COMPREHENSIVE INSTREAM FLOW STUDY FOR THE GONZALES REACH OF THE LOWER GUADALUPE RIVER

Final Report

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EXECUTIVE SUMMARY

The Guadalupe-Blanco River Authority (GBRA) provides stewardship for the lower Guadalupe River which maintains an ecologically diverse community of organisms supported by a dynamic flow regime. Future surface water projects, groundwater projects, and/or Edwards Aquifer management programs have the potential to alter this dynamic flow regime and thus influence the organisms and ecological processes that depend on it. The instream flow study was initiated in mid-2012 to examine the instream flow needs of the Gonzales reach of the lower Guadalupe River. Although this study was sponsored by GBRA, this report does not represent an analysis of the Mid-basin Project. From the outset, the goal of this effort was to conduct a comprehensive instream flow assessment and produce a technical report outlining instream flow recommendations for the Gonzales reach of the lower Guadalupe River to assist GBRA with water resource planning activities in this portion of the basin.

Based on a detailed reconnaissance of the Gonzales to Cuero reach of the lower Guadalupe River and other available data, an intensive study site was selected approximately 14 river miles downstream of Gonzales. Intensive physical and ecological data collection occurred from 2012-2015 within the river channel itself as well as in adjacent riparian and floodplain areas. Hydraulic data on discharge and associated water surface elevations collected at multiple flow levels were combined with data on channel bathymetry and substrate composition to generate a two-dimensional hydraulic model of the intensive study site using the Adaptive Hydraulics model (ADH). Fish habitat utilization data were collected on 37 species of riverine fishes across a range of flow conditions over two years of seasonal sampling and used to develop Habitat Suitability Criteria (HSC) for six habitat utilization guilds. Resulting HSC were applied to hydraulic model output from multiple model runs ranging from 50 to 2,100 cfs to model Weighted Usable Area (WUA) of fish habitat under varying flow levels. Additionally, changes in fish community structure within a unique floodplain aquatic habitat were assessed in relation to sporadic pulse flow events which resulted in hydraulic connection to the mainstem Guadalupe River.

Macroinvertebrate community structure within riffle habitats was similarly evaluated in relation to pulse flow events to examine flow levels which resulted in disturbance. Extensive freshwater mussel sampling was conducted to examine species composition within this reach, evaluate habitat utilization, and assess the importance of other factors such as shear stress and overall discharge on mussel abundance and catch rates. Distribution of seedling, sapling, and mature trees within riparian areas was evaluated in relation to pulse flow events, inundation levels, and soil moisture along established transects. Finally, habitat-specific point measurements and long-term sonde deployments were used to gather site-specific data on water quality and used in conjunction with other available data to evaluate relationships between water quality and discharge.

The intensive data collection effort and subsequent analysis confirmed the lower Guadalupe River supports a diverse ecological community that is influenced by the quality, magnitude, timing, and duration of water flowing through the system. A total of 15,258 fishes representing 14 families and 37 species was collected from distinct microhabitats in the mainstem of the Guadalupe River including four noteworthy regionally endemic species (Gray Redhorse *Moxostoma congestum*, Burrhead Chub *Macrhybopsis marconis*, Guadalupe Darter *Percina apristis*, and Texas Logperch *Percina carbonaria*). In addition, over the course of the study a total of 6,519 individual fishes representing 11 families and 32 species were captured from the unique floodplain feature upstream of the study site. Overall, over 1,200 individual mussels were collected representing 9 species, three of which (Golden Orb *Quadrula aurea*, Texas Pimpleback *Quadrula petrina*, and False Spike *Fusconaia mitchelli*) are recognized as "Threatened" by TPWD. Two of these

(Golden Orb and Texas Pimpleback) are also candidates for listing under the Endangered Species Act, while the third (False Spike) was once thought to be extinct before recently being collected during this study and at several other locations in the Guadalupe, Colorado, and Brazos River basins by other researchers (Randklev et al. 2013).

Monitoring efforts of benthic macroinvertebrates conducted in riffles within the study site resulted in 21,709 total individuals quantified representing 18 orders. The riparian analysis focused on a set of key indicator species including Black willow *Salix nigra*, Box elder *Acer negundo*, and Green ash *Fraxinus pennsylvanica*. These three species were selected as representatives of a healthy, functioning riparian zone because they are broadly distributed across the Guadalupe River watershed and are tightly connected to stream channel processes (primarily stream flow).

Information from the analyses described herein were compiled and used to generate a comprehensive flow regime as described in detail in Section 4.0. The goal for a successful instream flow regime is to provide flows that have an ecological linkage to the resident biota, while incorporating a level of variability supportive of diverse ecological conditions. The proposed instream flow recommendations generally follow the prescribed structure set forth in the Texas Instream Flow Program (TIFP) Technical Overview document (TIFP 2008), and consist of Subsistence, Base, and Pulse flow recommendations. A year-around subsistence flow rate of 130 cfs is recommended regardless of season or hydrologic condition. To capture ecologically meaningful patterns in within-year variability (seasonality) while simplifying implementation, a three-season approach (Spring, Summer, and Fall/Winter) to base and pulse flow recommendations was used. To capture between-year variability (i.e. wet, average, dry) both base and pulse flow recommendations also include two hydrologic conditions. The two base flow hydrologic conditions include Base Dry and Base. Base Dry conditions (200 to 300 cfs depending on season) are to be applied during naturally dry periods (25th percentile or less), and Base (300 to 550 cfs depending on season) would be applied all other times. The two hydrologic conditions proposed for flow pulses include Wet and Other. Wet conditions (2,000 to 6,000 cfs depending on season) are proposed to be applied during naturally wet periods (75th percentile or more), and Other (1,000 to 4,300 cfs depending on season) would be applied during all other times. Each pulse flow recommendation also has an assigned duration and frequency. Finally, a once-per-year high flow pulse of 12,500 cfs (to be provided by Mother Nature) is recommended to wet the majority of the riparian indicator species recruitment zones as well as push back upland tree species during Wet conditions.

In conclusion, instream flow recommendations provided in this report are based on the most comprehensive instream flow analysis conducted on the lower Guadalupe River to date. These recommendations will hopefully prove useful in future water management discussions within the basin and were purposely designed to be compatible with ongoing TIFP studies in the basin. The project team concurs with the TIFP (2008) and recognizes that a critical component of any instream flow recommendation is long-term monitoring. As such, a long-term monitoring plan to evaluate the effectiveness of recommendations and provide opportunities for refinement should be a high priority when evaluating future goals.

1.0 INTRODUCTION

The Guadalupe-Blanco River Authority (GBRA) provides stewardship for the water resources in its ten-county statutory district. Water resource planning and development activities are evaluated within the broader context of regional and statewide water needs in order to fulfill GBRA's primary responsibilities of developing, conserving and protecting these resources in the Guadalupe River basin. As documented in this report, the lower Guadalupe River supports a diverse ecological community that is influenced by the quality, magnitude, timing, and duration of water flowing through the system. Future projects have the potential to affect resident aquatic and riparian resources in the lower Guadalupe River which provides the rationale behind GBRA's Instream Flow Planning activities.

Instream flow work on the lower Guadalupe River has a long history with data collection being started nearly 20 years ago by Texas Parks and Wildlife Department (TPWD). This initial instream flow study was interrupted by a major flood event in 1998 and never completed. Recognizing the importance of environmental flows and competing needs for water, in 2001 the 77th Texas Legislature enacted Senate Bill 2 (SB2) and established the Texas Instream Flow Program (TIFP). The main goal of the TIFP is to perform scientific studies to determine flow conditions necessary to support a sound ecological environment in the rivers and streams of Texas. The lower Guadalupe River was recognized as a priority sub-basin and the TIFP subsequently initiated instream flow work in the basin, which is currently ongoing.

Again in 2007, the Texas Legislature restated the importance of environmental flows issues and established the Senate Bill 3 (SB3) environmental flows process. The SB3 process was designed to be an accelerated stakeholder-driven process using available science to generate flow recommendations which could be used by the Texas Commission on Environmental Quality (TCEQ) to establish environmental flow standards. This process included a Basin and Bay Expert Science Team (BBEST) in each basin to generate initial recommendations and a Basin and Bay Area Stakeholder Committee (BBASC) to incorporate stakeholder needs and propose revised recommendations to TCEQ. In the Guadalupe River basin, this process culminated with TCEQ environmental flow standards adopted in August 2012. In support of SB3, the Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays (GSA) BBEST and BBASC recognized the need for additional data on flow-ecology relationships within the basin. As such, the GSA BBASC instream flows workgroup listed a comprehensive SB2 instream flow study of the lower Guadalupe River as a main priority in the development of their basin-wide work plan.

The Gonzales reach instream flow study discussed herein represents a portion of the on-going flow-ecology applied research that is being conducted in the basin. BIO-WEST was contracted to conduct this study and began work in summer 2012 to examine the instream flow needs of the Gonzales reach of the lower Guadalupe River. It needs to be clear that although the study was sponsored by GBRA, this report does not represent an analysis of the Mid-basin Project. From the outset, the goal of this study was to conduct a comprehensive instream flow assessment and produce a technical report outlining instream flow recommendations for the Gonzales reach of the lower Guadalupe River. Data were collected and analyzed on multiple components of the ecological community including both riverine and floodplain fishes, freshwater mussels, aquatic macroinvertebrates, and riparian vegetation. This ecological data was then combined with intensive bathymetric and hydraulic data collection, resulting hydraulic and habitat modeling, and water quality analysis to develop comprehensive recommendations.

Understanding that the TIFP is actively conducting an SB2 instream flow investigation in the lower Guadalupe River, GBRA in coordination with BIO-WEST, met with the TIFP regarding study design to ensure results from this study would be compatible with TIFP activities. Over the course of the study TIFP members participated jointly with BIO-WEST in field data collection and hydraulic model analysis. Additionally, periodic updates were provided to TIFP personnel regarding results, analysis, and preliminary recommendation development approaches.

The report starts with a description of the intensive biological and physical data collection and presentation of results followed by how that information was used to develop hydraulic and habitat models for further examination. The report then shifts to a detailed examination of the analysis of the data and modeling results to provide insight on flow-ecology relationships. The identification of these relationships via qualitative and quantitative means are then used to develop comprehensive and integrated instream flow recommendations for the Gonzales reach of the lower Guadalupe River. The report closes with a brief discussion of next steps including potential application from an environmental perspective and the importance of long-term monitoring.

Finally, it should be noted that towards the end of this study (May 2015), a large flood event occurred within the Guadalupe River basin. Instantaneous flows from the USGS gage on the Guadalupe River at Gonzales (#08173900) peaked at over 44,000 cfs on May 25, 2015 and remained elevated for well over a month. The Guadalupe-Blanco River Authority recognized that this provided a unique opportunity to assess the impacts of such a flood event on both channel morphology and biological communities within the context of a recently completed instream flow study. As such, GBRA extended the study completion deadline and authorized separate GBRA funding to investigate hydraulic and biological factors that might require updating data, models, and analysis relative to the development of the instream flow recommendations. Descriptions of where this supplemental data was used to update existing bathymetry and further define flow-ecology relationships are provided within individual sections of this report.

2.0 DATA COLLECTION

2.1 RECON AND SITE SELECTION

A reconnaissance trip was conducted in May 2012 to examine the Gonzales to Cuero Reach of the lower Guadalupe River and assess potential study site locations. Two BIO-WEST biologists, assisted by one GBRA employee, covered the entire reach between Hwy. 183 at Gonzales and Hwy. 766 just north of Cuero by boat. Digital photographs and associated GPS waypoints were taken near areas of interest such as off-channel lakes/oxbows, riffle complexes, access points/boat launches, tributary mouths, and other unique habitat features.

Based on information gathered during this recon, as well as other available data, a study site was selected approximately 14 river miles downstream of the Hwy. 183 Bridge in Gonzales (**Figure 1**). This site was selected for several reasons, including: good access, presence of previous TPWD data from this site, diverse habitat conditions representative of the reach as a whole, and presence of a unique off-channel floodplain habitat a short distance upstream.

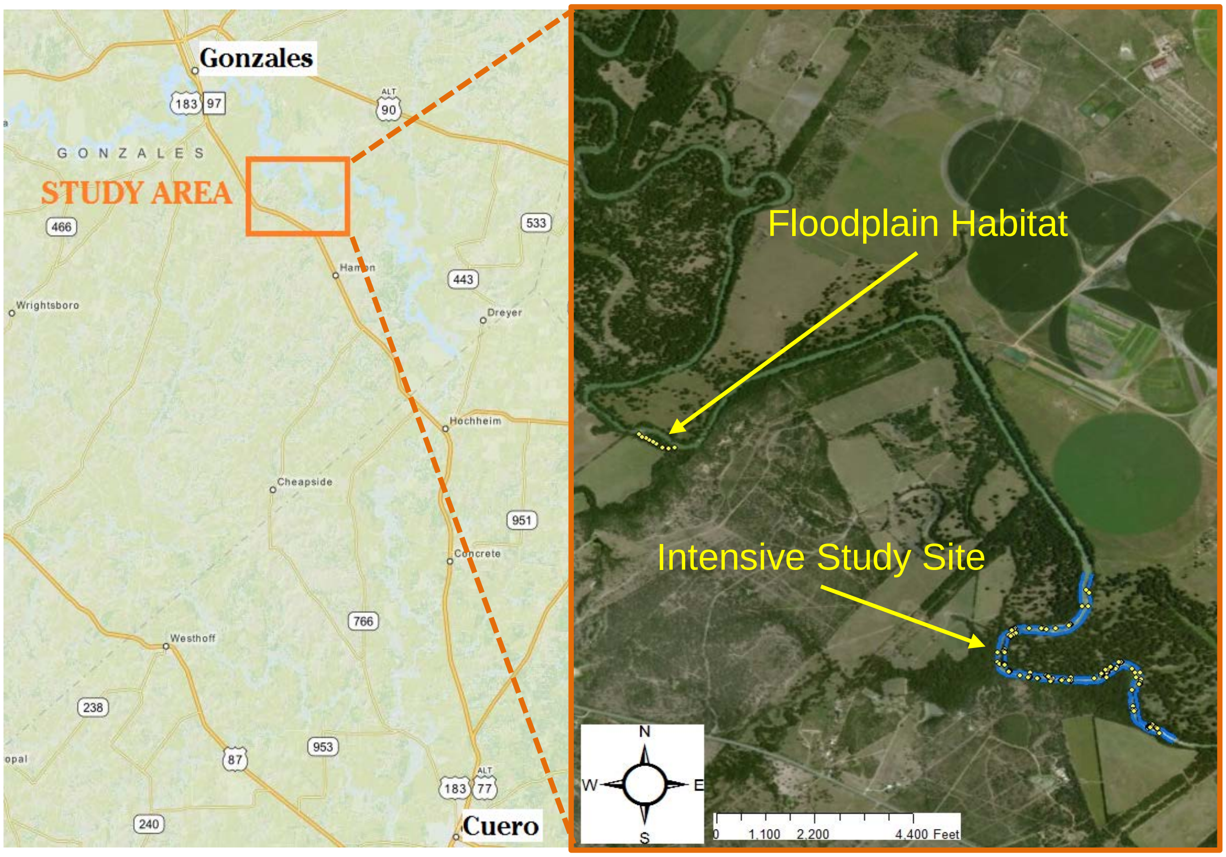

Figure 1. Map of study area showing general location and aerial view of intensive study site and floodplain habitat.

2.2 PHYSICAL DATA COLLECTION

2.2.1 SUBSTRATE MAPPING

Substrate mapping was conducted by wading/kayaking the site with a Trimble GeoExplorer 6000 Series GPS unit capable of sub-meter accuracy. In shallow areas, dominant surficial substrate was visually classified as clay, silt, sand, gravel, cobble, boulder, or bedrock based on standard Wentworth scale particle sizes. In deeper areas, dominant substrate was assessed by sounding with a survey rod. Occasional samples were collected to verify sounding in deep areas. Polygons were created to encompass areas of similar dominant substrate until the entire wetted area of the stream was mapped. ArcGIS software was then used to generate a map of dominant substrate within the study reach (**Figure 2**). A total of 72,904 square meters (m^2) were mapped. Of this, gravel was the most common substrate (50% of area mapped), followed by cobble (22%), bedrock (18%), sand (5%), and silt (4%). Clay and boulder each represented less that 1% of the total area mapped.

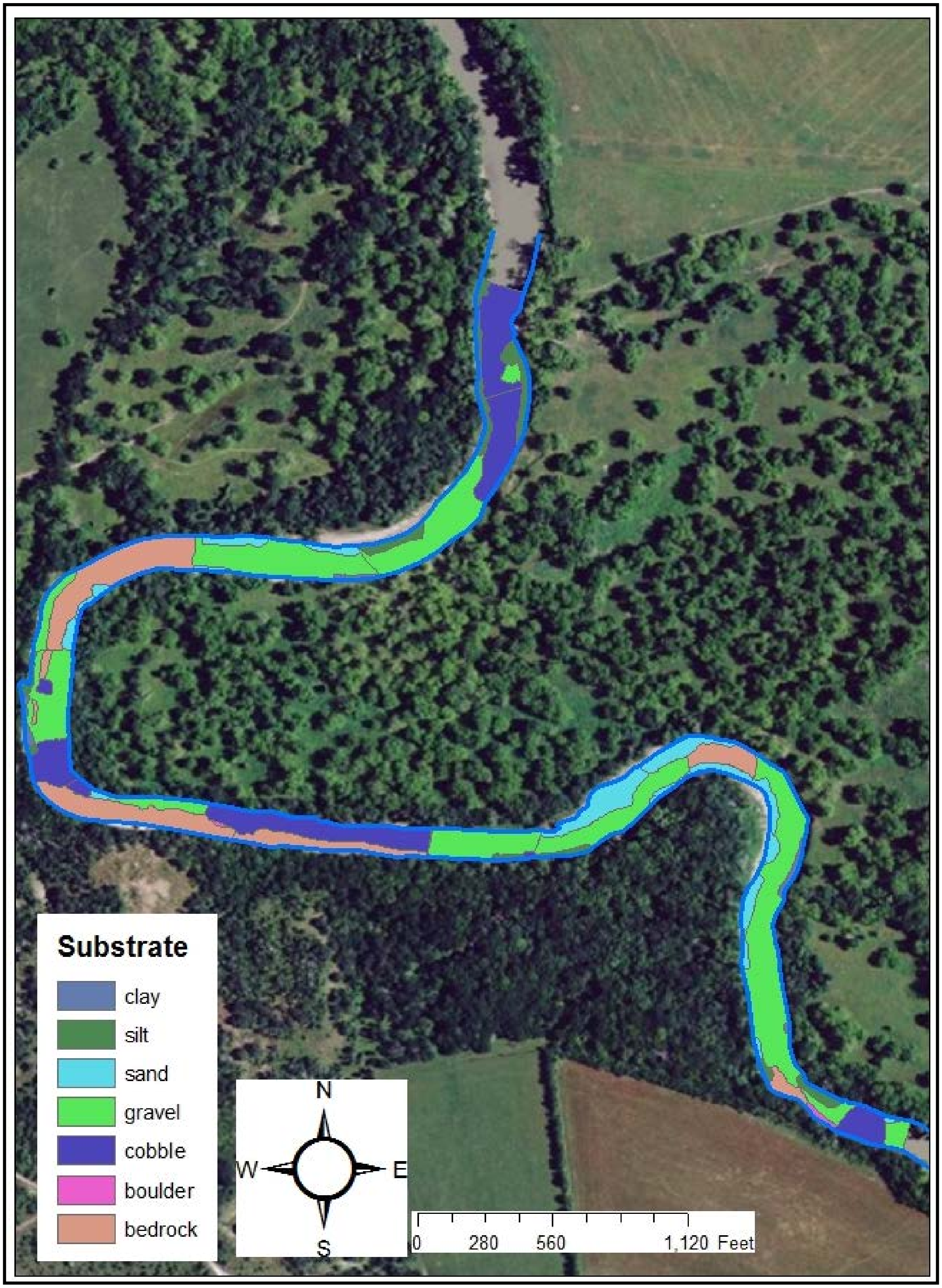

Figure 2. Map of dominant substrate within the study reach.

2.2.2 BATHYMETRY

2.2.2.1 2013 BATHYMETRY

To define the contours of the river bed for use in hydraulic modeling, bathymetric data was first collected from the study reach during November 2013 at discharges of approximately 1,800 – 2,000 cfs. Most data was collected using a SonTek M9 River Surveyor Acoustic Doppler Current Profiler (ADCP) mounted to a small john boat (**Figure 3**). This unit simultaneously collects data on water column depth, velocity, and instrument position multiple times per second. By maneuvering the instrument in a grid-like fashion across the study reach, a detailed georeferenced depth dataset was generated (**Figure 4**). Bathymetric data collection was targeted at a relatively stable period of high flows following a pulse event. The increased depth present during high flows allowed for bathymetric data to be collected even in areas of the site where it was typically too shallow to maneuver the boat. In areas where it was still too shallow for the boat, such as around islands or riffle edges, additional georeferenced depth data points were collected with a wading rod and Trimble GPS unit. These additional points were then combined with data collected from the boat-mounted M9 unit, and the resulting georeferenced depth dataset was tied to water surface elevations collected on the same day to generate a Digital Elevation Model (DEM) of the river bed within the study reach.

Figure 3. SonTek M9 River Surveyor mounted on a small john boat.

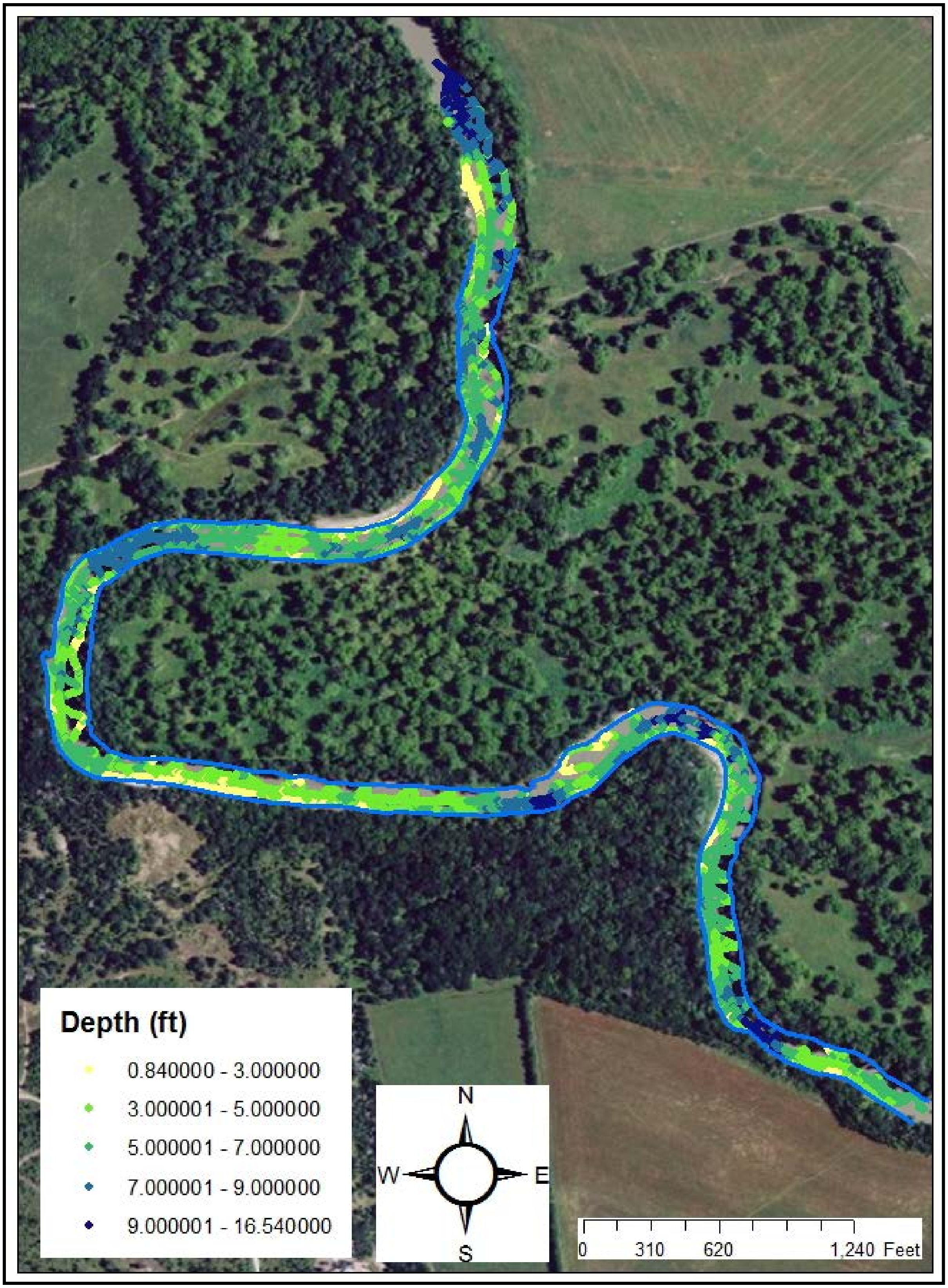

Figure 4. Map of bathymetric data collected from the study reach in 2013.

2.2.2.2 UPDATED 2015 BATHYMETRY

During model development, a large flood event in May 2015 resulted in peak discharges in excess of 40,000 cfs at the USGS gage (#08173900) on the Guadalupe River at Gonzales. Given the potential for a flood of this magnitude to alter the bathymetry within the study reach, and therefore influence fish habitat modeling results, the decision was made to collect additional bathymetric data post-flood. This allowed for a comparison of pre- and post-flood bathymetry, and also allowed for collection of additional detail in complex areas identified during the initial 2013 effort, resulting in a more comprehensive and polished final mesh.

The updated bathymetric dataset included data from LiDAR datasets flown in 2011 (overbank terrestrial areas) and from in-channel elevation and depth data measured on-site in September 2015 (between-bank and submerged areas). The in-channel bathymetry data was developed using a combination of survey instrumentation including: survey-grade RTK GPS, total station, autolevel, and a boat-mounted M9 ADCP unit.

The total station and RTK GPS were used to characterize non-submerged bank areas (**Figure 5**). Nearly one thousand point measurements were collected along banks and bars to identify slope breaklines. The RTK GPS was used to measure location of reference points used during the survey. As in 2013, the M9 unit was used to measure water depth throughout the site along a boat path (**Figure 6**).

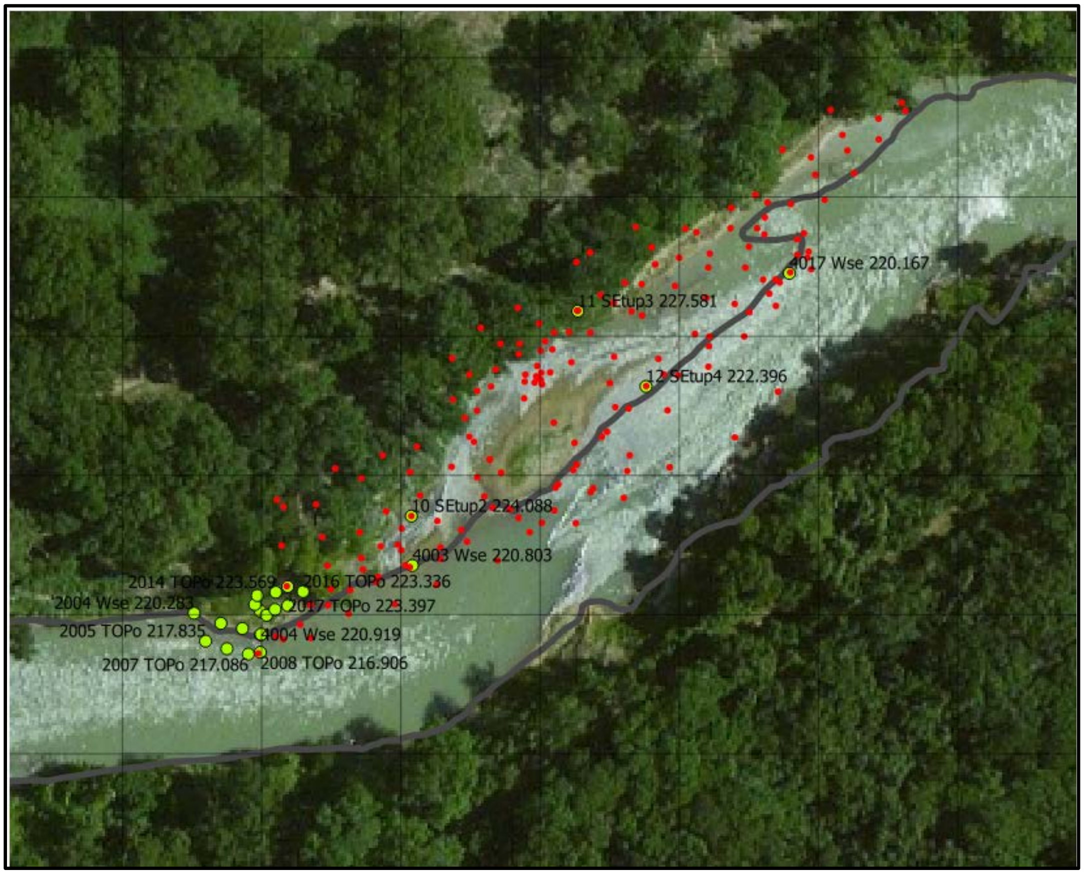

Figure 5. Site excerpt with example RTK GPS (green points) and total station (red points) data collected in September 2015.

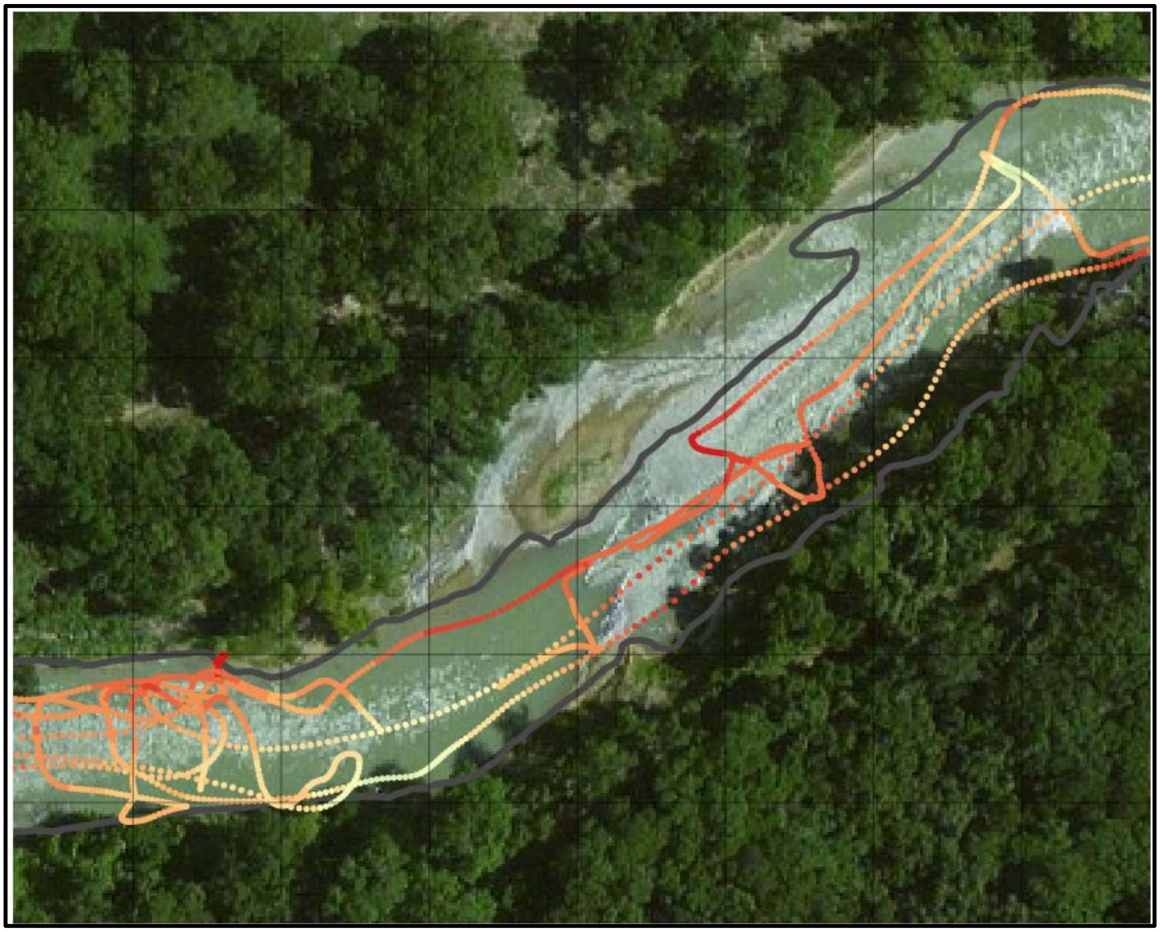

Figure 6. Site excerpt with M9 echosounder points collected in September 2015.

2.2.3 HYDRAULIC MEASUREMENTS

2.2.3.1 DISCHARGE MEASUREMENTS

On-site discharge measurements were taken using the SonTek M9 River Surveyor mentioned above or a Teledyne RDI StreamPro ADCP provided by GBRA. With the assistance of GBRA staff, most discharge measurements were taken at the same location – a deep run/pool area with relatively consistent depths, a bedrock substrate, and a relatively uniform and laminar flow pattern. Multiple measurements were taken and the mean discharge value was used.

2.2.3.2 WATER SURFACE ELEVATIONS

Two benchmarks were established as reference points for water surface elevations in October 2012. One benchmark was placed near the upstream boundary of the site, and one was placed near the downstream boundary. Upon each subsequent visit, water surface elevations were surveyed from these benchmarks using an autolevel or total station (**Figure 7**). Multiple measurements of water surface elevation were typically taken during each sampling event. The exact elevation of benchmarks was established using RTK GPS equipment. Water surface elevation data was collected at a range of discharges ranging from approximately 100 cfs to approximately 2,000 cfs.

Table 1 provides a summary of the date and discharge for each set of water surface elevation measurements.

In addition to measurements of upstream and downstream water surface elevation, complete water surface profiles were collected at multiple points using RTK GPS equipment during February 2014, May 2014, April 2015, and September 2015. These profile measurements were used in the development of the model grid, to convert M9 depth measurements to river bed elevation. Water level was interpolated for some flow rates where on-site data was not available. The water level was interpolated between known on-site measurements.

RTK GPS equipment was also used to collect elevation data at the floodplain area, and thus estimate the discharge at which this habitat connected to the river using linear interpolation from the upstream gauge (see Section 3.4).

Finally, a submersible pressure transducer (Solinst Levelogger) and associated Baralogger (for barometric compensation) was used to monitor short-term changes in water level at the site. This instrument, which was mounted to a post and submerged in the river, monitors water level every 15 minutes. It was installed with riparian equipment in summer 2013, and continually downloaded and monitored throughout the study period. Additional pressure transducers were installed at the upstream and downstream boundary to monitor water level changes during bathymetric data collection in September 2015.

Figure 7. Surveying water surface elevations from established benchmarks using autolevel (left) and total station (right).

Table 1. Date, approximate discharge range based on gage data and on-site measurements, and number of water surface elevation (WSE) measurements collected during each WSE data collection event.

Date	Approximate Discharge Range (cfs)	Number of WSE Measurements
October 22-25, 2012	215 – 650	10
January 22-24, 2013	428 – 662	7
May 29-30, 2013	883 - 1,770	9
September 3-6, 2013	94 – 143	9
November 7-8, 2013	1,827 - 2,110	5
December 10, 2013	316 – 378	3
January 6, 2014	349	1
February 18-19, 2014	412 – 590	30
May 15, 2014	533 – 802	19
April 2, 2015	606 – 718	25
September 8-9, 2015	580 – 729	50
Total		**168**

2.2.3.3 DEPTH/VELOCITY POINTS

Georeferenced depth and velocity data was also collected on several occasions for use in model calibration and validation. This data was collected in random locations within the wadeable portion of the site using a Marsh-McBirney Flowmate Model 2000 water current meter attached to an adjustable wading rod. Spatial data was simultaneously collected at each point with a Trimble GPS unit. Additionally, georeferenced depth and velocity data collected during fish habitat utilization sampling was also used for modeling purposes. **Table 2** provides the date, approximate discharge, and number of calibration/validation points collected.

Table 2. Date, discharge, and number of georeferenced depth/velocity points collected.

Date	Daily Mean Discharge (cfs)	Number of Points Collected
October 24, 2012	467	21
January 23, 2013	568	100
May 29, 2013	907	90
September 3, 2013	136	17
September 4, 2013	114	19
February 18, 2014	484	100
May 15, 2014	641	53
May 22, 2014	293	100
Total		**500**

2.2.4 WATER QUALITY

Water quality data was collected from the study reach during multiple sampling components over a wide range of discharge conditions as part of this study. Habitat-specific standard water quality parameters (temperature, dissolved oxygen, conductivity, pH) were collected at each fish habitat utilization sampling location, as described in Section 2.3.1.1. This represents 20 water quality point measurements collected seasonally for two years resulting in a total of 160 data points. Additionally, several multiple-day sonde deployments were conducted by GBRA staff while other sampling components were ongoing. This data allowed for analysis of diel swings in water quality parameters. Additional water quality data collected by GBRA and TPWD as part of the TIFP baseline aquatic surveys on the lower Guadalupe River were also analyzed. **Table 3** summarizes the available water quality data, along with sample date and discharge.

Table 3. Description of water quality data analyzed in this study along with associated dates and discharge.

Data Type	Collection Frequency	Number of Individual Measurements	Dates	Discharge (cfs)
Instantaneous point measurements	20 points/season for 2 years	160	July 2012 - May 2014	114 - 907
Multi-day diel deployment	hourly	54	January 22-24, 2013	436 - 733
Multi-day diel deployment	hourly	54	September 3-5, 2013	89 - 192
Multi-day diel deployment	15-minute interval	3153	August 15 - September 17, 2014	127 - 242

2.3 BIOLOGICAL DATA COLLECTION

2.3.1 FISHERIES DATA

2.3.1.1 HABITAT UTILIZATION SAMPLING

Fish habitat utilization data were collected seasonally from summer 2012 through spring 2014. This resulted in eight separate fish sampling events at flows ranging from 114 – 907 cfs (**Table 4**). During each sampling event, 20 separate microhabitats were sampled. To ensure samples were taken over a range of potential hydraulic habitat conditions, an effort was made to sample equal numbers of riffles, runs, pools, and backwaters over a variety of substrates. An attempt was made to sample fish from relatively small areas of approximately 3 meters x 3 meters with consistent depths, velocities, and substrates. However, exact size and dimensions of sample areas were often modified depending upon conditions encountered.

Table 4. Sampling event, date, and mean daily discharge measured from the USGS gage (#08173900) on the Guadalupe River at Gonzales.

Event	Date	Mean Daily Discharge (cfs)
Summer 2012	7/31/2012	381
Fall 2012	10/24/2012	467
Winter 2013	1/23/2013	568
Spring 2013	5/29/2013	907
Summer 2013	9/4/2013	114
Fall 2013	12/10/2013	369
Winter 2014	2/18/2014	484
Spring 2014	5/22/2014	293

Fishes were collected using a variety of methods including boat electrofishing, barge-style electrofishing, and seining to provide effective coverage of a wide range of habitats (**Figure 8**). In deeper areas (over approximately one meter) boat electrofishing was typically used. Seining was typically employed to most effectively sample shallower wadeable areas of slow to moderate velocity. In wadeable areas with large woody debris or coarse substrates that made seining difficult, barge-style electrofishing with a hand-held wand and 2-3 netters was used. In shallow high-velocity riffles and runs a barge electrofisher with hand-held wand was used with a seine set at the downstream boundary of the sampling area to collect stunned fishes. Sampling techniques were selected based on which would be most effective at capturing fish at each particular microhabitat given the depth, velocity, substrate, and cover conditions present. Once captured, larger fishes were identified to species, measured (total length in mm), enumerated, and released. Smaller fishes were often fixed in 10% formalin for later identification and enumeration in the laboratory.

Upon completion of fish sampling, velocity (ft/s), depth (ft), and dominant substrate were characterized at five points representing each corner and the middle of the sample area. Velocity and depth were measured using a Marsh-McBirney Flowmate Model 2000 portable flow meter and incremental wading rod. Dominant surficial substrates were classified as silt, sand, gravel, cobble, boulder, or bedrock following the standard Wentworth scale based on particle size. Physicochemical water quality field parameters were also measured in each sample area with a calibrated multiprobe instrument.

Figure 8. Examples of boat (top) and barge-style (bottom) electrofishing.

A total of 15,258 fishes representing 14 families and 37 species was collected from 160 distinct microhabitats during fish habitat utilization sampling (**Table 5**). Red Shiner *Cyprinella lutrensis* was by far the most abundant species, representing 58% of all individuals collected. Other abundant species included Western Mosquitofish *Gambusia affinis* (9%), Bullhead Minnow *Pimephales vigilax* (9%), Mimic Shiner *Notropis volucellus* (6%), and Ghost Shiner *Notropis buchanani* (6%). No threatened or endangered fish species were collected. However, four noteworthy regionally endemic species were collected - Gray Redhorse *Moxostoma congestum* (1%), Burrhead Chub *Macrhybopsis marconis* (1%, **Figure 9**), Guadalupe Darter *Percina apristis* (<1%), and Texas Logperch *Percina carbonaria* (<1%).

Figure 9. Burrhead chub captured in a seine.

Table 5. Number (#) and percent relative abundance (%) of fishes captured during habitat utilization sampling on the Guadalupe River near Gonzales, Texas.

Family	Scientific name	Common name	Summer 2012		Fall 2012		Winter 2013		Spring 2013		Summer 2013		Fall 2013		Winter 2014		Spring 2014		Total	
			#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%
Lepisosteidae	*Lepisosteus oculatus*	Spotted Gar			2	0.0			2	0.1		0.0	1	0.1		0.0		0.0	5	0.0
	Lepisosteus osseus	Longnose Gar	2	0.2	2	0.0			4	0.1		0.0		0.0		0.0		0.0	8	0.1
Clupeidae	*Dorosoma cepedianum*	Gizzard Shad	9	0.8	1	0.0	5	0.3	29	1.0	3	0.1	12	1.0		0.0	2	0.1	61	0.4
Cyprinidae	*Campostoma anomalum*	Central Stoneroller							62	2.2	3	0.1		0.0		0.0		0.0	65	0.4
	Cyprinella lutrensis	Red Shiner	784	66.4	2602	61.1	701	48.9	1898	65.8	1057	47.3	682	58.8	522	80.8	642	44.0	8888	58.3
	Cyprinus carpio	Common Carp			1	0.0						0.0		0.0		0.0		0.0	1	0.0
	Macrhybopsis marconis	Burrhead Chub	24	2.0	48	1.1	14	1.0	1	0.0	22	1.0	1	0.1	5	0.8	22	1.5	137	0.9
	Notropis buchanani	Ghost Shiner	1	0.1	516	12.1	21	1.5	74	2.6		0.0	6	0.5		0.0	326	22.3	944	6.2
	Notropis volucellus	Mimic Shiner	17	1.4	34	0.8	11	0.8	454	15.7	228	10.2	209	18.0	26	4.0		0.0	979	6.4
	Pimephales vigilax	Bullhead Minnow	65	5.5	450	10.6	418	29.2	39	1.4	180	8.1	108	9.3	41	6.3	112	7.7	1413	9.3
Catostomidae	*Carpiodes carpio*	River Carpsucker			1	0.0						0.0		0.0		0.0		0.0	1	0.0
	Ictiobus bubalus	Smallmouth Buffalo	2	0.2	1	0.0	1	0.1			2	0.1		0.0	1	0.2	3	0.2	10	0.1
	Moxostoma congestum	Gray Redhorse	2	0.2	4	0.1			47	1.6	2	0.1	6	0.5	2	0.3	154	10.5	217	1.4
Characidae	*Astyanax mexicanus*	Mexican Tetra	1	0.1	1	0.0						0.0		0.0		0.0		0.0	2	0.0
Ictaluridae	*Ictalurus furcatus*	Blue Catfish	1	0.1								0.0		0.0	1	0.2		0.0	2	0.0
	Ictalurus punctatus	Channel Catfish	8	0.7	17	0.4	4	0.3	4	0.1	12	0.5	2	0.2	2	0.3	1	0.1	50	0.3
	Pylodictis olivaris	Flathead Catfish	10	0.8					2	0.1	14	0.6		0.0	3	0.5		0.0	29	0.2
Mugilidae	*Agonostomus monticola*	Mountain Mullet					1	0.1			2	0.1	2	0.2	1	0.2		0.0	6	0.0
Atherinopsidae	*Menidia beryllina*	Inland Silverside			4	0.1	10	0.7	19	0.7	5	0.2	4	0.3		0.0	8	0.5	50	0.3
Fundulidae	*Fundulus notatus*	Blackstripe Topminnow	1	0.1							11	0.5	1	0.1		0.0		0.0	13	0.1
Poeciliidae	*Gambusia affinis*	Western Mosquitofish	170	14.4	367	8.6	142	9.9	80	2.8	490	21.9	52	4.5	3	0.5	114	7.8	1418	9.3
	Poecilia formosa	Amazon Molly										0.0	2	0.2		0.0		0.0	2	0.0
	Poecilia latipinna	Sailfin Molly	9	0.8	103	2.4	28	2.0	3	0.1	76	3.4	19	1.6		0.0	1	0.1	239	1.6
Centrarchidae	*Lepomis auritus*	Redbreast Sunfish									1	0.0		0.0		0.0		0.0	1	0.0
	Lepomis cyanellus	Green Sunfish	9	0.8	3	0.1	4	0.3	3	0.1	1	0.0		0.0		0.0		0.0	20	0.1
	Lepomis gulosus	Warmouth					1	0.1	1	0.0		0.0		0.0		0.0		0.0	2	0.0
	Lepomis macrochirus	Bluegill			4	0.1	7	0.5	2	0.1	2	0.1	4	0.3	2	0.3	3	0.2	24	0.2
	Lepomis megalotis	Longear Sunfish	30	2.5	73	1.7	37	2.6	48	1.7	62	2.8	24	2.1	25	3.9	6	0.4	305	2.0
	Lepomis microlophus	Redear Sunfish	1	0.1								0.0		0.0		0.0		0.0	1	0.0
	Lepomis sp.	sunfish										0.0	5	0.4		0.0		0.0	5	0.0
	Micropterus punctulatus	Spotted Bass	10	0.8	12	0.3	5	0.3	80	2.8	24	1.1	6	0.5	2	0.3	2	0.1	141	0.9
	Micropterus salmoides	Largemouth Bass									1	0.0	2	0.2		0.0	39	2.7	42	0.3
	Pomoxis annularis	White Crappie			1	0.0						0.0		0.0		0.0		0.0	1	0.0
Percidae	*Percina apristis*	Guadalupe Darter	3	0.3	1	0.0			21	0.7	3	0.1	1	0.1		0.0	1	0.1	30	0.2
	Percina carbonaria	Texas Logperch	2	0.2					4	0.1	1	0.0		0.0		0.0	8	0.5	15	0.1
	Percina shumardi	River Darter	17	1.4	4	0.1	22	1.5	3	0.1	10	0.4	10	0.9	8	1.2	16	1.1	90	0.6
Sciaenidae	*Aplodinotus grunniens*	Freshwater Drum			2	0.0			2	0.1		0.0		0.0	1	0.2		0.0	5	0.0
Cichlidae	*Herichthys cyanoguttatus*	Rio Grande Cichlid	2	0.2	7	0.2	1	0.1	1	0.0	23	1.0	1	0.1	1	0.2		0.0	36	0.2
Total Individuals			**1180**		**4261**		**1433**		**2883**		**2235**		**1160**		**646**		**1460**		**15258**	
Species			**24**		**26**		**19**		**25**		**25**		**22**		**17**		**18**		**37**	

2.3.1.2 FLOODPLAIN FISH SAMPLING

In addition to fish habitat utilization data collected at the intensive study site, additional fisheries data was also collected in an off-channel floodplain lake a short distance upstream. This area is a remnant side channel, most of which is only occasionally connected to the main stem. During typical base flow conditions, this channel consists of a series of 2-4 isolated pools of varying depths, disconnected from the main stem of the river. The goal of this analysis was to collect seasonal fisheries data from this unique habitat, estimate the discharge required to connect the channel to the main river, and examine how connection influences community composition.

During each seasonal fish collection event, fish community data was collected from the floodplain lake using seines (**Figure 10**). After each seine haul, fish were temporarily placed in a bucket containing river water. Once seining was complete in a given pool, larger fishes were identified to species, measured, enumerated, and released. Smaller fishes were often fixed in 10% formalin for identification and enumeration in the laboratory.

A total of 6,519 individual fishes representing 11 families and 32 species were captured from the floodplain area (**Table 6**). Overall, Western Mosquitofish was the most abundant species (48% of all fishes captured), followed by Red Shiner (11%), Gizzard Shad *Dorosoma cepedianum* (8%), and Mimic Shiner (8%). Longear Sunfish *Lepomis megalotis* (4%) and Bluegill *Lepomis macrochirus* (4%) were also relatively abundant. No threatened, endangered, or exceptionally rare fishes were collected. Although two regionally endemic species were collected (Gray Redhorse and Guadalupe Darter), both were rather rare in the floodplain lake, and were much more abundant in swifter areas of the main river channel. Eight species were unique to the floodplain lake, and were not captured in the river during fish habitat utilization sampling – Threadfin Shad *Dorosoma petenense*, Golden Shiner *Notemigonus crysoleucas*, Pugnose Minnow *Opsopoeodus emiliae*, Black Bullhead *Ameiurus melas*, Striped Mullet *Mugil cephalus*, Orangespotted Sunfish *Lepomis humilis*, Bluntnose Darter *Etheostoma chlorosoma*, and Slough Darter *Etheostoma gracile*. Excluding Striped Mullet, which is an estuarine species that often migrates long distances upstream in Gulf Coast rivers, all of these species are typically found in sluggish areas of sloughs, oxbows, and low gradient streams and rivers. Therefore, their occurrence in the floodplain lake and absence from the main river is not surprising, and demonstrates the ecological importance of such floodplain habitats in maintaining basin-level diversity.

Figure 10. Seining to capture fish in the floodplain lake.

Table 6. Number (#) and percent relative abundance (%) of fishes captured from a floodplain lake of the lower Guadalupe River near Gonzales, Texas.

Family	Scientific name	Common name	Summer 2012		Fall 2012		Winter 2013		Spring 2013		Summer 2013		Fall 2013		Winter 2014		Spring 2014		Total	
			#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%
Lepisosteidae	*Lepisosteus oculatus*	Spotted Gar							2	0.5							2	0.1	**4**	0.1
	Lepisosteus osseus	Longnose Gar	1	0.1					3	0.7									**4**	0.1
Clupeidae	*Dorosoma cepedianum*	Gizzard Shad	54	4.2			1	1.3	189	45.2							280	20.6	**524**	8.0
	Dorosoma petenense	Threadfin Shad	18	1.4							2	0.1							**20**	0.3
Cyprinidae	*Cyprinella lutrensis*	Red Shiner	6	0.5	68	24.9	5	6.7	52	12.4	2	0.1	77	32.6	464	33.6	60	4.4	**734**	11.3
	Notemigonus crysoleucas	Golden Shiner	20	1.5			6	8.0			8	0.5					6	0.4	**40**	0.6
	Notropis buchanani	Ghost Shiner	9	0.7			1	1.3											**10**	0.2
	Notropis volucellus	Mimic Shiner	41	3.2					2	0.5	1	0.1	1	0.4	476	34.4			**521**	8.0
	Opsopoeodus emiliae	Pugnose Minnow	15	1.2															**15**	0.2
	Pimephales vigilax	Bullhead Minnow	39	3.0	7	2.6	7	9.3	5	1.2	5	0.3	33	14.0	67	4.8	2	0.1	**165**	2.5
Catostomidae	*Carpiodes carpio*	River Carpsucker	1	0.1													7	0.5	**8**	0.1
	Ictiobus bubalus	Smallmouth Buffalo					1	1.3	6	1.4							2	0.1	**9**	0.1
	Moxostoma congestum	Gray Redhorse					1	1.3									21	1.5	**22**	0.3
Ictaluridae	*Ameiurus melas*	Black Bullhead	3	0.2	11	4.0			9	2.2	13	0.9					2	0.1	**38**	0.6
Mugilidae	*Mugil cephalus*	Striped Mullet							1	0.2									**1**	0.0
Atherinopsidae	*Menidia beryllina*	Inland Silverside					1	1.3			4	0.3	5	2.1					**10**	0.2
Poeciliidae	*Gambusia affinis*	Western Mosquitofish	915	70.8	143	52.4	2	2.7	79	18.9	1118	75.3	38	16.1	174	12.6	655	48.2	**3124**	47.9
	Poecilia formosa	Amazon Molly							1	0.2									**1**	0.0
	Poecilia latipinna	Sailfin Molly	1	0.1			1	1.3			50	3.4					8	0.6	**60**	0.9
Centrarchidae	*Lepomis cyanellus*	Green Sunfish	11	0.9	2	0.7	2	2.7	5	1.2	12	0.8							**32**	0.5
	Lepomis gulosus	Warmouth	11	0.9			1	1.3	2	0.5	70	4.7	1	0.4	2	0.1	2	0.1	**89**	1.4
	Lepomis humilis	Orangespotted Sunfish	13	1.0	12	4.4	1	1.3			7	0.5			102	7.4	100	7.4	**235**	3.6
	Lepomis macrochirus	Bluegill	19	1.5	9	3.3	17	22.7	17	4.1	56	3.8	30	12.7	71	5.1	57	4.2	**276**	4.2
	Lepomis megalotis	Longear Sunfish	24	1.9	19	7.0	20	26.7	41	9.8	103	6.9	21	8.9	19	1.4	24	1.8	**271**	4.2
	Lepomis microlophus	Redear Sunfish							1	0.2	1	0.1	3	1.3					**5**	0.1
	Lepomis sp.	sunfish	36	2.8							10	0.7	21	8.9			63	4.6	**130**	2.0
	Micropterus punctulatus	Spotted Bass	4	0.3			1	1.3	3	0.7									**8**	0.1
	Micropterus salmoides	Largemouth Bass	3	0.2							9	0.6	2	0.8			32	2.4	**46**	0.7
	Pomoxis annularis	White Crappie	44	3.4			5	6.7			1	0.1							**50**	0.8
Percidae	*Etheostoma chlorosoma*	Bluntnose Darter	1	0.1			2	2.7					3	1.3	7	0.5	21	1.5	**34**	0.5
	Etheostoma gracile	Slough Darter									1	0.1					14	1.0	**15**	0.2
	Percina apristis	Guadalupe Darter											1	0.4					**1**	0.0
Cichlidae	*Herichthys cyanoguttatus*	Rio Grande Cichlid	3	0.2	2	0.7					12	0.8							**17**	0.3
Total Individuals			**1292**		**273**		**75**		**418**		**1485**		**236**		**1382**		**1358**		**6519**	
Species			**23**		**9**		**18**		**17**		**19**		**12**		**9**		**18**		**32**	

2.3.2 FRESHWATER MUSSEL DATA

Little information is currently available on the distribution and abundance of freshwater mussels within the lower Guadalupe River. Therefore, freshwater mussel sampling was conducted to assess the species present within the study reach and gather data on community composition. A reconnaissance level mussel survey was conducted in August 2012. The goal of this survey was to assess the general abundance of mussels within the study reach, become familiar with the species present, and examine general habitat associations to assist in guiding future sampling efforts. More targeted seasonal surveys were then conducted for one year - occurring in October 2012, January 2013, May 2013, and September 2013. During each seasonal survey, six to eight separate locations were sampled using timed searches to standardize effort. Sampling locations were chosen to incorporate a variety of hydraulic habitat types (e.g., riffle, run, pool), and a GPS waypoint was collected near the center of each area. One person-hour of effort was conducted at each site. Mussels were located by both visual and tactile surveying methods, depending upon conditions encountered. SCUBA or Hookah dive gear was used to sample deeper runs and pools.

Overall, 1,212 individual mussels were collected during 32 person-hours of effort (Figure 11). This translates to an overall catch-per-unit-effort (CPUE) of 38 mussels/person-hour demonstrating freshwater mussels are common within the study reach. Threeridge *Amblema plicata* was by far the most abundant species, making up approximately 54% of all individuals collected (**Table 7**). Other common species included Golden Orb *Quadrula aurea* (20%), Texas Pimpleback *Quadrula petrina* (10%), Washboard *Megalonaias nervosa* (7%), and Yellow Sandshell *Lampsilis teres* (6%).

Three of the species collected (Golden Orb, Texas Pimpleback, and False Spike *Fusconaia mitchelli*) are recognized as “Threatened” by TPWD (**Figure 11**). Two of these (Golden Orb and Texas Pimpleback) are also candidates for listing under the Endangered Species Act. The third (False Spike) was once thought to be extinct before recently being collected during this study and at several other locations in the Guadalupe, Colorado, and Brazos River basins by other researchers (Randklev et al. 2013). Although Golden Orb and Texas Pimpleback are common to abundant in other locations, the lower Guadalupe River seems to be a stronghold for the False Spike, which is present but rare in other basins. Although False Spike was not abundant at this study site, it was consistently collected. False Spike was captured during each sampling event, and generally comprised approximately 2% of individuals collected.

Table 7. Number (#) and percent relative abundance (%) of freshwater mussels captured from the Guadalupe River near Gonzales, Texas.

Scientific Name	Common Name	October 2012		January 2013		May 2013		September 2013		Overall	
		#	%	#	%	#	%	#	%	#	%
Amblema plicata	Threeridge	112	55.7	107	50.5	107	45.0	324	57.8	650	53.6
Quadrula aurea	Golden Orb	48	23.9	26	12.3	50	21.0	116	20.7	240	19.8
Quadrula petrina	Texas Pimpleback	3	1.5	35	16.5	28	11.8	58	10.3	124	10.2
Megalonaias nervosa	Washboard	27	13.4	8	3.8	10	4.2	35	6.2	80	6.6
Lampsilis teres	Yellow Sandshell	8	4.0	18	8.5	35	14.7	9	1.6	70	5.8
Fusconaia mitchelli	False Spike	3	1.5	4	1.9	5	2.1	13	2.3	25	2.1
Cyrtonaias tampicoensis	Tampico Pearlymussel			10	4.7	2	0.8	5	0.9	17	1.4
Lampsilis hydiana	Louisiana Fatmucket			3	1.4	1	0.4	1	0.2	5	0.4
Toxolasma texasense	Texas Lillyput			1	0.5					1	0.1
Total Individuals		**201**		**212**		**238**		**561**		**1212**	
Species		**6**		**9**		**8**		**8**		**9**	

Figure 11. Examples of freshwater mussels collected during field surveys.

Figure 12. State-threatened freshwater mussels captured from the Guadalupe River near Gonzales, Texas - False Spike (top), Texas Pimpleback (middle), and Golden Orb (bottom).

2.3.3 MACROINVERTEBRATE DATA

To examine the influence of substrate disturbance from pulse flow events on macroinvertebrate community dynamics, three macroinvertebrate sampling transects were established within the intensive study site and marked with a GPS waypoint. These sites were then repeatedly sampled over the course of the study following various flow conditions and pulses to examine changes in macroinvertebrate community composition. A total of seven macroinvertebrate sampling events were conducted between October 2012 and May 2014 at flows ranging from 136 – 1,550 cfs (**Table 8**).

Table 8. Macroinvertebrate sampling dates and associated mean daily discharge from the USGS gage (#08173900) on the Guadalupe River at Gonzales, Texas.

Date	Mean Daily Discharge (cfs)
October 23, 2012	455
January 22, 2013	586
May 28, 2013	1,550
September 3, 2013	136
December 10, 2013	369
February 1, 2014	471
May 22, 2014	293

During each macroinvertebrate sampling event, five individual kick net samples were taken from each transect using a standard D-frame kick net (**Figure 13**). Samples were rinsed, picked of large debris, preserved in 90% ethanol in leak proof containers, and brought back to the laboratory for identification and enumeration. After a kicknet collection was made from a particular point, depth and velocity was measured using a Marsh-McBirney Flowmate Model 2000 flowmeter and incremental wading rod.

Figure 13. Collecting a macroinvertebrate kicknet sample from a riffle.

Monitoring efforts of benthic macroinvertebrates conducted in riffles within the study site resulted in quantification of 21,709 total individuals, representing 18 orders (**Table 9**). Of the orders collected, mayflies (Ephemeroptera) were the most abundant, followed by caddisflies (Trichoptera), and then beetles (Coleoptera). Annelids were present in all sample events but were not keyed further as they were not considered an appropriate indicator for evaluating the effects of stream flow. Although there is not a wealth of macroinvertebrate data for this section of the lower Guadalupe River, Tolley (2000) had a study site in riffle habitat in the Gonzales study reach of the Guadalupe River just downstream of the City of Gonzales. This location is considerably above our study site, but within the same general Gonzales reach. Interestingly, Tolley (2000) also reported the three most abundant macroinvertebrates collected in riffles at her Gonzales location were mayflies, caddisflies, and beetles, in the same order of abundance as we observed over 15 years later.

Ephemeroptera, Plecoptera (stoneflies), and Trichoptera (EPT) were also characterized as these orders are commonly used as stream indicators. The presence and diversity (overall genera/species present) of these three taxa are metrics typically used to evaluate stream health. Overall, EPT accounted for 41% of all macroinvertebrates captured during the surveys suggesting a healthy macroinvertebrate community. Mayflies represented approximately 33% of all individuals collected (**Table 9)**. Among EPT’s, mayflies accounted for 65%, caddisflies comprised 33%, and stoneflies 2%. Of these three orders, caddisflies were slightly more diverse in genera (n=17) compared to mayflies (n=16), with only 1 genus of stonefly collected.

Table 9. Macroinvertebrates collected per sampling event.

Macroinvertebrate Classification			Sampling Events							
Order / Sub-Order	**Family**	**Genus**	**Oct-12**	**Jan-13**	**May-13**	**Sep-13**	**Dec-13**	**Feb-14**	**May-14**	**Total**
Ephemeroptera	Isonychiidae	*Isonychia sicca*	3	0	0	2	3	0	8	16
"	Leptohyphidae	*Leptohyphid* early instar	0	0	0	0	6	0	3	9
"	Leptohyphidae	*Tricorythodes*	72	5	54	126	35	3	96	391
"	"	*Leptohyphes*	11	288	0	50	15	0	8	372
"	"	*Vacupernius*	0	0	0	0	0	0	5	5
"	Heptageniidae	*Maccaffertium*	3	25	7	0	9	8	6	58
"	Caenidae	*Caenis*	14	59	2	10	0	0	0	85
"	Leptophlebiidae	*Thraulodes gonzalesi*	483	0	19	1,005	211	35	211	1,964
"	"	*Traverella presidiana*	411	766	15	3,402	93	3	277	4,967
"	"	*Neochoroterpes*	0	0	1	1	0	0	0	2
"	Baetidae	*Camelobaetidius*	217	434	19	287	15	4	217	1,193
"	"	*Fallceon quilleri*	153	105	10	233	21	3	216	741
"	"	*Paracloeodes minutus*	1	87	0	2	0	0	0	90
"	"	*Baetodes bibranchius*	0	0	0	0	1	0	0	1
"	"	*Baetis*	0	0	0	0	0	0	5	5
"	"	*Plauditus/Acentrella* early instar	0	0	0	1	0	0	0	1
Plecoptera	Perlidae	*Neoperla*	101	0	7	159	39	9	37	352
Trichoptera	Leptoceridae	*Oecitis*	6	190	14	11	0	0	20	241
"	"	*Nectopsyche*	0	39	3	0	2	0	0	44
"	Heliocopsychidae	*Helicopsyche*	269	2	253	446	19	5	18	1,012
"	Hydropsychidae	*Hydropsychidae* pupa	0	183	0	0	0	0	6	189
"	"	*Smicridea fasciatella*	2	1	0	14	2	1	80	100
"	"	*Cheumatopsyche*	11	6	81	325	37	4	1,221	1,685
"	"	*Hydropsyche*	4	108	0	8	10	2	88	220
	Hydroptilidae	*Hydroptilidae* pupa	1	18	2	0	0	0	0	21
"	"	*Hydroptila*	24	6	2	28	2	0	6	68
"	"	*Ochrotrichia*	3	85	1	7	0	0	5	101
"	"	*Ithytrichia*	0	3	0	1	0	0	0	4
"	"	*Mayatrichia*	0	0	0	0	0	0	0	0
"	"	*Metrichia*	3	15	0	7	0	0	12	37
"	Glossosomatidae	*Glossosomatidae* pupa	6	4	1	0	0	0	0	11
"	"	*Protoptila*	179	0	21	274	5	0	0	479
"	"	*Culoptila*	5	784	1	6	2	0	2	800
"	Polycentropodidae	*Neurclipsis*	0	15	0	0	0	0	1	16
Odonata/Zygoptera	Coenagrionidae	*Argia*	6	1	0	11	0	0	2	20
Odonata/Anisoptera	Libelullidae	*Brechymorhoga mendax*	0	2	1	0	0	0	1	4
"	Gomphidae	early instar	1	2	0	5	0	0	0	8
"	"	*Erpetogomphus*	0	0	0	0	2	0	1	3
"	Corixidae	*Trichocorixa*	0	0	0	0	0	0	9	9
Lepidoptera	Crambidae	*Petrophila*	9	3	9	7	1	0	21	50
Hemiptera	Veliidae	*Rhagovelia*	0	0	0	0	0	0	0	0
"	Naucoridae	*Cryphocricos*	0	0	0	0	0	0	0	0

Table 9 continued. Macroinvertebrates collected per sampling event.

Macroinvertebrate Classification			**Sampling Events**							
Order / Sub-Order	**Family**	**Genus**	**Oct-12**	**Jan-13**	**May-13**	**Sep-13**	**Dec-13**	**Feb-14**	**May-14**	**Total**
Coleoptera	Elmidae	*Heterelmis* larvae	0	31	0	3	1	0	4	39
"	"	*Heterelmis* adult	1	4	0	0	0	0	1	6
"	"	*Hexacylloepus ferrugineus* larvae	8	0	0	9	2	0	1	20
"	"	*Hexacylloepus ferrugineus* adult	1	4	0	17	8	1	16	47
"	"	*Stenelmis* larvae	387	3	133	1,031	260	41	345	2,200
"	"	*Stenelmis* adult	5	552	3	0	4	0	27	591
"	"	*Microcylloepus pusillus* larvae	2	3	0	11	0	0	0	16
"	"	*Microcylloepus pusillus* adult	3	4	0	12	7	0	6	32
"	"	*Neoelmis caesa* larvae	3	4	0	6	0	0	1	14
"	"	*Neoelmis caesa* adult	1	9	1	3	11	0	9	34
"	"	*Macrelmis* larvae	4	0	0	4	0	0	0	8
"	"	*Macrelmis* adult	0	0	0	0	0	0	1	1
"	"	*Dubiraphia* larvae	0	0	0	0	1	0	0	1
"	Dryopidae	*Helichus*	0	0	0	0	0	0	1	1
"	Hydrophilidae	*Berosus* larvae	0	0	0	0	0	0	0	0
Megaloptera	Corydalidae	*Corydalus*	34	1	0	81	5	3	3	127
"	Sisyride	*Sisyra*	0	0	0	0	0	0	1	1
Diptera	Empididae	*Hemerodromia*	0	13	0	1	1	0	3	18
"	Ceratopogonidae	*Ceratopogon*	0	7	0	1	0	0	0	8
"	"	*Culicoides*	0	3	0	1	0	0	0	4
"	"	*Bezzia*	0	2	0	0	0	0	0	2
"	Chironomidae									
"	"	*Chironomidae* pupa	10	30	0	0	0	0	0	40
	" Subfamily									
	" Chironomini		31	1	1	28	1	1	7	70
"	" Pupating Chironomini		0	0	17	249	29	9	87	391
"	" Tanytarsini		1	256	11	14	3	0	1	286
"	" Orthocladiinae		61	17	0	283	20	16	10	407
"	" Tanypodinae		9	278	0	66	2	5	18	378
"	" Pseudo chironomini		4	29	44	4	0	1	8	90
"	Simuliidae	*Simulium*	18	26	0	8	157	81	5	295
Amphipoda	Hyalellidae	*Hyalella*	0	0	1	1	1	0	0	3
"	Hydrobiidae		11	138	26	14	0	0	0	189
"	Physidae	*Physa*	0	3	6	1	0	0	0	10
"	Lymnaeidae		0	0	4	0	0	0	0	4
Veneroida	Corbiculida	*Corbicula*	129	30	25	456	18	5	38	701
"	Sphaeriidae		6	201	9	2	0	0	0	218
Unionoida	Unionidae	small	0	0	0	2	0	0	0	2
Ostrocada		*Ostrocada*	15	0	21	12	0	0	0	48
Turbellaria		*Turbellaria*	0	10	5	0	0	0	0	15
Hydracarina		*Hydracarina*	0	1	2	0	0	0	0	3
Hirudinea		*Hirudinea*	3	7	1	2	0	0	0	13
Nematoda		*Nematoda*	1	0	0	0	1	0	0	2
Annelida		*Annelida*	Present	Present	Present	Present	Present	Present	Present	Present
Total for each sampling event:			2,746	4,903	833	8,750	1,062	240	3,175	21,709

2.3.4 RIPARIAN DATA

The riparian study period extended over three growing seasons, from March 2013 through October 2015. Data was collected on seedling, sapling and tree size woody species in monitoring plots across the width of the riparian zone. Physical environmental variables including river level, discharge, rainfall, soil moisture, canopy closure and ground cover were also measured to assess the potential environmental flow needs of the riparian community at each site. The riparian sampling employed a random permanent transect method to locate 2-m x 2-m sample plots (4-m^2) in the riparian zone between the water's edge and the surrounding uplands. Three replicate transects were randomly located perpendicular to the river, within 300-ft of monitoring equipment. Along each transect, sample plots extended across the entire width of the bottomland hardwood riparian zone. To enable repeat sampling of each plot, the upstream side corners of plots were marked with ½ inch diameter rebar installed just above ground level and capped with a plastic survey marker. A PVC square was hooked onto the two corner rebar markers to designate each plot's boundary.

In order to characterize the topography of the site in relation to river stage, each transect was surveyed using a Nikon total station and Trimble S6 data collector to measure relative elevations of the transect profiles at an approximate 2 meter (6.6 ft.) horizontal scale at the onset of the study. The transect elevations were tied into a surveyed elevation benchmark at the site to adjust measurements to actual elevation. During the growing season, trees [>5 cm diameter at breast height (DBH)], saplings (1-5 cm DBH), and seedlings (<1 cm DBH) were counted and recorded by species in each plot (**Figure 14)**. Sampling was conducted from the upstream side of the transect line to prevent trampling of species. An estimate of canopy closure was measured on a densiometer at the center of each plot and an estimate of percent ground cover for live herbaceous plants, leaf or dead plant litter, large woody debris, and bare ground was made within each plot.

Figure 14. PVC square plot placed along the riparian transect.

A Solinst brand Levelogger Edge pressure transducer logger (PT) was installed in the river (in sediment-resistant housing) to record water level relative to the USGS gage flow record. Barometric pressure was recorded at each site using a Solinst brand Barologger to compensate PT measurements with local air pressure. Crest stage gages (**Figure 15)** were installed at the center transect to record the elevation of the flood crest of the river during overbank pulse events, at intervals across the riparian zone corresponding with the height of the gages and elevation gradient across the site. The gages were measured following each overbank pulse event.

Figure 15. Soil moisture recording equipment (left) and crest stage gage (right) along a riparian transect.

Soil moisture was recorded as volumetric water content (as measured by the dielectric constant of the soil) using HOBO EC-5 Soil Moisture Smart Sensors logging every 15 minutes. Soil moisture sensors were installed as an array at four depths (1-, 2-, 4-, and 6 feet) to capture the variation in the soil profile within a potential seedling's root zone. Soil moisture recording equipment was installed adjacent to each crest stage gage. To account for the influence of rainfall on soil moisture, precipitation was measured using an Onset (2011) electronic rain gage (installed nearby in an open canopy area) which recorded rainfall events in 0.01-inch increments.

Elevation above the stream was recorded along the transect lines and channel slope/stream bank profiles were generated. Measured site inundation stream flows were used both to determine direct water levels and to calibrate recorded flow to the USGS gage 08173900 (Guadalupe River at Gonzales). The USGS Gonzales gage was used for long-term, historical flows as calibrated by on-site measurements. First stream logger data was compared against corresponding USGS data, to determine corresponding flow events based on flow event timing and peak heights. Differences in peak height at the USGS gage and the study reach were then used to calibrate USGS flows to study reach elevations when datasets required stream flow measurements prior to logger installation (long-term flows) or when missing data.

Total number of seedlings, saplings and mature trees for each indicator species in each 2x2 transect plot were counted, and spatial coverage recorded during each sampling event except January 2015 (the deciduous trees were dormant). Age classes (life stages) were grouped into seedling, sapling and mature. Trees between 1 and 5 cm DBH were classified as saplings, and seedlings as <1 cm DBH or shorter than 1m; all other trees were classed as mature. Changes to site seedling, sapling, and mature counts through seasons were calculated to determine if stream flow had an effect on survival and/or recruitment.

Within channel flow pulses are important in regulating groundwater levels and providing soil moisture to tree species on the bank of the river. Over the course of the study (2012-2015), 68 days of greater than 4,000 cfs were recorded with 54 of them occurring during the incredibly wet 2015. Excluding two extended flooding events in May and October of 2015, the average duration of pulse flows greater than 3,000 cfs over this four-year period was 2.9 days. Overbank pulse events occur when the river level rises above the top of bank and spreads out into the floodplain. This type of pulse event is important for creating a connection between the river and riparian habitats, providing a source of soil moisture to the riparian area, creating scour along the bank where velocities are highest, and depositing seeds in different locations as the floodwater recedes. Based on observations at the site, an overbank pulse event occurs when discharge at the USGS Gonzales gage is approximately 12,000 cfs. During the aforementioned time period, 14 days were recorded greater than 12,000 cfs with 10 of them occurring in 2015. As previously noted, significant overbank conditions were experienced in November 2013, May 2015, and October 2015.

The relative abundance of woody species within the study plots are presented in **Table 10**. Collectively box elders were 10.8% of the forest and green ash are 16.8% for a combined total of 27.6% in September 2013. By March 2015 they were: box elder – 16.3% and green ash – 10.4%; for a combined total of 26.7%. This riparian zone is a diverse community, but recently it has seen a lot of encroachment from hackberry, and also is dominated more by dogwood than any other species. Dogwood is considered a riparian-functioning species.

