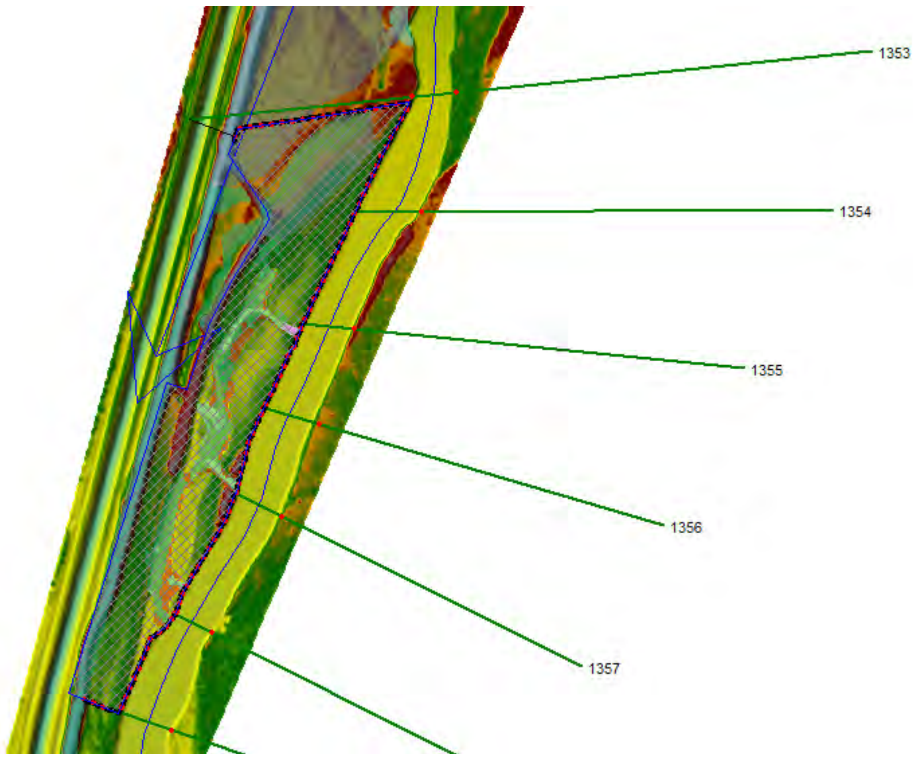
HYDRAULIC HABITAT SUITABILITY
FOR RIO GRANDE SILVERY MINNOW
AT SAN ACACIA RESTORATION SITES

PREPARED FOR THE BUREAU OF RECLAMATION



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Executive Summary

The Rio Grande Silvery Minnow (*Hybognathus amarus,* Silvery Minnow) is an endangered species that persists in the Middle Rio Grande (from Cochiti Dam tailwaters to above the Elephant Butte Dam reservoir pool near Truth or Consequences, NM). The species has been impacted by several factors: in-stream infrastructure segmenting the Middle Rio Grande; river channelization efforts which have increased active channel depths and velocities; and anthropogenic and climatic trends reducing available water in the Rio Grande basin. The Silvery Minnow has been under direct management efforts since it was listed as an endangered species in 1994. These include rescuing the Silvery Minnow from stranded pools, conducting population counts throughout the year, and augmenting the population with minnows raised in hatcheries. There have been habitat restoration efforts to countervail the channelization of the main stem of the Rio Grande in an effort to increase the extent of shallow, slow-moving, inundation areas called 'restoration sites'. Restoration efforts are mainly configured at the edges of the channel and floodplain to generate nursery or feeding habitats for this species. There has been research regarding the spawning and movement of the Silvery Minnow to inform adaptive management actions. Scientists and others have presented recommendations to water managers to manage snowmelt captured upstream to support the Silvery Minnow.

This study characterizes hydraulic habitat on restoration sites relative to documented habitat preferences for larval and adult life stages for the Silvery Minnow. Using literature and field-measured data, a hydraulic habitat suitability curve was created and paired with 2-dimensional (2-D) hydrodynamic modeling data to map habitat areas based on velocity and depth. Field-measured hydraulics and areas of inundation at (8) habitat restoration sites in San Acacia were used for site-by-site calibration.

The hydraulic habitat effectiveness for each restoration site was estimated based on surveyed terrains and hydraulic results. The models reflect the effects of short-term sediment deposition patterns with "As-Built" (or baseline) and "Post- Runoff" (after the monsoon season) topography. In addition, adjacent floodplain hydraulics are evaluated. The evaluation compares the hydraulic habitat contribution of non-constructed, adjacent terraces to the constructed areas. The restoration sites represent different configurations of backwater, side channels, and bank line lowering on terraces that are connected to the active channel at varying degrees. The results demonstrate how project siting contributes to Silvery Minnow habitat hydraulics.

This report defines and implements site performance metrics based on the on-site hydraulics and the frequency and duration of hydrologic events. Site performance is quantified based on duration and spatial extents. Design criteria for these sites were to 1) inundate the floodplain at less than bank full conditions; and 2) increase refugia habitat for larval life stages of the minnow. However, hydraulic habitat analysis found that much of the total inundated area is too fast-moving or too deep for quality larval habitat. Large habitat sites may not fully inundate, indicating excavated area alone is not good proxy for habitat contributions.

Generally, it was found that the habitat quality degraded at lower discharges (<2000 cfs) due to sedimentation at the interface between the restoration site and the Rio Grande active channel. The sedimentation benefited higher discharges, however, likely by reducing the depths and velocities as water disperses on the site. It was also found that the post-runoff terrains had more

channelized features than the designed features. This indicates that sediment transport affects the performance of these sites in various ways.

The objective of this study is to present a baseline and post-runoff hydraulic analysis for restoration sites designed for Silvery Minnow habitat. The process transforms qualitative habitat characteristics (slow moving, shallow water) into spatially based quantities for performance forecasting, evaluating alternatives in adaptive management, and design analysis for future restoration sites. As with any model, field-validation is necessary. Though the hydraulic habitat preferences are available in the literature, this study recommends incremental improvement of the Silvery Minnow habitat conceptual model which can be directly analyzed via geospatial analysis.

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1D or 2D	One-dimensional or two-dimensional
AB	As-Built analysis (or Baseline)
BOR	US Bureau of Reclamation
cfs	Cubic feet per second
fps	Feet per second
ft	Feet
GIS	Geographic Information System
GSA	GeoSystems Analysis
HEC-EFM	Hydrologic Engineering Center’s Ecological Function Model
HEC-RAS	Hydrologic Engineering Center’s River Analysis System
HR	Habitat restoration (site)
HSI	(Hydraulic) Habitat Suitability Index;
ISC	New Mexico Interstate Stream Commission
LiDAR	Light Detection and Ranging
NM	New Mexico
PR	Post-runoff analysis (Post-monsoon, October)
PTI	Percent time inundated
RGSM	Rio Grande Silvery Minnow
RM	River Mile
RMSE	Root mean square error
SOBTF	Save Our Bosque Task Force
USACE	United States Army Corps of Engineers
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WUA	Weighted Useable Area

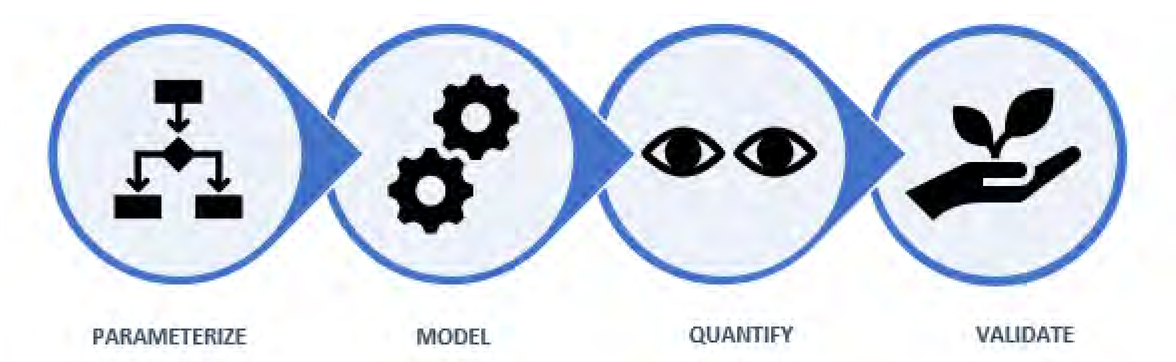
1 - Background

1.1 Purpose

The Bureau of Reclamation (BOR), the New Mexico Interstate Stream Commission (ISC) and the US Army Corps of Engineers (USACE) have implemented habitat restoration and other projects to support the Rio Grande Silvery Minnow (Silvery Minnow or RGSM) since its listing as an endangered species in 1994. Following flood mitigation and channel conveyance efforts, the Middle Rio Grande now flows as a sinuous, predominantly single-threaded channel, fragmented by diversion and flood control dams, and increasingly disconnected from the surrounding floodplain. The changes to Middle Rio Grande geomorphology and hydrology have negatively impacted species that depend on the shallow, low-velocity areas of the once braided anastomosing channel. Agencies have invested in the construction of habitat restoration sites; however, there has been little documentation or quantification methods to measure how effectively these sites provide habitat for the Silvery Minnow.

The purpose of this study is to develop and implement a methodology to estimate hydraulic habitat suitability (i.e., depths and velocities) of habitat restoration sites using hydraulic modeling and hydrologic analysis. The restoration sites evaluated varied in size, but were generally earth-worked features, designed and excavated to inundate at lower river discharges than the surrounding floodplain.

These analyses present acreages of suitable hydraulic habitat for various life stages of the RGSM. Hydrologic and hydraulic analyses were conducted with various software applications in the Hydrologic Engineering Center's River Analysis System (HEC-RAS) version 5.0.6, Ecological Function Model (HEC-EFM) version 5.0.1, and ArcMap version 10.4. A schematic of the methodology is shown in Figure 1.



Transform field observations into hydraulic habitat parameters.	**Calibrate and simulate restoration site hydraulics.**	**Quantify duration of suitable hydraulics as a performance measure.**	**Present recommendations for validation.**

Figure 1. Process diagram for this study.

This study evaluates the effectiveness of these sites following inundation. There are monitoring suggestions to support repeated analyses as the sites continue to change due to vegetative growth, sedimentation, or maintenance activities.

1.2 Scope of Study

1.2.1 Study Area

The areas of interest are eight habitat restoration sites between the San Acacia Diversion Dam and San Antonio, NM (near US Route 380) in central New Mexico (Figure 2). This stretch of the Rio Grande intersects two geomorphic sub-reaches: the San Acacia Reach and the Arroyo de las Cañas Reach; these correspond to the Water Operation Reach "San Acacia". Geomorphic characteristics of these reaches are channel narrowing due to vegetation encroachment and increased channel uniformity. The San Acacia Reach is experiencing high incision, which is less dramatic as one travels downstream. Though the Arroyo de las Cañas Reach has an upstream degradation trend that progresses to aggradation downstream, segment of the reach which intersects the most downstream restoration site (RM 93) may be assumed to be generally degrading. These geomorphic trends are documented in AuBuchon and Makar, 2012.

The restoration sites were constructed by either ISC or BOR between 2016 and 2019. The design features include backwaters, lowered terraces, and side channels. The eight habitat restoration sites are referred to by the nearest River Mile (RM) location. Listing from downstream to upstream in Table 1. For each of these restoration sites, two terrains were evaluated: As-Built (AB) and Post-Runoff (PR) sedimentation.

