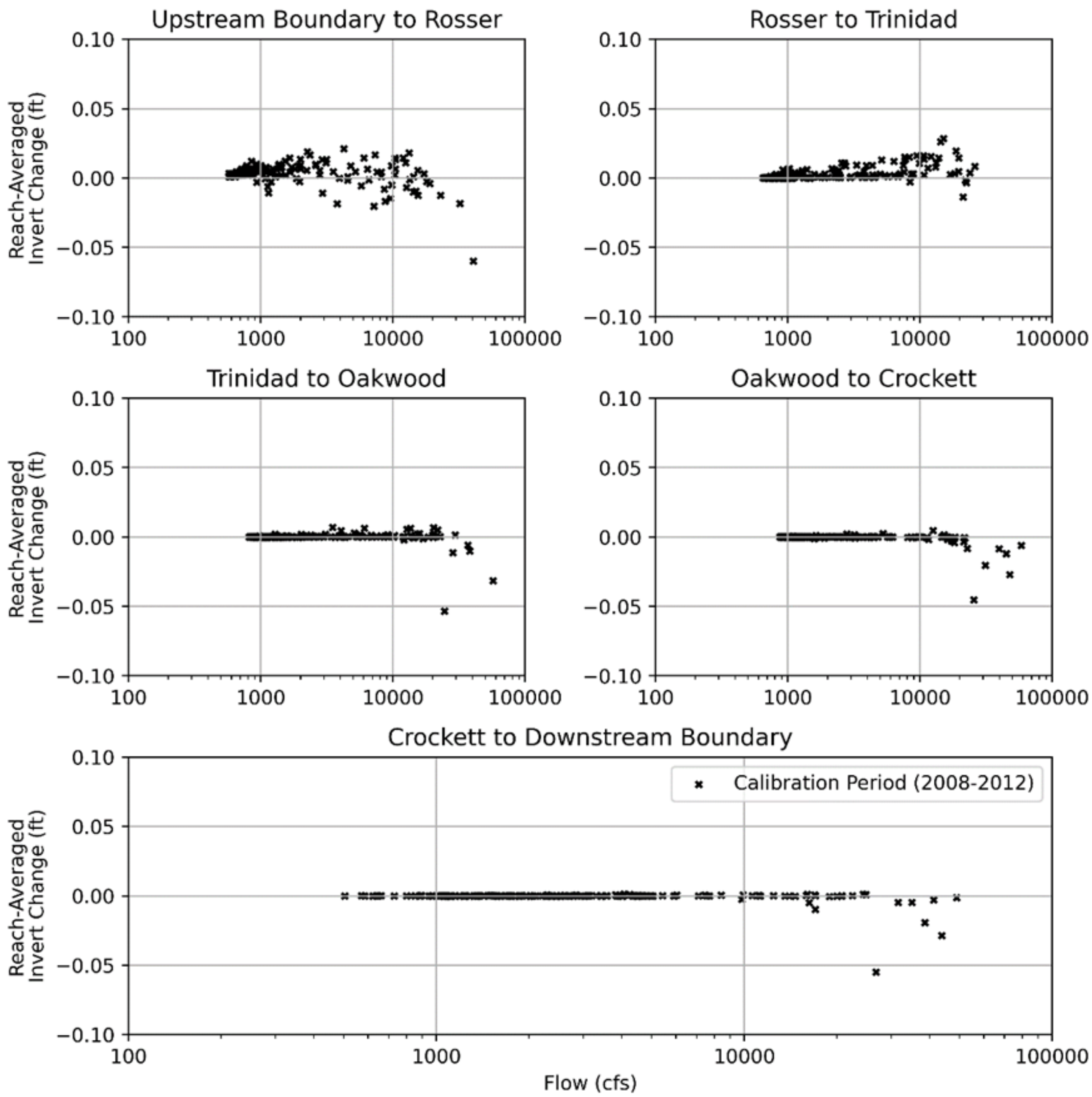

Figure 19: Reach-averaged invert change (ft) vs. Flow in reaches between boundary/streamgage locations for Upper Calibration Period Model. Invert change was output at every computational increment, and is accordingly presented as a rate of ft of invert change per 10 days.

3.2.2 Lower Model Sediment Transport Calibration

The Lower sediment transport Model was created for the period 6/1/2018 – 12/31/2022. We were unable to identify a full five-year period of flows that included high and low flow events due to data gaps at some of the gages. This calibration period, slightly more than 4.5 years long, was the best calibration period available. This model was also run as a hot-start model for the same reasons as in the Upper Model. We initially attempted to use the same initial gradation for the spin-up model as we used in the Upper Model, but this established a bed that rapidly eroded in hot-start model runs and especially in the WAM Flows scenario hot-start model runs. To address this, we iteratively increased the gradation used to initialize the spin-up model until the hot-start model bed was stabilized due to armoring.

Sediment data was available for the Lower Model from three USGS streamgages:

1. USGS 08066250 – Goodrich
2. USGS 08066500 – Romayor
3. USGS 08067000 – Liberty

The UH study did not extend to this portion of the river and so there is significantly less information on bed sediment load. Additionally, only the USGS streamgage at Romayor included information on total suspended sediment load, the other two only had suspended sediment information. The sediment transport model was again calibrated iteratively by choosing values from these data sources to define the incoming sediment load rating curve and gradations, running the combination of the 3-year effective discharge spin-up model and the 4.5-year hot-start model, viewing results, and accordingly adjusting the incoming sediment load rating curve and gradations. Various boundary condition implementations were tried in this process that combined USGS total and suspended load rating curve data and USGS bed gradation data.

There is no incoming bed sediment load at the upstream end of the model because of the presence of the Livingston Dam. Therefore, it was crucially important to define sediment loads associated with intervening inflows in this area to provide any incoming sediment load to the model. We included sediment inflows at intervening inflows towards the upper end of this model. We did not include sediment inflows for inflows Davis Bayou and Little Bayou, because they were towards the lower end of this model where gradients were low and because they were downstream of all of our available information on bedload data. The sparseness of sediment data made creation of a conceptual model for bed sediment difficult. Comparison of USGS streamgage observations at the three streamgage locations along the length of the river, shown in Figure 20, does not provide much information about longitudinal changes due to the fact that bed sediment information is only available at the Romayor streamgage location, but does have sufficient information to identify an observed rating curve and gradations for the Romayor gage location that we can target with our parameterization of incoming sediment load at model boundary conditions. No data was available to help identify sediment loads from tributaries in this reach, so an assumption was required to set the sediment contributions from tributaries. To do this, we divided the total load at the Romayor gage by their portion of the total tributary drainage area. Then, we iteratively varied the set of flows associated with the new load-gradation points until a stable model that did a reasonable job of recreating the flow-load-gradation at the Romayor gage was achieved.

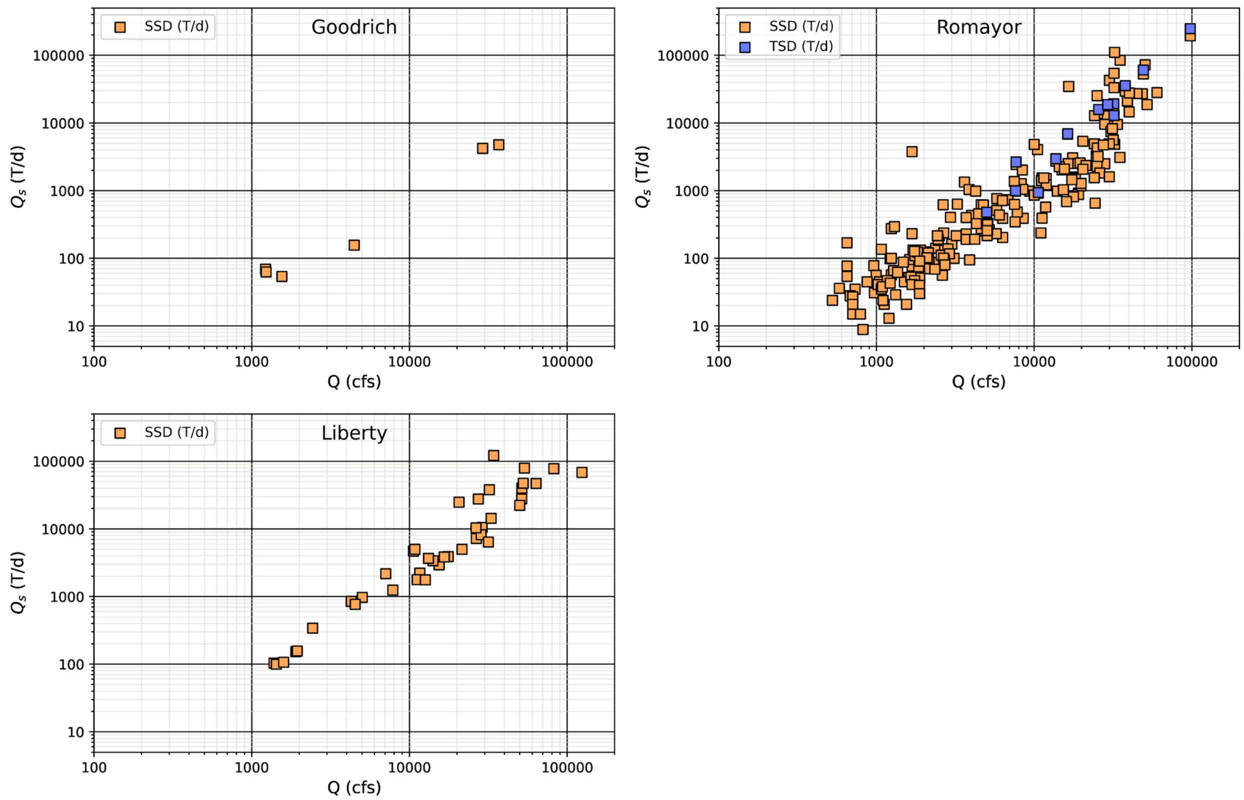

Figure 20: Comparison of 1) USGS suspended sediment load observations, and 2) USGS total sediment load observations at three Trinity River streamgage locations in Upper Model reach.

Selected calibrated rating curves and gradations for tributaries are shown in Figure 21, and zero load is specified for zero cfs, since the tributaries experience significantly lower flows than the mainstem of the river. Iterative runs were performed to tune the lateral sediment inflows to calibrate them to the Romayor rating curve information, but we could ultimately only increase them so much before they caused model instabilities from deposition occurring where the lateral inflows entered the mainstem. The conceptual model of this reach is that significant amounts of sediment are sourced from the channels own bed and banks and that net erosion is occurring downstream of the dam.

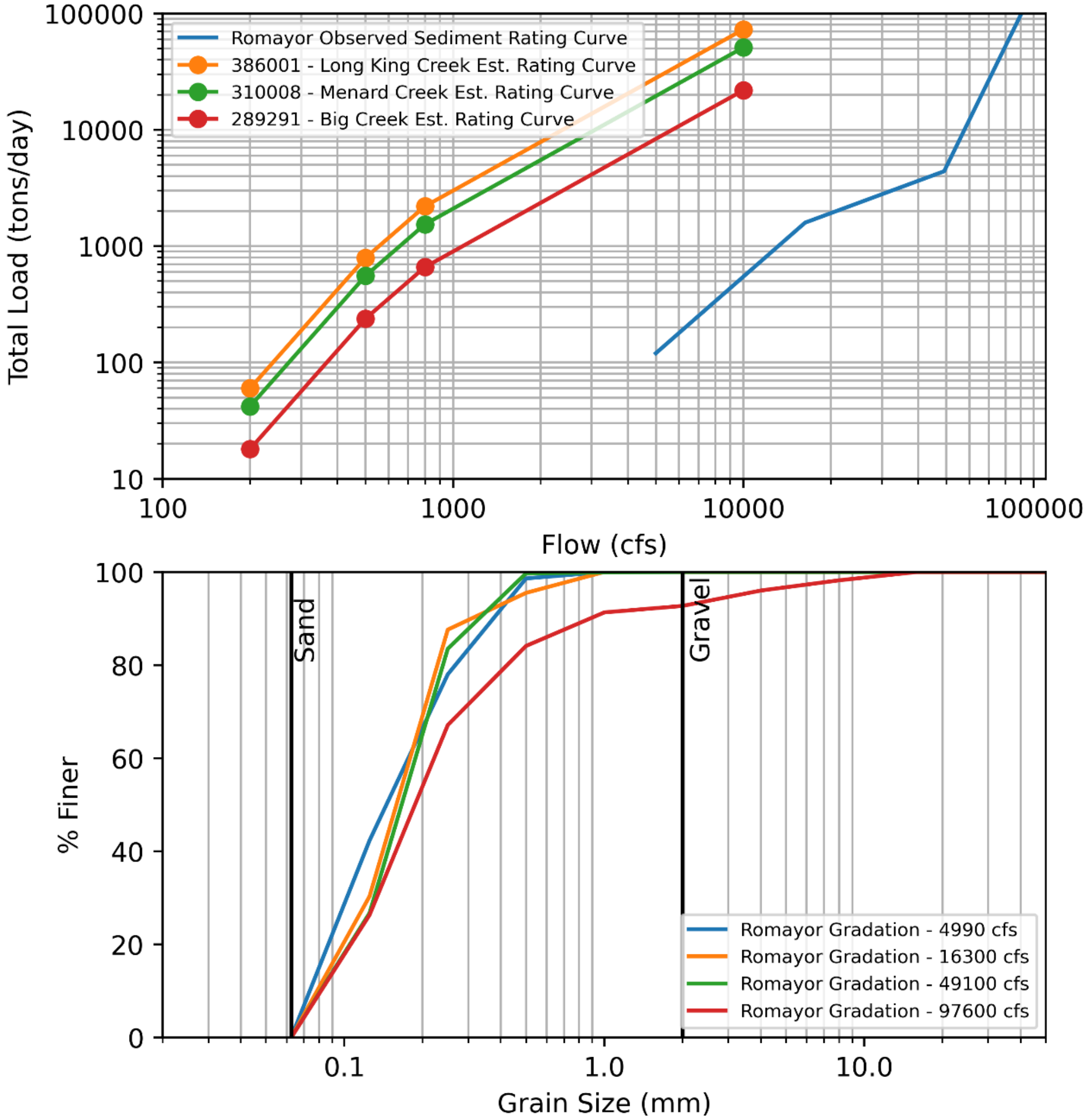

Figure 21: Top: Observed bed load rating curve from USGS Romayor gage and Lower Model incoming sediment load boundary conditions for three major tributary inflows. Bottom: Gradations defining grain size distributions of incoming sediments at various flows. Main numbers identify associated flow for observed bed load gradation at USGS Romayor Gage. Numbers in legend identify flow associated with this gradation for Lower Model tributary sediment inflows.

Modeled sediment rating curve results for the Lower Calibration Period Model are shown in Figure 22. No information about bed sediment load is available for Goodrich or Liberty streamgage locations, so it is difficult to assess the calibration in areas of the model other than the central portion near Romayor. The modeled load results at Romayor, for flows less than about 40,000 cfs, are significantly smaller than the estimated Romayor rating curve, at times by almost an order of magnitude. Results at the Goodrich location indicate a few timesteps where flow-load points are close to the estimated Romayor rating curve. These results may indicate that the model's configuration of sediment inflows at tributaries, although implemented to be as high as could be achieved while prioritizing model stability, is not capable of supplying enough sediment to the channel to match the Romayor rating curve. The fact that modeled loads at the Goodrich location occasionally match the Romayor rating curve, however, also shows that there are times where deposition in the channel is a more likely culprit for any mismatch between modeled and observed sediment load. For the most part, modeled load for a given flow peaks at the Romayor location and is lower at Goodrich and Liberty, with a few exceptions. The load decreases between the Romayor and Liberty locations is likely due to a combination of deposition and clear water lateral inflows from low-gradient bayou tributaries that exist downstream of any bed sediment data observations and thus could not be calibrated.

These observations are supported by load duration curves, shown in Figure 23. The minimum load at the Romayor Location was about 3 tons/day, and the load was shown to be essentially negligible (<1 ton/day) about 10% and 55% of the time at the Goodrich and Liberty locations, respectively. Modeled loads greater than 1,000 tons/day occurred about 8%, 13%, and 3% of the time at the Goodrich, Romayor, and Liberty locations, respectively. Modeled loads greater than 100 tons/day occurred about 23%, 30% and 17% of the time at the Goodrich, Romayor, and Liberty locations, respectively. The peak load during the calibration period was about 15,000 tons/day at the Romayor location, which is similar to USGS observations at this location (reflected in the Romayor rating curve).