The riparian analysis (Section 3.7) focuses on riparian indicator species, rather than the riparian community as a whole, in order to best determine short-term responses to stream flows. A set of key indicator species previously developed for the San Antonio River by Duke (2011) was chosen a priori for this study. These species include: Black willow (*Salix nigra*), Box elder (*Acer negundo*), and Green ash *(Fraxinus pennsylvanica*). These three species were selected as representatives of a healthy, functioning riparian zone because they are broadly distributed across the Guadalupe River watershed and are tightly connected to stream channel processes (primarily stream flow).

Table 10. Relative abundances of woody species at the Gonzales site, grouped by tree type and age class, and changes to abundances shown through time.

Tree Species	Class	September 2013 Relative Abundance (%)	March 2015 Relative Abundance (%)	Change (+/-)
American Elm	Mature	0.2	0.1	-0.1
American Elm	Sapling	0.9	0.9	0
American Elm	Seedling	0.4	0.3	-0.1
Anacua	Sapling	0.4	0.3	-0.1
Anacua	Seedling	0.2	0	-0.2
Box Elder	Mature	0.2	0.3	+0.1
Box Elder	Sapling	6.7	5.9	-0.8
Box Elder	Seedling	3.2	10.1	+6.9
Cedar Elm	Mature	0.4	0.3	-0.1
Cedar Elm	Sapling	8.2	8.6	+0.4
Cedar Elm	Seedling	7.7	6.2	-1.5
Cottonwood	Seedling	0.4	0	-0.4
Dogwood	Mature	13.7	12.8	-0.9
Dogwood	Seedling	3.7	3.7	0
Green Ash	Mature	0.2	0.1	-0.1
Green Ash	Sapling	6.7	7.3	+0.6
Green Ash	Seedling	9.9	3	-6.9
Gum Bumelia	Sapling	0	0.3	+0.3
Gum Bumelia	Seedling	0.7	2.1	+1.4
Hackberry	Mature	0.4	0.4	0
Hackberry	Sapling	2.4	0	-2.4
Hackberry	Seedling	23.8	23.5	-0.3
Pecan	Mature	0.4	0.3	-0.1
Pecan	Sapling	0.2	0.3	+0.1
Pecan	Seedling	4.5	0	-4.5
Slippery Elm	Sapling	0	0.3	+0.3
Slippery Elm	Seedling	3.6	7.6	+4.0
Sycamore	Mature	0.2	0.1	-0.1
Sycamore	Sapling	0.2	0.1	-0.1
Sycamore	Seedling	0	0.1	+0.1
Western Soapberry	Mature	6	0.6	-5.4

Several characteristics of these species make them valuable indicators of riparian health. Seedlings of these species are either tolerant of flooding or require considerable flooding to germinate. Black willows generally tend to drop seeds from April to July, which must then germinate immediately. Green ash and box elder generally tend to drop seeds in late fall and winter, but do not germinate until the next spring. Once germinated, all three indicator species then require periodic wetting in order to survive and thrive (Stromberg 1998). Small flow pulses facilitate resiliency to larger floods in young members of these species

(Middleton 2002). Lack of streamside soil moisture not only threatens seedlings (Smith et.al. 1998) but also allows for encroachment by upland plants (Myers 1989). Willows have been shown to be particularly sensitive to long-term flow alterations and susceptible to takeover by invasive species in areas of altered stream flows (Williams and Cooper 2005). Unfortunately, the randomly selected transects at this site did not include any black willows. However, the species counts by life stage for the box elder and green ash over the study period are presented in **Table 11**.

Table 11. Gonzales site species counts through time grouped by class.

Species	Class	Sep. 2013	Apr. 2014	Aug. 2014	Oct. 2014	Mar. 2015
Box Elder	Mature	1	1	2	2	2
Box Elder	Sapling	36	14	41	41	40
Box Elder	Seedling	17	8	12	10	68
Green Ash	Mature	1	1	2	2	1
Green Ash	Sapling	36	46	53	52	49
Green Ash	Seedling	53	23	37	38	20

3.0 MODELING AND ANALYSIS

3.1 HYDRAULIC MODELING

3.1.1 MODEL DESCRIPTION

The Adaptive Hydraulics (ADH) model was used for this project to generate a grid of velocity and depth values across the study site for a range of flow conditions. ADH was developed by the US Army Corps of Engineers (USACE) Engineering Research Development Center (ERDC) for hydrodynamic and sediment studies in river and coastal environments. ADH is a two dimensional (depth averaged, laterally varying) finite element model; a three dimensional version of ADH also exists for government research use. The Surface Water Modeling System (SMS) was used to adjust input files including finite element mesh, flow and water level series. SMS was also used to open, edit and save the output files in a GIS-usable format.

For this study, a preliminary model was constructed using bathymetry data collected in 2013. However, after the May 2015 flood, additional bathymetry data was collected and an updated model was developed. The final ADH model was developed using a 6-foot grid spacing within the channel, and a 15-foot grid spacing within overbank areas (**Figure 16**). While the model is running, the model can automatically adjust the grid size to be smaller and improve model stability in areas with complex geometry or flow patterns. Model units are English (feet and cubic feet per second [cfs]), with spatial reference to Texas State Plane South Central coordinate system (4204) and vertical reference NAVD88.

Bed roughness is the primary calibration parameter, and is implemented as a Manning's roughness value. Roughness can be different for each element. In this Guadalupe River model application of roughness values varied inside of polygons mapped on-site to delineate different substrate types including clay, silt, sand, gravel, cobble, boulder, and bedrock. A higher roughness value is applied to overbank areas. Values were adjusted (**Table 12**) during model calibration to promote match of predicted upstream water levels with observed upstream water levels.

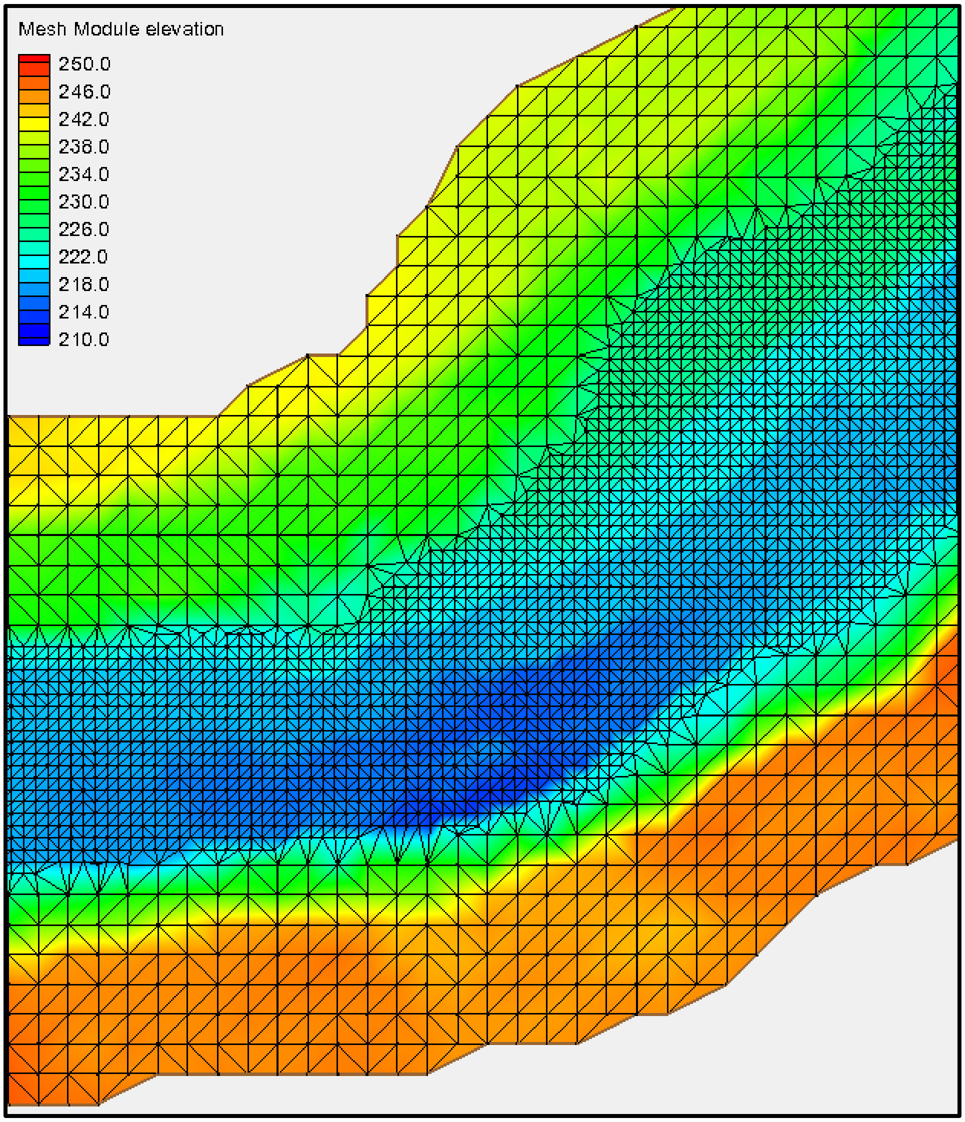

Figure 16. Sample image of grid with 6-foot in-channel spacing and 15-foot overbank spacing. Color contours are elevation in feet, NAVD88.

Table 12. Manning's n values used in calibrated model for each substrate type.

Substrate Type	**Manning's *n* roughness**
Clay	0.020
Silt	0.023
Sand	0.025
Gravel	0.027
Cobble	0.029
Boulder	0.060
Bedrock	0.020
Overbank	0.075

3.1.2 MODEL RESULTS

The updated model was run for a range of flow rates between 50 and 2,100 cfs. The model is executed by applying a flow rate at the upstream boundary of the model and a water level at the downstream boundary of the model. The model predicts water level at the upstream boundary based upon calculated hydrodynamic conditions within the site. This upstream boundary water surface elevation (US_WSE) is used as a measure to compare model predictions to on-site observations.

The mean difference between upstream water level predictions and observations is -0.07 feet, which means on average for all flow scenarios the model prediction is within 1 inch of the observations and there is a slight model bias to predict lower upstream water levels than observed. This model is within the typical desired tolerance of +/- 2 inches. Of 18 flow scenarios, half are within 1 inch, 14 are within 2 inches, and all are within 3 inches of observed upstream water surface elevation values (**Table 13**).

Table 13. Flow rate scenarios, water surface elevation, and 2015 model predictions.

Flow (cfs)	Downstream WSE (ft)	WSE Type	Upstream WSE (ft) Observed/Rating	Upstream WSE (ft) Model Prediction	Upstream WSE (ft) Difference
50	217.25	Rating	223.13	223.15	0.02
136	217.39	Observed	223.38	223.35	-0.03
225	217.80	Rating	223.62	223.61	-0.01
325	218.04	Rating	223.90	223.87	-0.02
427	218.23	Observed	224.19	224.13	-0.06
539	219.06	Observed	224.34	224.33	-0.01
625	218.54	Rating	224.66	224.58	-0.08
763	218.76	Rating	224.97	224.86	-0.11
763	219.45	Observed	224.80	224.85	0.05
818	218.85	Rating	225.10	224.99	-0.11
925	219.02	Rating	225.32	225.17	-0.15
1025	219.18	Rating	225.52	225.37	-0.15
1125	219.33	Rating	225.70	225.55	-0.15
1250	219.52	Rating	225.91	225.73	-0.18
1400	219.75	Rating	226.15	225.96	-0.19
1563	220.24	Observed	226.41	226.18	-0.23
1827	220.64	Observed	226.65	226.57	-0.08
2100	220.77	Rating	226.67	226.92	0.25
Average Difference					**-0.07**

The ADH model is based upon the updated bathymetry measured in 2015. Water level across the entire site experienced localized changes as a result of shifting bars and resculpted banks. Since model calibration data was measured over a longer period between 2012 and 2015, largely prior to the flood event in May 2015, validation using fall 2015 bathymetry is difficult because data is not available under current conditions across the range of flow levels. This condition of changing morphology is a common theme; the instream flow study initiated in the mid-1990s was interrupted by a major flow event, as was a study re-started in the mid-2000s, and now again in 2015. Only a very rapid and intense data measurement program may be able to measure the amount of data necessary to fully calibrate and validate a complex hydraulic and habitat model of this type. Ultimately, the channel is continuously evolving and the best analysis will take this into account by considering the relative range and distribution of relevant, representative habitats within a longer river segment and how those habitats change over a range of flow levels.

Because of factors discussed above, the 763 cfs model was executed for two water level scenarios: according to a stage rating developed using pre-2015 data, and according to the observed data measured on-site during the September 2015 resurvey (**Table 13**). These water levels changed after the 2015 flood event as a result of shifting gravel bars in the vicinity of the site boundaries.

Localized differences are also apparent when comparing the point velocity and depth measurements. Point observations at low flows were compared to model predictions located within a 10 foot radius of the point observations **(Figure 17**). The radius was used as a way to account for positional uncertainty resulting from GPS location measurements collected at different times using different types of GPS equipment. These are two significant factors when considering GPS accuracy characteristics.

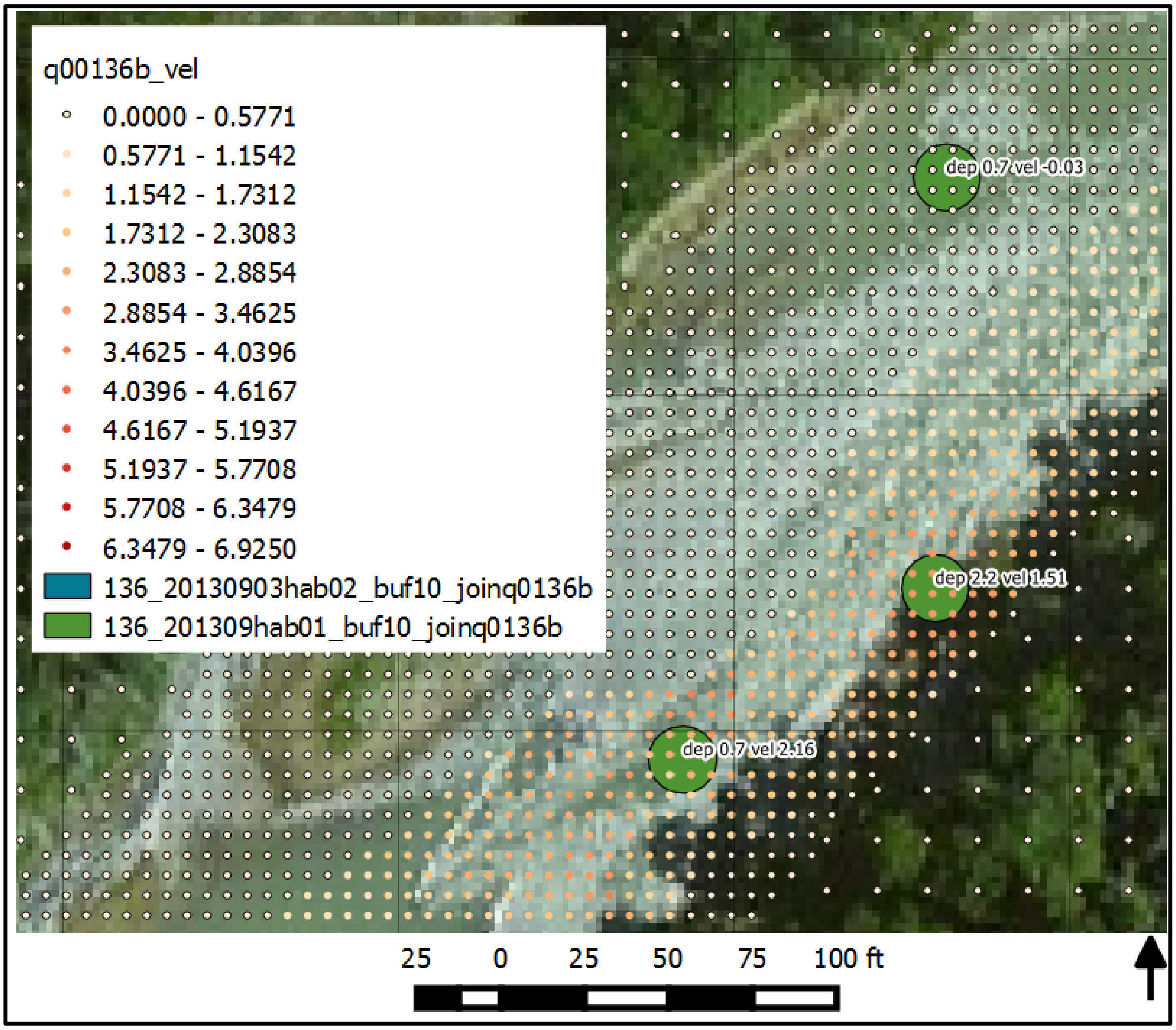

Figure 17. Comparison of depth and velocity point measurements to model predictions within 10-foot radius.

Comparison statistics were developed for each point measurement based upon the subset of model prediction points located inside the 10 foot radius. If the point observation value was within the range of model predictions, then a residual of 0.0 was assigned. For example, if the observed depth is 0.7 feet and the range of model predicted depths within the 10 foot radius are between 0.6 and 1.0, then the model prediction is consistent with the observation and the residual is zero feet. For the same 0.7 foot observation, if the model prediction range is between 0.8 and 1.0, then the residual is set at +0.10 feet since the range of model predictions was outside (higher than) the observation.

Comparison of depth observations and predictions indicates that approximately 38% of observation points correspond with zero residual to the model predictions (**Table 14**, row "%zeros"). The mean depth residual across all point observations (n =139 for 427 cfs and n=35 for 136 cfs) is 0.44 feet and 0.20 feet, respectively, indicating that the model may have a slight over-prediction of depth. Similarly for velocity, the percent of zero residuals is 34% and 54% with a mean velocity residual of +0.18 feet per second (fps) for 427 cfs and -0.14 fps for 136 cfs (**Table 15**).

Since a model had already been developed using 2013 model bathymetry and since that bathymetry may correspond more directly with point observations measured before the flood, comparison statistics were calculated using the original 2013 model results (see **Table 14** and **Table 15**). The comparison statistics are similar to statistics based upon the 2015 model.

Table 14. Comparison statistics of point depth observations and model predictions.

Model	**2015**	**2013**	**2015**	**2013**
Flow (cfs)	427	428	136	127
count	139	140	35	35
Residuals				
%zeros	38%	39%	37%	23%
min (ft)	-2.76	-1.37	-0.78	-1.76
mean (ft)	0.44	0.31	0.20	-0.09
max (ft)	7.95	3.76	2.13	2.18
RMSE (ft)	1.21	0.87	0.56	0.82

Table 15. Comparison statistics of point velocity observations and model predictions.

Model	**2015**	**2013**	**2015**	**2013**
Flow (cfs)	427	428	136	127
count	139	140	35	35
Residuals				
%zeros	34%	14%	54%	20%
min (fps)	-1.72	-1.21	-1.47	-0.99
mean (fps)	0.18	0.46	-0.14	0.04
max (fps)	3.01	2.81	0.94	1.45
RMSE (fps)	0.69	0.89	0.36	0.41

3.1.3 MORPHOLOGY CHANGES

Historical aerial photos allow for investigation of channel change migration patterns. Two areas within the study site were investigated using aerial imagery from January 1995, October 2008, and January 2015. Peak stream flow at the USGS Guadalupe River at Gonzales gaging station in each year for years between 1978 and 2014 range from 1,710 cfs in 2011 to almost 350,000 cfs in 1998 (**Figure 18**). Peak flow during the 2015 flood was approximately 45,000 cfs.

The bank line measured on-site during the post-flood resurvey in September 2015 was also used as part of this investigation to characterize current conditions. Whereas channel areas in straight river runs remain largely unchanged through the years, in bendways the largest bank shifts of 20 to 35 feet appear to have occurred during the 13 years between 1995 and 2008 (**Figure 19** and **Figure 20).** This is most likely an episodic change resulting from the major event flood in 1998 of approximately 350,000 cfs near the site and another major 100,000 cfs event in 2005.

Since 2006 no peak flow events have exceeded 50,000 cfs. Comparing the 2008 and 2015 bank lines, bank changes are localized within the channel and are most closely associated with migration and re-sculpting of in-channel gravel bars and habitats.

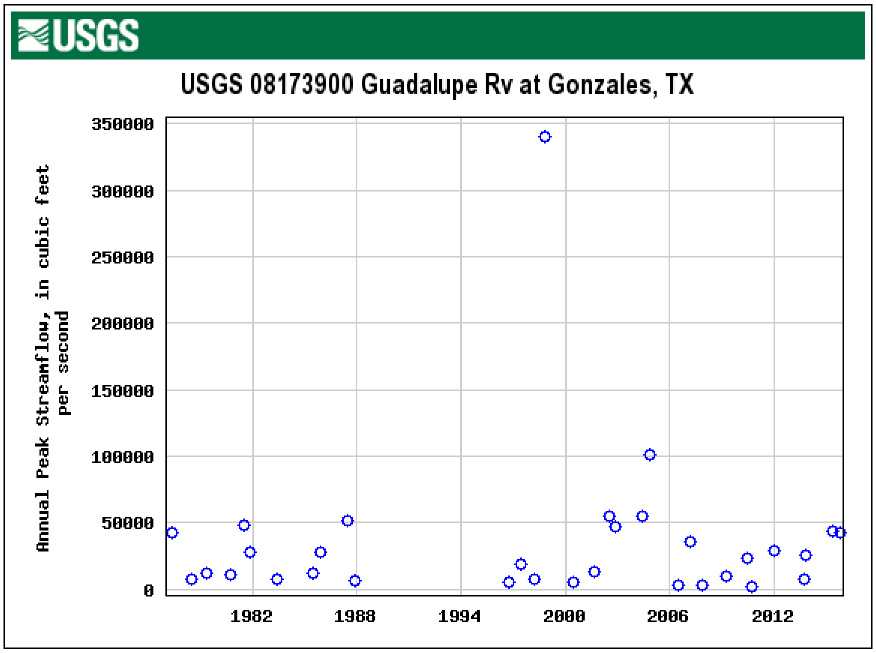

Figure 18. Peak streamflow records for each year at the USGS stream gage on the Guadalupe River at Gonzales, Texas (#08173900).

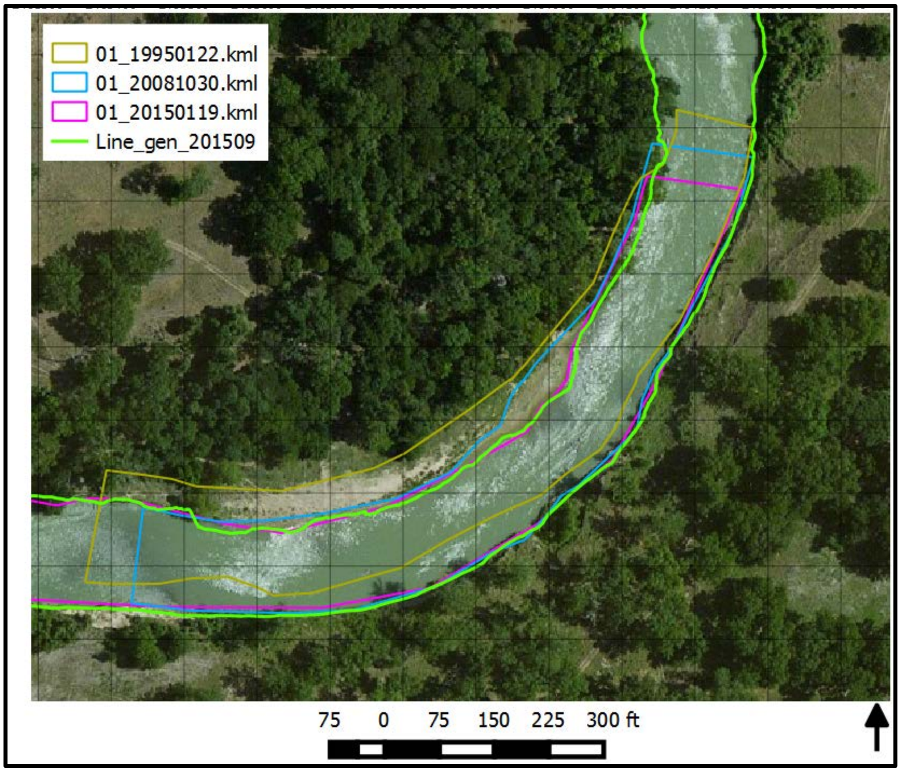

Figure 19. Location of bank lines near the upstream end of the site in 1995, 2008, and 2015.

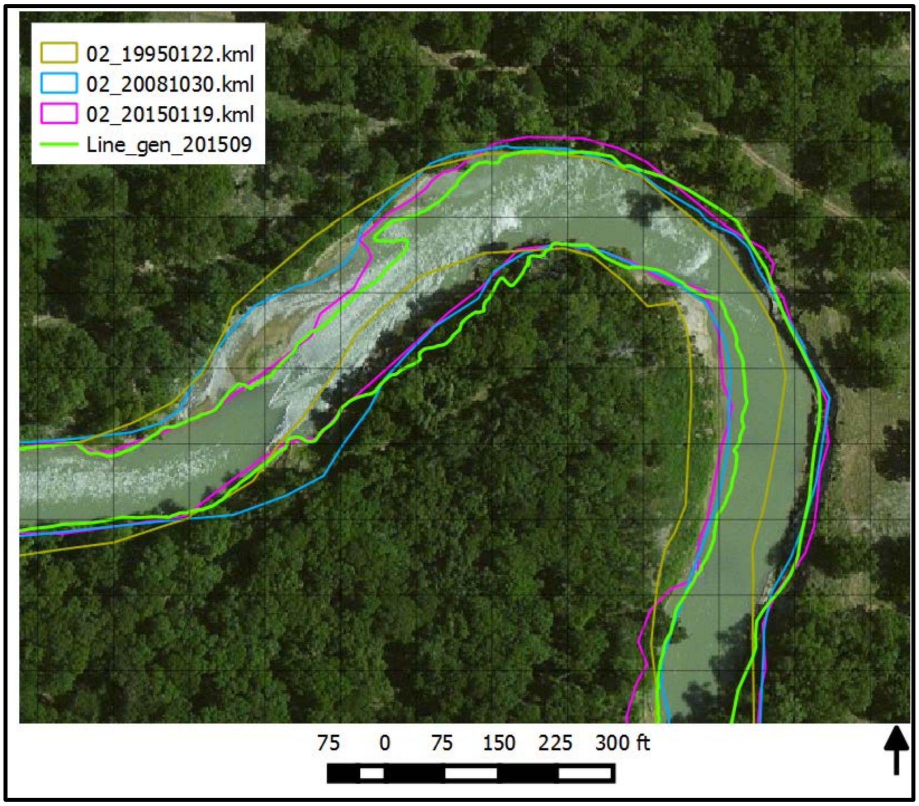

Figure 20. Location of bank lines near the downstream end of the site in 1995, 2008, and 2015.

To evaluate the degree of morphologic change of in-channel habitats, the 2015 model surface was compared to the 2013 model surface to identify areas of sediment accumulation and sediment erosion (**Figure 21** and **Figure 22**, green represents erosion and brown represents deposition). **Figure 23** shows the location of selected cross-sectional profiles presented in **Figure 24**. As can be expected, areas along the outside of channel bends tend to exhibit erosion and areas on the inside of bends exhibit deposition. Some areas exhibited significant change, including the downstream gravel bar/island complex where an old side channel filled in and accumulated over 5 feet of sediment in some areas (**Figure 22 -** left bank upstream of the bend, and **Figure 24 –** Profile 2), and over 5 feet or erosion occurred on the opposite (right) bank. Within the tight bend shown in **Figure 22**, the channel shifted and eroded 30 to 40 feet laterally, and the ground surface was reduced by up to 30 feet where large areas of the bank experienced mass failures (**Figure 24 -** Profile 3).

Overall, approximately 65% of the channel experienced a morphologic change of greater than 0.5 feet and approximately 20% of the channel experienced a change of greater than 2 feet. On an area basis, 52% of the area accumulated sediment compared to 48% of the area that exhibited erosion. On a sediment volume basis, a net loss of sediment may be indicated in an amount of 428,000 cubic feet (approximately 9.8 acre-feet); based upon map visualization the main areas of sediment loss appear to be on the outside of steep river banks.

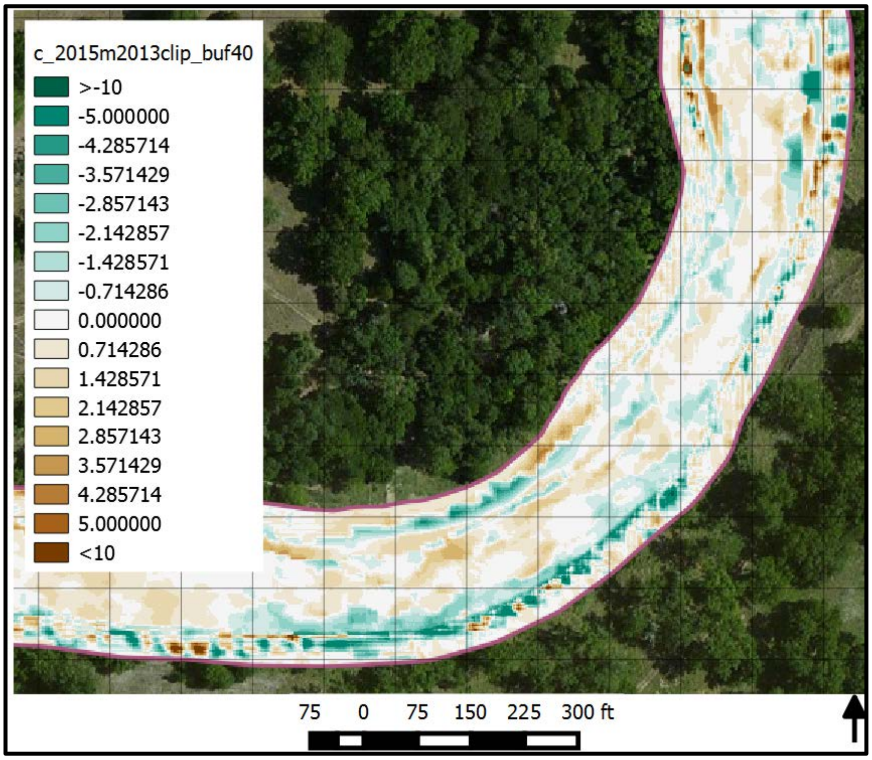

Figure 21. Morphologic change near the upstream end of the site between 2013 and 2015.

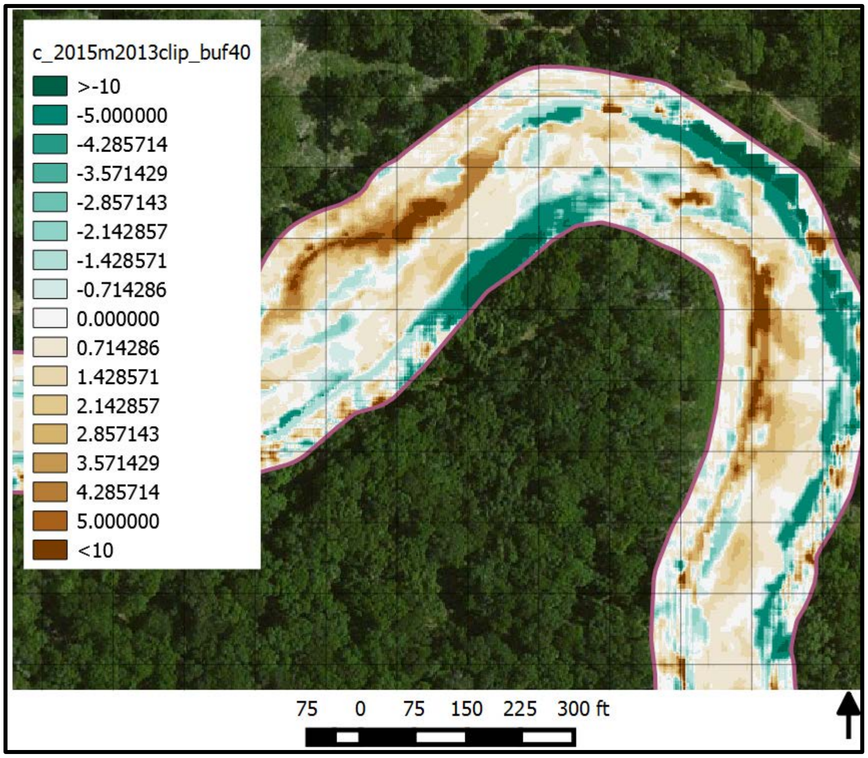

Figure 22. Morphological change near the downstream end of the site between 2013 and 2015.

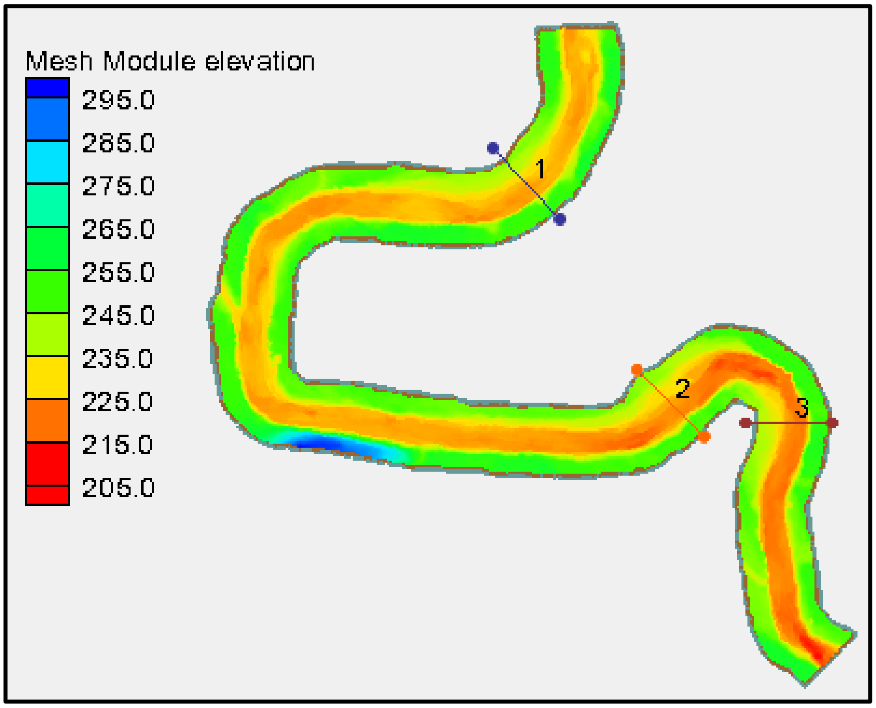

Figure 23. Location of profiles; flow is from top to bottom (north to south) and profile stationing is from river left to river right.

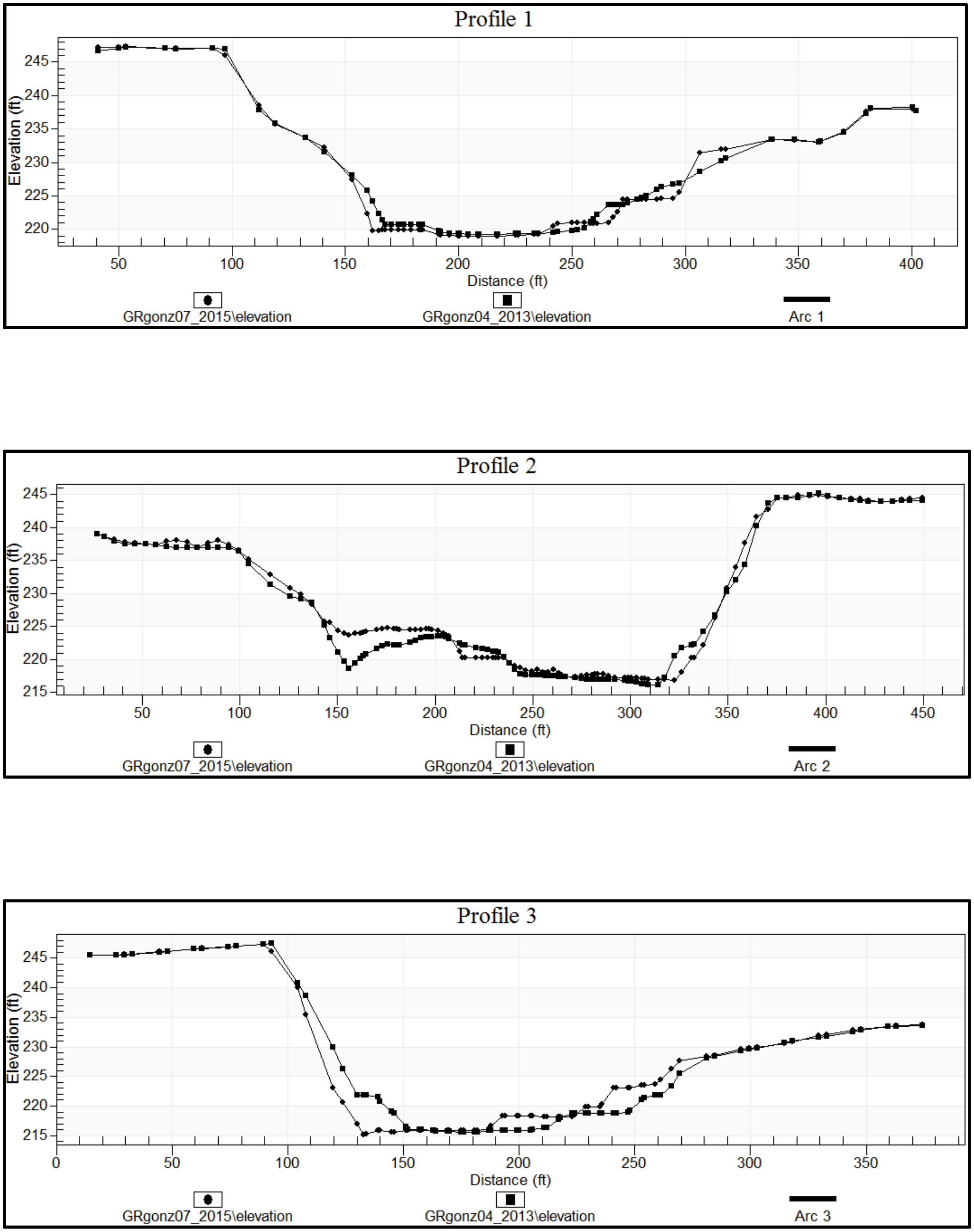

Figure 24. Comparison of 2015 cross-sectional surface (dots) to 2013 cross-sectional surface (squares) at three select transect locations defined in **Figure 23**.

3.2 DEVELOPMENT OF FISH HABITAT SUITABILITY CRITERIA

3.2.1 HABITAT UTILIZATION GUILDS

As described in Section 2.3.1.1, fish habitat utilization sampling resulted in capture of over 15,000 fishes representing 37 species from 160 distinct microhabitats. Six of these species (Common Carp *Cyprinus carpio*, Mexican Tetra *Astyanax mexicanus*, Amazon Molly *Poecilia formosa*, Sailfin Molly *Poecilia latipinna*, Redbreast Sunfish *Lepomis auritus*, and Rio Grande Cichlid *Herichthys cyanoguttatus*) are considered non-native to the system and were dropped from further analysis. Several other species were relatively rare and were captured at only a few locations. To exclude species for which there were insufficient data, only species collected in five or more microhabitats were included in the analysis. This excluded five additional species: River Carpsucker *Carpiodes carpio*, Blue Catfish *Ictalurus furcatus*, Warmouth *Lepomis gulosus*, Redear Sunfish *Lepomis microlophus*, and White Crappie *Pomoxis annularis*.

Many fish species are known to change their habitat preferences as they grow, with small juveniles of a species occupying different habitats than mature adults. To examine such size-dependent changes in habitat utilization, average depth and average velocity were plotted against total length for each species with sufficient data. Based on this analysis, along with observations of size-dependent habitat utilization from previous studies, any species which was thought to exhibit such changes was split into two size/life-stage categories (assuming each life-stage category still maintained data from ≥ 5 microhabitats). This analysis resulted in life-stage splits for the following species: Red Shiner, Bullhead Minnow, Burrhead Chub, Channel Catfish *Ictalurus punctatus*, Ghost Shiner, Gizzard Shad, Gray Redhorse, Inland Silverside *Menidia beryllina*, Longear Sunfish, Mimic Shiner, and Spotted Bass *Micropterus punctulatus*. However, several of these splits were later recombined after they fell into the same habitat utilization guild, as described below.

Generating habitat suitability criteria (HSC) for multiple species and life-stage categories can complicate interpretation of study results, yet basing flow recommendations on the needs of a few key species may be detrimental to other species. Therefore, a habitat guild approach was used to best represent the habitat needs of the entire fish community. A habitat guild is defined as a group of species that utilize similar habitat. Grouping species based on similar habitat utilization, and creating HSC for each resulting habitat guild, simplifies interpretation of study results while still representing the flow requirements of the entire fish community. This habitat guild approach is often used for instream flow studies on warmwater rivers with high species richness such as the lower Guadalupe River (BIO-WEST 2008, Persinger et al. 2011, TIFP 2011).

To create the guilds, habitat conditions were characterized for each microhabitat (N=160) by calculating the mean of the depth and velocity data for the five individual measurements taken at each. Mean depth, mean velocity, and dominant substrate were then combined with abundance data from each species/life-stage and summarized in a Canonical Correspondence Analysis (CCA). Based on the resulting CCA ordination plot, multiple species/life stage categories were visually grouped into six habitat guilds (**Figure 25**). Where a particular species/life stage category fell in close proximity to guild boundaries, habitat descriptions from the literature, and professional experience of the study team biologists were used to make final guild determination. When both life-stage categories for a particular species fell within the same guild, data were recombined to the species level. The final species/life-stage categories and number of each collected within each of the resulting habitat guilds are presented in **Table 16**.

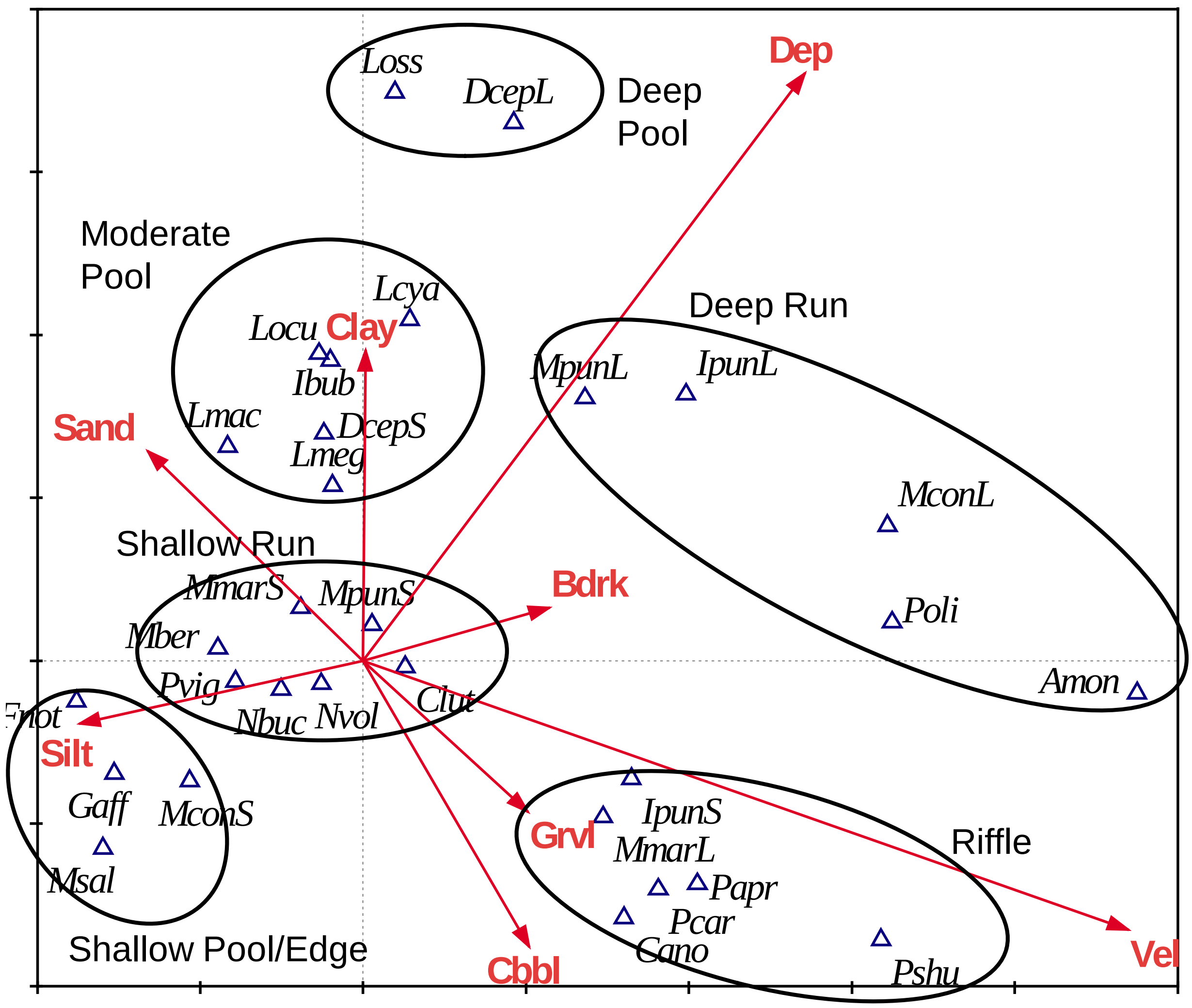

Figure 25. Multivariate ordination plot showing species associations among gradients of depth, velocity, and dominant substrate. Black circles designate habitat utilization guilds. Species/life-stage abbreviations are provided in **Table 16**.

Table 16. Number of locations observed and total number of individuals observed for each habitat utilization guild and their component species/life-stages.

Guild Name	Species/Life-stage		Species/Life-stage Abbreviation	Number of Locations Observed	Total Number Observed
Deep Pool	Longnose Gar	*Lepisosteus osseus*	Loss	7	8
	Gizzard Shad (adult)	*Dorosoma cepedianum*	DcepL	11	20
	Guild Total			**17**	**28**
Moderate Pool	Spotted Gar	*Lepisosteus oculatus*	Locu	5	5
	Gizzard Shad (juvenile)	*Dorosoma cepedianum*	DcepS	11	41
	Smallmouth Buffalo	*Ictiobus bubalus*	Ibub	9	10
	Bluegill	*Lepomis macrochirus*	Lmac	16	24
	Green Sunfish	*Lepomis cyanellus*	Lcya	14	20
	Longear Sunfish	*Lepomis megalotis*	Lmeg	66	305
	Guild Total			**74**	**405**
Deep Run	Gray Redhorse (adult)	*Moxostoma congestum*	MconL	11	12
	Channel Catfish (adult)	*Ictalurus punctatus*	IpunL	21	35
	Flathead Catfish	*Pylodictis olivaris*	Poli	11	29
	Mountain Mullet	*Agonostomus monticola*	Amon	5	6
	Spotted Bass (adult)	*Micropterus punctulatus*	MpunL	26	37
	Guild Total			**47**	**119**
Shallow Run	Red Shiner	*Cyprinella lutrensis*	Clut	126	8888
	Burrhead Chub (juvenile)	*Macrhybopsis marconis*	MmarS	6	35
	Ghost Shiner	*Notropis buchanani*	Nbuc	29	944
	Mimic Shiner	*Notropis volucellus*	Nvol	32	979
	Bullhead Minnow	*Pimephales vigilax*	Pvig	71	1413
	Inland Silverside	*Menidia beryllina*	Mber	17	50
	Spotted Bass (juvenile)	*Micropterus punctulatus*	MpunS	36	104
	Guild Total			**132**	**12413**
Riffle	Central Stoneroller	*Campostoma anomalum*	Cano	6	65
	Burrhead Chub (adult)	*Macrhybopsis marconis*	MmarL	25	102
	Channel Catfish (juvenile)	*Ictalurus punctatus*	IpunS	11	15
	Guadalupe Darter	*Percina apristis*	Papr	12	30
	Texas Logperch	*Percina carbonaria*	Pcar	9	15
	River Darter	*Percina shumardi*	Pshu	25	90
	Guild Total			**55**	**317**
Shallow Pool / Edge	Gray Redhorse (juvenile)	*Moxostoma congestum*	MconS	19	205
	Blackstripe Topminnow	*Fundulus notatus*	Fnot	5	13
	Western Mosquitofish	*Gambusia affinis*	Gaff	42	1418
	Largemough Bass	*Micropterus salmoides*	Msal	9	42
	Guild Total			**56**	**1678**

3.2.2 HABITAT SUITABILITY CRITERIA DEVELOPMENT

Habitat data from all species/life stage categories within a particular guild were combined to generate frequency histograms for the continuous variables depth and velocity. Data were binned using 0.1 feet (ft) increments for depth and 0.1 feet/second (ft/s) increments for velocity. Habitat suitability criteria (HSC) were then created using nonparametric tolerance limits (NPTL) based on the central 50%, 75%, 90%, and 95% of the data (Bovee 1986). Values for NPTL were interpolated or extrapolated from the table provided in Somerville (1958) using a 0.95 confidence level. Tolerance limits for the central 50% of the data were used as boundaries for the most selected habitat and the range of data between these two points was assigned a suitability of 1.0. Data between the 50% tolerance limits and the 75% tolerance limits were assigned a suitability of 0.5. Data between the 75% tolerance limits and the 90% tolerance limits were assigned a suitability of 0.2; and the data between the 90% tolerance limits and the 95% tolerance limits received a suitability of 0.1. The data beyond the 95% tolerance limits were considered unsuitable and given a suitability of zero.

Habitat suitability criteria (HSC) for the categorical variable substrate were developed using normalized frequencies. The substrate with the highest frequency (most utilized) received a suitability value of 1.0. All other substrates received a suitability value dependent on their relative frequency.

Using the methodology described above, initial depth, velocity, and substrate HSC were developed for each habitat guild. These methods are standard in instream flow science and have been used in several similar studies (Bovee 1986, BIO-WEST 2008, Persinger et al. 2011, TIFP 2011). However, modifications to raw HSC are often made to account for logical limitations to fish habitat utilization and to address known sampling limitations. For example, habitats shallower than one inch (0.08 ft) were considered too shallow for fish to occupy and thus unsuitable. Therefore, minimum depth criteria of approximately one inch (0.08 ft) were established for all guilds with non-zero suitability at depths less than 0.1 feet (Shallow Run and Shallow Pool/Edge). Additionally, given the known reduction in electrofishing capture efficiency at greater depths, reductions in suitability for the Deep Pool guild at depths greater than 3.6 feet were more likely a result of sampling limitations rather than a pattern in habitat utilization. Fishes of the Deep Pool guild (Longnose Gar *Lepisosteus osseus* and adult Gizzard Shad) are known to commonly inhabit areas considerably deeper than those from which they were captured in this study. As a result, the depth HSC curve for Deep Pools was modified to exhibit a suitability of 1.0 for all depths of approximately 3.6 feet or greater (**Figure 26**). Similarly, some fishes in the Deep Run guild commonly inhabit deeper areas, and reductions in Deep Run depth suitability at depths greater than 2.9 feet were likely influenced by sampling limitations. Therefore, the Deep Run depth HSC curve was modified to exhibit a suitability of 0.5 for all depths greater than 2.9 feet. (**Figure 28**). Final depth, velocity, and substrate HSC curves for each habitat guild are presented in **Figure 26-Figure 31.**

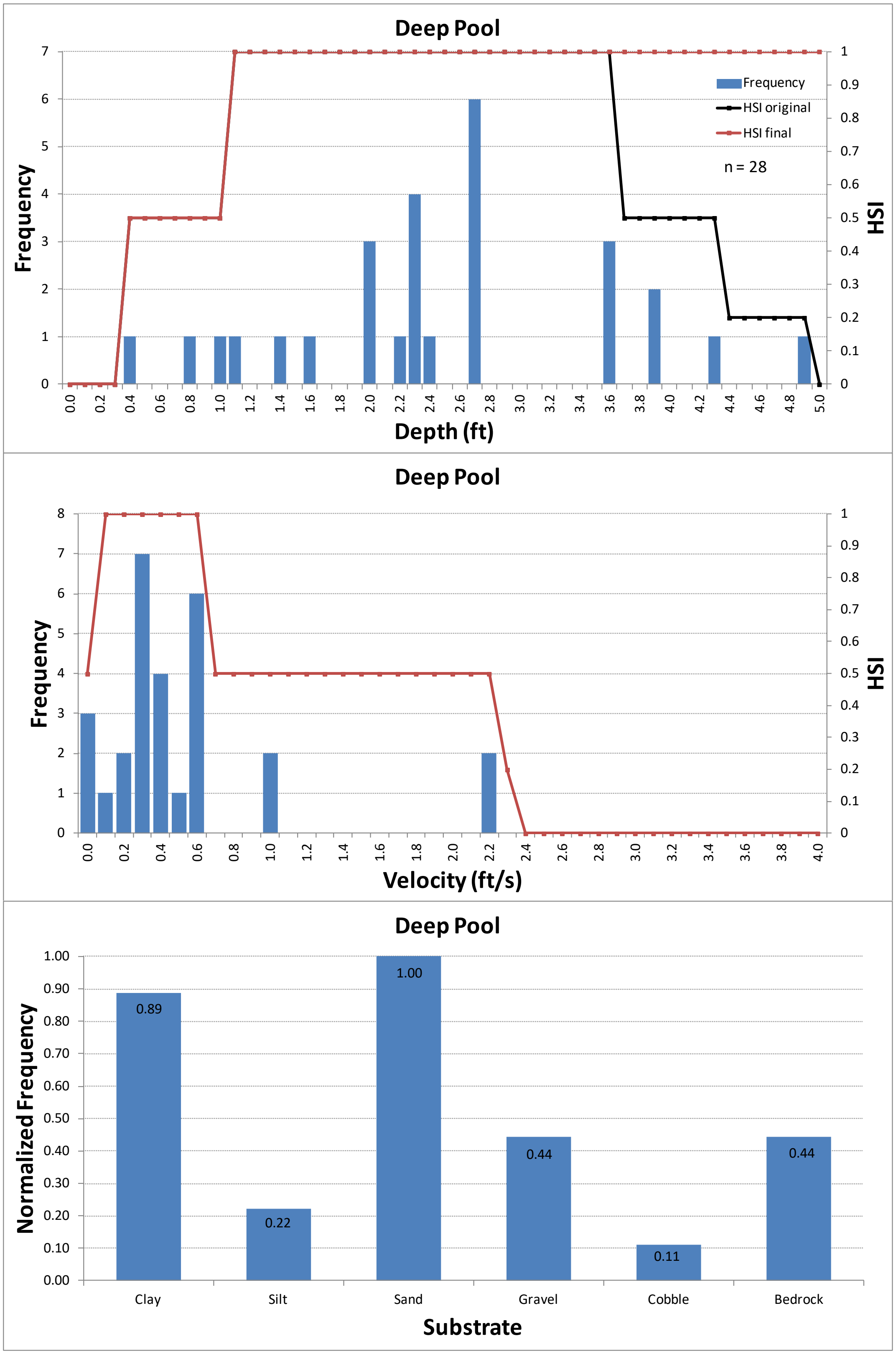

Figure 26. Frequency distribution and resulting HSC values for the Deep Pool Fish Habitat Guild. Black line indicates original HSC curve, whereas red line indicates final modified curve.

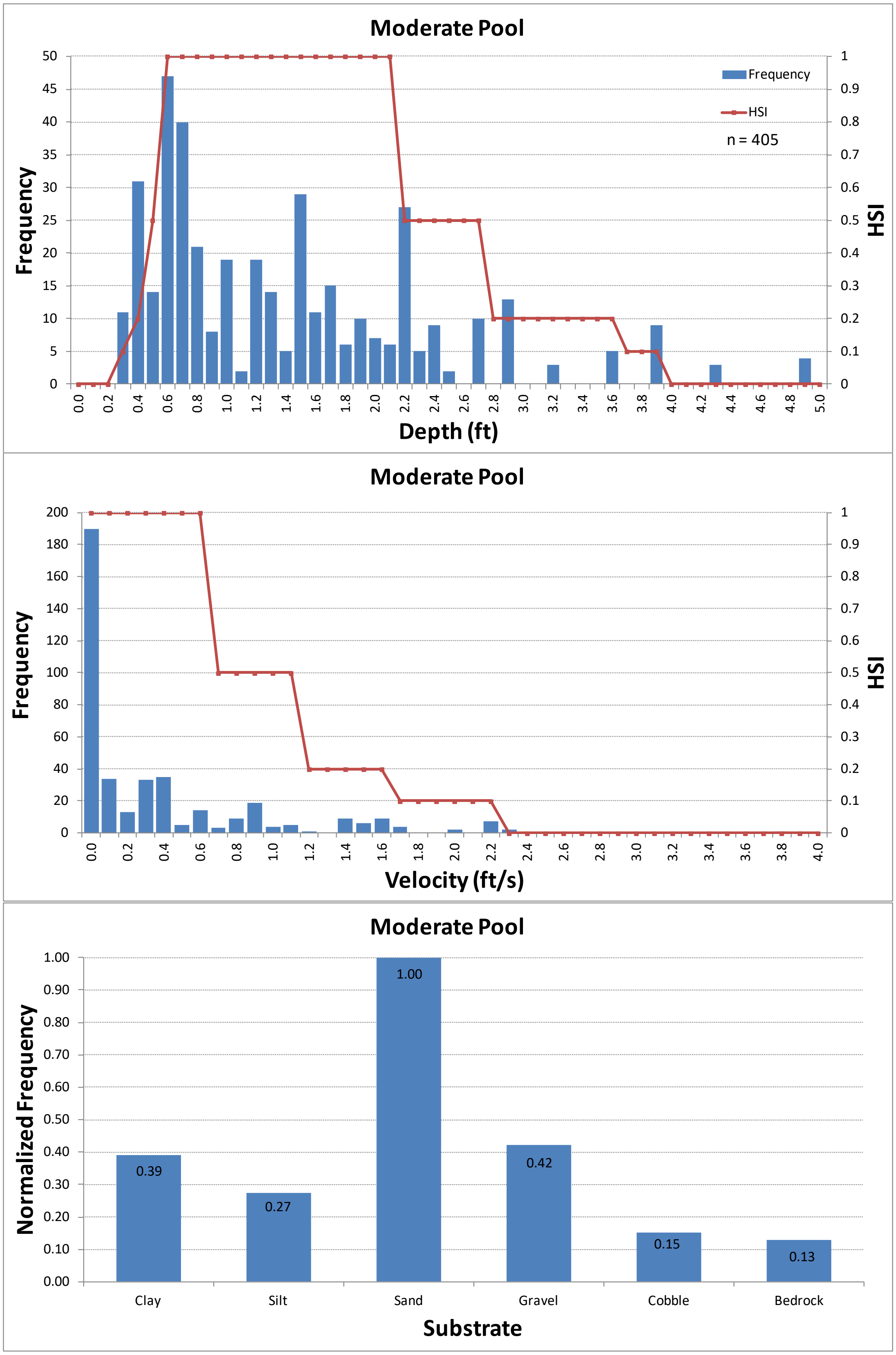

Figure 27. Frequency distribution and resulting HSC values for the Moderate Pool Fish Habitat Guild.

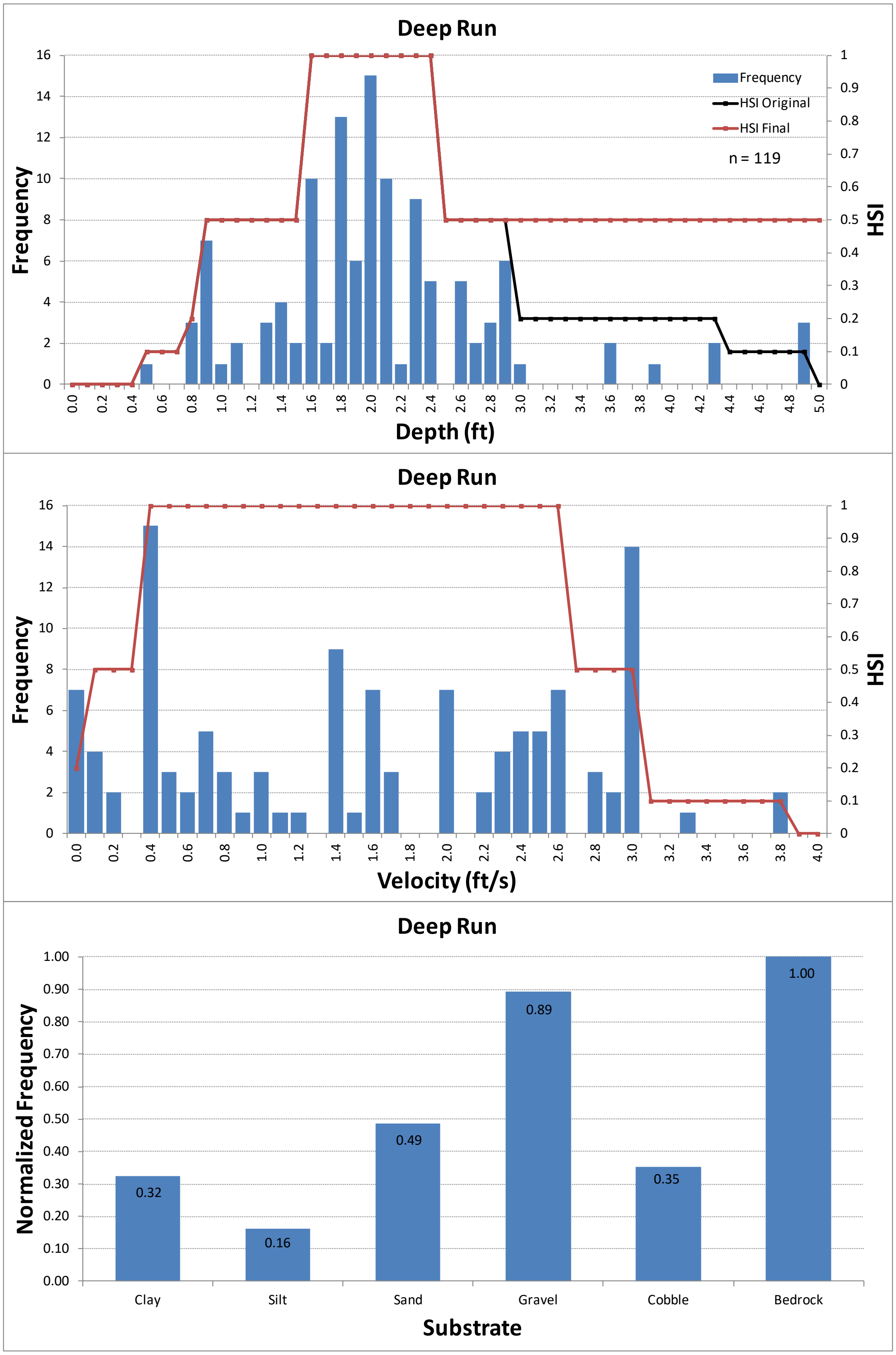

Figure 28. Frequency distribution and resulting HSC values for the Deep Run Fish Habitat Guild. Black line indicates original HSC curve, whereas red line indicates final modified curve.

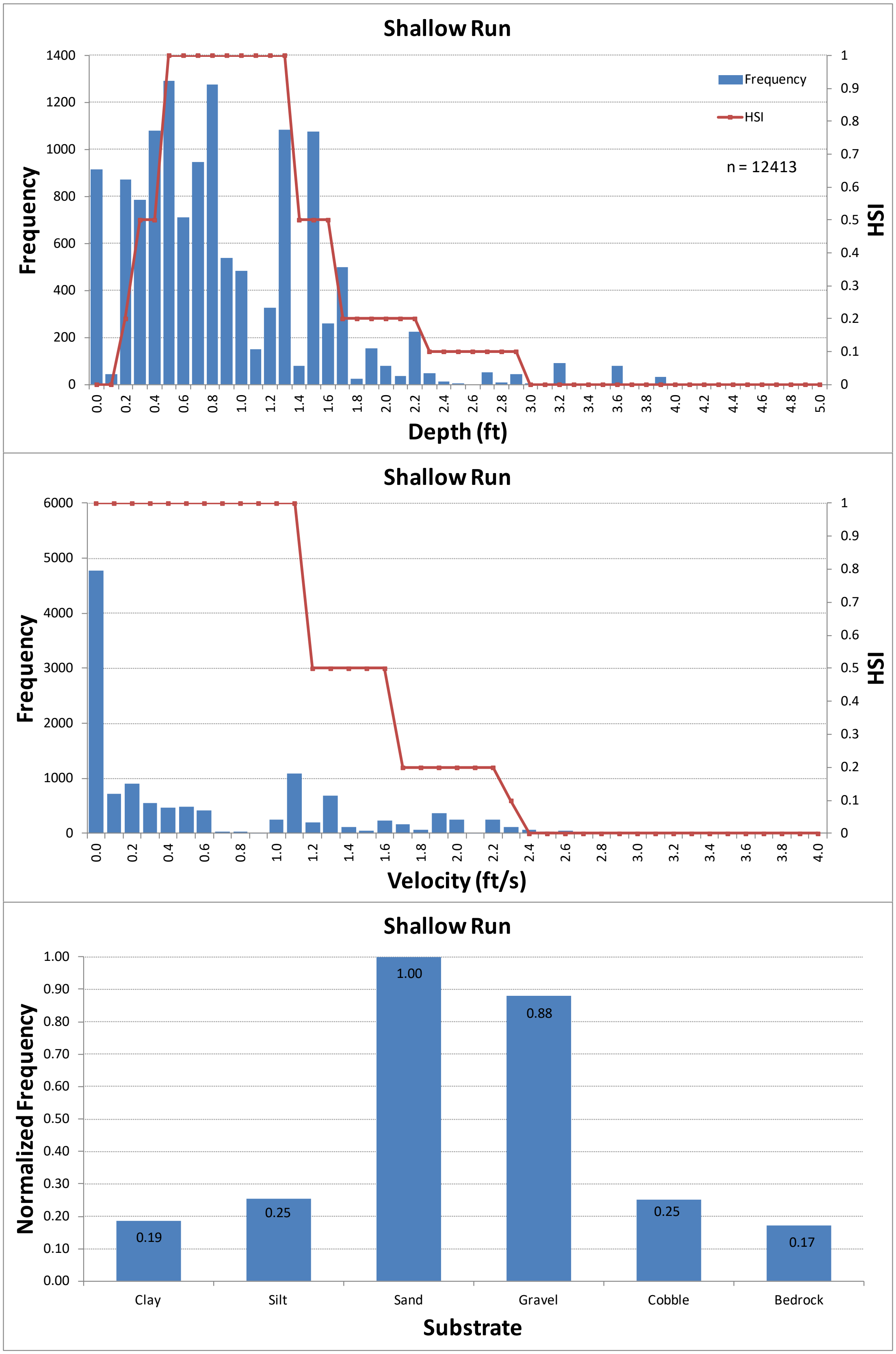

Figure 29. Frequency distribution and resulting HSC values for the Shallow Run Fish Habitat Guild.

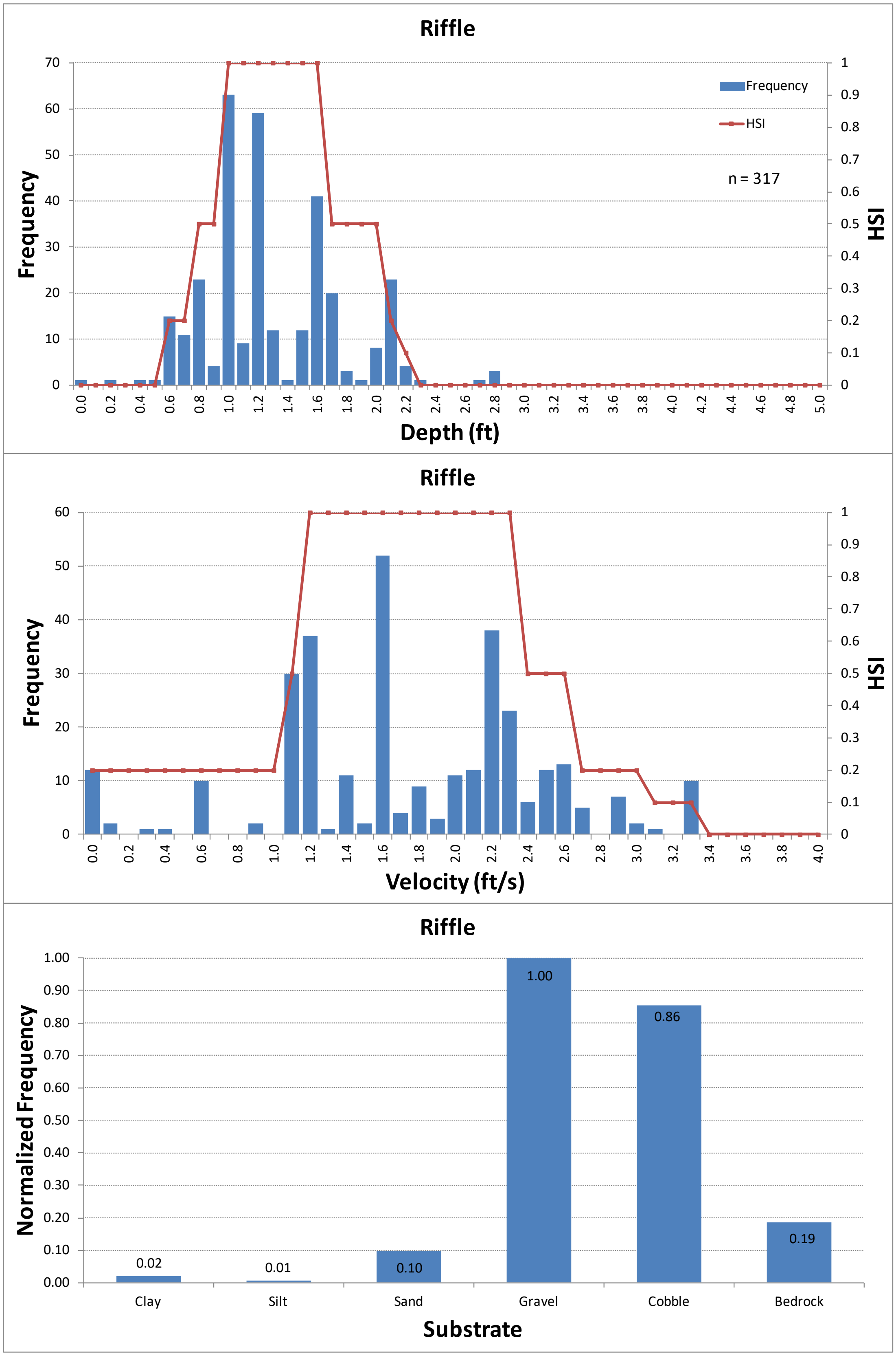

Figure 30. Frequency distribution and resulting HSC values for the Riffle Fish Habitat Guild.

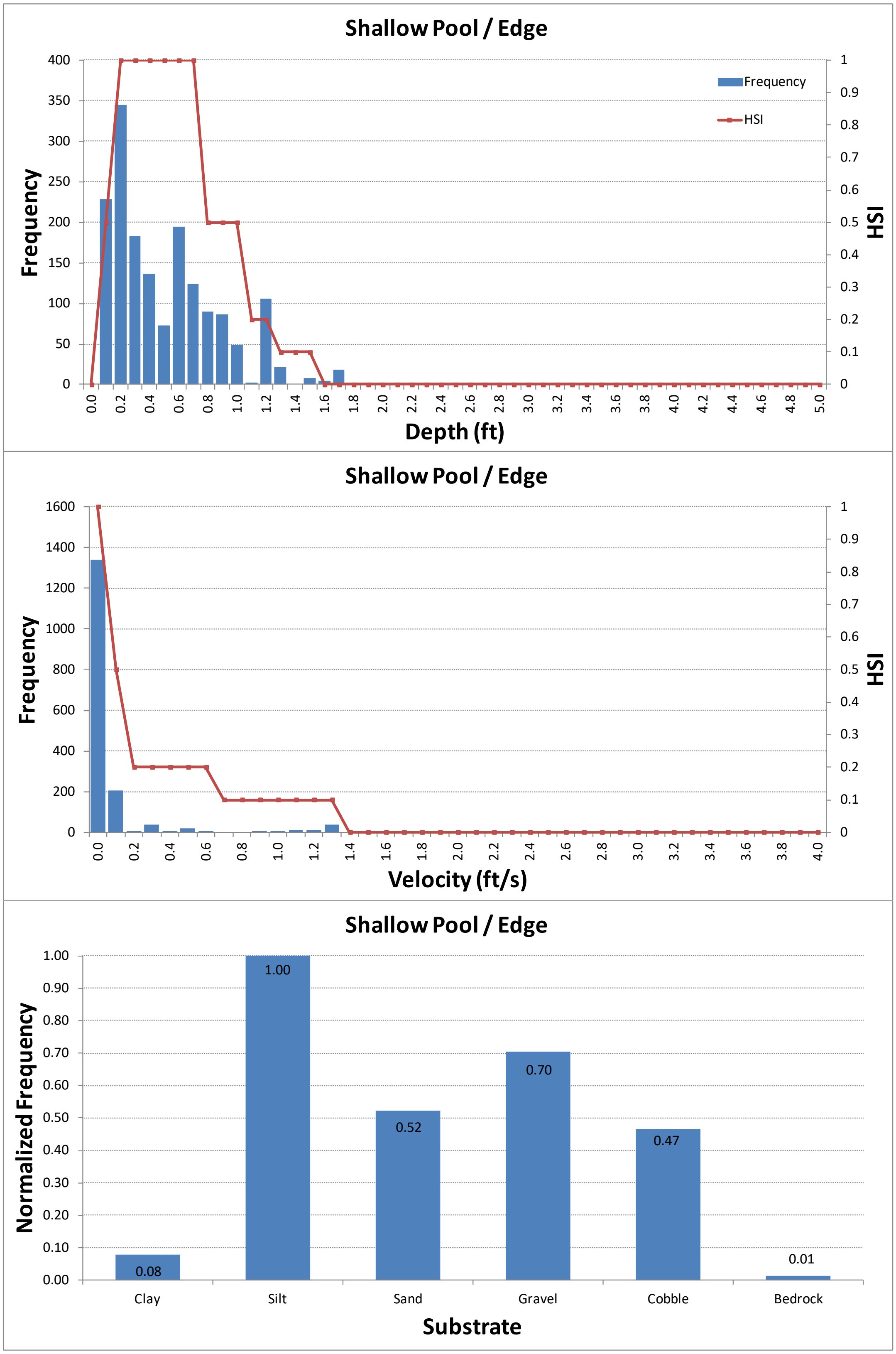

Figure 31. Frequency distribution and resulting HSC values for the Shallow Pool / Edge Fish Habitat Guild.