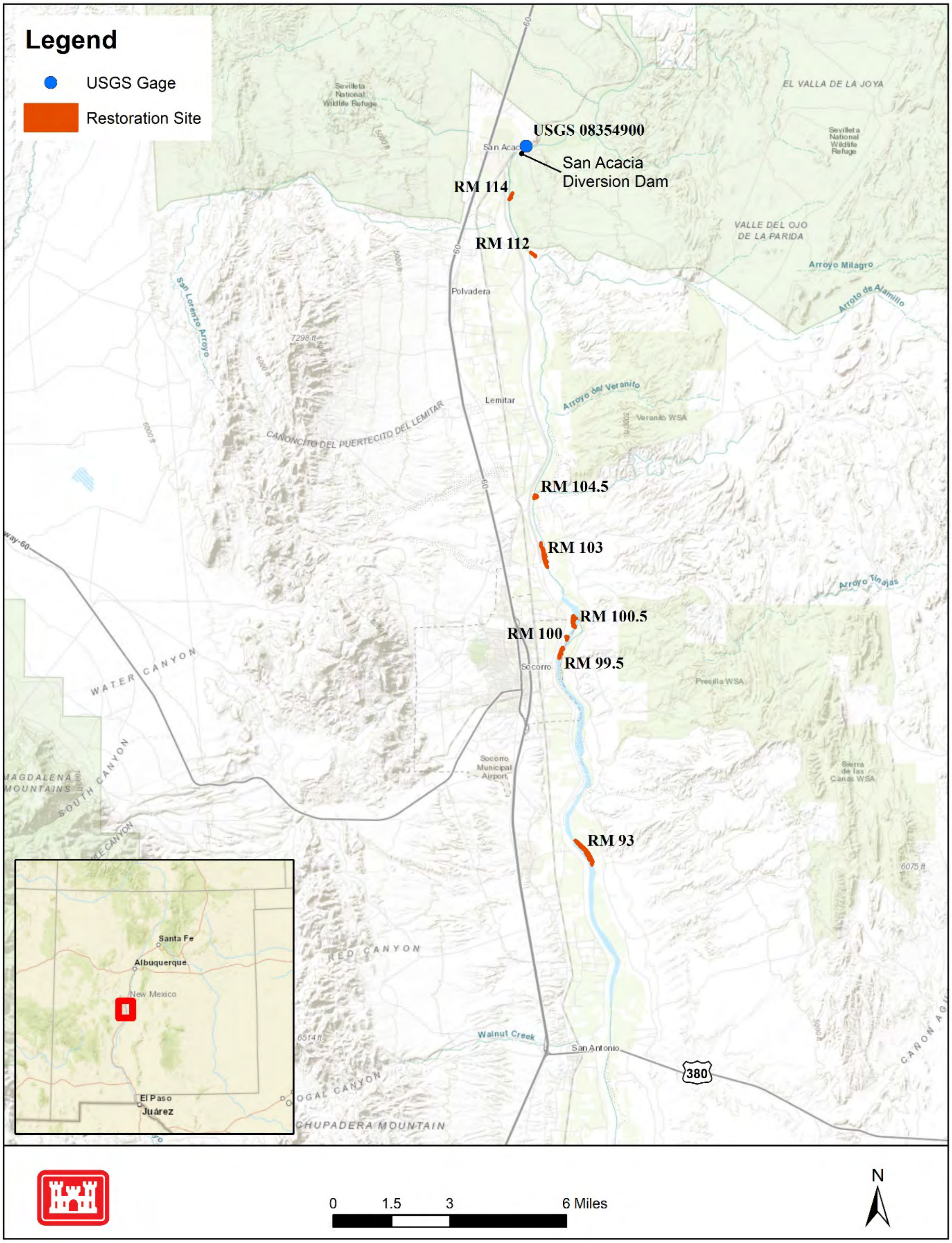


Figure 2. Locations of restoration sites evaluated in this study.

Table 1. Restoration sites evaluated in this study.

Site Location	Project Sponsor	Type	Size (acres)	Design Discharge (Incipient Inundation)
RM 93	BOR	(11) embayments attached to a high-flow channel	17.2	300 cfs
RM 99.5	ISC	(4) inlets that become attached as a single backwater at higher discharges	3.5	800 cfs
RM 100	ISC	(1) backwater	1.4	800 cfs
RM 100.5	ISC	(3) backwaters that become attached at higher discharges	8.2	800 cfs
RM 103	BOR	(5) embayments that connect as side channels	10.5	300 cfs
RM 104.5	BOR	regraded arroyo confluence	3.2	300 cfs
RM 112	ISC	backwater that attaches to a natural side channel at higher discharges	1.5	800 cfs
RM 114	ISC	(2) inlets attaching to a single backwater	1.7	800 cfs

1.2.2 Hydraulic Habitat Suitability Indices

Habitat Suitability Indices (HSI) are an effort to quantify qualitative habitat feature characteristics relative to optimal habitat conditions (USFWS, 1981). The key process is to identify key habitat variables for a species using literature review as a means to construct a conceptual model representing optimum habitat quality. For each key habitat variable (such as depth) an HSI is derived as a ratio of that key habitat variable to a “most ideal” standard of comparison. When multiple habitat variables are mapped spatially, the modeled HSI may be multiplied by the representative area, to generate a habitat unit (HU) or weighted useable area (WUA).

$$HU \ or \ WUA = HSI * Area$$

HSI is an index from 0 to 1, with 0 indicating inhospitable or poor habitat, and 1 indicating preferred habitat qualities. In the case of fish, an inundated area can be evaluated with a habitat quality index to estimate the quantity of available habitat. This transformation allows for more granular visualization of habitat quality and can be evaluated in a quantitative analysis.

The goal of this study is to use HSI to generate performance metrics for restoration sites and adjacent natural terraces. The purpose of evaluating the natural terraces is to compare the quality of the excavated restoration areas relative to surrounding, unconstructed topography. For HSI to be applied, habitat variables must be linked to spatial parameters. Bachus and Gonzales (2018) conducted a literature review relating RGSM habitat to hydraulic parameters: depth and velocity. Mortensen et al (2019) confirmed these parameters as relevant to habitat quality. In addition, several field studies identified RGSM presence alongside depth and velocity measurements. In the original implementation of this method, the hydraulic HSI was a binary index: 0 or 1. However, following discussions with ISC, there was a strong preference to present the HSI with the traditional "continuous curve" method, where the HSI features a gradation from inhospitable to preferred habitat. This is more consistent with ecological observations that species reside in environments at varying frequencies according to habitat preferences.

Raw data from publications provided the average velocities, water depths, and counts of RGSM in these areas. Valdez et al (2019) was used for the larval RGSM metrics (Figure 3), and Braun et al (2015) was used for the adult RGSM metrics (Figure 4). Two studies were used because each studied a different life stage of RGSM. Generally, the data presented in these two studies represent a small sample size. The data were collected over the course of 1 year and particularly in Braun (2015), the RGSM population was small relative to other years. It is recommended that as more monitoring data becomes available, that it is added to the HSI curve to improve its statistical relevance.

The data were used to generate histograms of fish population frequency versus both hydraulic parameters (shown as bar graphs in Figure 3 and 4). The histograms were then translated to a 0 to 1 index by using a line graph to bound the population distribution (double red line in Figures 3 and 4). An HSI of 1 is associated with the depths and velocities where most fish were found, and gradual slopes to 0 to the bounds where fish were not detected. Depths and velocities where fish were captured were set to a minimum HSI of 0.1, as fish were found in these locations but in a much lower frequency than most of the other fish captured. The larval velocity HSI has an inflection at 0.3 feet/second because an overwhelming proportion of the silvery minnow larvae are captured at velocities from 0 to 0.15 feet/second. The shape of these lines were reviewed by fisheries biologists in a meeting facilitated by BOR in 2020. Based on uncertainties in capturing adult stage fish at deeper areas, fisheries biologists (BOR and ISC, personal comm. 2020) recommended the index of adult depth should be extended to 4 feet. Literature cited in Mortensen et al. (2019) was used as the initial bounds for the maximum index output (HSI = 1).

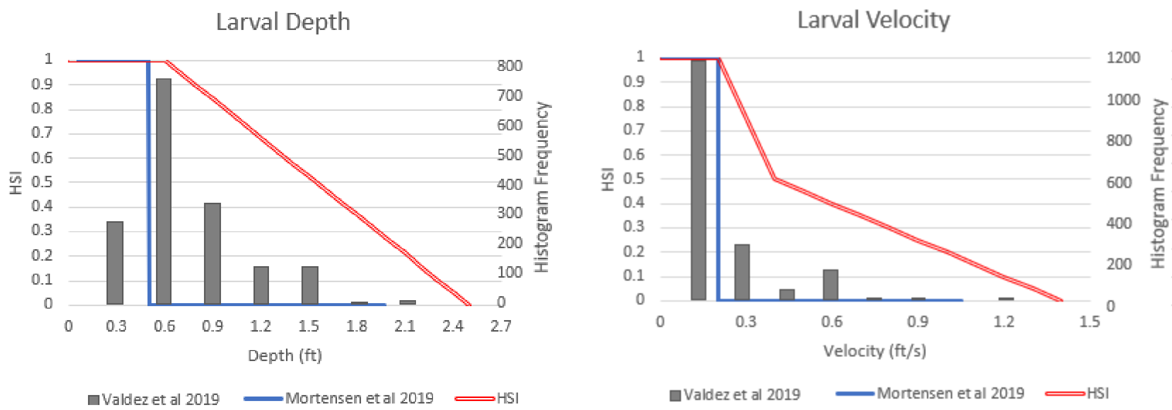


Figure 3. Larval depth and velocity hydraulic-suitability indices based on Valdez et al (2019) and Mortensen et al (2019).

Table 2. Functions describing the Larval HSI curve from input variables.

Range	**Function (dimensionless)**	**Range**	**Function (dimensionless)**
Depth < 0.6 ft	HSI = 1	Velocity < 0.2 feet	HSI = 1
0.6 ft <Depth < 2.5 ft	$HSI = 1.32 - \frac{Depth}{1.9}$	0.2 ≤Velocity <0.4 feet	$HSI = 1.5 - \frac{5*Velocity}{2}$
2.5 ft< Depth	HSI = 0	0.4≤Velocity ≤1.4 feet	$HSI = 0.7 - \frac{Velocity}{2}$
--	--	1.4 feet < Velocity	HSI = 0

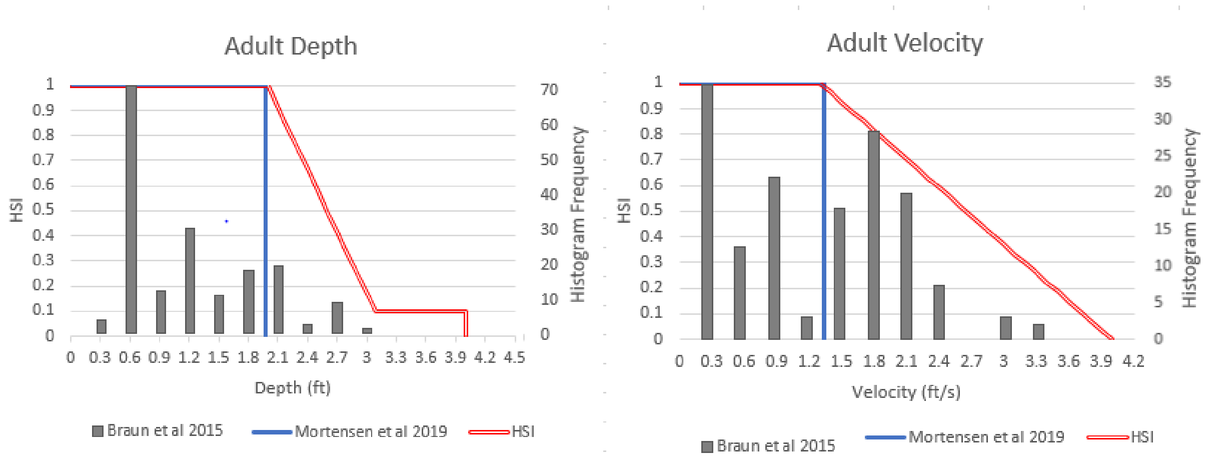


Figure 4. Adult depth and velocity hydraulic suitability indices based on Braun et al 2015 and Mortensen et al 2019.

Table 3. Functions describing the Adult HSI curve from input variables.

Range	**Function (dimensionless)**	**Range**	**Function (dimensionless)**
Depth ≤ 2 feet	HSI = 1	Velocity < 1.3 ft/s	HSI = 1
2 <Depth <3.1 feet	$HSI = 2.6 - \frac{4*Depth}{5}$	1.3 ft/s <Velocity < 4 ft/s	$HSI = 1.48 - 0.37 * Velocity$
3.1≤Depth ≤4 feet	HSI = 0.1	4 ft/s ≤ Velocity	HSI = 0
4 feet < Depth	HSI = 0	--	--

Two dimensional (2D) hydraulic modeling (described in Section 2.3) generates rasters of hydraulic variables at a given timestep from an unsteady state simulation. Unsteady state simulations are required for 2D modeling in HEC-RAS, however the hydrographs used in these models are "steady", meaning that the discharge flow rates do not change over the course of the simulation. The hydraulic output used in the analysis is based on an equilibrium status, where depth and velocity in the modeled areas are no longer changing from time-step to time-step. Depth and velocity rasters are exported and then translated into HSI values with the "Reclassify" tool from ArcMap (See Appendix A for step-by-step process). For this analysis, depth and velocity criteria are assumed to be mutually inclusive, meaning that ideal hydraulic habitat requires both suitable depths and velocities. For a given raster cell, the depth and velocity HSI's are multiplied with one another, giving the following results matrix (Figure 5).