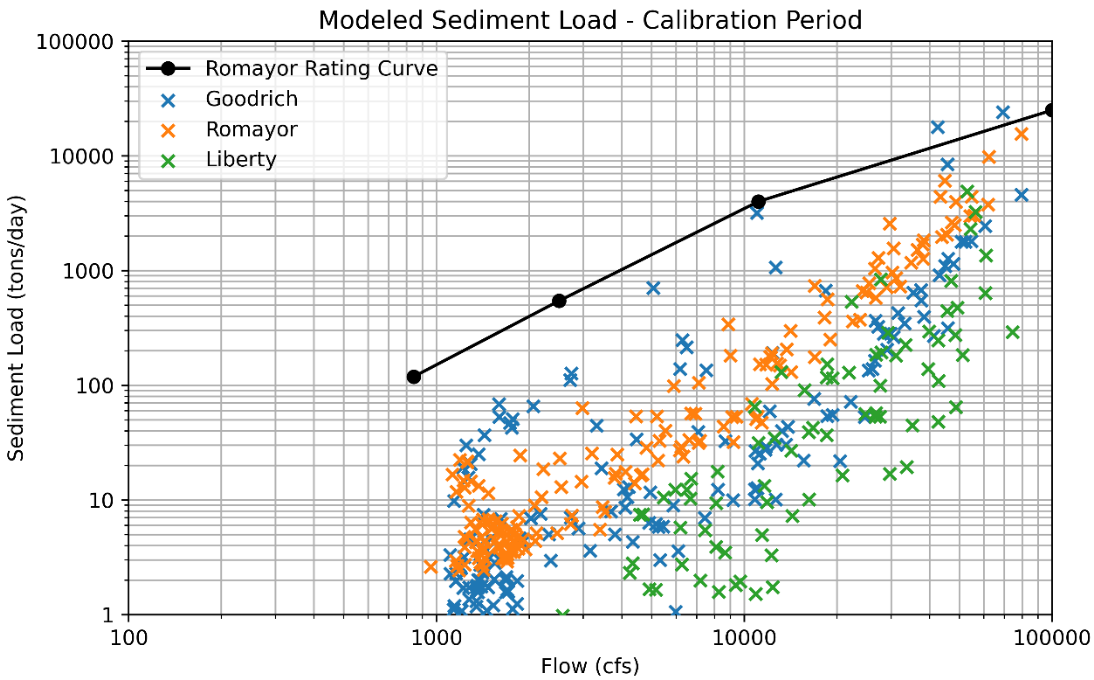

Figure 22: Modeled sediment load at streamgage locations compared to Romayor sediment rating curve estimated from observed data for the Lower Calibration Period Model. Note that upstream boundary is a clear water boundary condition due to the presence of the dam.

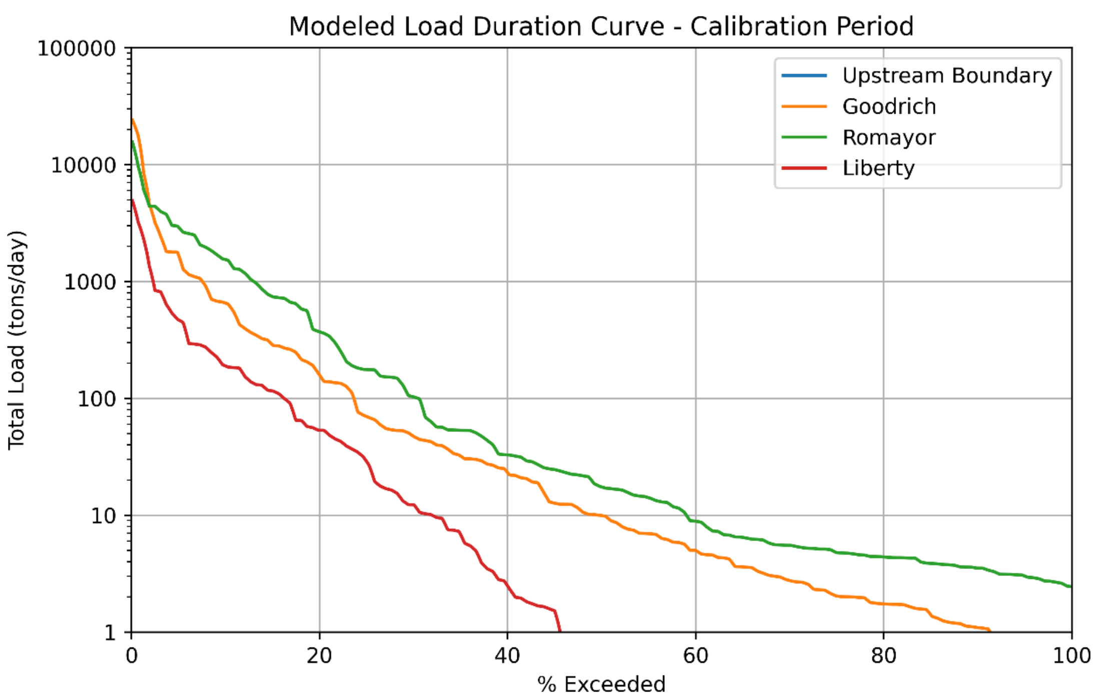

Figure 23: Modeled load duration curves at streamgage locations for the Lower Calibration Period Model. Note that upstream boundary is a clear water boundary condition due to the presence of the dam. Associated Flows are provided in Figure 10.

Net invert change results for the Lower Calibration Period Model show net erosion throughout the model reach, as shown in Figure 24. For the reach between the upstream boundary and the Romayor location, net deposition greater than 0.1 ft was only observed at 13 out of 122 cross-sections. The average net invert change in this reach was -0.24 ft and 43 out of 122 cross-sections showed net deposition of more than 0.1 ft. Several cross-sections in this reach showed more than 1 ft of net deposition. The reach between the Romayor location and the downstream boundary was similar, with an average net invert change of -0.22 ft. In this reach, more cross-sections experienced net deposition of more than 0.1 ft than experienced net erosion of more than 0.1 ft, but several cross-sections eroded more than 1 ft. Invert changes are fairly stepped at the upstream end of the model, indicating that sediment transport is only occurring at high flows. This makes sense given the clear water upstream boundary. For the portion of the model downstream from the first tributary to the Romayor gage, the time series plots of invert change are more continuous, indicating that sediment transport is occurring more frequently and at lower flows. Time series plots of invert change at the downstream end of the model were, again, often stepped, indicating that sediment transport was mostly occurring during high flows.

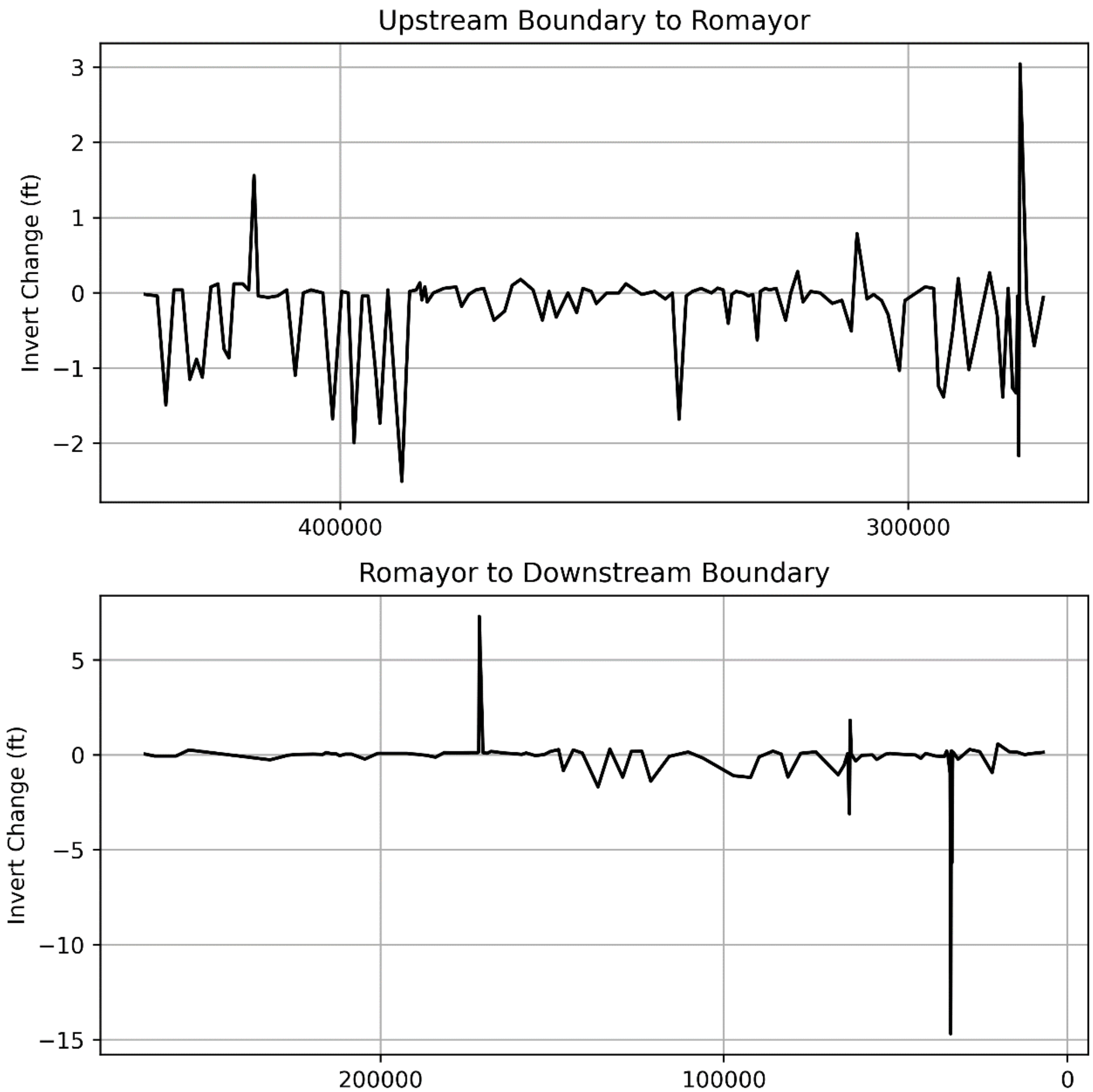

Figure 24: Modeled net invert change (ft) for the Lower Calibration Period Model.

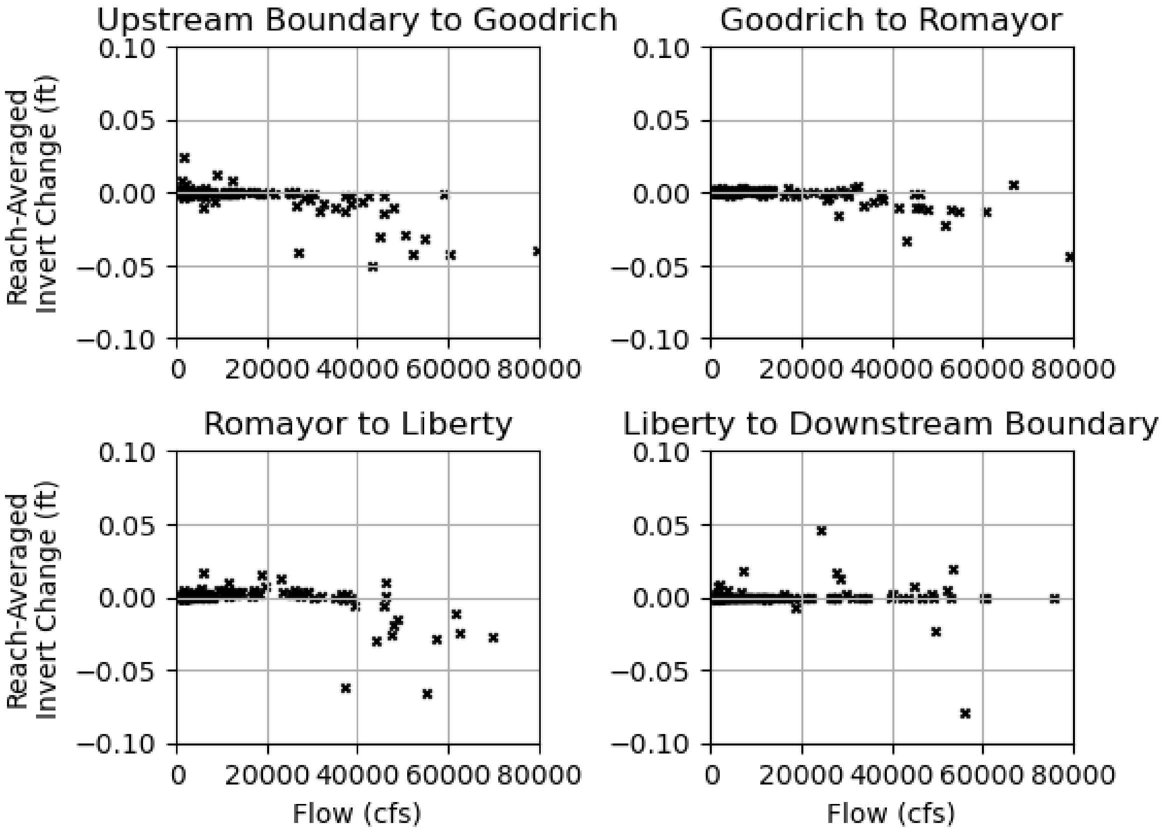

Figure 25: Reach-averaged invert change (ft) vs. Flow in reaches between boundary/streamgage locations for Lower Calibration Period Model. Invert change value is incremental between timesteps, and represents the change in invert elevation over a 10-day period.

4 Subtask 2: Suspended Sediment Data

At the beginning of this project, in 2021, we worked collaboratively with TRA staff to define a work order with the USGS for new sediment data that could potentially supplement sediment transport models. USGS completed the project and provided discharge, sediment and other field parameter data for five sites on the Trinity River and within the sediment modeling study area for this project (USGS, 2021).

Ultimately, this data was not used in the sediment modeling effort. Much of this data was suspended sediment data, and we ultimately opted to exclude suspended sediment from our modeling because it was not important for project goals. The only data available from this study that was pertinent to the project was bedload gradation data from 5 samples that were accompanied by streamflow measurements, but not to any bedload discharge measurements. Of this, two samplings were made at the Rosser streamgage that did not include the whole sample because of the maximum diameter of sieve used, and three samplings were made at the Liberty streamgage that did include the whole sample. Data from the Rosser streamgage was not used in favor of using more complete information from the UH sediment study report (Strom & Hosseiny, 2015) and historical sediment data. Data from the Liberty streamgage could not be tied to any bedload discharge measurements, which were also not available in historical data, and thus was not used as a calibration target. For the Lower Model, the Romayor streamgage had far more available and complete data that was used for calibration purposes.

5 Subtask 3: Scenario Development and Analysis

5.1 WAM Scenario Hydraulics

The goal of the scenario modeling was to use the calibrated sediment models to identify breakpoints in sediment processes across a spectrum of flows and locations by modeling up to three hydrologic scenarios. We identified TRA's Run 3 Compact Mod, described in detail in a report from a previous phase (Mangham, Osting, & Flores, 2017), of the Trinity River monthly WAM as an appropriate baseline set of flows. This model represents full utilization of water rights at their priority dates – a "worst case scenario" from a water availability and instream flows standpoint for the current permitting state of the basin. In order to produce the three required hydrologic scenarios, TRA staff ran the Run 3 model as is and then made two additional versions of the Run 3 Compact Mod WAM where return flows were either 1) increased by 50% (High WAM Flows) or 2) decreased by 50% (Low WAM Flows) (Modified from (Texas Commission on Environmental Quality).

To produce HEC-RAS hydrologic inputs from WAM model outputs, we first needed to spatially disaggregate monthly regulated flows from WAM outputs to all of the model boundary conditions, including the upstream boundary and any tributary inflows. We calculated monthly regulated intervening inflows between control points by subtracting monthly regulated flow at the upstream control point from monthly regulated flow at the downstream control point. Monthly regulated intervening inflows could be either positive or negative. In order to match the spatial representation of the calibrated model system as closely as possible, we identified the same set of tributaries used for the calibration model as points for input of any positive intervening inflows. We divided up the intervening monthly regulated inflow between all of the tributaries by multiplying it by the ratio of each tributary's drainage area to the total tributary drainage area of that reach. We identified uniform lateral inflows stretching all along the reach between control points as single points for withdrawal of any intervening inflows when they were negative.

WAM outputs are at a monthly timestep, which typically isn't appropriate for sediment modeling – sediment processes vary greatly with flows, and representing flow with a monthly average value and wiping out the peaks and valleys stored in daily data would not represent the system well. To address this, we utilized daily unregulated flow data stored in the input files for the daily WAM (Mangham, Personal Communication: Daily WAM Input Files, 2023) to disaggregate all of our monthly regulated flow values into daily flows. To do so, we multiplied the monthly regulated flow at model boundary by the ratio of daily unregulated flow to monthly unregulated flow at the control point representing the upstream end of the model. This did a sufficient job of approximating daily flow patterns for the basin such that the model experienced a full range of low to high flows.

This ultimately represented the best possible approach to estimating daily inflows for all model boundary conditions, but due to things like flow lag times, the presence of large diversions, and the assumption of the peak daily hydrograph being applied for all boundaries, there were periods where the model predicted very low or zero flow in the channel. While zero flow could obviously crash a hydraulic model when the channel fully dried, this source of instability is significantly more of a concern in a sediment simulation. This is because the sediment model assumes that the channel has filled with sediment and terminates any time the channel fully dries at a cross-section, and this often gets triggered at low flows in the process of the model trying to solve even when a non-zero-flow solution would eventually be obtained by the solver. We opted to solve this issue in our hydraulics to stabilize the model with the following workflow, which varied slightly between the Upper and Lower Models.