To assess overlap of criteria, depth and velocity criteria were plotted for each guild at an HSC level of 1.0 (**Figure 32**). At the highest suitability level, there was relatively little overlap in depth and velocity criteria among guilds, except for the Moderate Pool guild which overlapped with two other guilds. The largest overlap occurs between Moderate Pool and Deep Pool, which both exhibited a suitability of 1.0 at depths of 1.1 – 2.1 feet, and velocities from 0.1 – 0.6 ft/s. Moderate Pool also overlapped with Shallow Run at depths of 0.6 – 1.3 feet and velocities less than 0.6 ft/s. Despite this overlap, the Moderate Pool guild was thought to represent a unique habitat component of the aquatic community, and HSC from all fish habitat guilds were maintained for habitat modeling and further analysis.

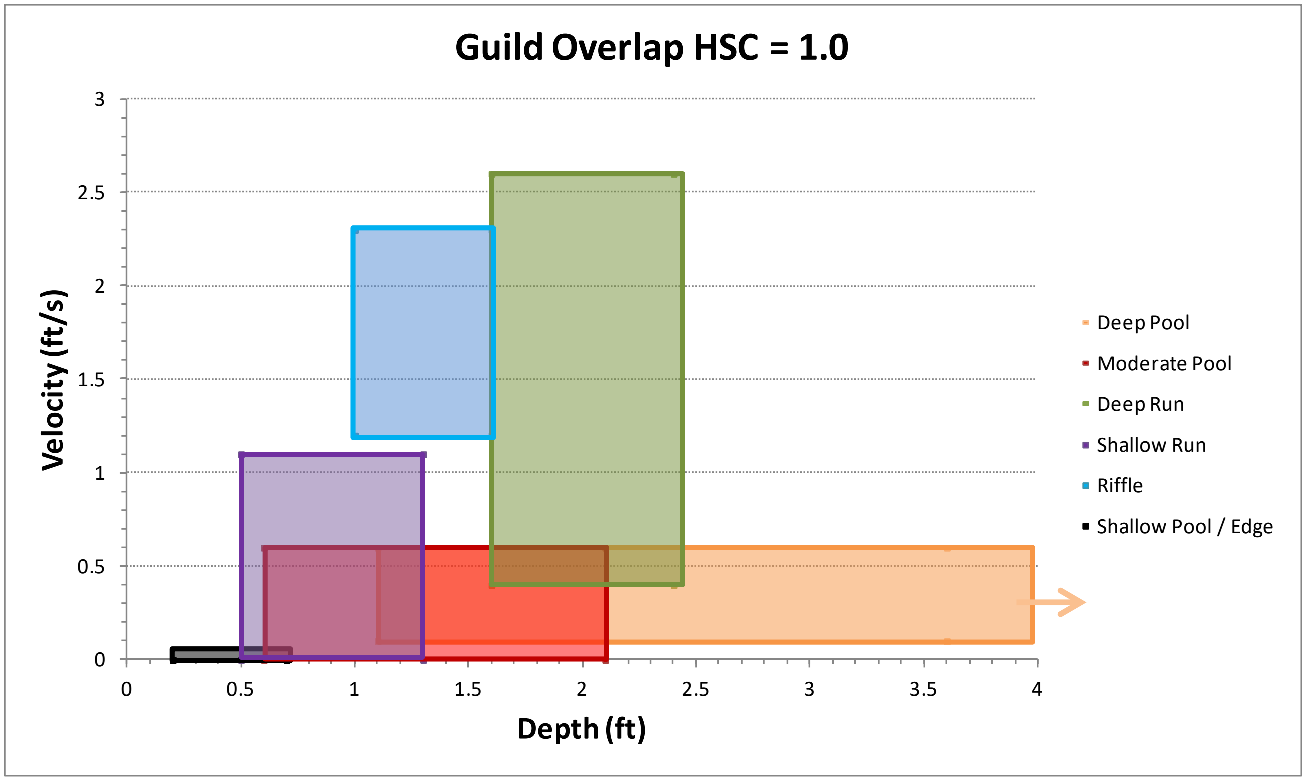

Figure 32. Guild overlap analysis showing depth and velocity criteria for each guild at an HSC level of 1.0.

3.3 HABITAT MODELING

3.3.1 WUA CALCULATIONS

To apply HSC to hydraulic model output, a Composite Suitability Index (CSI) was calculated for each habitat guild at each node in a given hydraulic model run by calculating the geometric mean of the suitability for depth (Depth_{SI}), velocity ($\text{Velocity}_{\text{SI}}$), and substrate ($\text{Substrate}_{\text{SI}}$) as follows:

$$\text{CSI} = (\text{Velocity}_{\text{SI}} * \text{Depth}_{\text{SI}} * \text{Substrate}_{\text{SI}})^{1/3}.$$

The CSI for each node was then multiplied by the area of that node to generate a WUA, and these values were summed for each habitat guild. The total WUAs for each habitat guild at each modeled flow rate were then compiled to create WUA to discharge curves (**Figure 33**).

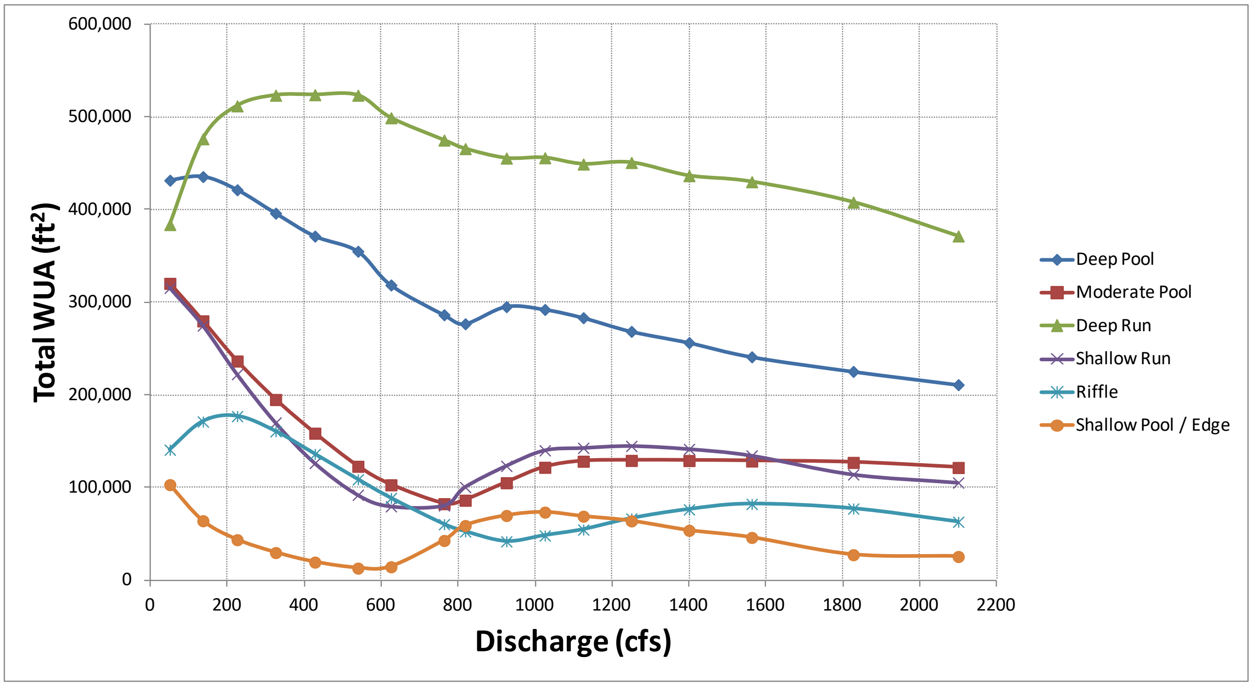

Figure 33. Weighted Usable Area (WUA) to discharge curves for each habitat guild.

One drawback to the above graph is that common habitat guilds (e.g., Deep Run) exhibit much greater magnitude than other rare habitat guilds (e.g., Shallow Pool/Edge). As a result, changes in rare guilds are somewhat masked due to scaling. Therefore, in an attempt to assess all habitat guilds equally, graphs were created to depict percent of maximum WUA versus discharge for each habitat guild. This graph was then scaled to examine base flow levels only, and thus was cut off at a maximum discharge of 1,200 cfs (**Figure 34**).

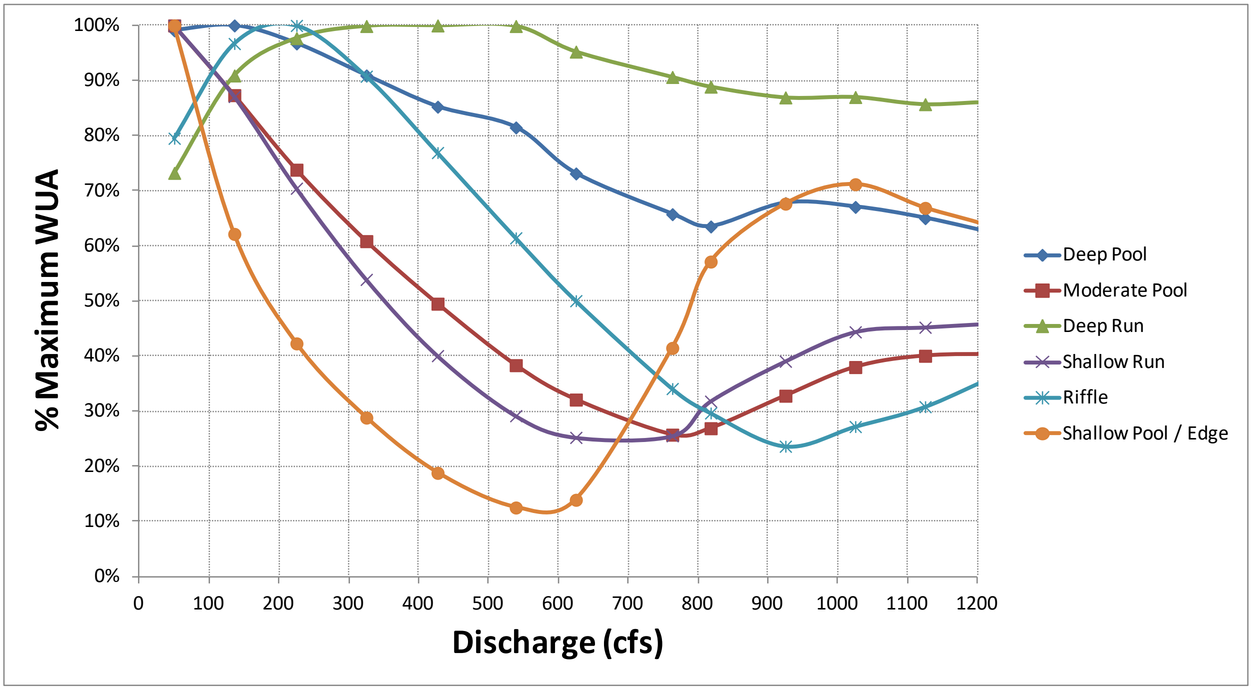

Figure 34. Percent maximum WUA versus discharge for each habitat guild.

Another consideration when examining WUA results is habitat quality. The graphs above examine total WUA. However, it is possible that large amounts of low-quality habitat contribute substantially to overall WUA, and little high-quality habitat exists. To examine changes in habitat quality, the contribution of high quality (CSI ≥ 0.8), moderate quality (CSI = 0.5-0.79), and low quality (CSI < 0.5) habitat to overall WUA was examined for each habitat guild at each modeled flow rate (**Figure 35**).

The spatial distribution of habitat is also a concern when evaluating WUA output. Even if high-quality habitat is present, if it is patchily distributed and does not occur in contiguous patches of appropriate size, then it is of little utility to the fish dependent upon that habitat. Therefore, the spatial distribution of habitat quality for each guild at each modeled flow rate was examined. As an example, the spatial distribution of Riffle habitat at 50, 225, and 925 cfs is provided in **Figure 36**. Similar output for all habitat guilds at all modeled flow rates is provided in **Appendix A.**

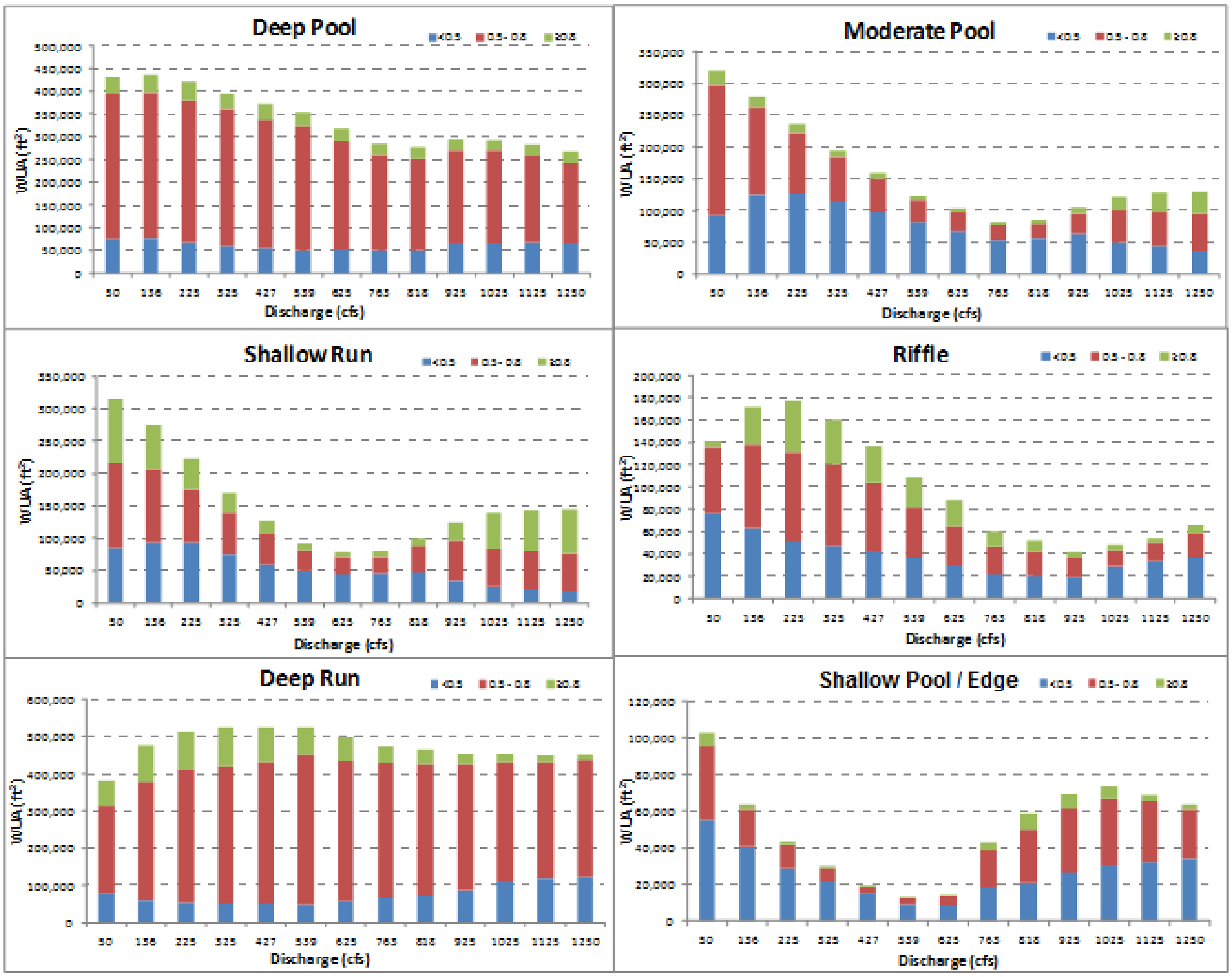

Figure 35. Magnitude of high quality (CSI≥0.8, green), moderate quality (CSI = 0.5 - 0.79, red), and low quality (CSI<0.5, blue) habitat for each habitat guild at various flow rates.

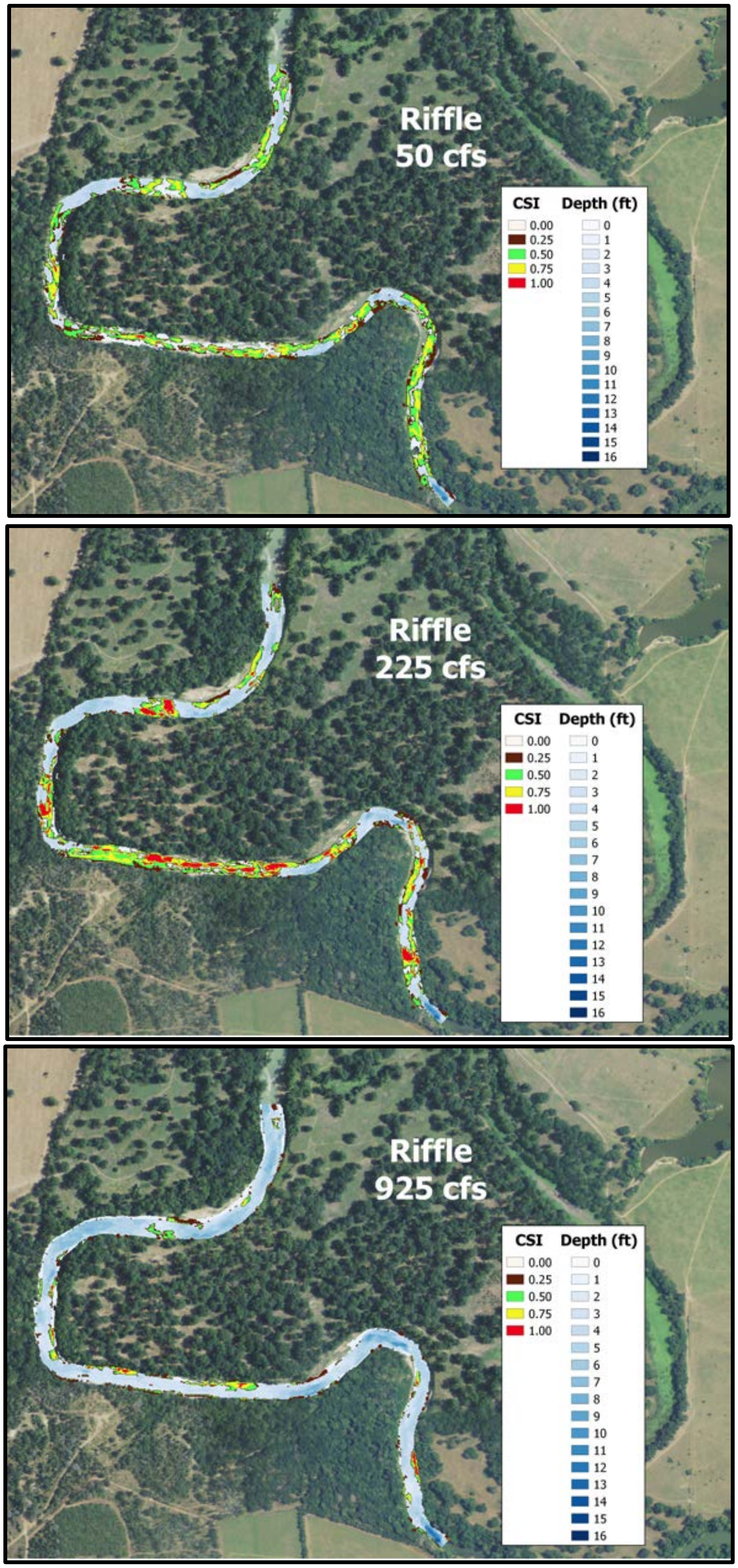

Figure 36. Spatial output of habitat quality for the Riffle Habitat Guild at modeled flows of 50, 225, and 925 cfs.

3.4 FLOODPLAIN ANALYSIS

To estimate the discharge which results in surface water connectivity between the floodplain lake and the main channel of the river, on-site topography data and water surface elevation data were collected. These data were then tied to corresponding data on water surface elevation and flow rate at the nearest USGS gauge on the Guadalupe River at Gonzales (#08173900) approximately 11 miles upstream, and to similar data at the intensive study site approximately 3 miles downstream, using methods similar to Osting et al. (2004).

The "control point" elevation was estimated from on-the-ground surveys and represented the water surface elevation which would result in connection of the upper end of the floodplain lake to the main channel of the river. To establish a relationship between the control point elevation and the upstream gauge record, the change in elevation between the water surface elevation at these two points, and the intensive study site downstream, was estimated. This slope relationship (assumed to be linear) was then used to estimate a flow rate at the gauge which would result in connection of the floodplain lake.

Based on the analysis described above, a discharge of approximately 2,822 cfs was estimated to connect the upper end of the floodplain lake. It should be noted that although a small downstream portion of the floodplain lake connects to the river at lower elevations/discharges, thus creating a large backwater, it is not until the upper end connects that this habitat becomes an active flowing channel and substantial community shifts are expected. To examine when such connections occurred over the study period, and thus link fish community data to hydrologic data, floodplain lake fish community data were overlaid on the hydrograph along with the estimated connection discharge (**Figure 37**).

Based on this analysis, it appears that the upper control point of the floodplain lake was connected to the mainstem Guadalupe River four times over the study period. The first time was a brief connection on May 26-27, 2013. During this event, the river reached a maximum instantaneous discharge of 3,070 cfs (only slightly higher than the 2,822 cfs estimated for connection) and was estimated to maintain connectivity for less than 12 hours. A fish sampling event occurred immediately following this connection event on May 28, 2013.

The other three connections all occurred between September 29, 2013 and November 5, 2013. During this time, three large pulses passed, with the last pulse exhibiting a maximum discharge of over 26,000 cfs and maintaining connectivity for approximately 5 days. A fish sampling event was conducted approximately one month before this series of pulses on September 3, 2013, and another event was conducted approximately one month afterwards on December 10, 2013.

To analyze fish community dynamics during each sampling event, each fish species was categorized into one of three basic habitat utilization categories based on available life history information and previous sampling experience – Riverine, Floodplain, or Generalist (**Table 17**). Generalist species were then removed from the analysis and the percent relative abundance of riverine versus floodplain species were examined for each sampling date (**Figure 37**). A sharp increase in the relative abundance of riverine fishes (and concomitant decrease in the relative abundance of floodplain fishes) is noted in the floodplain lake after the series of high flow pulses in fall 2013. Riverine species continue to dominate the assemblage through the winter and still dominate the assemblage in February 2014. However, floodplain species again begin to dominate the assemblage by May 2014.

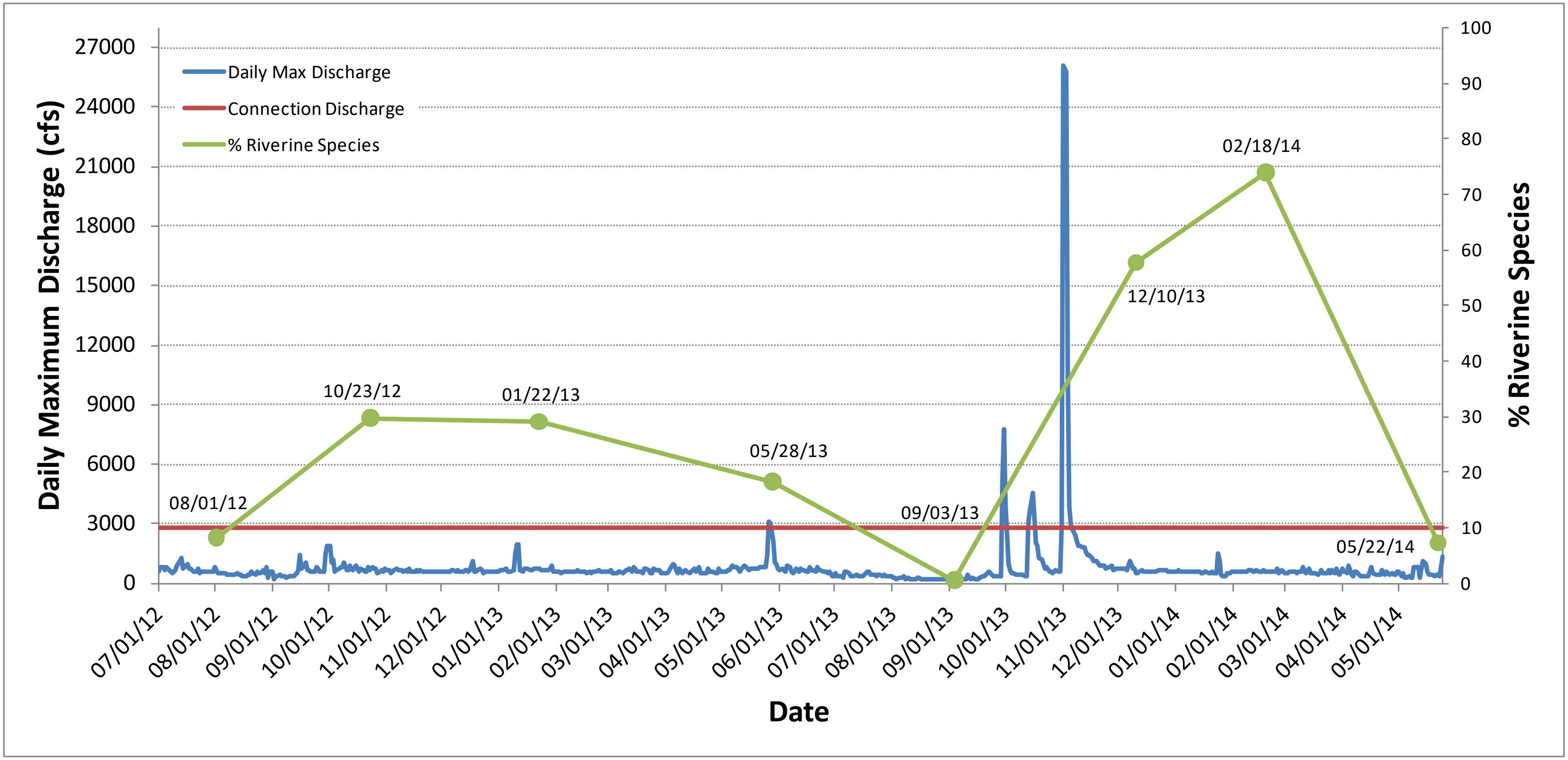

Figure 37. Daily maximum discharge (blue line) from the USGS gauge on the Guadalupe River at Gonzales (#08173900), estimated connection discharge for the floodplain lake (red line), and percent riverine species in each fish collection (green line).

Table 17. Fish species collected from the floodplain lake and their resulting classification for floodplain analysis.

Family	Scientific Name	Common Name	Classification
Lepisosteidae	*Lepisosteus oculatus*	Spotted Gar	Floodplain
	Lepisosteus osseus	Longnose Gar	Generalist
Clupeidae	*Dorosoma cepedianum*	Gizzard Shad	Floodplain
	Dorosoma petenense	Threadfin Shad	Floodplain
Cyprinidae	*Cyprinella lutrensis*	Red Shiner	Riverine
	Notemigonus crysoleucas	Golden Shiner	Floodplain
	Notropis buchanani	Ghost Shiner	Riverine
	Notropis volucellus	Mimic Shiner	Riverine
	Opsopoeodus emiliae	Pugnose Minnow	Floodplain
	Pimephales vigilax	Bullhead Minnow	Riverine
Catostomidae	*Carpiodes carpio*	River Carpsucker	Riverine
	Ictiobus bubalus	Smallmouth Buffalo	Riverine
	Moxostoma congestum	Gray Redhorse	Riverine
Ictaluridae	*Ameiurus melas*	Black Bullhead	Floodplain
Mugilidae	*Mugil cephalus*	Striped Mullet	Generalist
Atherinopsidae	*Menidia beryllina*	Inland Silverside	Floodplain
Poeciliidae	*Gambusia affinis*	Western Mosquitofish	Floodplain
	Poecilia formosa	Amazon Molly	Generalist
	Poecilia latipinna	Sailfin Molly	Floodplain
Centrarchidae	*Lepomis cyanellus*	Green Sunfish	Floodplain
	Lepomis gulosus	Warmouth	Floodplain
	Lepomis humilis	Orangespotted Sunfish	Floodplain
	Lepomis macrochirus	Bluegill	Floodplain
	Lepomis megalotis	Longear Sunfish	Generalist
	Lepomis microlophus	Redear Sunfish	Floodplain
	Lepomis sp.	sunfish	Generalist
	Micropterus punctulatus	Spotted Bass	Riverine
	Micropterus salmoides	Largemouth Bass	Floodplain
	Pomoxis annularis	White Crappie	Floodplain
Percidae	*Etheostoma chlorosoma*	Bluntnose Darter	Floodplain
	Etheostoma gracile	Slough Darter	Floodplain
	Percina apristis	Guadalupe Darter	Riverine
Cichlidae	*Herichthys cyanoguttatus*	Rio Grande Cichlid	Generalist

It is interesting to note that although the large pulse events in fall 2013 resulted in large shifts within the fish community, the smaller connection event documented in May 2013 did not result in substantial changes. Visual observations made during the May 28, 2013 sampling event did suggest that the oxbow was recently connected. However, this event only exceeded the estimated connection discharge for approximately 12 hours, and may not have been of sufficient duration to allow substantial biotic exchange.

3.5 FRESHWATER MUSSEL ANALYSIS

Given the sedentary nature of freshwater mussels and their inability to quickly respond to changing flow conditions by moving, traditional instream flow habitat modeling approaches using habitat suitability criteria based on depth and velocity are not particularly appropriate for quantifying the instream flow requirements of this group. The location of dense mussel congregations is typically rather static, despite short-term changes in variables such as depth and velocity as flows fluctuate. Instead, hydraulic factors such as shear stress, which influence the substrate, typically show the strongest association with mussel abundance (Morales et al. 2006). High shear stress results in less substrate stability and is generally linked to a decrease in mussel abundance and richness (Randklev et al. 2014). Rather than assessing mussel flow requirements on a flow-specific basis (as is typical with fish), a more appropriate technique for sedentary organisms is to measure habitat availability across a wide range of flow conditions and examine persistent habitat (Maloney et al. 2012). Therefore, the mussel analysis conducted herein had three main goals: 1) assess general habitat associations of the species present; 2) examine relationships between shear stress and mussel abundance; and 3) examine other factors influencing mussel catch rates.

3.5.1 MUSSEL HABITAT ASSOCIATIONS

To explore mussel habitat associations, sampling points were overlaid on a map of dominant substrate (see **Figure 2**) and each point was assigned to one of several substrate categories: clay, silt, sand, gravel, cobble, boulder, or bedrock. Additionally, based on hydraulic conditions, each sampling point was also classified into one of three general mesohabitat categories (Pool, Run, Riffle), and one of several more specific mussel habitat categories defined by Randklev et al. (2014). These categories were: Bank Habitat (BH), Behind Point Bar (BPB), Front of Point Bar (FPB), and Mid-Channel (MC). Although Randklev et al. (2014) also included Backwater (BW) habitats, our initial mussel recon suggested there were few mussels in these habitats, and therefore, this habitat type was not sampled in our study. To summarize the relationships between mussel abundance and the various substrate and habitat categories a Canonical Correspondence Analysis (CCA) was conducted (**Figure 38**). Mussels were grouped by species, with two additional categories added to assess all mussels in aggregate and all members of the genus *Quadrula* in aggregate. It is important to note that the *Quadrula* aggregate group included False Spike *Fusconaia mitchelli*, which was considered to be in the genus *Quadrula* at the time but has since undergone taxonomic revision. Only mussel species which were found in at least five separate habitats were included in the species-specific portion of this analysis. This resulted in excluding Louisiana Fatmucket and Texas Lillyput due to insufficient data.

Analysis of **Figure 38** suggests that the overall abundance of mussels within sampling areas (*Mussels*) was not strongly associated with any particular substrate or habitat category; however, species-specific associations were quite variable. Placement of False Spike (*Qmit*) suggested an association with gravel run habitats, whereas Tampico Pearlymussel (*Ctam*) was more strongly aligned with Riffle areas. Similarly, placement of Yellow Sandshell (*Lter*) suggested an association with Front of Point Bar habitats, whereas Washboard (*Mner*) was more abundant in sandy pool areas.

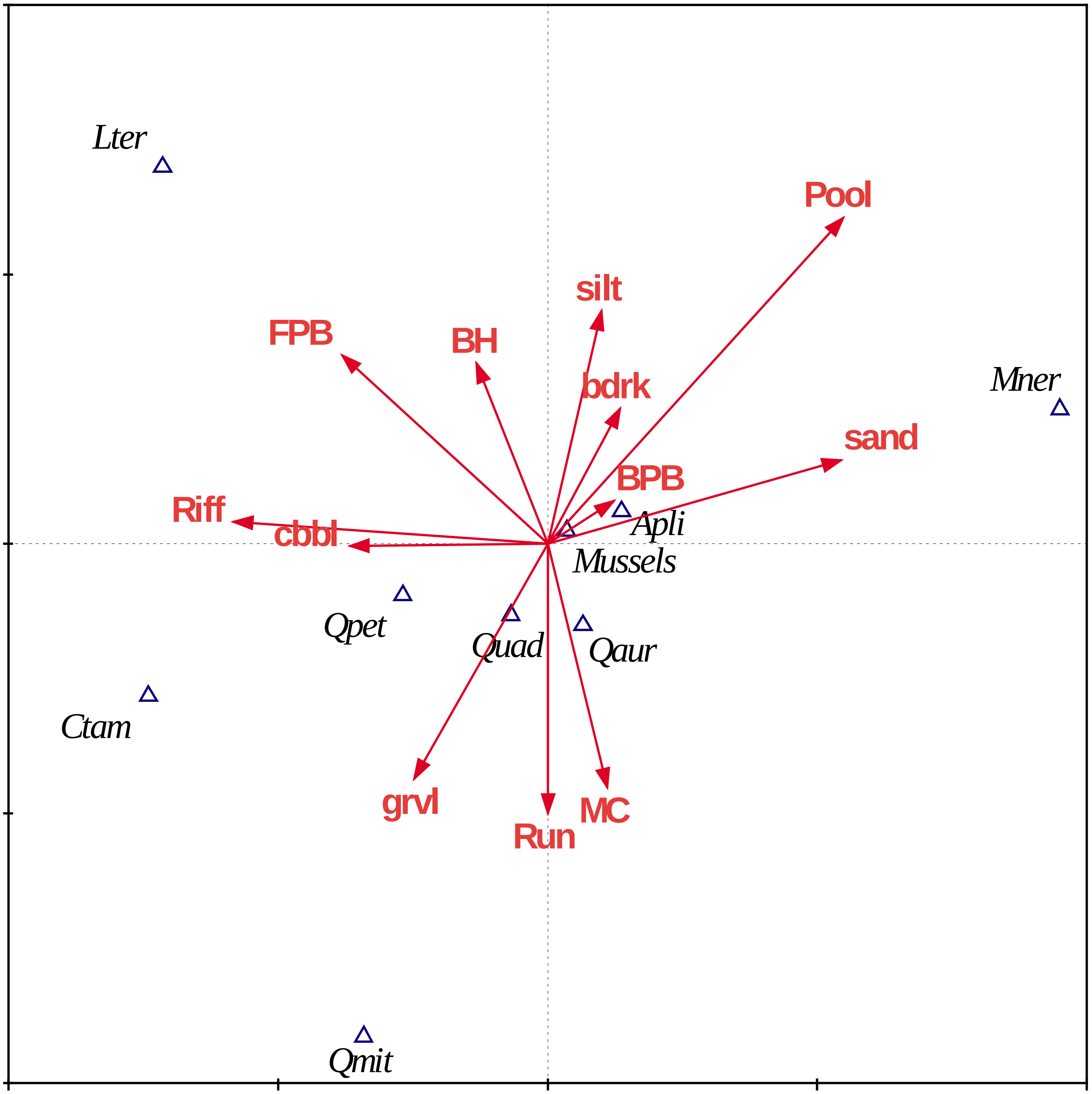

Figure 38. Multivariate ordination plot show species associations among substrate and habitat categories. Species codes: *Apli* – Threeridge, *Ctam* – Tampico Pearlymussel, *Lter* – Yellow Sandshell, *Mner* – Washboard, *Qaur* – Golden Orb, *Qmit* – False Spike, *Qpet* – Texas Pimpleback, *Quad* – all *Quadrula* in aggregate (Golden Orb, Texas Pimpleback, False Spike), *Mussels* – all mussels in aggregate. Habitat codes: FPB – Front of Point Bar, BH – Bank Habitat, BPB – Behind Point Bar, MC – Mid-channel.

To further explore associations among habitat/substrate categories, the Strauss Linear Index was used to examine habitat preference. The Strauss Linear Index (*L*) is calculated by taking the unweighted difference in the relative abundance of mussel *i* in each category (expressed as a proportion - r_i) and the relative abundance of habitats available (expressed as a proportion of habitats/substrates sampled - p_i):

$$L = r_i - p_i$$

Values of this index range from -1 to 1, with larger positive values indicating selection for a particular habitat/substrate, and negative values indicating avoidance. Although developed to assess food preference, this index has previously been used to examine habitat preference of fish and mussels (Persinger et al. 2011, Randklev et al. 2014). The sampling variance of this index is defined, so statistical comparisons can be made between a calculated value and the null hypothesis value of 0.00 using *t*-statistics (Strauss 1979).

Strauss Linear Index Values for each taxonomic group within each habitat/substrate category are provided in **Table 18**. Of the 88 values calculated, two significant preferences were observed. False Spike showed a preference for gravel substrates and Washboard demonstrated a preference for sand substrates.

Table 18. Strauss Linear Index values for each taxonomic group of mussels within each habitat/substrate category. Asterisks designate values which are statistically different from the null value of 0.00.

Species	**Mesohabitat Categories**			**Additional Habitat Categories**			**Substrate Categories**				
	Riffle	**Run**	**Pool**	**BH**	**BPB**	**FPB**	**Silt**	**Sand**	**Gravel**	**Cobble**	**Bedrock**
False Spike *Fusconaia mitchelli*	-0.07	0.20	-0.13	0.02	-0.03	-0.03	-0.06	0.00	0.32*	-0.17	-0.09
Golden Orb *Quadrula aurea*	-0.11	0.16	-0.06	-0.07	0.06	-0.02	0.00	0.11	0.14	-0.17	-0.08
Texas Pimpleback *Quadrula petrina*	-0.08	0.18	-0.10	-0.01	0.14	-0.02	0.02	0.02	0.03	0.01	-0.08
All *Quadrula* in aggregate (includes False Spike)	-0.09	0.17	-0.08	-0.04	0.08	-0.02	0.00	0.08	0.11	-0.11	-0.08
Washboard *Megolonaias nervosa*	-0.16	0.01	0.15	-0.09	0.18	-0.03	0.01	0.43*	-0.18	-0.19	-0.07
Threeridge *Amblema plicata*	-0.12	0.13	-0.01	-0.05	0.06	-0.01	0.00	0.08	0.11	-0.12	-0.07
Yellow Sandshell *Lampsilis teres*	0.01	-0.03	0.02	0.13	0.05	-0.02	0.04	0.05	0.07	-0.10	-0.06
Tampico Pearlymussel *Cyrtonaias tampicoensis*	-0.03	0.16	-0.13	-0.13	0.28	0.03	-0.06	0.06	-0.09	0.19	-0.09

3.5.2 MUSSEL SHEAR STRESS EVALUATION

To examine relationships between model-predicted shear stress and mussel abundance, the following equation was used to estimate shear stress (τ) based on model output:

$$\tau = U/5.75\log10(12d/k_s);$$

where U is mean column velocity (cm/s) predicted by the model, d is water depth (cm) predicted by the model, and k_s is an estimate of bed roughness based upon substrate mapping and known particle sizes from the modified Wentworth scale. Supplemental data from Randklev et al. (2014) show that although this equation tends to overestimate actual shears stress values when compared to measured values, there is a strong positive correlation between the two. Therefore, model-predicted shear stress values may be inflated, but were only used in this study to assess relationships between the two variables, and not to examine value-specific shear stress criteria.

Mussel abundance from each sampling location was compared to model-predicted shear stress at multiple flow rates using GIS software. In general, areas exhibiting the highest shear stress contained few mussels, whereas areas of highest mussel abundance were typically found at moderate shear stress across flow rates. Since shear stress at high flow rates is thought to have the largest impact on mussel distributions, relationships between mussel abundance and shear stress from the highest flow rate modeled (2,100 cfs) are provided in **Figure 39** and can be viewed spatially in **Figure 40**. More directed data collection with on-site measurements of shear stress are needed to further explore this relationship and to examine persistent habitats across flow rates.

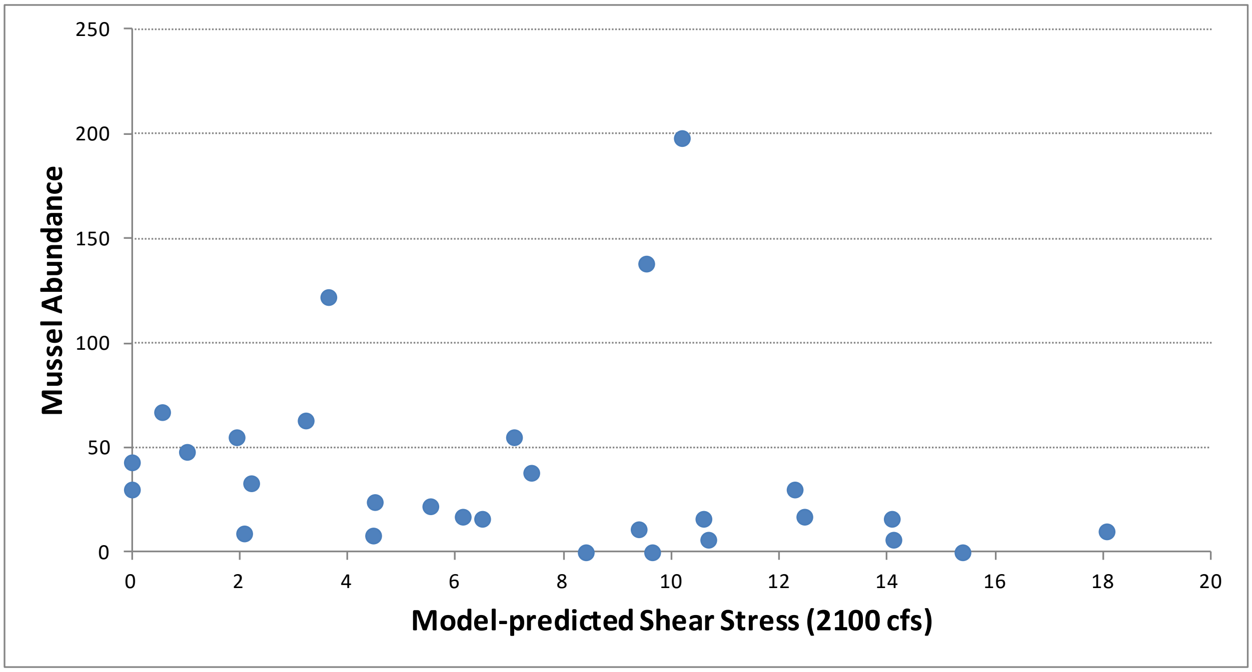

Figure 39. Relationship between model-predicted shear stress and mussel abundance at each sampling location.

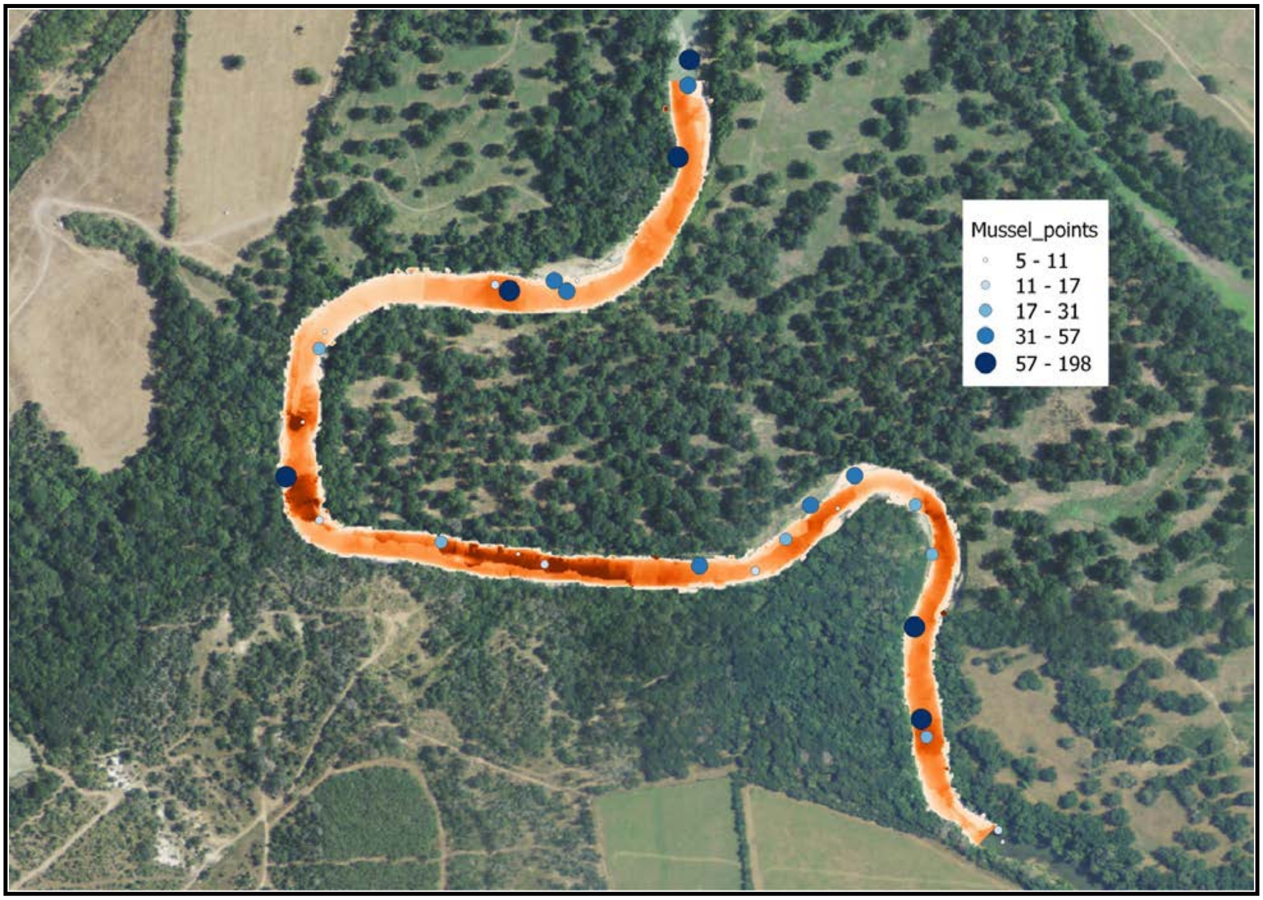

Figure 40. Mussel abundance at each sampling point overlaid on model-predicted shear stress at the highest flow rate modeled (2,100 cfs). Dark reds indicate areas of higher shear stress whereas lighter colors indicate lower shear stress.

3.5.3 MUSSEL CATCH PER UNIT EFFORT AND DISCHARGE

Of all the factors influencing mussel abundance and catch rates, the most obvious was discharge. Overall mussel catch-per-unit-effort (CPUE) was relatively consistent (22.3 – 26.5 mussels/person-hour) during sampling trips conducted at flows between 470 and 796 cfs. However, CPUE spiked to 93.5 mussels/person-hour at a discharge of approximately 100 cfs during September 2013 (**Table 19**). This increase in CPUE was no doubt a result of increased sampling efficiency under low flow conditions. At flows of approximately 100 cfs, many mid-channel gravel and cobble shoals begin to become exposed, as do the edges of many run and riffle areas (**Figure 41**). As a result, much of the available mussel habitat in these areas is either beginning to dry up or extremely shallow. During this sampling trip, mussels were easily found by walking the edges of the stream or shallow edges of exposed shoals. Many of the mussels were dislodged from their normal siphon-up feeding/resting position, and were simply laying on top of the substrate – presumably in an attempt to move to more favorable habitat conditions. Although only live mussels were enumerated, evidence of increased predation from raccoons and other terrestrial predators was evident from the large number of recently-dead shells in these areas.

Table 19. Mussel sampling date, mean daily discharge from the USGS gage at Gonzales (#08173900), and overall mussel catch-per-unit-effort (CPUE).

Sampling Date	Mean Daily Discharge (cfs)	Overall Mussel CPUE (mussels/person-hour)
10/25/2012	470	22.3
1/23/2013	568	26.5
5/30/2013	796	26.4
9/5/2013	101	93.5

Figure 41. Exposed mid-channel gravel shoal near the upstream end of the study site at flows of approximately 100 cfs during September 2013.

3.5.4 POST-FLOOD MUSSEL EVALUATION

Given substantial changes to channel morphology documented after the May 2015 flood event (see Section 3.1.3), a post-flood mussel evaluation was conducted in September 2015 to assess impacts to freshwater mussels following this event. This evaluation involved revisiting sites already sampled during previous surveys to document any changes in overall abundance of mussels or catch rates. Ten previously surveyed sites were visited, and the same protocol was used, with one-person hour of sampling effort conducted at each site. Overall CPUE during this event was 45.4 mussels/person-hour. This was slightly higher than most previous events, but lower than that observed during extreme low flow conditions in September 2013. In general, species composition was relatively similar compared to previous sampling events (**Table 20**). Despite substantial changes to channel morphology resulting from the May 2015 flood event, no obvious changes to mussel community composition or habitat utilization were noted.

Table 20. Number (#) and percent relative abundance (%) of freshwater mussels captured during 10 person-hours of sampling effort in September 2015 (after May 2015 flood event).

Scientific Name	Common Name	September 2015	
		#	%
Amblema plicata	Threeridge	356	78.4
Quadrula aurea	Golden Orb	26	5.7
Quadrula petrina	Texas Pimpleback	29	6.4
Megalonaias nervosa	Washboard	28	6.2
Lampsilis teres	Yellow Sandshell	3	0.7
Fusconaia mitchelli	False Spike	5	1.1
Cyrtonaias tampicoensis	Tampico Pearlymussel	6	1.3
Lampsilis hydiana	Louisiana Fatmucket	1	0.2
Total Individuals		**454**	
Species		**8**	

3.6 MACROINVERTEBRATE ANALYSIS

A common macroinvertebrate index in the literature used to evaluate stream water quality is the Hilsenhoff Family Biotic Index (Hilsenhoff 1988). Additionally, metrics such as EPT have been used to categorize the composition of the sample site relative to water quality, with a higher percentage of EPT and low percentage of Chironomidae often highly correlated with high quality water (Barbour et al. 1999). However, the focus of the macroinvertebrate assessment for this study was not water quality but rather to evaluate the effects of flow pulses on habitat disturbance in riffles and resulting effects on macroinvertebrate communities. Townsend and Scarsbrook (1997) provide a nice overview of the origin, evolution, and application of the intermediate disturbance hypothesis in ecology. Townsend and Scarsbrook (1997) went on to test the hypothesis that maximum taxon richness of macroinvertebrates will occur in communities subject to intermediate levels of disturbance that differed in the frequency and intensity of flood-related episodes of bed movement at over 50 stream sites in southern New Zealand. Their results support the intermediate disturbance hypothesis, with both highly mobile and relatively sedentary taxa responding as predicted and stream bed disturbance being the best variable at accounting for variation in taxonomic richness (Townsend and Scarsbrook 1997). Based on the intermediate disturbance hypothesis, it is expected that some level of periodic disturbance benefits diversity of macroinvertebrate communities.

The main objective of this assessment was to evaluate whether a flow threshold could be identified at which the macroinvertebrate communities were disturbed. **Table 21** shows the dates and discharges associated with the seven macroinvertebrate sampling events. By design, the events targeted different types of pulse events occurring in different seasons. The recent pulse activity leading up to each sampling event is also briefly described in **Table 20** and shown graphically in **Figure 42**. After considerable analysis of the raw data which helped establish an understanding of the inherent variability in this type of data, and a review of existing literature on this topic, insect and EPT abundance, as well as average number of taxa for insects and EPT were used as indicators for macroinvertebrate community disturbance. Higher abundance and diversity (average of taxa count) for the categories represent more stable macroinvertebrate conditions, while the lower numbers represent varying levels of disturbance – a condition necessary to maintain diversity.

A qualitative evaluation of the recent pulse activity suggests that long periods with no pulses and pulses up to approximately 1,000 cfs do not appear to cause disturbance to riffle habitats to the degree that it affects the macroinvertebrate community; whereas pulses greater than 1,500 cfs start to cause disturbances to the macroinvertebrate community in the riffles with major events causing instability for several months post event (**Table 21**, **Figure 42**).

It is acknowledged that this is a qualitative assessment with several assumptions; a major one being that the preceding pulse activity was indeed the driver of the results. Data collection over a longer time period is needed to further evaluate the trends observed. Additional data may help refine the pulse magnitude necessary for macroinvertebrate disturbance and also help in understanding recolonization rates. Despite these caveats, this qualitative macroinvertebrate assessment provides a good first step in advancing the science toward understanding potential ecological linkages between flow pulses and the resulting macroinvertebrate community.

Table 21. Macroinvertebrate sample dates, discharge, recent pulse activity, and macroinvertebrate index scores. Boxes are color coded with green representing high scores (low disturbance), yellow representing moderate scores (some disturbance), and red representing low scores (high disturbance).

Season	Recent Pulse Activity prior to sampling	Sample Dates	Discharge at time of sample (cfs)	Insect Abundance (number)	EPT Abundance (number)	Insect Avg Of Taxa Count	EPT Avg Of Taxa Count
Fall	Recent Pulse > 1,500 cfs	10/23/2012	455	2,308	1,862	14.06	10.12
Fall	No pulses for 3+ months	9/3/2013	136	7,617	6,404	18.17	12.33
Winter	Recent Pulse > 1,000 cfs	1/22/2013	586	4,008	3,222	20.59	14.75
Winter	1 month after extreme pulse > 15,000 cfs	12/10/2013	369	980	521	11.73	8.13
Winter	3 months post extreme pulse > 15,000 cfs	2/1/2014	471	203	77	5.86	4.00
Spring	Receding Pulse > 2,000 cfs	5/28/2013	1,550	657	510	8.37	6.58
Spring	No pulses for 5+ months	5/22/2014	293	2,980	2,534	18.45	12.55

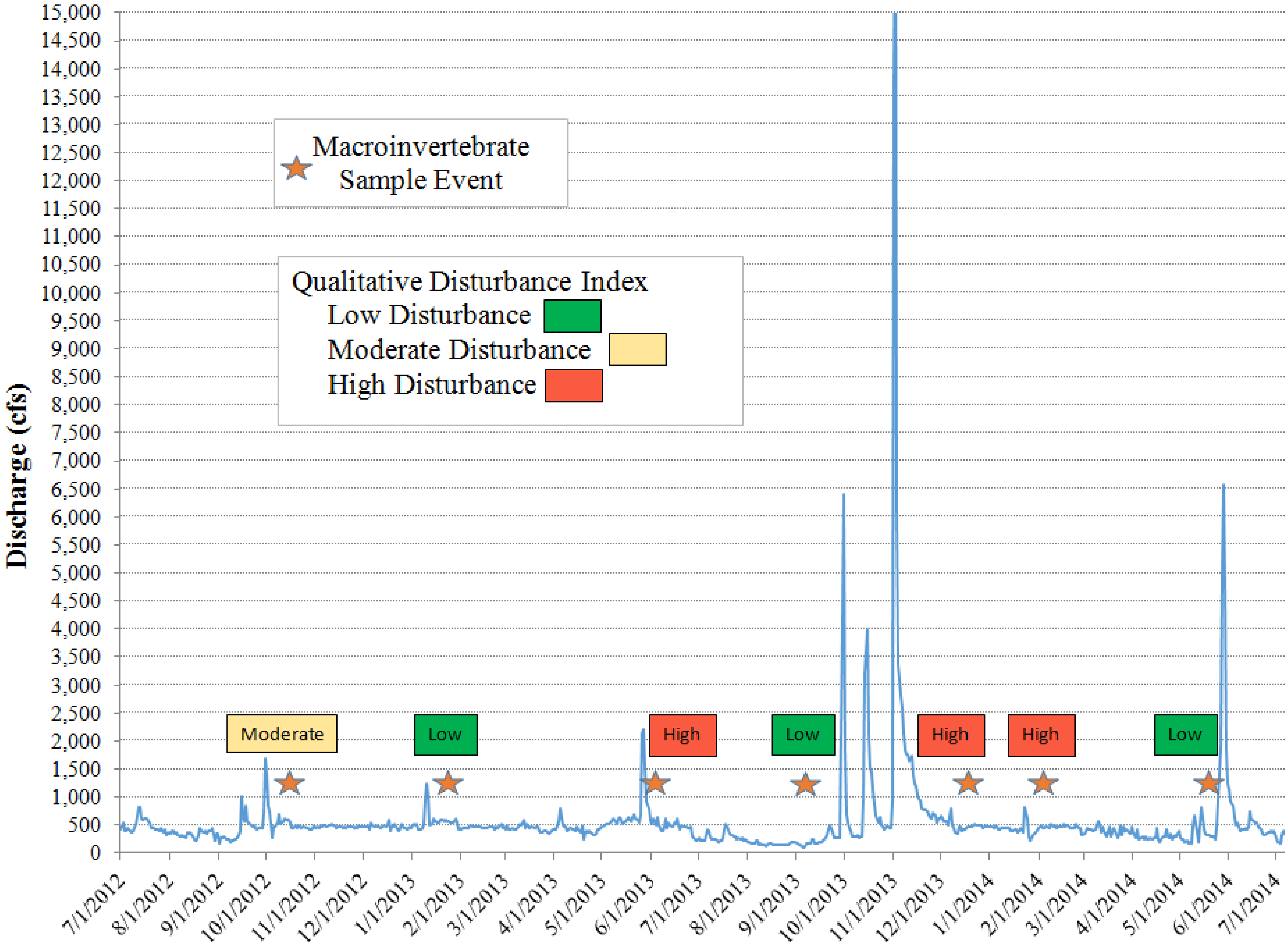

Figure 42. Macroinvertebrate sample dates and color-coded qualitative disturbance index.

3.7 RIPARIAN ANALYSIS

Several key riparian processes/characteristics are given below, grouped by general life stage. For the riparian assessment, the responses of these processes were considered in relation to stream flow:

1. seedling distribution/germination;
2. seedling survival;
3. sapling survival; and
4. mature tree survival/maintenance and distribution.

Although seed germination is critically dependent on flood pulsing (Junk and Piedade, 1997), as plants mature they become both less dependent on frequent pulses and more tolerant of severe flow fluctuations. Seedling dispersal, establishment, and survival are key life stages to ensuring that riparian forest replacement is maintained.

Representative incremental high flow pulses from the record during 2012-2015 were selected for detailed analysis to determine the inundation level of the riparian indicator species. This pulse analysis was used to identify the pulse events that provide a water source to each tree species' recruitment zone. The river level elevation depicted is based on data from the pressure transducer installed in the river at each site. Topographic survey data enabled the use of actual elevation data. At this site, the slope from river's edge to the uppermost extent is 0.15 (meters rise/meters run). Beyond a steep, almost 6m rise in elevation, the slope levels to 0.05 (**Figure 43**). Interestingly, the ranges for the two indicator species mature trees found here (box elder and green ash) overlap completely, are extremely truncated, and are confined to a height of 6m and distance of 18-20 meters. This elevation requires a discharge of greater than 14,000 cfs to wet the majority of the mature tree distribution for both indicator species.

In comparison, the percent coverage of box elder and green ash saplings (**Figure 44, Figure 45**) with ranges including lower tiers of the channel slopes experiences more inundation than their mature counterparts at lower discharges. Approximately 4,000 cfs starts to wet the lower range of the distribution of seedlings and saplings for both indicator species. Box elder seedlings (**Figure 44)** dispersed just above 2 m elevation and 2 m distance up to 6.3 m elevation and 34 m distance, both above and below the mature trees' ranges. The seedlings' distribution follows the spatial coverage provided by two large flow pulses of 6.2 m (14,800 cfs) and 8.2 m (24,900 cfs) inundation in fall 2013. However, there were no subsequent flows at this level during 2014 presumably necessary to ensure survival this far up in the recruitment zone.

Green ash seedling dispersal occurred up to an elevation of 7.2 m, and sapling distributions fell within a comparable range (**Figure 45**). Both of these age classes were well above and below the mature stands. As with the box elders, the likely flow pulse(s) that deposited the seedlings were the fall 2013 8.2 m (24,900 cfs) and/or 6.2 m (14,800 cfs) flows. Based on the present distribution of mature box elders and green ash, the flow conditions observed during fall 2013 are considered well above what would be necessary to maintain the existing riparian community at this site. However, these less frequent (1 per year) and greater events do serve an important function in maintaining a diverse riparian community over time.

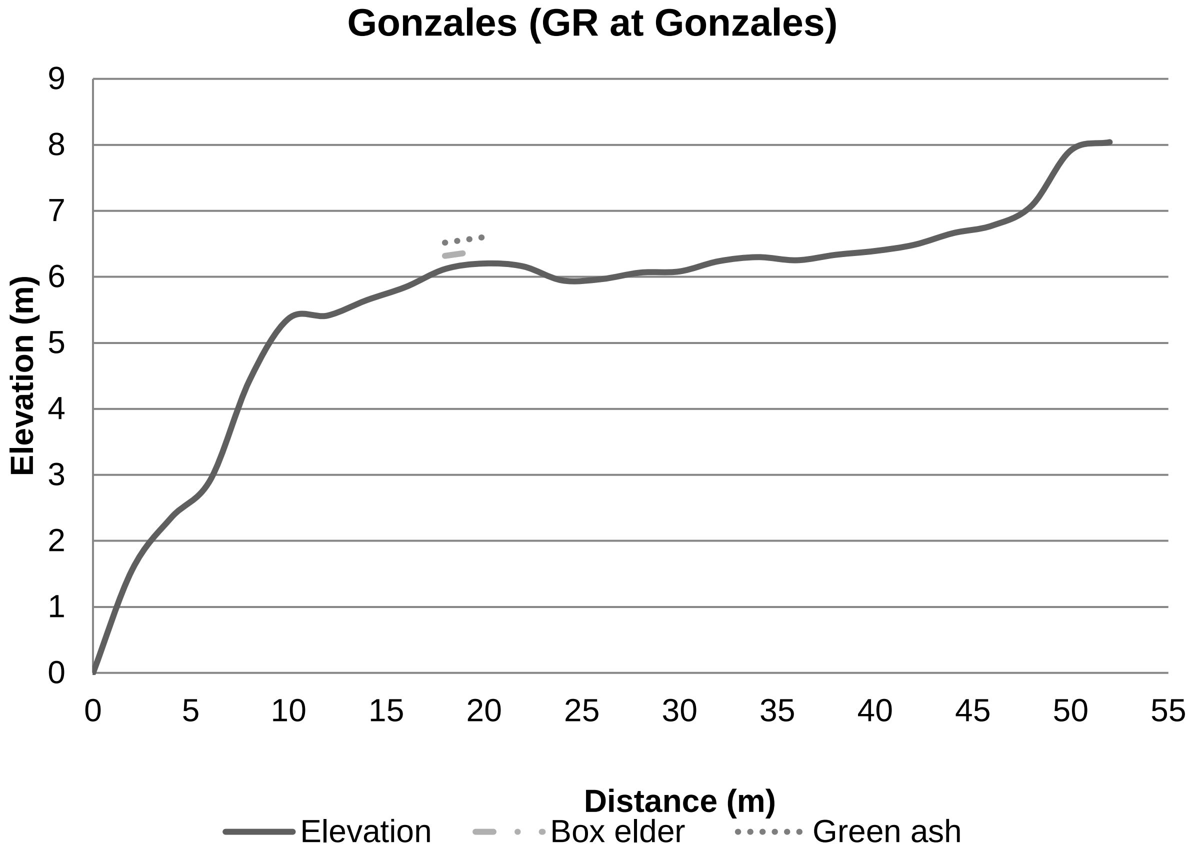

Figure 43. Gonzales site profile. Elevation is height above water's edge. Spatial distributions of mature indicator species are shown along the site profile.

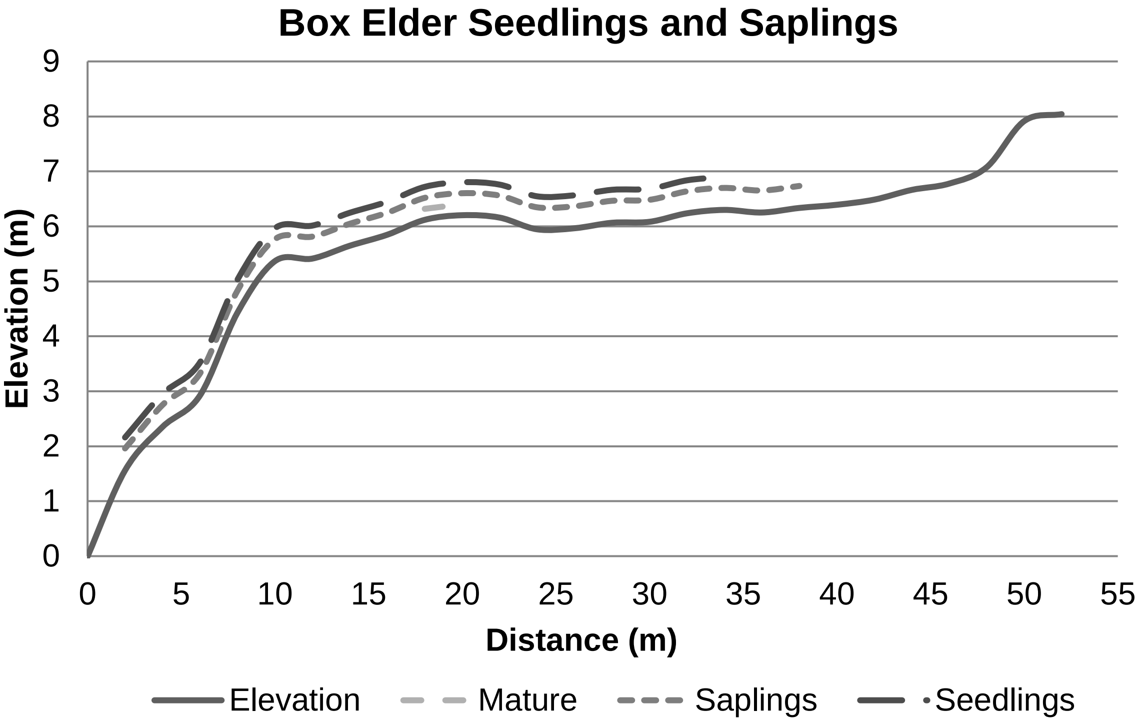

Figure 44. Box elder seedling and sapling distributions at the Gonzales site.

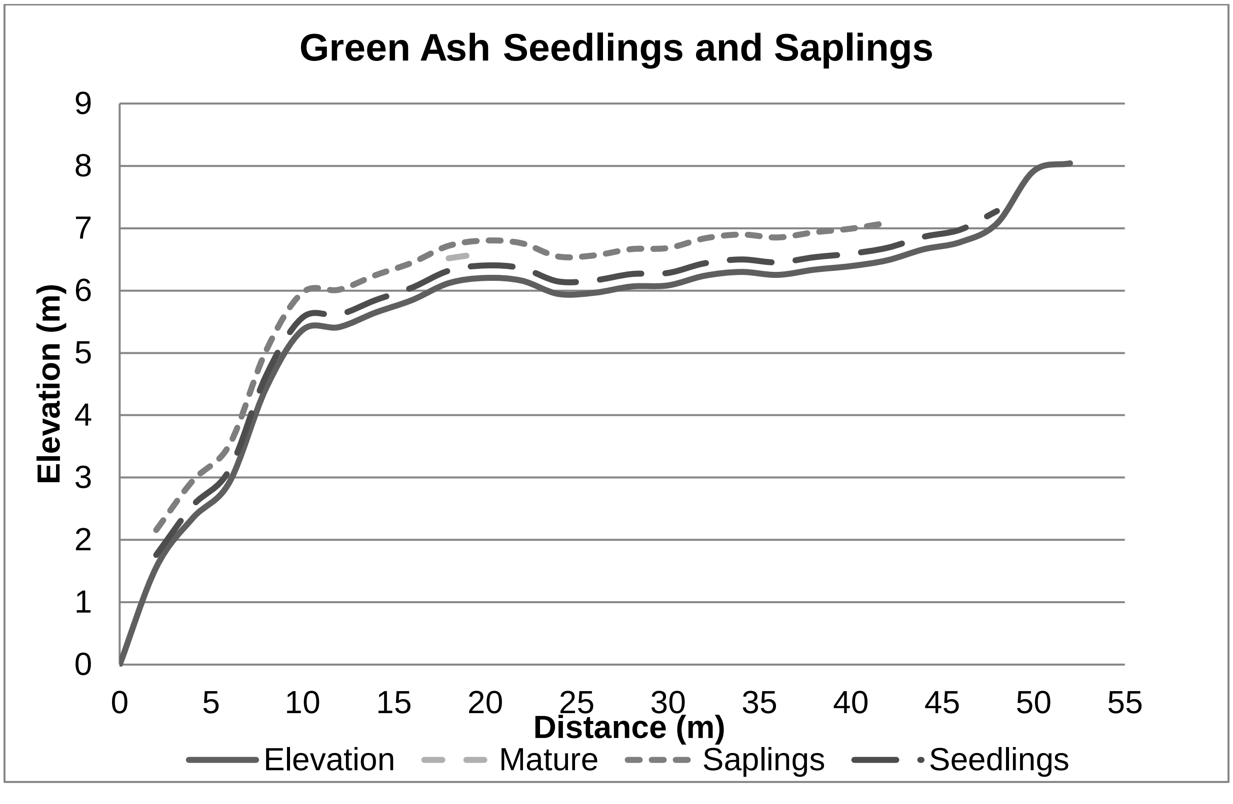

Figure 45. Green ash seedling and sapling distributions at the Gonzales site.

When evaluating responses to flow pulses on a finer scale (see **Table 11**, Section 2.3.4), box elder seedlings lost 5 members and had 5 recruited to saplings from September 2013 to the next spring. Through the 2014 growing season another one was recruited and 5 new germinated. Two died by October, but another 58 were added early in 2015. Saplings of this species remained fairly healthy (only one perished over the study period and one was recruited to the mature class). Green ash seedlings saw a recruitment of 10 members to sapling and a loss of 20 members from September 2013 to the next spring. During the 2014 growing season several more were added and recruited up, but between fall 2014 and spring 2015 18 perished. At the same time that seedling loss was occurring by 2014 year's end, sapling and mature loss also occurred. It appears that the late 2013 high-flow pulses (6.2 m and 8.2 m) jumpstarted the green ash's reproduction and growth, but by the end of the very dry 2014 year, the stands were showing the stress of a lack of further flow pulses.

In addition to an assessment of the two indicator species discussed above, an assessment of the black willow community was also conducted. As previously mentioned, there were no black willows within the randomly selected Gonzales site transects. However, the Victoria study site that was part of the Senate Bill 3 environmental flows validation project (SARA 2015) did contain black willows and provides a relevant example of what would likely be necessary at the Gonzales location to support black willows along the river's edge. Black willow is an important indicator in that it typically grows adjacent to the water level and much lower on the channel slope. The growing season is similar to the box elder, but the flow levels required to disperse seeds within the majority of black willow distribution along a river's edge is typically much lower. As this species typically inhabits near stream banks, the frequency for wetting of seedlings to ensure survival is typically increased relative to other more woody riparian species. As such, the proper timing of high flow pulses to distribute black willow seedlings is paramount but must be followed up by periodic wetting over the recently distributed seeds and existing saplings. An examination of the black willow data from the Victoria site (SARA 2015) reveals that the black willow distribution of seedlings, saplings and adults starts at approximately a 0.8 m elevation on the slope. This corresponds to approximately 1,750 cfs at the Gonzales site to start direct wetting of black willows.

In summary, high flow pulses that did occur over the study period at the Gonzales site appeared to have a positive influence on the box elders and green ash seedlings, whose distributions in 2014 directly correlated with a fall 2013 flow event. A lack of flow pulses in 2014 had a negative effect on dispersal and seedling/sapling distribution, and green ash seedling survival. As such, recommendations for maintaining a healthy riparian community described in Section 4.3 focus not only on seed distribution and germination, but seed and sapling survival as well. It is important to note that other mechanisms are in play beyond just the wetting of surface area within the indicator species historical distribution zone. During high flow pulse events, river water level infiltrates along the bank and recharges the groundwater (SARA 2015). Both rainfall and high flow pulses have the potential to increase soil moisture in the riparian area, with rainfall events contributing to more frequent soil wetting in the shallow seedling root zone along the slope within the study plots.

It is also important to note that the occasional pushing back of upland species by significant overbanking events is warranted to maintain a healthy riparian ecosystem. It was noted in Section 2.3.4 that the existing Gonzales site riparian zone maintains a diverse community, but has recently seen encroachment from hackberry. Periodic high flow pulses on the order of 1 per year or greater are needed to push back upland species in order to maintain riparian species dominance.

As with any ecological system, extremes often cause benefits and damage simultaneously which is part of the complexity in developing instream flow recommendations. While the sizable overbanking events that occurred in Fall 2013, Spring 2015 and Fall 2015 served a valuable role in pushing back upland plant species, they also reshaped a lot of the lower channel slope riparian habitat causing scouring out of black willow habitat and even causing mortality of well established sycamore saplings and mature trees on islands at the lower end of the site. **Figure 46** shows a stand of sycamores on a channel island with only the tops of a few of the trees visible from the bank during the high flows experienced in June 2015. Subsequently, **Figure 47** shows the destruction and dead trees left when the high discharges subsided in late summer.

Figure 46. Large sycamore saplings on an island (center of photo) nearly completely underwater during high flows in June 2015.

Figure 47. Sycamore saplings and small mature trees on channel island all dead or scoured and removed when flows subsided in late summer 2015.