Depth HSI

Velocity HSI	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0	0	0	0	0	0	0	0	0	0	0
0.1	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
0.2	0	0.02	0.04	0.06	0.08	0.1	0.12	0.14	0.16	0.18	0.2
0.3	0	0.03	0.06	0.09	0.12	0.15	0.18	0.21	0.24	0.27	0.3
0.4	0	0.04	0.08	0.12	0.16	0.2	0.24	0.28	0.32	0.36	0.4
0.5	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
0.6	0	0.06	0.12	0.18	0.24	0.3	0.36	0.42	0.48	0.54	0.6
0.7	0	0.07	0.14	0.21	0.28	0.35	0.42	0.49	0.56	0.63	0.7
0.8	0	0.08	0.16	0.24	0.32	0.4	0.48	0.56	0.64	0.72	0.8
0.9	0	0.09	0.18	0.27	0.36	0.45	0.54	0.63	0.72	0.81	0.9
1	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1

Figure 5. Matrix of HSI results from velocity and depth sub-parameters. Scores are demarcated from least to most preferred hydraulic habitat "bins" used for visualizing results on a site-by-site basis.

The bins used for visualization of the HSI results for each restoration site and both life stages are presented in Figure 5. The bins are: 0-0.4 HSI, 0.4-0.8 HSI, 0.8-0.9 HSI, and 0.9-1 HSI. Higher scores indicated more highly preferred conditions for RGSM. The bin extents were selected by using the Natural Breaks (Jenks) method (Smith et al, 2018). Under this method, a set number of breaks (4) are selected, and the breaks are determined by natural groupings where large changes in raster values occur. Though Natural Breaks may vary per dataset, the same bins were applied across all figures for comparison. The selected Natural Breaks (from RM 100.5) provides higher resolution at the higher HSI scores.

The HSI analysis results in every cell of the spatial analysis being assigned an index value from 0 to 1. To calculate a weighted useable area, the weight (suitability index) is multiplied by the cell area, and then summed to give an area of suitable hydraulics (See Appendix A for more detail). Weighted useable areas are tabulated and presented in the results section for each restoration site. The quantities can be graphed as habitat areas per discharge for the As-Built (AB) and the Post-Runoff (PR) events. This quantification allows for a comparison of the hydraulic habitat condition across sites, as well as how areas of suitable hydraulics have changed following sedimentation caused by the spring runoff and summer monsoon events.

1.2.3 Hydrology

The RGSM environment is strongly affected by Middle Rio Grande hydrology. The magnitude of water discharge and the frequency of hydrologic events impacts the duration of floodplain inundation critical to RGSM larval life stages. Following channelization efforts and installation of flood control dams, the flow regime and riverine habitat has changed significantly from the conditions that RGSM has evolved with the riverine environment. Therefore, hydrologic characterization of the current system is necessary to implement hydraulic habitat analysis.

The restoration site performance is linked with Middle Rio Grande hydrology via a frequency analysis to identify the most “effective” or most highly influential discharges that are occurring in the current hydrologic regimes. The range of potential flows that could occur in the Middle Rio Grande at the San Acacia gage limits the scope of the hydraulic analysis. Cochiti Dam regulates much of the flows entering the Middle Rio Grande. This Dam has a “maximum desirable flow” of 7,000 cubic feet per second (cfs) during flood conditions in the Rio Grande reach (USACE 1996). The recent years (2000-2019) spring season (April through June) were evaluated to represent the RGSM population monitoring period and reflect the river conditions during which restoration sites were designed and constructed.

This time period reflects recent hydrologic trends in the Middle Rio Grande: reduced frequency of high discharge events and longer durations of 500 cfs or lower. The cause of these trends is uncertain and may be due to geomorphic planforms that affect river conveyance, in-stream or groundwater diversions and flood control, changes in land use, or others. This drying condition is important to capture within this analysis, as the restoration sites’ effectiveness are affected by the present hydrologic regime. A longer period of record may overestimate hydraulic habitat potential.

The maximum discharge for the spring season over this time period was less than 4000 cfs (Figure 6). For 75% of the time period, the mean seasonal flow was 2000 cfs or less. HEC-EFM 5.0 was used to create frequency figures for the period of interest to contextualize most recent spring flow data. Peak discharge during the spring runoff is a design criterion for restoration sites.

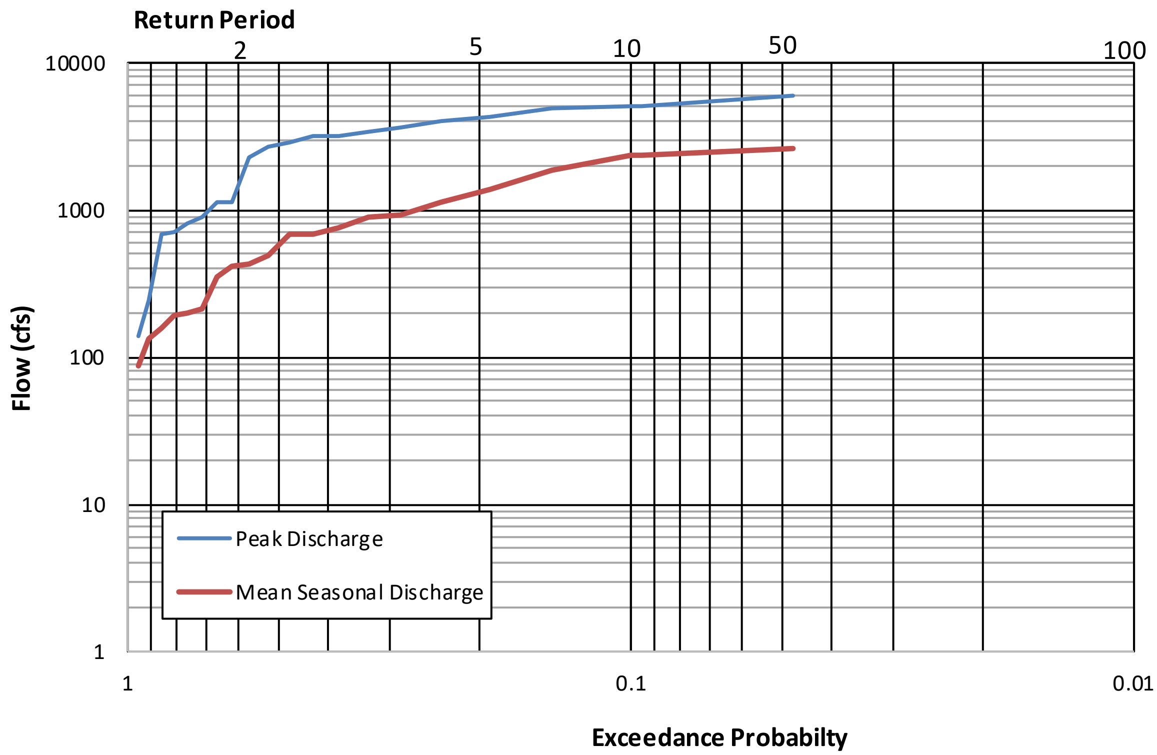


Figure 6. San Acacia peak and mean seasonal discharges for the spring runoff (April through June) from 2000 to 2019.

The hydraulic models were run at 1000 cfs increments, starting with a minimum discharge of 1000 cfs. It was assumed that the results of any intermediate discharge would fall within the range of the simulated discharges. If there was appreciable inundation at 1000 cfs (>0.5 acres), a 500 cfs discharge event was also simulated. This condition occurred at RM 93.

The areal hydraulic results per discharge and the frequency of hydrologic events are presented as an "effective hydraulic suitability curve", indicating that though some discharges generate more areas of suitable hydraulics, more frequent events may contribute more areas of hydraulic suitability overall. The results of effective hydraulic suitability curves indicate how well the habitat restoration sites are performing relative to hydrologic regimes in the San Acacia reach of the Middle Rio Grande.

HEC-EFM was used to determine hydrology statistics from the daily average discharge. Two time periods were evaluated: the 2019 hydrologic year (November 2018 to October 2019) and the average discharge frequency from 2000-2019. 2019 was a very high discharge year and is well-centered on the 2019 terrain data collection. Considering it was a high discharge year, a comparison to the past two decades better reflects the typical performance of these sites.

Frequency of flow rates occurring in four seasons was evaluated for the 2019 hydrologic year and the 2000–2019 timeframe. Table 4 summarizes the seasons evaluated for comparison. In Figure 7, flows in 2019 showed a much higher tendency for discharges from 3000 cfs to 4000 cfs than the typical year. The winter flows (November 2018 to February 2019) were much lower than usual. The pre-spring runoff season had higher duration than typical spring flows, in the 1000-2000 cfs range.

Table 4. Definitions of seasons from Bui (2014).

Season (Name in Figure 7)	Duration
Pre-Runoff (Pre)	March to April
Spring Runoff (Spring)	May to June
Post-Runoff (Post)	July to October
Winter (Winter)	November to February

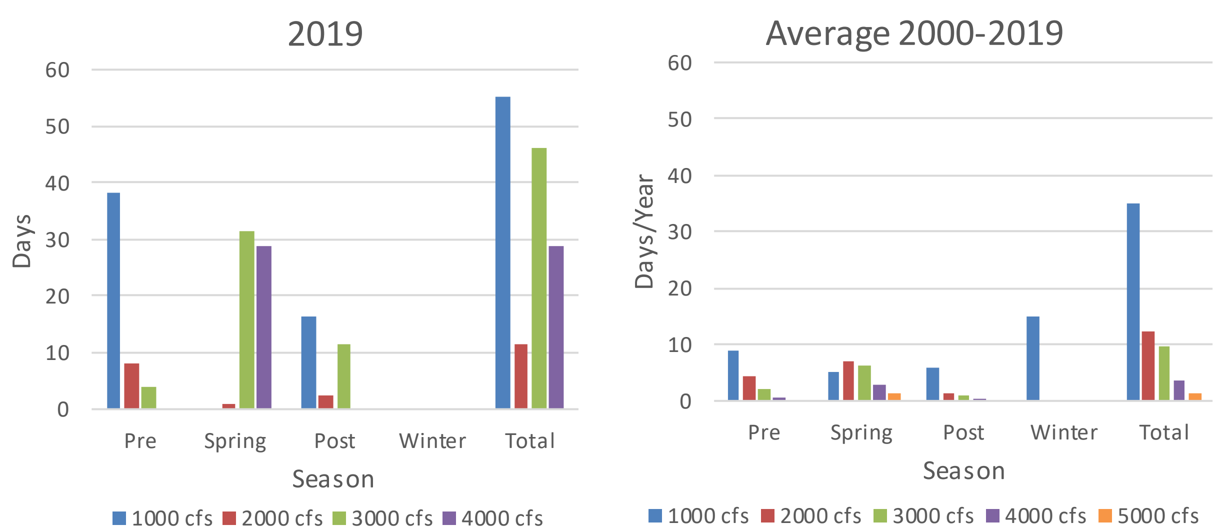


Figure 7. Hydrology from San Acacia gage USGS 08354900 daily data, presenting occurrence frequency in terms of days per season in a year for 1) 2019; and 2) from 2000-2019. Bars indicate duration of hydrology from 1000-1999 cfs, 2000 -2999 cfs, etc. Hydrologic seasons were based on Bui (2014)

2 - Methodology

2.1 Data Sources

For each of the eight habitat restoration sites, two hydraulic models were built based on the "AB" terrain and the "PR" terrain provided by BOR. The AB terrains were collected after each restoration site completion between 2016 and 2019, using Real Time Kinematic Global Positioning Systems at 1-foot contours, and at higher resolution in locations where slope change was evident. PR terrains were collected following monsoonal events, in October 2019. These two data sets demonstrated the sedimentation patterns over several years, though 2019 was the largest runoff year and most influential in the time period. The resulting grids of restoration sites had either a 1-foot by 1-foot or 2-foot by 2-foot resolution, depending on the resolution of the contractor-provided data.

Each site's terrains were imposed on a 2012 LiDAR dataset with a 5-foot by 5-foot resolution using the HEC-RAS Mapper "Create Terrain Tool". All data was US Survey Foot New Mexico State Plane (Central) with a NAD83 horizontal datum and a vertical datum at NAVD 88. The composite of surveyed excavated areas and the LiDAR of the surrounding floodplain were used for 2D modeling terrains.

The water surface profiles entering the site are based on a 1D component of the HEC-RAS model. The 1D was based on a 2012 1-Dimension (1D) HEC-RAS dataset from aggradation-degradation (Agg-Deg) lines, generated by the Bureau of Reclamation (see Varyu 2013 for line locations). The 1D model has a single elevation for its channel bed elevation, which was to represent the mean bed elevation. The simplification of this cross-section is to aid in calibration to a measured water surface elevation and used in assessing Middle Rio Grande channel conveyance capacity.