1. First, we checked every day to see if inflows were less than diversions.
2. On days where they were:
    a. We turned off all diversions in the model for the next 30 days.
    b. We set the flow at the upstream boundary to X cfs for the next 10 days. In the Upper Model, we set X = 100. In the Lower Model, we set X = 200.
3. This got most of the periods of instability, but due to the length of the model and the effect of lag times, there were still a few when we ran the model. For these dates, we also applied this same low flow specification starting on the day before the HEC-RAS model crashed from the low flow instability.

Although the WAM runs stretch from 1940-1996, we opted to run a fifty-year period starting on 1/1/1940 and ending on 12/31/1989. At the lowest computational timesteps that we were able to achieve, this still represented multiple days of computer runtime for each model, and this time period was deemed sufficiently long to achieve the research goals of this project.

5.1.1 Upper Model Hydraulic Inputs and Results

The configuration of boundary conditions and representation of flow at each cross-section for the Upper Model is detailed in Table 8. Neither of the major diversions from this reach that we wanted to include are included sufficiently for our purposes in the WAM model. The Wetlands diversion represents reuse amounts and cannot be pulled out of WAM water right diversions outputs. Instead, we specified a constant daily diversion in cfs that equated to its annual authorized amount of 210,000 AFY (Texas Water Commission). Because this is specifically reuse water, we also added in this amount at the upstream boundary on top of the amounts calculated from WAM regulated flow values. The Huntsville diversion is also not straightforward – the City of Huntsville contracts with TRA to divert a portion of the water from one of their water rights. In the WAM model, this water right was spatially represented on Livingston, instead of on the mainstem where the diversion occurs in the real world. For these reasons, it was again appropriate to specify the Huntsville diversion as a constant daily diversion in cfs that equated to the City's contracted amount of 29,146 AFY (Mangham, Personal Communication: Huntsville Contracted Diversion Amount, 2023).

The downstream boundary of the model extends part of the way out into Lake Livingston when the lake level is high, but not to the deepest point of the lake. Some periods where Lake Livingston was low would cause instability at the downstream end of the model because the elevation of the lake was near or below the channel invert at the downstream boundary. We identified a minimum lake elevation of 96 ft and forced this as the minimum value in the Livingston stage series used as a downstream boundary condition.

Table 8: Inflow Configuration for Upper Model Scenario Runs. Fill color indicates whether boundary condition at each location is an upstream boundary flow series (yellow), a gage location that provided flow information but was not used as an actual model boundary condition (no fill), a lateral inflow (green), a lateral diversion (brown) or a downstream boundary (gray). Representation column indicates how flows were calculated from WAM outputs. Drainage Area was assessed using the NHDPlus HR dataset. Bold rows indicate points where data is available.

Boundary Name	XS	Representation	Drainage Area (mi2)
Upstream Boundary	1513706	WAM CP 8TRRS Plus Wetlands Diversion amount	-
Rosser Gage	**1468756**	**Equivalent WAM CP 8TRRS**	-
Village Creek	1413606	DA-Adjusted 8TRTR Minus 8TRRS Inflows	62.0
Bois d'Arc Creek	1387411	DA-Adjusted 8TRTR Minus 8TRRS Inflows	73.3
Cedar Creek Upper	1247379	DA-Adjusted 8TRTR Minus 8TRRS Inflows	253.6
Rosser – Trinidad Uniform Outflow	1468756 – 1184057*	8TRTR Minus 8TRRS Outflows	-
Trinidad Gage	**1184057***	**Equivalent WAM CP 8TRTR**	-
TRWD Wetlands Diversion	1127356	Uniform Daily Withdrawal 290 cfs (210,000 AFY of permitted diversions)	-
Rush Creek	1161541	DA-Adjusted 8TROA Minus 8TRTR Inflows	79.3
Cedar Creek Lower	1145783	DA-Adjusted 8TROA Minus 8TRTR Inflows	253.6
Richland Creek	1077070	DA-Adjusted 8TROA Minus 8TRTR Inflows	1,975.4
Tehuacana Creek	945331	DA-Adjusted 8TROA Minus 8TRTR Inflows	424.2
Catfish Creek	905808	DA-Adjusted 8TROA Minus 8TRTR Inflows	288.5
Keechie Creek	790974	DA-Adjusted 8TROA Minus 8TRTR Inflows	93.6
Trinidad – Oakwood Uniform Outflow	1184057* - 769166	8TROA Minus 8TRTR Outflows	-
Oakwood Gage	**769166**	**Equivalent WAM CP 8TROA**	-
Upper Keechi Creek	555808	DA-Adjusted 8TRCR Minus 8TROA Inflows	498.9
Big Elkhart Creek	550478	DA-Adjusted 8TRCR Minus 8TROA Inflows	141.4
Hurricane Bayou	530306	DA-Adjusted 8TRCR Minus 8TROA Inflows	104.6
Oakwood – Crockett Uniform Outflow	769166 – 526675	8TRCR Minus 8TROA Outflows	-

Boundary Name	XS	Representation	Drainage Area (mi2)
Crockett Gage	**526675**	**Equivalent WAM CP 8TRCR**	**-**
Huntsville Diversion	223198	Uniform Daily Withdrawal 40.25 cfs (29,146 AFY contracted from TRA)	-
Lake Livingston	**393**	**WAM Object LVN Storage converted to Elevation. Min Elev = 96 ft**	**-**

Flow inputs resulting from this calculation scheme are detailed in flow-duration curve form in Figure 26 for the baseline WAM scenario, to highlight the relative contributions/reductions from each model boundary condition. Implementation of the uniform withdrawal to reduce flow in the model between control points is generally shown to happen fairly infrequently (<= 20% of the time). In this scenario, the upstream boundary inflow was set to 100 cfs a little less than 10% of the time and modeled diversions were shut off about 20% of the time to help with model stability. Relative contributions from tributaries are proportional to their drainage area, as expected.

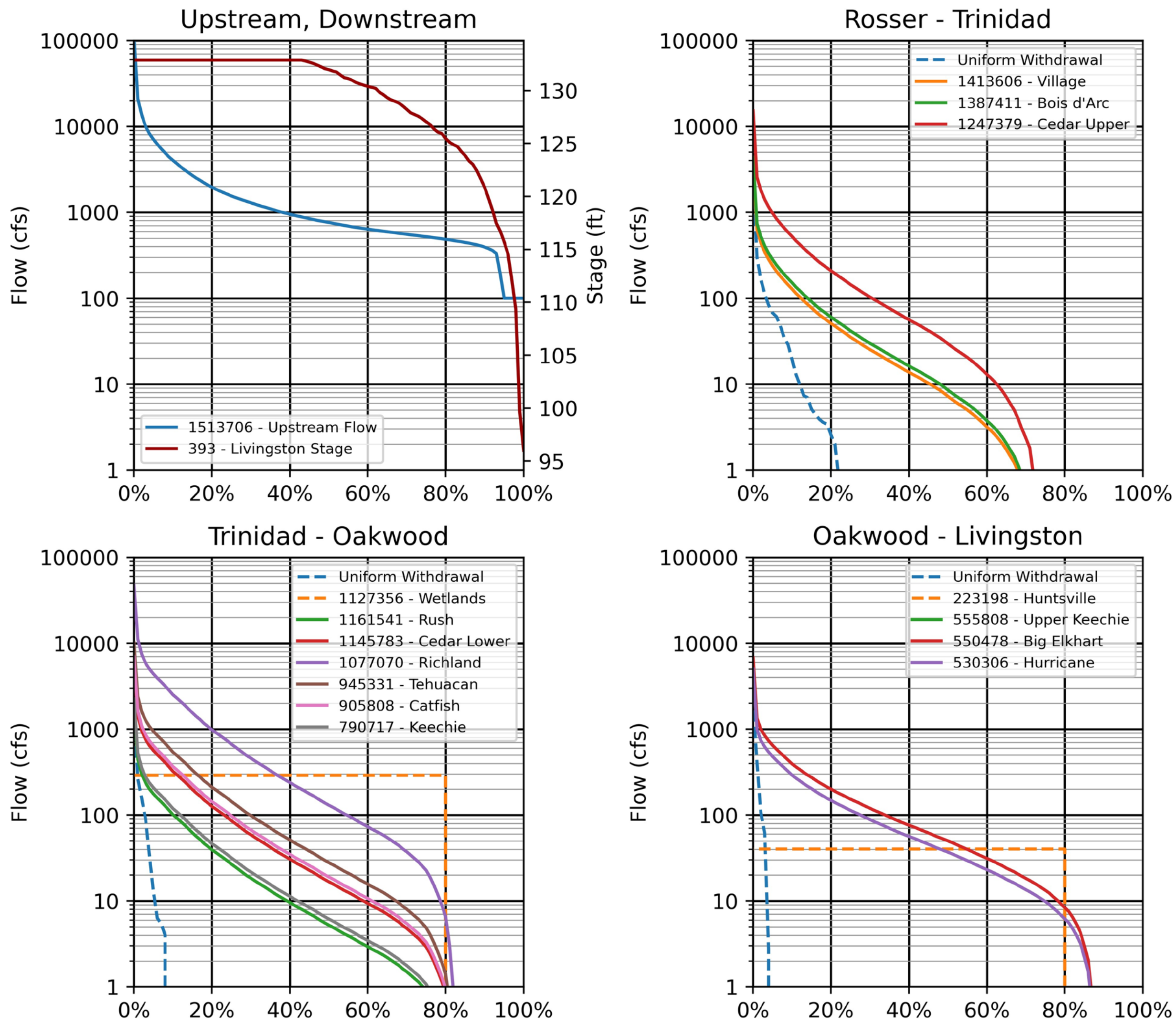

Figure 26: Flow duration curves for upstream boundary (top left), lateral in- and outflows between Rosser and Trinidad streamgage locations (top right), lateral in- and outflows between Trinidad and Oakwood streamgage locations (bottom left), and lateral in- and outflows between Oakwood and Livingston streamgage locations (bottom right). Solid lines represent inflows to the model and dashed lines represent outflows from the model. Stage duration curve for downstream boundary (top right).

Model flow outputs for the scenarios are shown in Figure 27. Percent exceeded values for the WAM Scenario hydraulic models are similar to those of the Calibration Period hydraulic model (Figure 6) for medium to high flows, which indicates that our disaggregation scheme is reasonable and that it is appropriate to apply the sediment input file set that was calibrated to observed flows to these hydraulic scenarios. Significant differences in flow duration can be observed between the three WAM Scenarios for flows in the range of 100-2,000 cfs, and durations appear to be negligibly different for flows higher than that. Generally, the difference in percent exceeded for a given flow was between 5 and 15% for the Low WAM Flows and the High WAM Flows scenarios. At all of the streamgage locations, the difference in the median flow between the Low WAM Flows and the High WAM Flows scenario was about 200 cfs, with the Baseline WAM Flows scenario located squarely in between the two.

The observed differences in flows between scenarios were deemed sufficient for study of flow breakpoints where sediment processes change. The minimum flow for all scenarios was as low as possible without sacrificing model stability, and all have periods where the minimum flow at the upstream boundary was 100 cfs.

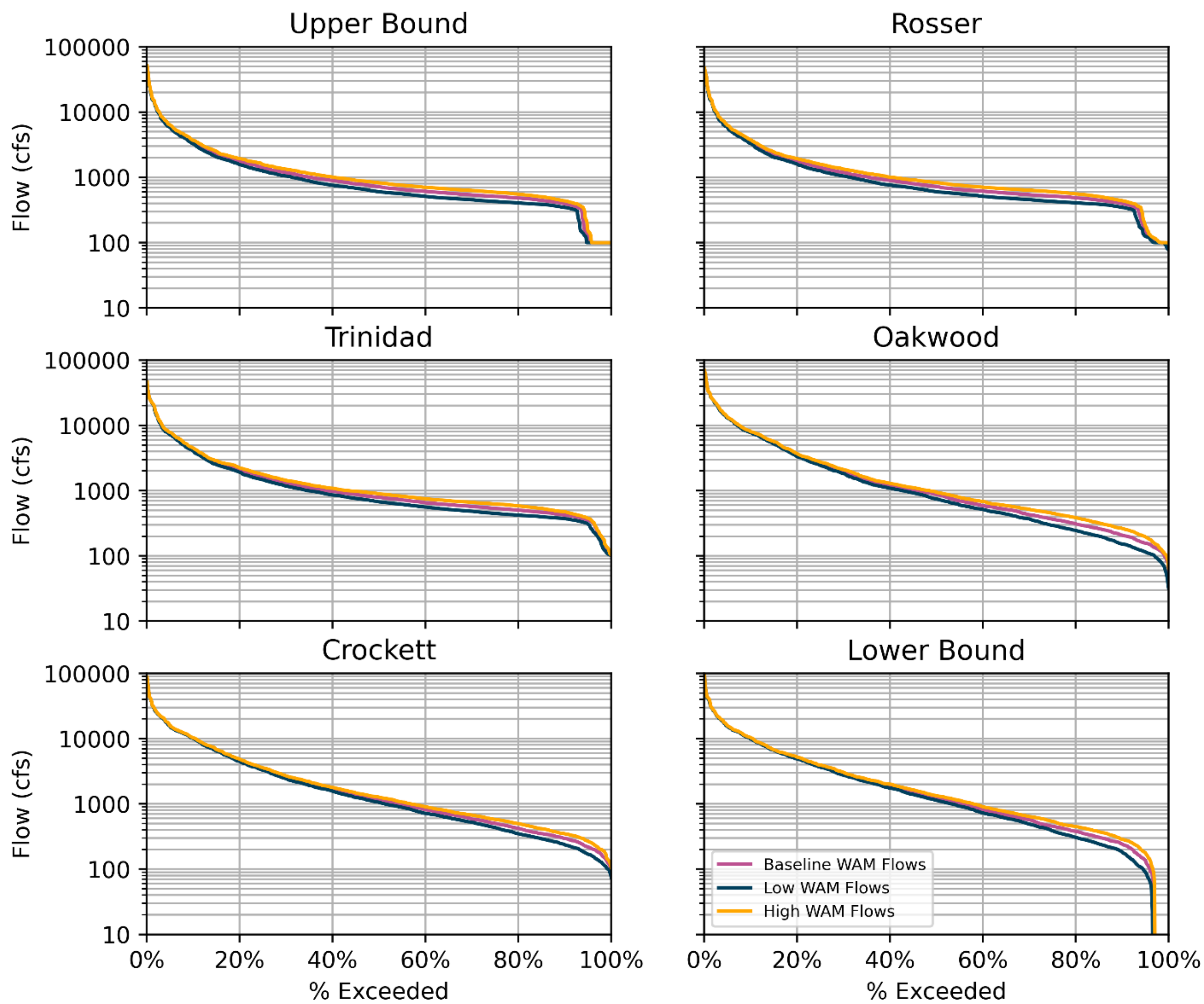

Figure 27: Flow duration curves at upstream boundary, downstream boundary, and streamgage locations for all three scenarios.

5.1.2 Lower Model Hydraulic Inputs and Results

The configuration of boundary conditions and representation of flow at each cross-section for the Lower Model is detailed in Table 9. The Luce Bayou diversion is not represented in exactly the same way in the WAM model as our understanding of its actual diversions, and some assumptions had to be made to represent it in the scenario model. The Luce Bayou diversion is associated with two water rights (60804261004 COHLVSTN and 60804261005 COHLVSTN in the WAM) that belong to the Coastal Water Authority. It is not known what portion of these water rights is diverted at Luce Bayou, so a one-to-one conversion was not possible. We did identify that the maximum pumping rate at Luce Bayou was 500 mgd, which translates to about 768 cfs of diversions. To include this diversion in the scenario models, we set the diversion to the minimum of the total diversions from the water rights in the WAM outputs and the maximum pumpage rate.

Table 9: Inflow Configuration for Lower Model Scenario Runs. Fill color indicates whether boundary condition at each location is an upstream boundary flow series (yellow), a gage location that provided flow information but was not used as an actual model boundary condition (no fill), a lateral inflow (green), a lateral diversion (brown) or a downstream boundary (gray). Representation column indicates how flows were calculated from WAM outputs. Drainage Area was assessed using the NHDPlus HR dataset. Bold rows indicate points where data is available.

Boundary Name	XS	Representation	Drainage Area (mi2)
Upstream Boundary	**434355**	**WAM CP 803**	-
Village Creek	386001	DA-Adjusted 8TRRO Minus 803 Inflows	223.7
Bois d'Arc Creek	310008	DA-Adjusted 8TRRO Minus 803 Inflows	159.9
Cedar Creek Upper	289291	DA-Adjusted 8TRRO Minus 803 Inflows	77.2
Livingston – Romayor Uniform Outflow	432254 – 276202	8TRRO Minus 803 Outflows	-
Romayor Gage	**276202**	**Equivalent WAM CP 8TRRO**	-
Davis Bayou	168960	DA-Adjusted 802 Minus 8TRRO Inflows	74.7
Little Bayou	136655	DA-Adjusted 802 Minus 8TRRO Inflows	51.7
Luce Bayou Diversion	133218	Minimum of [WAM WR 60804261004 & 60804261005 Diversions OR Reported Max Pumpage Rate at Luce Bayou (768 cfs)]	-
Romayor – Liberty Uniform Outflow	268494 – 33359	802 Minus 8TRRO Outflows	-
Liberty Gage	**33359**	**Equivalent WAM CP 802**	-
Downstream Boundary	**1998**	**Rating Curve Developed Using Liberty Series and USGS 08067100: Trinity Rv nr Moss Bluff, TX**	-

Flow inputs resulting from this calculation scheme are detailed in flow-duration curve form in Figure 28 for the baseline WAM scenario, to highlight the relative contributions/reductions from each model boundary condition. Implementation of the uniform withdrawal to reduce flow in the model between control points occurs about 20% of the time in the Livingston – Romayor reach and not at all below Romayor. In this scenario, the upstream boundary inflow was set to 200 cfs about 15% of the time and modeled diversions were shut off almost 40% of the time to help with model stability. Relative contributions from tributaries are proportional to their drainage area, as expected.