3.8 WATER QUALITY ANALYSIS

Summary statistics for the 160 habitat-specific water quality measurements collected during fish habitat utilization sampling are provided in **Table 22**. Water temperature ranged from 10.19 °C in December 2013 to 32.82 °C in a pool habitat in September 2013 under hot summertime low-flow conditions (≈100 cfs). Individual dissolved oxygen measurements ranged from 4.67 mg/L in a stagnant pool during hot low-flow conditions in September 2013 to over 27 mg/L in a sun-drenched algae-filled backwater in May 2014. Individual pH measurements ranged from 7.20 – 8.72, with a mean of 8.21. Conductivity was relatively consistent and varied between 435 µS/cm and 589 µS/cm, with a mean of 529 µS/cm. Not surprisingly, habitat-specific point measurements were more variable than those observed during sonde deployments. Stagnant pools and backwaters which exhibit little water exchange with the main channel often have larger fluctuations in water quality parameters. Sondes were typically deployed in flowing run habitats which exhibit less variation in water quality parameters, but better represent the conditions experienced by most riverine fishes.

Table 22. Summary statistics for 160 point water quality measurements taken in various habitats over a two-year period during seasonal fish habitat utilization sampling.

	Temperature (°C)	**Dissolved Oxygen (mg/L)**	**pH**	**Conductivity (µS/cm)**
Minimum	10.19	4.67	7.20	435
25th percentile	14.48	7.21	8.10	507
Median	25.60	8.56	8.22	531
75th percentile	28.99	10.26	8.34	548
Maximum	32.82	27.56	8.72	589
Mean	22.66	9.01	8.21	529

Multi-day sonde deployment data is available from three separate deployment events. Since temperature and dissolved oxygen concentrations are the main constituents of concern as it relates to stress of aquatic organisms within this system, plots of diel fluctuations in these variables are provided for each event. First, data from January 22-24, 2013 demonstrate that water temperature fluctuated between 12.32 and 14.39 °C and dissolved oxygen concentrations ranged from 11.29 to 12.23 mg/L (**Figure 48**). Instantaneous flow data from the USGS gage at Gonzales (#08173900) shows discharge ranged between 436 and 733 during this time period. This represents a nice snapshot of diel water quality conditions during the cooler months under rather typical flow conditions. However, it is usually the hot low-flow months of July-September that result in the greatest stress to aquatic organisms due to higher water temperatures and lower dissolved oxygen concentrations. To examine conditions during this critical time period, diel water temperature and dissolved oxygen data from August 15, 2014 through September 17, 2014 are provided in **Figure 49**. Instantaneous flow data shows discharge ranged between 127 and 242 cfs on those dates. These data show a minimum dissolved oxygen value of 5.82 mg/L and a maximum water temperature of 32.51 °C. A significant rainfall event occurred in mid-September subsequently causing temporary reductions in both water temperature and dissolved oxygen.

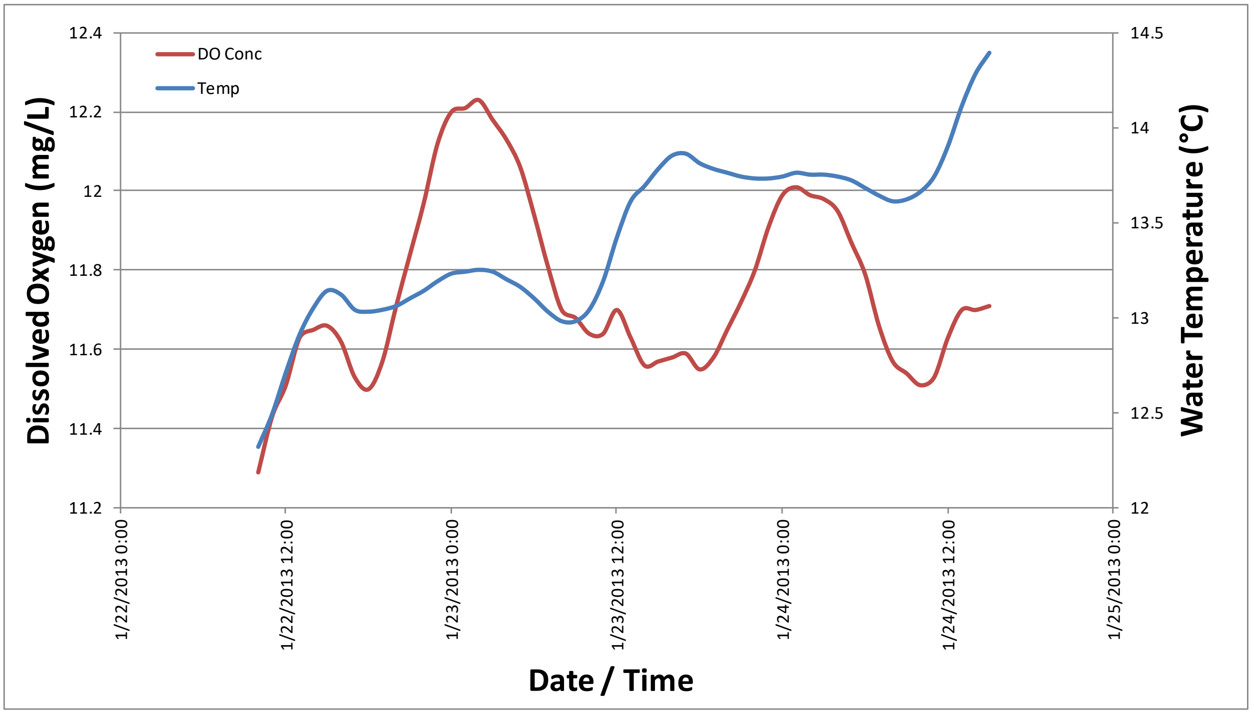

Figure 48. Diel pattern in water temperature and dissolved oxygen within the study reach on January 22-24, 2013.

Additional diel data is available at even lower flows during September 3-5, 2013 when instantaneous flow data show discharge ranging from 89-192 cfs (**Figure 50**). Minimum DO during this deployment was 6.37 mg/L, and maximum water temperature was 32.27 °C.

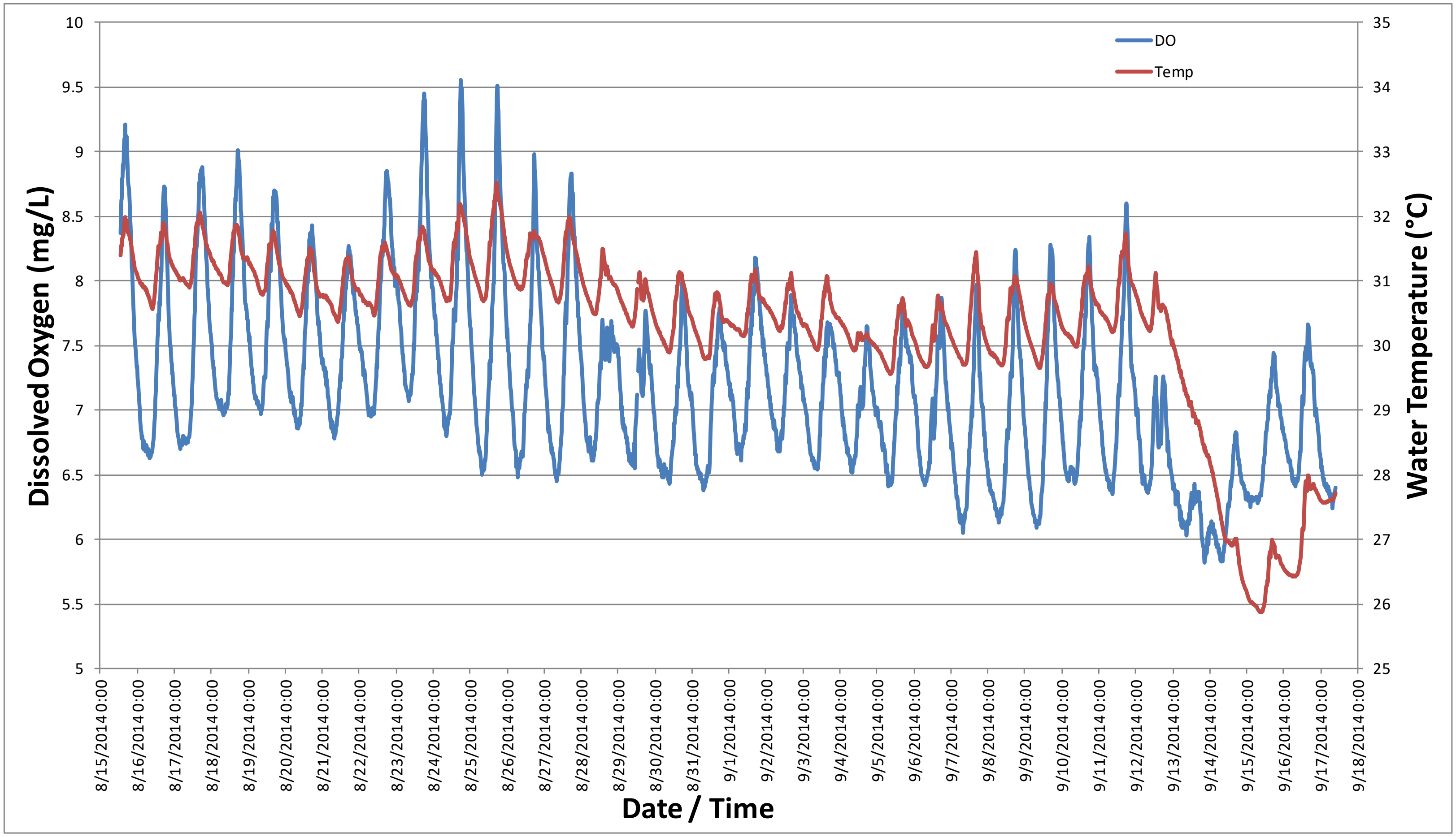

Figure 49. Diel temperature and dissolved oxygen data from the study reach during August 15 – September 17, 2014 at flows ranging from 127 – 242 cfs. Note: A significant rainfall event occurred in mid-September subsequently causing temporary reductions in both parameters.

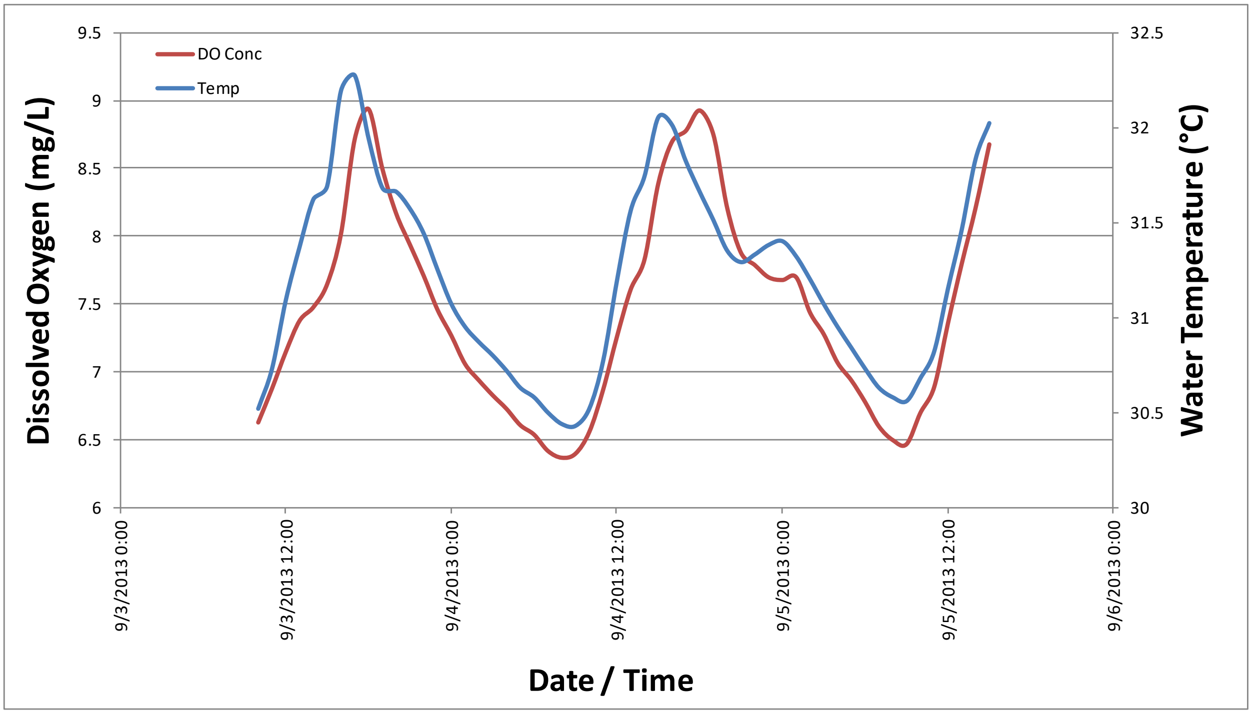

Figure 50. Diel temperature and dissolved oxygen data from the study reach during September 3-5, 2013 at flows of 89-192 cfs.

4.0 INTEGRATION AND RECOMMENDATIONS

The development of comprehensive instream flow recommendations require integration of all the key components described above into a single flow regime. Such a regime must be complex enough to account for the needs of the fish community (both in-channel and floodplain), the macroinvertebrate community, the freshwater mussel community, and the riparian vegetation community, yet be simple enough to allow for reasonable implementation in real-world water management scenarios. Typically, instream flow recommendations focus on four key components of the hydrologic regime – subsistence flows, base flows, high flow pulses, and overbank flows - as outlined in the Texas Instream Flow Program technical overview document (TIFP 2008). A brief overview of the definitions and objectives of the instream flow components as presented in TIFP (2008) is presented in **Table 23**.

Table 23. Definitions and objectives of instream flow components (adapted from TIFP 2008).

Subsistence Flows	
Definition:	Infrequent, seasonal periods of low flow.
Objectives:	Primary objective is to maintain water quality criteria. Secondary objectives to provide important low flow life cycle cues or refugia habitat.
Base Flows	
Definition:	Normal flow conditions between storm events.
Objectives:	Ensure adequate habitat conditions, including variability, to support the natural biological community.
High Pulse Flows	
Definition:	Short-duration, within-channel, high flow events following storm events.
Objectives:	Maintain important physical habitat features. Provide longitudinal connectivity along the river channel.
Overbank Flows	
Definition:	Infrequent, high flow events that exceed the normal channel.
Objectives:	Maintain riparian areas. Provide lateral connectivity between the river and floodplain.

Overbank / channel maintenance flows typically occur during rare extreme flood events that are beyond the control of infrastructure and often result in significant risk to property and lives. As a result, although their ecological importance is recognized, overbank flows are often lacking from final flow recommendations due to liability issues. For these reasons, extreme overbank / channel maintenance flows are not discussed in this document. However, the following sections outline recommended subsistence, base, and pulse flow levels and the ecological linkages used to develop them.

4.1 SUBSISTENCE FLOWS

Subsistence flows represent infrequent periods of low flow. These conditions naturally occur, typically during late summer, and cause stress to the aquatic community through limited habitat, increased temperatures, low dissolved oxygen levels, etc. The primary objective of subsistence flow recommendations is to ensure maintenance of appropriate water quality conditions for survival of aquatic organisms. Secondary objectives include providing important low-flow life cycle cues and refugia habitat. Extreme low flows were observed during this study in late summer 2013. Data were collected at flows below 100 cfs during early September 2013, allowing the study team to directly observe conditions at subsistence-level flow rates.

A detailed water quality analysis conducted by the GSA BBEST analyzed several water quality parameters and their relationship to discharge in the lower Guadalupe River (GSA BBEST 2011). This analysis, which incorporated over 4,000 sampling events from 30 sites between 1973 and 2010, was unable to identify flow rates at which water quality would be unable to support a sound ecological environment. Water quality data collected as part of this study generally support that conclusion and demonstrate that even at the lowest flows observed (below 100 cfs), water quality conditions within the study reach remain sufficient for survival of resident aquatic organisms. Minimum dissolved oxygen concentrations observed during diel sonde deployments under low flow conditions near 100 cfs in September 2013 and August/September 2014 were 6.4 and 5.8 mg/L, respectively. Dissolved oxygen values as low as 4.7 mg/L were documented in stagnant pool and backwater habitats during fish habitat utilization sampling. However, these values were specific to small microhabitats, and measurements in the main river during the same time period exceeded 8 mg/L.

Maximum water temperatures during this same time period were approximately 32.5 °C. Based on previous data collected by BIO-WEST, similar summertime temperatures occur in other central Texas rivers including the lower San Antonio River and the lower Colorado River (TIFP 2011, BIO-WEST 2008). A quick review of the literature on fish thermal tolerances suggest that this may represent stressful conditions for some species, but these temperatures are not considered lethal for any of the resident fish species. However, little information is available on thermal tolerances of Guadalupe River mussels. Therefore, until more data is available on temperature tolerances of Guadalupe River mussel species, the effect of water temperatures higher than those observed in this study is unknown.

Fish habitat modeling shows relatively good habitat conditions at flows as low as 136 cfs. Deep Run and Riffle habitat decrease sharply down to 50 cfs. However, at both 50 and 136 cfs, all habitat guilds maintain over 60% of their maximum, with most guilds maintaining over 80% of maximum. This suggests that even under such low flow conditions, fish habitat is adequately maintained.

In contrast, mussel habitat becomes extremely limited at flows below 136 cfs. At flows of approximately 100 cfs, many mid-channel gravel and cobble shoals begin to become exposed. Wetted area shrinks considerably, exposing the edges of many riffle complexes. At these flow rates, the study team observed desiccation of considerable mussel habitat, likely resulting in mortality of a large number of mussels. Although additional mussel sampling conducted after this event yielded similar catch rates, sustained flows below approximately 130 cfs were considered undesirable due to potential impact to mussel habitat and given unknown temperature tolerances of mussels. Therefore, a subsistence flow of 130 cfs is recommended year-around regardless of hydrologic condition.

4.2 BASE FLOWS

The goal of base flow recommendations is to ensure adequate habitat conditions, including variability, to support the natural aquatic community. Therefore, fish habitat modeling provided the basis for assessing base flow conditions. To provide variability, two base flow hydrologic conditions are proposed – Base Dry and Base. Base Dry conditions are to be applied during naturally dry periods (25th percentile or less), and Base would be applied all other times. Although TIFP (2008) recommends considering a third base (Base Wet) category, based primarily on hydrologic statistics, our experience suggests that continuous flows exceeding Base Wet recommendations typically only occur during back-to-back pulse events or on the tailing edge of really large pulses. Continuous flat-line flows rarely if ever occur on the hydrograph at typical Base Wet magnitudes and did not occur at the Gonzales site over the course (2012 through 2015) of this study. Given this, and the lack of an ecological link to continuous flows of this magnitude, a Base Wet recommendation is not provided herein.

A three-season approach is recommended to provide intra-annual variability in base flow conditions. A spring season is designed to capture the typically wetter months of March through June, a summer season to capture the typically dryer low-flow months of July through September, and a fall/winter season to capture the months of October through February. This three-season approach simplifies implementation while still capturing the important and ecologically meaningful patterns in within-year flow variability.

As stated above, fish habitat modeling provided the basis for assessing base flow magnitudes. If all habitat guilds are treated equally, a flow of 50 cfs results in the highest average percent maximum across habitat guilds (92%). This is due to a sharp increase in the amount of Shallow Pool/Edge, Shallow Run, Moderate Pool, and Deep Pool habitats at low flows. These three guilds are dominated by ubiquitous generalist species such as Western Mosquitofish, Gizzard Shad, Red Shiner, Bullhead Minnow, Longear Sunfish, and Bluegill which would be expected to proliferate under more lentic-like low-flow conditions. In contrast, the Riffle and Deep Run guilds contain all of the regionally endemic flow-sensitive species which make the lower Guadalupe River fish assemblage distinct from other Western Gulf Slope assemblages. These include the Guadalupe Darter, Burrhead Chub, River Darter, Texas Logperch, and Gray Redhorse. Therefore, maximizing Riffle and Deep Run habitat was given higher priority over other guilds.

Habitat modeling shows a peak in Riffle habitat at a flow of 225 cfs. Therefore, to capture this peak in habitat availability for important flow-sensitive species, while still maintaining intra-annual variability, Base Dry flow recommendations were set at 200 or 300 cfs. A Base Dry recommendation of 200 cfs was set during the typically dry summer months, whereas a Base Dry recommendation of 300 cfs was set during the remainder of the year. Deep Run habitat availability peaked at a flow of 427 cfs but maintained over 99% of its maximum available habitat between 325 cfs and 539 cfs. Given this broad peak in habitat availability, Base recommendations were set between 300 and 550 cfs. To capture seasonal variability, a higher Spring Base of 550 cfs was recommended along with a lower Summer Base of 450 cfs. A Fall/Winter Base recommendation of 300 cfs was designed to maintain good Deep Run habitat availability while also improving Riffle habitat availability since most of the darter species within the Riffle guild spawn during the Winter season. It is recognized that Base recommendations in the 450-550 cfs range result in relatively low availability for some guilds (i.e., Shallow Pool/Edge, Shallow Run, Moderate Pool). However, these guilds contain mostly ubiquitous generalist species, and the need for interannual base flow variability was seen as more important than maximizing habitat for this suite of common species.

4.3 PULSE FLOWS

Over the course of the study it was evident that pulse flows of varying levels had direct ecological linkages to the riparian community, as well as aquatic communities present in floodplain habitats and riffle environments within the main river channel. To provide variability in flow pulses two hydrologic conditions are proposed – Wet and Other. Wet conditions are proposed to be applied during naturally wet periods (75th percentile or more), and "Other" would be applied during all other times.

An analysis of pulse flows that occurred during the riparian seedling recruitment period indicate the seedling recruitment zones appear to correspond to a series of instream flow conditions that benefit seed dispersal, germination, and seedling survival. Black willow are most common near the river's edge on the lower, wetter, and often less sandy areas of the bank. They typically begin to produce seed around 10 years of age, and seed is dispersed by wind and water. Black willow seed must reach a suitable seedbed within 12 to 24 hours because viability is greatly reduced by even a few days of dry conditions. Due to location of black willow on the bank, smaller high flow pulses of approximately 2,000 cfs and higher inundate portions of the bank necessary to ensure moist seedbed areas within its current habitat. In addition, since black willow is an obligate wetland species, providing additional pulse flows during the summer and fall months would allow for continued growth and survival of seedlings.

While sycamore seedlings were not considered an indicator species in this study, this species does occur in the riparian community as well as along the bank and on island areas in the Gonzales reach. Sycamore trees begin to produce seed around 25 years of age, and are typically dispersed February through May. Green ash seed may ripen as early as April or May, and fall as soon as they ripen. With sycamore and green ash occurring further up the bank than black willows, higher flow pulses that inundate portions of the upper bank are important in early spring to create seed germination sites and provide soil moisture to seed and seedlings. To account for coverage of a portion of the existing recruitment zone each year, spring time pulses ranging from approximately 4,000 to 6,000 cfs are recommended.

Box elder seed crops are produced on trees as young as 8 years old, which ripen August through October and are primarily wind distributed through spring. With box elder also occurring further up the bank than black willows, higher flow pulses that inundate portions of the upper bank during both the fall and spring seasonal window are also important to the riparian community. Based on the existing distribution of seedlings and saplings for this indicator species, fall/winter pulses ranging from approximately 4,000 to 5,500 cfs are recommended.

Section 3.4 describes a direct ecological linkage to flow evident at the Gonzales site relative to connectivity to floodplain habitats. In addition, recent work conducted to evaluate/refine SB3 flow recommendations and standards also conducted an evaluation of floodplain connectivity at 5 sites within the lower Guadalupe River basin (SARA 2015). Data from that study confirm that floodplain features within the lower Guadalupe River basin harbor a unique community of fishes significantly different from that found in the mainstem. Occasional connection of floodplain lakes to the main stem of the lower Guadalupe River is crucial to prevent desiccation and allow biotic exchange. Estimates of connection discharge varied widely, ranging from approximately 150 cfs to approximately 3,000 cfs for the 5 sites examined in the lower Guadalupe River. Three of the 5 floodplain lakes actually maintained connection with the main stem of the Guadalupe River under base flow conditions, with these sites tending to be the most speciose (SARA 2015).

An estimated flow of 2,822 cfs was calculated as being needed at the USGS gage at Gonzales to fully connect the floodplain feature discussed in this report. The estimated historical connection frequency for this feature based on that discharge was 5.2 connections per year. Flows of this magnitude are rare during the summer, and thus no high-flow pulse recommendations were made to reach this magnitude for the summer season (July – September) during the “Other” hydrological condition. However, the “Other” condition does include pulse flow recommendations which would result in one connection during the spring and one during the fall/winter while simultaneously benefiting riparian recruitment. During Wet conditions, recommendations include an opportunity for three connections during the spring, one in the summer, and one in the fall/winter.

The third ecological component evaluated relative to pulse flows was habitat disturbance to support a healthy macroinvertebrate community in riffles. As discussed in Section 3.6, long periods with no pulses and pulses up to approximately 1,000 cfs do not appear to cause disturbance to the riffle habitat to the degree that it affects the macroinvertebrate community. However, pulses greater than 1,500 cfs appear to cause disturbances to the macroinvertebrate community in the riffles with major events causing instability for several months post event. As this data is preliminary in nature, it was only used to support recommendations developed based on riparian and floodplain connectivity.

Attached to each pulse flow recommendation described above is a duration and frequency. Based on site-specific soil moisture data and previous riparian work on the San Antonio River (TIFP 2011), ample flushing and regeneration time for floodplain connectivity, and sufficient macroinvertebrate habitat disturbance based on observed events, a duration of 3 days above the designated pulse discharge magnitude per event is recommended. The duration of the pulse is independent of the hydrologic condition being experienced.

Unlike duration, the frequency of pulse events is dependent upon the hydrologic condition. The frequency during each hydrologic period is based on addressing the ecological needs of these three ecological components: riparian recruitment, floodplain fisheries, and riffle macroinvertebrate communities. To meet these needs, 3 pulses of varying levels to provide diversity (1 high, 2 lower) are recommended for the Spring and Summer, with 1 high flow pulse recommended during the fall/winter during a Wet year. A reduction in the high flow pulse frequency for the fall/winter period was based on the end of the riparian growing season and the typical reduction in activity of aquatic biota during winter months.

In summary, the following parameters were used to set the seasonal pulse flow recommendations for this study.

Spring pulses

- Riparian
    - Seed distribution for black willow, green ash, and sycamore
    - Seedling germination for indicator species
    - Sapling watering for indicator species
- Floodplain connectivity
- Seasonal macroinvertebrate habitat disturbance at both a moderate and higher level

Summer pulses

- Riparian
    - Wetting for seed germination for black willow and sycamore seedlings on islands

    - Sapling watering for lower slope riparian species
- Floodplain connectivity during wet years
- Periodic water quality maintenance within infrequently connected floodplain features during Other years
- Seasonal macroinvertebrate habitat disturbance during wet years

Fall/Winter pulses
- Riparian
    - Seed distribution for box elder
    - Sapling watering for indicator species
- Floodplain connectivity
- Seasonal macroinvertebrate habitat disturbance at both a moderate and higher level

Finally, a once-per-year high flow pulse of 12,500 cfs is recommended to wet the majority of the riparian indicator species recruitment zones as well as push back upland tree species during Wet conditions.

4.4 FLOW REGIME

The goal for a successful instream flow regime is to provide flows that have an ecological linkage to the resident flora and fauna of the system, while incorporating a level of variability in the regime to support diverse ecological conditions. Based on the results of this study, recent Senate Bill 3 investigations in the Guadalupe River basin, similar studies in the adjacent San Antonio River basin, and the current literature, the following flow recommendations are proposed for the Gonzales reach of the lower Guadalupe River (**Figures 51** and **52**). An examination of these figures shows that there are 3 different flow level categories incorporated; namely subsistence, base, and pulses. Subsistence remains constant regardless of season or base or pulse hydrologic condition. Base flows are first dependent on hydrological condition (Base Dry and Base) and subsequently driven by seasonality (spring, summer, and fall/winter). In a similar fashion, pulse flows are first dependent on hydrologic conditions (Wet and Other), and subsequently driven by seasonality (spring, summer, and fall/winter) with added components of duration and frequency. Frequency of pulse events is dependent upon hydrologic condition, whereas duration is not.

In conclusion, we feel this approach results in a sound ecological flow regime for the Gonzales reach of the lower Guadalupe River based on the best available science to date. We have worked directly with the TIFP on field data collection associated with this study and have periodically provided updates to TIFP personnel regarding results, analysis, and preliminary recommendation development approaches. By design, this study was conducted and analyzed in a manner that we feel is supportive of the on-going TIFP instream flow study on the lower Guadalupe River.

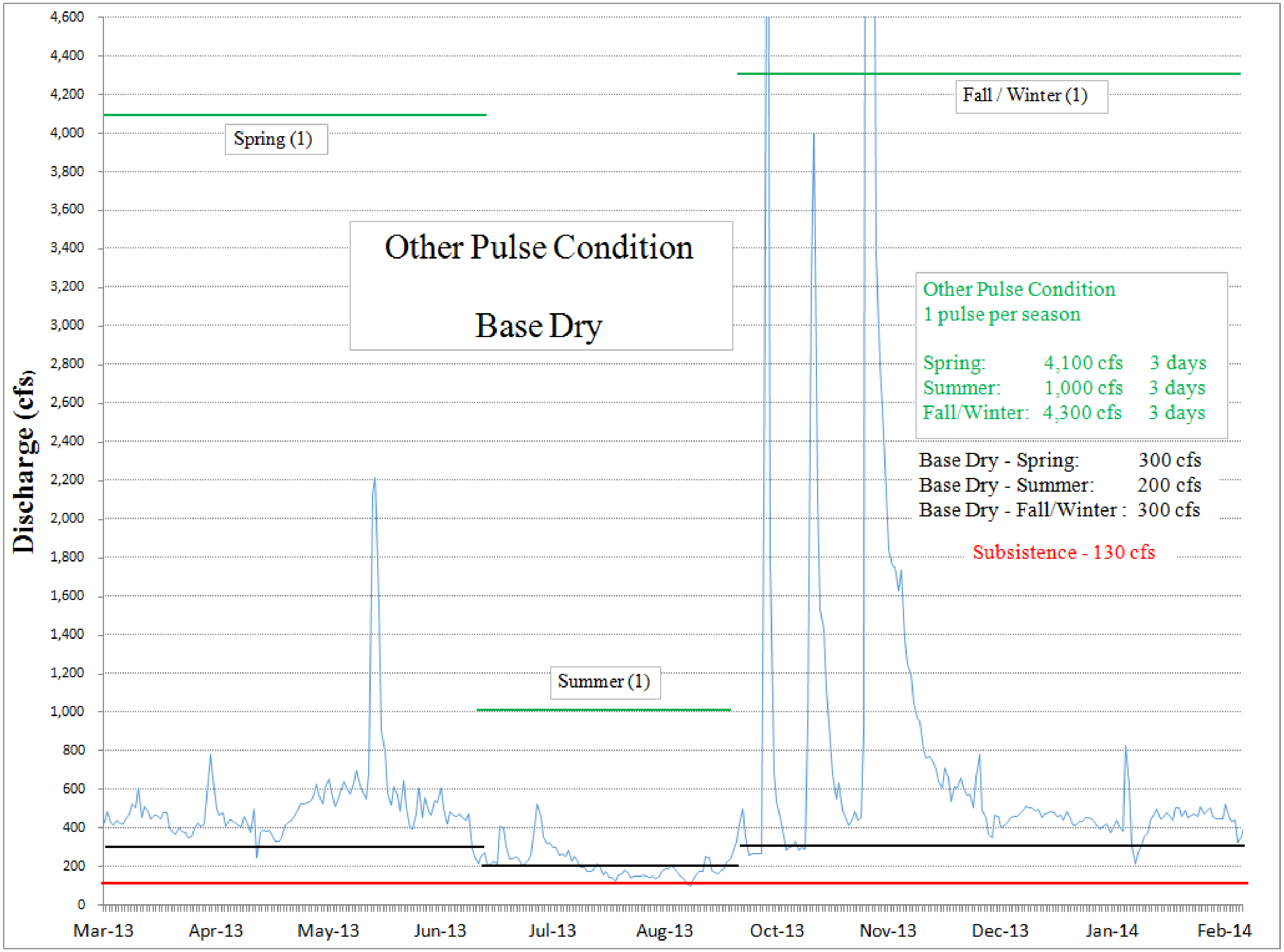

Figure 51. Instream Flow Guidelines for “Other” Pulse Condition and Base Dry.

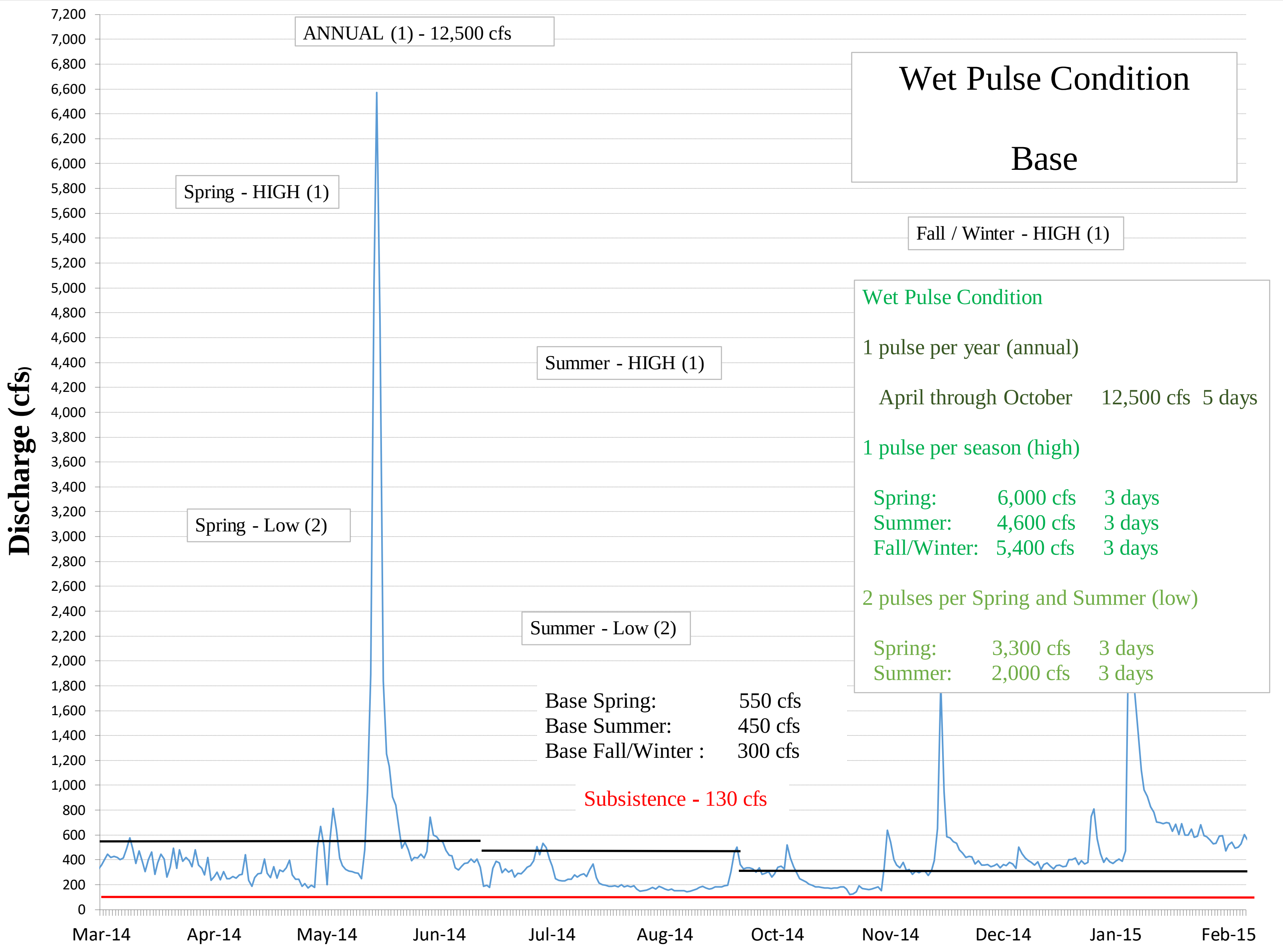

Figure 52. Instream Flow Guidelines for Wet Pulse Condition and Base.

5.0 NEXT STEPS

Often, the most difficult parts of an instream flow study are the decisions regarding application, implementation, and long-term monitoring. These decisions involve environmental considerations, operational constraints, social implications (human needs), political implications, etc. The following discussion focuses only on the environmental considerations relative to the Gonzales reach of the lower Guadalupe River.

5.1 APPLICATION

Modern scientific literature suggests that subsistence flows or ecological base flows are "hands off flows" (Hardy et al. 2006, Acreman et al. 2006). Therefore, an environmental goal is that flows do not fall below the subsistence flow guidelines. This would be similar in application to the existing TCEQ standards for subsistence flow. The application of base flow recommendations in the literature is highly variable and river-specific in most cases. From a purely environmental consideration, the goal would be to achieve the BASE flow guidelines approximately 75% of the time and the BASE-DRY approximately 25% of the time, which means allowing water to pass through this section of river unless exceeding those base amounts. Pulse and overbanking flow recommendations are relatively new in the scheme of instream flow science although the concept has been around for many years. From a purely environmental consideration, the goal would be to allow recommended seasonal pulse flows (based on hydrologic condition) to pass through this section of river until the peak flow and durations are achieved. Overbanking / channel maintenance flows will be provided by natural rainfall events and thus were not discussed in this report. Although this section provides the environmental perspective on application of instream flow recommendations, it is recognized that other considerations will likely be important in determining how recommendations are ultimately applied.

5.2 LONG-TERM MONITORING

The biggest omission from many instream flow studies has been an evaluation of the effectiveness of proposed recommendations. Recent studies in this field have immensely improved this component. The project team concurs with the TIFP (2008) and recognizes that a critical component of all recommendations for this project is a long-term monitoring program to evaluate the effectiveness of the recommended instream flow recommendations for the lower Guadalupe River. Ecological components recommended for long-term monitoring include river and floodplain fisheries, mussels, and riparian assessments. It is acknowledged that the timing and frequency of sampling events may or may not be on the same spatial or temporal scale of implementation. A solid starting place would be the development of a long-term monitoring plan for the lower Guadalupe River in the event that funding at a later date becomes available to support this important endeavor.

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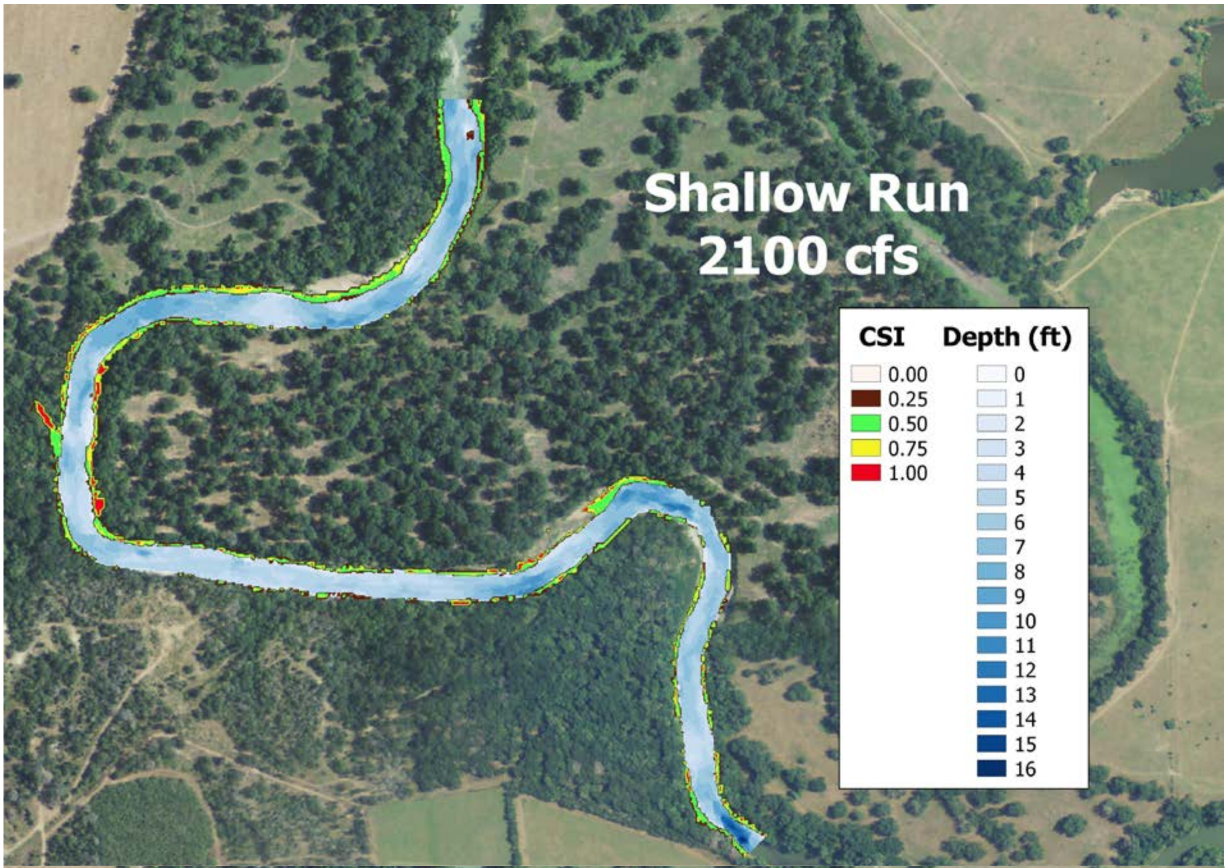
APPENDIX A. SPATIAL OUTPUT FROM FISH HABITAT MODELING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2100 cfs
CSI
0.00
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0.75
1.00
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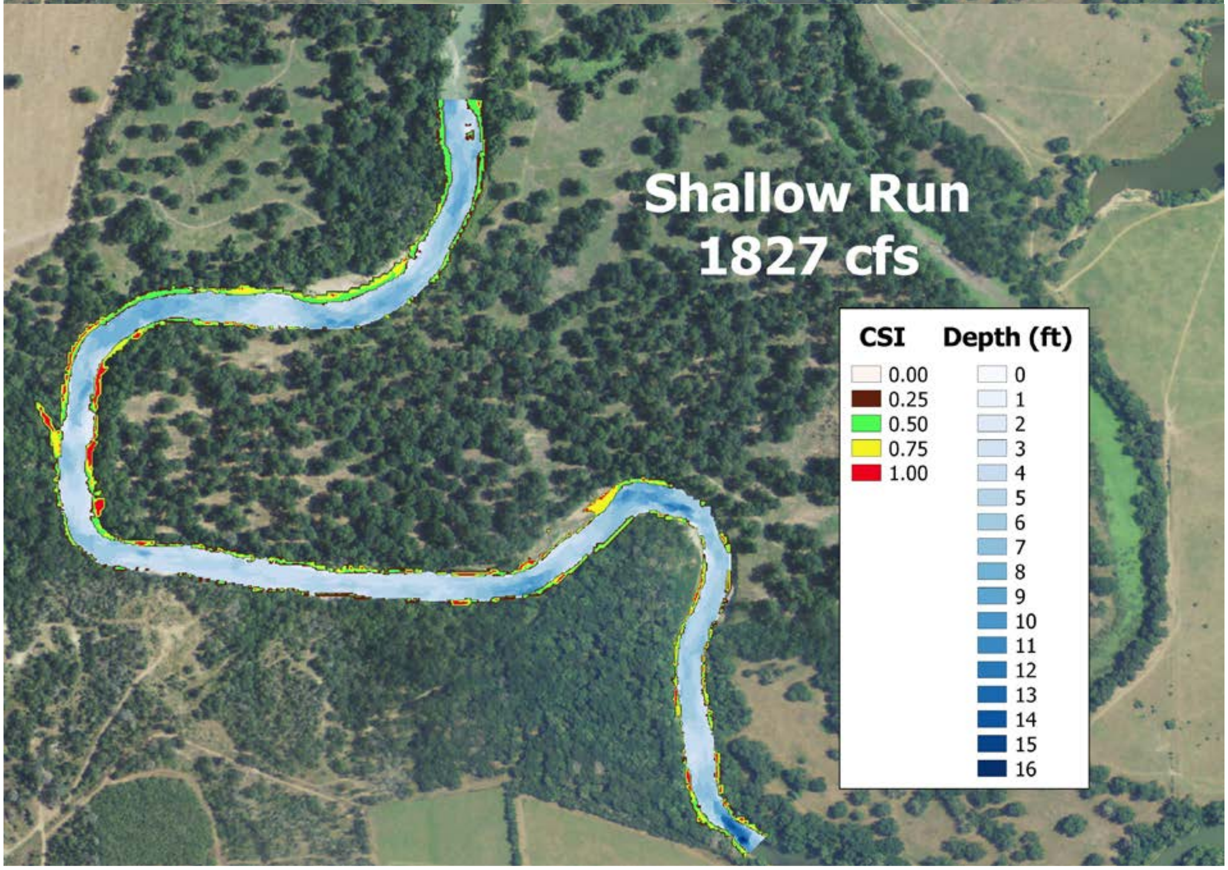
Shallow Run
1827 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
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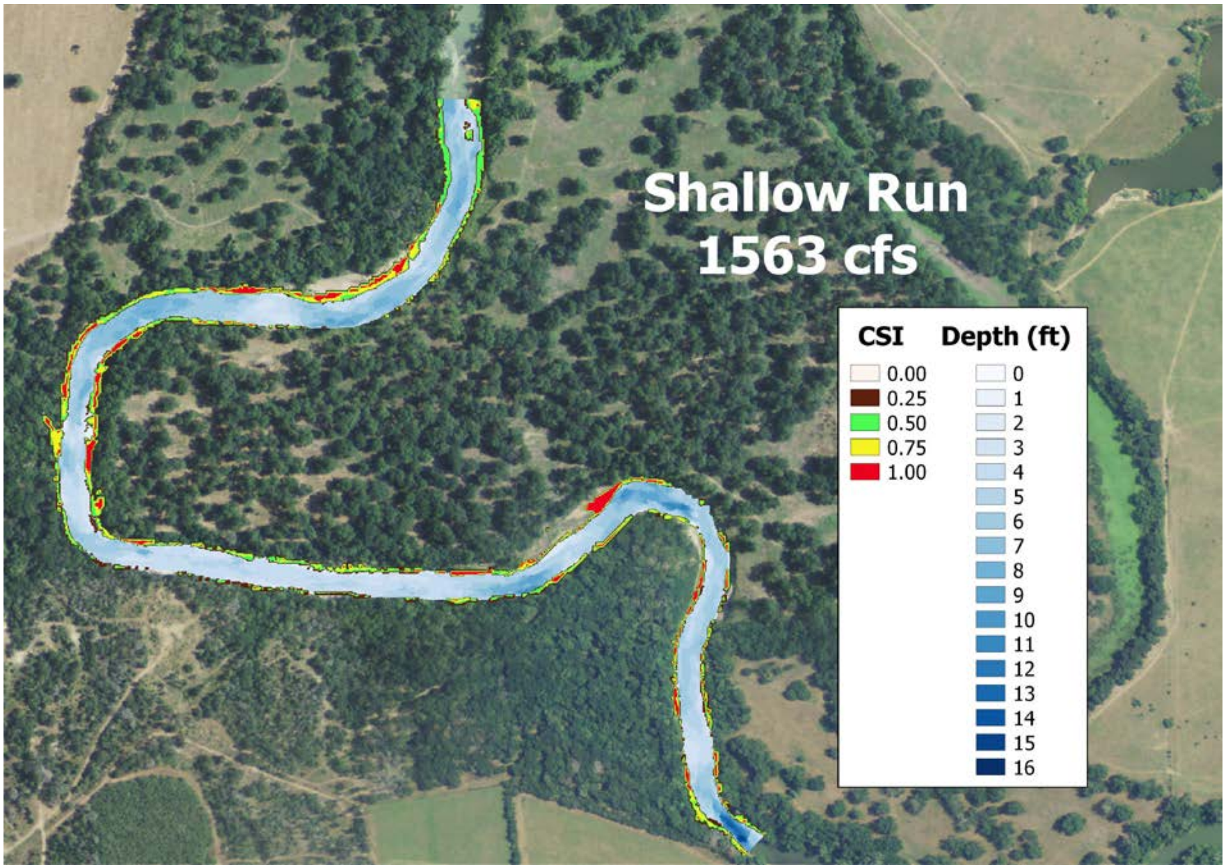
Shallow Run
1563 cfs
CSI
0.00
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0.50
0.75
1.00
Depth (ft)
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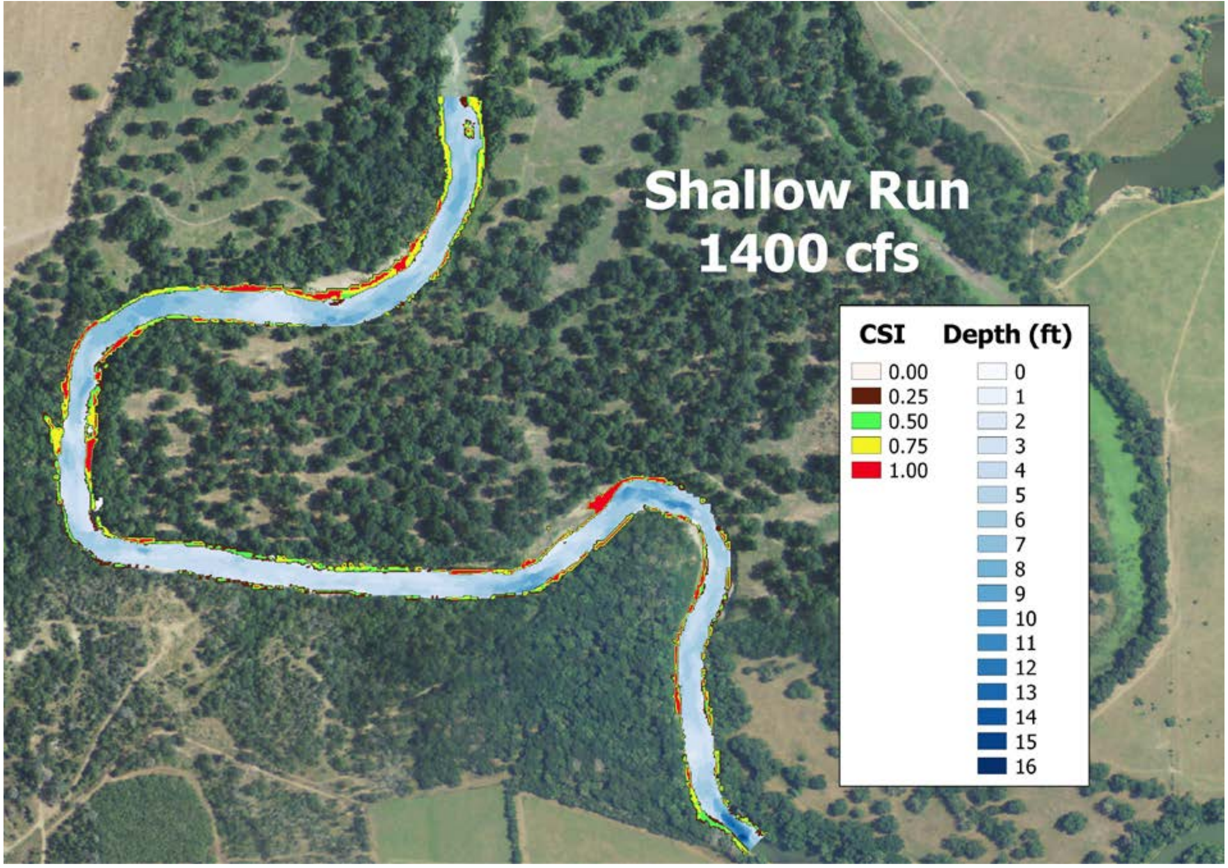
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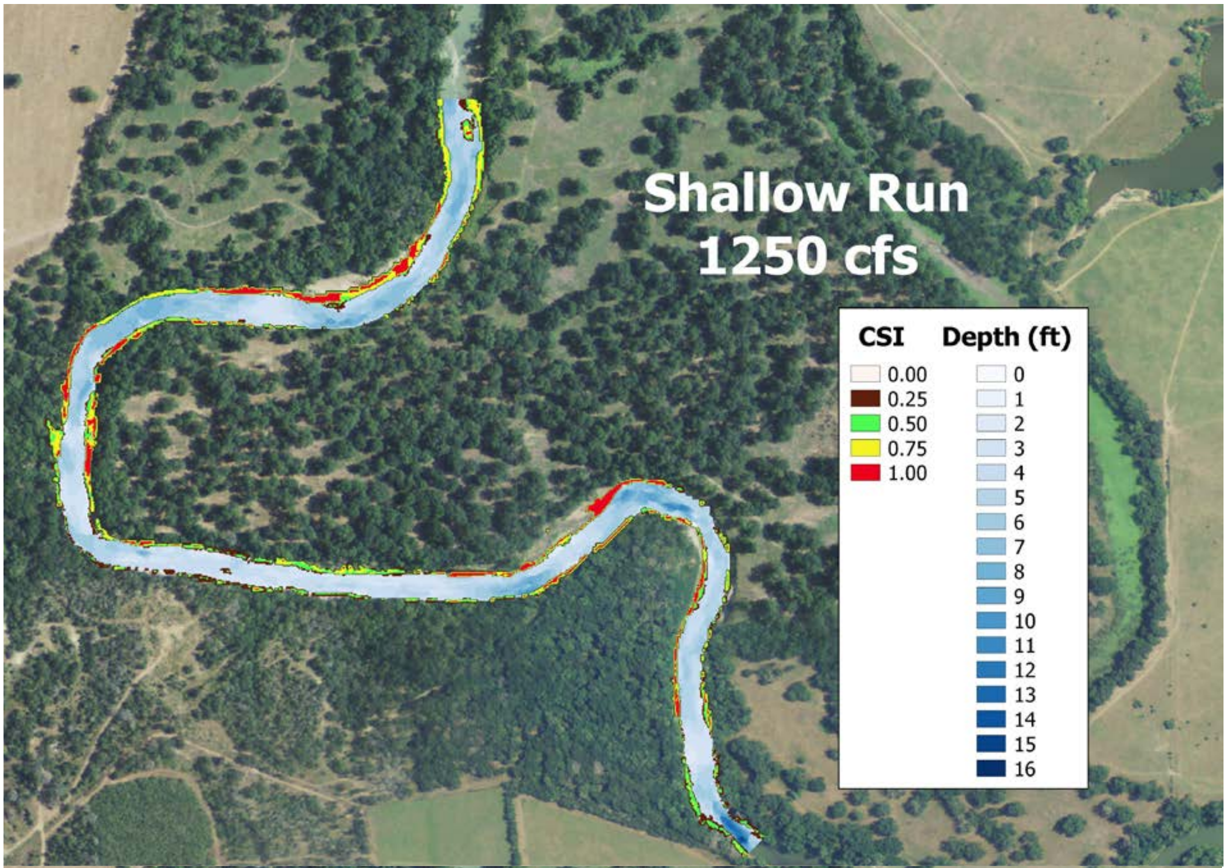
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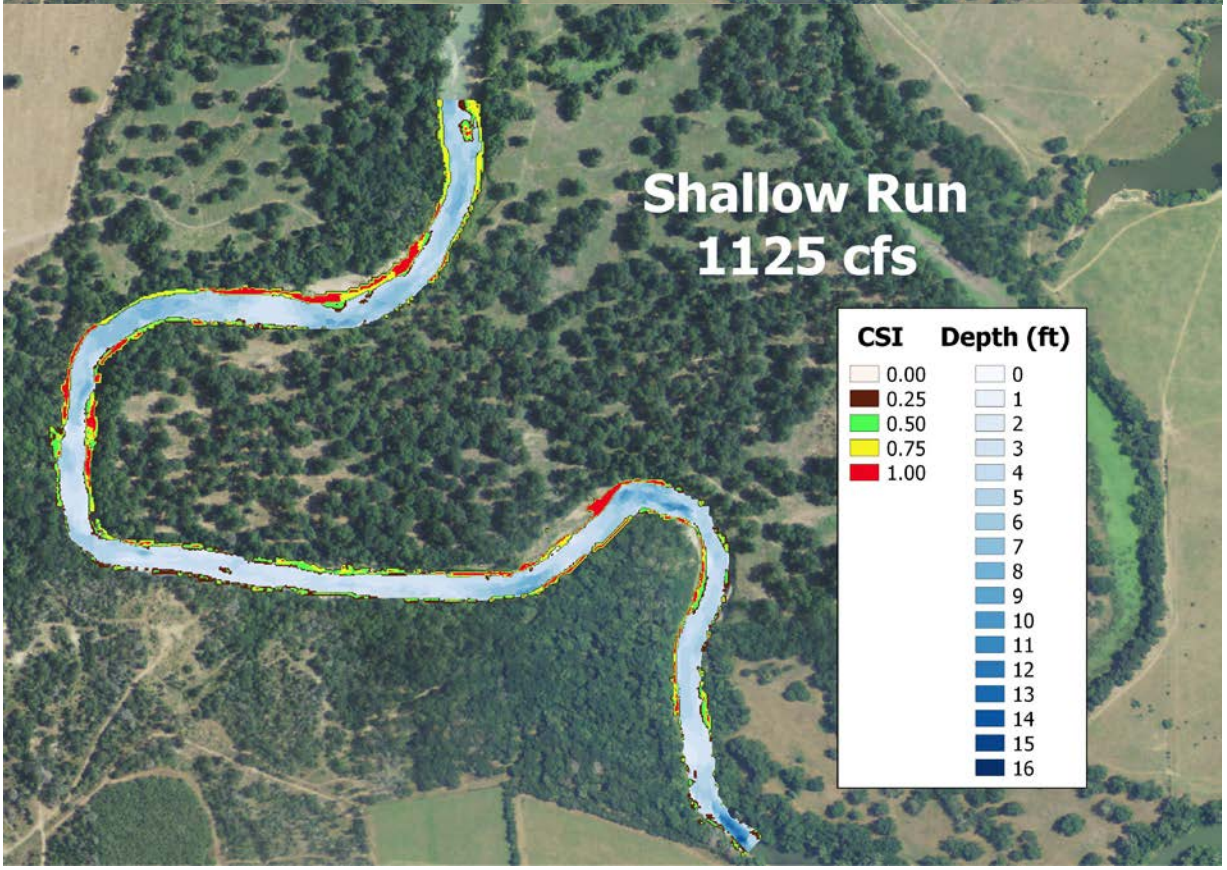
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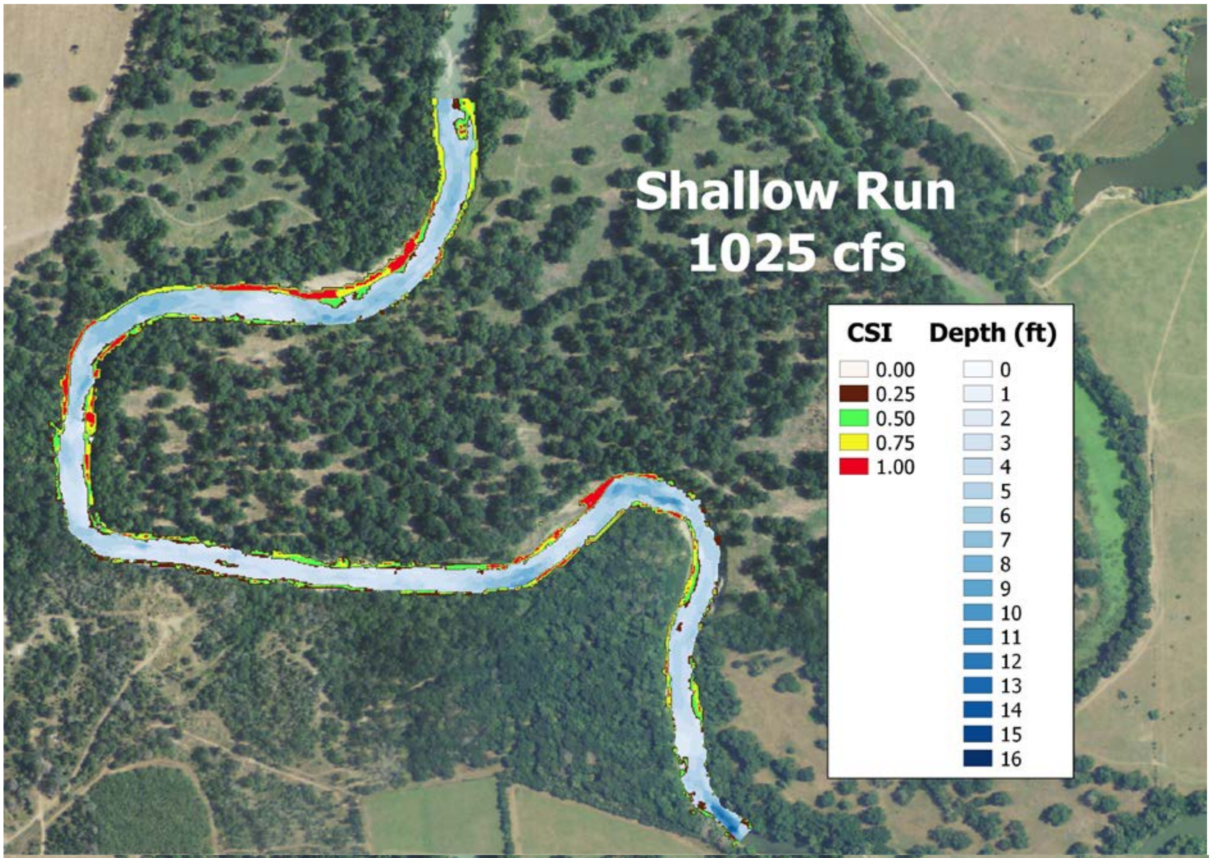
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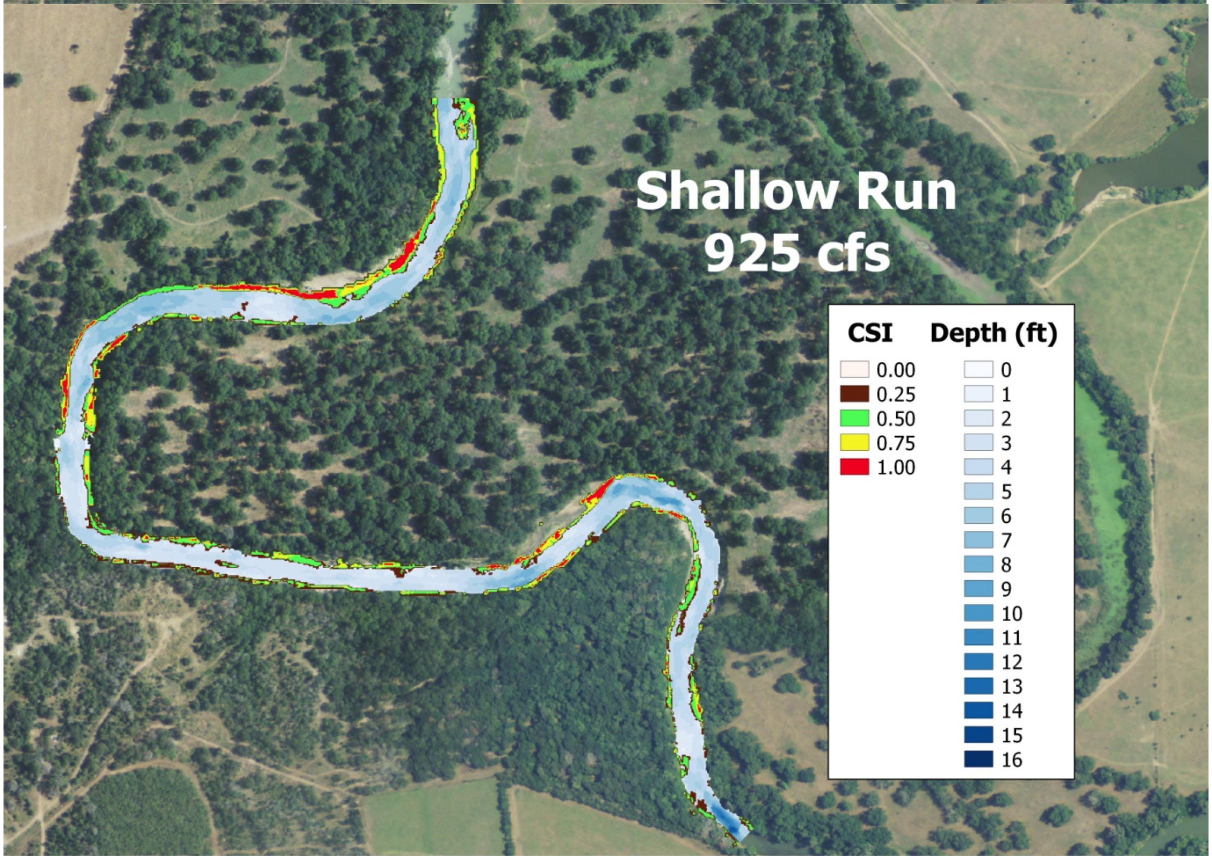
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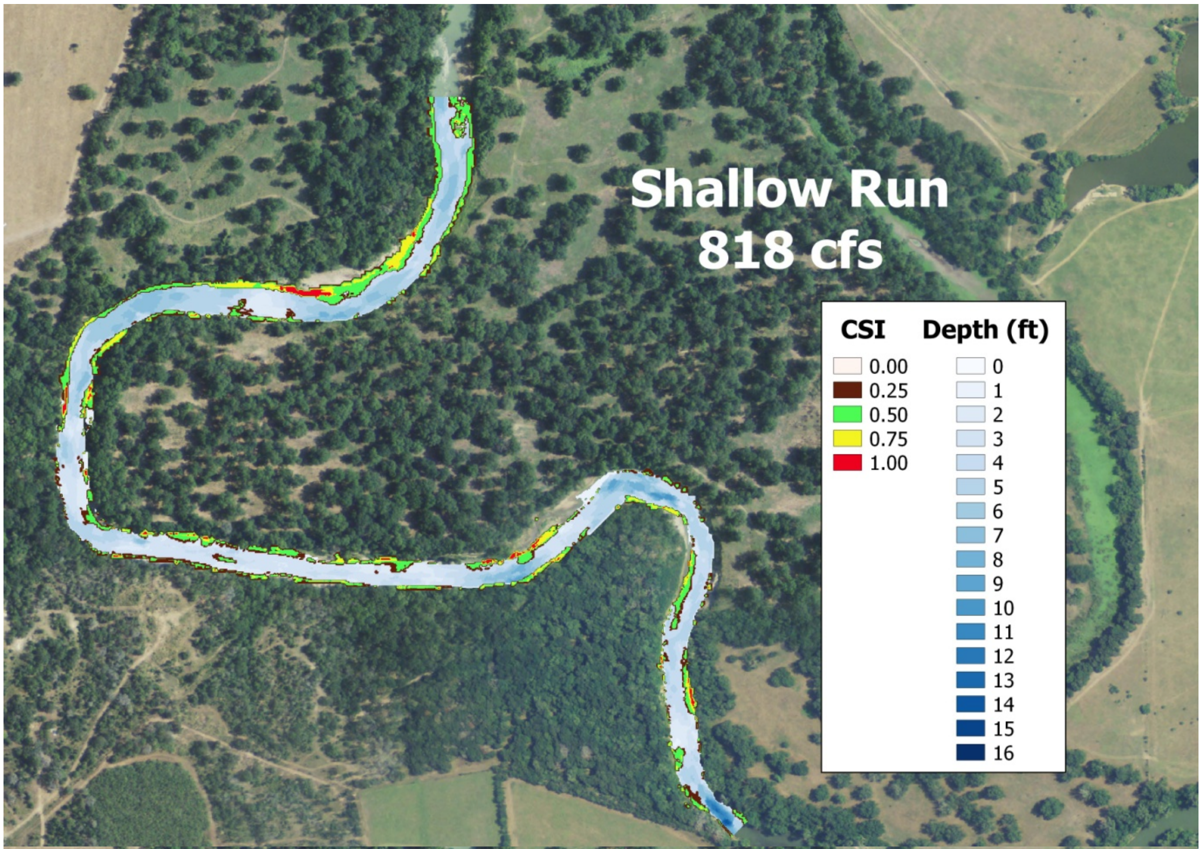
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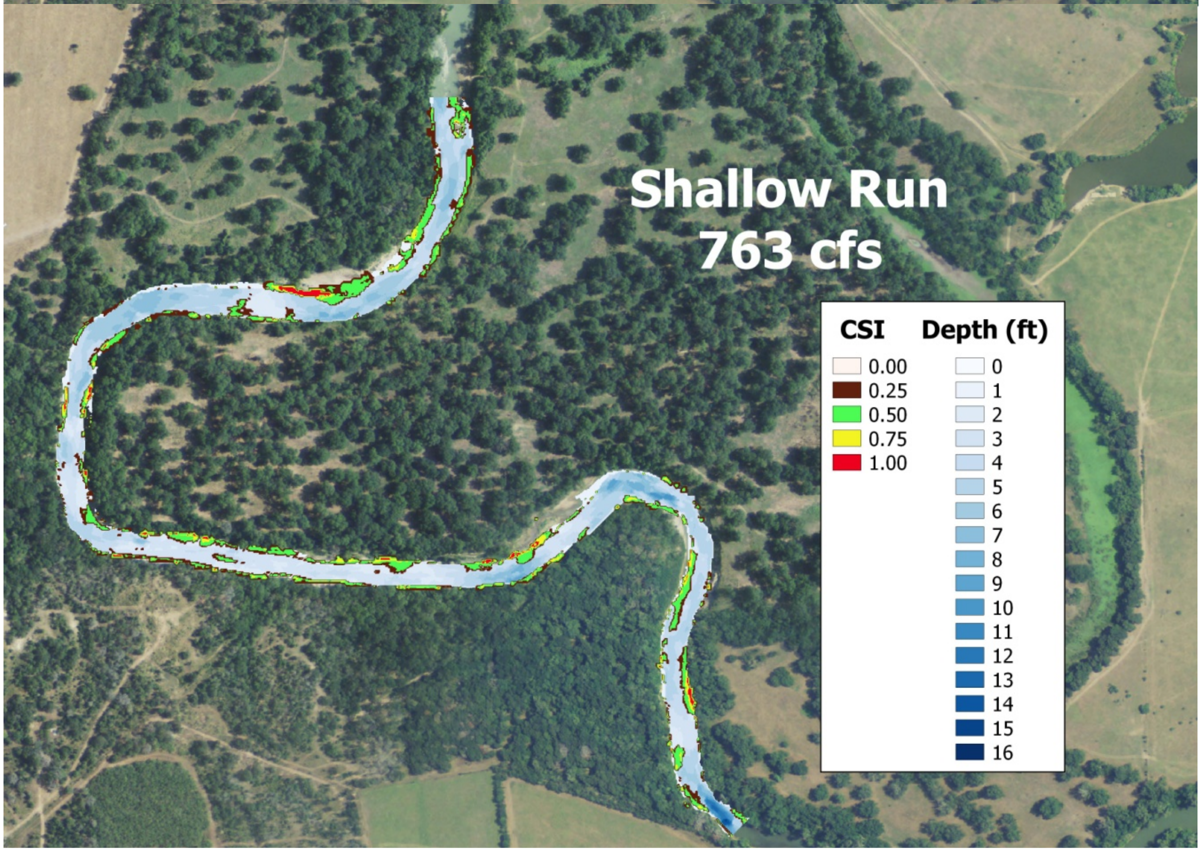
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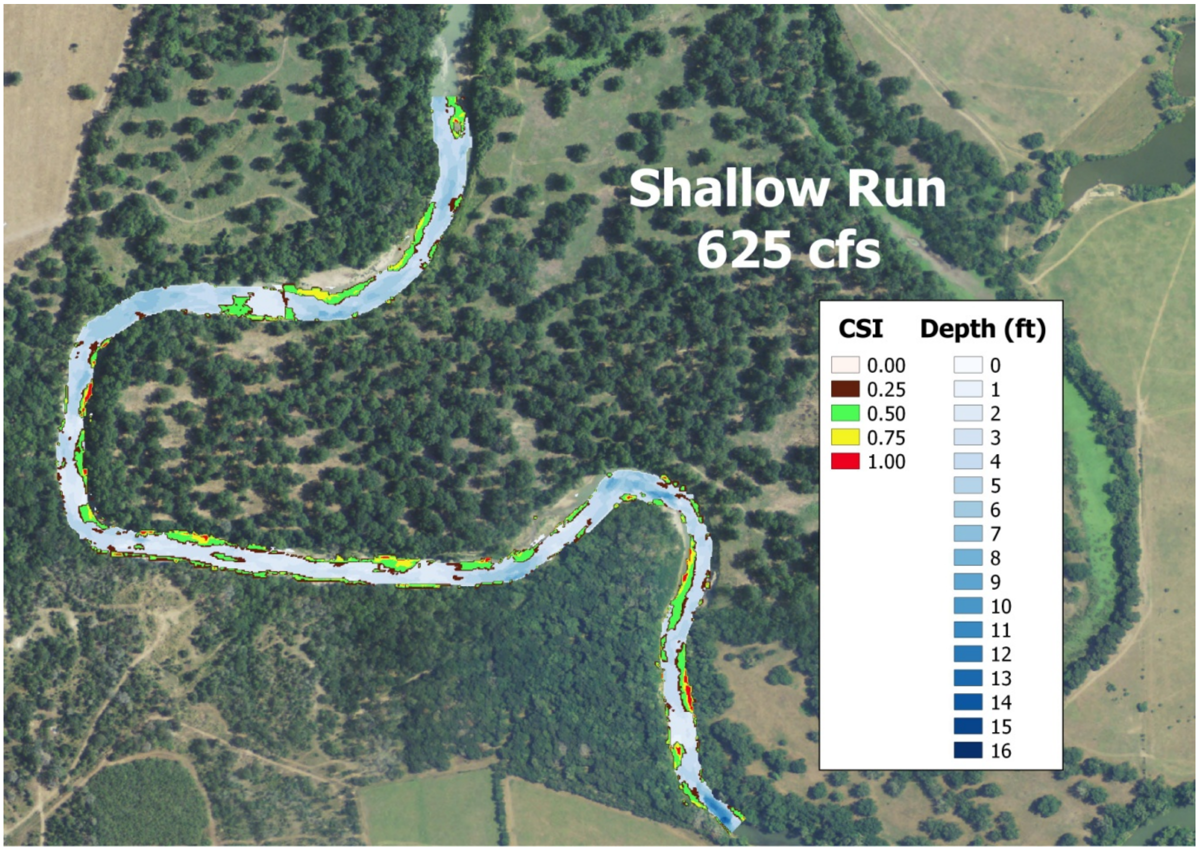
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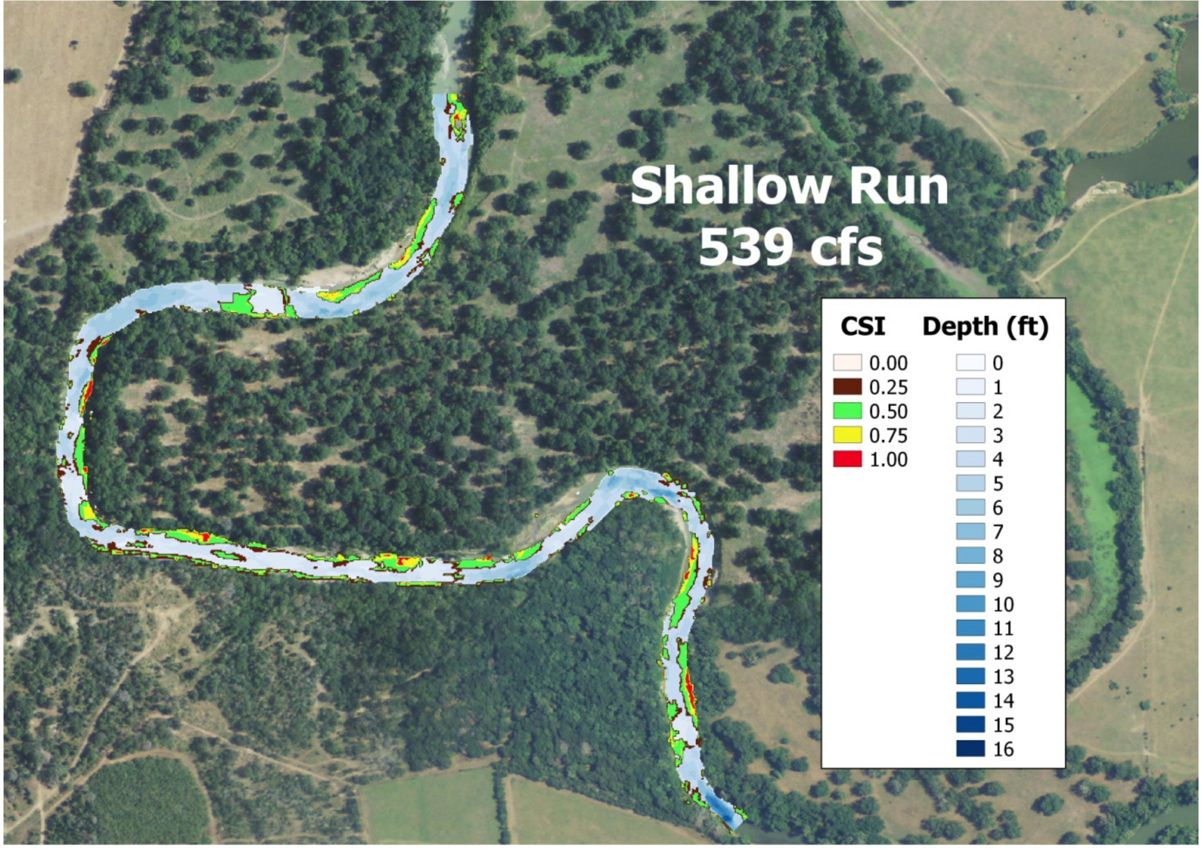
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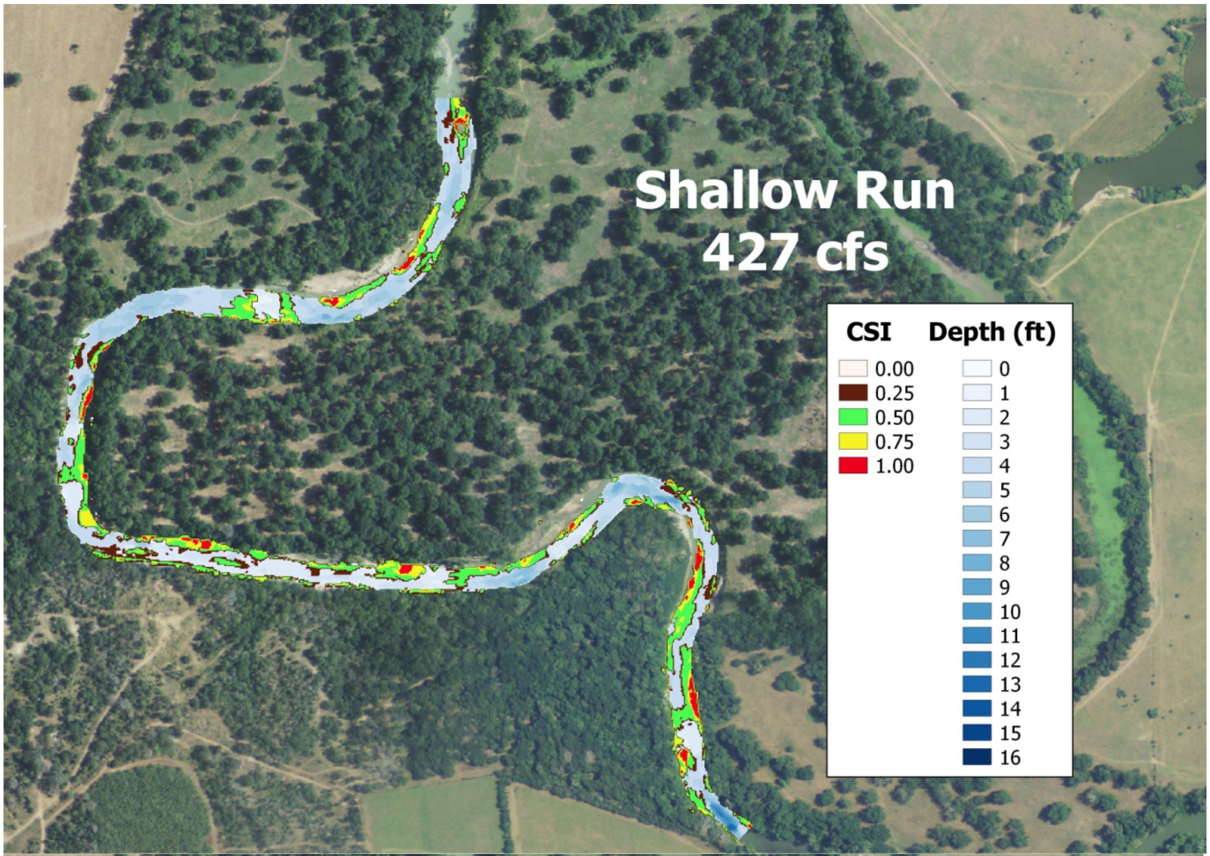
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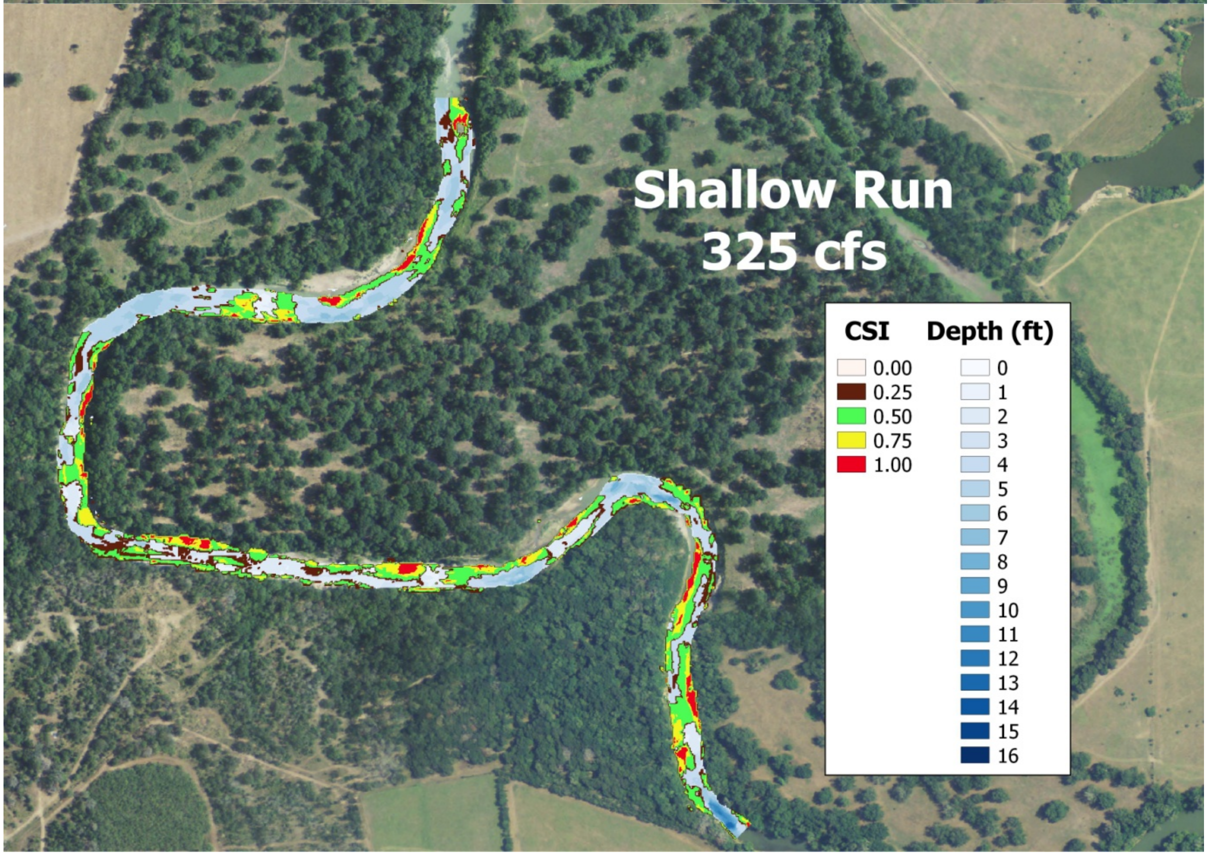
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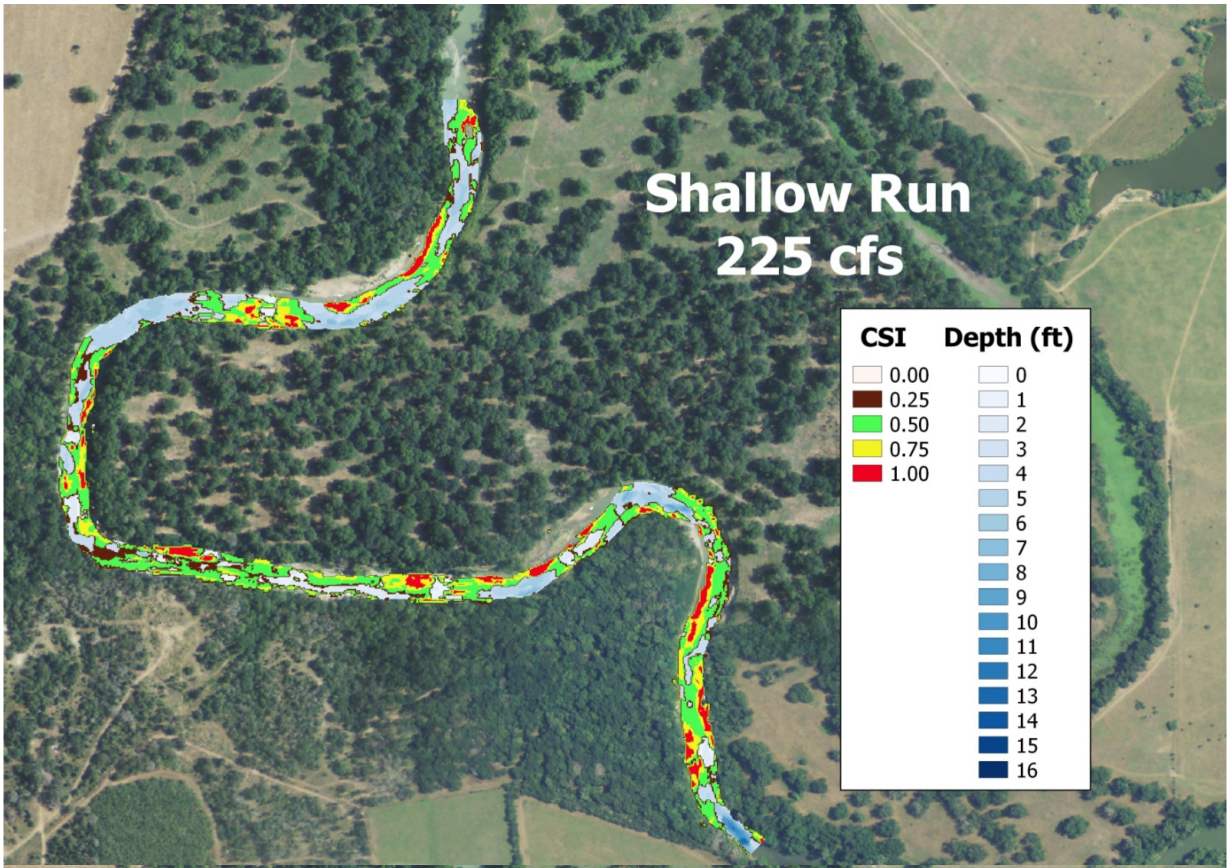
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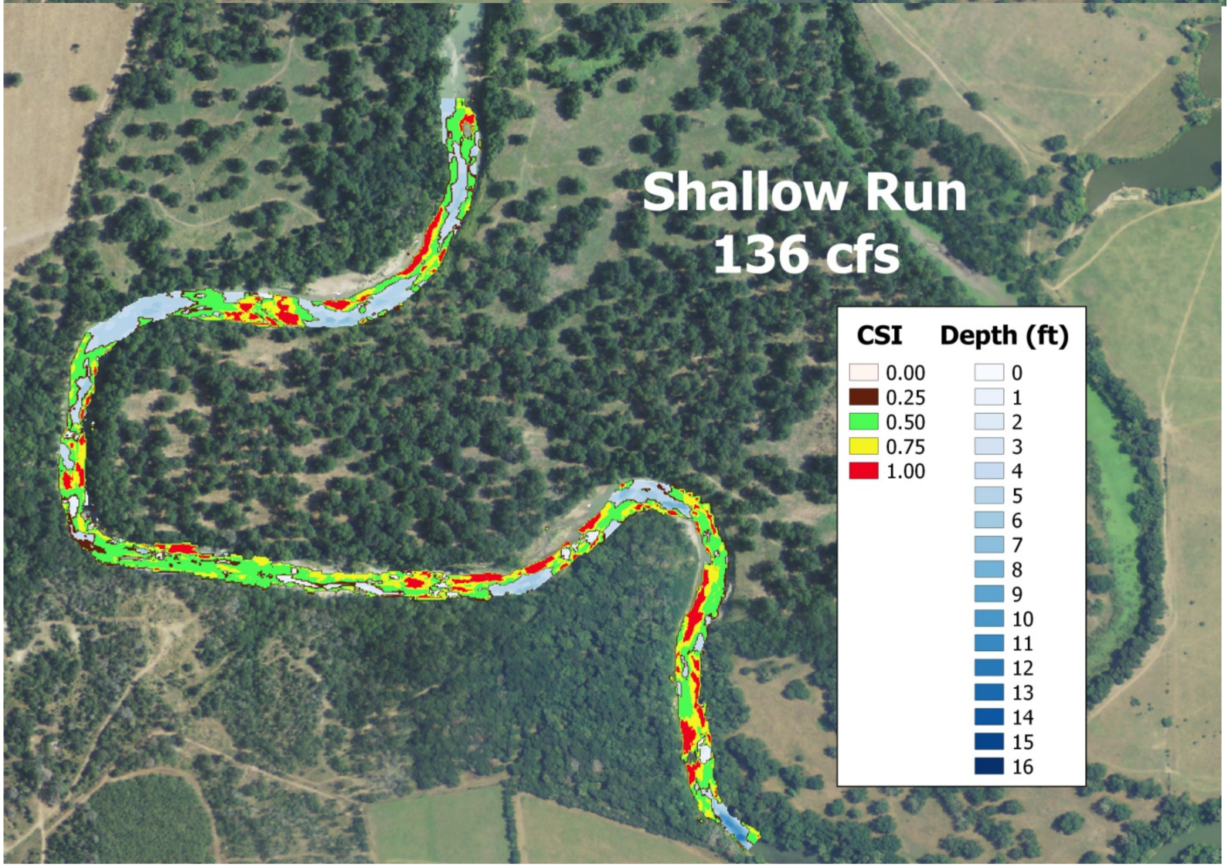
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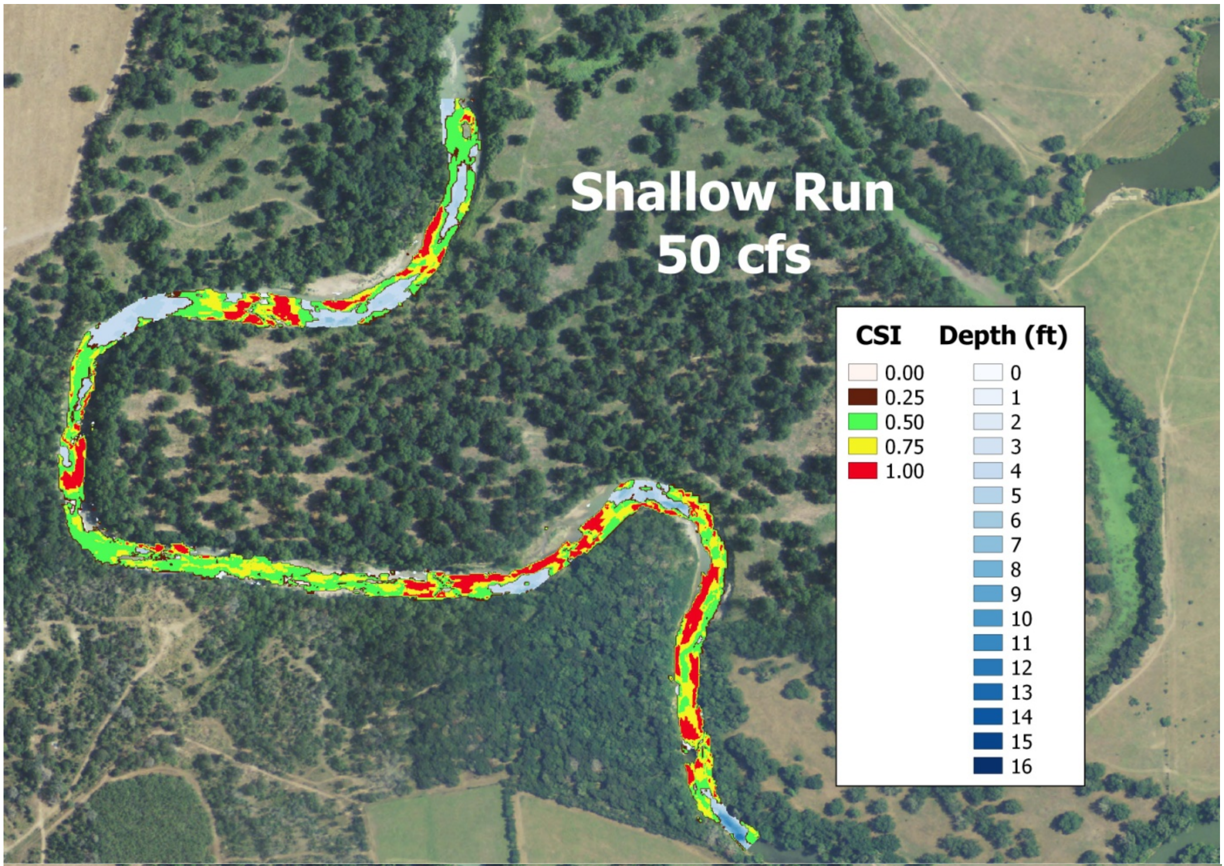