The active channel of the Rio Grande is predominantly a mobile sediment bed, which experiences significant changes in channel geometry and therefore channel capacity from year to year. In order to update the 2012 1D geometry, bathymetric survey data from 2019 was used to estimate channel geometry changes and anticipated water surface elevations. Bureau of Reclamation collects bathymetric surveys on a regular basis, and data was collected within the project area in April 2019. These rangeline data were used to update the 2012 1D geometry according to aggradation or degradation trends in the river (Figure 8). This was used as a starting off point in the 1D geometry, further calibration and validation steps are described in Section 2.1.1.

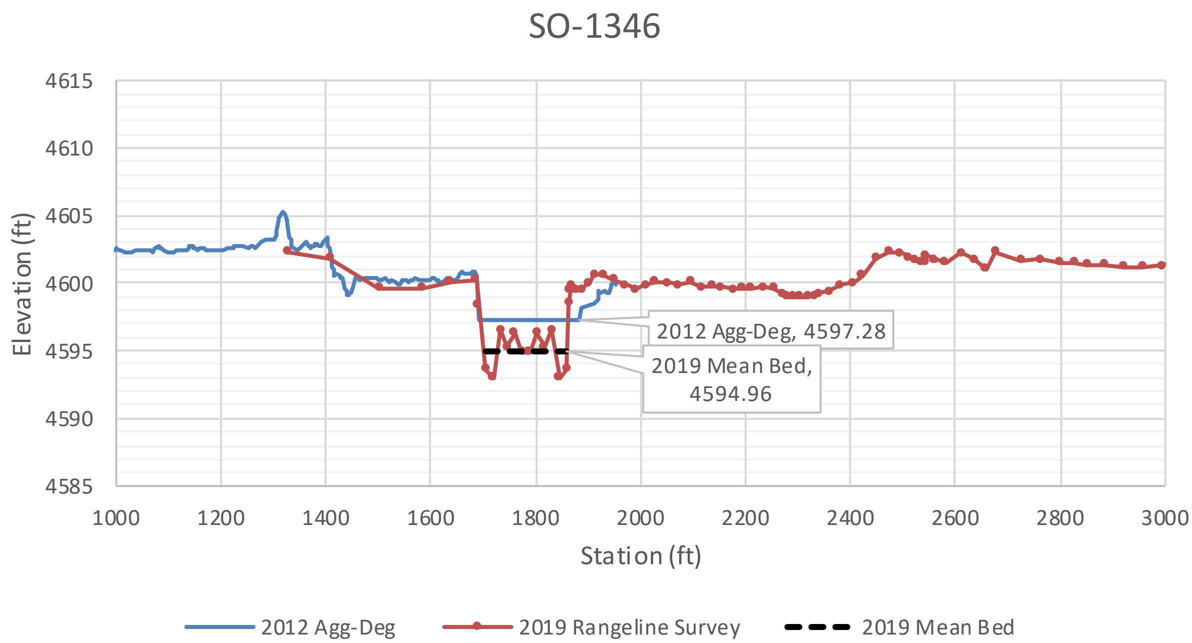


Figure 8. An example cross-section where the 2019 rangeline survey was used to update the mean bed of the 2012 1D Agg-Deg model.

The 1D Agg-Deg model was also modified for two types of considerations:

1. Levees were placed to confine flow to the active channel or within the levee boundaries. Aerial photography from approximately 4000 cfs (see Table 5) was used to confirm this placement.
2. Consistent placement of ineffective flow areas, especially in perched channel conditions that are prevalent in the San Acacia reach.

There is very little quality assurance data for incipient overbanking (around 3000 to 4000 cfs). 1D Agg-Deg model geometry may be validated when quality assurance data is available.

2.1.1 Quality Assurance Data

Site-specific data were collected throughout the 2019 spring runoff and provided to USACE by BOR and ISC contractors. Some of these data were collected and reported in GSA 2020. During the rising limb of the hydrograph, around 2700 cfs, velocities and water depth transects were collected at the eight habitat restoration sites. Inundation boundary extents were mapped on three occasions, once at a low discharge and twice during the spring runoff. Two sets of high-resolution aerial imagery were also collected in May 2019 and October 2019. For the May 2019 data, an unmanned aerial vehicle was used to collect 0.1 ft spatial resolution photography; the October data set had no metadata provided (GSA 2020). The BOR field-measured rangelines were used to update the 1D section of the model has water surface elevation data, which was used as quality assurance. The provided field-measured inundation and hydraulic data were used to calibrate and validate each hydraulic model. The quality assurance data used are presented in Table 5.

Table 5. Quality assurance data.

Data Type	Date(s) Collected	Discharge
Inundation	March 14 and April 23-25 2019	1190-1310 cfs and 2530-2830 cfs, respectively
Flow tracker monitoring, velocity, and depth	April 23- 25, 2019	2330 – 3110 cfs
Water surface elevation and aerial photography	May 7-8, 2019	3850 - 4600 cfs
Rio Grande field-measured water surface elevation from BOR rangeline data	April 2019	Varies

Upon running the first 1D/2D simulation for each site, the area of inundation for 1000 cfs and 4000 cfs were compared to aerial inundation mapped at the sites. One limitation in using the inundation mapping for quality assurance was that the inundation mapping was conducted with a hand-held GPS with 10-foot horizontal accuracy. Therefore, quality assurance was visually assessed by observing whether the same features were inundated in the model simulation as in the field observations.

The velocities and water depths measured in the field were compared to hydraulic outputs of the model at discharges matching the discharges at the time of field collection (around 2700 cfs). Both the AB and the PR conditions were simulated and compared. The field-measured points and the HEC-RAS results were compared utilizing the “Extract Values to Points” tool in ArcGIS. The point raster-values were compared to the field measurements by the root-mean-square-error (RMSE) method. Because of the ever-changing field topography, exact concurrence between the field measurements and the model were not expected. The absolute error average was determined by indexing the minimum error for each point from either the AB or the PR analysis and averaging the result.

Table 6. Error reporting for the restoration site hydraulic quality assurance based on transects that were collected by GSA in 2019.

SITE	AB Depth Root Mean Square Error (ft)	AB Velocity Root Mean Square Error (fps)	PR Depth Root Mean Square Error (ft)	PR Velocity Root Mean Square Error (fps)	Avg. Absolute Error for Depth (ft)	Avg. Absolute Error for Velocity (fps)
RM 93	0.48	0.52	0.49	0.44	0.05	0.17
RM 99.5	0.42	0.42	0.45	0.32	0.24	0.20
RM 100	0.61	0.54	0.59	0.31	-0.01	-0.17
RM 100.5	0.49	0.29	0.59	0.34	-0.24	-0.08
RM 103	0.91	0.96	0.84	0.74	0.39	0.21
RM 104.5	1.05	1.21	1.12	1.21	-0.83	0.89
RM 112	0.43	0.75	0.47	0.43	0.25	0.03
RM 114	1.43	0.20	0.87	0.24	-0.24	-0.06

Upon calculating the error in the first simulation, using 2012 1D geometry, the 2019 rangeline bathymetry and site-specific field-data were used to modify the 1D channel geometry to generate water surface elevations that conformed to the field measured data. This modification is necessary to accommodate geomorphic changes in the Rio Grande that occurred after 2012 and avoid the need for detailed bathymetric surveys. The summary of changes from the 2012 Agg-Deg are in Appendix B.

1D portions of these models should not be used for any in-stream hydraulic evaluations, as the cross-section was simplified as a trapezoid with a mean bed elevation for conveyance capacity evaluation. The calibration process allows for the 1D to generate an accurate water surface elevation, but in order to achieve these water surface elevations, there are uncertainties in the channel geometry and therefore hydraulic conditions. The 2019 rangelines were not measured at every cross-section of the Agg-Deg model, so mean bed elevations were interpolated between measured rangelines. The AB and PR 1D geometry are the same. Descriptions of how the 1D Agg-Deg model was modified from 2012 data can be found in the Appendix B.

2.2 Modeling and Mapping Limitations

The varying nature of the Middle Rio Grande geomorphology in both the river channel and floodplain became apparent during this analysis. Flow paths may change, and water surface elevations at a particular discharge may not persist throughout the spring run-off season or throughout the year. It had been observed that a recession in flows from May 12 to May 31 demonstrated a reduction in areal inundation, causing 3020 cfs to have less connected inundation to the restoration sites than observed in April at 1320 cfs (GSA 2020). This indicates that there were either changes in the Rio Grande main channel capacity or that the flow recession affected sedimentation at the inlets of the habitat restoration site. Because Rio Grande bathymetry was not collected multiple times throughout the 2019 spring runoff, analysis of temporal changes in channel capacity was not possible except from observations of inundation on the floodplain. Changes in Rio Grande channel capacity have been observed in literature, varying from 0.5 to 4 feet changes in depth over the spring runoff season from May to June (Occam, 2016).

There are limited validation data available to determine Rio Grande conveyance capacity and the dynamics of the site at varying discharges. The 2D modeling extent is limited to the overbanking areas only and Rio Grande hydraulics were not within the scope of the analysis. The overbanking connection outside excavated project extents was not documented; therefore, calibration of the 1D/2D interface is based on field-measured inundation extents, velocities, and depths in monitored areas. The BOR 2012 LiDAR terrain was used to represent the overbanking area outside the project excavation boundary and may not represent any changes in terrain that have occurred since these data were collected.

2.3 Hydraulic Modeling

2.3.1 Model Set-up

The provided terrains were generated into two scenarios for each habitat restoration site: an "AB" (As-Built) and "PR" (Post-Runoff) terrain as described in Section 2.1. Each habitat restoration site had two hydraulic models generated, one for each terrain. The landcover was based on aerial photography provided by BOR (May 7 -8, 2019 data) and traced using the Create

Feature tool in ArcGIS. Areas with no vegetation were set to having a Manning's 'n' roughness of 0.03, corresponding to a cleared floodplain or channel (Chow 1959), and the areas of vegetation were given a value of 0.06 to 0.08 as a Manning's 'n' roughness, corresponding to willows. The landcover was either enforced by a landcover shapefile or by having the default 2D area (areas not delineated by landcover type) as being "vegetated" or "cleared" which is discussed in Section 2.3.2. Model-by-model description of Manning's 'n' roughness settings can be found in the Appendix C.

The 2012 1D model by the Bureau of Reclamation (Varyu 2013) was modified so that 1D cross-sections did not intersect the 2D flow areas (Figure 9). The overbank Manning's "n" on the excavated areas of the habitat restoration site was set to a roughness of 0.03, based on Chow 1959.

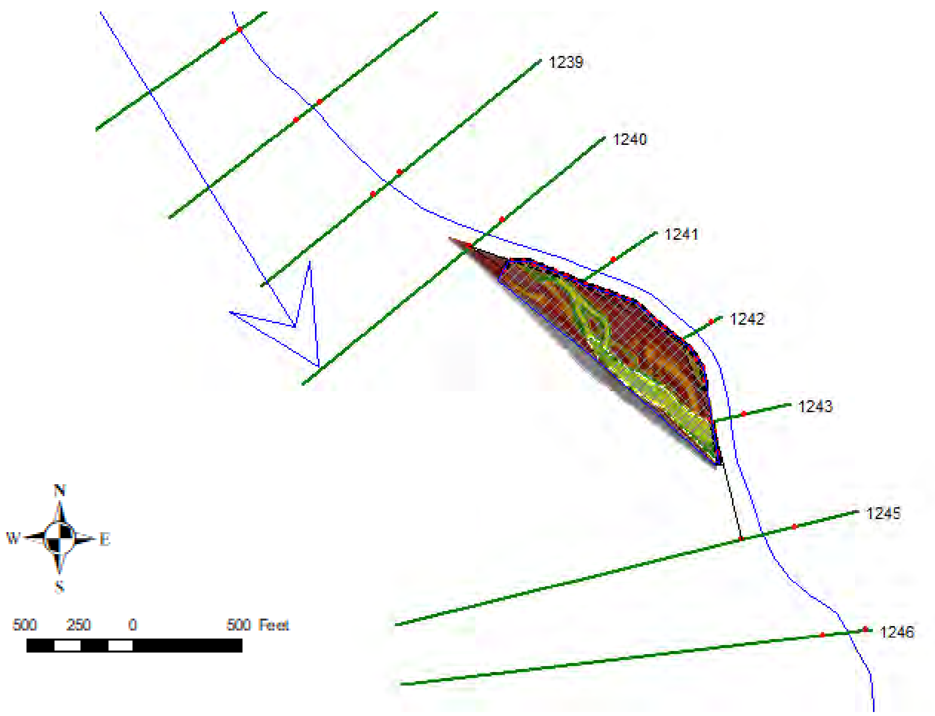


Figure 9. 1D/2D interface for RM 112, where the 1D cross-sections were clipped to not overlap the 2D mesh area.