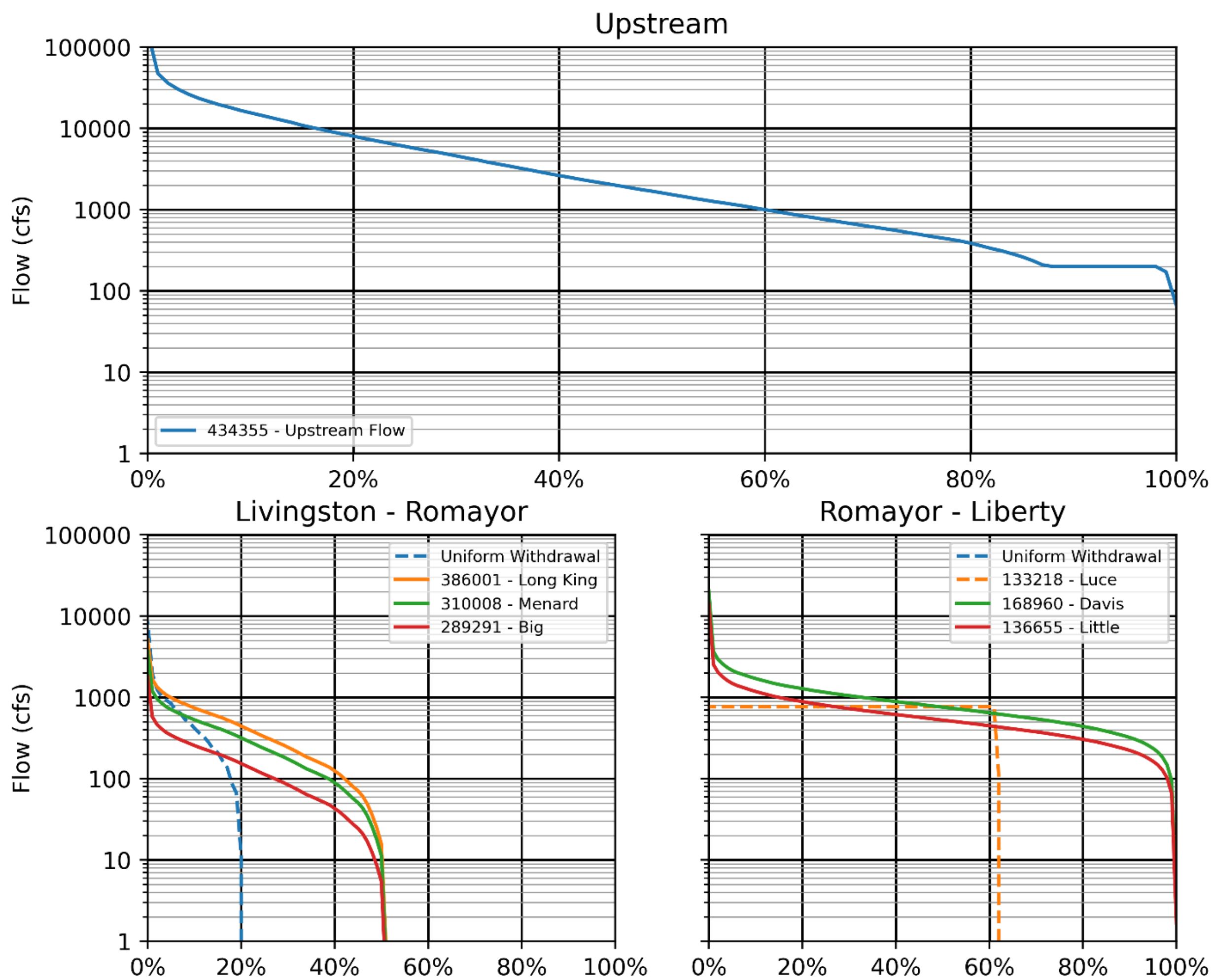

Figure 28: Flow duration curves for upstream boundary (top), lateral in- and outflows between Livingston and the Romayor streamgage location (bottom left), lateral in- and outflows (note that uniform withdrawal was always zero in this reach) between Romayor and Liberty streamgage locations (bottom right). Solid lines represent inflows to the model and dashed lines represent outflows from the model. Downstream boundary uses the same rating curve as the calibration model, as shown in Figure 9.

Model flow outputs for the scenarios are shown in Figure 29. Percent exceeded values are similar in the scenario hydraulic models to those of the calibration hydraulic model (Figure 7) for medium flows. The minimum flow in the calibration model was about 1,000 cfs, which is significantly higher than the minimum flow in the scenario models, although this was not as true further downstream. The flow duration curve for the calibration model has a generally different shape from the scenario models, which is likely because of dam release behavior that our WAM disaggregation methodology didn't capture. Flow also increased more significantly in the downstream direction in the WAM scenarios than in the calibration period model. Differences in flow durations can be observed between the three scenarios for flows in the range of 100-2,000 cfs, although the differences between scenarios were smaller than in the Upper Model. Durations appear to be negligibly different for flows higher than about 2,000 cfs. At all of the streamgage locations, the difference in the median flow between the Low WAM Flows and the High WAM Flows scenario was about 100 cfs, with the Baseline WAM Flows scenario located squarely in between the two, but these differences appear much smaller than in the Upper Model because flows are generally higher. These flow duration curves still indicate that the scenario hydraulics capture an appropriate range of flows and are suitable for use with the calibrated sediment model. If more distinct flow durations for the different scenarios are desired in any future work with this model, the best solution would likely to be to re-examine the disaggregation methods for the WAM scenarios or use a different scheme to create a synthetic hydraulic time series.

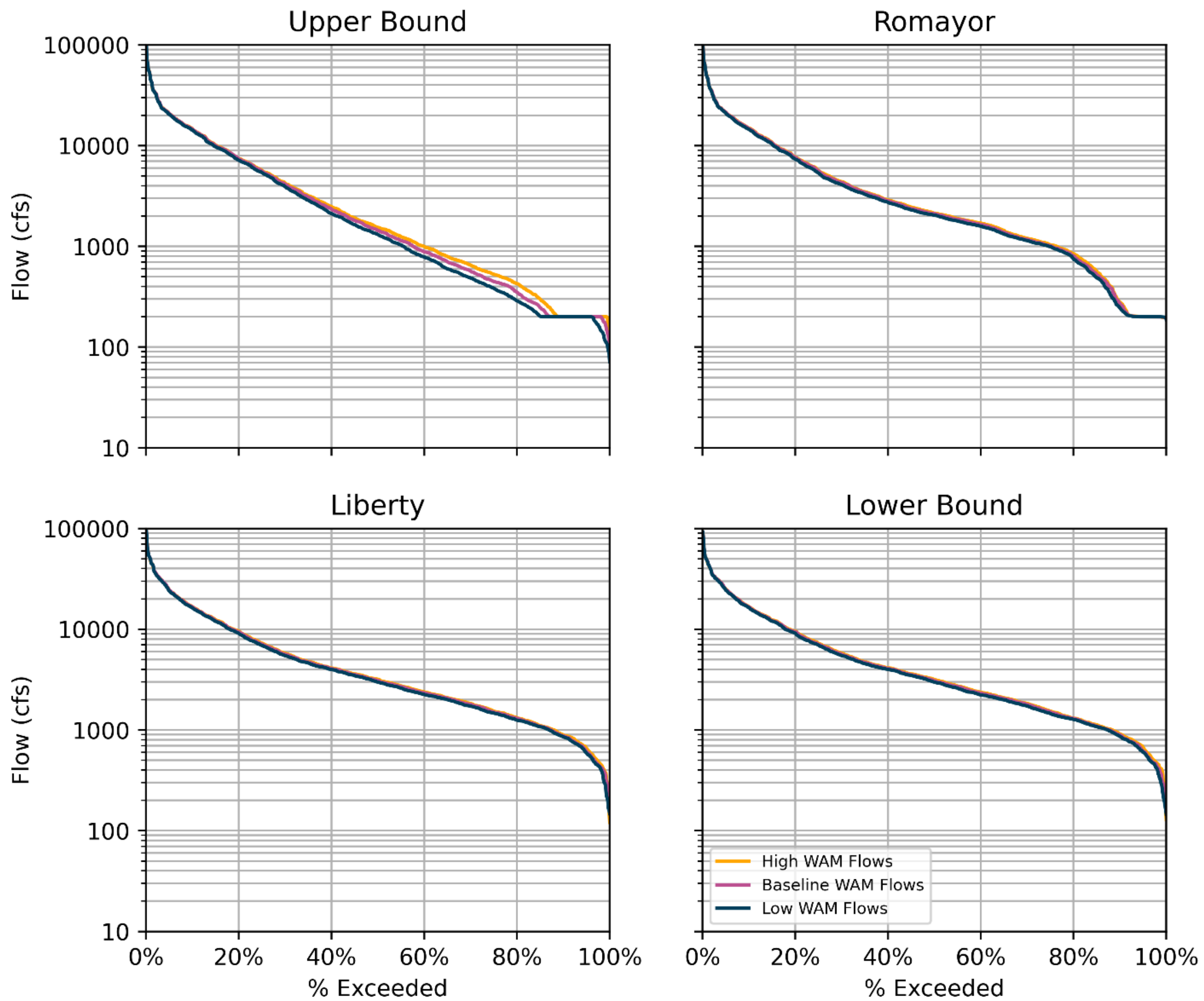

Figure 29: Flow duration curves at upstream boundary, downstream boundary, and streamgage locations for all three scenarios.

5.2 WAM Scenario Model Sediment Transport Results

5.2.1 Upper Model Sediment Results

The calibrated Upper sediment transport Model was run with Run 3 Compact Mod WAM scenario hydraulics for the fifty-year period 1/1/1940 – 12/31/1989. All of the models were run as hot-start models to set the same initial gradations that were used in the calibration model. Adding sediment transport processes makes the models significantly less stable, and it was a major challenge to balance 1) using the WAM scenario hydraulics, 2) including very low flow periods in the model, and 3) making sure the models ran to completion without crashing. The target low flow value for the Upper Model to achieve this balance was 100 cfs, and we were able to run all the models using this as the minimum flow.

Modeled load duration curves for all three WAM Flow scenarios at the upstream boundary and streamgage locations are shown in Figure 30. These load duration curves are different from those for the calibration period model (Figure 17), primarily because of the lower flows in the WAM Flow scenarios. Percent exceeded values for a given load were all lower in the WAM Flow scenarios than in the calibration period, with this effect being more pronounced in the upstream end of the model. There are many more periods of negligible (<1 ton/day) sediment inflow (5-8% of the time) at the upstream boundary in these scenarios. Significant differences in loads are seen between the different WAM Flow scenarios at the upstream boundary and at the Rosser location, with the High WAM Flows sediment load often being more than twice as large as the Low WAM Flows sediment load. This difference became smaller at high loads. Little difference could be seen between the WAM Flow scenarios at the Trinidad, Oakwood and Crockett locations.

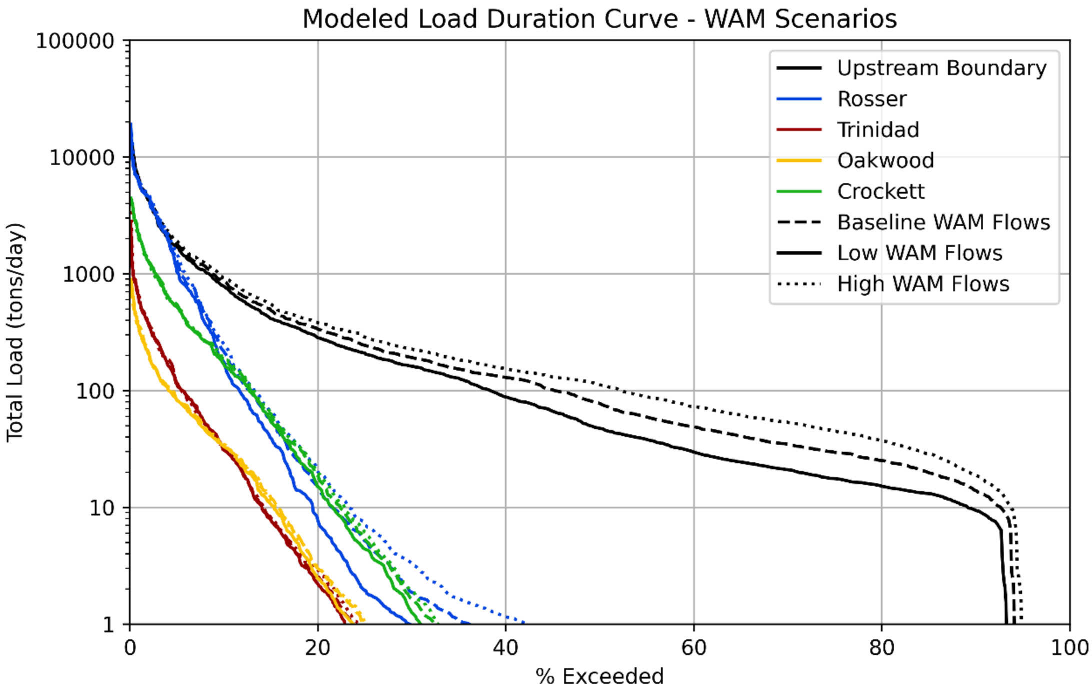

Figure 30: Modeled load duration curves at Upstream boundary and streamgage locations for the Upper WAM Scenario Models. Associated flows are provided in Figure 27.

Net invert change results for the three WAM Flow scenario models are shown in Figure 31. Due to the longer time period of this model, net invert change magnitudes were larger than in the Calibration Period model. A handful of cross-sections spread throughout the model domain saw net erosion or deposition of 10-25 ft. Major differences in net invert change between WAM Flow scenarios were largely confined to the reach between the upstream boundary and the Trinidad location, and particularly to cross-sections upstream of the Rosser location. This indicates that much of the difference in incoming sediment load for the WAM Flow scenarios is at the upstream boundary, and that much of the additional sediment load that flows in for the higher flow scenarios is deposited in the upper reaches of the model.

Reach-averaged invert change values for the whole period are shown in Table 10. The most significant difference is, again, seen in the upstream-most reach, where almost 0.25 ft more net deposition occurred in the High WAM Flows scenario than in the Low WAM Flows scenario. In the WAM Flow scenario models, the net invert change in the reach between the Trinidad and Crockett locations is actually positive, while it was negative in the Calibration Period model. Additionally, the net erosion in the reach between Crockett and the downstream boundary for the WAM Flow scenario models is equal to or slightly more than the change observed in the Calibration Period model, despite the much longer time-period. These results generally show that the lower flows of the WAM Flow scenarios cause less sediment transport. In the depositional upper portion of the model, this means that more of the incoming load is deposited, and in the erosional lower portion of the model, this means that less sediment is eroded.

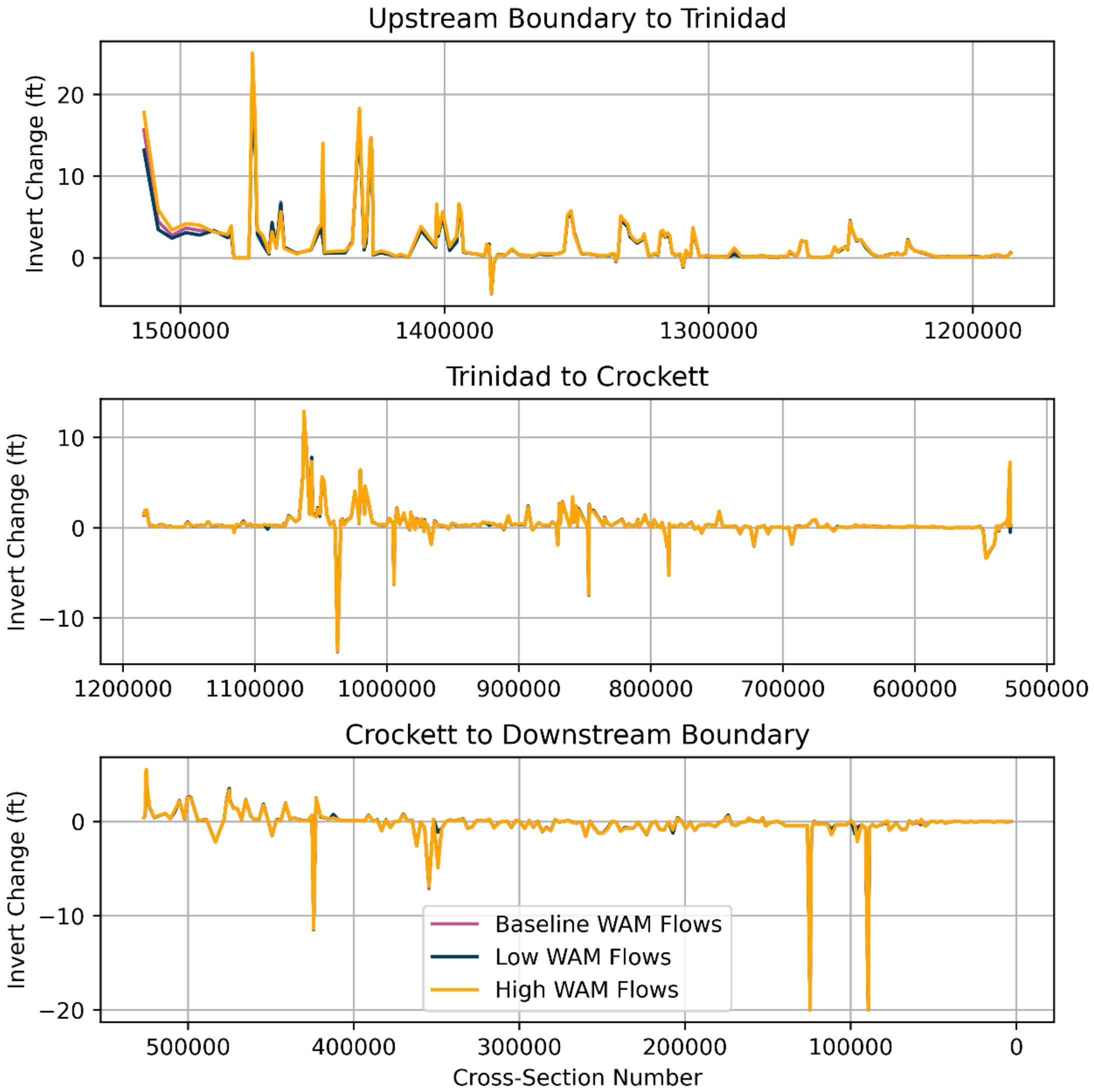

Figure 31: Modeled net invert change (ft) for the Upper WMA Scenario Models.