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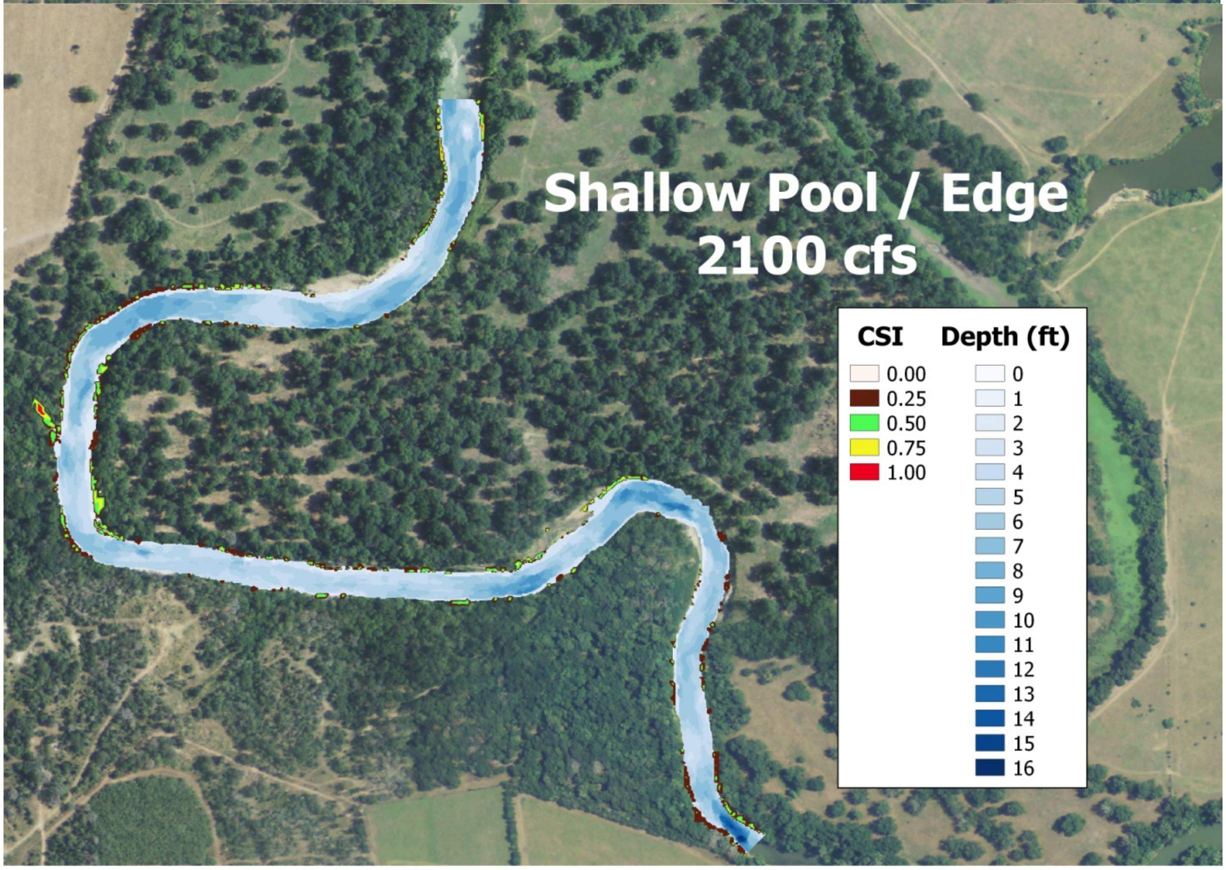