2019 Rio Grande bathymetric data collected in April by BOR were used to identify aggradation or degradation trends since 2012. The 1D bed elevation was changed to fit the field-measured data, and in some occasions widths for the channel were modified as well. Changes in 1D channel cross-section are necessary, as changes in the cross-section effect channel conveyance and the overbanking volumes for each discharge. The changes employed are reported in Appendix C. These adjustments reflect the change between discrete point in time from the field-measured data in 2019 from 2012 and does not encompass the temporal changes that occur during the runoff event discussed in Section 2.2.

For areas between the restoration sites, where more than one field-measured cross-section was available, the intermediate cross section changes were interpolated. The aggradation-degradation cross-sections used in the 1D model are spaced approximately 500 feet apart. According to Samuel's Equation (Samuels, 1989), where the average bankfull depth of a cross section is approximately 3 to 4 feet, and the normal depth slope is 0.1%, the 500-foot spacing for cross-sections should be sufficient for conveyance equations convergence.

In HEC-RAS, 2D areas were connected to the 1D area by means of a lateral structure. The lateral structures were placed at the 1D/2D interface from the Middle Rio Grande to the restoration site, and at each excavated outlet and inlet. The lateral structure was treated either as a zero-height weir or with a normal 2D domain equation. Overflow calculations for the lateral structure were calibrated to field-measured velocities. A zero-height weir was typically used in locations where there was a natural barrier of 1 foot at the edge of the terrain. In other cases, the 2D domain equation produced more accurate results. The height of the lateral structure was clipped to 0.1 foot above the terrain, as required by HEC-RAS 2D. The cell-size for the 2D areas were set to a uniform cell size, varying from 5 to 15 feet across projects. A break line would be set near the lateral structure at inlets and outlets for the habitat feature with a spacing of 5 feet. This practice improves model stability across the 1D/2D interface. Figure 10 illustrates the HEC-RAS geometry for the restoration sites. These geometrical settings are reported in Appendix C.

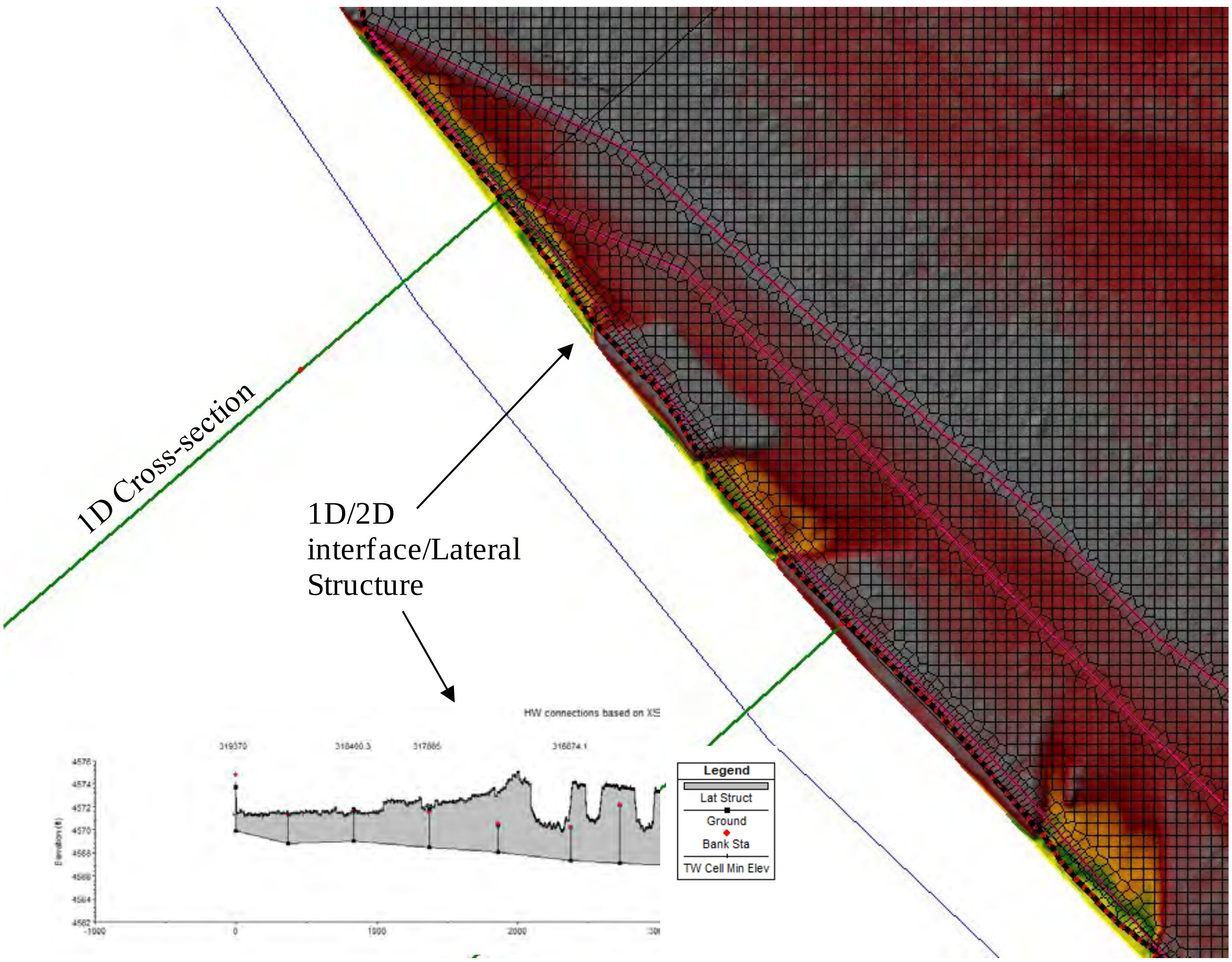


Figure 10. Components of a 1D/2D model.

Boundary conditions for the 1D portion of the model featured a flow hydrograph at the upstream boundary and normal depth at the downstream. Normal depth was based on a water surface elevation profile from April 2019 BOR rangeline bathymetry data. The water surface slope was generated based on three rangeline cross-sections near the downstream end of each model. The change of water surface elevation was divided by the distance between the rangelines to generate the normal depth.

The exception to the 1D/2D modeling method was RM 104.5, Escondida East. This feature is a regraded arroyo. The 1D/2D method produced high error at this location, perhaps due to high turbulence that has been observed at the site (restricted use data, 2019). The site was modeled as entirely 2D, using the 1D Agg-Deg bathymetry to correct for underwater topography. It was found in this method that the range of velocities within the restoration site conformed better to field-measured conditions. Because of the intensity of energy grade changes for this site, further monitoring data is recommended to validate the model.

2.3.2 Model Calibration

The models were calibrated based on 2019 field measurements of velocity and depth collected at each site around 2800 cfs. This data collection occurred on the rising limb of the spring runoff hydrograph. The HEC-RAS 1D/2D model was run at a discharge corresponding to the field data collection conditions for a duration of 4 to 8 model-hours, until the depth and velocities reached a constant value. A depth and velocity raster were generated at a time-step of "dynamic equilibrium" (where velocity and depth were no longer changing with time) and exported. In ArcGIS, the point field-measured data collection was compared to the modeled depth and velocity by using the "Extract Values by Points" tool. The root-mean-square error of the simulated hydraulics versus the field-collected data was calculated for all field-measured points. The mechanisms for calibration were modifying the Rio Grande channel/1D bed elevations, the weir computation method, or the vegetated roughness of the habitat restoration site. Modifications were reported in Appendix B.

Once calibrated, a simulation of 4000 cfs was run to compare with the Water Surface Elevations reported by GSA at a similar discharge. This validates whether the inundation extents were similar for a range of discharges. Following this validation, the hydraulic habitat suitability analysis was run.

2.3.3 Simulations and Spatial Analysis

The first step of the hydraulic habitat suitability analysis was to generate hydraulic profiles at a range of potential discharges for the Rio Grande. Simulations were run at 1000 cfs increments from 1000 cfs to 7000 cfs. If 1000 cfs simulations generated appreciable inundation (>0.5 acres), a 500 cfs simulation was also run. This occurred at RM 93.

2D modeling in HEC-RAS requires an unsteady state plan for inputting hydrology. The duration of the unsteady state simulation with a constant flow rate was run, and the output was selected for the simulation time where depths and velocities varied by less than 0.1 units over time, or "dynamic equilibrium". Generally, the simulation duration is 4 to 8 model-hours, with 15-minute to 1-hour result mapping intervals. The "Adjust Time Step Based on Courant" option was selected under "Advanced Time Step Control" in HEC-RAS. This ensures the model does not oscillate while seeking computation convergence. Oscillations may occur when the time-step and mesh size are not well-fit for the simulated velocities. The model calculation outputs were observed for errors. A 1D/2D flow error, for both 2D area storage and 1D/2D discharge, of 1% or less was the target for acceptable error.

In addition to discrete discharges, an unsteady simulation representing the 2019 spring runoff (April 1 to June 30) was ran to generate Percent Time Inundation (PTI) maps for the AB condition (Figure 11). The daily average discharge data was condensed to 15-minute time steps to reduce the computation time of the simulation. The PTI analysis demonstrates the duration of inundation throughout the restoration site and the surrounding terraces for the 2019 spring runoff.

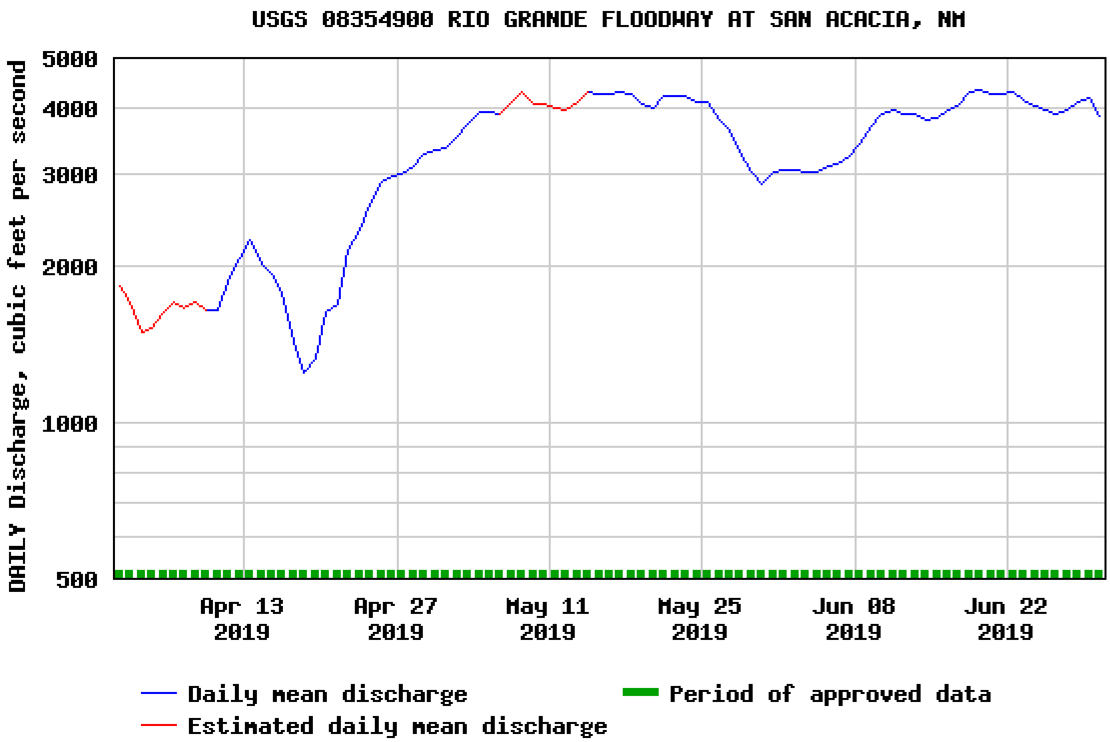


Figure 11. Discharge hydrograph used in the Percent Time Inundated (PTI) simulations.

3 - Results

3.1 Summary

Weighted useable area (WUA) and hydrologic evaluation can be used to generate performance metrics compared for each restoration site. These metrics can be used to evaluate change in performance over time as well as comparisons across different sites. The procedure transforms hydraulic analysis into habitat areas per discharge. The typical spring runoff event (2000-2019) evaluation represents an average annual performance for the sites in acre-days. An acre-day is a combination of duration and area. These criteria are correlated with floodplain habitat characteristics for the selected life stages of silvery minnow (adult and larvae).