Table 10. Reach-averaged net invert change (ft) for Upper WAM Scenario Models.

Reach	Reach-Averaged Invert Change (ft) Low WAM Flows	Reach-Averaged Invert Change (ft) Baseline WAM Flows	Reach-Averaged Invert Change (ft) High WAM Flows
Upstream Boundary to Trinidad	1.67	1.78	1.91
Trinidad to Crockett	0.5	0.51	0.51
Crockett to Downstream Boundary	-0.21	-0.23	-0.24

In order to examine flow breakpoints where sediment processes change with respect to erosion and deposition, we compared reach-averaged invert change to flow between streamgage/boundary locations for the Baseline WAM Flows model in Figure 32. This plot is very useful for identifying flow breakpoints where the sediment regime of the channel transitions between erosion and deposition and where these breakpoints are pertinent. A detailed breakdown of the flow breakpoints identified in this plot is shown in Table 11.

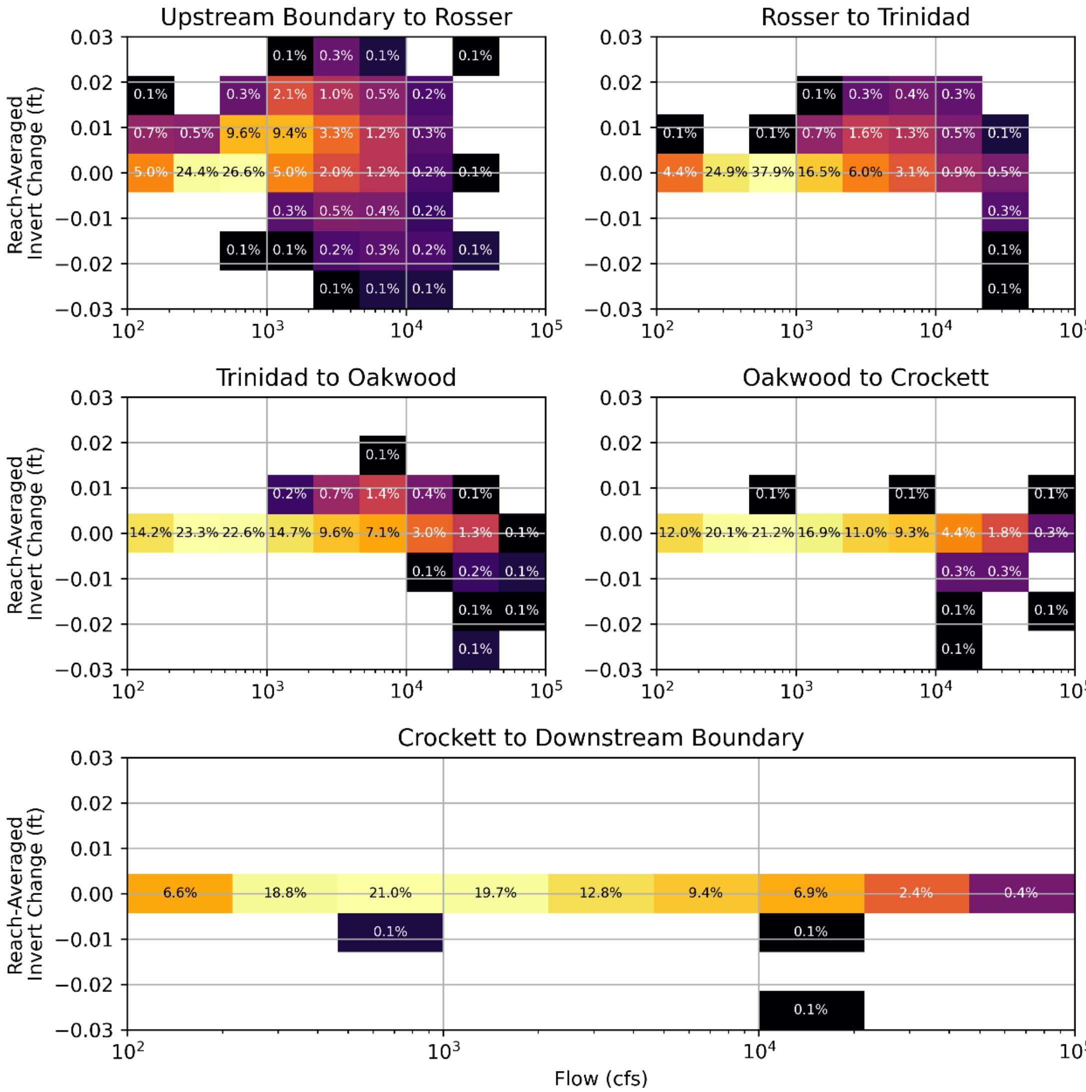

Figure 32: 2D heatmap of reach-averaged invert change (ft) vs. flow in reaches between boundary/streamgage locations for Upper Baseline WAM Flows Model. This figure shows the same data as Figure 19, but uses a heatmap to visualize it because there are more data points due to the longer WAM time period. The color of each square represents how many points fall in that square – the lighter the color, the more points it contains. The color is log-normalized, so the lightest square contains exponentially more points than the darkest square. Any white areas contained 0 points. The percentage of the total number of output time steps that fell in that square is reported with text in the square. Invert change value is incremental between timesteps, and represents the change in invert elevation over a 10-day period.

Table 11: Flow breakpoints for Upper Model where sediment regime changes, identified from Figure 32.

	Flow Range (cfs)	Deposition?	Erosion?
Upstream Boundary to Rosser	100-1,000	Frequent; Low-Medium	-
Upstream Boundary to Rosser	1,000-5,000	Frequent; Medium	Occasional; Low
Upstream Boundary to Rosser	5,000-50,000	Occasional; Medium	Frequent; Medium
Rosser to Trinidad	100-1,000	Occasional; Low	-
Rosser to Trinidad	1,000-20,000	Frequent; Low-Medium	-
Rosser to Trinidad	20,000-50,000	Frequent; Low-Medium	Occasional; Low
Trinidad to Oakwood	100-1,000	-	-
Trinidad to Oakwood	1,000-20,000	Frequent; Low	-
Trinidad to Oakwood	20,000-100,000	-	Occasional; Low-Medium
Oakwood to Crockett	100-10,000	-	-
Oakwood to Crockett	10,000-50,000	-	Occasional; Low
Crockett to Downstream Boundary	100-100,000	-	Rare; Low – High

In order to further assess flow breakpoints at which sediment processes change, we decided to examine a known low flow period in the 1950's where differences in WAM Flow scenarios would be more pronounced and we could look at small-scale responses of the channel to changes in flow. The period of 6/11/1953 – 4/11/1957, shown in Figure 33, provides almost a 5-year period where flows never exceed 10,000 cfs, and is useful for examining how sustained low flows impact sediment dynamics. During this low flow period flow values hover around 600-700 cfs, with a minimum flow of 100 cfs occurring several times and flows over about 2,000 cfs occurring only a handful of times for all WAM Flow scenario models. The difference in flow between the High WAM Flows and Low WAM Flows scenarios is often between 100-1,500 cfs. This translates to quite a large relative difference, with High WAM Flows flow often being 2-5x as much as the Low WAM Flows flow.

Reach-averaged relative invert change since 6/11/1953 is plotted alongside flow in Figure 33 to highlight how differences in flow translate to differences in deposition in this reach. During this low-flow period, the reach experiences more than twice as much deposition, and differences in deposition increase primarily during periods where the WAM Flow scenario flows differ. During this low-flow period, it is most commonly during times where flows are between 1,000-5,000 cfs and the difference between the Low WAM Flows scenario and the High WAM Flows scenario flows are between 1,000-1,500 cfs that major differences in deposition arise. Differences in the amount of deposition that occur also increase when flows are lower, in the range of 100-1,000 cfs, but they are not as pronounced.

Reach-averaged sediment load is also plotted alongside flow in Figure 33. The reach-averaged sediment load is related closely to relative invert change in this reach, and spikes in sediment load translate to increased deposition. Differences in sediment load are again highest when flows are between 1,000-5,000 cfs.

Finally, reach-averaged cover layer d10, d50, and d90 are plotted alongside flow in Figure 26. Grain size is generally shown to decrease after high flow events (>2,000 cfs) and increase after low flow events (<300 cfs). It responds quickly to sediment dynamics, and there isn't an observable long-term trend during this time period due to the sustained low flows. Cover layer grain size does not show a clear trend in how it reacts to differences in flow between the WAM Flow scenarios.

These observations generally support the presence of the flow breakpoints identified in the first two sections of Table 11. Differences in sediment dynamics between the WAM scenarios were much less significant for other reaches downstream of the Trinidad gage.

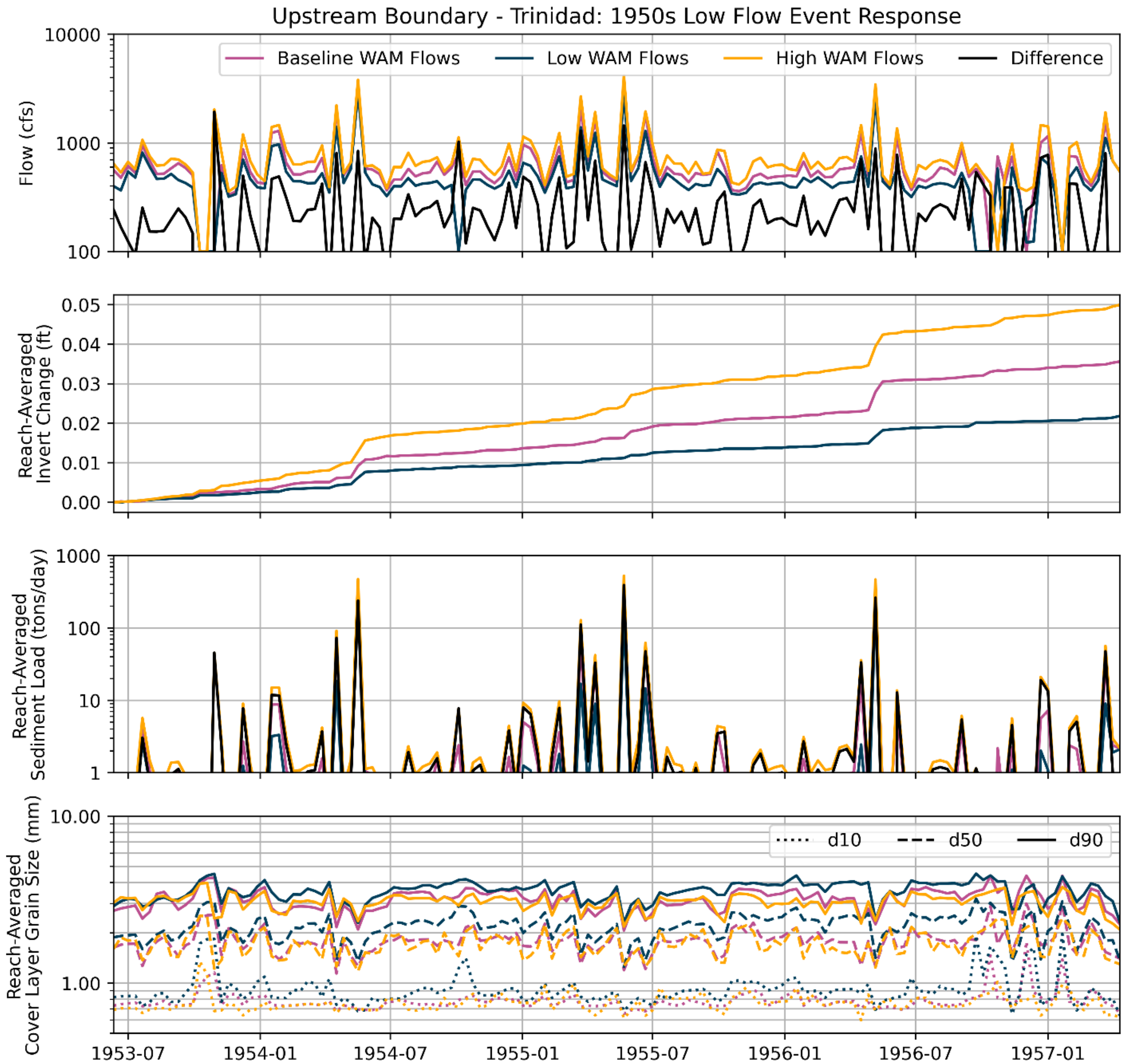

Figure 33: Sediment response to 1950s low flow event (6/11/1953 – 4/11/1957) for Upper WAM Scenario Models. Panel 1: Flow (cfs) entering at upstream boundary and difference between High and Low WAM Flows. Panel 2: Reach-averaged invert change since 6/11/1953 for Upper WAM Scenario Models. Panel 3: Reach-averaged sediment load for Upper WAM Scenario Models. Panel 4: Reach-averaged cover layer d10, d50 and d90 grain size for Upper WAM Scenario Models.

5.2.2 Lower Model Sediment Results

The calibrated Lower sediment transport Model was run with WAM scenario hydraulics for the fifty-year period 1/1/1940 – 12/31/1989. All of the models were run as hot-start models to set the same initial gradations that were used in the calibration model. Adding sediment transport processes makes the models significantly less stable, and similar challenges were faced in this model as in the Upper Model (see Section 1.1.1). The target low flow value for the Upper Model to achieve this balance was 200 cfs, and we were able to run all the models using this as the minimum flow.

Modeled load duration curves for all three WAM Flow scenarios at the upstream boundary and streamgage locations are shown in Figure 30. The load duration curves for Goodrich and Romayor are somewhat different from those for the calibration period model (Figure 23), primarily because of the lower and differently spatially-distributed flows in the WAM Flow scenarios. The rating curve at the Goodrich location was quite different in the WAM Flow scenarios model than in the calibration period model, with a load greater than 1 ton/day occurring 7.50-10% less frequently, but generally more frequent higher loads. For example, a load greater than 100 tons day was observed more than 40% of the time here and a load greater than 1,000 tons/day was observed about 18% of the time here. Percent exceeded values for a given load were mostly similar at the Romayor location for the WAM Flow scenarios and the calibration period model, but loads < 1 ton/day occurred about 16% of the time, whereas the minimum load observed during the calibration period was about 3 tons/day. Small differences in loads are seen between the different WAM Flow scenarios at the Goodrich location, counterintuitively with the Low WAM Flows sediment load being between 10-200% as large as the High WAM Flows sediment load. This difference became smaller at high loads. Little difference could be seen between the WAM Flow scenarios at the Romayor and Liberty locations, although the High WAM Flows sediment load was slightly higher than the Low WAM Flows sediment load for low flows at Romayor. This counterintuitive flow-load relationship at the Goodrich location seems to be due to the manner in which the WAM Flow Series creation methodology parcels out flow amounts between the upstream boundary and the tributaries. This means that, while flows at the Goodrich gage are slightly higher in the High WAM Flows scenario, more of that flow coming from the zero sediment load upstream boundary as opposed to the non-zero sediment load tributary may actually translate to less sediment being introduced to the model.