Shallow Pool / Edge
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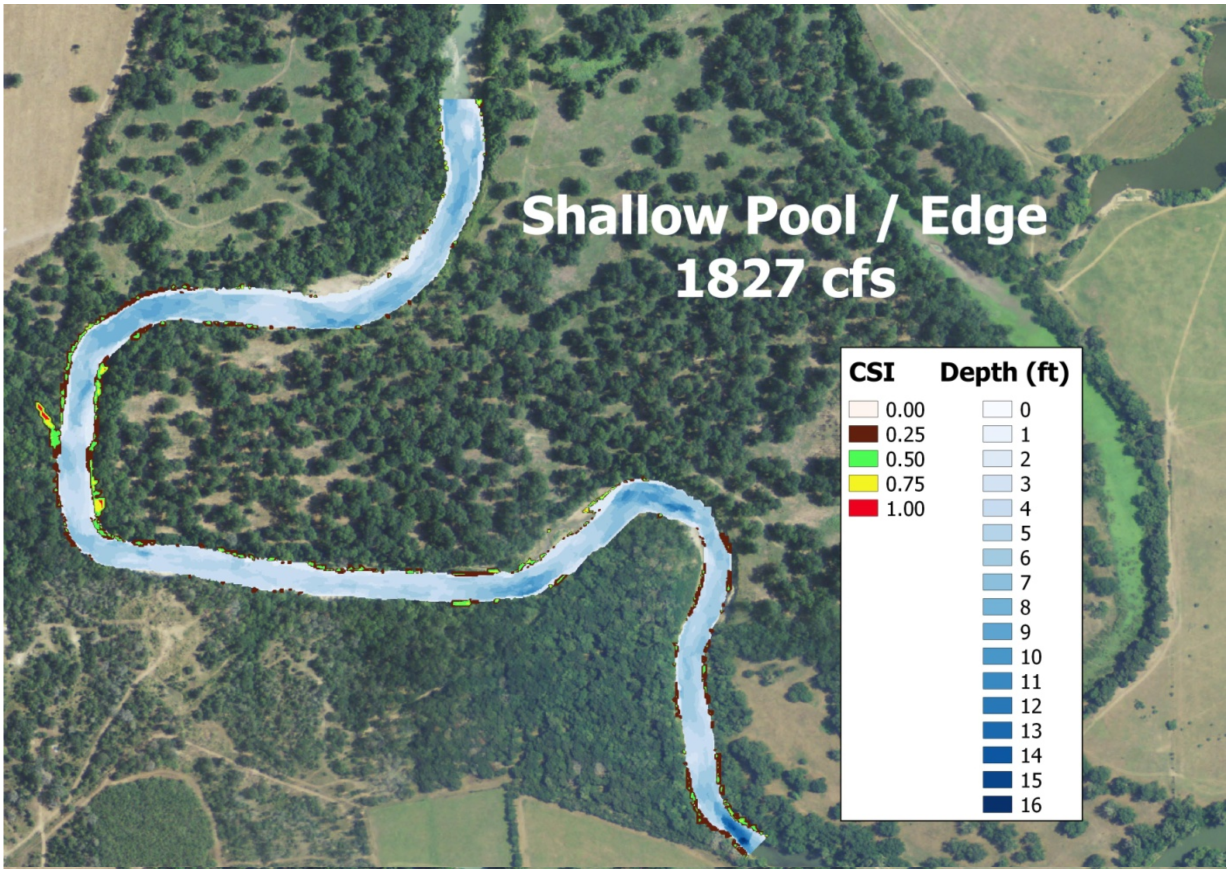
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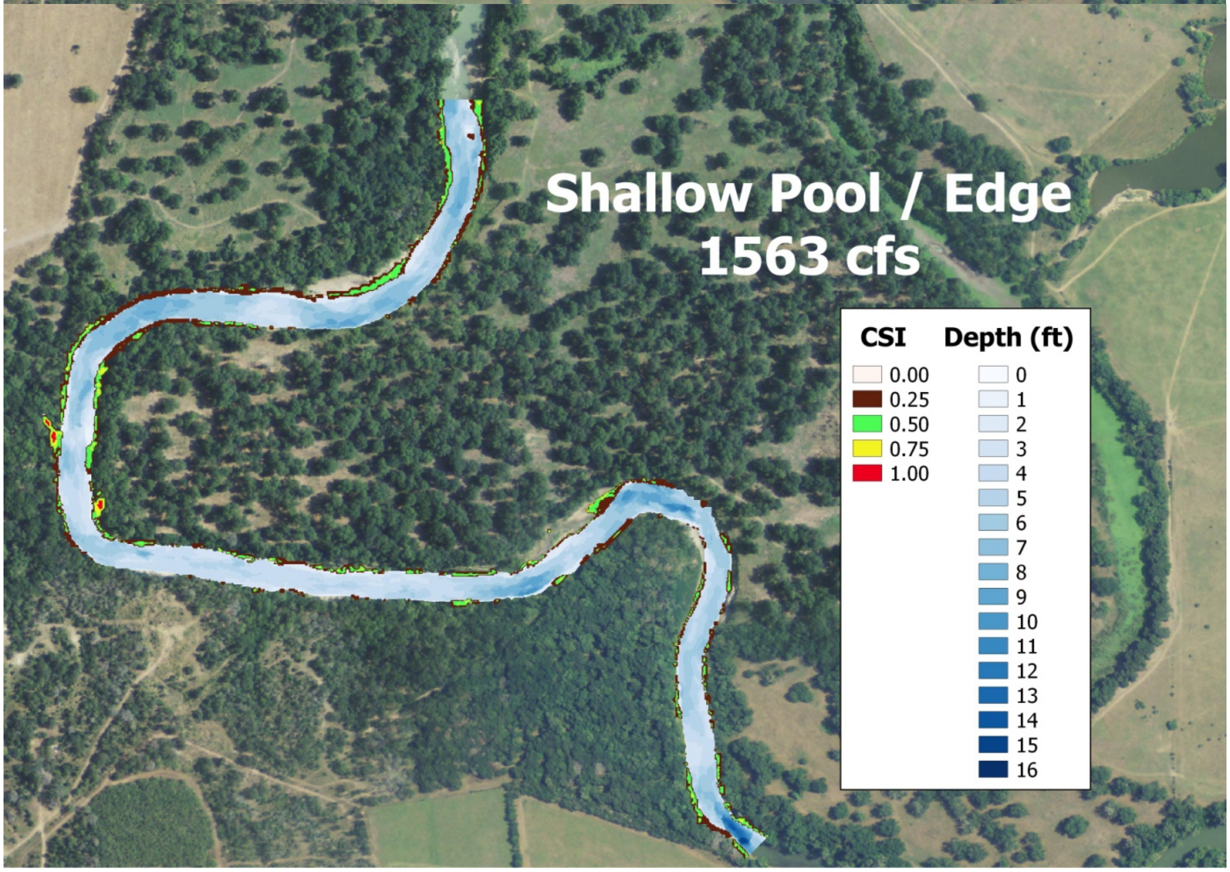
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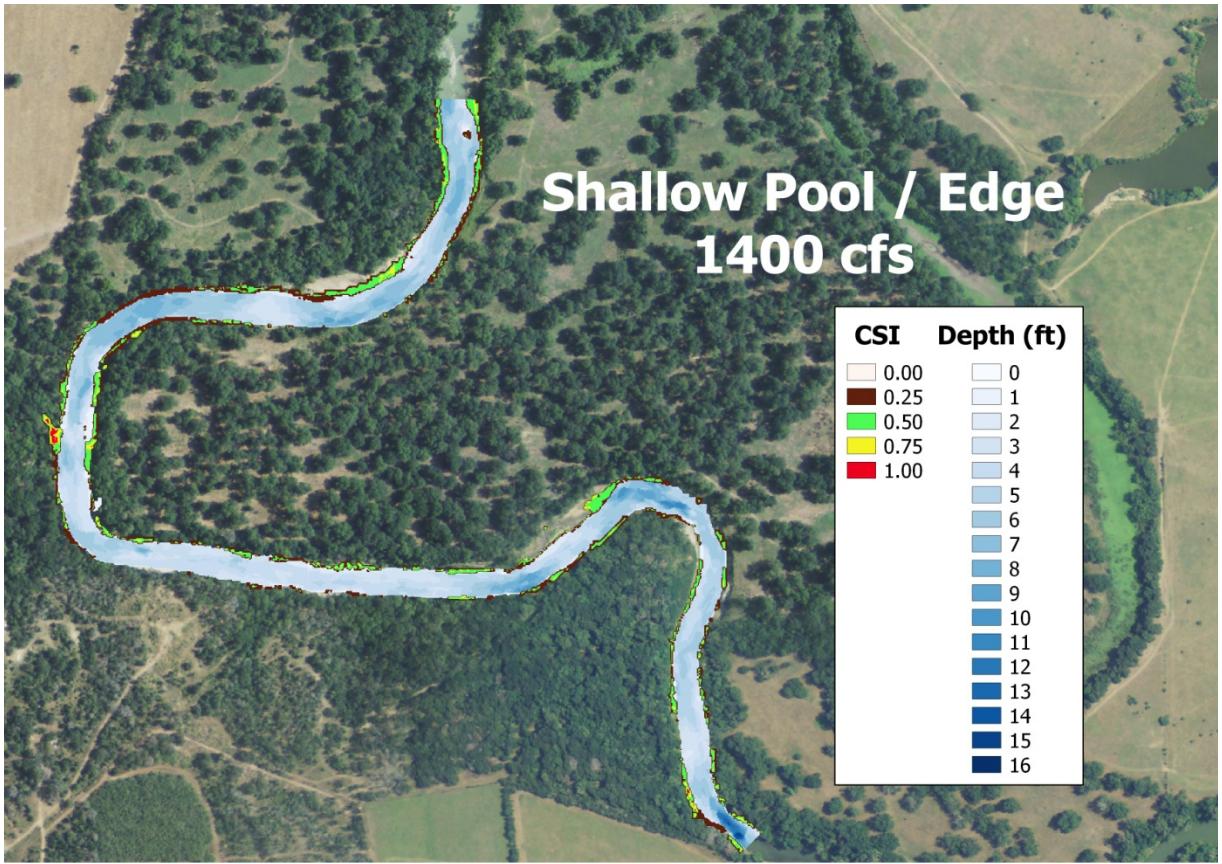
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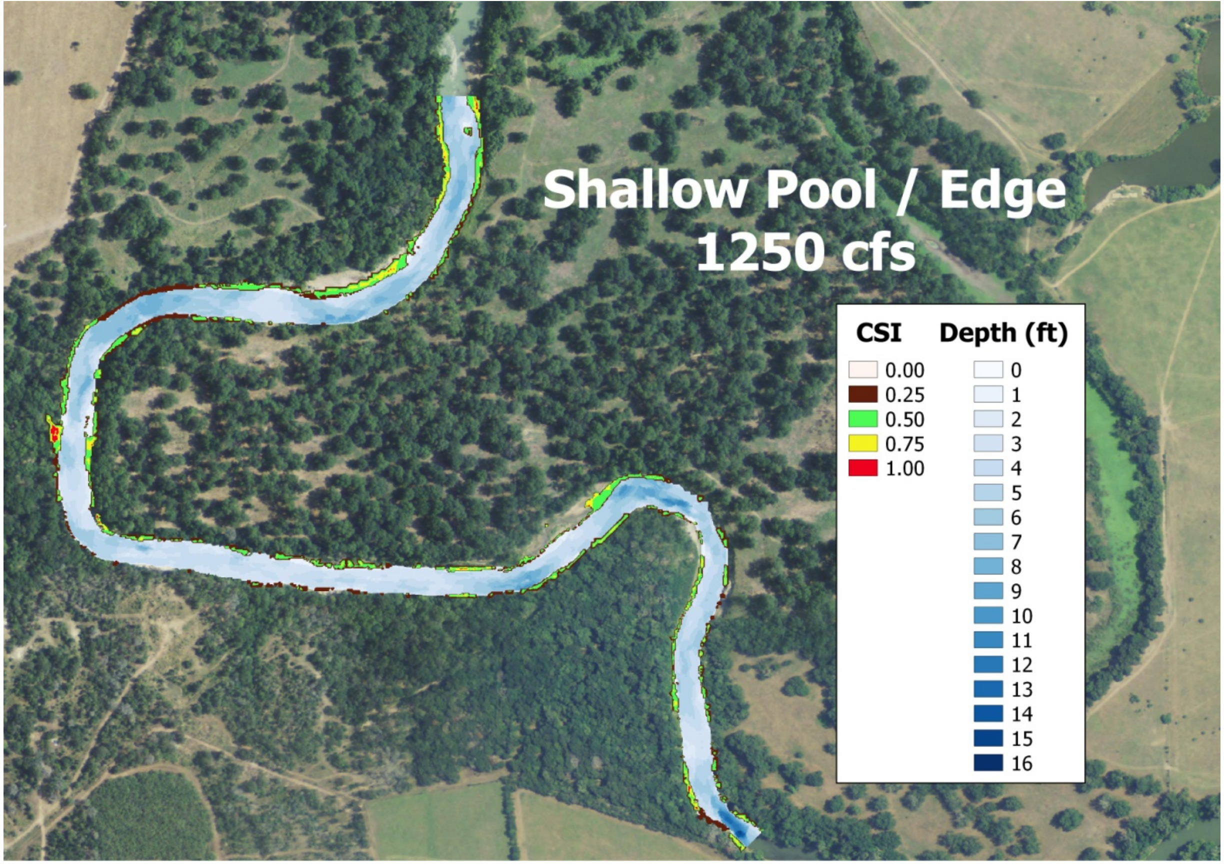
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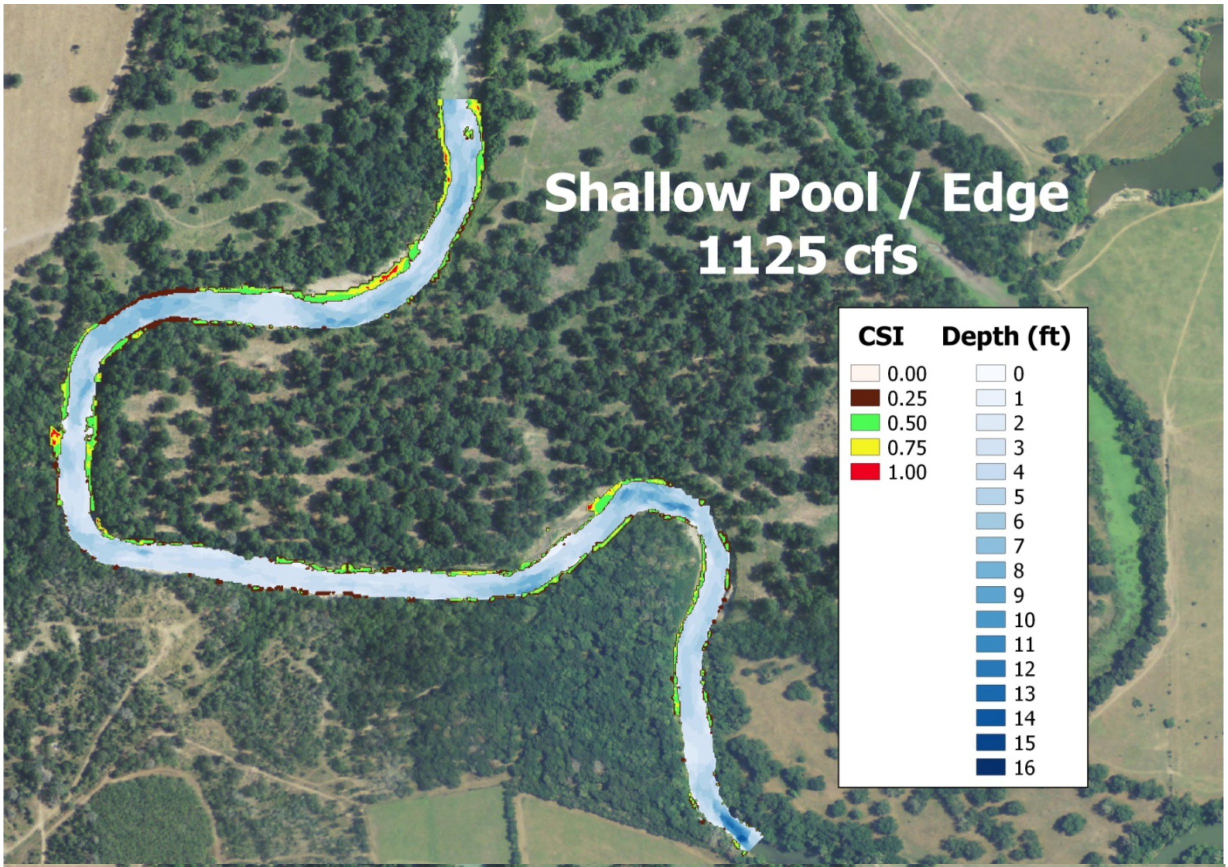
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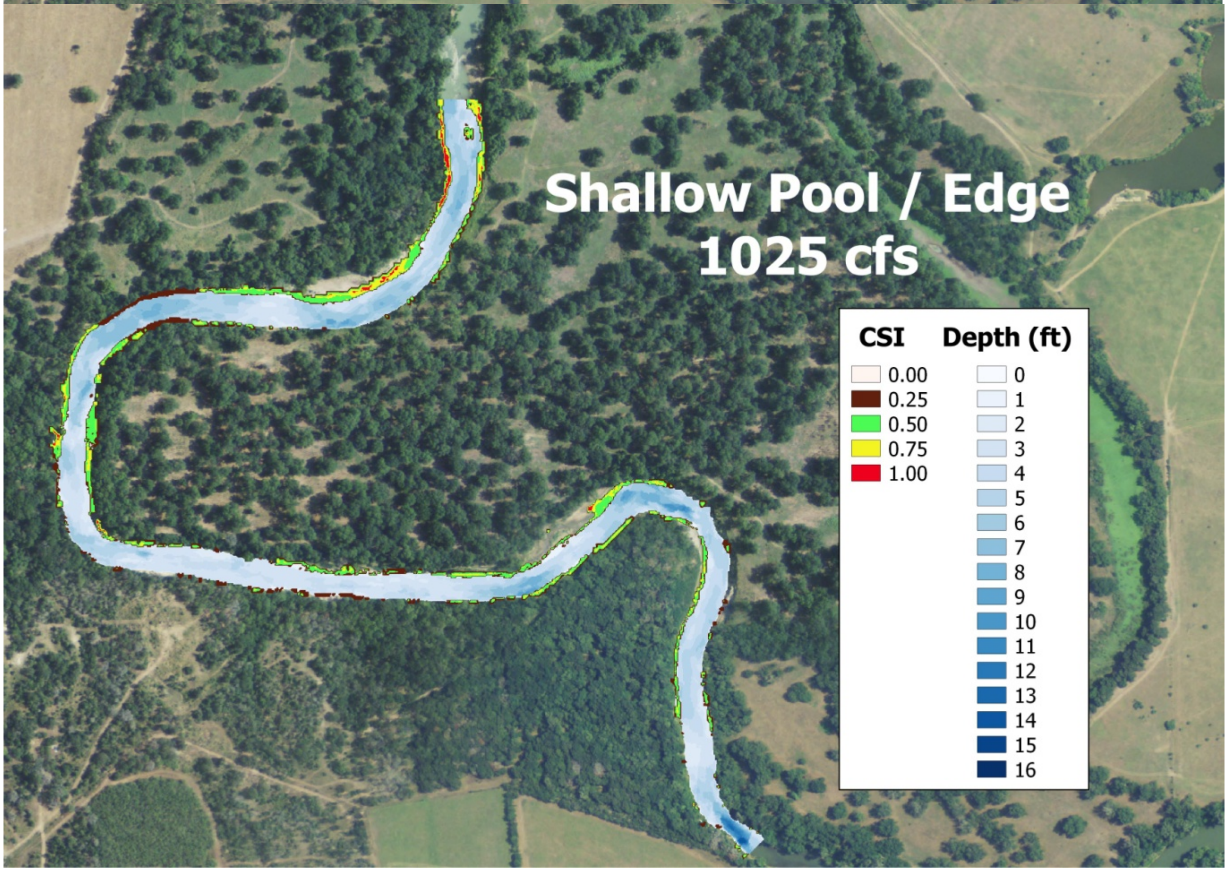
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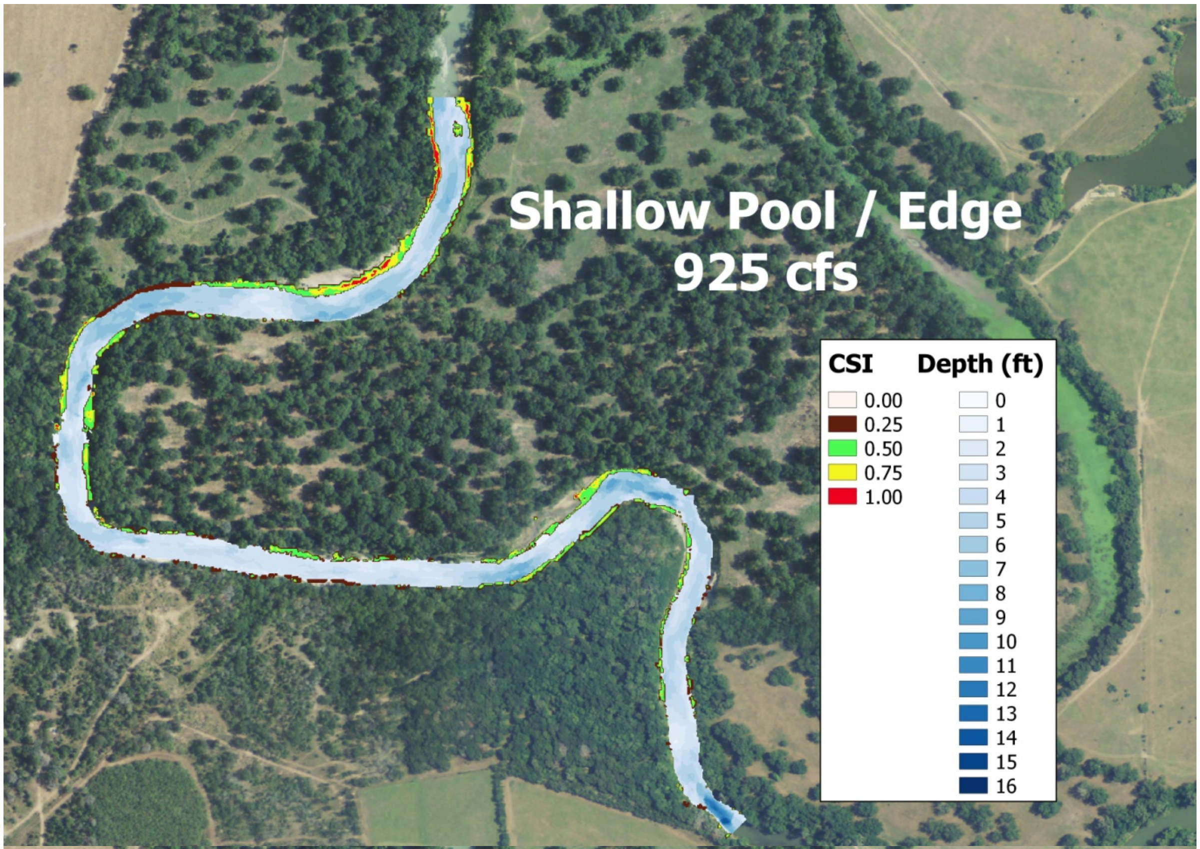
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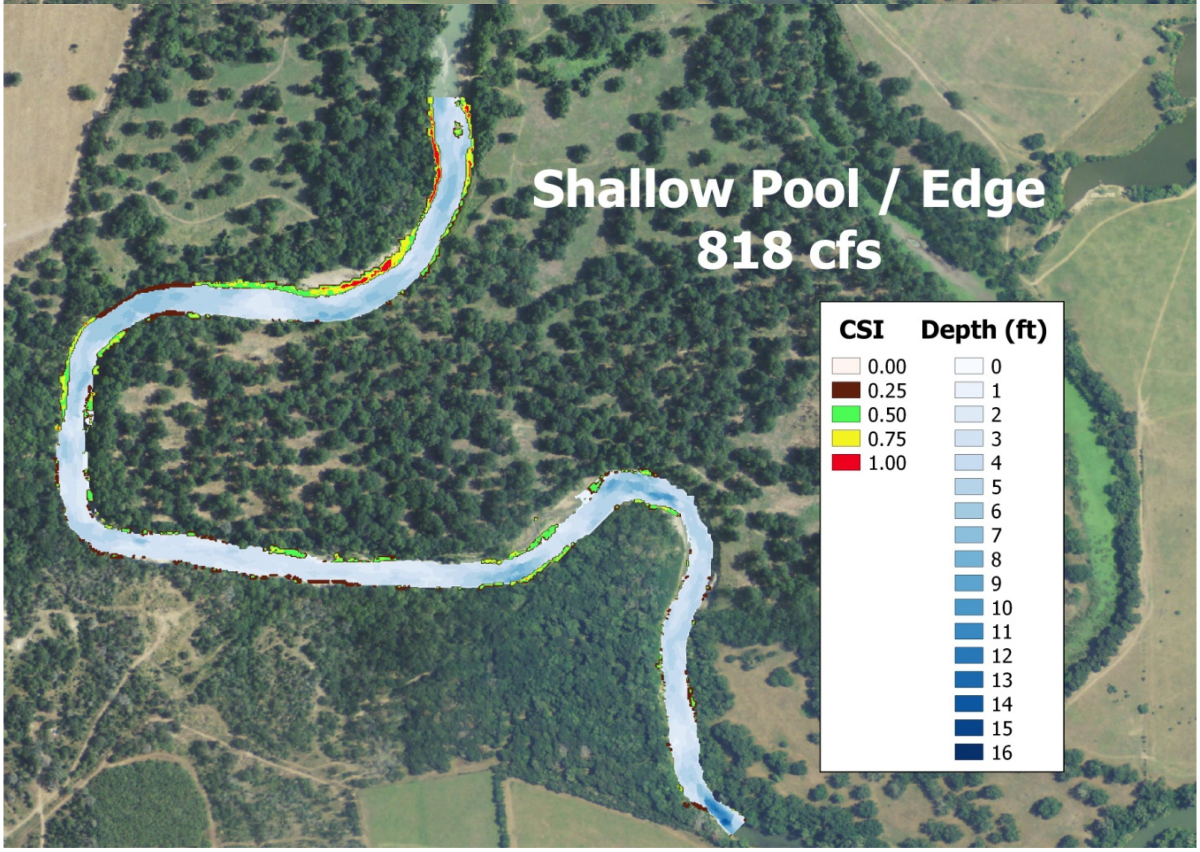
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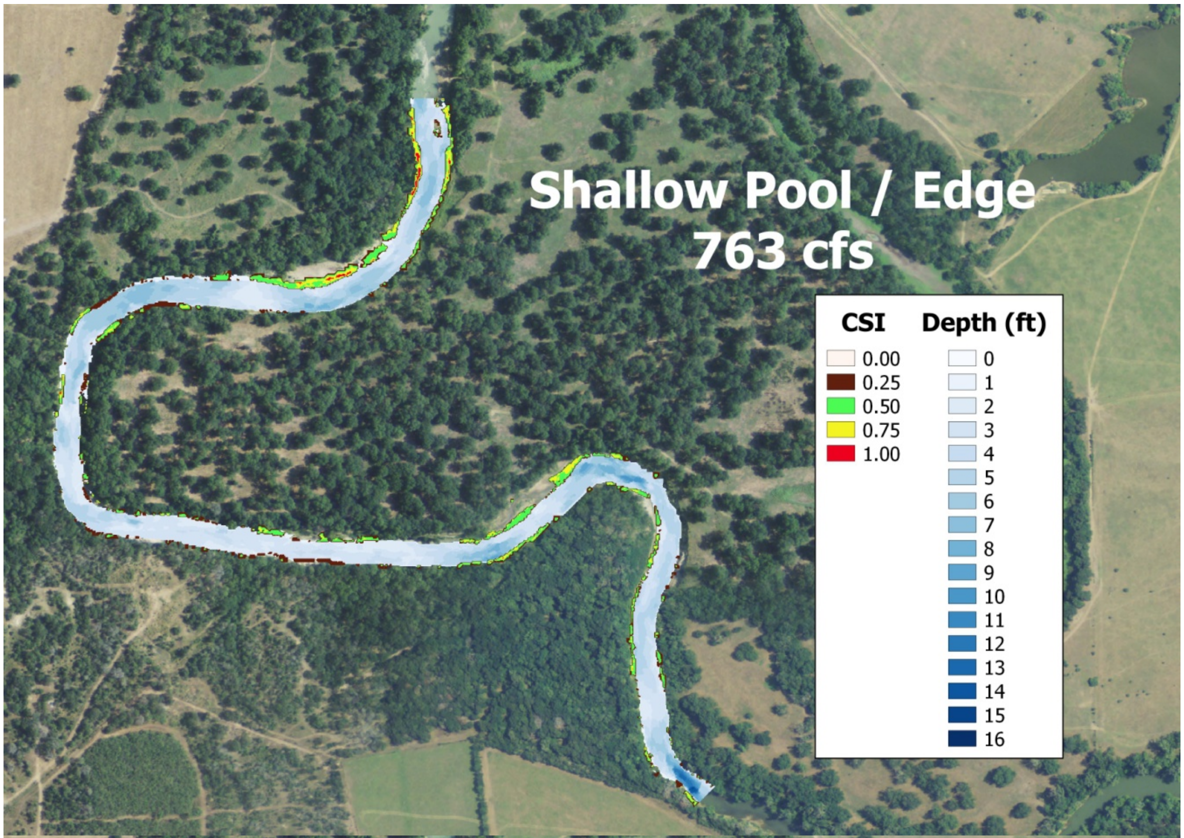
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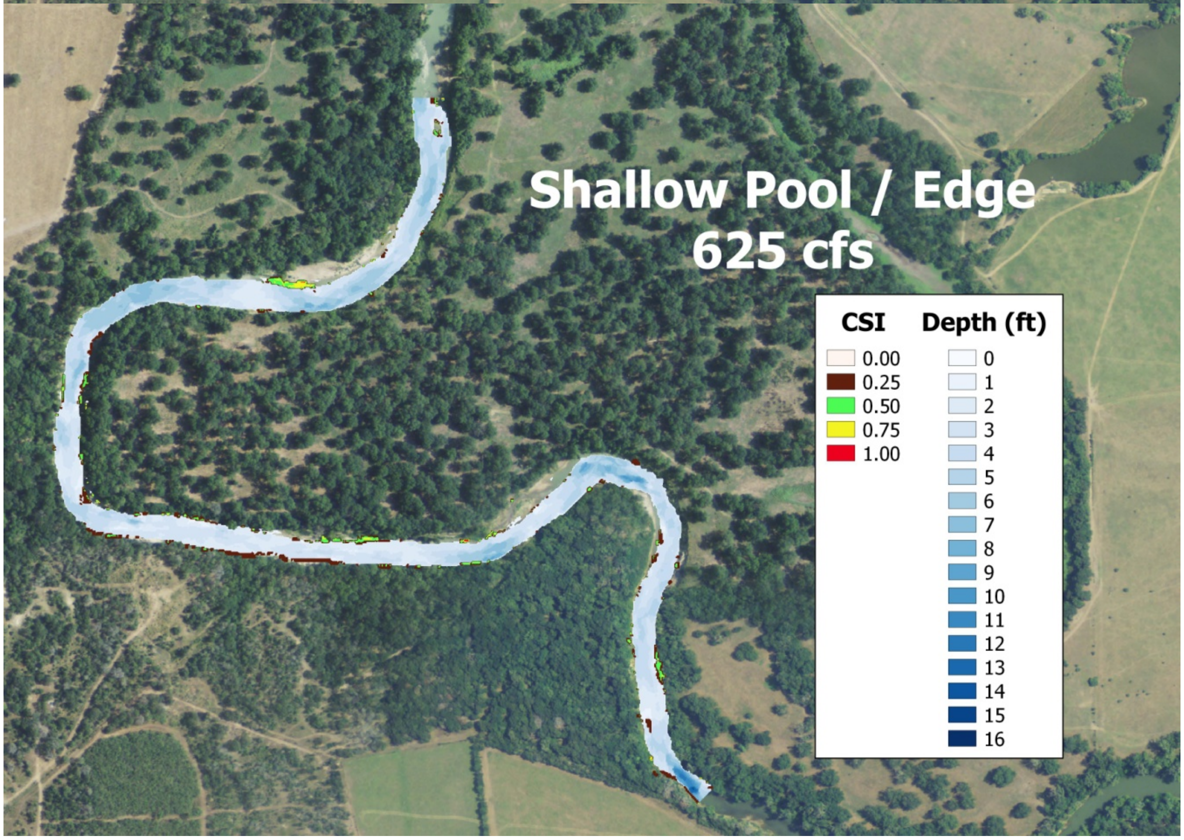
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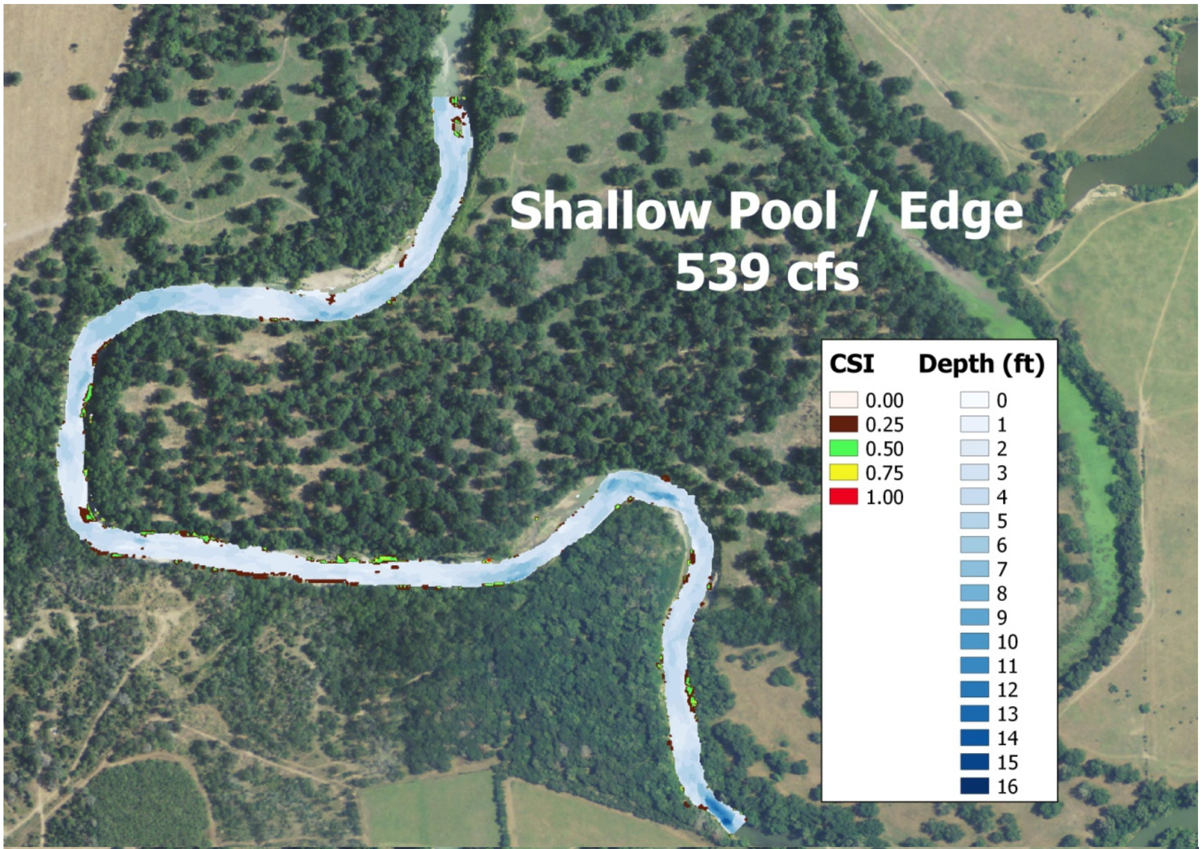
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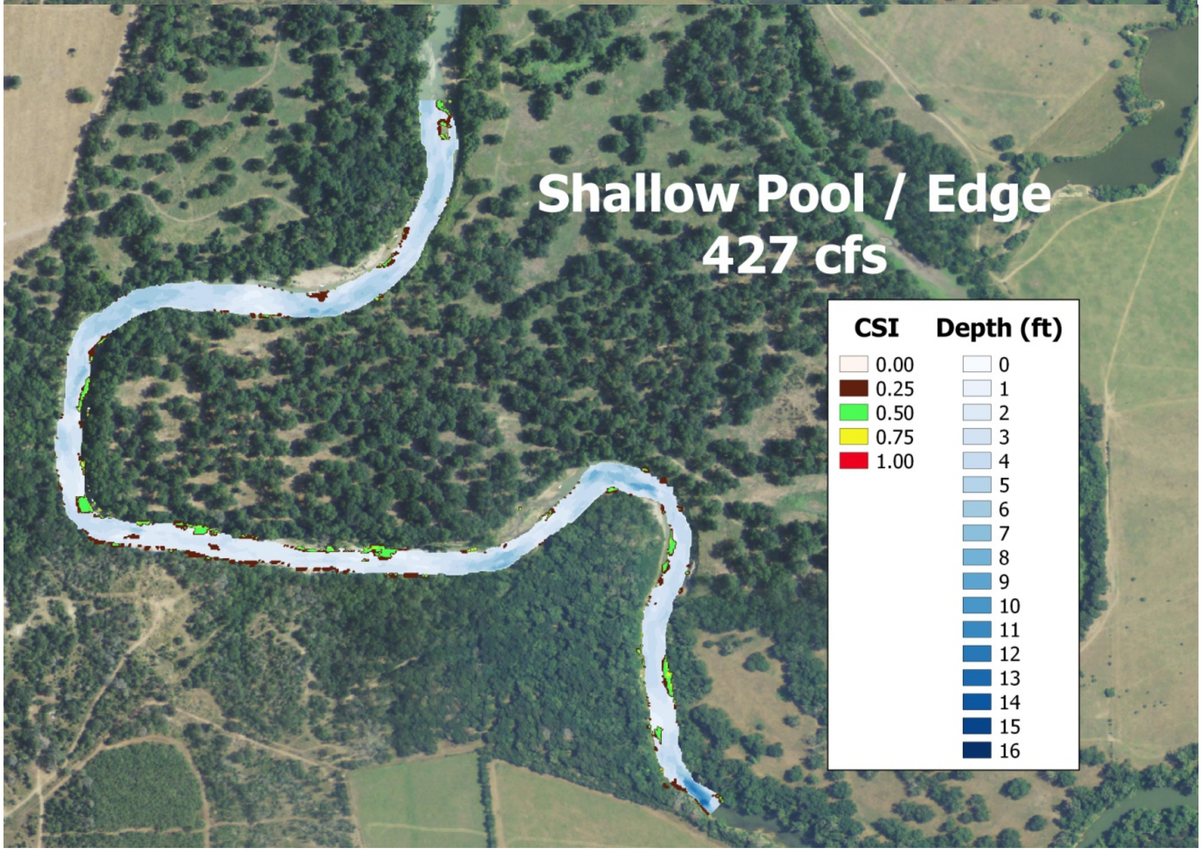
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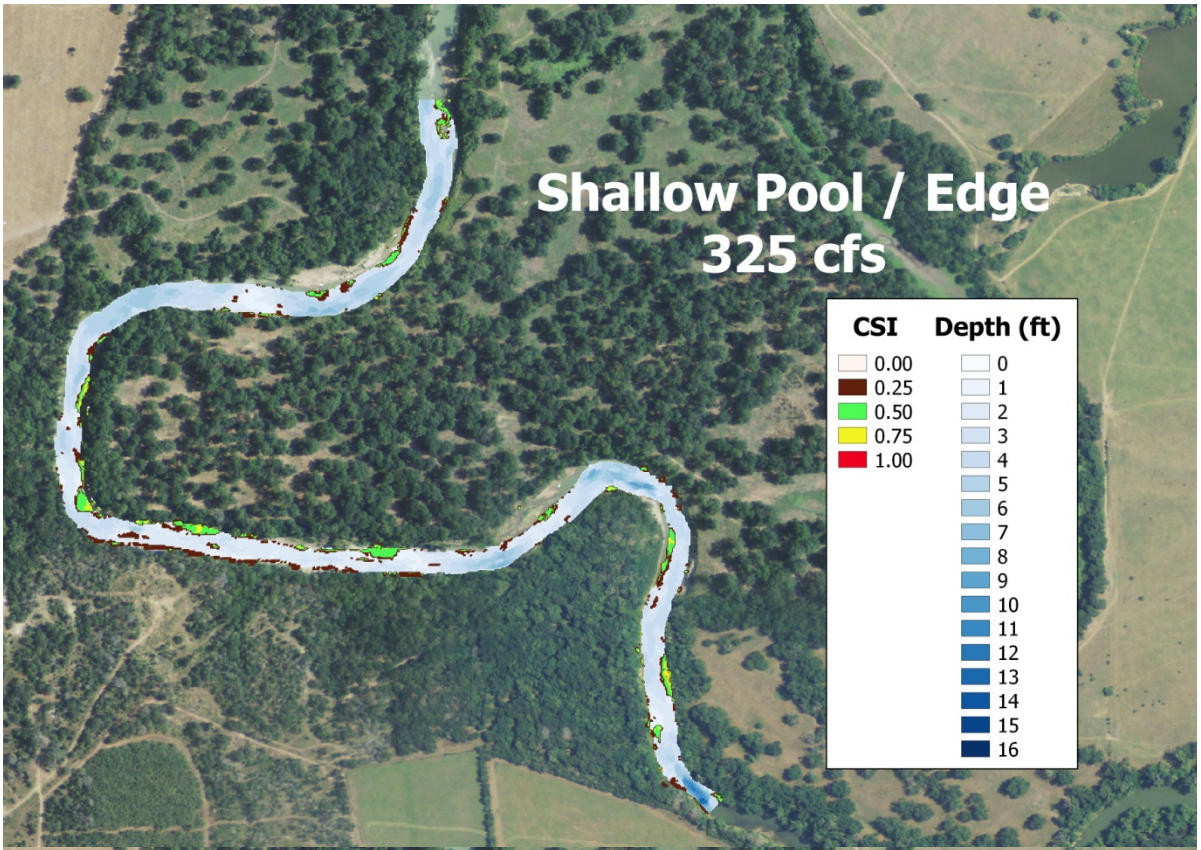
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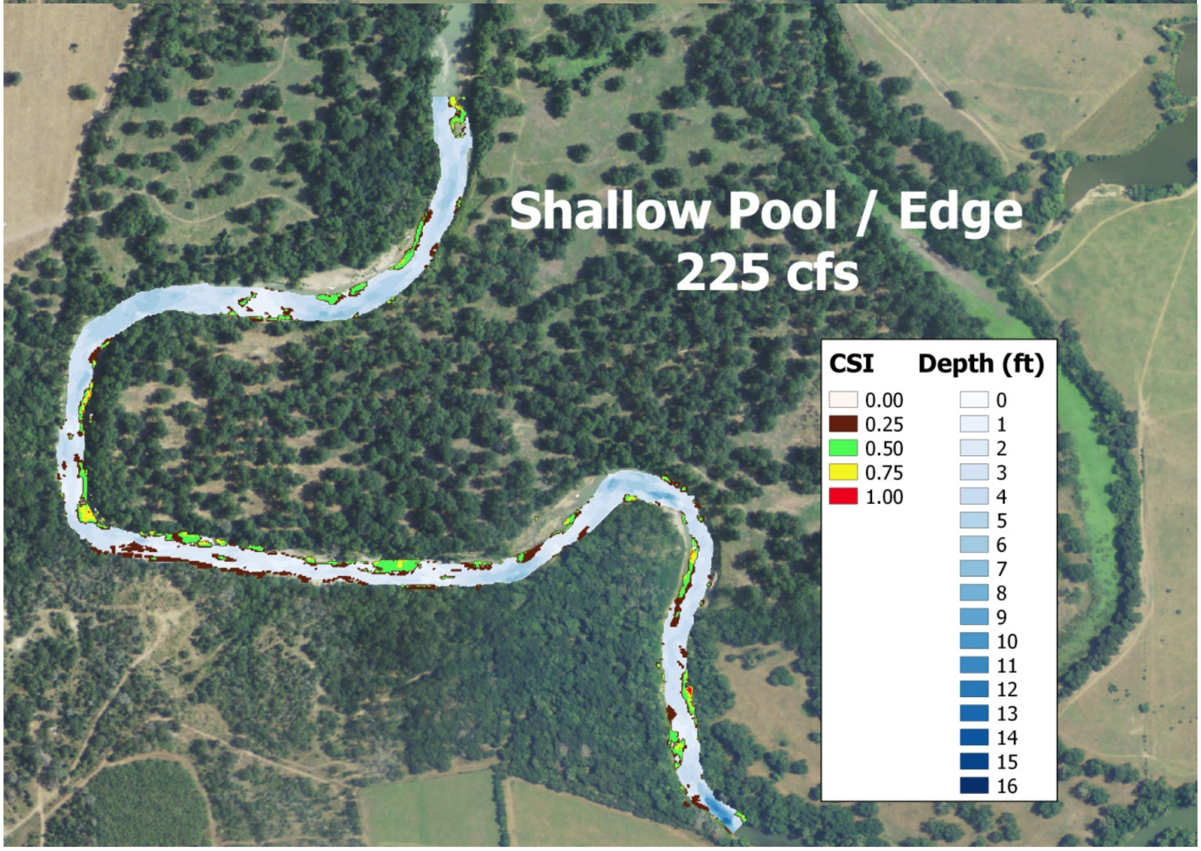
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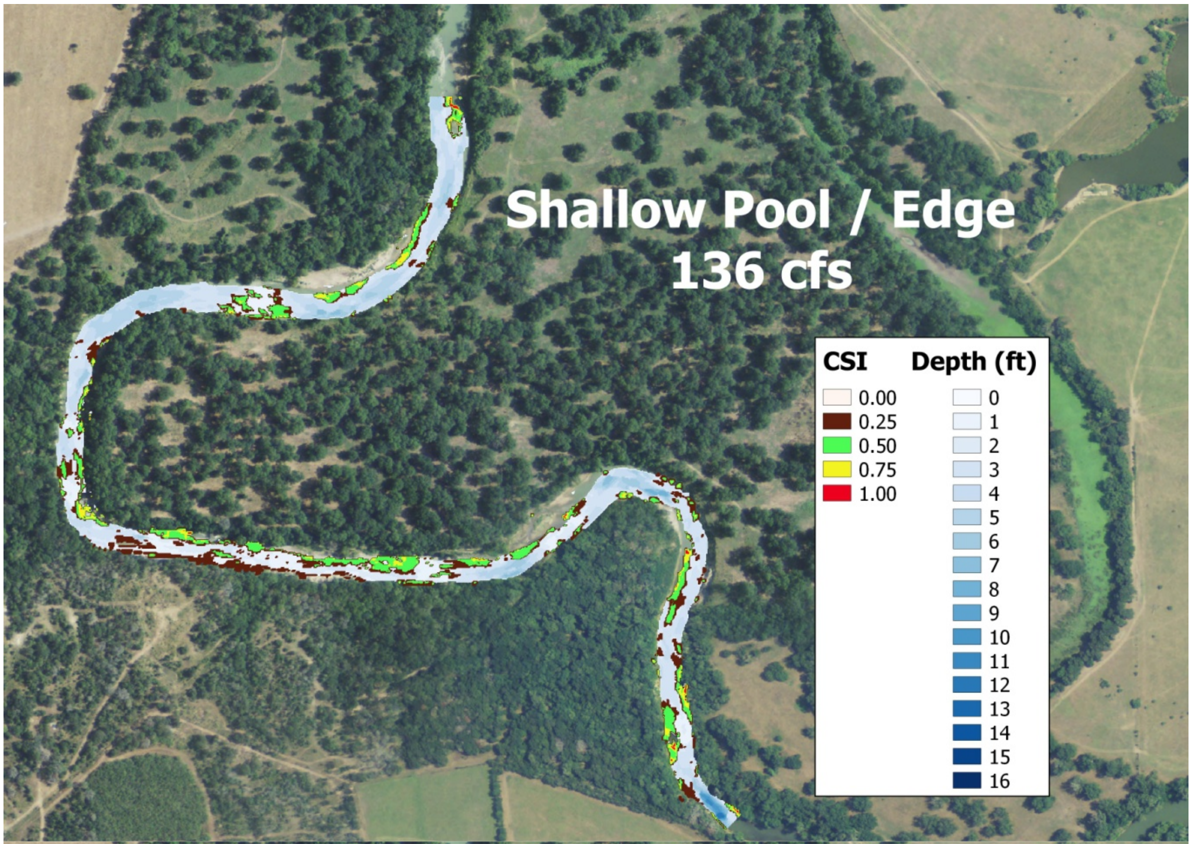
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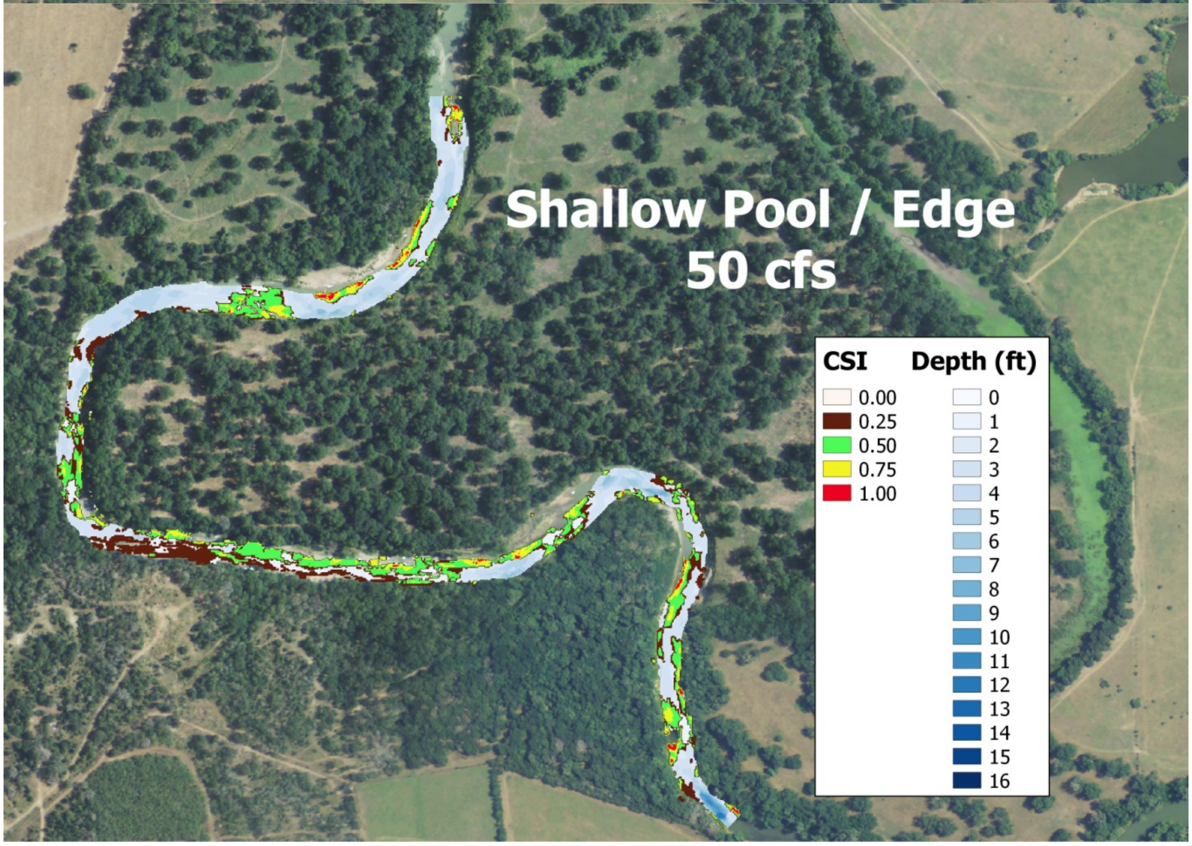
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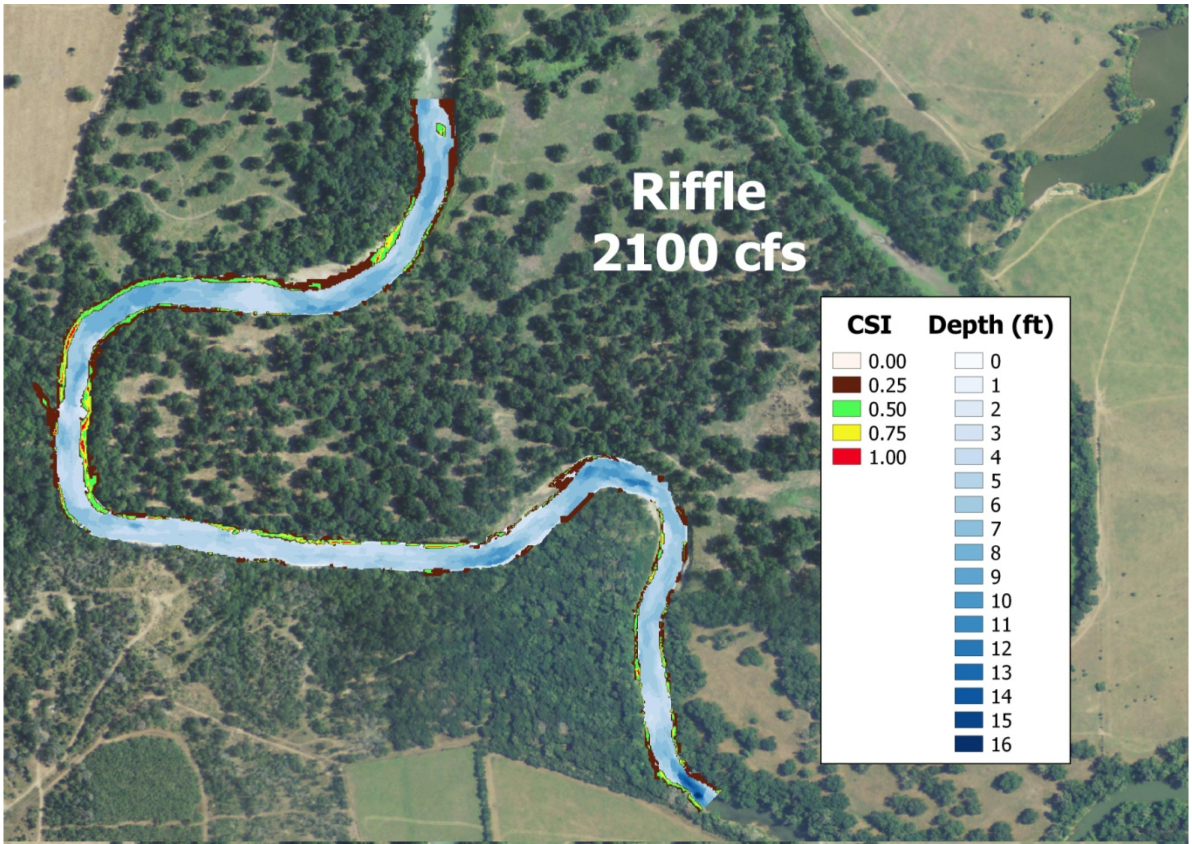
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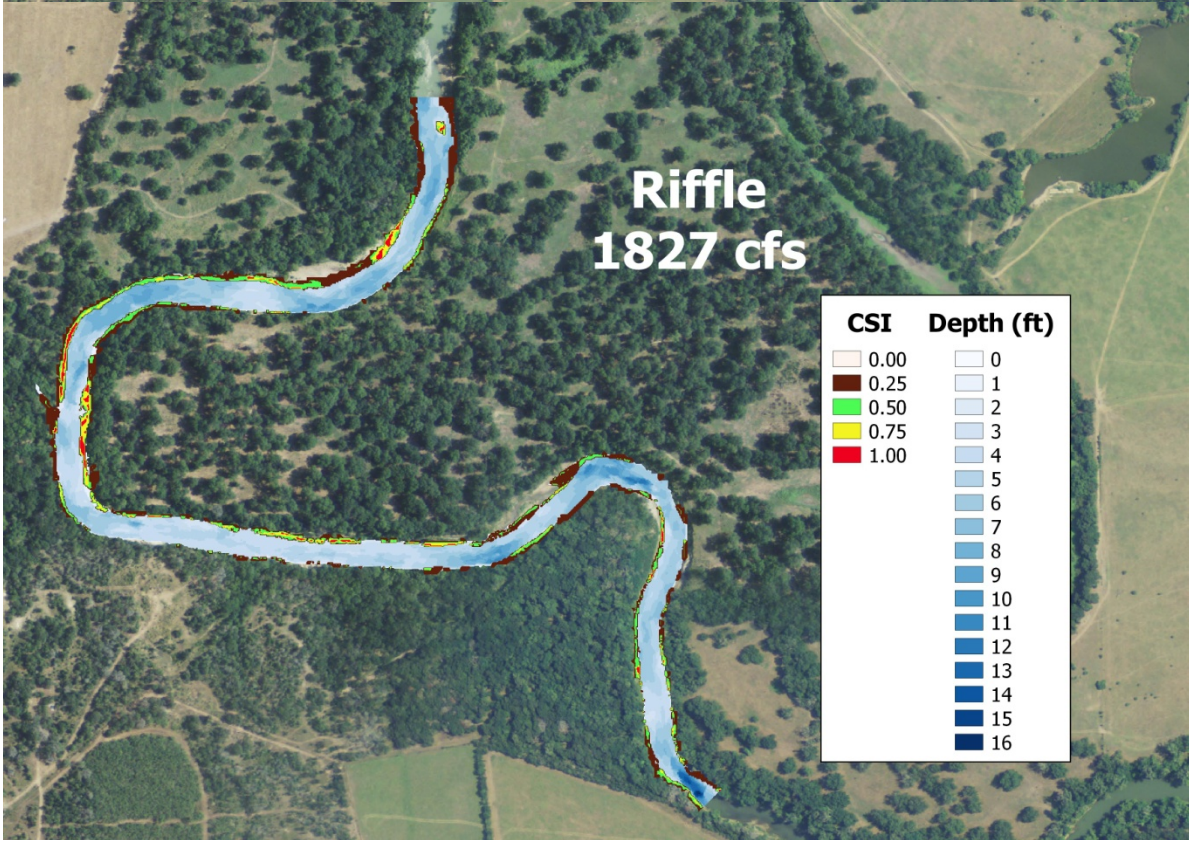
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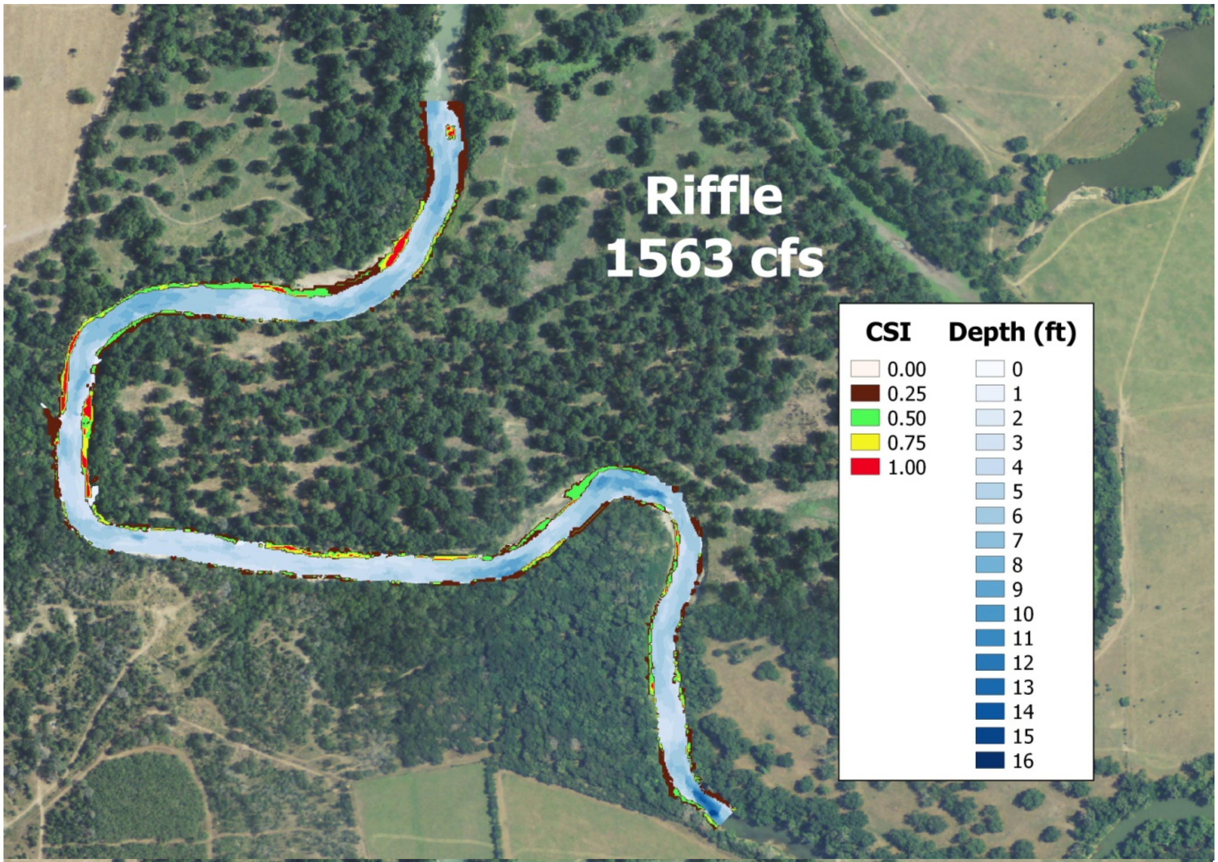
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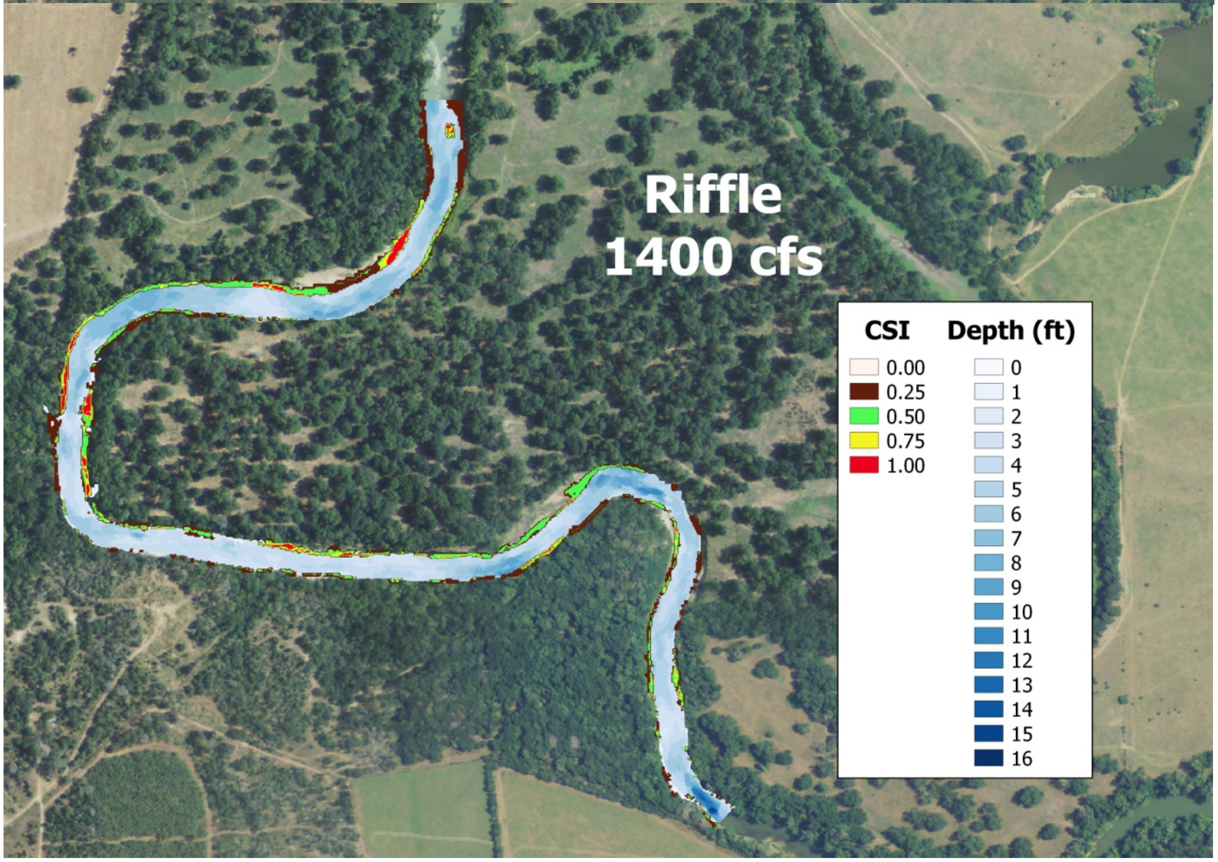
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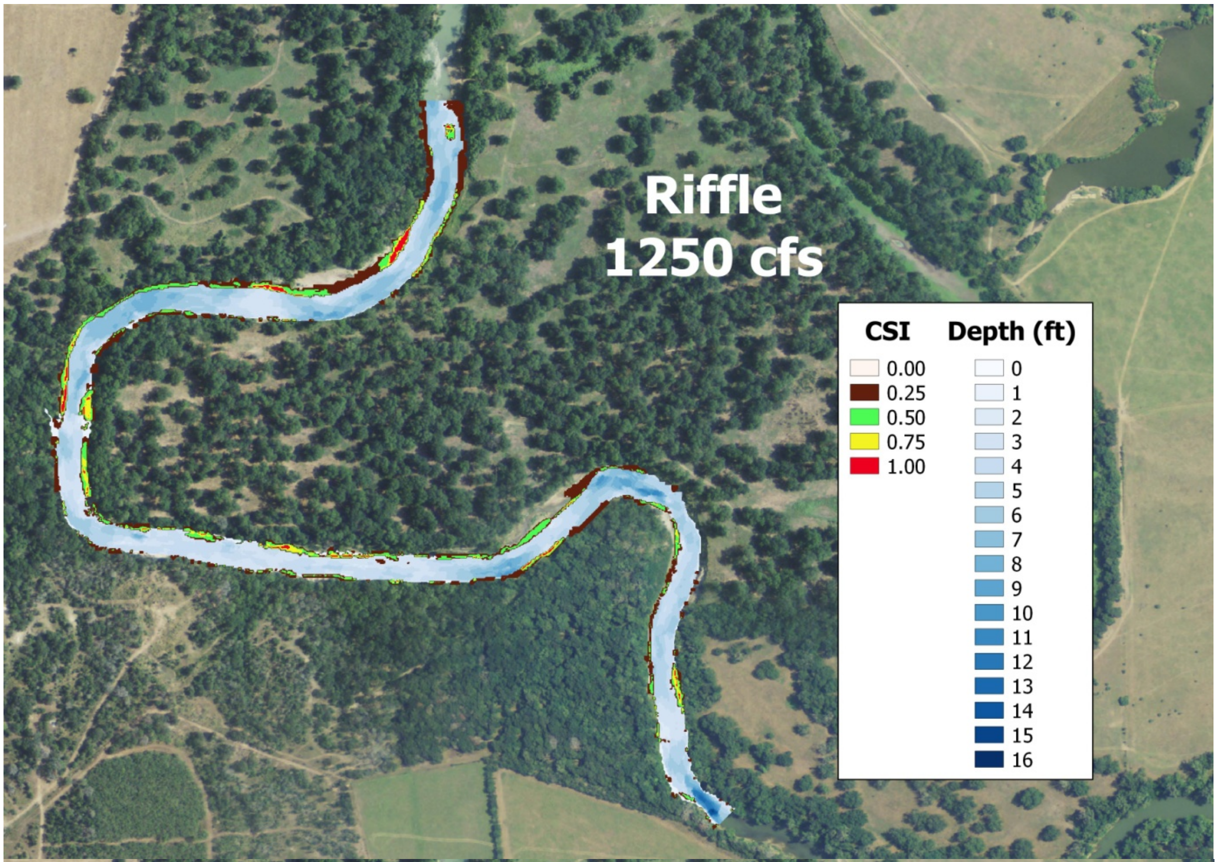
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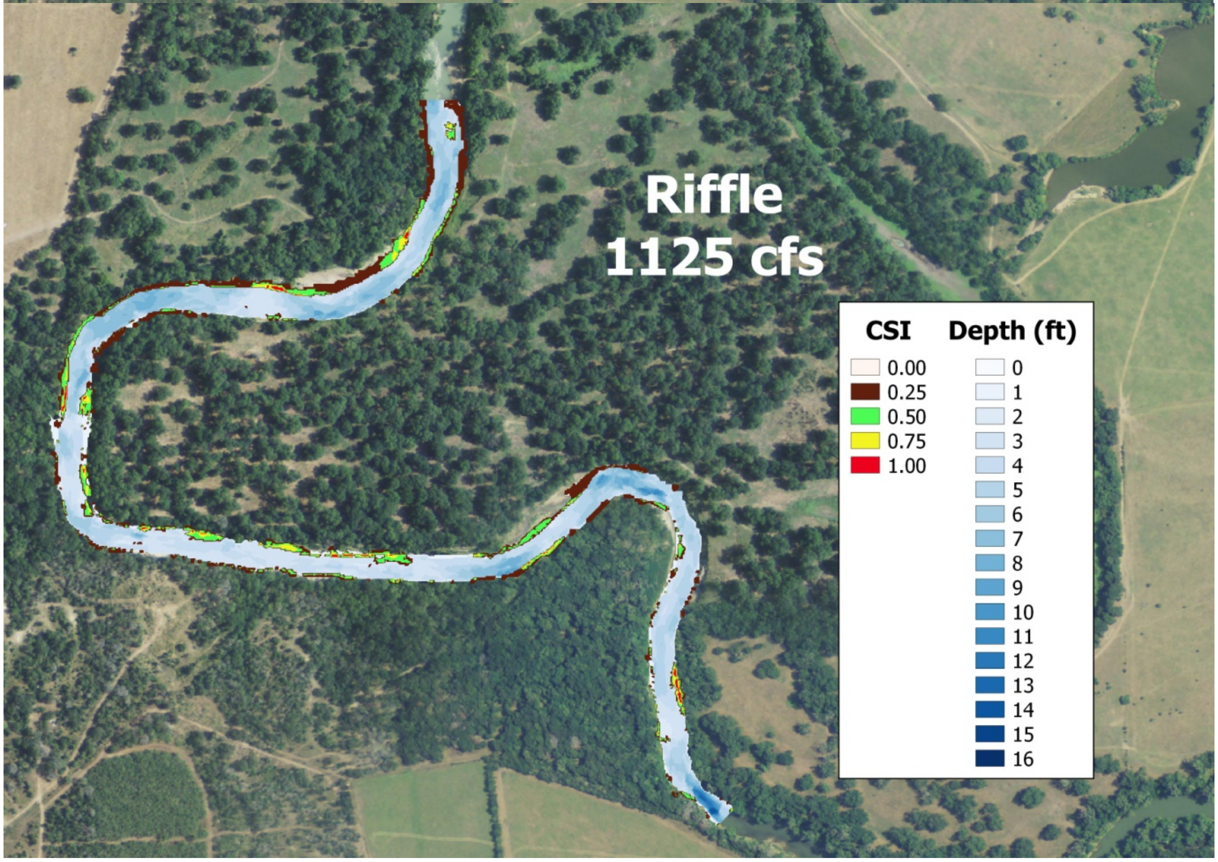
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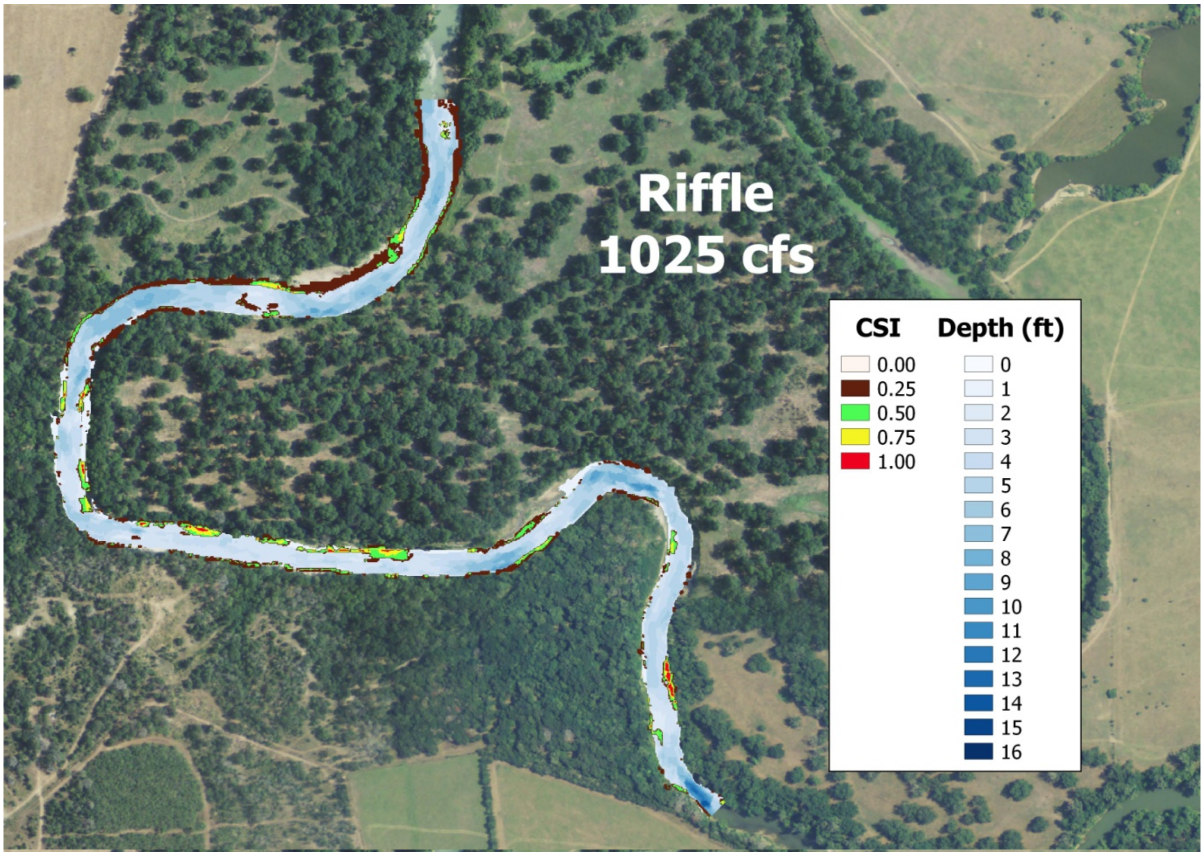
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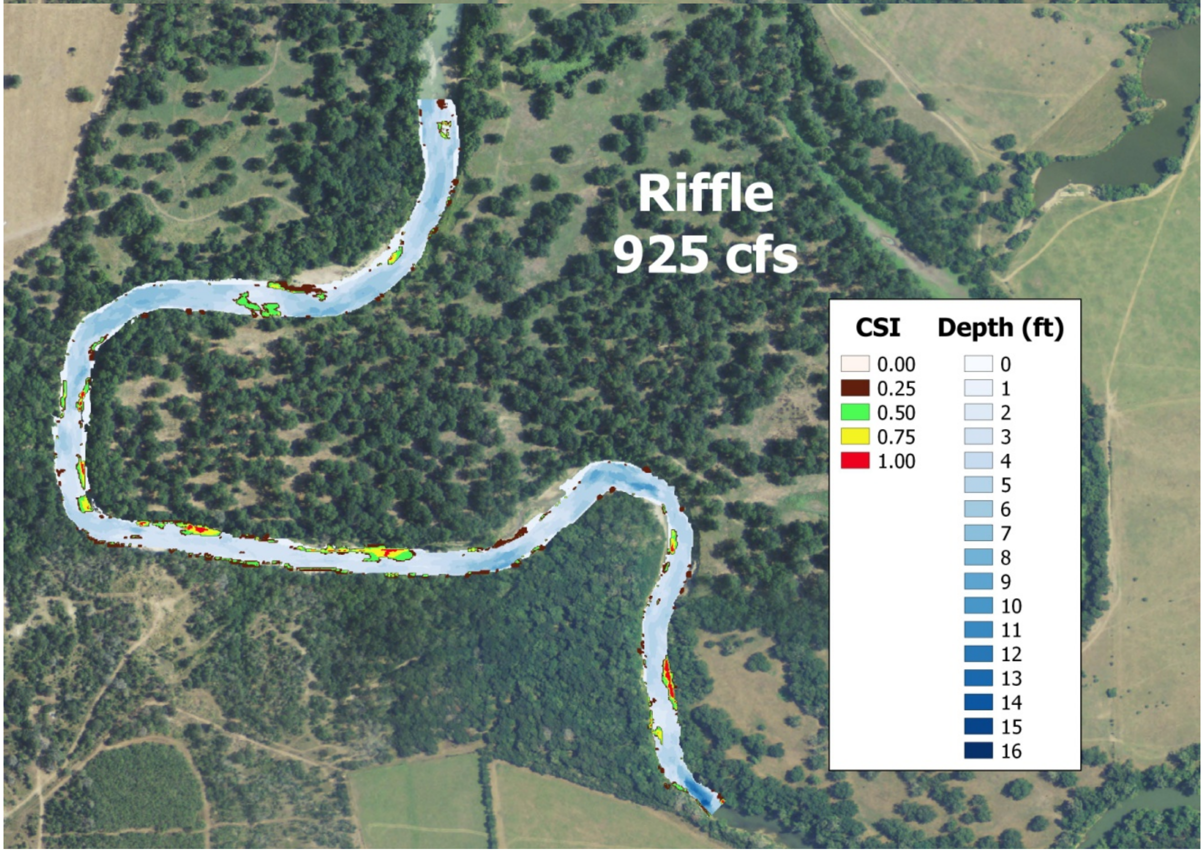
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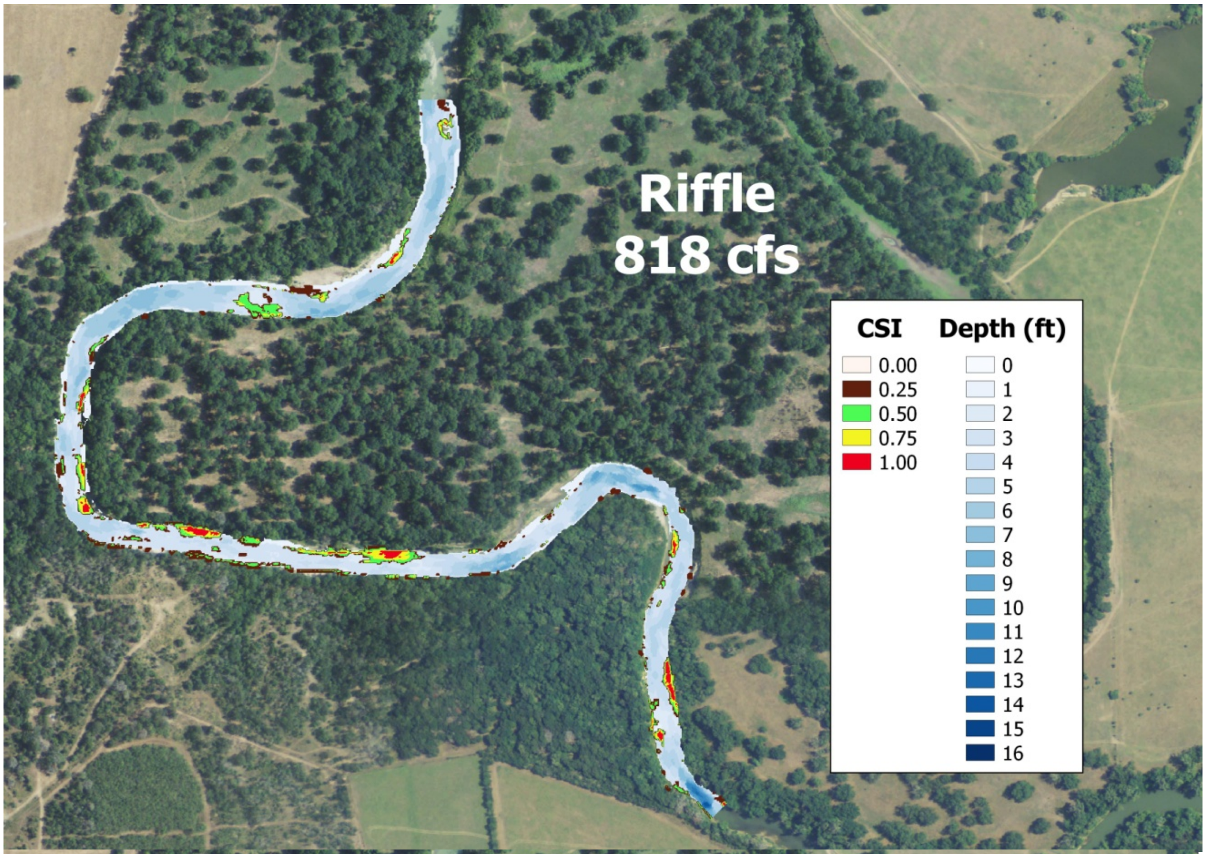
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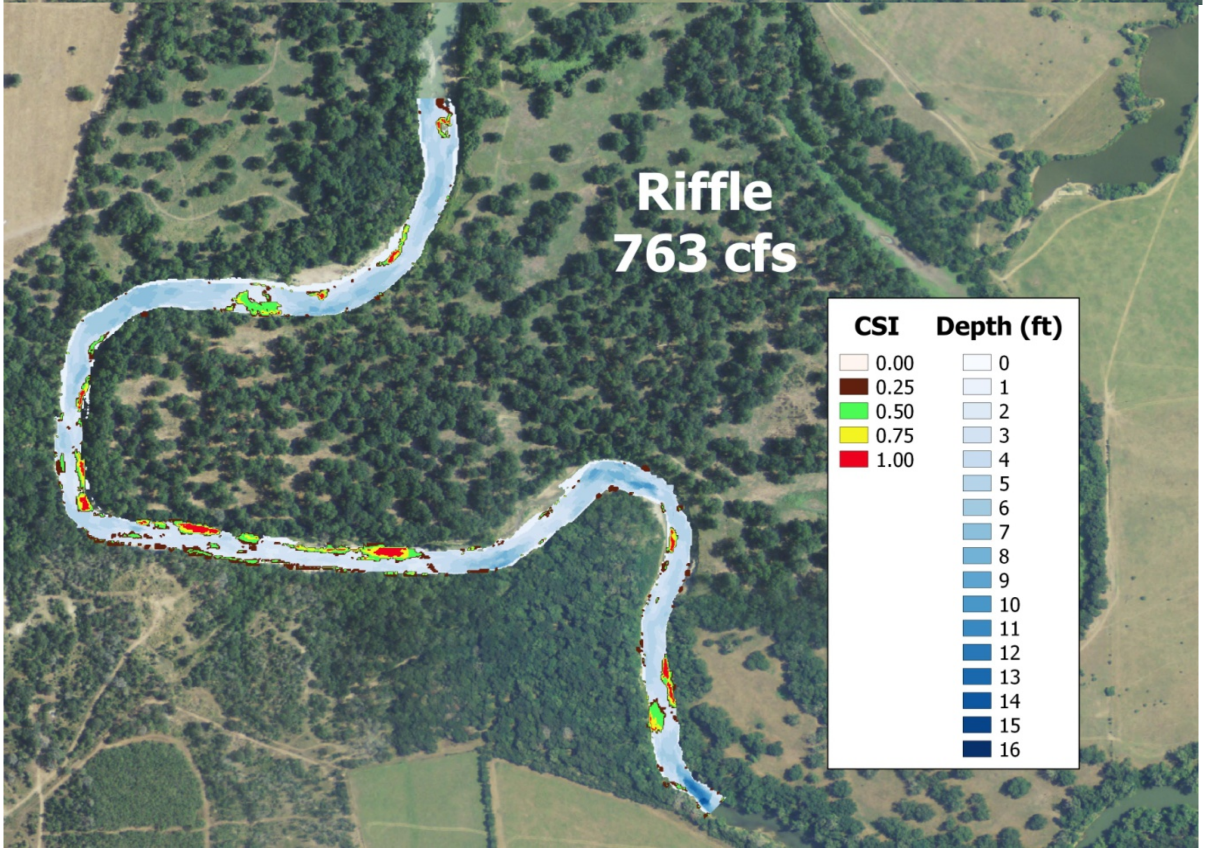
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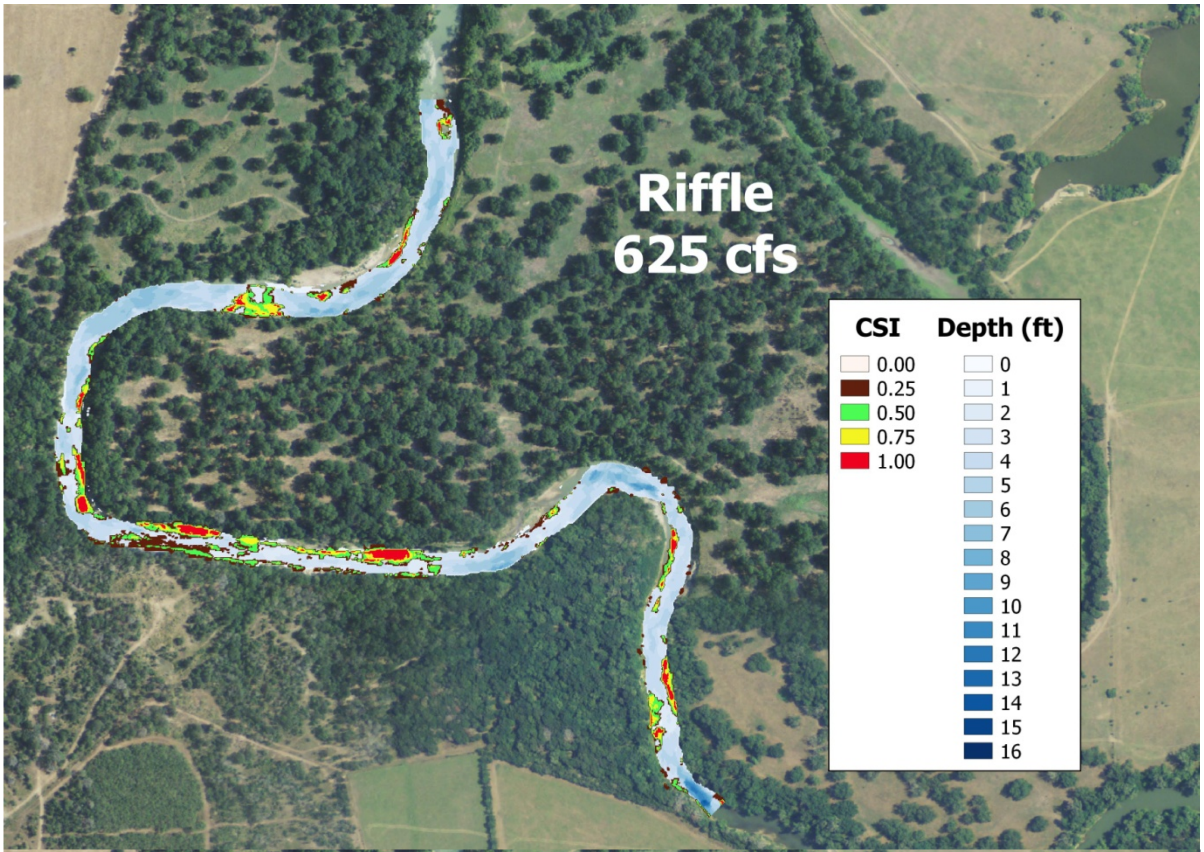
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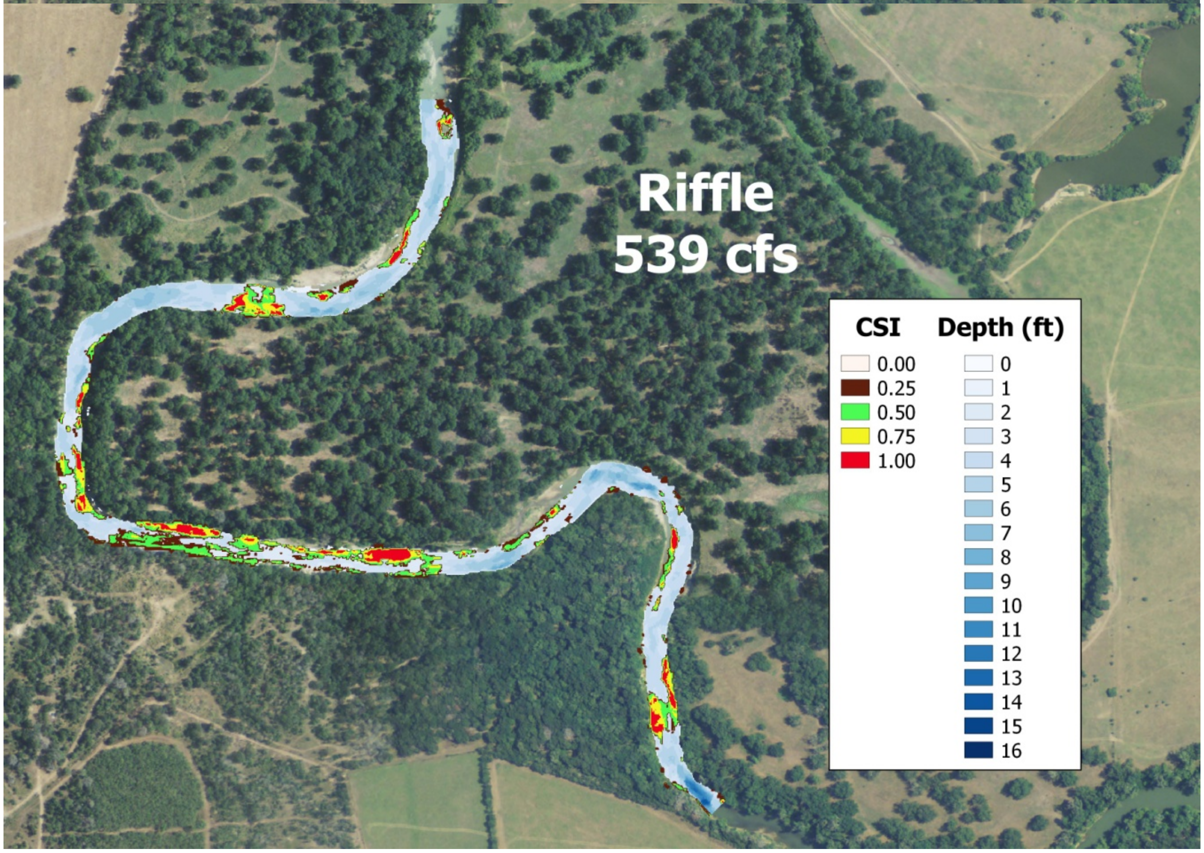
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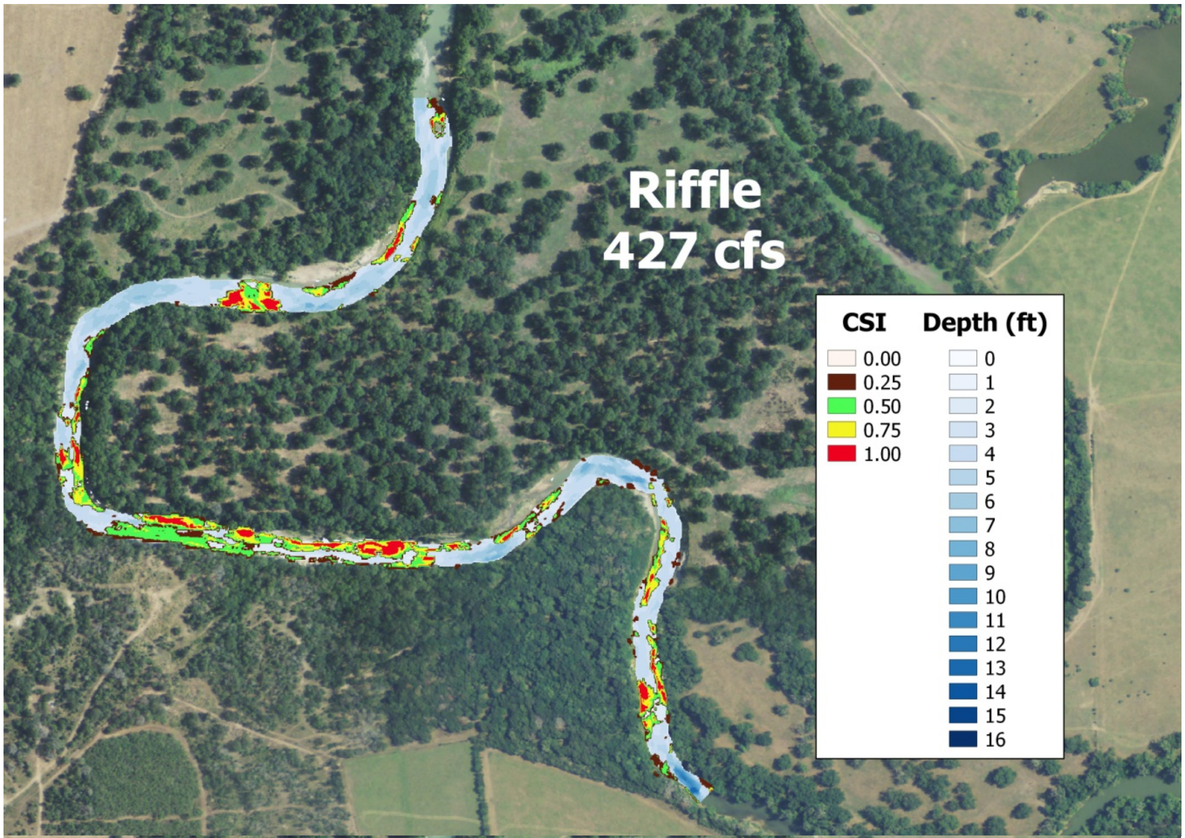
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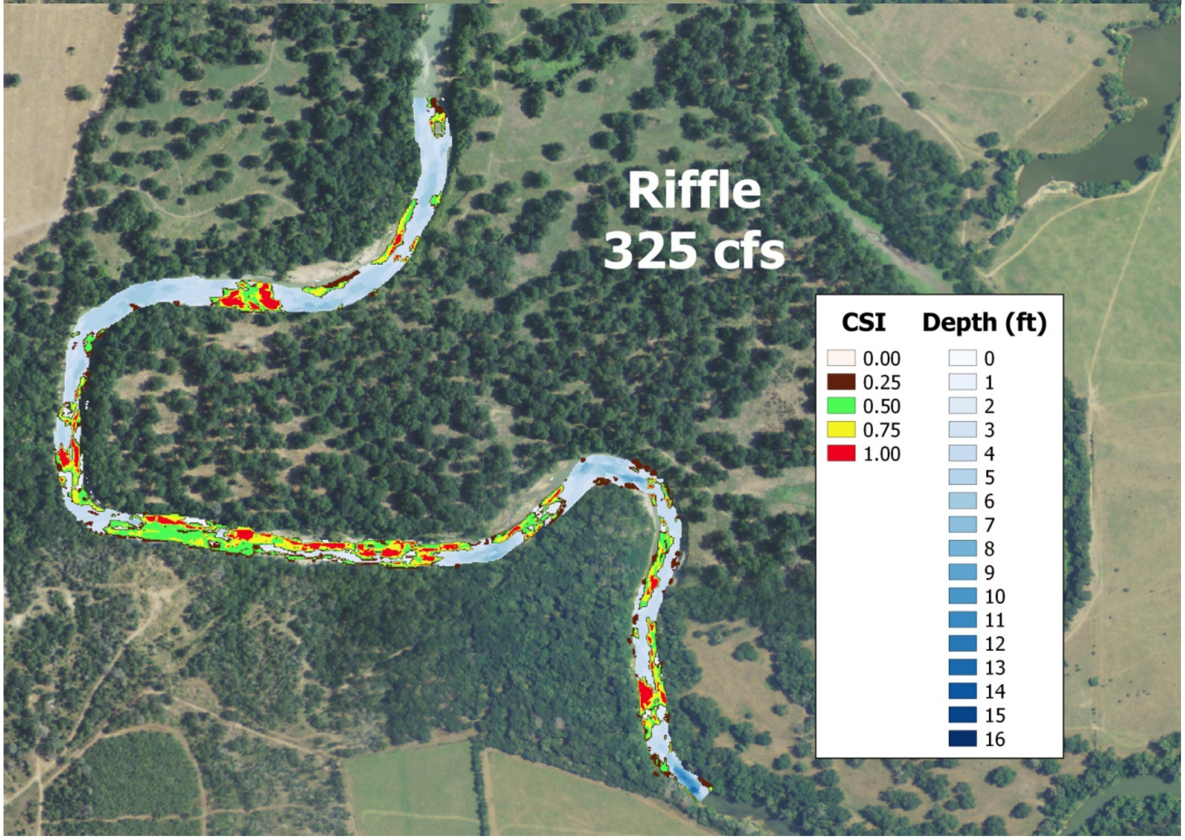
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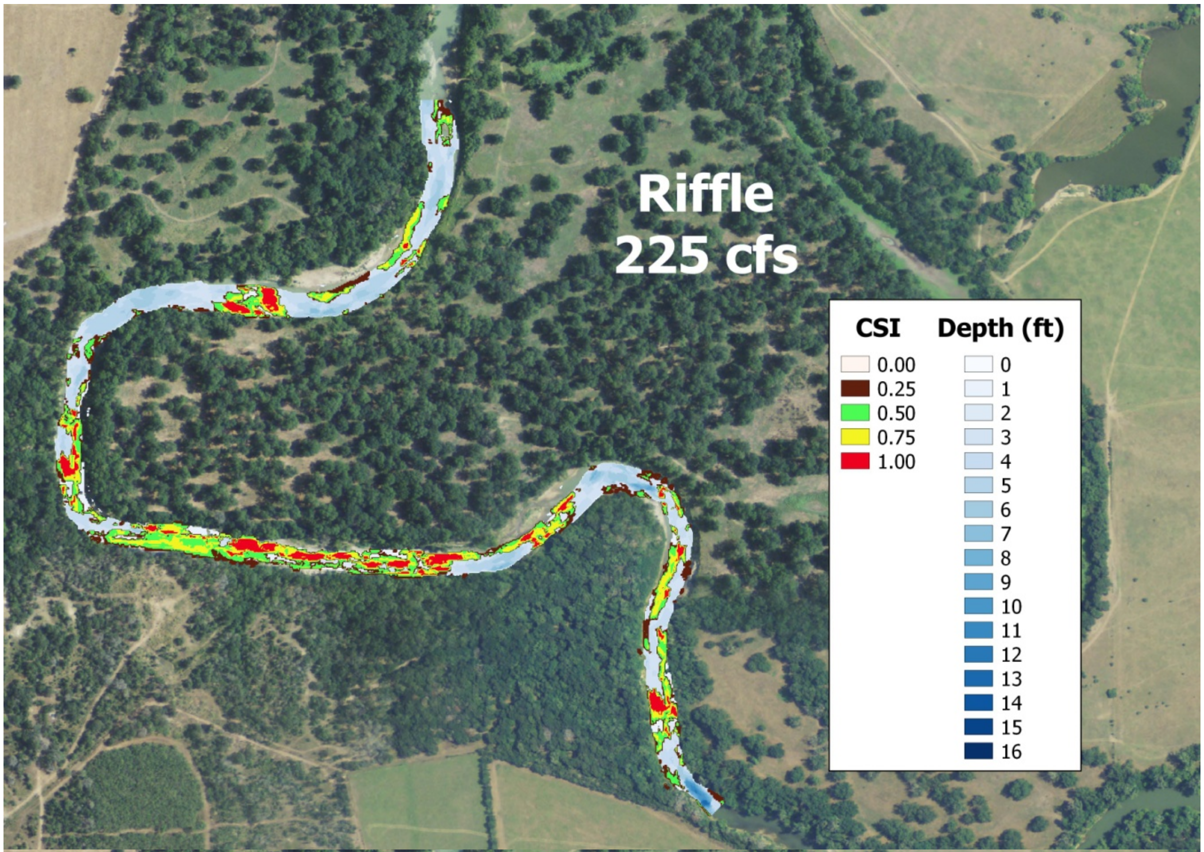
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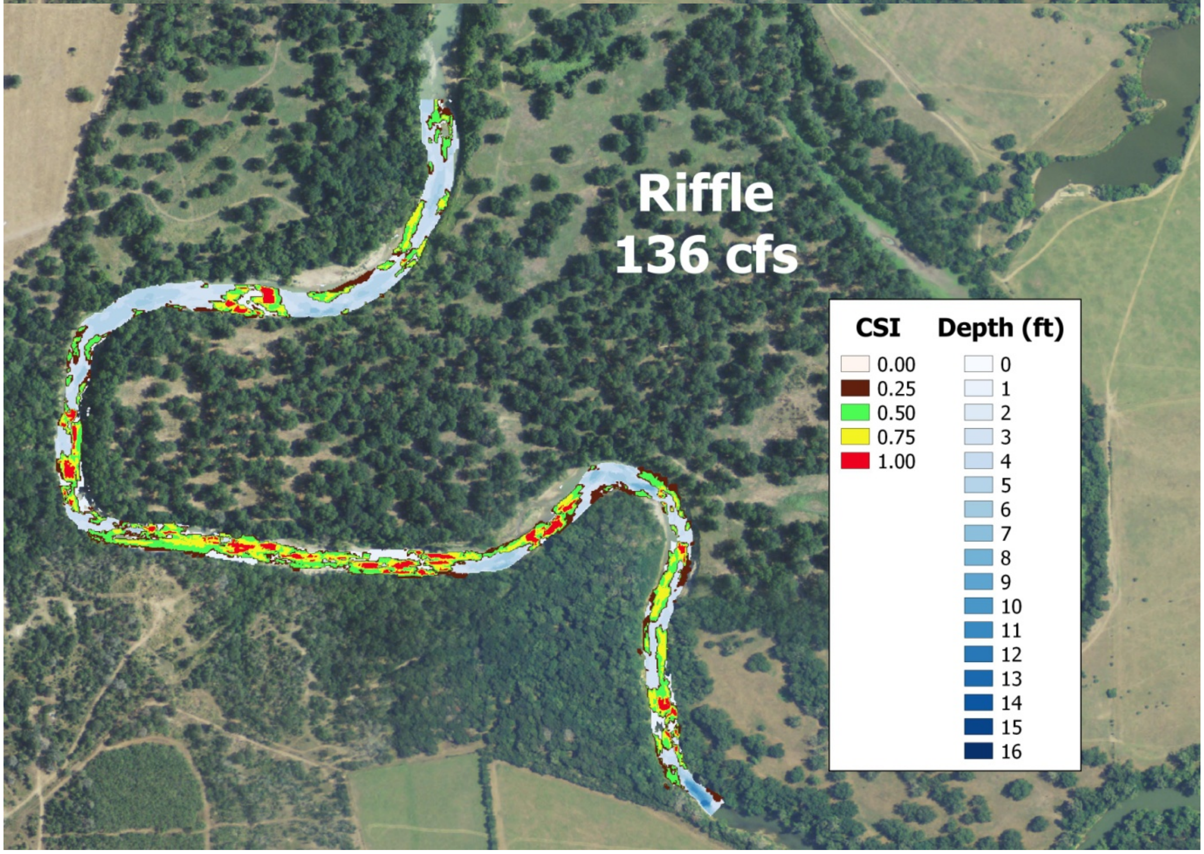
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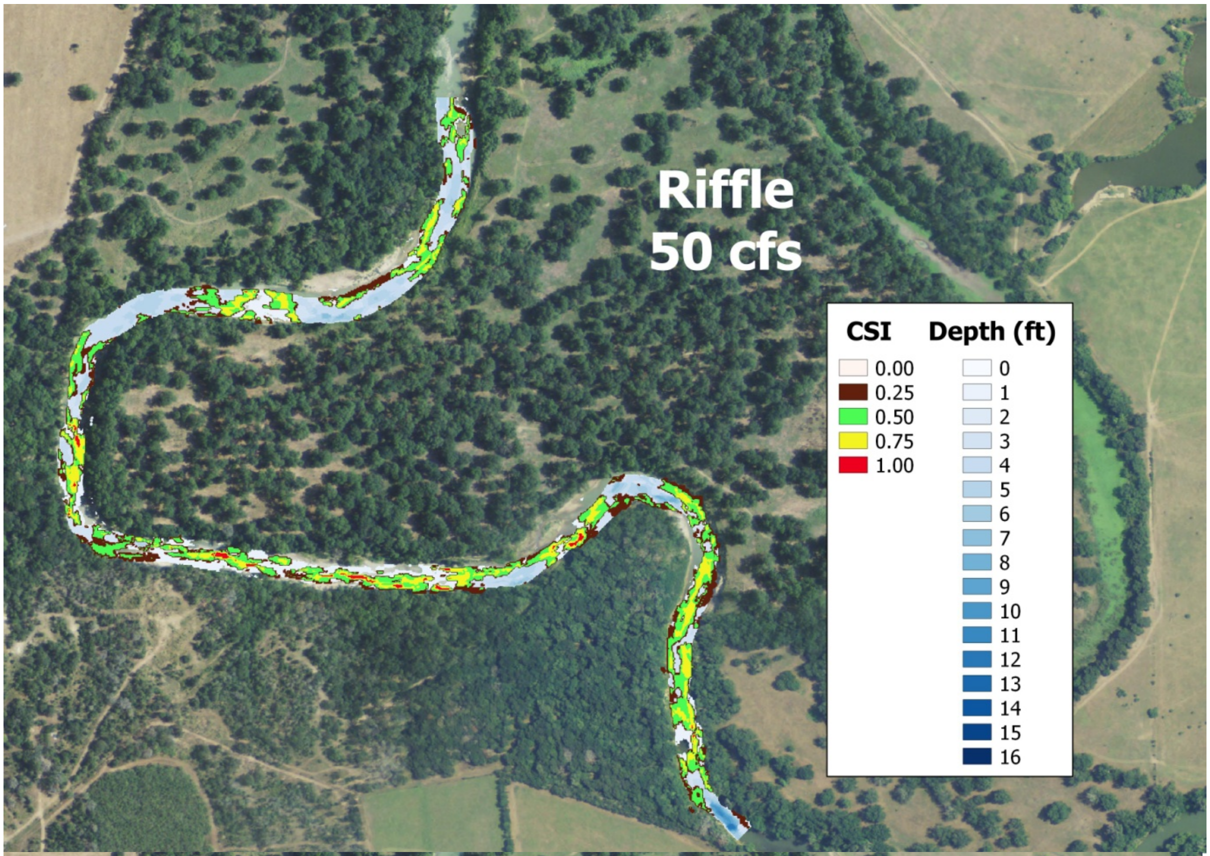
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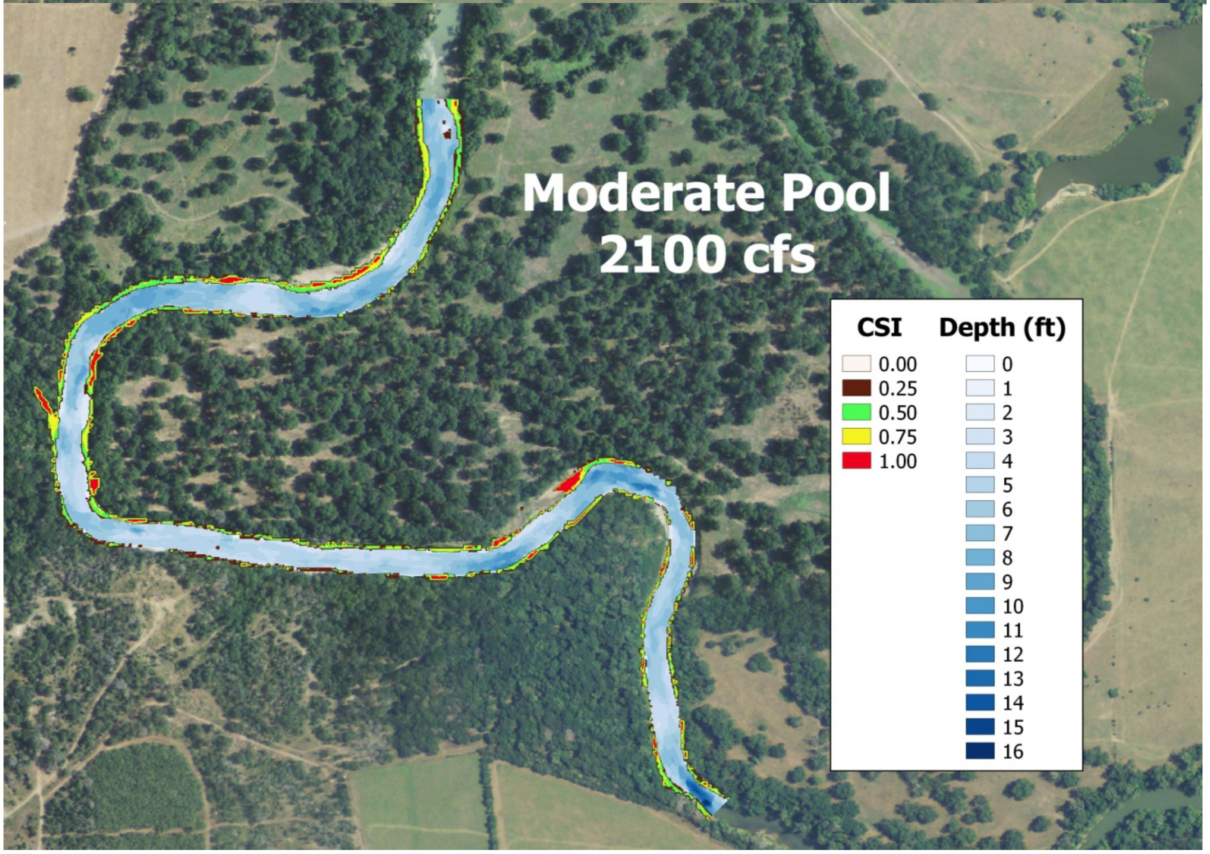
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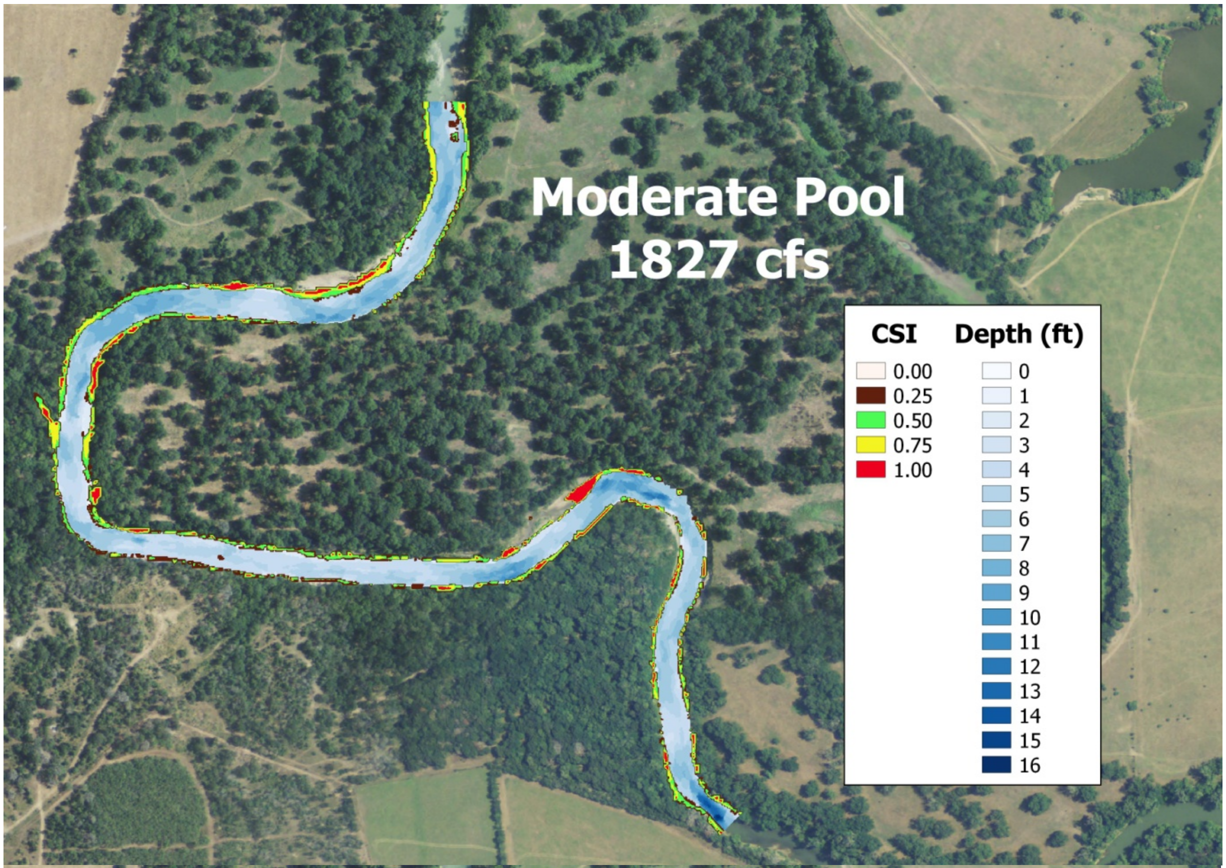
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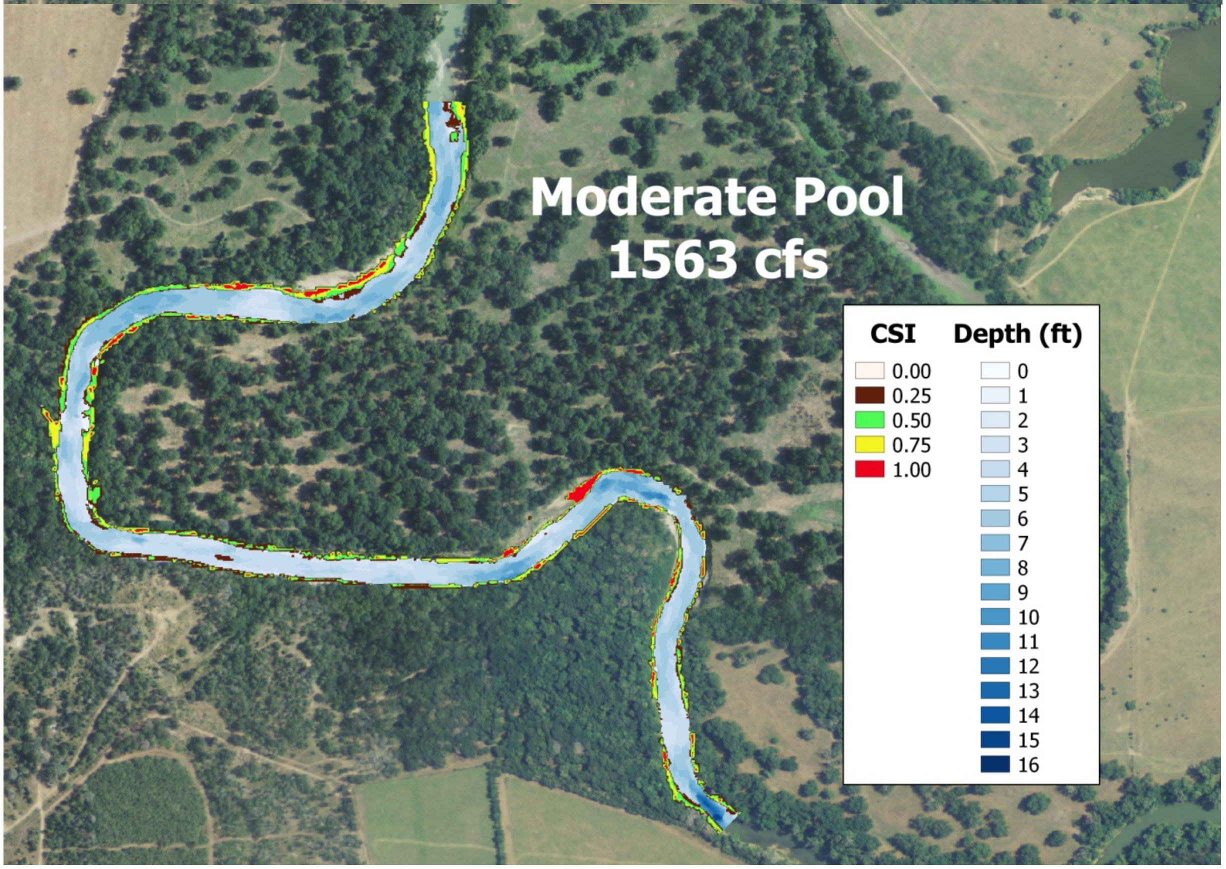
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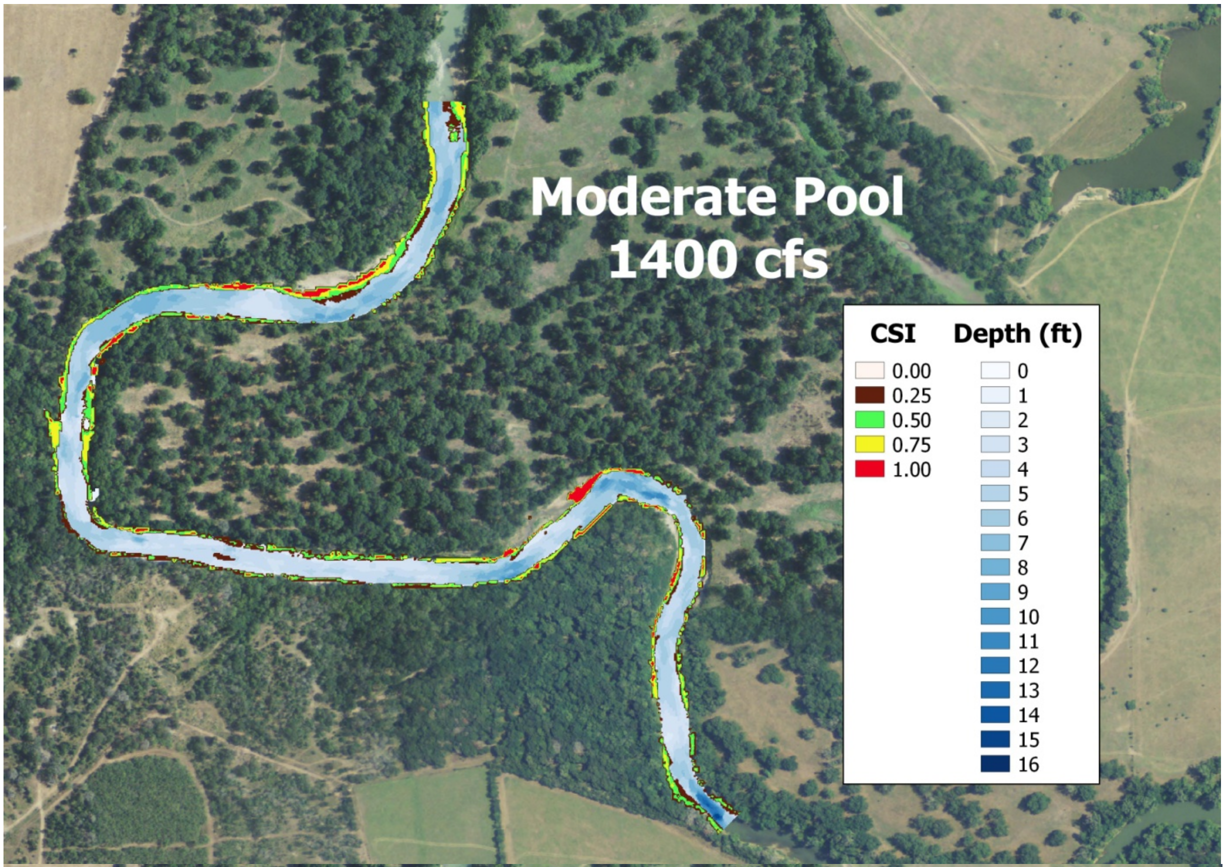
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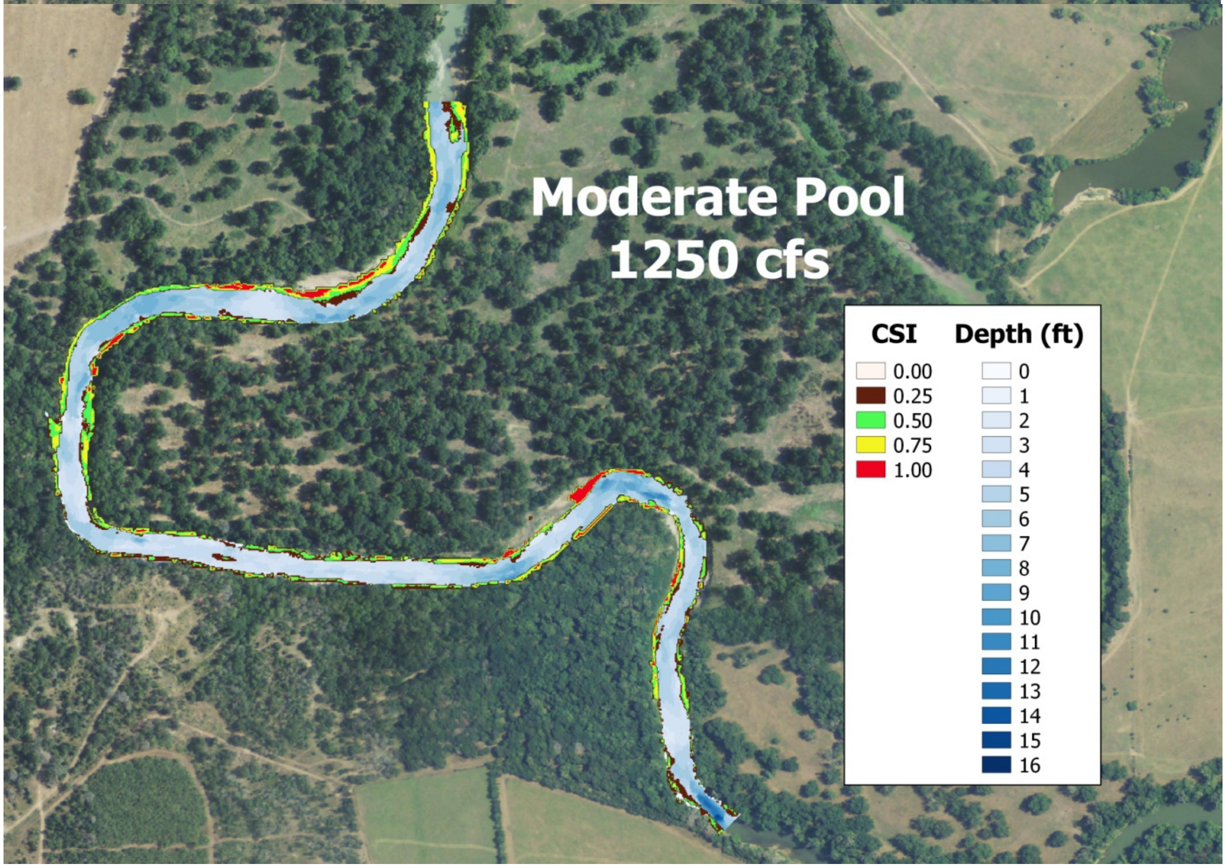
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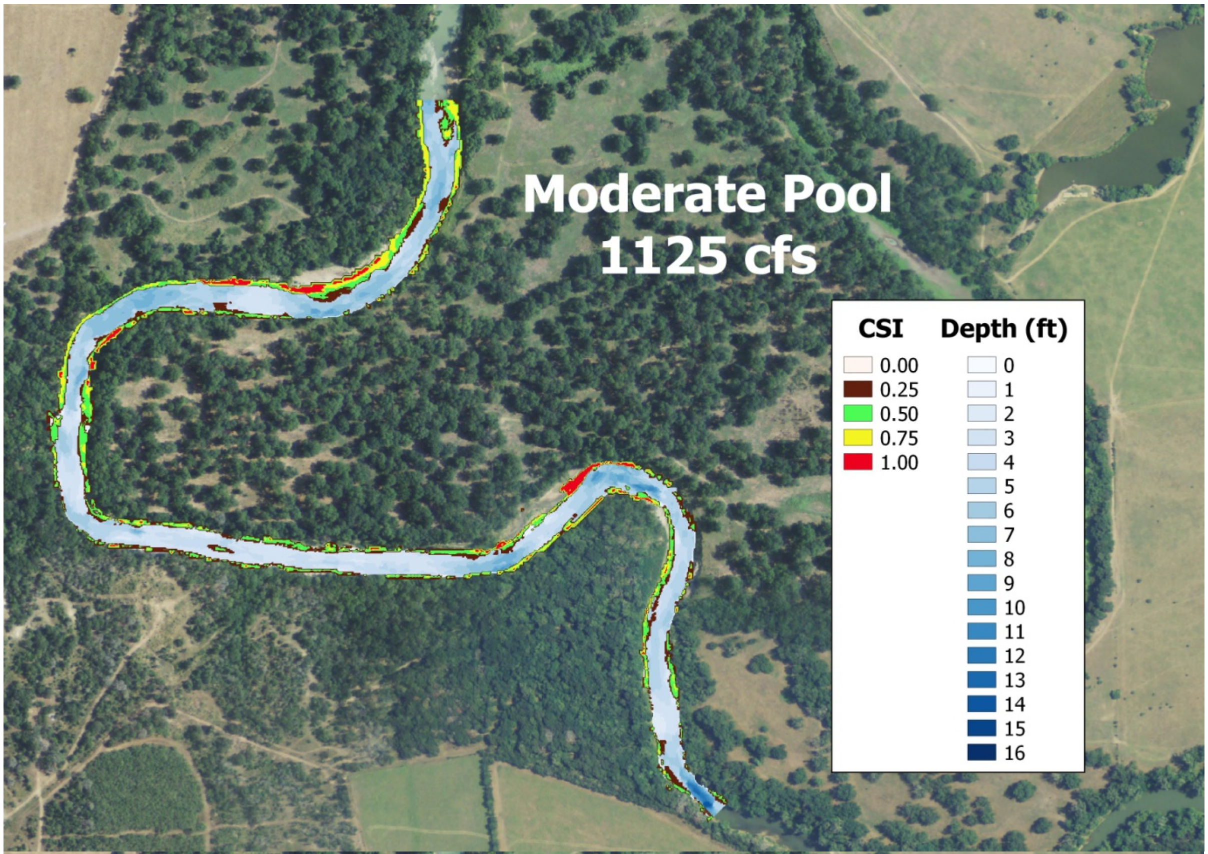
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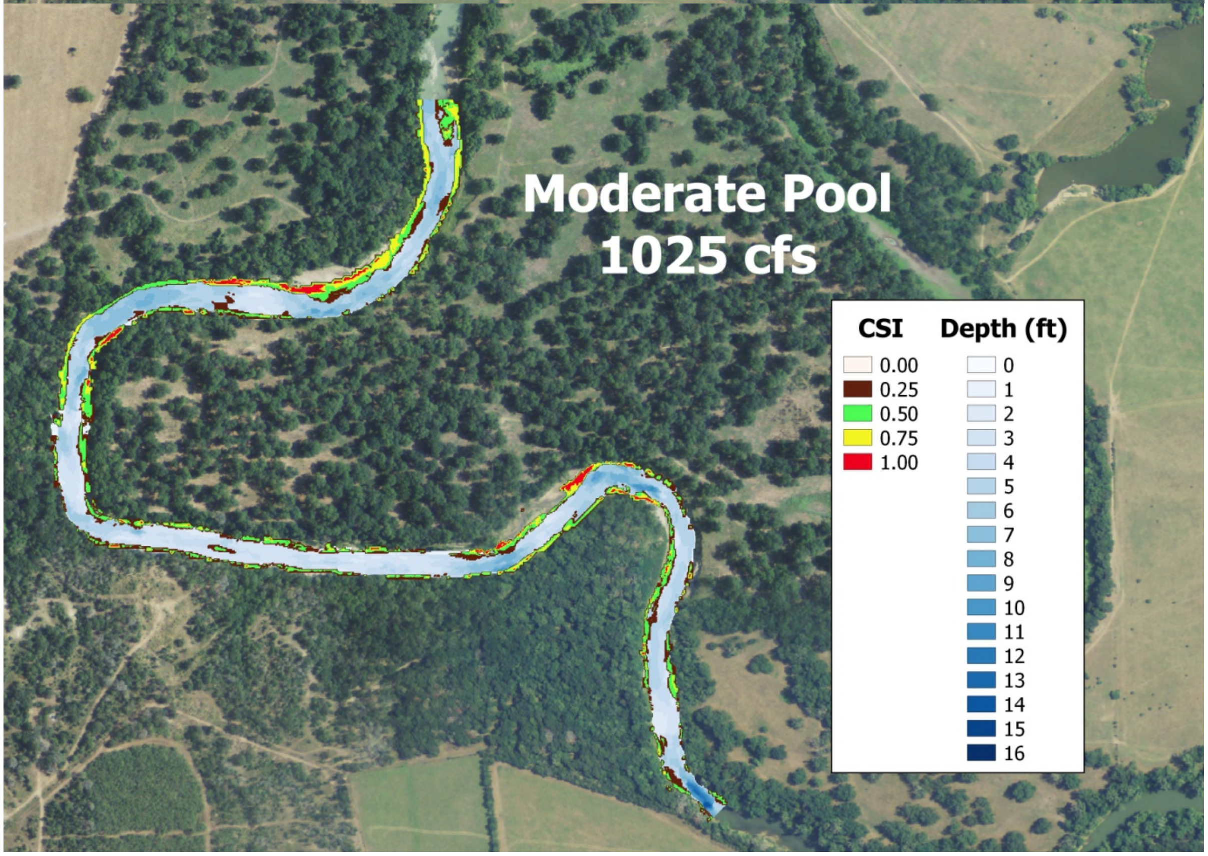
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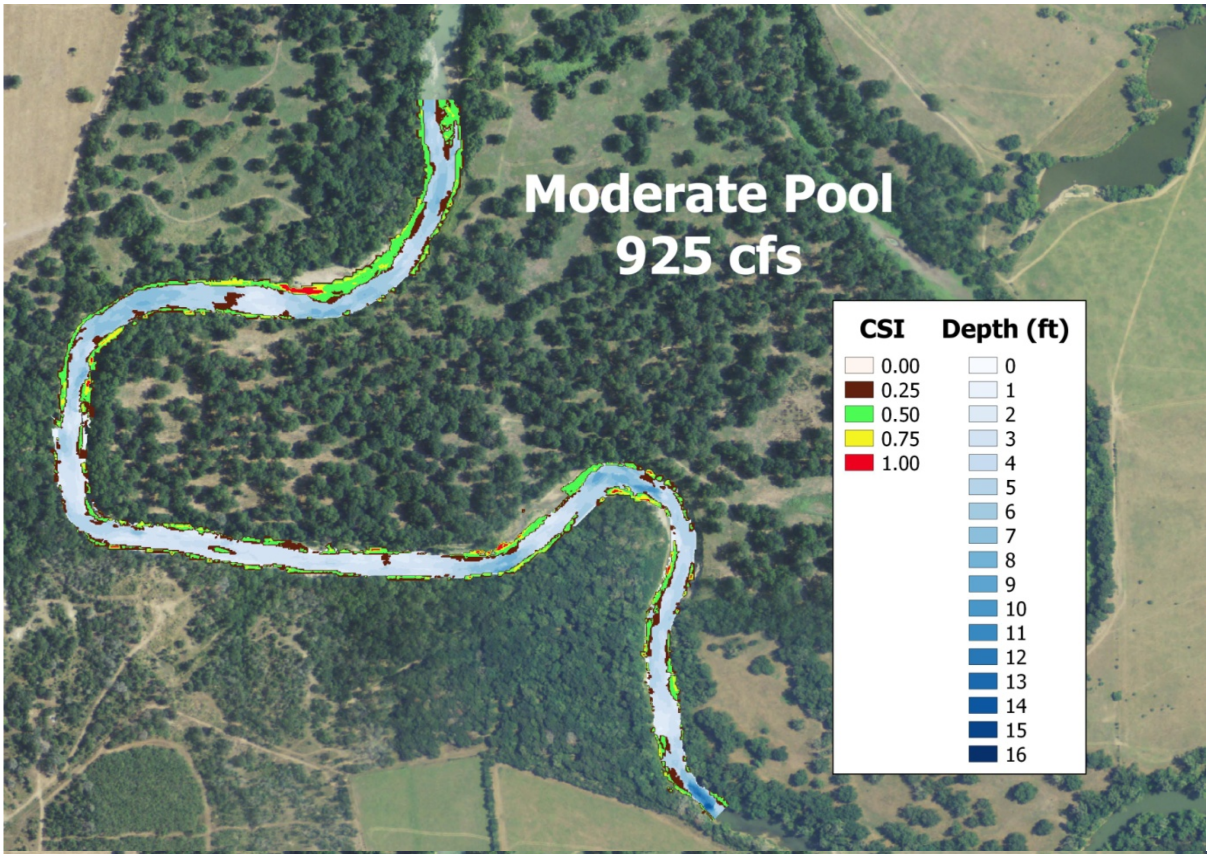
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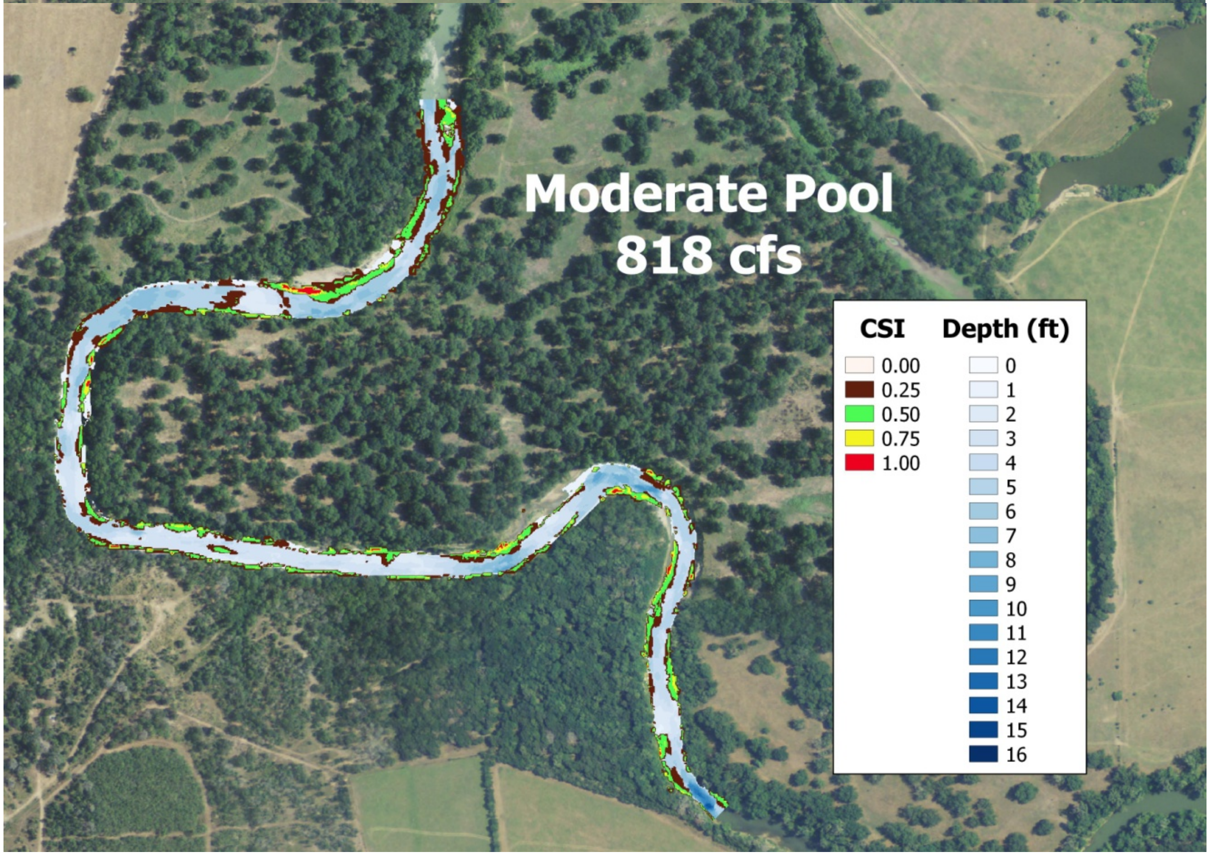
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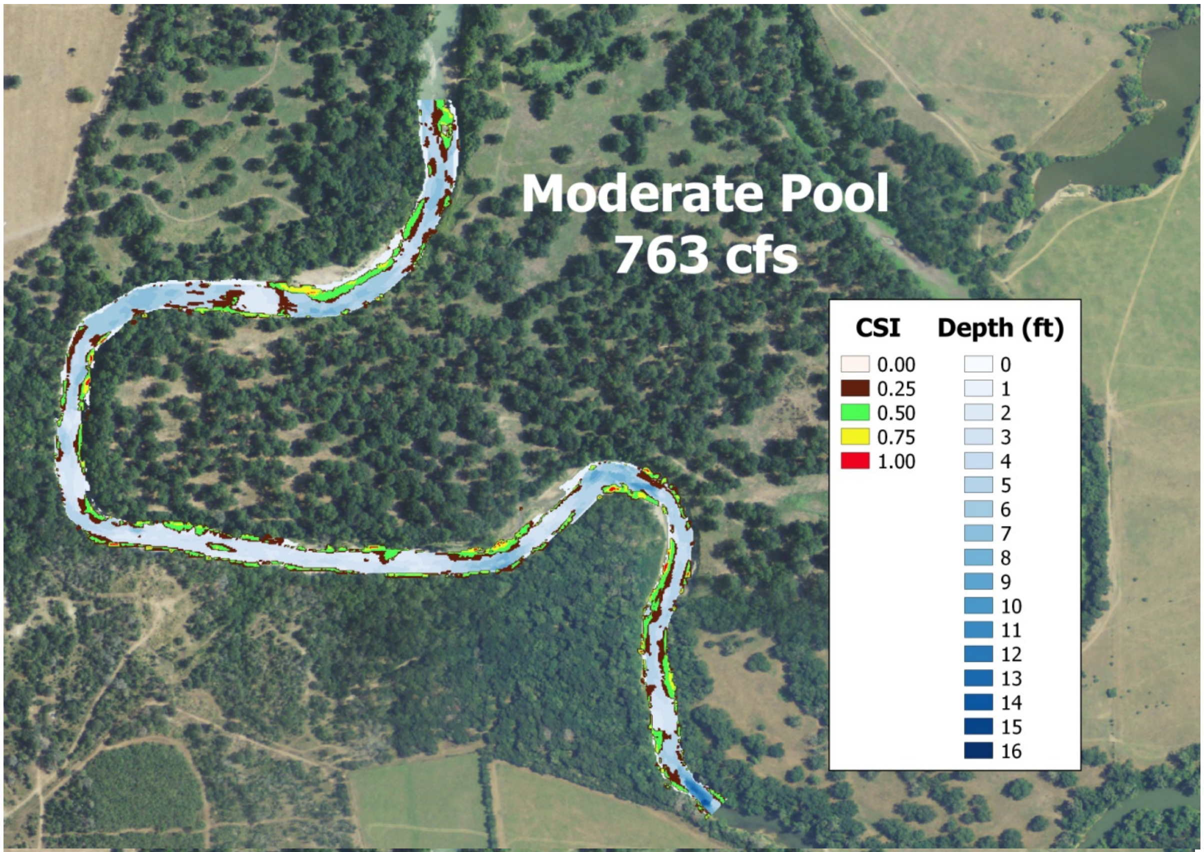
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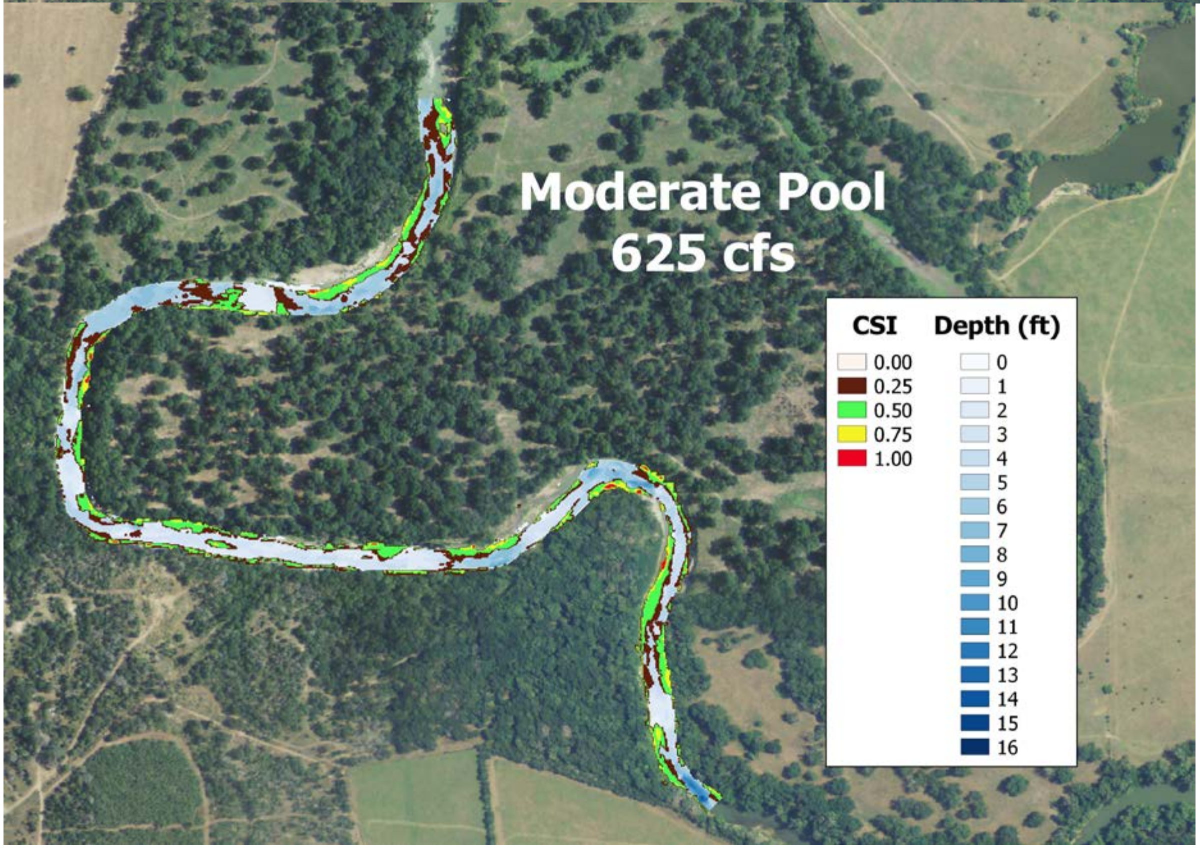
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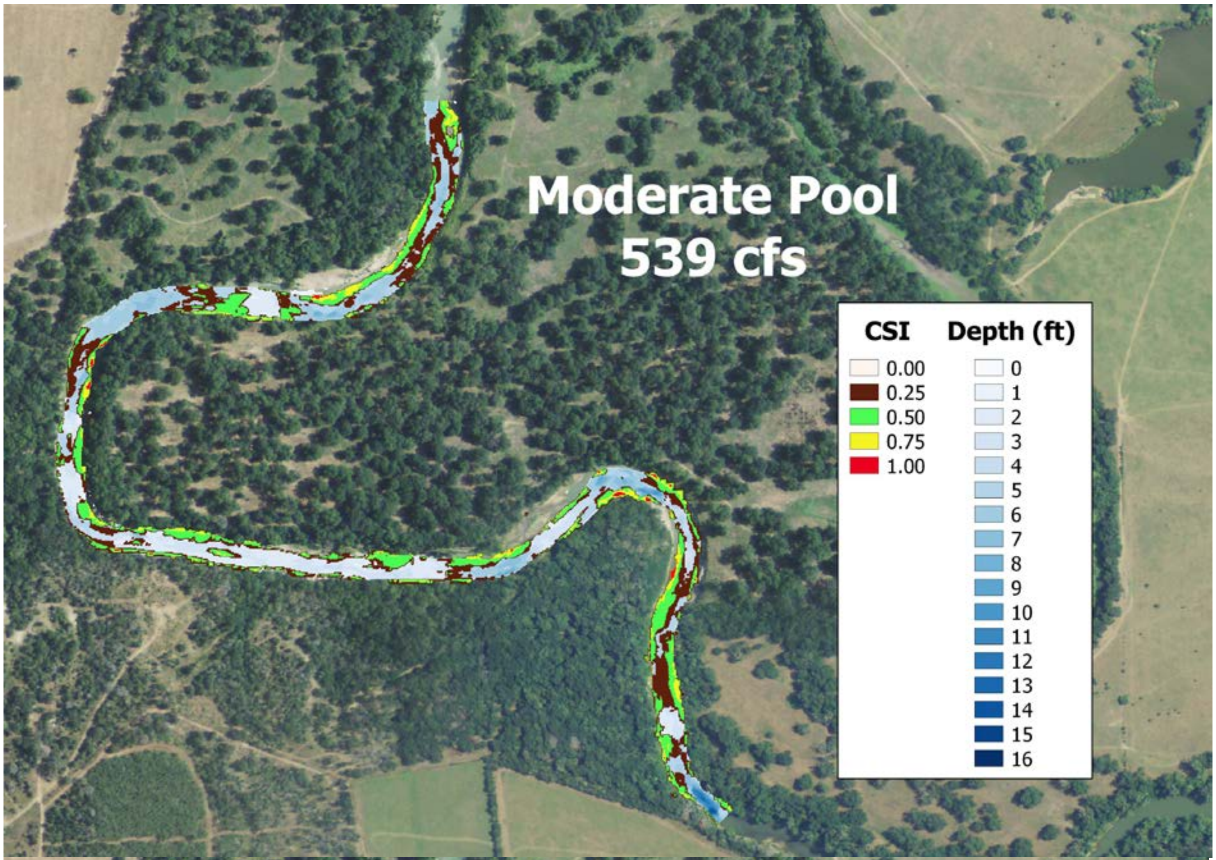
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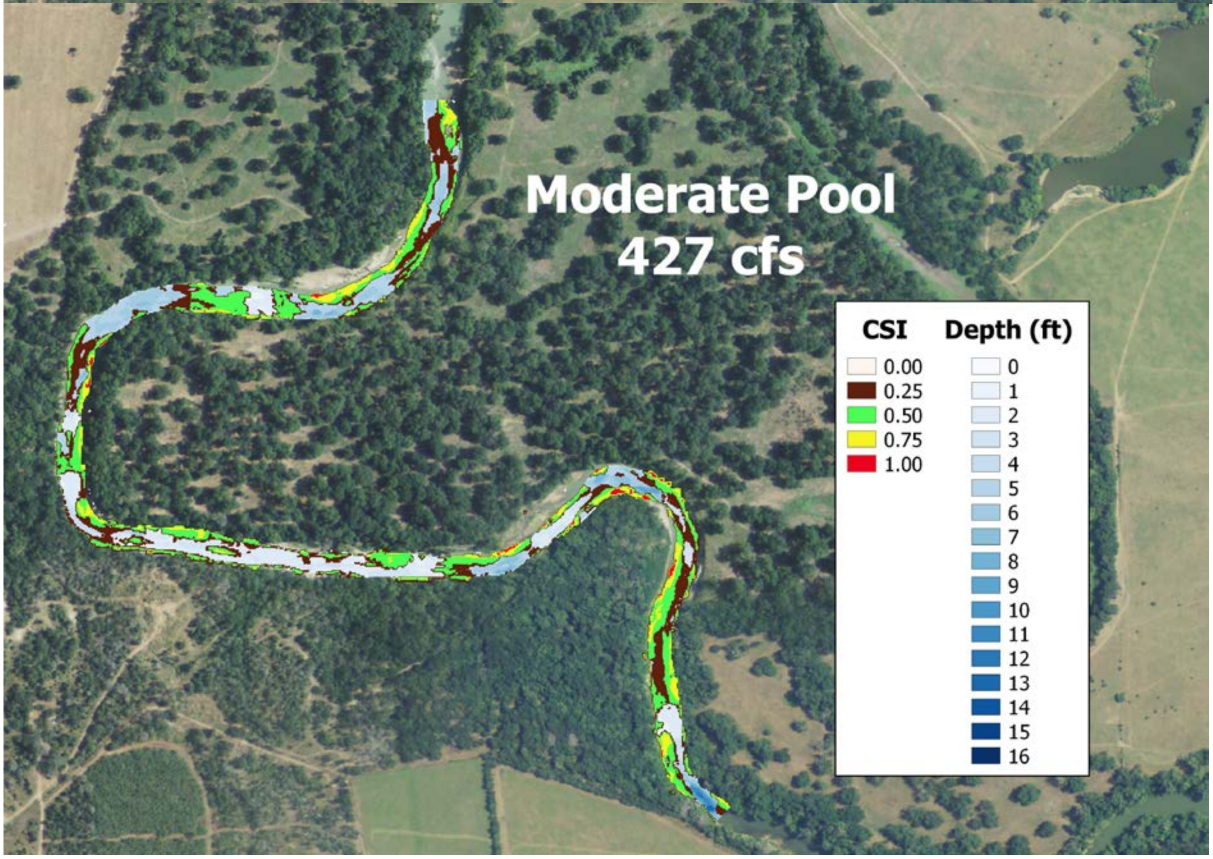
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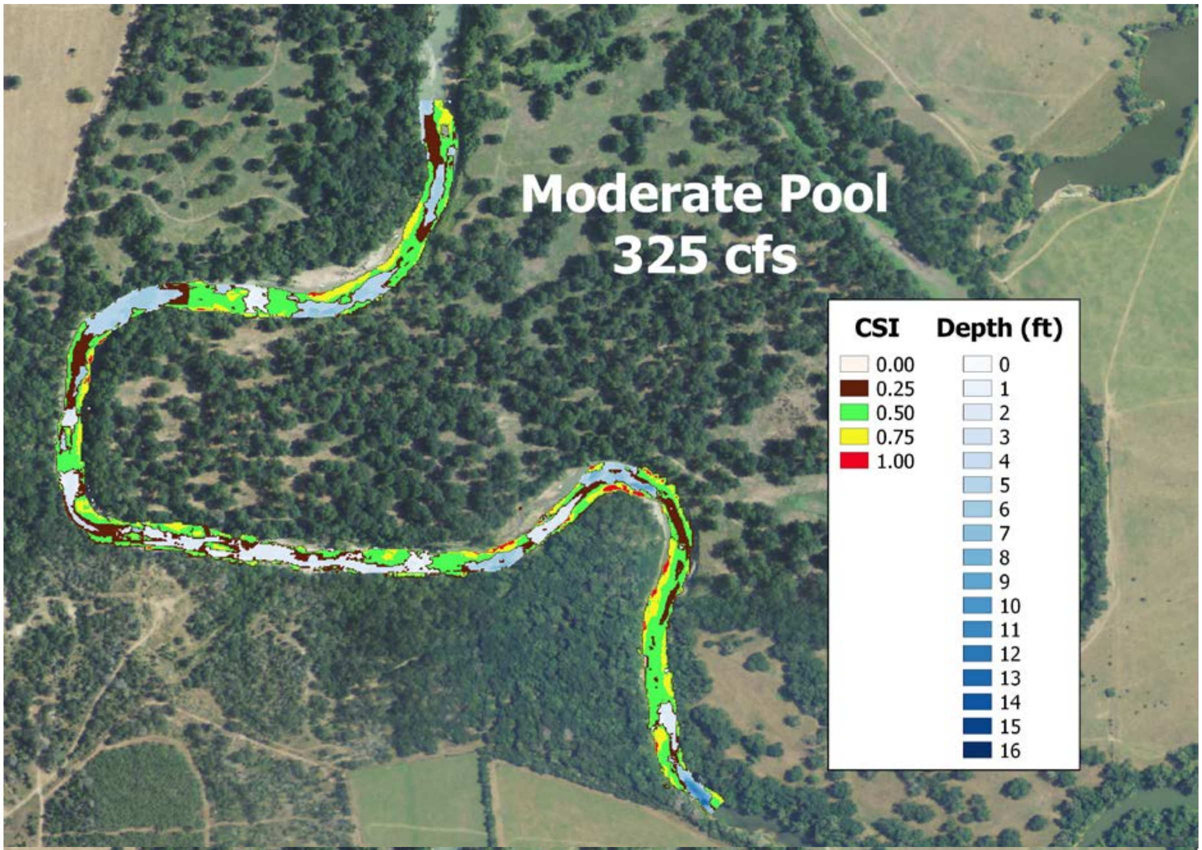
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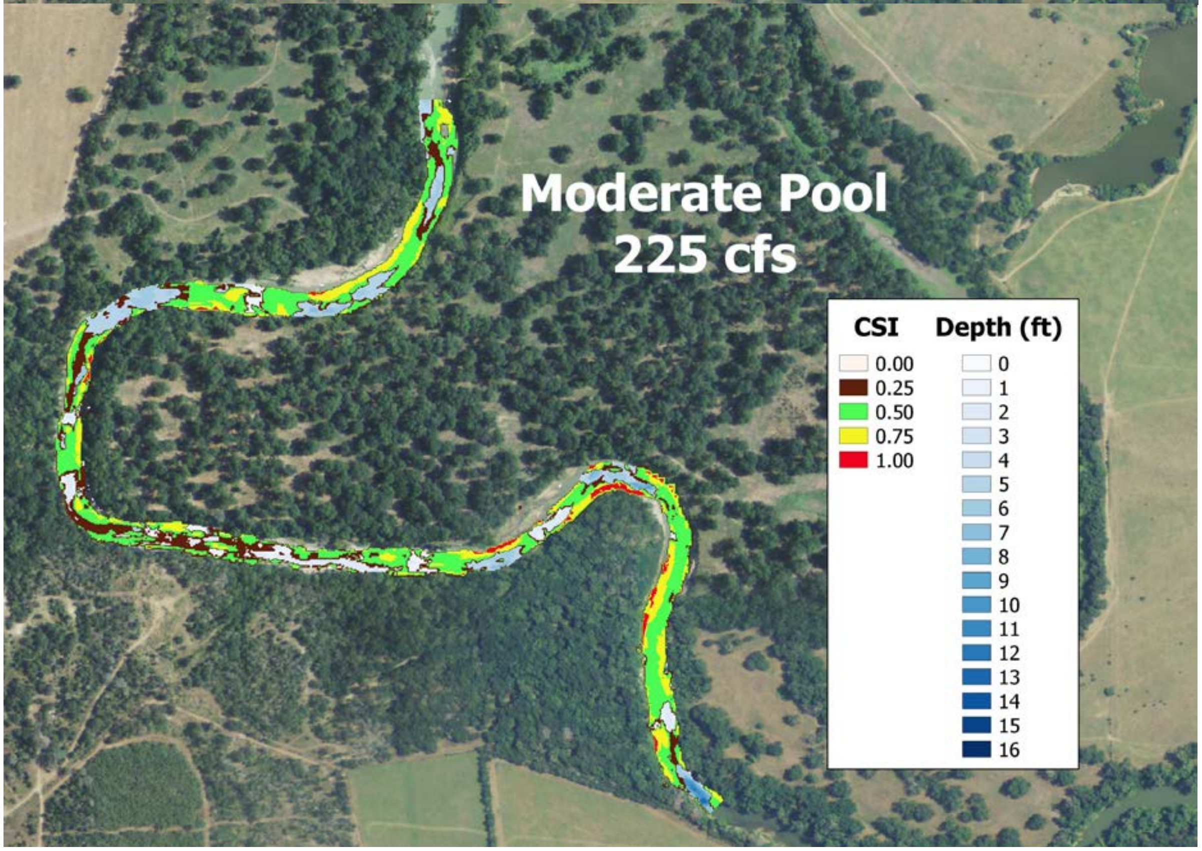
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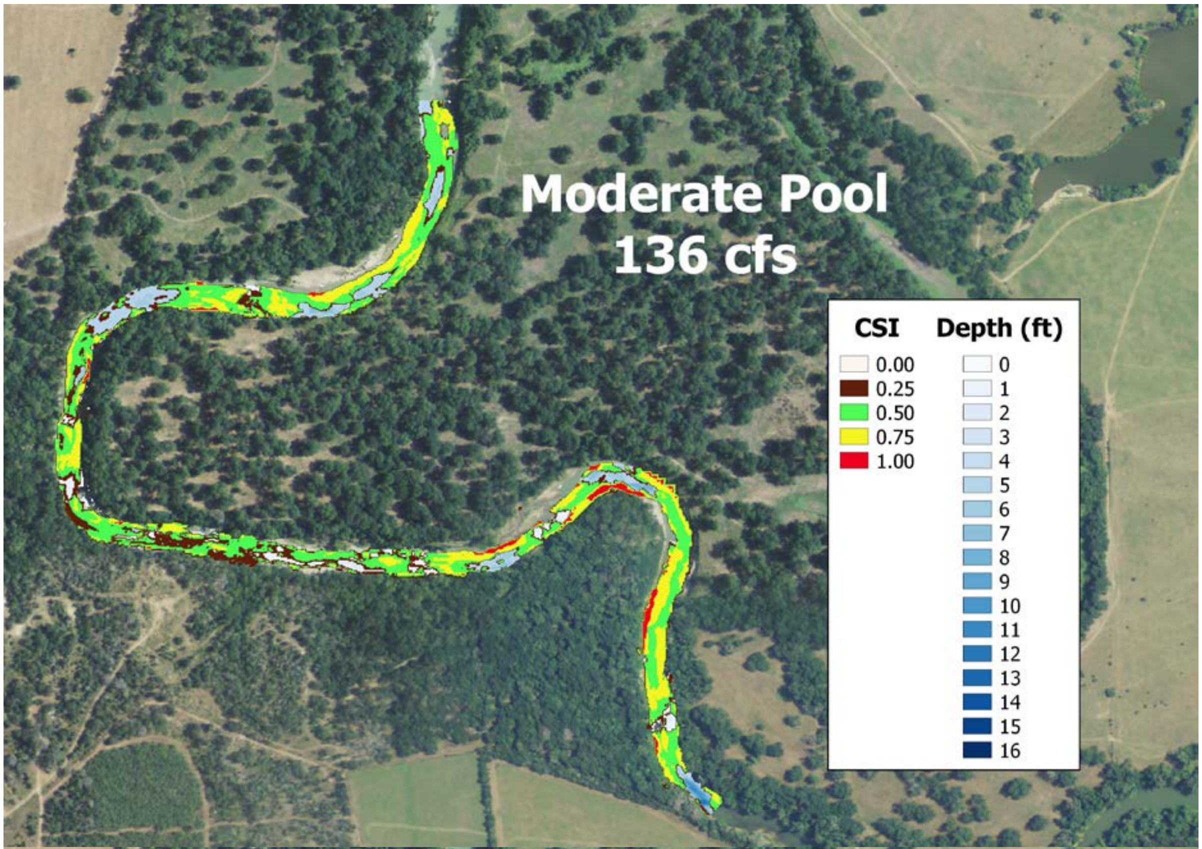
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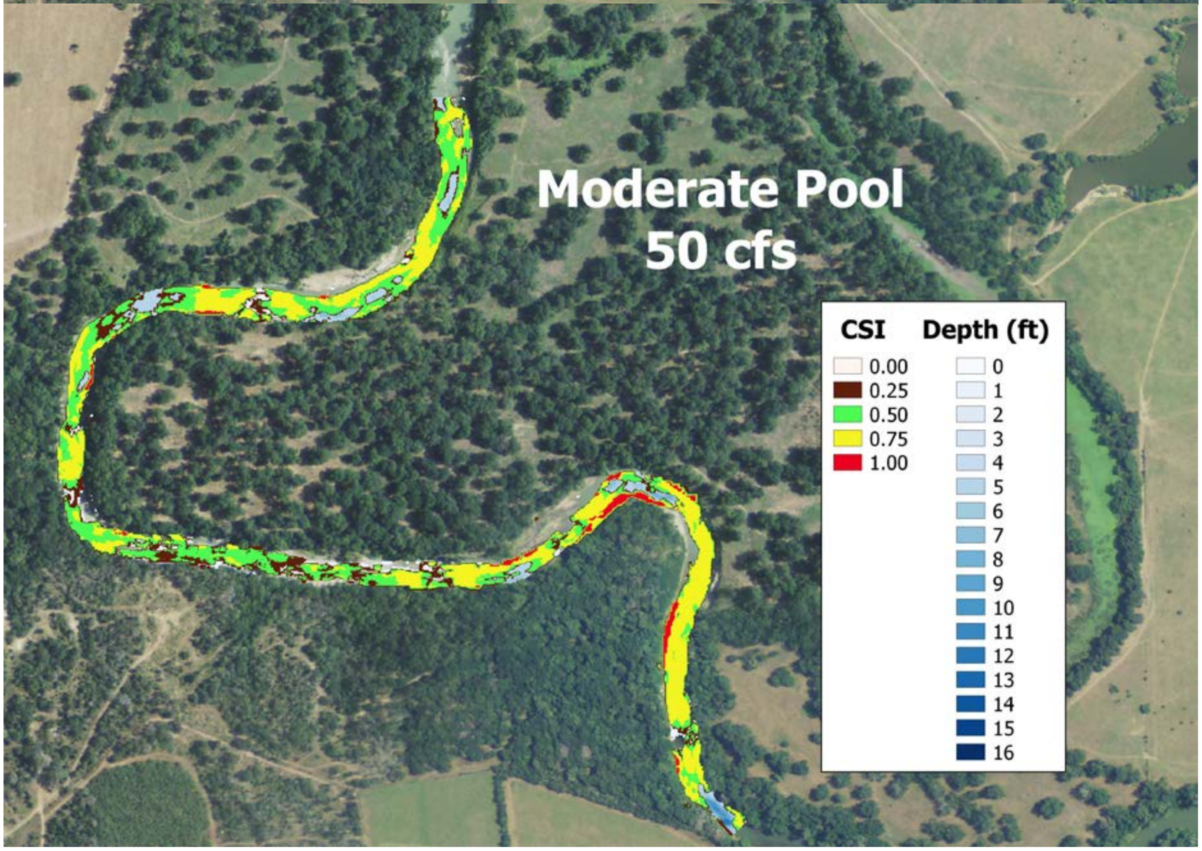
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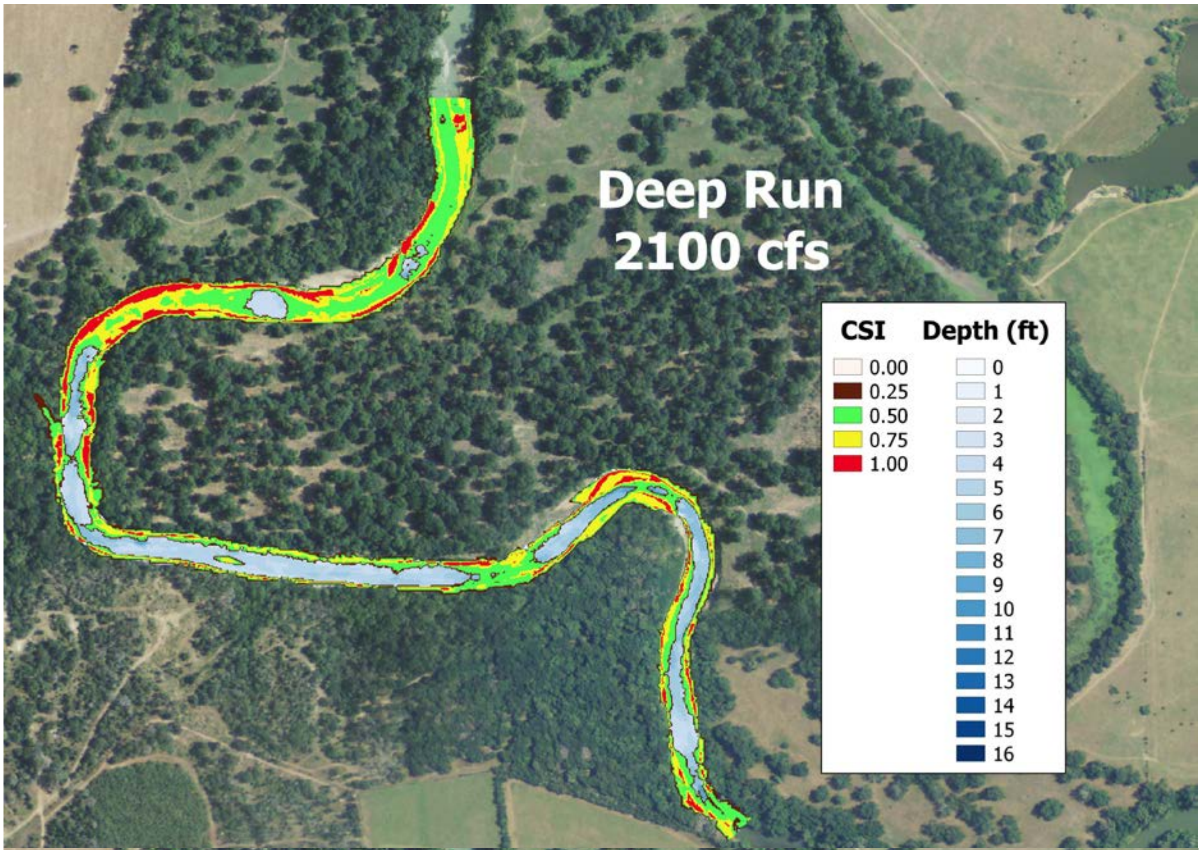
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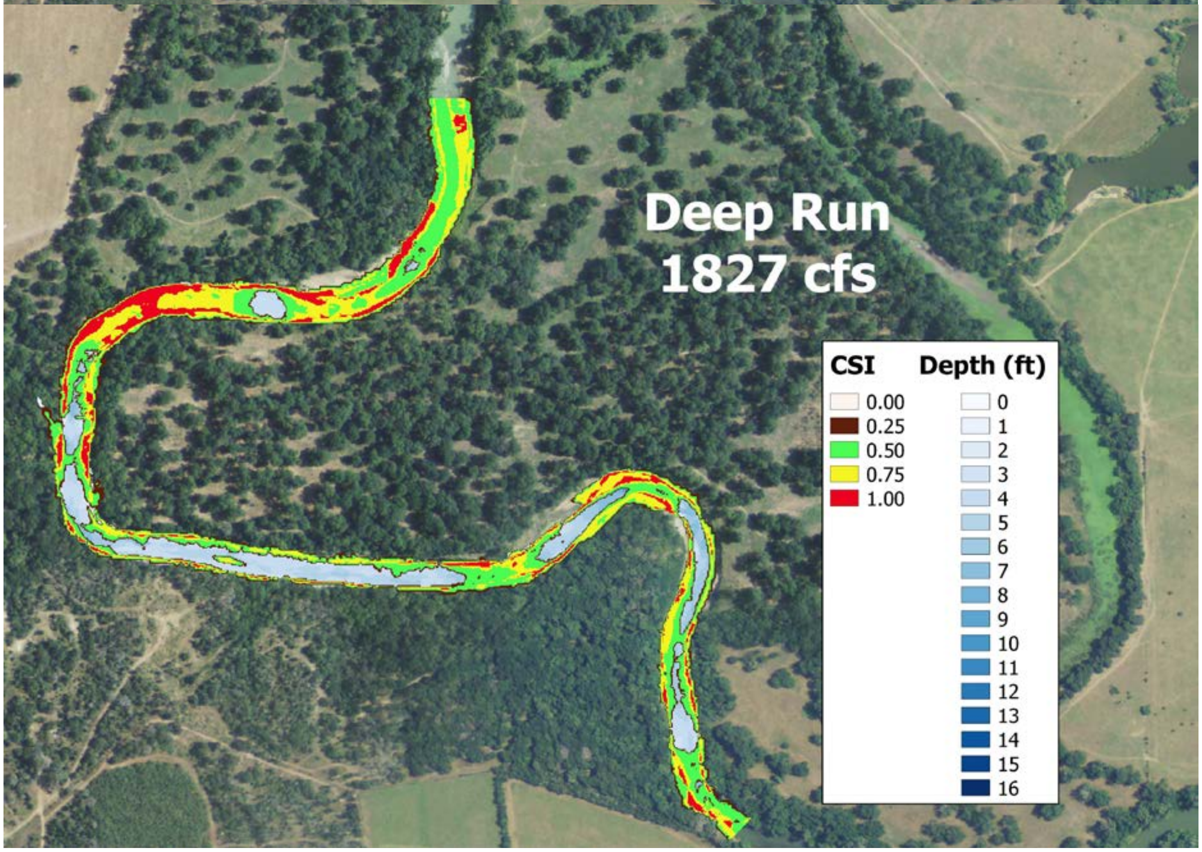
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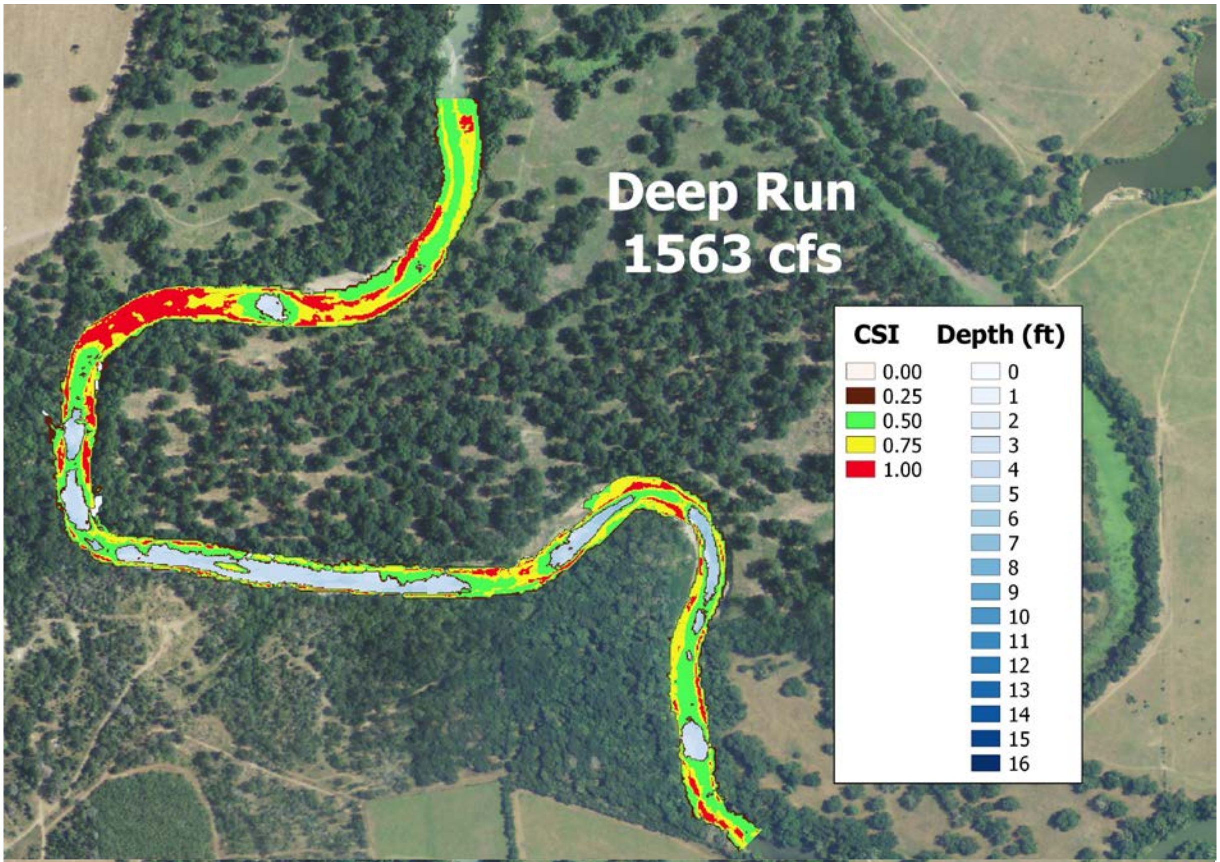
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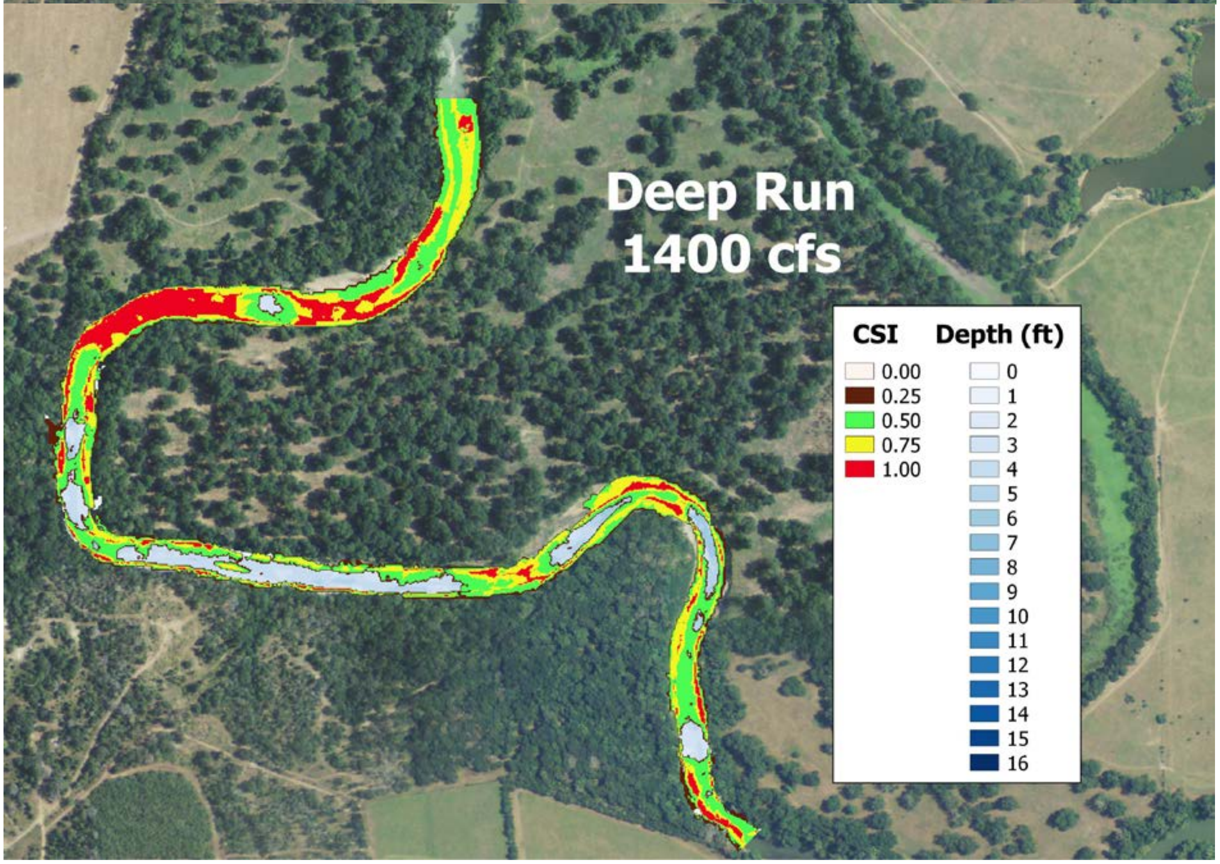
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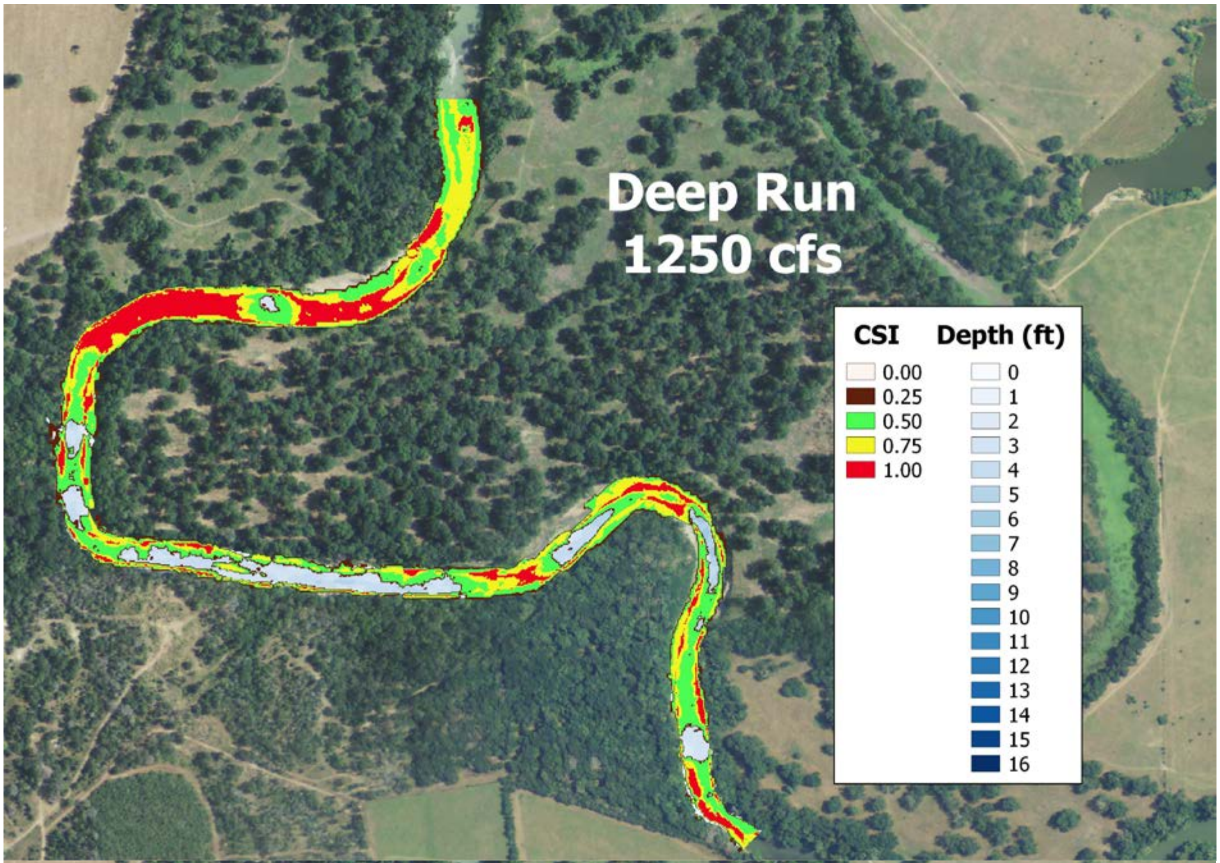
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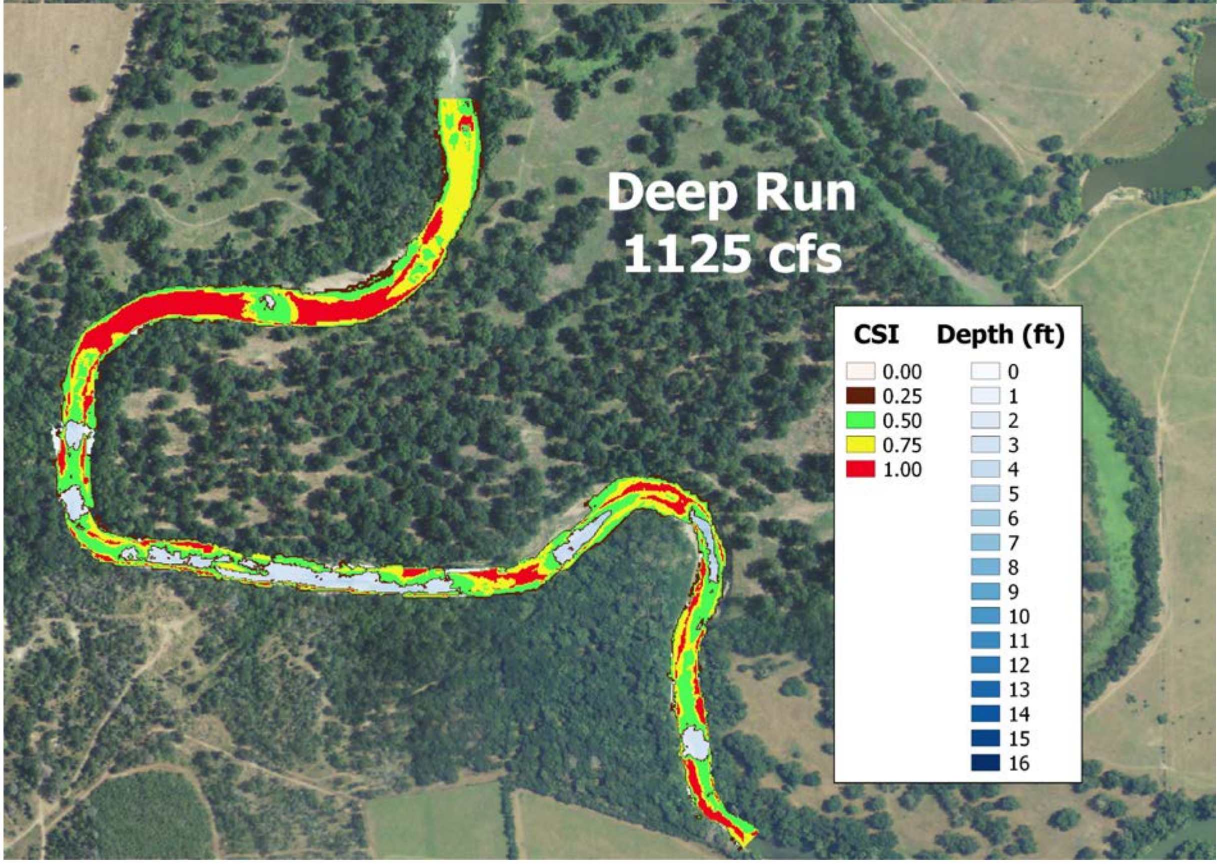
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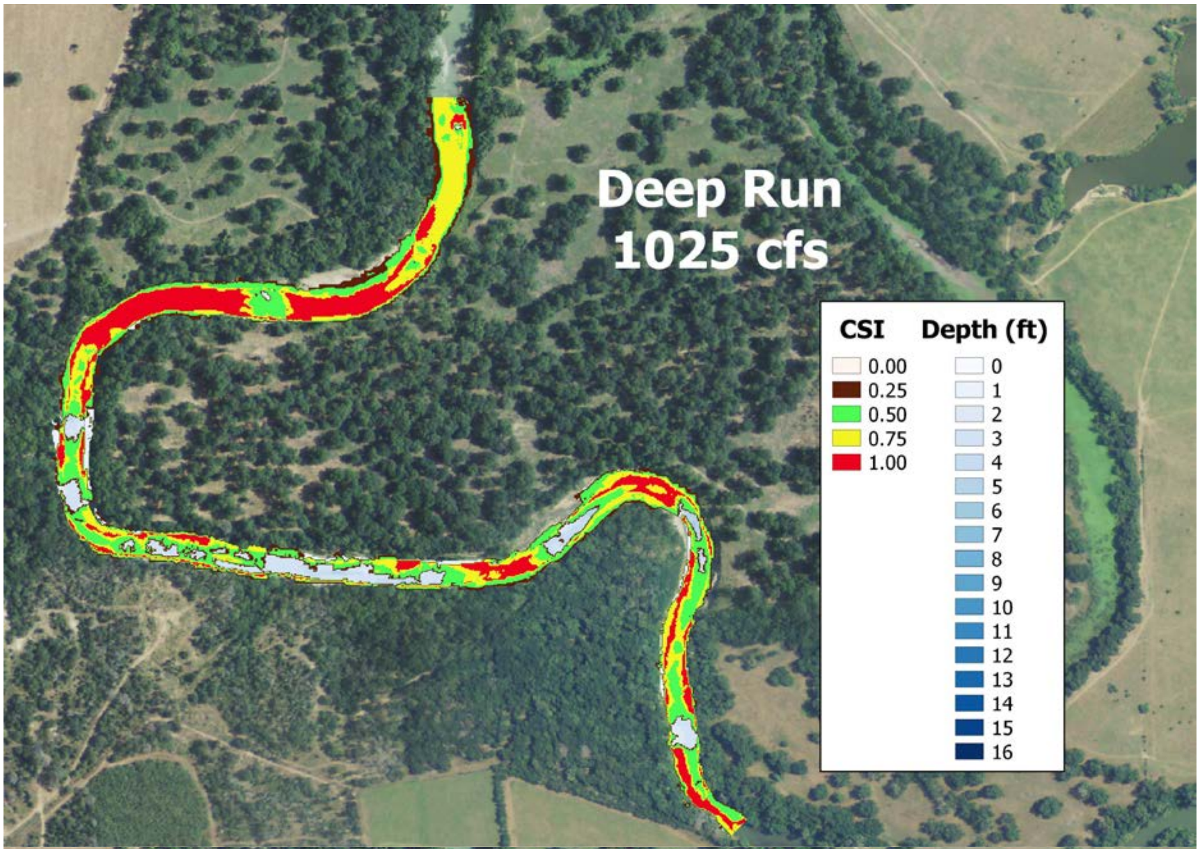
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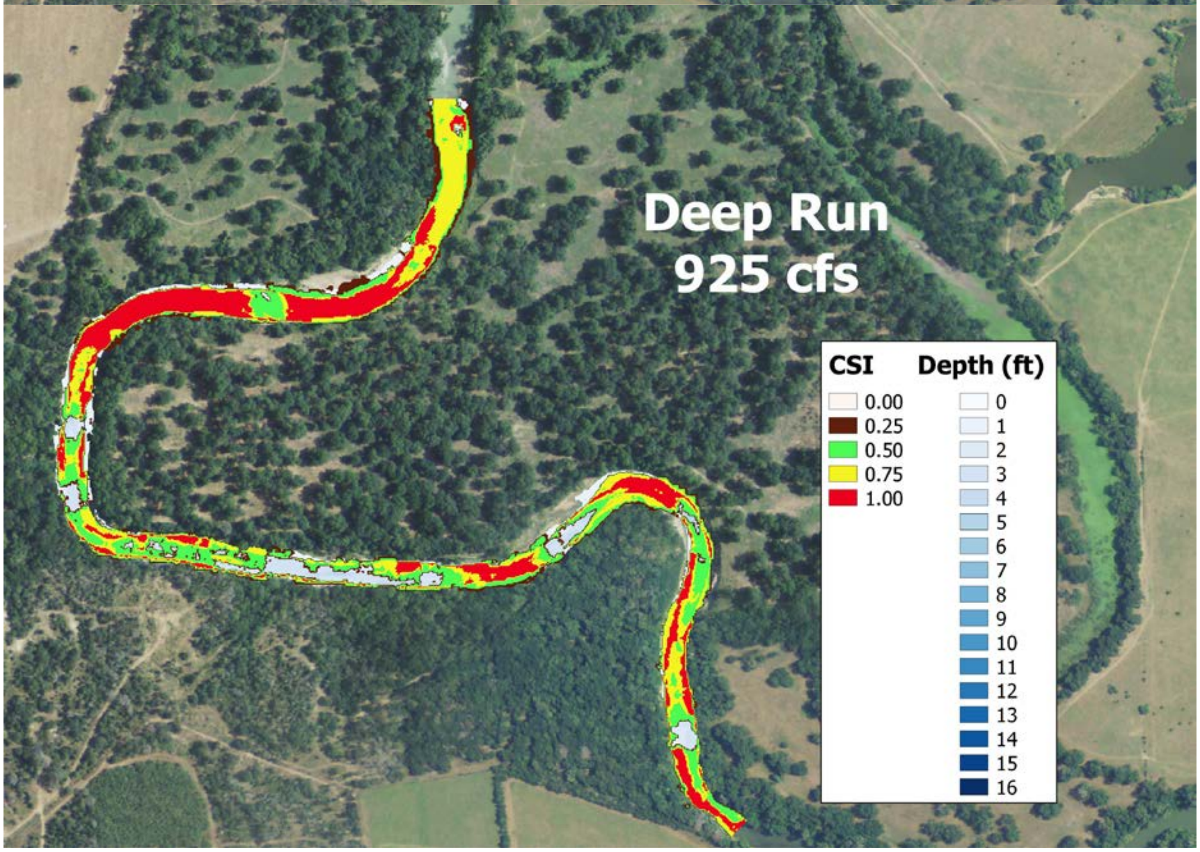
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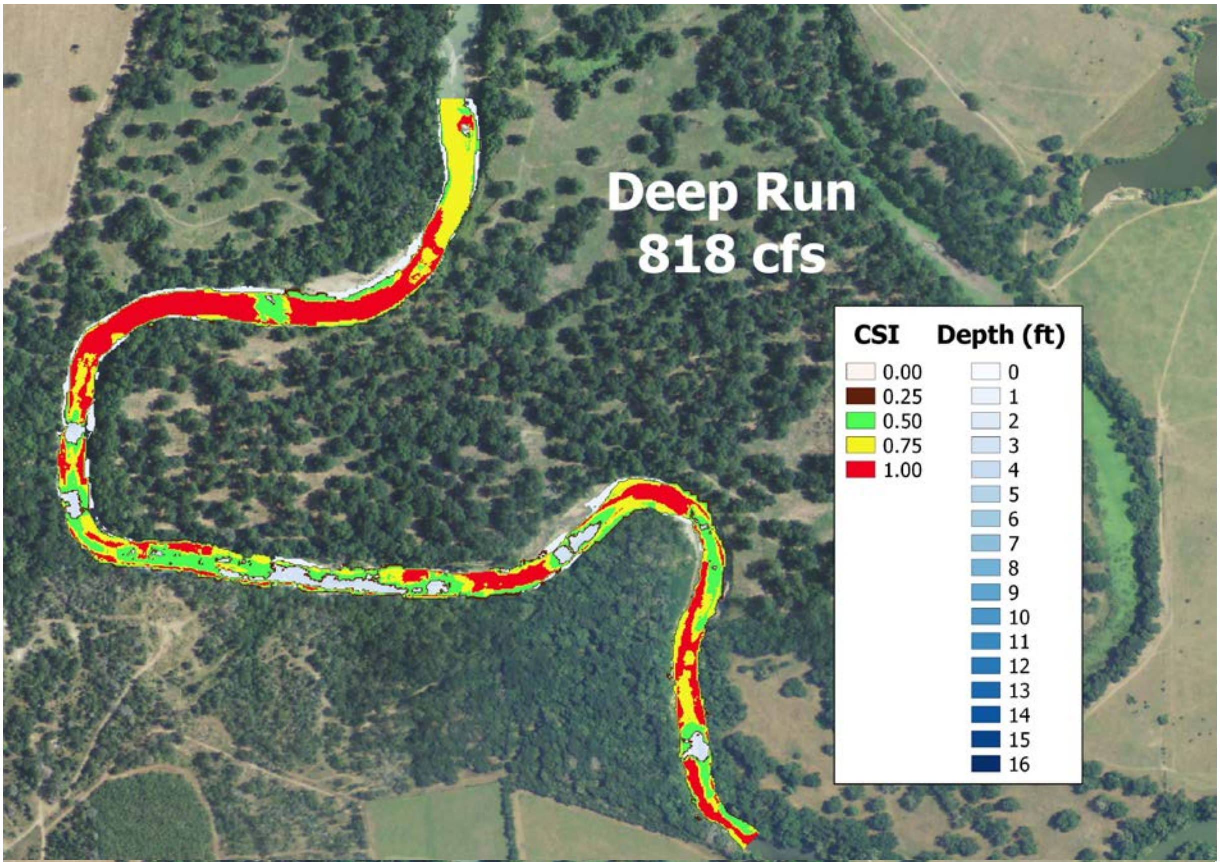
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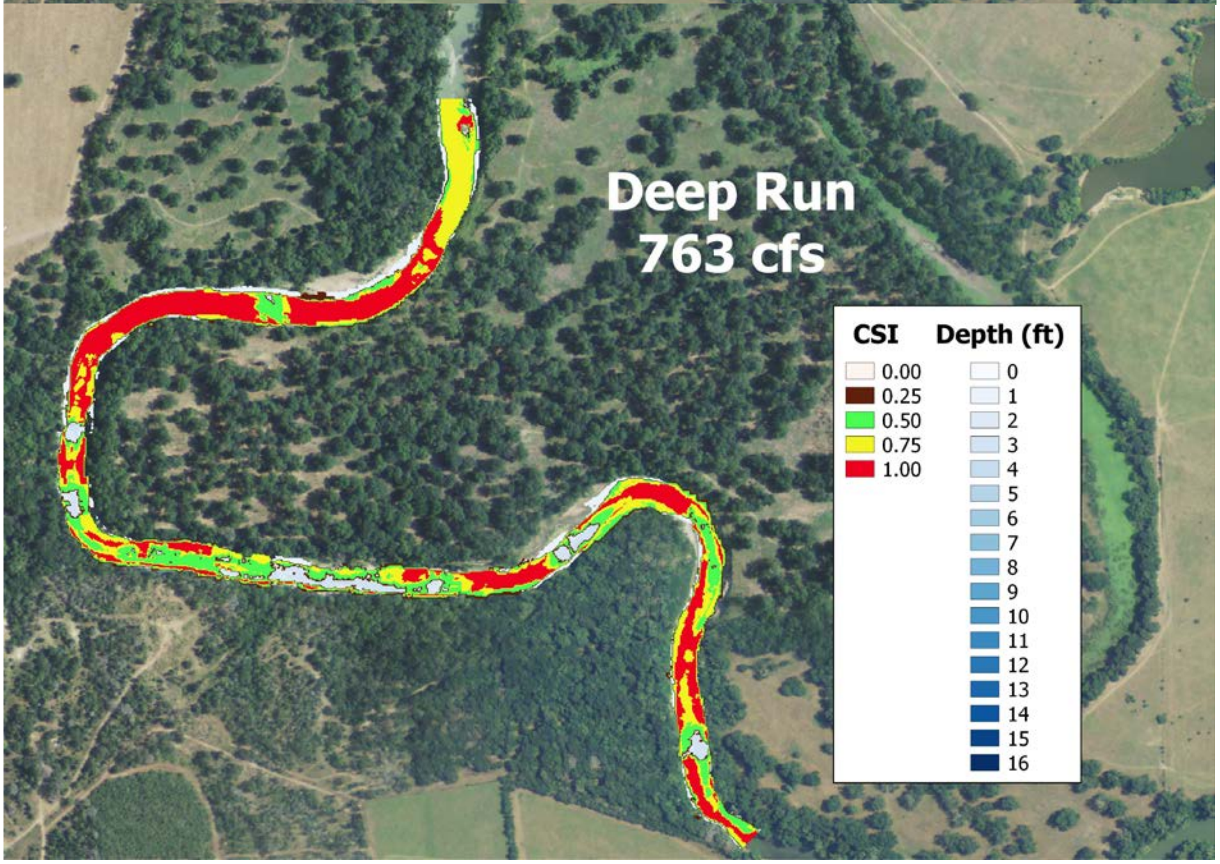
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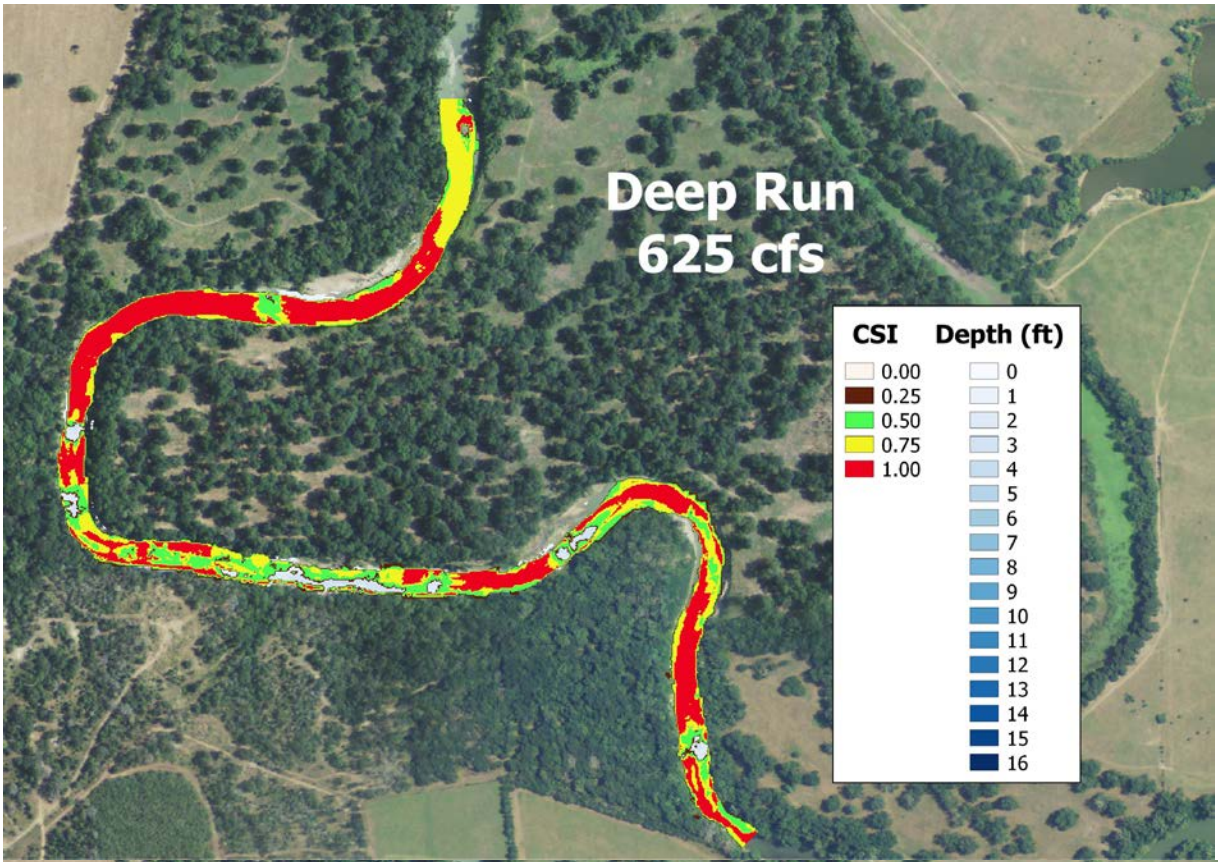
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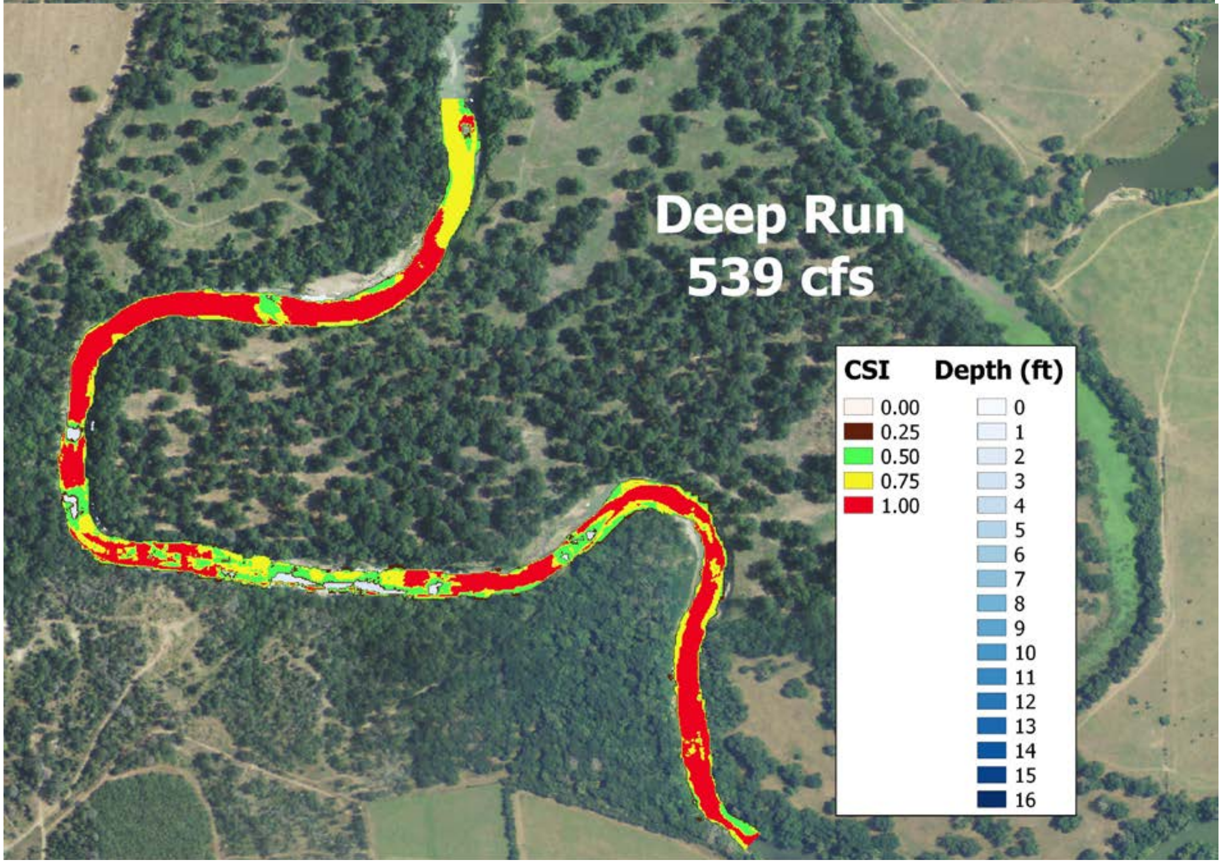
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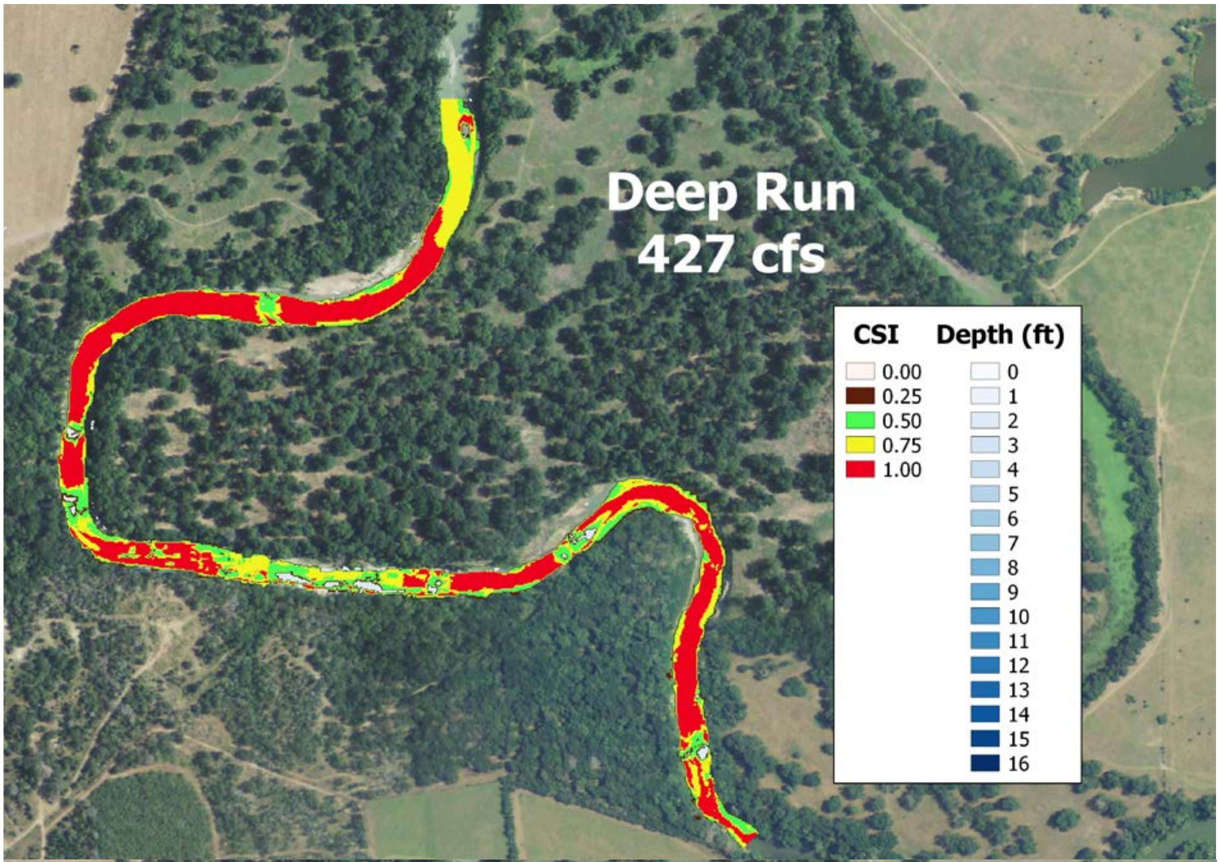
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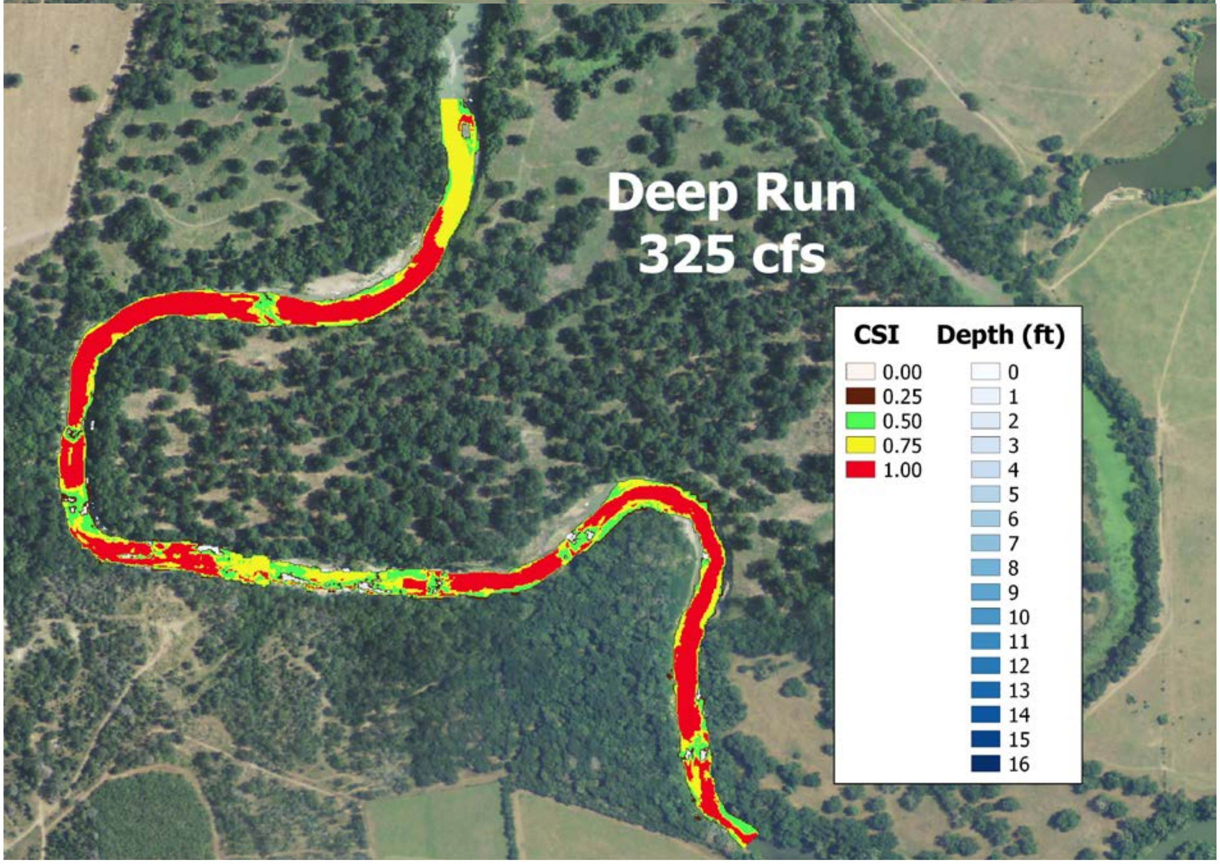
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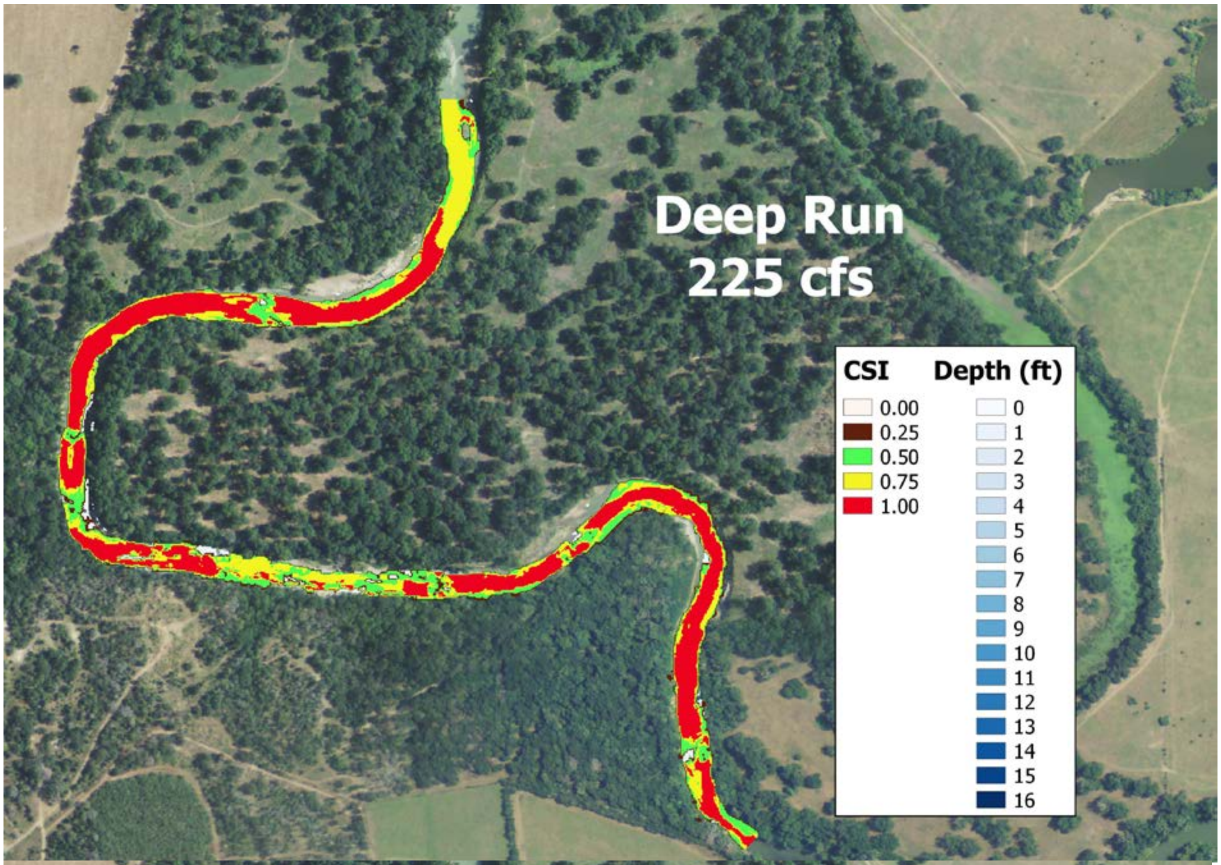
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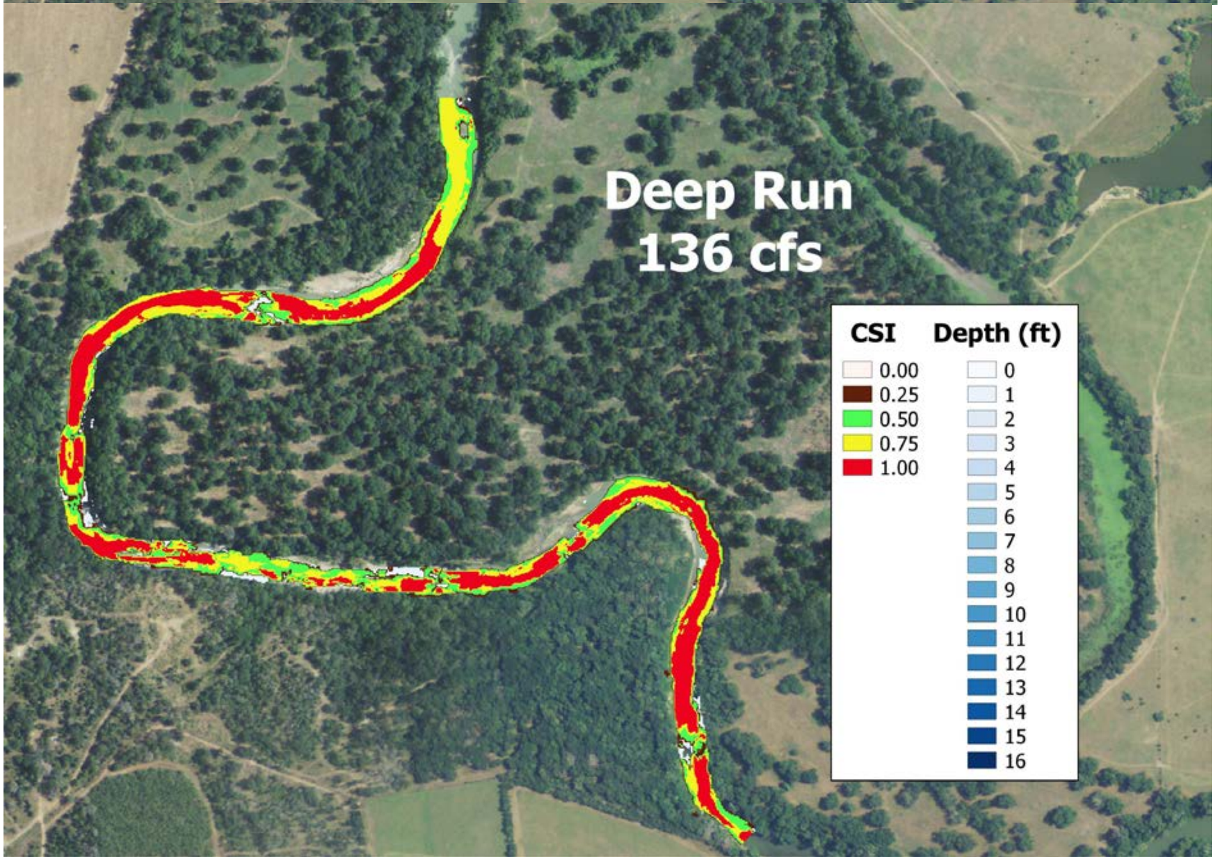
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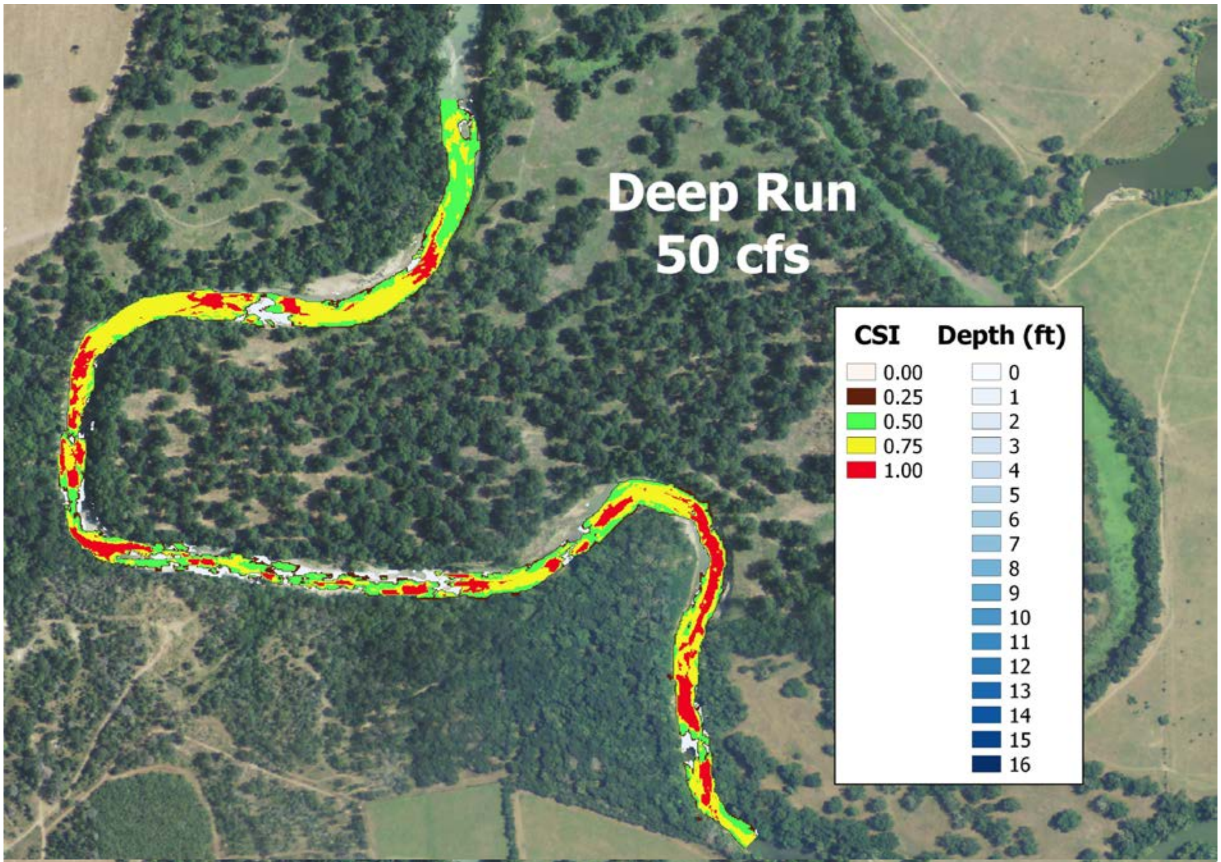
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0.75
1.00
Depth (ft)
0
1
2
3
4
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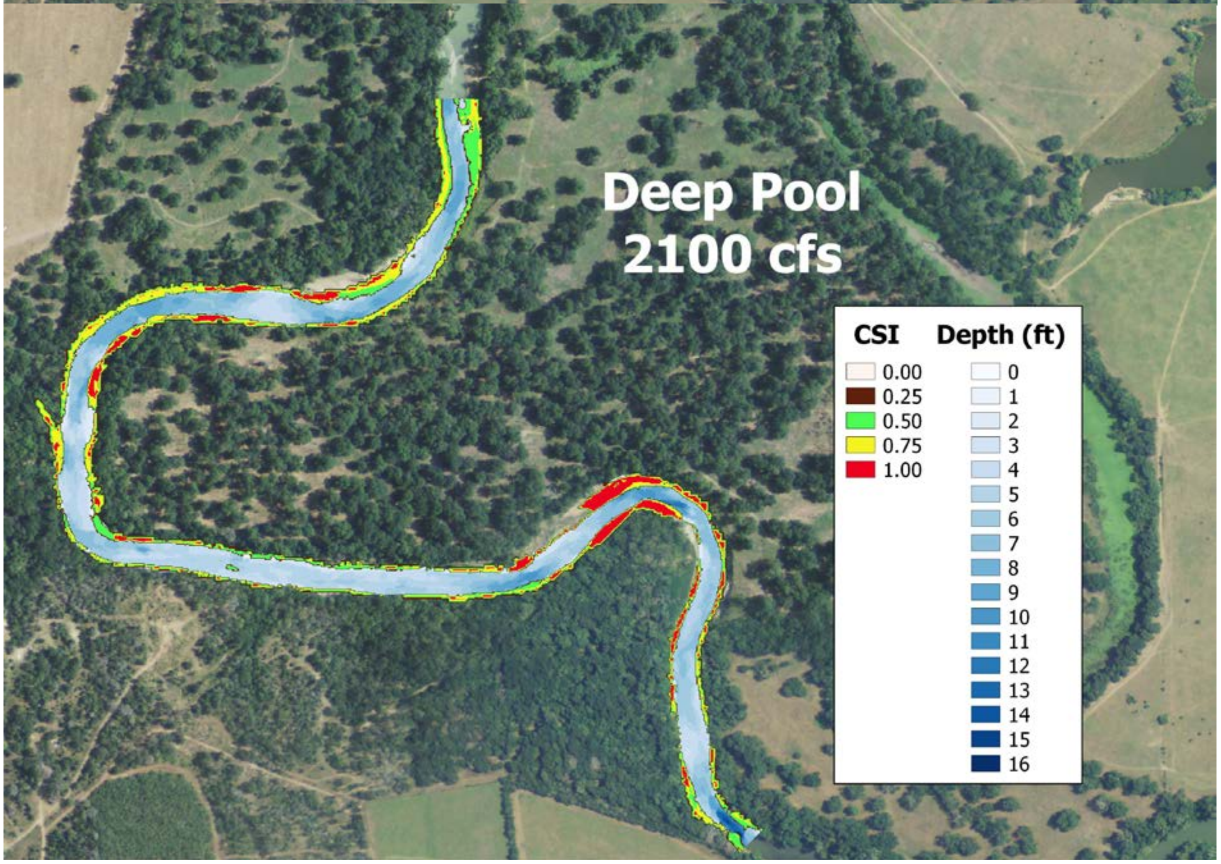
14
15
16