The subsequent sections will discuss site-by-site performance. Tables 7 through 10 discuss general characteristics of the restoration sites and their performance. 10 presents the excavated area of each of the restoration sites. The sites varied from 1.4 to 17.2 acres, with a median of 3.4 acres (GSA 2020). The largest excavated sites: RM 93 and RM 103; are sites that did not completely inundate at the maximum simulated discharge. RM 93 contributed the largest WUA for larval fish within its restoration site boundaries. Both these projects were sited on locations that were previously disconnected from the river channel. Generally, the maximum areas of suitable larval habitat relative to the total excavated area did not exceed 50% meaning most of the site footprints either had depths or velocities that exceeded suitable habitat hydraulics.

Table 7. Summary of the Restoration Sites evaluated in this study.

SITE	EXCAVATED AREA (ACRES)	MAX. INUNDATION ON EXCAVATED AREA (ACRES)	MAX. INUNDATED: EXCAVATED AREAS (%)	MAX. LARVAL WUA ON EXCAVATED AREA (ACRES)	MAX. LARVAL: EXCAVATED AREAS (%)	MAX. TERRACE AREA (7000 CFS) (ACRES)
RM 93	17.2	12.2	71%	6.9	40%	60*
RM 99.5	3.5	3.4	97%	1.9	54%	16.5
RM 100	1.4	1.4	100%	0.6	43%	11.4
RM 100.5	8.2	8.2	100%	4.0	49%	22.8
RM 103	10.5	5.1	49%	1.6	15%	5.1
RM 104.5	3.2	2.9	91%	1.1	34%	1.2
RM 112	1.5	1.5	100%	0.7	47%	5.2
RM 114	1.7	1.6	94%	0.6	35%	16.2

*RM 93 is sited near a perched floodplain; the entire floodplain was not evaluated in the habitat hydraulics evaluation.

In the 2019 Annual Monitoring Results and Maintenance Plan for San Acacia Reach Restoration Sites, GSA evaluated sedimentation patterns throughout the restoration sites by comparing AB and PR topographies. Though sedimentation occurred at all sites, the habitat hydraulics were not necessarily negatively affected. RM 99.5, RM 100, RM 104.5, and RM 114 saw increases in suitable larval weighted useable areas for average spring runoff hydrology. Most sites saw less than 10% loss in performance amounting to a total average loss of 2.3 acre-days for larval life stage across all sites in a typical year. The site most negatively impacted by geomorphic change was RM 103: It appears that scouring has increased depths and velocities at this site.

Table 8. Summary of the Larval Hydraulic Habitat performance metrics for the evaluated sites.

SITE	AB TYPICAL LARVAL PERFORMANCE (ACRE-DAYS)	PR TYPICAL LARVAL PERFORMANCE (ACRE-DAYS)	% CHANGE IN PERFORMANCE IN 2019	PERFORMANCE: EXCAVATED AREA
RM 93	77.6	72.4	-7%	4.5
RM 99.5	26.4	28.9	9%	7.5
RM 100	9.6	11.1	16%	6.9
RM 100.5	42.4	38.3	-10%	5.2
RM 103	23.4	11.5	-51%	2.2
RM 104.5	13.2	12.7	-4%	4.0
RM 112	7.8	5.6	-28%	5.2
RM 114	7.1	8	13%	4.2

The restoration sites generally saw better performance for the adult life stage than larval, owed to a larger suitable hydraulic habitat envelope for the adult. RM 100 saw dramatic increases in site performance due to sedimentation over 2019. RM 99.5, RM 100.5, RM 104.5, and RM 112 had decreased areas of suitable hydraulics following sedimentation. Overall, the sites showed a 2% increase in suitable hydraulic habitat areas, or approximately 14.4 more acre-days on a given year. RM 104.5 and RM 112 showed decreased performance in both larval and adult life stages.

In evaluating all the sites, the most effective discharge for larval habitat is the 3000 cfs discharge increment (Figure 12). Generally, the post runoff sedimentation decreased the duration of hydraulics suitable for the larval life stage by 9%, or 18.2 acre-days. The duration of hydraulics suitable for the adult life stage increased by 3%. Cumulatively, the San Acacia restoration site projects provide 188.5 acre-days in an average year for larval life stage; and 690 acre-days for the adult life stage.

Table 9. Summary of the Restoration Sites evaluated in this study.

SITE	EXCAVATED AREA (ACRES)	MAX. INUNDATION ON EXCAVATED AREA (ACRES)	MAX. INUNDATED: EXCAVATED AREAS (%)	MAX. ADULT WUA ON EXCAVATED AREA (ACRES)	MAX. ADULT EXCAVATED AREAS (%)	MAX. TERRACE AREA (7000 CFS) (ACRES)
RM 93	17.2	12.2	71%	10.9	63%	60*
RM 99.5	3.5	3.4	97%	3.2	91%	16.5
RM 100	1.4	1.4	100%	1.1	78%	11.4
RM 100.5	8.2	8.2	100%	7.3	89%	22.8
RM 103	10.5	5.1	49%	3.3	31%	5.1
RM 104.5	3.2	2.9	91%	1.7	53%	1.2
RM 112	1.5	1.5	100%	1.3	86%	5.2
RM 114	1.7	1.6	94%	1.2	70%	16.2

Table 10. Summary of Adult Habitat Hydraulics performance results for the restoration sites.

SITE	AB TYPICAL ADULT PERFORMANCE (ACRE-DAYS)	PR TYPICAL ADULT PERFORMANCE (ACRE-DAYS)	% CHANGE IN PERFORMANCE IN 2019	PERFORMANCE: EXCAVATED AREA
RM 93	209.5	225.7	8%	12.2
RM 99.5	65.1	52	-20%	18.6
RM 100	19.6	29.8	52%	14.0
RM 100.5	121.3	116.3	-4%	14.8
RM 103	150.9	170.1	13%	14.4
RM 104.5	70.2	56.1	-20%	21.9
RM 112	18.8	18.6	-1%	12.5
RM 114	19.4	20.8	7%	11.4

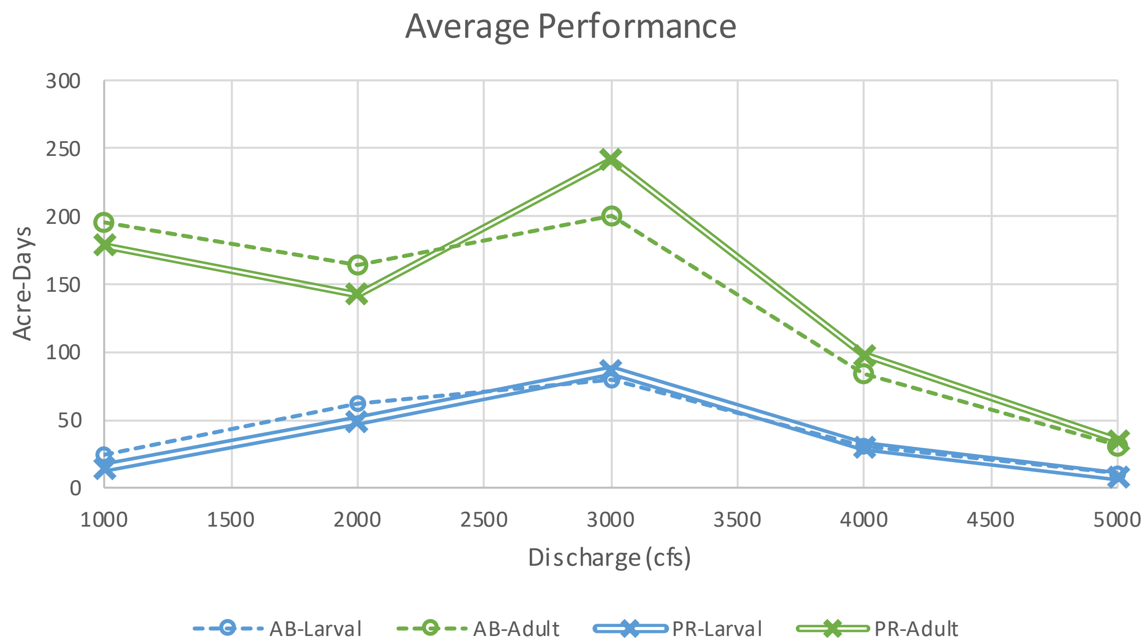


Figure 12. Cumulative effective hydraulic habitat for all restoration sites in this study. (AB= As-Built; PR = Post-Runoff models)

Identifying an associated parameter per discharge, such as a weighted useable area, makes this analysis eligible for an environmental flow (e-flow) evaluation. E-flow analysis transforms a discharge hydrograph into a graph showing habitat quantities over time by using an eco-value curve: a discharge and habitat quality relationship. The 2019 hydrograph is presented in Figure 13. In translating the species habitat requirements into performance metrics, it is important to address the temporality of inundation and how it affects what fish experience. The habitat effectiveness graphs presented in Figure 12 are helpful in demonstrating cumulative durations of available habitat at restoration sites, but does not present temporal inundation, which influences fish recruitment success. The eco-value curves presented in the site-by-site tables (first example in Table 11) may be input into HEC-EFM to generate e-flow hydrographs to evaluate daily and cumulative performance of sites based on annual hydrology. The resolution of data can help interpret noisy hydrographs and relevant events in the species life experience. HEC-EFM e-flow hydrographs are a useful tool for evaluating the performance of restoration sites and makes the hydraulic data useful for reach-wide habitat analysis.

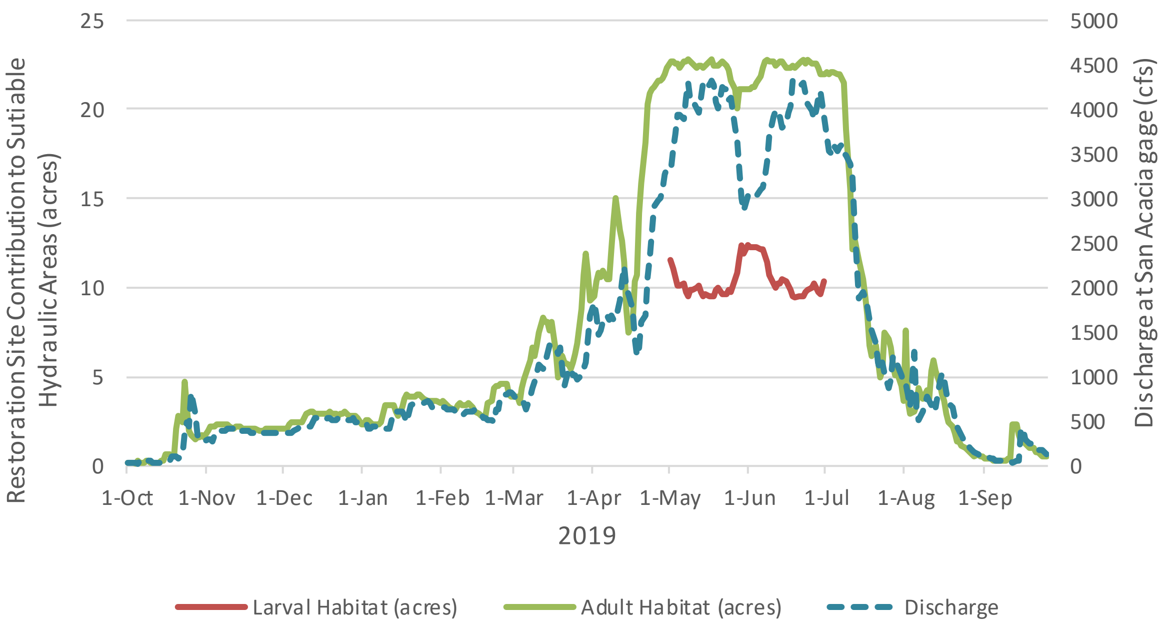


Figure 13. E-Flow Hydrographs generated in HEC-EFM presented with the discharge measured at the San Acacia gage throughout the 2019 water year.

In Figure 13, Larval Habitat represents the summation of the weighted useable area per discharge within the 8 San Acacia habitat sites. These summations represent areas that meet the depth and velocity criteria, scaled according to the larval HSI, during the larval life stage for the months of May and June, the spring runoff season. The weighted useable areas meeting depth and velocity criteria, according to the adult HSI, for Adult Habitat within the 8 restoration sites correlates proportionally with discharge, particularly at discharges less than 1500 cfs. At higher discharges, the e-flow results show that Larval Habitat does not necessarily increase with increasing discharge, with 3000 cfs producing more suitable habitat than the peak discharges of the spring runoff.