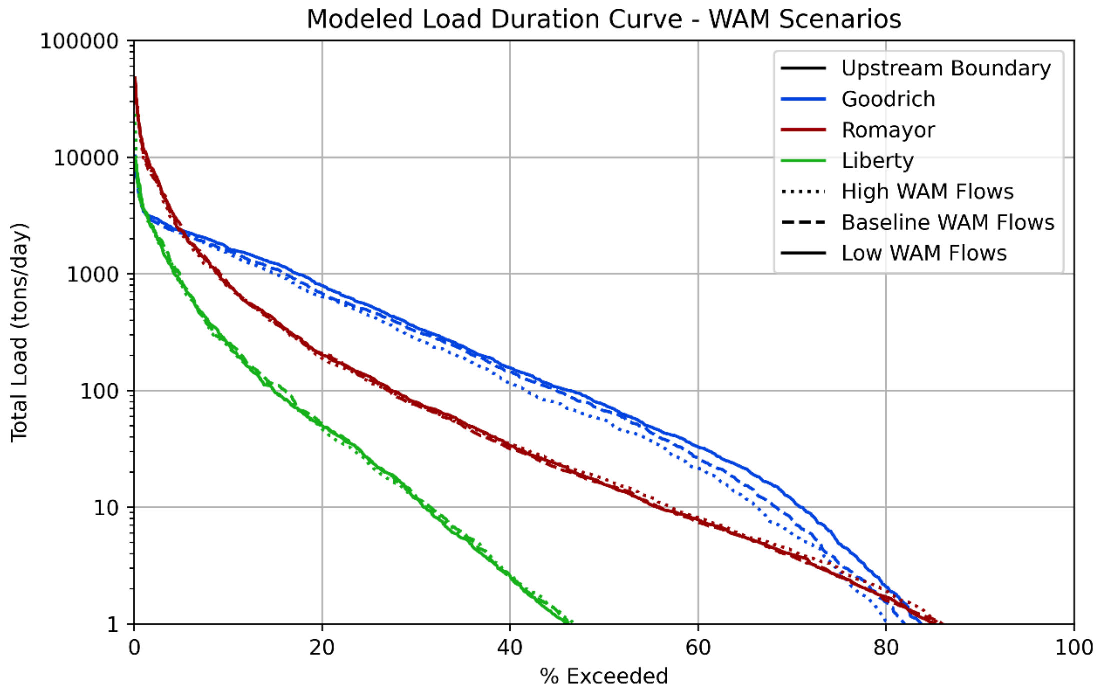

Figure 34: Modeled load duration curves at Upstream boundary and streamgage locations for the Lower WAM Scenario Models. Note that the Upstream boundary is from the dam and has a load of zero, so it does not show on the plot. Associated flows are provided in Figure 29.

Net invert change results for the three WAM Flow scenario models are shown in Figure 35. Due to the longer time period of this model, net invert change magnitudes were larger than in the Calibration Period model. A few cross-sections spread throughout the model domain saw net erosion or deposition of 10-20 ft, although there were fewer cross-sections showing changes of these magnitudes than in the Upper Model. Major differences in net invert change between WAM Flow scenarios were largely confined to the reach between the upstream boundary and the Romayor location. This indicates that much of the difference sediment dynamics between the WAM Flow scenarios has to do with different inflows from tributaries upstream of the Romayor gage.

Reach-averaged invert change values for the whole period are shown in Table 12. In the Lower Model, there were significant differences in net invert change between WAM Flows scenarios for both the reach between the upstream boundary and the Romayor location and the reach between the Romayor location and the downstream boundary. In the upstream portion of the model, 0.09 ft more net erosion occurred in the Low WAM Flows scenario than in the High WAM Flows scenario. In the downstream portion of the model, 0.16 ft more net deposition occurred in the Low WAM Flows scenario than in the High WAM Flows scenario. This result indicates that higher flows in this model translate to less erosion in erosional locations and less deposition in depositional locations. In the WAM Flow scenario models, the net invert change in the reach between the Romayor location and the downstream boundary of the model is actually positive, while it was negative in the Calibration Period model.

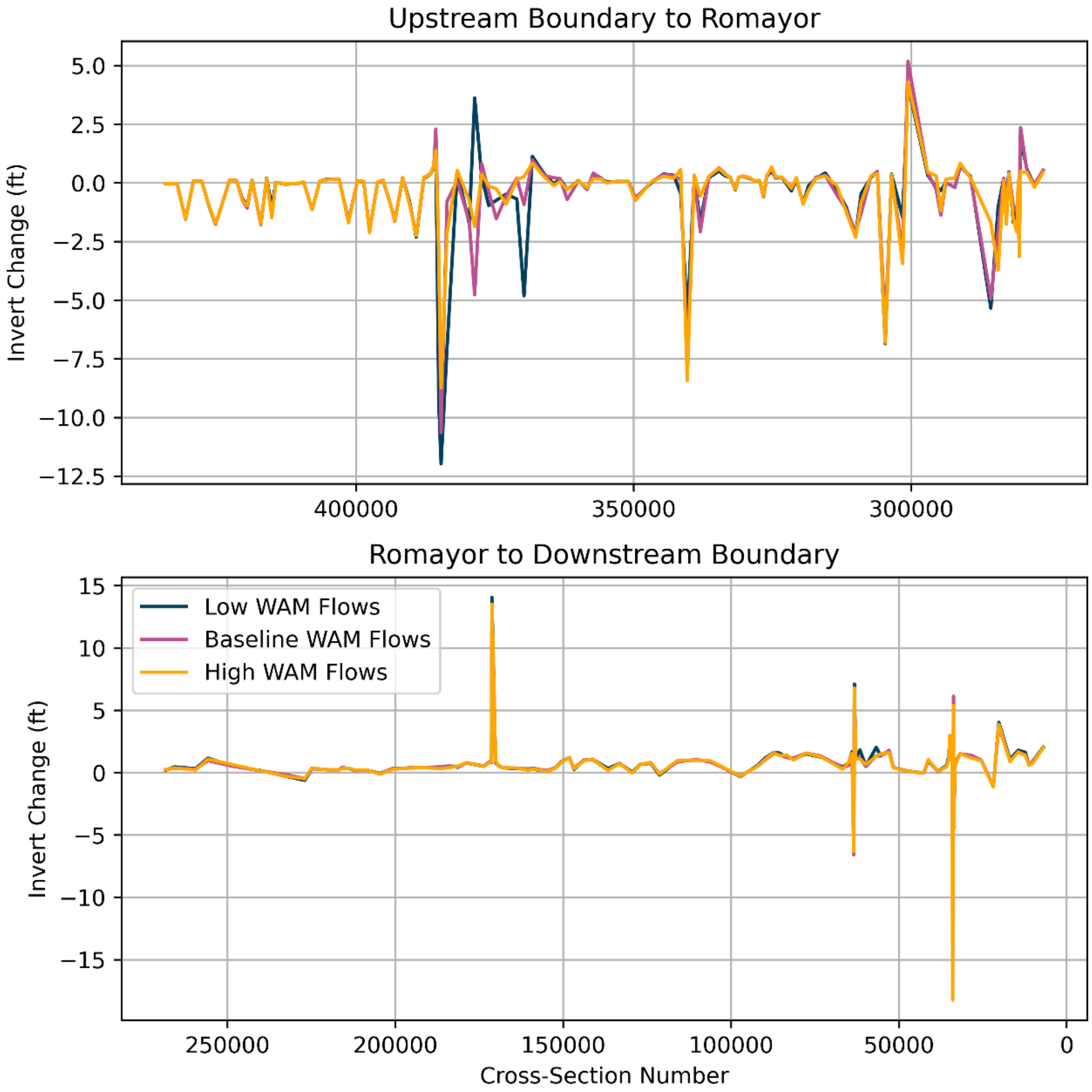

Figure 35: Modeled net invert change (ft) for the Lower WMA Scenario Models.

Table 12: Reach-averaged net invert change (ft) for Lower WAM Scenario Models.

Reach	Reach-Averaged Invert Change (ft) Low WAM Flows	Reach-Averaged Invert Change (ft) Baseline WAM Flows	Reach-Averaged Invert Change (ft) High WAM Flows
Upstream Boundary to Romayor	-0.57	-0.49	-0.48
Romayor to Downstream Boundary	0.78	0.7	0.62

In order to examine flow breakpoints where sediment processes change with respect to erosion and deposition, we compared reach-averaged invert change to flow between streamgage/boundary locations for the Baseline WAM Flows model in Figure 36. This plot is very useful for identifying flow breakpoints where the sediment regime of the channel transitions between erosion and deposition and where these breakpoints are pertinent. A detailed breakdown of the flow breakpoints identified in this plot is shown in Table 13.

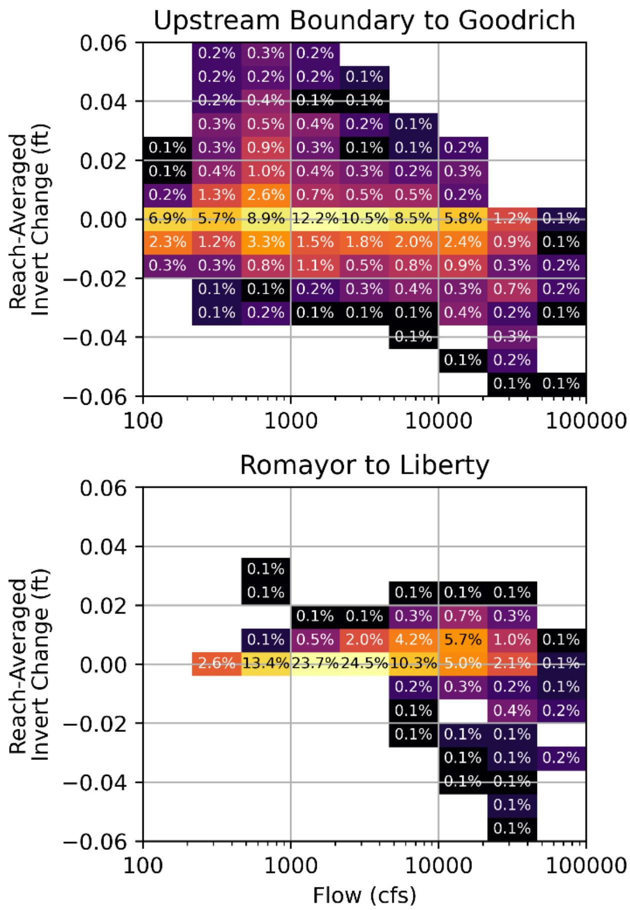

Figure 36: 2D heatmap of reach-averaged invert change (ft) vs. flow in reaches between boundary/streamgage locations for Lower Baseline WAM Flows Model. This figure shows the same data as Figure 25, but uses a heatmap to visualize it because there are more data points due to the longer WAM time period. The color of each square represents how many points fall in that square – the lighter the color, the more points it contains. The color is log-normalized, so the lightest square contains exponentially more points than the darkest square. Any white areas contained 0 points. The percentage of the total number of output time steps that fell in that square is reported with text in the square. Invert change value is incremental between timesteps, and represents the change in invert elevation over a 10-day period.

Table 13: Flow breakpoints for Lower Model where sediment regime changes, identified from Figure 36.

	Flow Range (cfs)	Deposition?	Erosion?
Upstream Boundary to Goodrich	100-200	Occasional; Low – High	Frequent; Low
Upstream Boundary to Goodrich	200-1,000	Frequent; Low – Medium	Occasional; Low
Upstream Boundary to Goodrich	1,000-5,000	Occasional; Low – High	Frequent; Low – Medium
Upstream Boundary to Goodrich	5,000-2,0000	Occasional; Low – Medium	Frequent; Low – Medium
Upstream Boundary to Goodrich	20,000-100,000	-	Frequent; Low – High
Goodrich to Romayor	100-500	Occasional; Low	-
Goodrich to Romayor	500-5,000	Frequent; Low – High	Occasional; Low
Goodrich to Romayor	5,000-100,000	Occasional; Low	Frequent; Low – High
Romayor to Liberty	100-1,000	-	-
Romayor to Liberty	1,000-10,000	Frequent; Low	-
Romayor to Liberty	10,000-50,000	Frequent; Low	Occasional; Low
Romayor to Liberty	50,000-100,000	-	Frequent; Low – Medium
Liberty to Downstream Boundary	100-1,000	-	-
Liberty to Downstream Boundary	1,000-5,000	Frequent; Low	-
Liberty to Downstream Boundary	5,000-100,000	Frequent; Low – High	-

In order to further assess flow breakpoints at which sediment processes change, we examined the same low-flow period in the 1950's. In the Lower Model reach, the period of 6/11/1953 – 4/11/1957, shown in Figure 37, provides almost a 5-year period where flows only exceed 10,000 cfs one time. During this low flow period flow values are often in the range of 200-2,000 cfs, with a minimum flow of 200 cfs occurring often. The difference in flow between the High WAM Flows and Low WAM Flows scenarios is occasionally more than 100 cfs. At times, the difference is more than 500 cfs, typically when flows are between 1,000-10,000 cfs. This translates to a reasonably large relative difference on a few occasions, with High WAM Flows flow being between 2-10x as much as the Low WAM Flows flow. Note that results from this model are more complicated because of the clear water upstream boundary and the dependence on tributary flows for sediment inputs, compared to the Upper Model where sediment inputs from the upstream boundary dominate. Regardless of complicated tributary dynamics, though, we can classify breakpoints where we see sediment processes change with the stipulation that they may only represent a true breakpoint under a certain hydrologic condition (e.g. high upstream flows vs. low upstream flows with high tributary inputs).

Reach-averaged relative invert change since 6/11/1953 is plotted alongside flow in Figure 37 to highlight how differences in flow translate to differences in deposition in this reach. During this low-flow period, the reach actually experiences almost the same amount of deposition, but significant differences in deposition do occur where the WAM Flow scenario flows differ. There are a few specific events where more deposition occurs in the Low WAM Flows scenario. They are typically when the flow in the Low scenario is about 500-5,000 cfs and the Baseline/High scenario flows are between 1,000-5,000 cfs, and when the sediment load in the reach is more than 100 tons/day. This suggests the presence of a breakpoint somewhere around 1,000 cfs in this reach, which is supported by Table 13. Additionally, there is a period towards the end of 1956 where High WAM Flows flow is around 1,000 cfs and Low WAM Flows flow is around 200 cfs. During this period, the sediment load in the reach is much higher in the High WAM Flows scenario, and you can actually see net erosion occur in the reach for the Low WAM Flows scenario, while deposition continues for the High WAM Flows scenario. The sediment load is much higher in the High WAM Flows scenario during this period, showing that for the higher flows the model is likely receiving more sediment deliveries from tributaries, whereas for the lower flows there is not much tributary input of sediment and the clear water from the upstream boundary begins to erode the bed. This similarly indicates the presence of a breakpoint in flow where the reach transitions from being deposition to erosional somewhere between 200-1,000 cfs.

Reach-averaged sediment load is also plotted alongside flow in Figure 37. The reach-averaged sediment load is related closely to relative invert change in this reach, and spikes in sediment load often translate to increased deposition. Interestingly, the Low WAM Flows scenario often exhibits a slightly higher sediment load than the High WAM Flows scenario, which may arise from quirks of the WAM hydrology or the disaggregation scheme. Differences in sediment load are again highest when flows are between 1,000-5,000 cfs.

These observations generally support the presence of the flow breakpoints identified in the first two sections of Table 13. Differences in sediment dynamics between the WAM scenarios were slightly less significant for the reach downstream of the Romayor location, but the same observations about sediment dynamics are true there during this period.

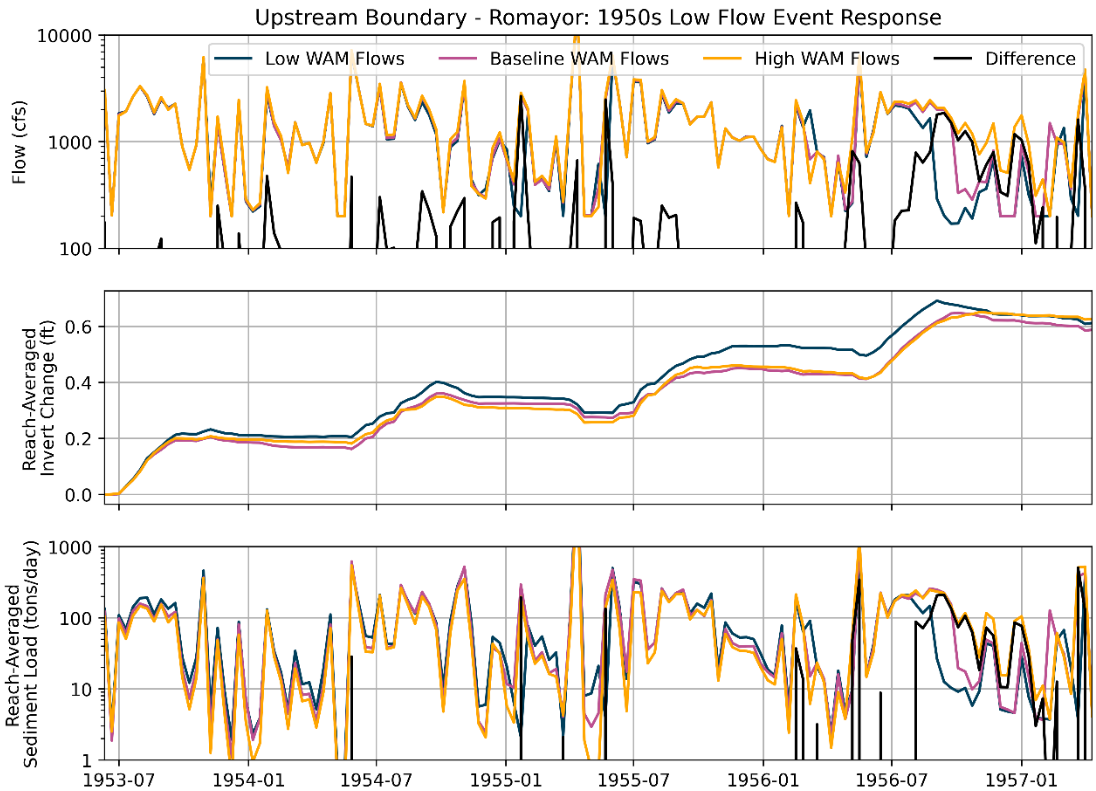

Figure 37: Sediment response to 1950s low flow event (6/11/1953 – 4/11/1957) for Lower WAM Scenario Models. Panel 1: Flow (cfs) entering at upstream boundary and difference between High and Low WAM Flows. Panel 2: Reach-averaged invert change since 6/11/1953 for Lower WAM Scenario Models. Panel 3: Reach-averaged sediment load for Lower WAM Scenario Models.