Deep Pool
2100 cfs
CSI
0.00
0.25
0.50
0.75
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Depth (ft)
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1
2
3
4
5
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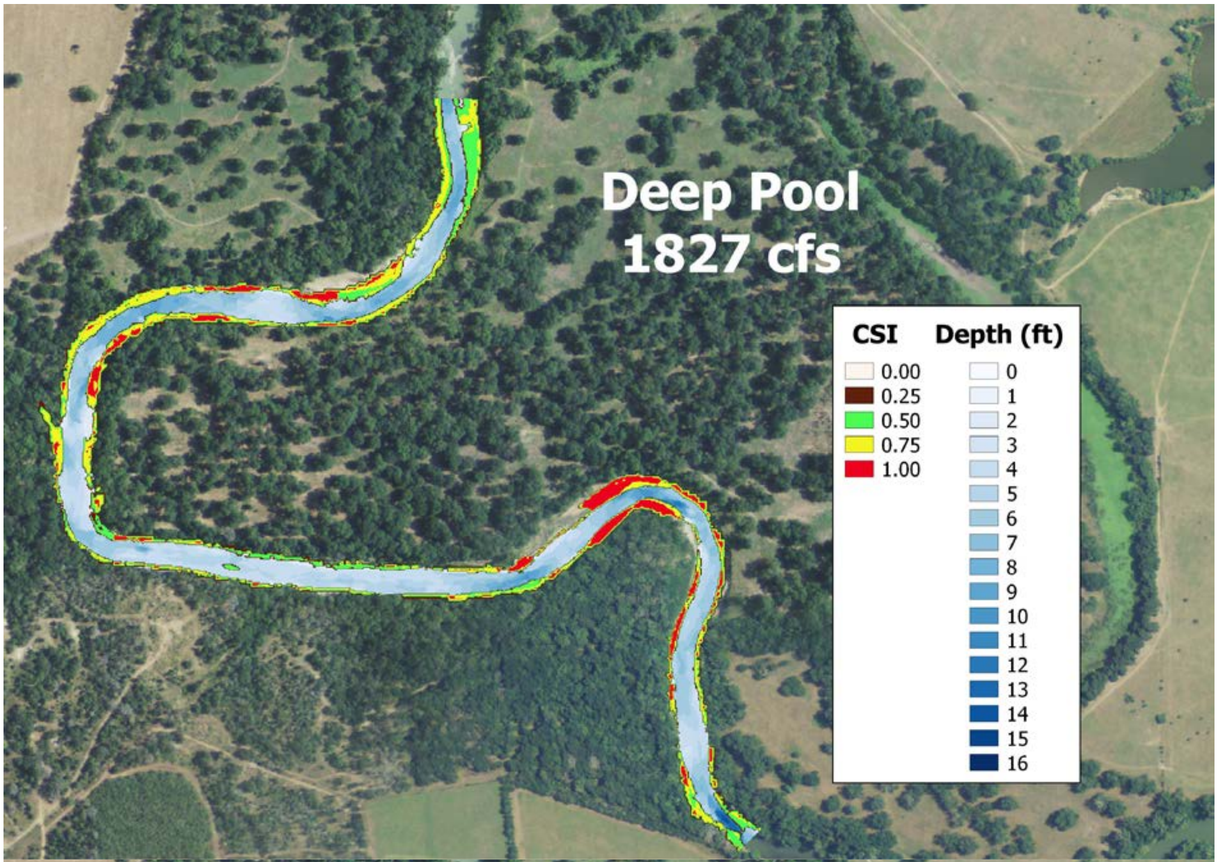
13
14
15
16