3.2 RM 93

3.2.1 Hydraulic Analysis for RM 93

Habitat Restoration Site RM 93 features 11 backwater channels that connect to a single side channel. The site was designed by the BOR with a starting inundation of 300 cfs. The active river channel adjacent to the restoration site visibly shifted to the east following the 2019 runoff, so there is some uncertainty about the change in channel capacity. The site is adjacent to a lower floodplain, which in the past captured water during flows above ~3500 cfs (Figure 14).

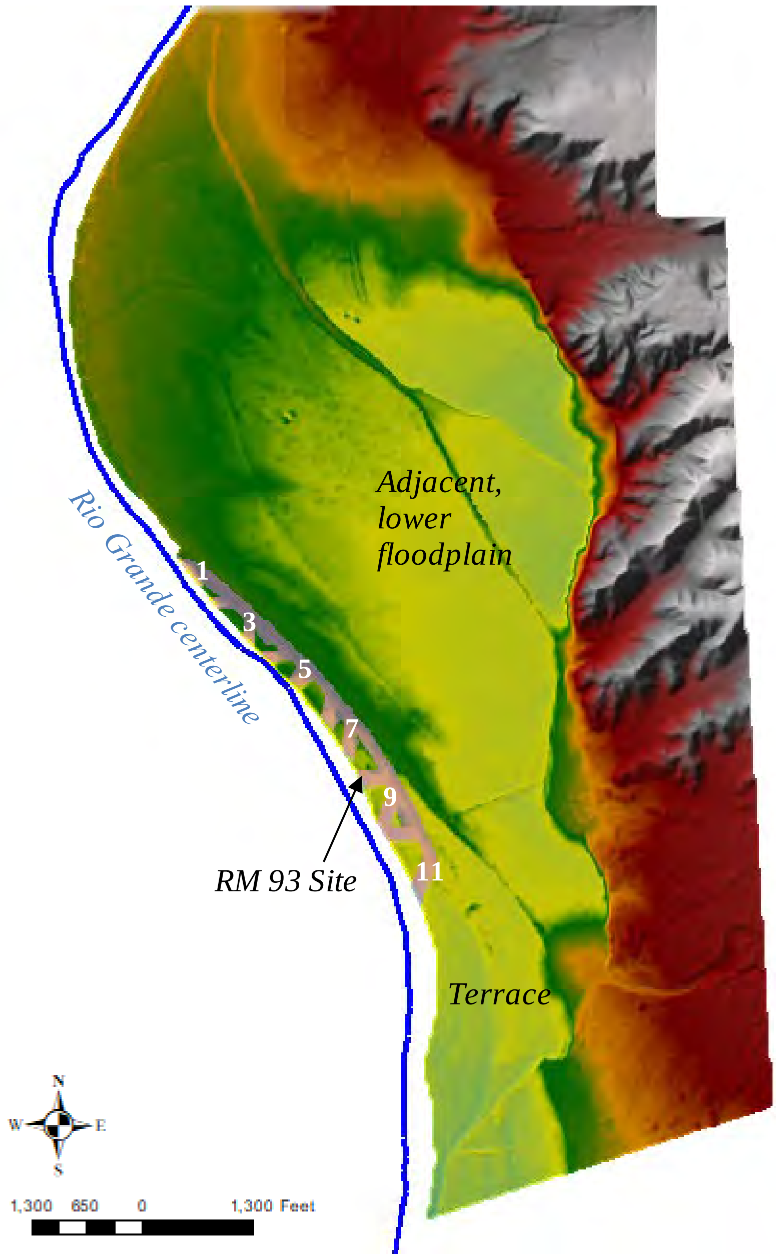


Figure 14. RM 93 relative to surrounding floodplain. Odd-numbered embayments are labeled.

The floodplain was simulated for conservation of water volume, but due to the lack of validation data, the suitable hydraulics in this area was not quantified. The terrace downstream of the restoration site was evaluated as the surrounding terrace. Dramatic changes in the terrace total area are attributed to the changes in the Rio Grande geomorphic planform.

The construction of RM 93 concluded in the winter of 2019. During the spring runoff of that same year the river widened and reduced the lengths of several embayments (numbers 7-10, see Figure 14). Generally, the sedimentation at these embayments improved the hydraulics for the larval life stage, as demonstrated in the AB and PR comparison in the following figure (Figure 15). However, total area of inundation decreased for this site due geomorphic changes on the Rio Grande reducing the lengths of the embayments.

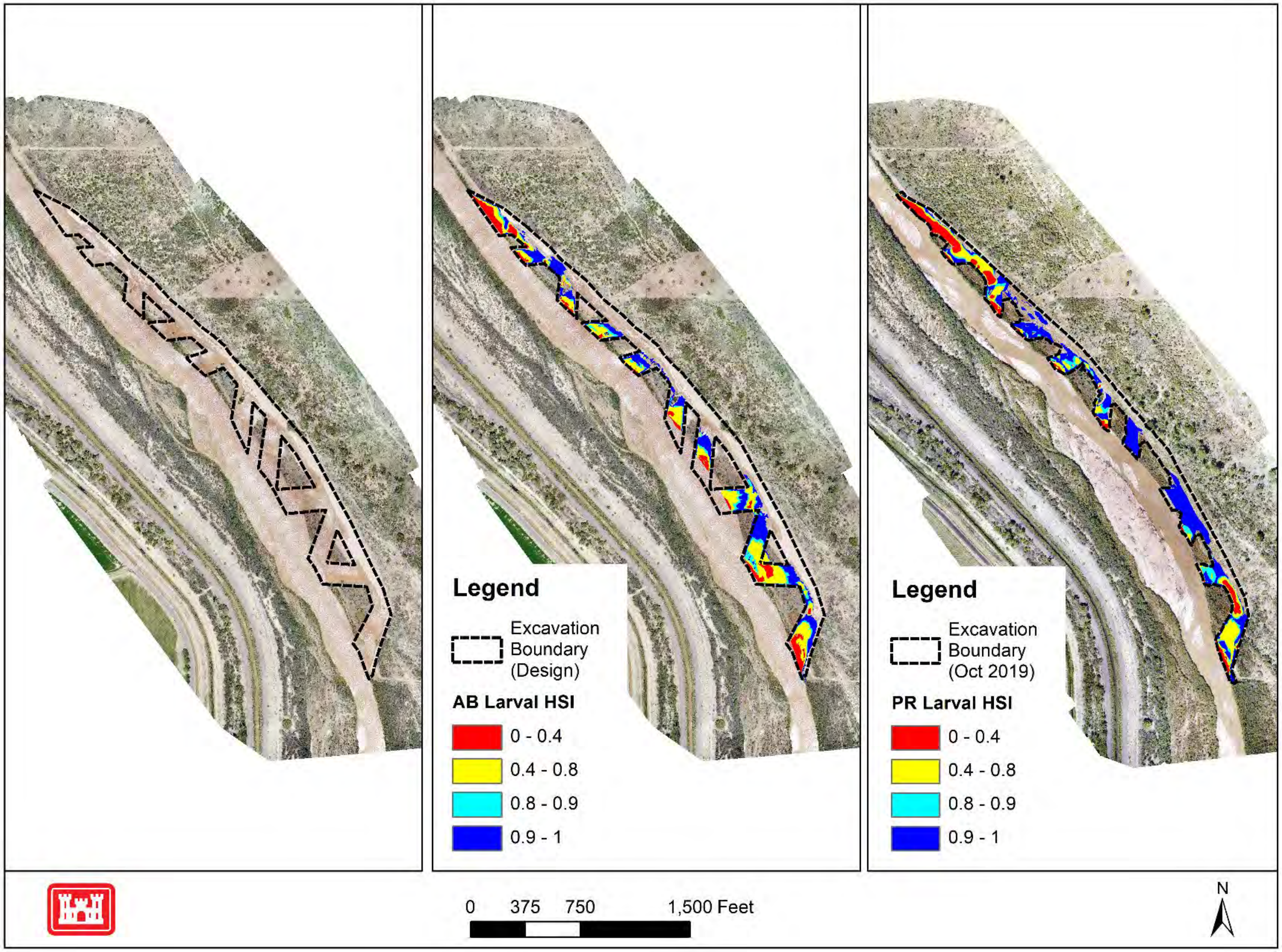


Figure 15. RM 93, from left to right: Hydraulic suitability maps for larval RGSM at approximately 2800 cfs in 1) the AB condition (aerial photography from GSA 2020 collected in May 2019), and 2) the PR condition (aerial photography from GSA 2020 collected in October 2019).

At RM 93, site performance generally improved for the adult life stage during discharges exceeding 3000 cfs. From the AB to the PR condition, areas of suitable hydraulic habitat for the larval fish decreased. Though, generally, the hydraulics for larval fish improved in embayments 4-10, the upstream three embayments became connected with water moving too fast for a high hydraulic HSI rating. In addition, the length of embayments and habitat area decreased due geomorphic changes in the river (Figure 15). This culminated in a decrease of suitable hydraulics for the larval life stage.

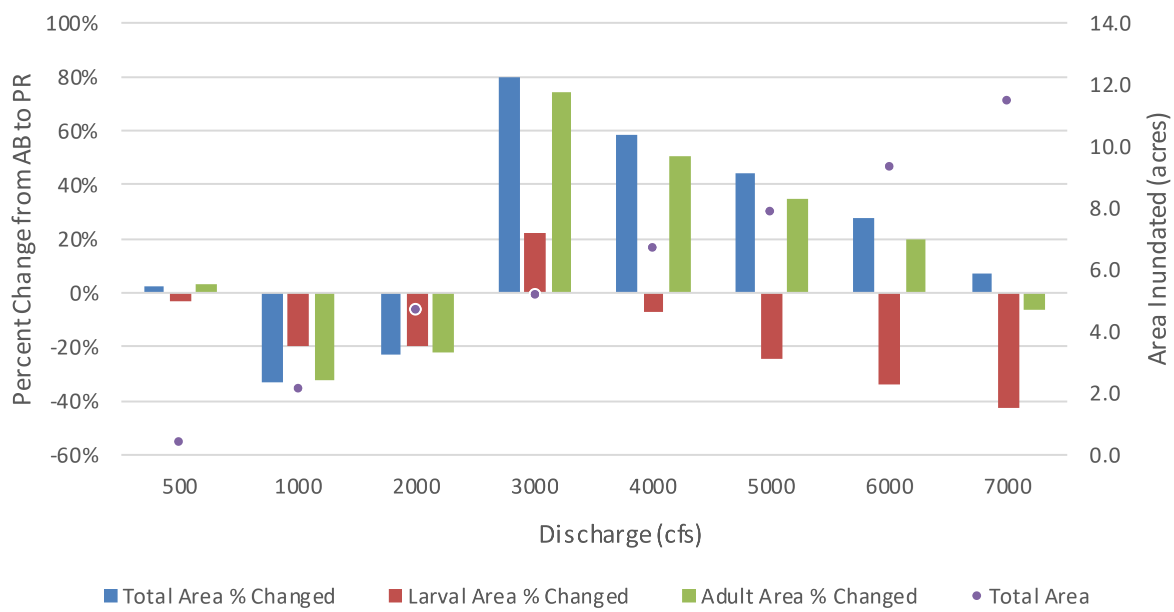


Figure 16. RM 93 percent change in inundation areas in the PR and AB suitable hydraulics for larval and adult life stages of RGSM within the restoration construction footprint.

Generally, the PR condition improved site conditions for silvery minnow hydraulics on the terrace and for the adult life stage. Areas of inundation both on the downstream terrace and for the restoration site increased following geomorphic change and the sedimentation of 2019. Areas of suitable hydraulics for the adult life stage increased, while larval hydraulics remained the same or deteriorated once discharges exceeded 4000 cfs. This is owed to decreased areas of suitable velocities for the larval life stage.

The downstream terrace began showing inundation at 1000 cfs. The floodplain upstream of the restoration site showed significant inundation as soon as discharges began overbanking (Figure 17). The inundated areas on the terraces provide suitable hydraulics for the adult life stage.