6 Discussion

The main research outputs of this project were as follows:

1. The development and calibration of a HEC-RAS 1D hydraulic model for the Lower Model Study Region, spanning from Lake Livingston to below the USGS Liberty streamgage station.
2. Preparation of a calibrated sediment transport model for the existing HEC-RAS 1D hydraulic model for the Upper Model Study Region.
3. Preparation of a calibrated sediment transport model for the HEC-RAS 1D hydraulic model for the Lower Model Study Region.
4. Preparation of three 50-year hydraulic scenarios for both models using data from the Trinity River WAM Run 3 model outputs.
5. Analysis of flow breakpoints at which sediment processes change for both models using the fifty-year WAM hydraulic scenarios.

Some aspects of calibrated model and scenario model results indicate that refinements should be made to the model in order for results to be taken at face value as predictions of channel response to a given change in basin hydrology. Several refinements are suggested here that would help to enable use of the models in this manner, effectively taking the lessons learned from this project to make them better suited to answering the questions posed to them. Despite their shortcomings, though, the model results 1) provide an excellent framework for how to interpret results of the sediment models with respect to breakpoints in flow, and 2) clearly indicate that there are breakpoints in flow where sediment processes change that are in the range of environmental flow standards such that they are relevant to discussion of environmental flow standards.

6.1 Lower Hydraulic Model Development

The HEC-RAS 1D hydraulic model for the Lower Model Study Region was developed using LiDAR and bathymetry data collected by TRA. The model used an existing HEC-RAS geometry where available in the middle of the Lower Model Study Region reach. Bridges were not included in the model geometry due to the difficulties they often present when implemented in HEC-RAS sediment transport models. Model hydraulics were successfully calibrated for flows from 500 – 100,000 cfs at a level sufficient for the completion of sediment modeling exercises. Future work on this hydraulic model could focus on a number of improvements. For one, any work using this model with the explicit goal of modeling hydraulics (instead of sediment) should likely work to include the bridges in the model geometry. Additionally, if TRA plans future bathymetric data collection in this area, they could use a high flow window as an opportunity to better define the in-channel bathymetric data. Finally, any future work with this model that is highly dependent on hydraulics, e.g. water quality modeling during low flows, should likely re-examine the hydraulic calibration as that was not the primary focus of this project.

6.2 Sediment Transport Model Calibration

Upper and Lower Model sediment transport was calibrated to the extent that 1) the models were generally stable and did not show excessive deposition or erosion other than at a single cross-section near the downstream boundary of both models, 2) invert change had stabilized and did not change as rapidly at the end of the five-year calibration period, and 3) the models were capable of both eroding and depositing sediment at cross-sections. Dozens of model runs that tested widely varying model configurations (boundary conditions, initial conditions, geometries, and sediment transport settings) were performed in the process of calibrating sediment transport parameters in an attempt to prevent high erosion or deposition at the handful of cross-sections where it occurs and to match observed sediment loads more closely with modeled sediment loads.

Achieving a stable model for the Upper Model proved to be difficult, and when a stable model was achieved, the best possible parameterizations yielded the patterns shown in Section 1.1.1 where a handful of cross-sections near the upstream end of the model experienced significant deposition and the sediment load did not make it all the way through the reach. It was also difficult to achieve a stable model for the Lower Model. The best possible parameterization for the Lower Model involved a quite coarse initial bed gradation, although this model did show considerably better continuity in sediment transport. We believe the cause for this, in both cases, is that the models we employed 1) were large, 2) had generally closely-spaced cross-sections, and 3) had to simulate an extremely wide range of flows. Computational increments were set as low as possible given the available computing power, but due to the long runtimes for the fifty-year scenario models, this only equated to a 1-minute timestep for the hydraulics and a 10-minute timestep for the sediment processes. As a result, the depositional patterns near the upstream end of the model may arise from issues with the computational timestep being too large for one of or both the hydraulic and the sediment model and causing numeric instabilities, and this should be a first target if any re-calibration attempts are made in the future.

The Upper Calibration Period Model had median flows between 1,000-2,000 cfs depending on the location, and spanned a range of flows from 500-60,000 cfs. Modeled sediment load generally matched observed sediment load more closely for higher flows than lower flows. The match between modeled and observed sediment load got progressively worse moving from upstream to downstream, and by the Crockett streamgage location was up to an order of magnitude off. This seemed to be because too much of the incoming load at the upstream boundary was depositing out in the upper reaches of the model. In the upstream portion of the model up to the Trinidad streamgage location, sediment tended to deposit for flows between 5,000-20,000 cfs, and eroded for flows above 20,000 cfs. Further downstream, no consistent invert change trend was observed for flows up to 20,000 cfs, and sediment eroded for flows above 20,000 cfs.

The Lower Calibration Period Model had median flows between 2,000-3,000 cfs depending on the location, and spanned a range of flows from 800-80,000 cfs. Modeled sediment load was ½-1 order of magnitude lower than observed sediment load, but pushed the upper limit of what kind of match was possible while retaining model stability because all sediment inflows had to come from tributaries. In the calibration, throughout most of the model reach, deposition seemed to occur during flows below 25,000 cfs and erosion occurred during flows above this. Net erosion occurred in the portion of the model above the Romayor location and in the portion of the model below the Romayor location.

6.3 Scenario Sediment Transport Models

Upper Baseline, Low and High WAM Flows hydraulic scenarios were run with the calibrated Upper sediment transport Model to investigate flow breakpoints where sediment processes changed. The WAM Flows scenario hydraulics were similar to those of the calibration period for flows above about 2,000 cfs, but had much lower minimum flows. Significant differences between the different WAM Flows scenarios were evidenced for flows from 100-2,000 cfs. There was about a 200 cfs difference between the median flow for the High WAM Flows and the median flow for the Low WAM Flows scenario, equation to a 10-15% difference in median flow. Modeled load was significantly different between WAM scenarios only at the upstream boundary and the Rosser location – further downstream differences in modeled load were typically very small between scenarios. Across the board, loads had lower percent exceedances than they did in the Upper Calibration Period model.

Erosion and deposition dynamics only changed significantly between WAM Flows scenarios upstream of the Trinidad location. Over the 50-year time period, the reach between the upstream boundary and the Trinidad location saw almost 15% more net deposition at the channel invert for the High WAM Flows scenario than for the Low WAM flows scenario. To a much smaller extent, the reach between the Crockett location and the downstream boundary actually saw more net erosion at the channel invert for the High WAM Flows scenario than for the Low WAM Flows scenario. These results highlight the impact of reduced return flows and associated lower inflows at the upstream boundary on sediment dynamics in the Upper Model.

Lower Baseline, Low and High WAM Flows hydraulic scenarios were also run with the calibrated Lower sediment transport Model to investigate flow breakpoints where sediment processes changed. The WAM Flows scenario hydraulics were not as similar to those of the calibration period, having much lower minimum flows and generally lower durations for high flows. This is likely a consequence of using daily unregulated flow at the Livingston location to inform the daily disaggregation because a better data source for the period that reflected dam impacts was not readily available. Significant differences between the different WAM Flows scenarios were only really evidenced at the Upstream Boundary and only for flows from 100-2,000 cfs. There was about a 100 cfs difference between the median flow for the High WAM Flows and the median flow for the Low WAM Flows scenario, equating to about a 10% difference in median flow. Modeled load was significantly different between WAM scenarios only at the Goodrich location – further downstream differences in modeled load were typically very small between scenarios. Goodrich had higher percent exceedances up to about 3,000 tons/day in the Baseline WAM Flows model than in the Calibration Period Model, although it did have a non-negligible load (>1 ton/day) slightly less frequently than in the Calibration Period model. For Romayor and Liberty, percent exceedances were essentially the same in the Baseline WAM Flows model as they were in the Calibration Period model.

Erosion and deposition dynamics changed significantly between WAM Flows scenarios throughout the Lower Model. Over the 50-year time period, the reach between the upstream boundary and the Romayor location saw about 25% more net erosion for the Low WAM Flows scenario than for the High WAM flows scenario. The reach between the Romayor location and the downstream boundary saw about 25% more net deposition for the Low WAM Flows scenario than for the High WAM flows scenario. This reach had actually showed net erosion in the calibration model, but showed net deposition for all WAM Flows scenario models. These results show, much like the Upper Model, that there is a significant impact of reduced return flows and associated lower flows on sediment dynamics in the Lower Model.

We were able to identify breakpoints in flow where sediment regime changed for each of the reaches between primary model boundaries/streamgage locations. These breakpoints identify under what flows reaches tend to erode, deposit or do both and to what relative extent.

In the Upper Model, the most significant breakpoint we identified was a transition from a primarily net depositional system to a primarily net erosional system at a flow of 5,000 cfs for the reach between the upstream boundary and the Rosser location. We also identified that the three upstream-most reaches all become the most strongly depositional at a breakpoint of 1,000 cfs. Investigation of results from a sustained low flow period in the 1950s confirmed that this 1,000 cfs breakpoint is significant in the upper reaches of the Upper Model. Deposition was seen to spike mostly when flows were over 1,000 cfs. Differences between the WAM Flow Scenarios hydraulics were most significant when flows were in the range of 1,000-5,000 cfs, and this combined with the presence of sediment breakpoints in this flow range led to noticeable differences in sediment dynamics between the WAM Flow Scenarios during this period.

In the Lower Model, breakpoints were a bit less discrete. Deposition and erosion were observed to occur at a variety of flows with one or the other usually being a bit more dominant. We identified that the reach between the upstream boundary and the Goodrich location was primarily depositional from between 200-1,000 cfs, but was otherwise primarily erosional. The reach between the Goodrich and Romayor locations was similarly primarily depositional from 100-5,000 cfs, and erosional for flows above that. The reaches between the Romayor location and the Liberty location and the Liberty location and the downstream boundary both saw little bed change for flows below 1,000 cfs. For flows from 1,000-50,000 cfs and 1,000-100,000 cfs, respectively, they were primarily depositional. Above 50,000 cfs, the reach between the Romayor location and the Liberty location was primarily erosional. Investigation of results from a sustained low flow period in the 1950s confirmed a breakpoint around 200 cfs where the regime transitions from erosional to depositional, and a breakpoint around 1,000 cfs where the degree of deposition decreases considerably. Differences between the WAM Flow Scenarios hydraulics were most significant when flows were in the range of 1,000-10,000 cfs, and this combined with the presence of sediment breakpoints in this flow range led to noticeable differences in sediment dynamics between the WAM Flow Scenarios during this period.

Pairing WAM daily and monthly data with a disaggregation scheme ended up being a reasonable way to create long hydrologic scenario time series that represented basin hydrology and were flexible enough to be adapted to the calibrated sediment model configuration. The Lower WAM Flows Models are not quite as well-suited to the calibrated sediment model, because unregulated flows (rather than regulated flows that indicate impacts of Livingston Dam) had to be used due to a regulated flows output not being available. This could be alleviated in the future by running an appropriate version of the daily WAM. The flexibility of the disaggregation scheme is, however, a major advantage, in addition to the fact that there are no gaps present in the WAM unregulated flow inputs the way there might be in e.g. streamgage data.

It was possible to run fairly low flows (100-200 cfs) with the WAM Flows scenario hydraulics while still maintaining a stable model, but we were not able to get down to the lowest subsistence flow values from the environmental flow standards for this region. It would be ideal to implement this if future work were to be done with this model related to environmental flow standards. This is difficult to achieve in a HEC-RAS sediment model, because HEC-RAS does not have any capabilities to prevent a situation where all the flow is diverted from the channel that we could identify. The more complex the basin hydrology gets, the harder it is to maintain very low flows, especially when there are diversions somewhere in the model domain.

The Low, Baseline and High WAM Flows scenarios that were chosen represent WAM Run 3 with 1) a 50% decrease in return flows specified, 2) no change in return flows specified, and 3) a 50% increase in return flows specified. These conveniently provided time series for similar basin hydrologies with differences at low flows that were a target of this study and allowed for comparisons of sediment dynamics to see the impact of the decrease in return flows. If, in the future, there is a desire to put more emphasis on identifying flow breakpoints where sediment processes change, a more useful approach might be to create long-term normal time series and drop in more regularized, sustained periods of suspected flow breakpoints to look at their long-term impacts. This could, for example, be done with environmental flow standard flows if desired by specifying the entire season to which the standard is applied be the flow in question.

6.4 Recommendations

This work provides several science tools that further TRA's goal of better understanding the environmental characteristics of the Trinity River Basin. There are several avenues where TRA could perform additional work to improve or extract additional value from these science products.

The footprint of the Lower Model was extended to cover the entire Lower Model Study Region. The geometry was constructed explicitly for sediment modeling in this phase of the project, so bridges were not added to the model. If this model is used for primarily hydraulic studies in the future, it should have bridges added to improve the calibration of model hydraulics. The bank geometry of some model cross-sections could also be represented better if bathymetry data was collected during a period of higher flows. This is only recommended if TRA identifies that the current representation is not adequate for its hydraulic modeling purposes.

Calibrated sediment models were developed for the Upper and Lower Models as part of this project. A future version of the TRA Upper and Lower Sediment Models may consider several steps to improve sediment model calibration. First, deleting cross-sections to increase cross-section spacing could be a first step – this is a recommendation in the User Manual, because it decreases model runtimes and allows for decreasing the computational timestep without causing model instabilities. Characteristic cross-sections could be deleted/retained in such a way that it reinforces the conceptualization of sedimentation in the Trinity to make the model more robust and more representative of TRA's understanding of how sediment processes function in the river. Second, sections of each model could effectively be cut out of the existing model geometry and re-purposed as smaller sediment models to look at specific areas – their smaller length would likely mean that they could be better calibrated or could be run with a smaller computational timestep. Third, if the target of a future study is to study impacts of low flows, a version of the existing model that doesn't include high flows could likely be run in the existing configuration with the existing computational timestep with less worry about numerical instabilities.

Baseline, High and Low WAM Flows scenarios were developed to run with each model and results from these scenario models were used to identify 1) the impacts of reductions in flow in the basin on sediment transport processes, and 2) breakpoints in flow where sediment processes change. If further analyses using these scenarios are performed, an effort should be made to re-prepare the Lower Model scenarios using regulated flows from a daily WAM model that has been run rather than unregulated flows from the model input dataset – this would better represent how Livingston Dam impacts flows.

Some reconsideration of the scenario flows configuration might also be warranted in future work using these scenarios, depending on what the targets of study are. For example, it might be ideal to modify the creation scheme or use a different flow series to attain flows as low as or lower than the lowest environmental flow standards in these reaches (75 cfs for the Upper Model and 200 cfs for the Lower Model) if those are still a subject of interest. Additional thought could also be given to where flow reductions occur – with regards to sediment dynamics, it makes a considerable difference if changes in flows are implemented upstream in the river, at tributaries to the river, or at diversions from the river. Finally, the complexity of flow series did make interpretation of results fairly challenging in this project – if there are clear flow ranges that are intended for study in future phases of work, a better scenario might be to identify a "normal" ~10-year flow series and then modify it to force the flow condition of interest. This might be a decrease in upstream flows, a change in return flows, or a change to diversions from the channel in the basin. As an example, if the goal was explicitly to study the subsistence summer environmental flow standard, the "normal" flow series could be modified to force subsistence flows in the summer, or force periods of subsistence flows with varying lengths.

Sediment rating curves, currently constrained by four points, could also be defined at a higher resolution (smaller magnitudes of flow between flow-load-gradation points defining the curve) if flow ranges that were run for the model were lower, or investigation was more targeted at a specific range of flows. This should be possible to achieve by using the same input datasets that were used in this project, but devoting more time to their analysis than was possible in this project. This step could incorporate knowledge gained from this project about approximately where flow breakpoints are located.

7 References

Gibson, S., & Sanchez, A. (2020). *HEC-RAS Sediment Transport User's Manual: Version 6.0.* Davis, CA: U.S. Army Corps of Engineers Hydrologic Engineering Center.