Deep Pool
1827 cfs
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0.00
0.25
0.50
0.75
1.00
Depth (ft)
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1
2
3
4
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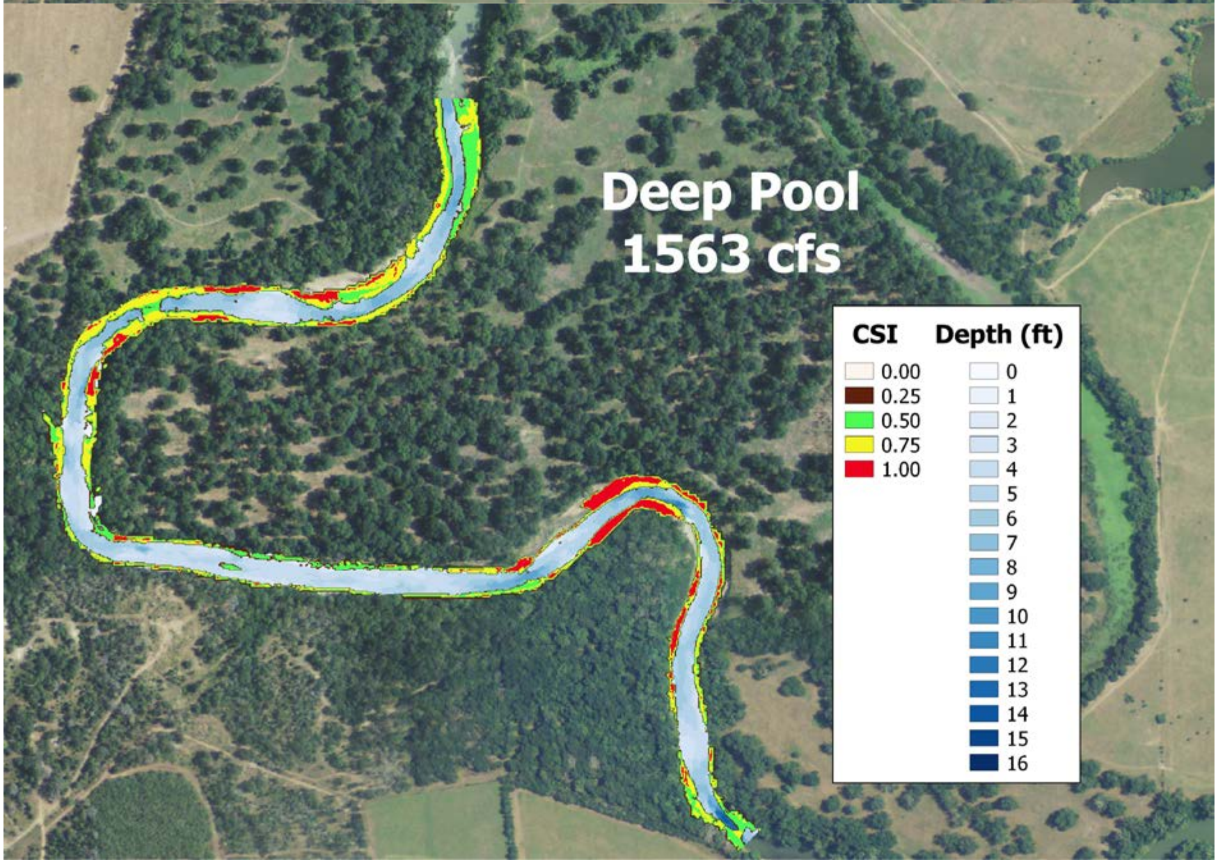
14
15
16


Deep Pool
1563 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
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1
2
3
4
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11
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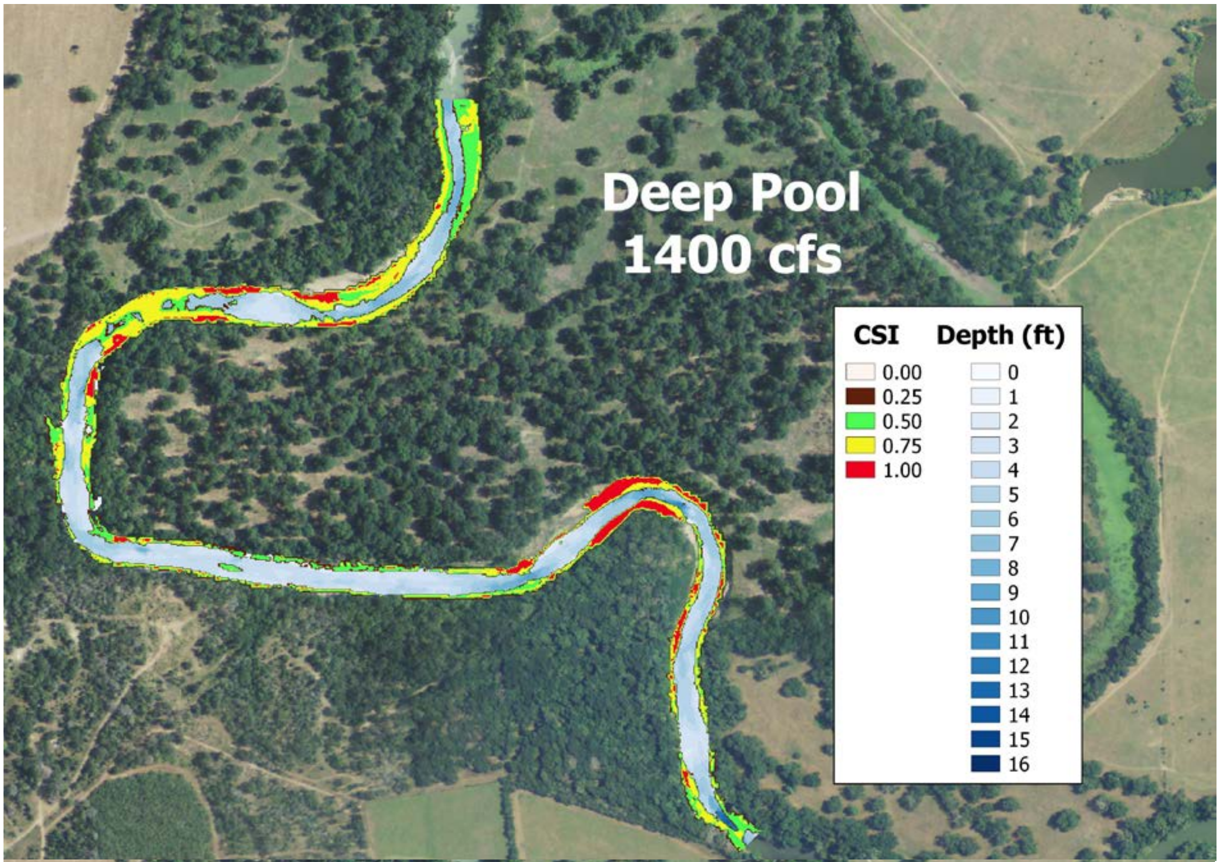
13
14
15
16


Deep Pool
1400 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
0
1
2
3
4
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6
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11
12
13
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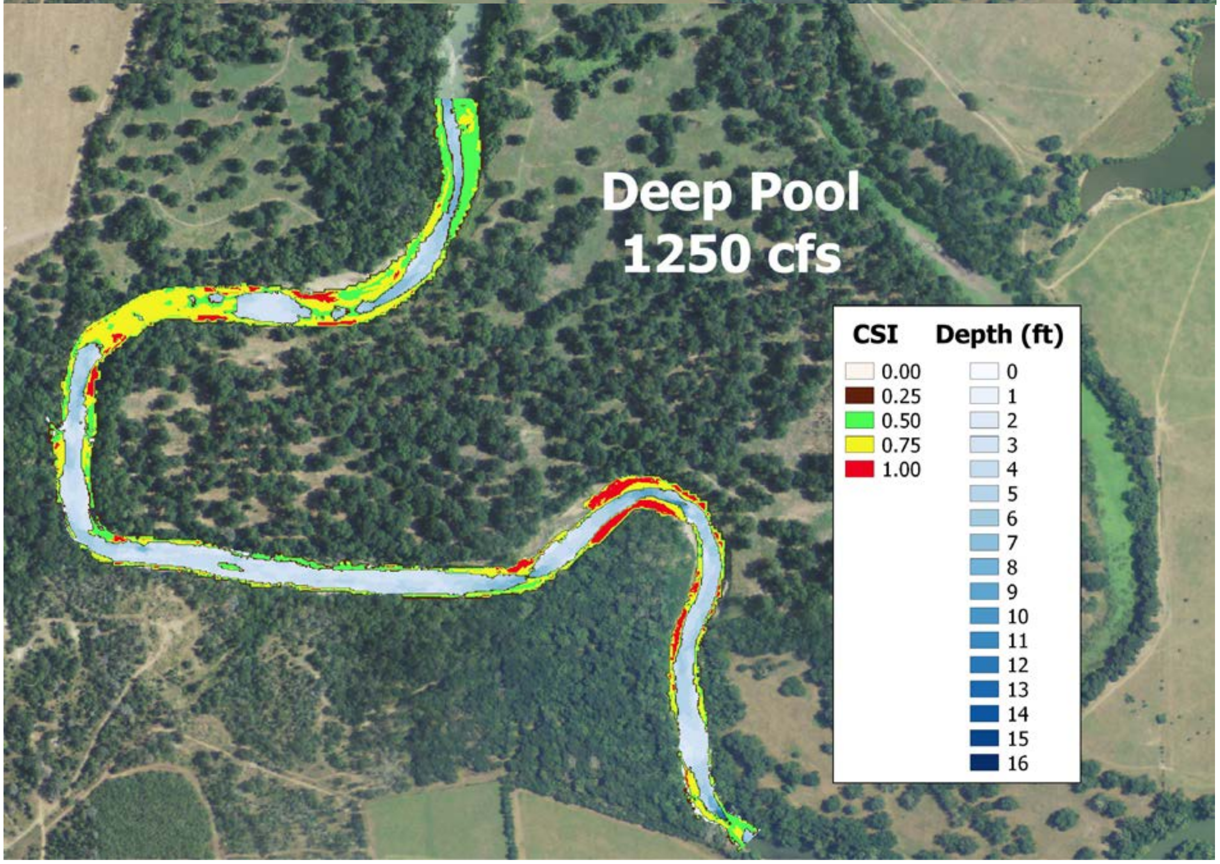
15
16


Deep Pool
1250 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
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1
2
3
4
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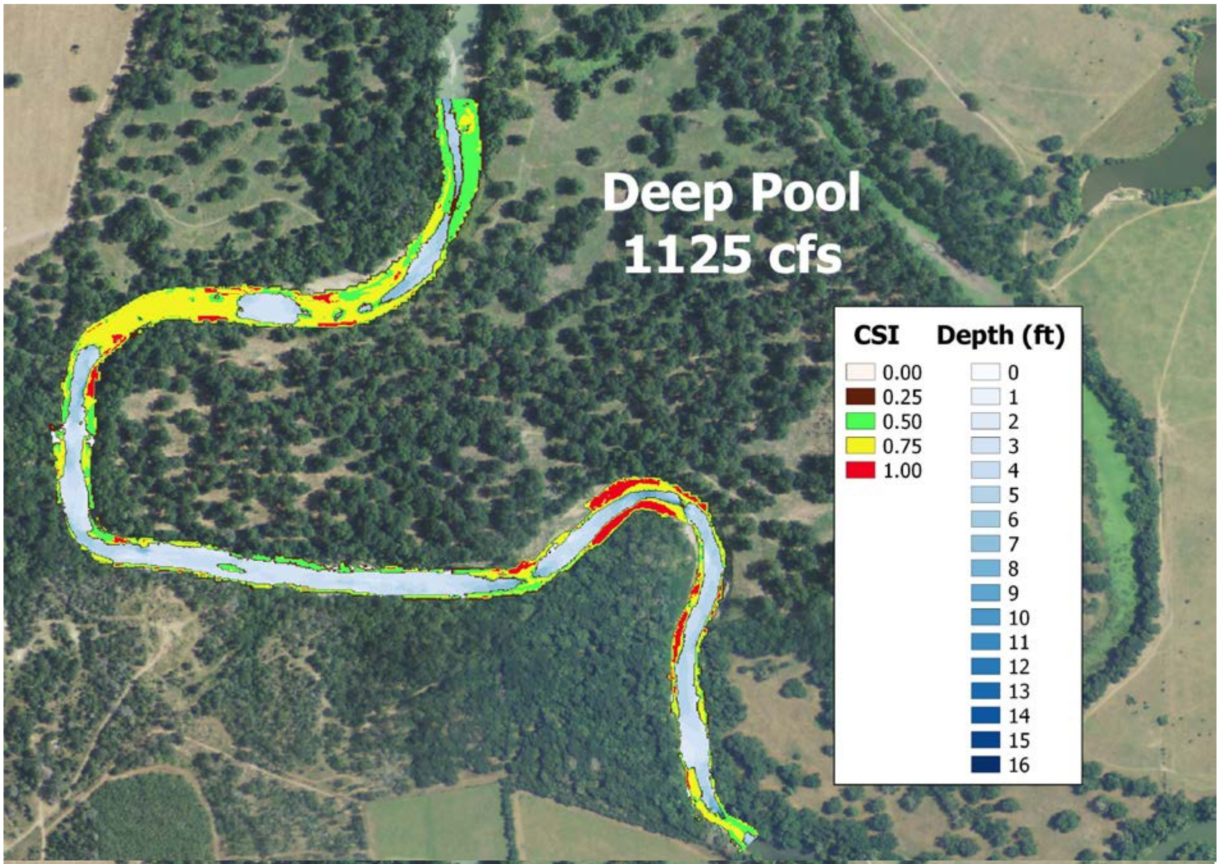
16


Deep Pool
1125 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
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1
2
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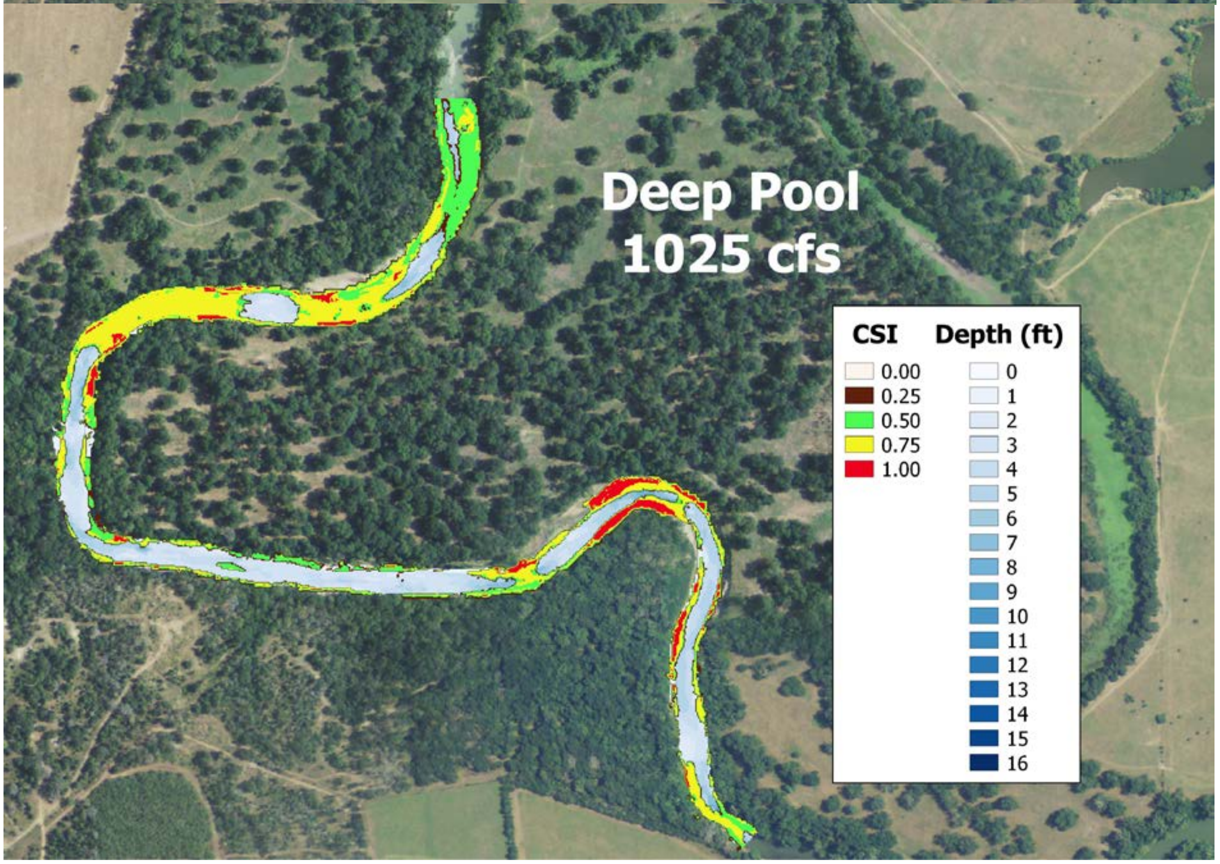
16


Deep Pool
1025 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
0
1
2
3
4
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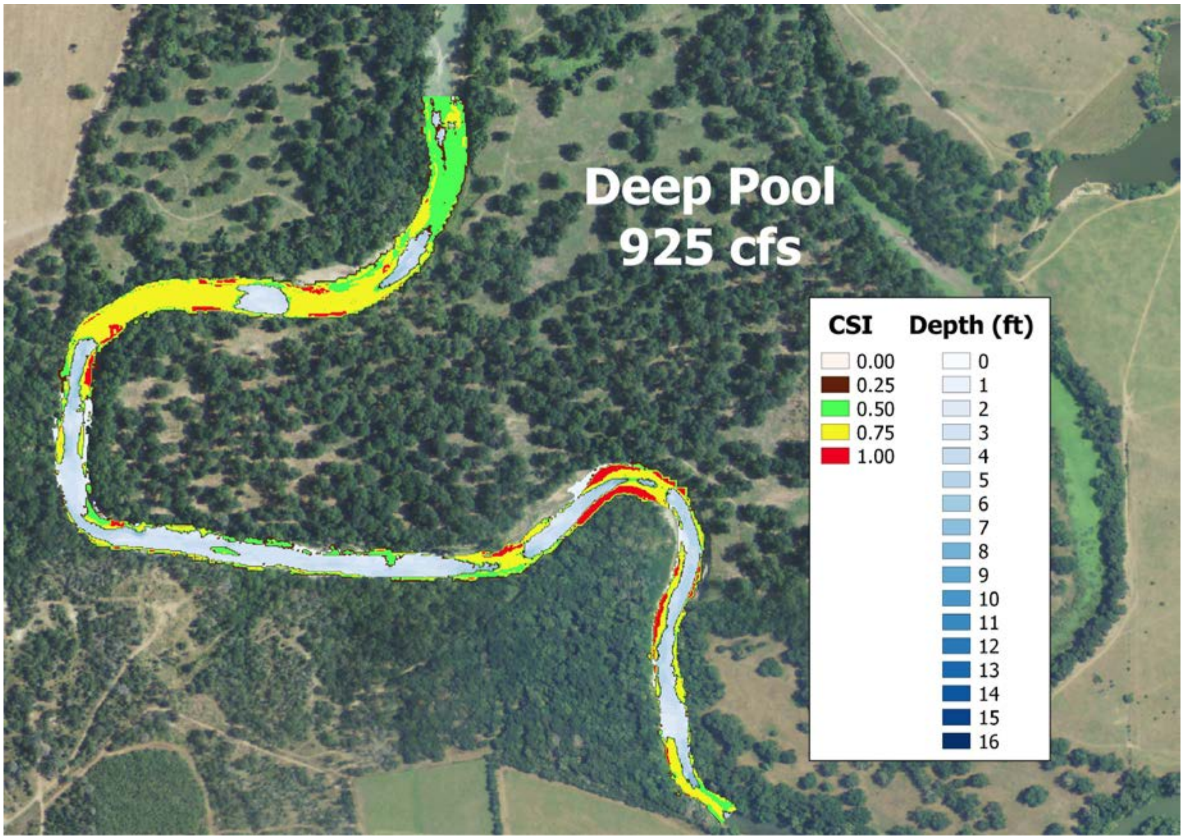
16


Deep Pool
925 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
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1
2
3
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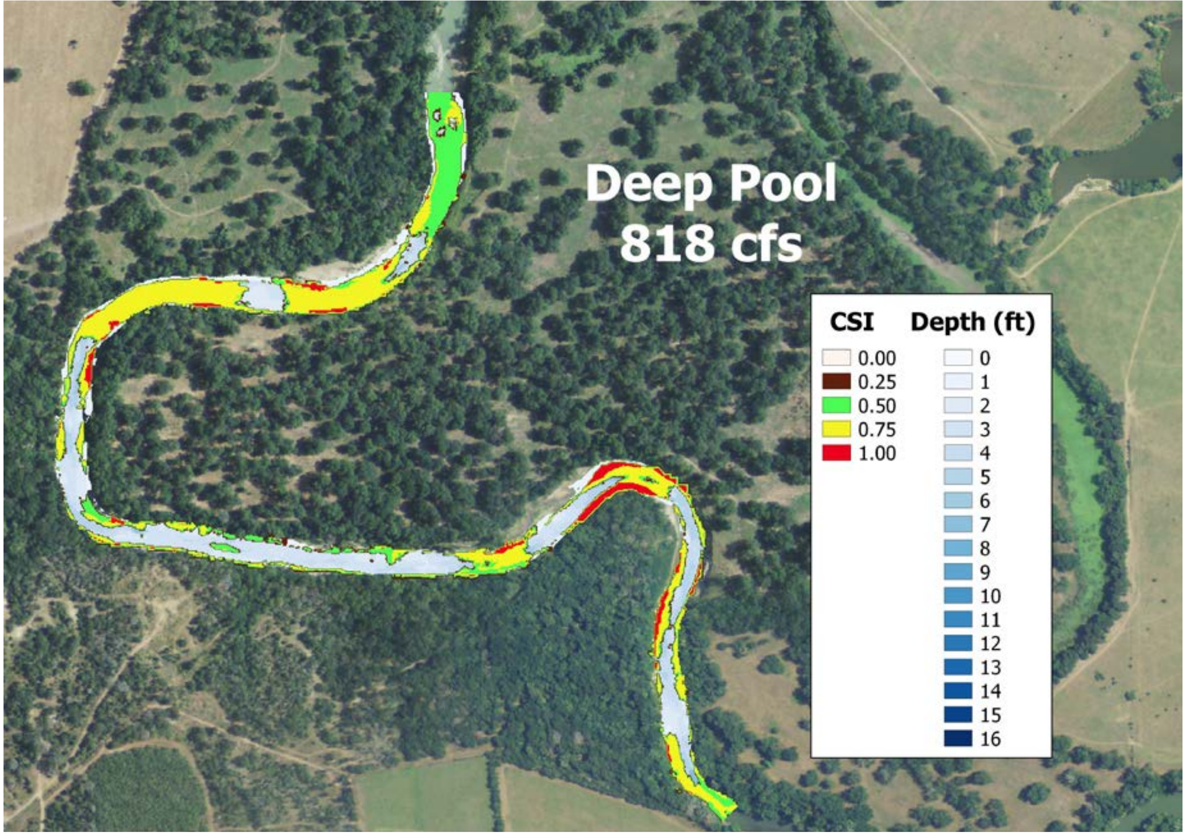
Deep Pool
818 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
0
1
2
3
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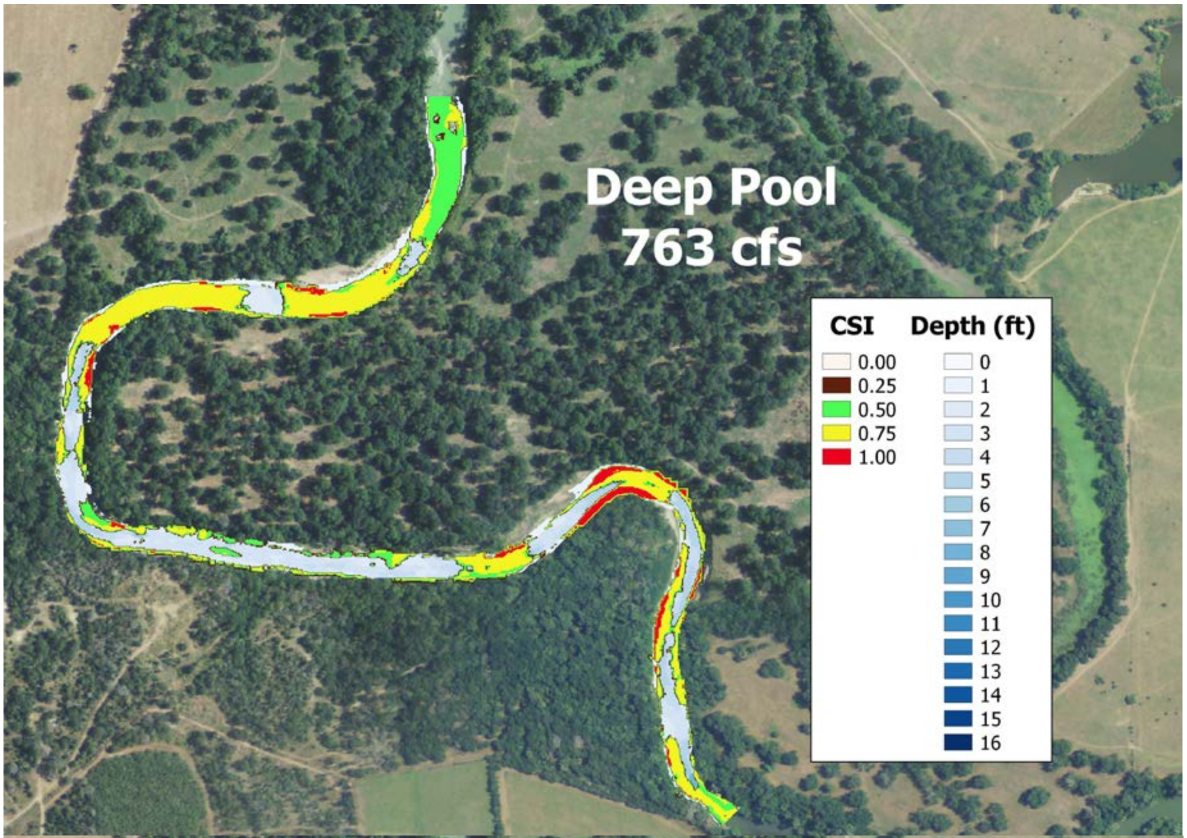
Deep Pool
763 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
0
1
2
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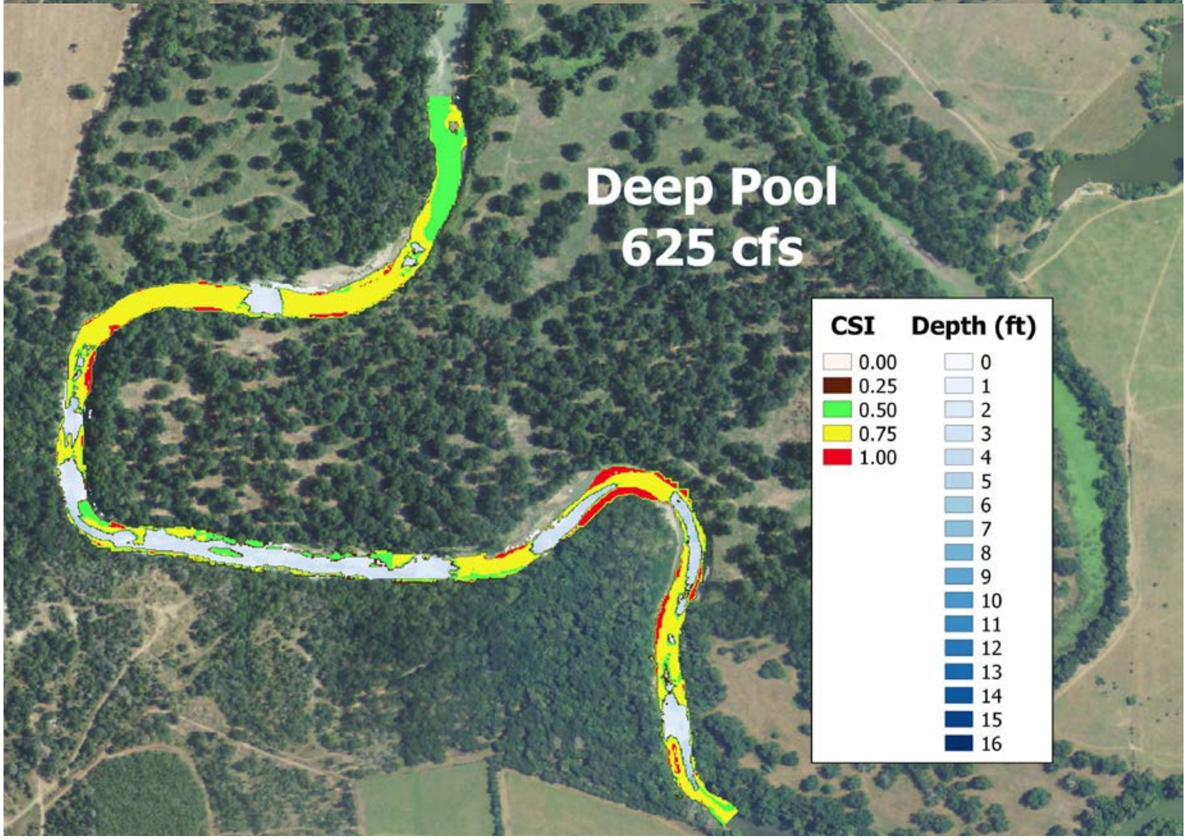
Deep Pool
625 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
0
1
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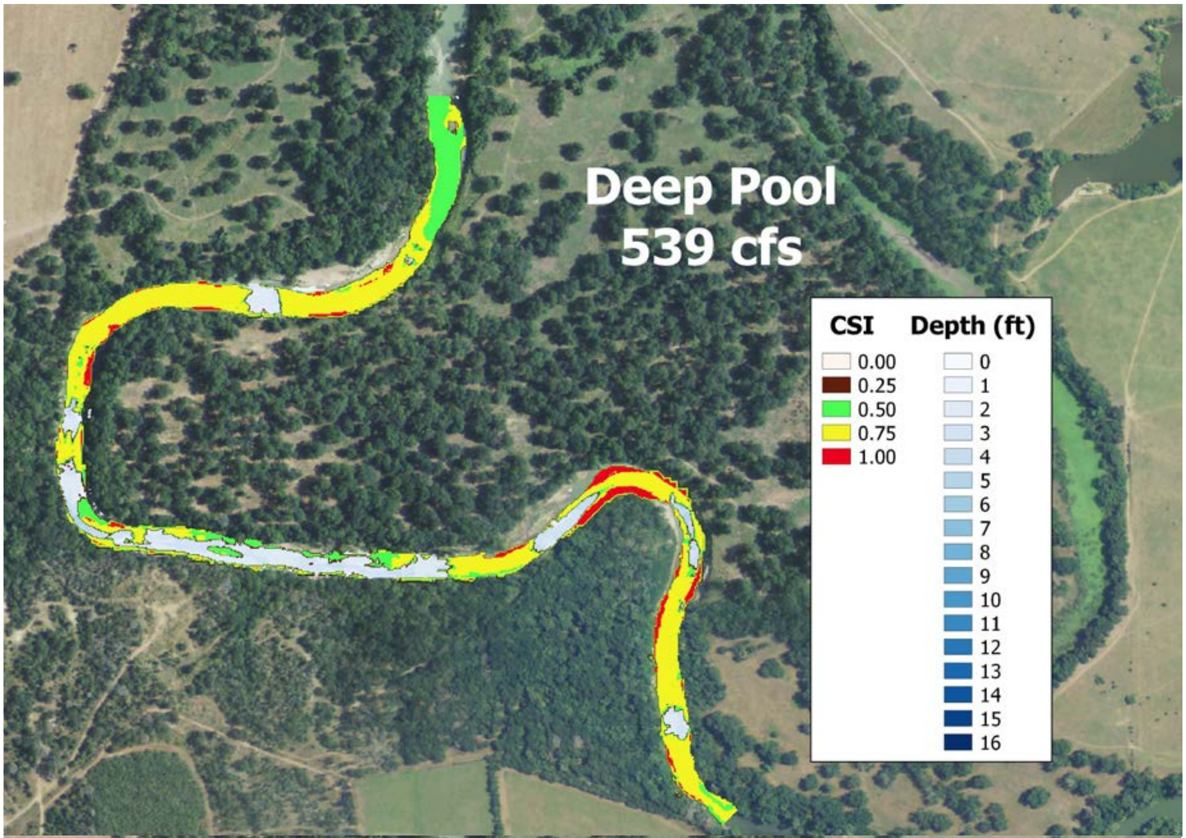
Deep Pool
539 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
0
1
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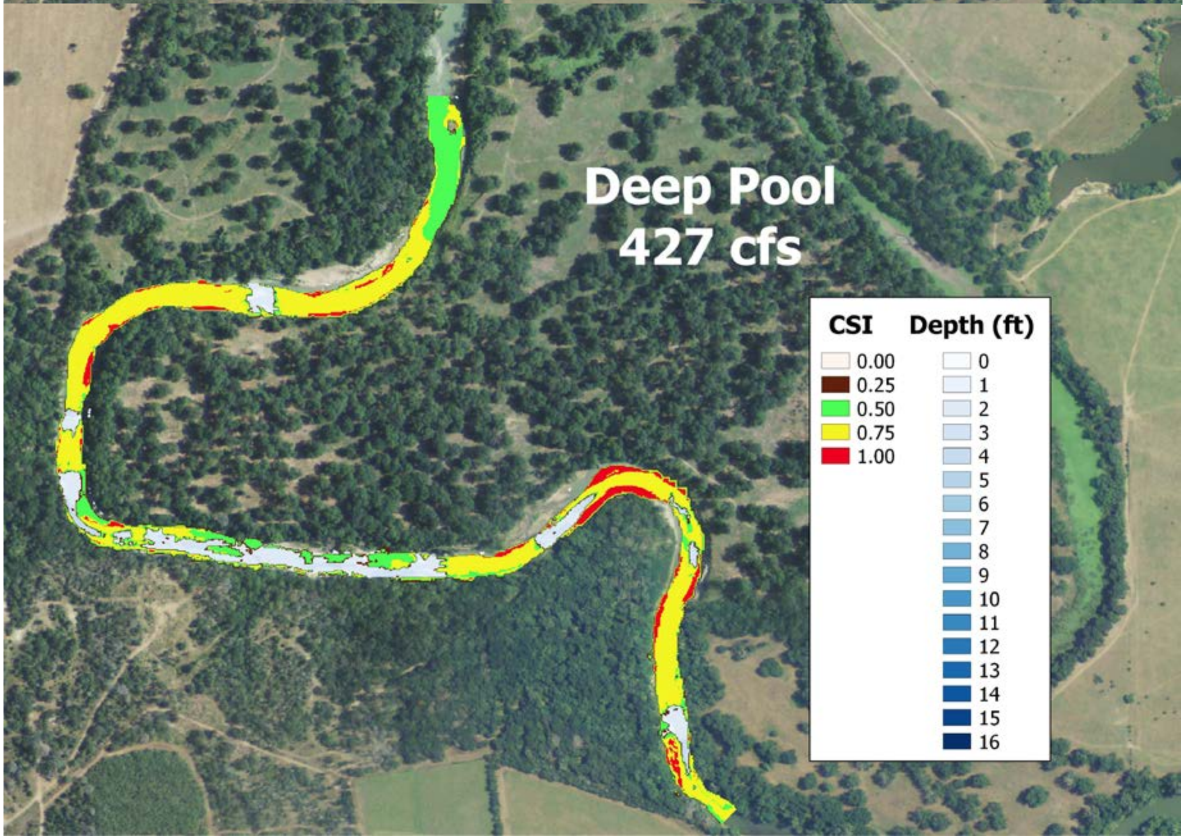
Deep Pool
427 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
0
1
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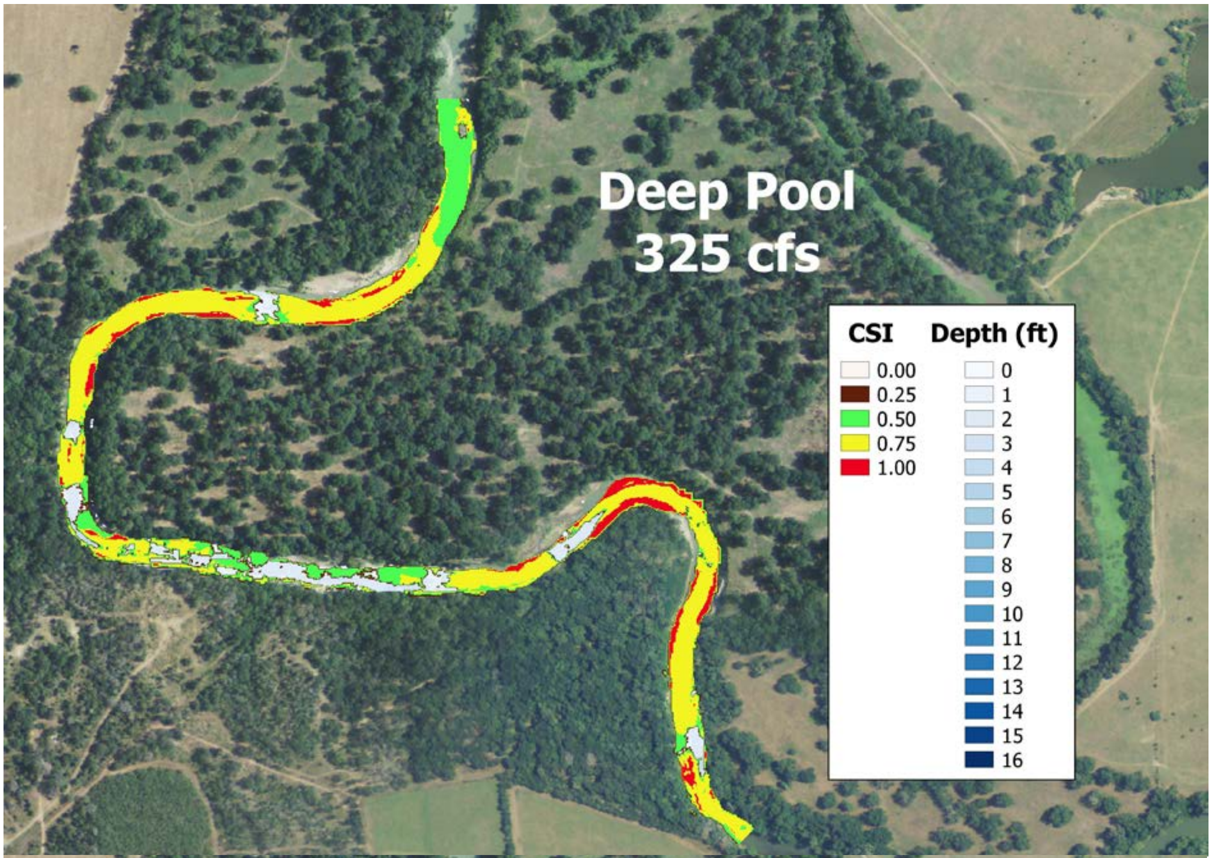
16


Deep Pool
325 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
0
1
2
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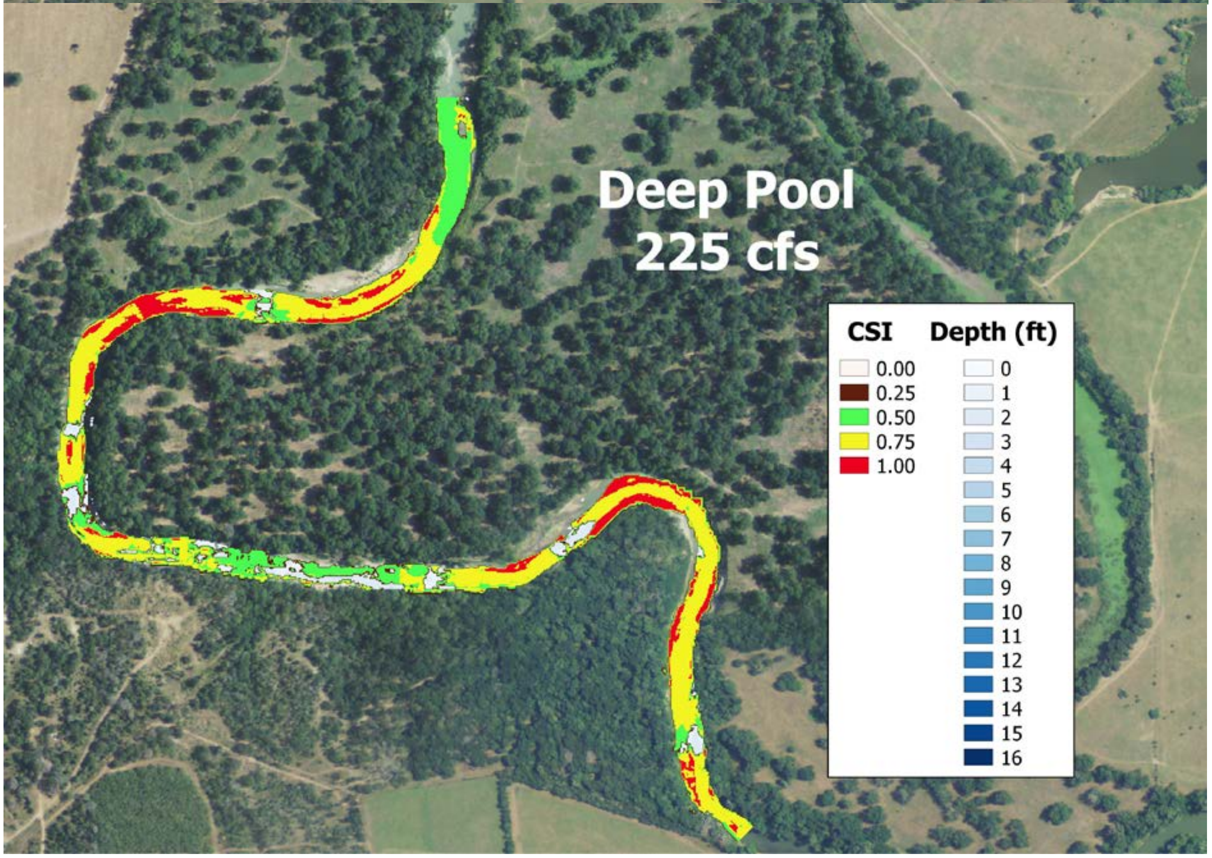
Deep Pool
225 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
0
1
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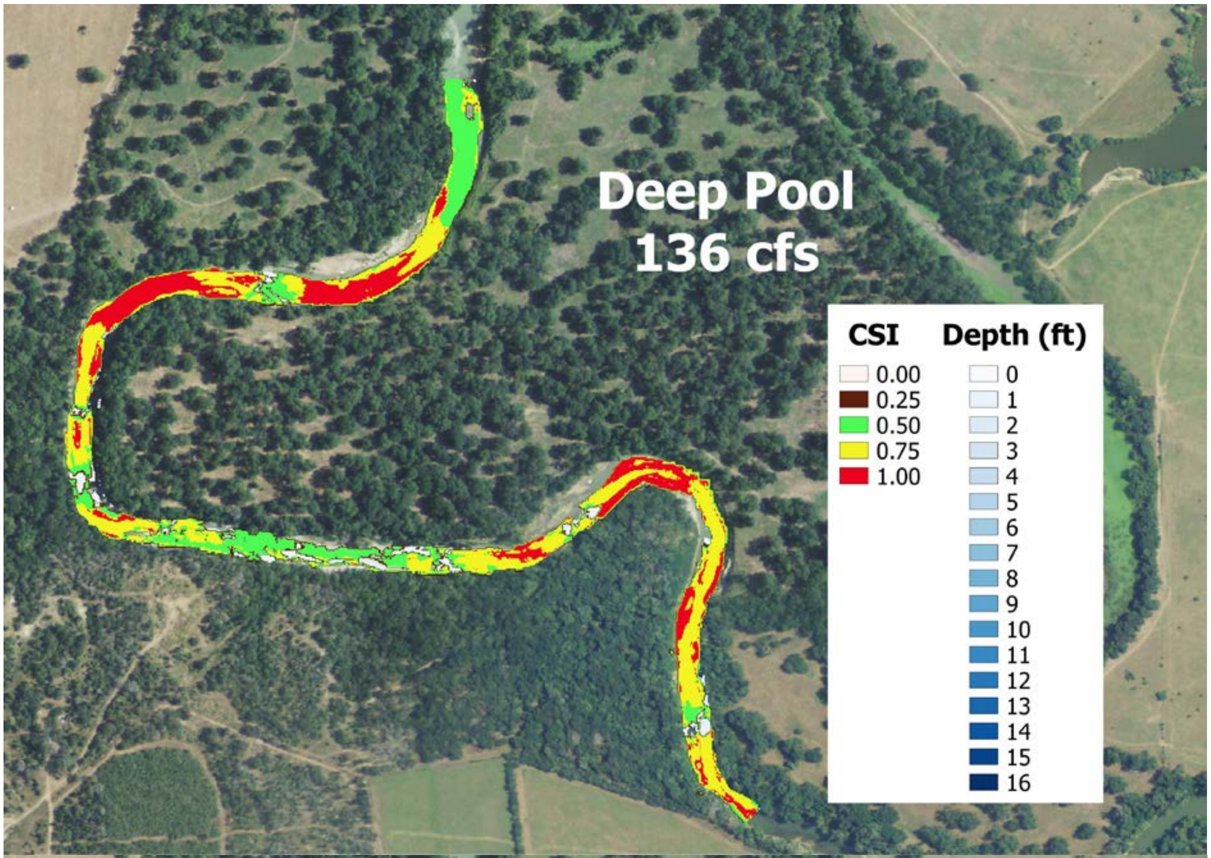
Deep Pool
136 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
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1
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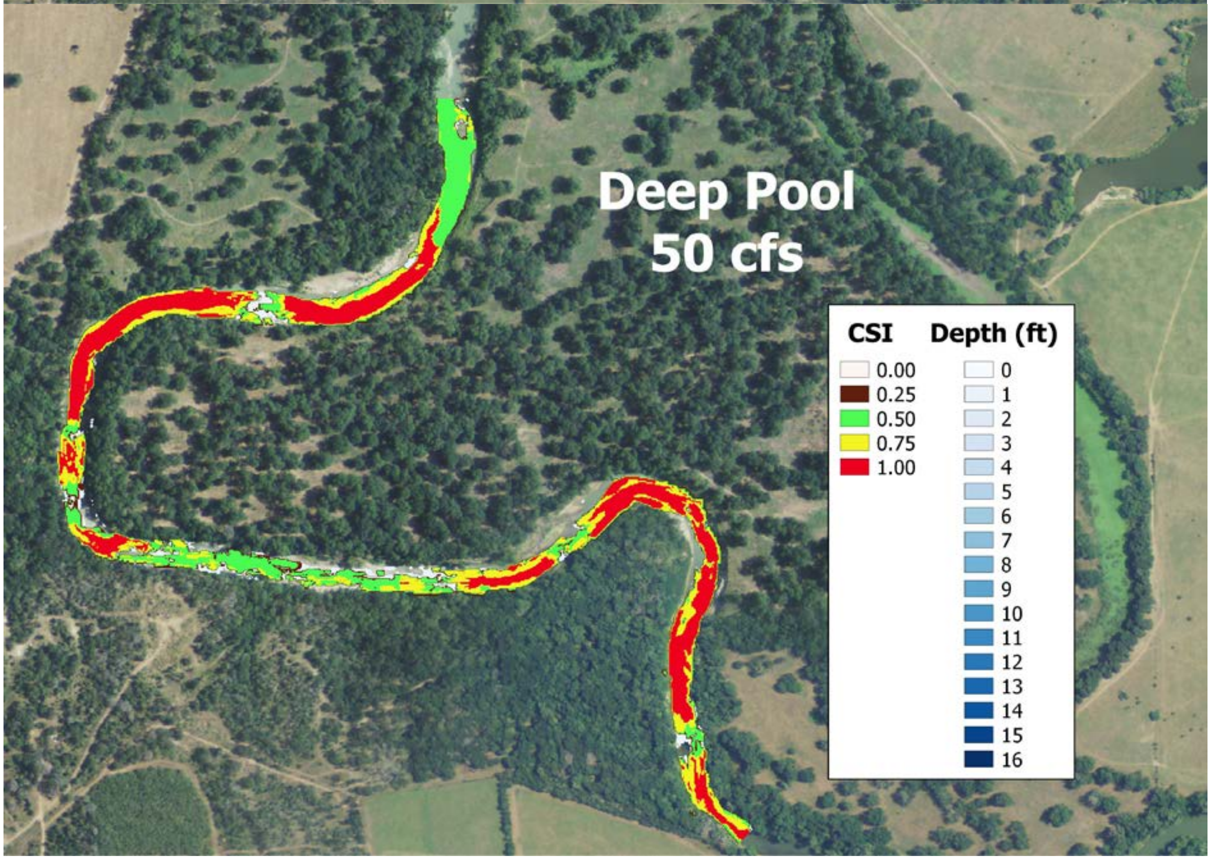
Deep Pool
50 cfs
CSI
0.00
0.25
0.50
0.75
1.00
Depth (ft)
0
1
2
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6
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9
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