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Mangham, W., McKnight, K., Osting, T., Southard, P., & Flores, D. (2020). *Evaluation of Adopted Flow Standards for the Trinity River, Phase 3.*

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Appendix 2 – Response to comments for Final Report: Evaluation of Adopted Flow Standards for the Trinity River, Phase 4

Trinity River Authority of Texas

Technical Services and Basin Planning

July 22, 2024

Dr. Nolan Raphelt, P.E.
Water Science & Conservation: Surface Water
P.O. Box 13231
1700 N. Congress Ave.
Austin, Texas 78711-3231

RE: Final Report Transmittal Letter and Response to Comments for Trinity River Authority Contract No. 2000012407 entitled "Evaluation of Adopted Flow Standards for the Trinity River, Phase 4"

Dear Dr. Raphelt,

I am pleased to submit the PDF Document Accessibility Checklist and Certification and Final Report for Contract Number 2000012407, titled "Evaluation of Adopted Flow Standards for the Trinity River, Phase 4." We have addressed the Board's comments in the final report, as detailed starting on page 2 of this letter. The electronic data submittal and final retainage invoice will be sent in a separate email.

We appreciate the Board's input and technical expertise on the modeling aspects of this report and look forward to future collaborations.

Kind regards,

Webster Mangham
Manager SR, Environmental & Watershed Resources
TSBP

WMM/crt

P.O. Box 60
Arlington, Texas 76018
(817) 467-4343

Response to Comments:
Evaluation of Adopted Flow Standards for the Trinity River, Phase 4

Draft-final report to the Texas Water Development Board TWDB Contract No. 2000012407

REQUIRED CHANGES
Specific Draft Final Report Comments

1. Added 2 paragraphs to address this comment in section 6.7.
2. Complete.
3. Subsections a. - g. Complete.
4. Complete.
5. Completed - Added underlined text: All data were collected in United States survey feet in the appropriate Texas State Plane Zone coordinates (4204, 4203, or 4204 depending on location) and reference the North American Vertical Datum 1988 (NAVD88).
6. Completed – Changed to grams.
7. Completed. Good point. Replaced all instances of Bed Sediment with Bedload.
8. Completed. Underlined words below changed for clarity: While identifying breakpoints in flow where sediment transport processes change is useful for management purposes across all flows, investigating lower flows, in the range of the SB3 flows, was the main priority in this project due to their relevance to the SB3 adaptive management process.
9. Completed. Added text to the first paragraph of Section 6.2
10. Completed. Added text in the last paragraph of Section 6.6 and added wording in 6.9.
11. Completed. All "mg/l" as suggested.

Figures and Tables Comments

12. Completed.
13. Completed.
14. Completed.
15. Completed.

SUGGESTED CHANGES

16. Added a subheading for the Discussion portion of the Nekton Section and changed the title to 6.6 from Results to 6.6 Results and Discussion. Each section of this project was intended to gather data for a specific purpose and there is discussion within each heading. Because of the nature of this study, an overall Discussion section was not added.
17. Complete.
18. Complete.
19. Complete.
20. Complete. See last paragraph of Section 6.6 for new wording.
21. Complete. Added wording in the last two paragraphs of Section 6.7.

Appendix 3 - Texas Water Development Board Comments on Draft Report

ATTACHMENT 1

Evaluation of Adopted Flow Standards for the Trinity River, Phase 4

Draft-final report to the Texas Water Development Board

TWDB Contract No. 2000012407

General Draft Final Report Comments

The draft report documents the activities and results of the fourth phase of this project, a long-term effort to fill in data gaps and develop flow-ecology relationships for the Trinity River. Activities conducted during this phase of the project were related to long-term channel monitoring and surveying; water quality, sediment, and nekton sampling; and sediment transport modeling. The draft report adequately documents methods and results for these activities with one exception.

The project appears to have used a novel technique to utilize reach-averaged invert change and flow during 10-day periods within the 50-year sediment transport model runs to determine breakpoints “where sediment processes change with respect to erosion and deposition.” Reviewers are unfamiliar with this technique and could find no references in the technical literature where this technique has undergone peer review or been successfully applied to analysis of sediment transport in rivers. In the final report, the authors are urged to provide references for this technique and to communicate that the approach is novel.

In addition to contributions related to water quality and nekton data collection, the project was successful in developing and calibrating two sediment models (upper and lower models of the Trinity River) and applying the sediment models to three Water Availability Model (WAM) scenarios. This task involved integrating data from numerous sources collected across different periods and utilizing different technologies. Results provide an excellent starting point for future studies of sediment issues on the Trinity River by providing an example of how to run a base condition and follow with proposed hydrologic changes.

<u>REQUIRED CHANGES</u>

Specific Draft Final Report Comments

1. As described in Sections 6.7 and 6.8 (pages 49-58) and the Appendix (pages 67-72 and 76-80), the project appears to have used a novel technique to utilize reach-averaged invert change and flow during 10-day periods within the 50-year sediment transport model runs to determine breakpoints “where sediment processes change with respect to erosion and deposition.” Reviewers are unfamiliar with this technique and could find no references in the technical literature where this technique has undergone peer review or been successfully applied to analysis of sediment transport in rivers. Please provide references documenting how this technique has been validated or applied successfully to the evaluation of sediment transport in rivers. Priority should be given to scientifically peer reviewed literature, but references from other literature may

also be helpful. If suitable references are limited, please add caveats in the report noting that this approach is novel and relatively unproven. If no references are available, please consider removing reference to this technique and results from the report.

2. Title Page. Please update the first sentence of the paragraph on the lower half of the title page: "AS APPROVED BY THE 85TH TEXAS LEGISLATURE" should be "AS APPROVED BY THE 86TH TEXAS LEGISLATURE."
3. Please review the report for typos (such as the following, non-exhaustive list) and correct as necessary:
    a. Page 13, Section 3.1, 1st paragraph, 5th sentence: "a gully that focus overland runoff" should be "a gully that focuses overland runoff."
    b. Page 23, Section 4.1, 1st paragraph, 1st sentence: "across four sites" should be "across five sites."
    c. Page 31, 1st paragraph, 1st goal: "San Jacento" should be "San Jacinto."
    d. Page 53, Section 6.8, 1st paragraph, last sentence: "flow value for the Upper Model" should be "flow value for the Lower Model."
    e. Page 54, 1st paragraph, last sentence: "the difference sediment dynamics" should be "the difference in sediment dynamics."
    f. Page 64, 1st paragraph, 4th sentence: "listed as historical present" should be "listed as historically present" and "during either this current round of surveys" should be "during any of the recent surveys."
    g. Page 64, 1st paragraph, last sentence: "during both the historical and current studies" should be "during either the historical or current studies."
4. Page 9: Consider labeling USGS gages with a "USGS" prefix (similar to the TRA long term monitoring sites prefixed with an "LT") to make it easier to distinguish between sites listed in figures later in the document.
5. Page 11: Please specify which State Plane coordinate zone was used for survey data collection.
6. Page 27, Section 5.1, 2nd paragraph: The units of bed sediment mass used in this paragraph are a bit confusing. The paragraph refers to "grams" while the referenced figure (Figure 19) refers to milligrams per liter. Please rewrite to provide consistency.
7. Page 27, Section 5.1: Please be precise and consistent with the use of terms related to bed material and bedload transport. According to the US Geological Survey's Water Basics Glossary, "bed sediment" refers to "the material that temporarily is stationary in the bottom of a stream or other watercourse." Bed sediment is characterized by taking samples directly from the bed of the stream or river, typically when the bed material is at rest and not in motion due to a flow event. As used in the draft report, the term "bed sediment" seems to refer to bedload transport ("sediment that moves on or near the streambed"). Bedload

transport is characterized by taking samples of moving sediment from the water column near the bed during a flow event. Bedload transport measurements are an order of magnitude more difficult and expensive to collect than samples of bed sediment. For clarity, please provide your definition for the term “bed sediment” used in the document (or adopt the definitions from the US Geological Survey’s Water Basics Glossary).

8. Page 31, Section 6, 2nd paragraph, 1st sentence: Please reword this sentence for clarity. It is unclear what flows or range of flows are being referred to in the phrase “investigating these low flow ranges was the main priority.”
9. Page 34, Section 6.2: The hydraulic calibration of the Lower Model used data from 2018-2023 while the hydraulic calibration of the Upper Model used data from 2008-2013. Please explain in more detail why the different calibration time periods were chosen.
10. Page 48, Section 6.6: WAM flows from 1940 to 1989 for the three scenarios were applied to the calibrated models to compute how the scenario affected cross-section changes. The report then implies that the models could be used to evaluate environmental flow standards (Page 59, Section 6.9). While a 1D HEC-RAS model can show scour deposition locations between different proposed alternatives, it cannot predict cross-section shapes. Please add a cautionary statement to the report warning that cross-section output should not be used for aquatic habitat analysis.
11. Page 25, Table 4 and Figure 16; and throughout the document: Several abbreviations for milligrams per liter are utilized, including “Mg/L”, “mg/L”, and “mg/l”. Please consider using the accepted abbreviation “mg/l” throughout the document.

Figures and Tables Comments

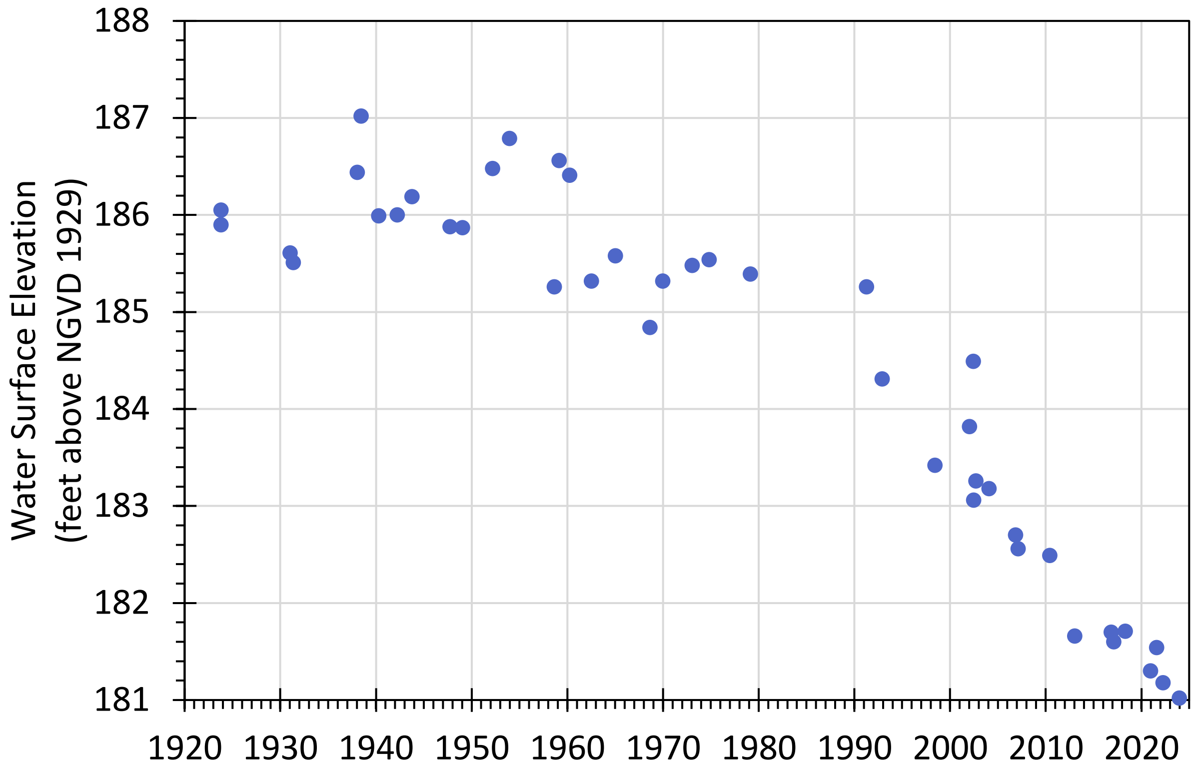
12. Page 24, Table 3: The abbreviation for Celsius in the header for Column 9 should be “C” not “c”.
13. Page 30, Table 5: Please provide appropriate units in column headers. For example, the appropriate units of Column 4 are “between 0.063 and 4 mm, grams” and the units of Column 7 are “<0.0625 mm, percent.”
14. Page 50, Figure 33: Change “WMA” in figure description to “WAM”.
15. Page 55, Figure 35: Change “WMA” in figure description to "WAM”.

SUGGESTED CHANGES

16. Consider adding a Discussion or Conclusion section to the report.
17. Page 6, Section 2.2, 1st paragraph, 5th reference: To be consist with format of other references, please consider placing date in brackets [i.e., “(2014).”].

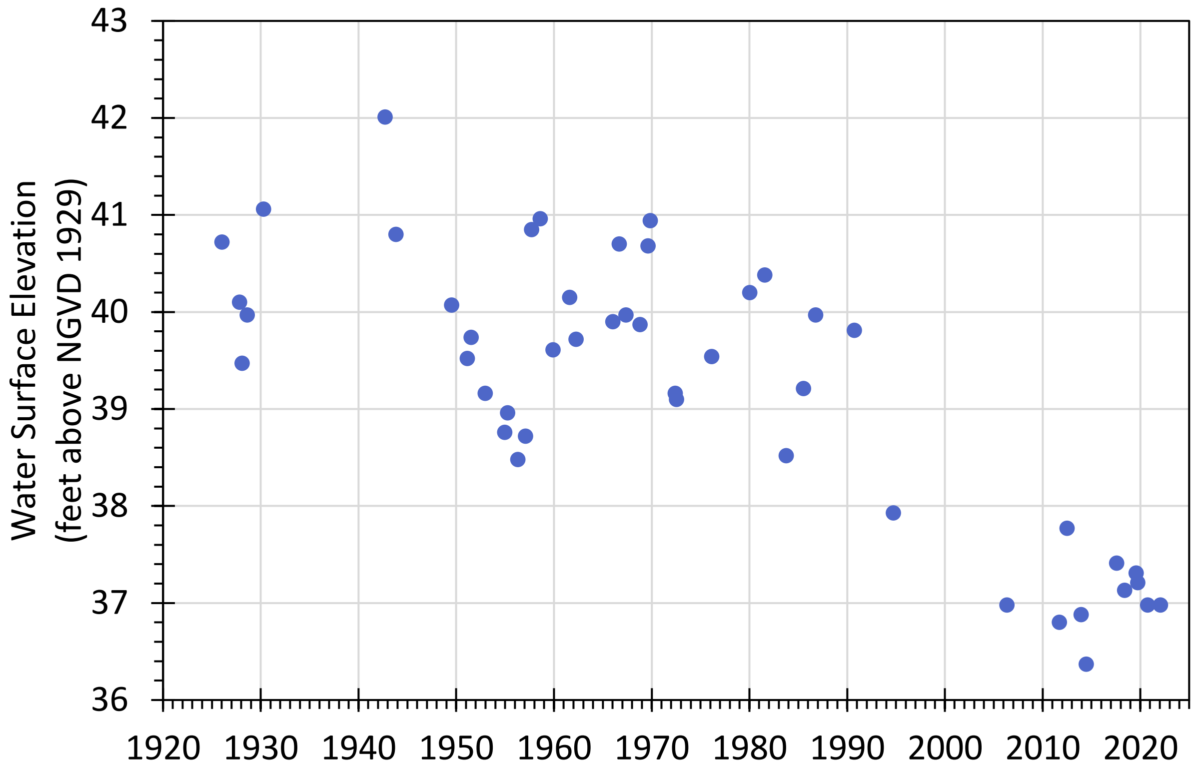
18. Page 11, Section 3.1, 4th paragraph, 4th sentence (and other locations in the document): To better reflect the level of accuracy of gaged flows, please consider not reporting flow values with tenths and hundredths of cubic feet per second (e.g., “328 cfs” rather than “328.00 cfs).
19. Page 27, Section 5.1, last paragraph: The authors mention that the bedload sediment data “did not result as expected” because back-to-back samples showed results “almost an order of magnitude” in difference. Please consider describing the data as “not entirely unexpected, given the chaotic nature of sediment transport and the difficulties of measuring these processes.” As mentioned in the previous paragraph of the document, bedload data is “highly variable” and “additional data should be collected whenever possible.”
20. Page 47, Section 6.6: For the benefit of all readers, please consider noting within the report that during the period of the model runs (1940-1989) the basin experienced many changes (including reservoir construction, land use changes, urbanization, levees, and flow diversions) impacting flow and sediment characteristics and thus making it impossible for the model to reproduce historic channel changes. .
21. Page 59, Section 6.9: Please consider adding an additional topic of future work that could enlighten use of the model and/or interpretation of results, specifically an investigation of the historical geomorphic conditions of the upper and lower reaches. During the time-period of the model runs (1940-1989), the channel in both the upper and lower reaches was rapidly adjusting to changes in the basin (including reservoir construction, land use changes, urbanization, levees, and flow diversions). This can be seen in measurements collected at the long-term US Geological Survey stream gages in the basin. For example, the water surface elevation associated with flow measurements between 1,350 and 1,650 cfs are shown below for the Oakwood (first graph) and Romayor (second graph) gage sites. At the Oakwood site, the data indicates the channel has been incising at a rate of approximately 1 foot per decade since about 1950. Similarly, the channel at the Romayor sites appears to have been incising at a rate of about half a foot per decade over the same period.

ATTACHMENT 1



Water surface elevations associated with flow measurements between 1,350 and 1,650 cfs for the USGS gage 08065000 near Oakwood.

ATTACHMENT 1



Water surface elevations associated with flow measurements between 1,350 and 1,650 cfs for USGS gage 08066500 Trinity River near Romayor.