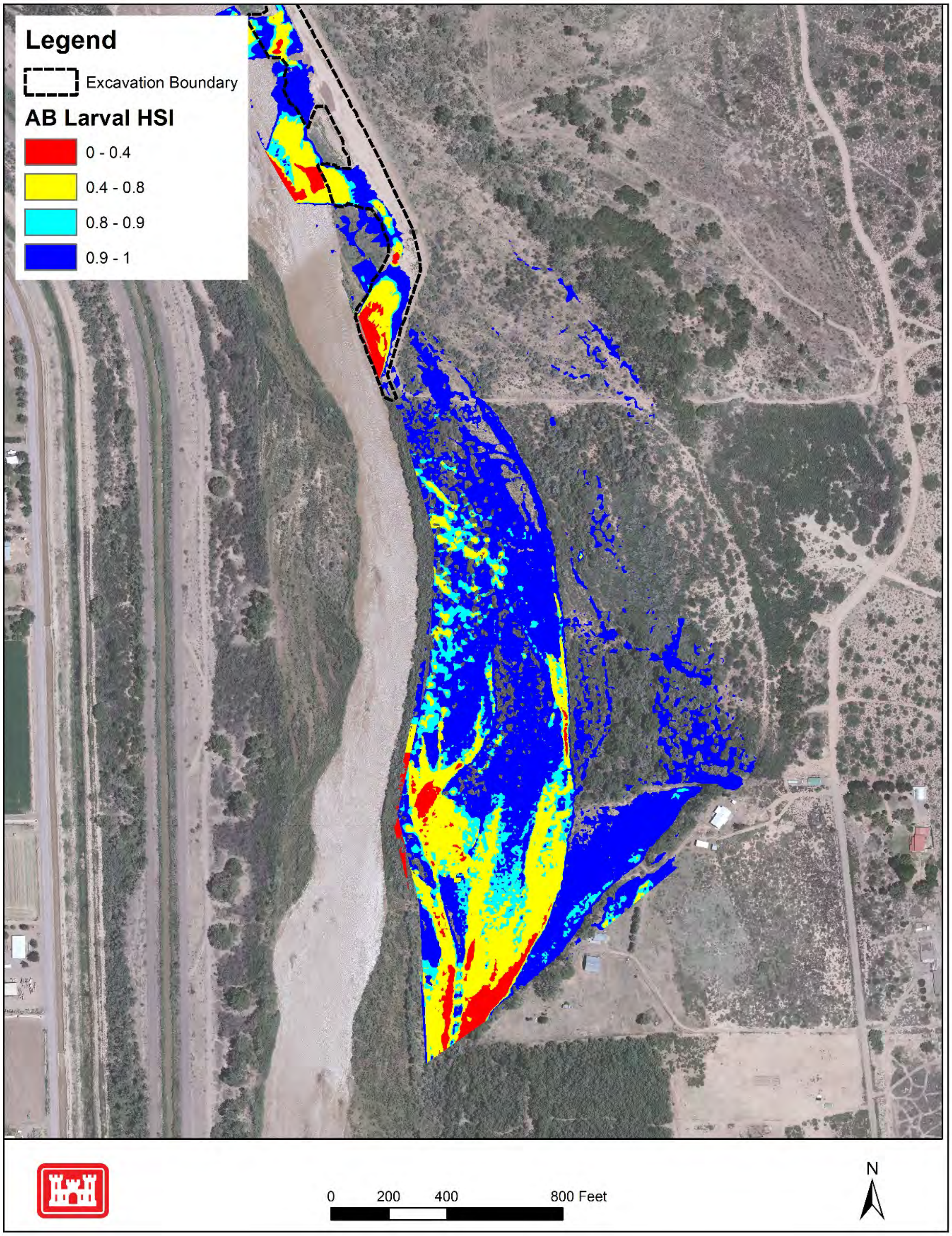


Figure 17. Hydraulic suitability maps of the RM 93 downstream terrace for larval RGSM at approximately 2800 cfs in the AB condition. Aerial photography is an ArcMap Imagery base map.

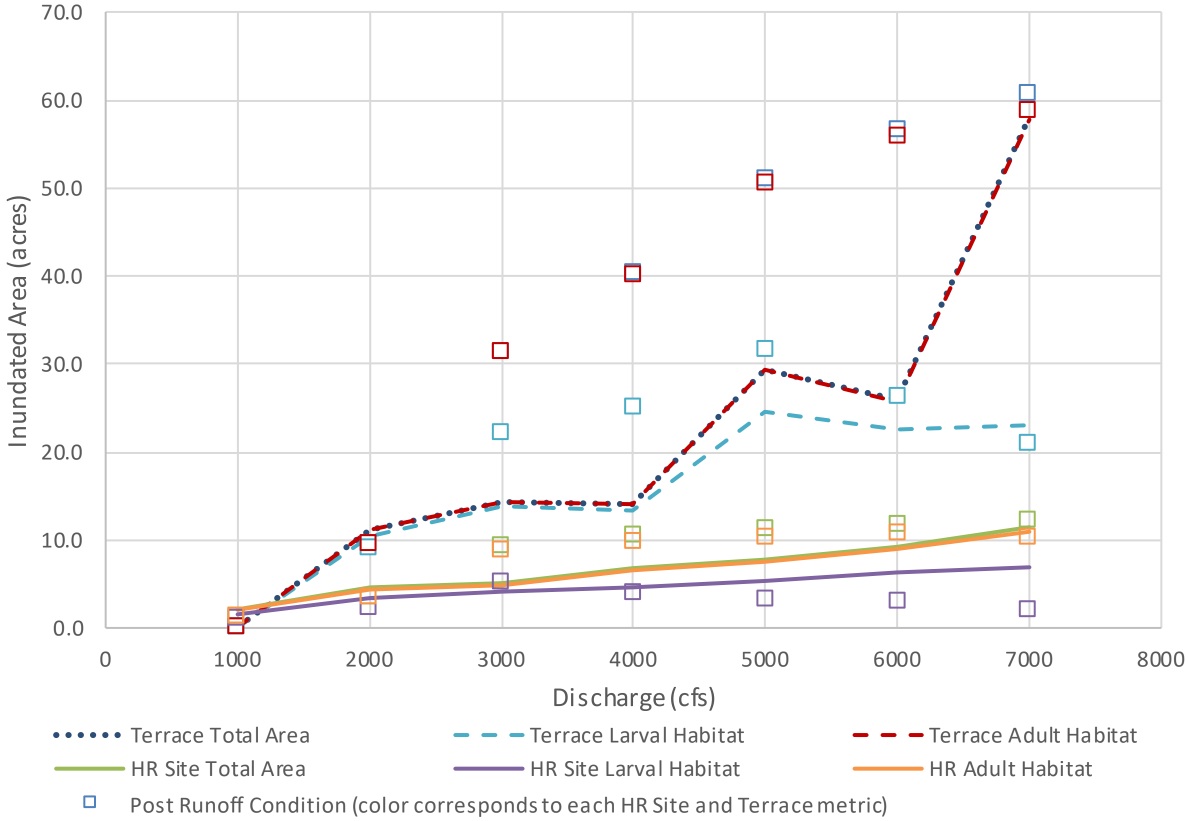


Figure 18. RM 93 Areal results for AB (shown as line graphs) and PR (shown as square points) scenarios for adult and larval life stages of the RGSM on constructed habitat restoration (HR) site footprint and the adjacent floodplain (Terrace).

Table 11. Hydraulic suitability areal acreages for the AB terrain for RM 93 (corresponds to HR Site data presented in Figure 18).

		LARVAL			ADULT		
DISCHARGE (CFS)	**Total Area (ACRES)**	**Velocity (ACRES)**	**Depth (ACRES)**	**Both (ACRES)**	**Velocity (ACRES)**	**Depth (ACRES)**	**Both (ACRES)**
500	0.4	0.3	0.3	0.2	0.4	0.4	0.4
1000	2.1	1.7	1.9	1.5	2.1	2.1	2.1
2000	4.7	3.9	3.8	3.3	4.7	4.5	4.5
3000	5.2	4.8	4.2	4.0	5.1	5.0	5.0
4000	6.7	5.5	5.5	4.6	6.6	6.5	6.5
5000	7.9	6.5	6.2	5.2	7.8	7.6	7.5
6000	9.3	7.9	7.3	6.2	9.2	9.0	9.0
7000	11.5	9.1	8.7	6.9	11.4	11.0	10.9

Table 12. Habitat suitability areal acreages for the PR terrain of RM 93

		LARVAL			ADULT		
DISCHARGE (CFS)	**Total Area (ACRES)**	**Velocity (ACRES)**	**Depth (ACRES)**	**Both (ACRES)**	**Velocity (ACRES)**	**Depth (ACRES)**	**Both (ACRES)**
500	0.4	0.3	0.3	0.2	0.4	0.4	0.4
1000	1.4	1.2	1.3	1.1	1.4	1.4	1.4
2000	3.6	2.7	3.1	2.4	3.6	3.5	3.5
3000	9.3	6.0	8.0	5.2	9.0	9.0	8.8
4000	10.6	5.1	8.8	4.1	10.2	10.3	9.9
5000	11.3	4.4	8.9	3.3	10.7	10.9	10.3
6000	11.8	4.1	9.1	3.0	11.2	11.4	10.8
7000	12.2	3.0	8.5	2.0	10.8	11.6	10.2

3.2.2 Hydrology Analysis for RM 93

Recent hydrology is combined with the hydraulics to quantify performance of RM 93 in both 2019 and on an average year. The peak performance for both adult and larval stages of the minnow for this site are associated with the 3000 cfs discharge (Figure 19). This site is unique from the other restoration sites, in that during an average year and the AB condition, the area of ideal adult habitat is highest at the lowest discharges and decreases performance as discharges increase. Following sedimentation in the PR condition, the effective performance becomes more typical (relative to other sites in this study) as a parabolic curve. For larval fish, the typical performance is 78 acre-days in the AB condition. Sedimentation decreased this by 7%. For the adult life stage, performance is 210 acre-days in the AB condition. Areas of suitable hydraulics for the adult life stage increased following sedimentation. This site is the largest of the restoration sites in this study and contributes the most area and duration of suitable hydraulics. Models of this location would benefit from more evaluation of the river channel's bathymetry, as there was significant geomorphic change in the surrounding area following the 2019 runoff.

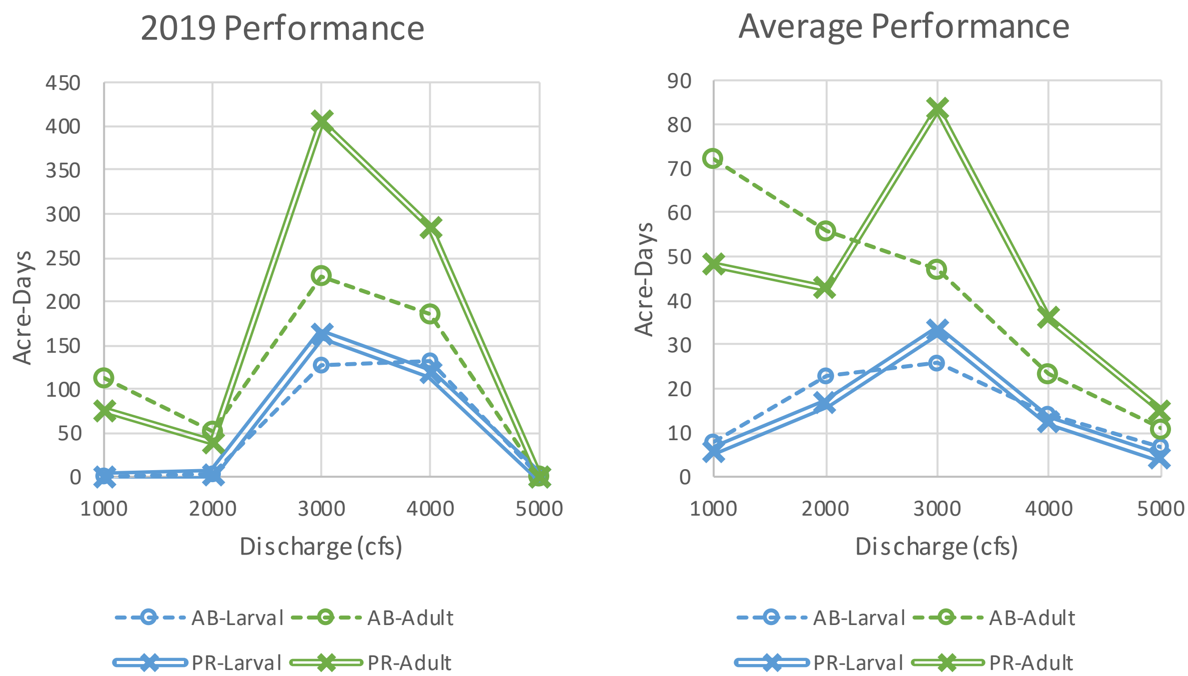


Figure 19. Hydraulic habitat effectiveness curve based on frequency of discharge events from 1000 to 5000 cfs. Note the difference in scale on the y-axis for the two figures.

Percent time inundated for the 2019 Spring runoff is shown in Figure 20. The side channel is shown to be connected between the second and third embayments of the feature. All embayments showed high durations of inundation throughout the runoff. The embayment inundated length varied from 130 to 250 feet. The terrace downstream of the site demonstrates a shorter duration of inundation during the runoff. This inundation is a combination of local overbanking from the Rio Grande, as well as returning flows from the surrounding, perched floodplain.

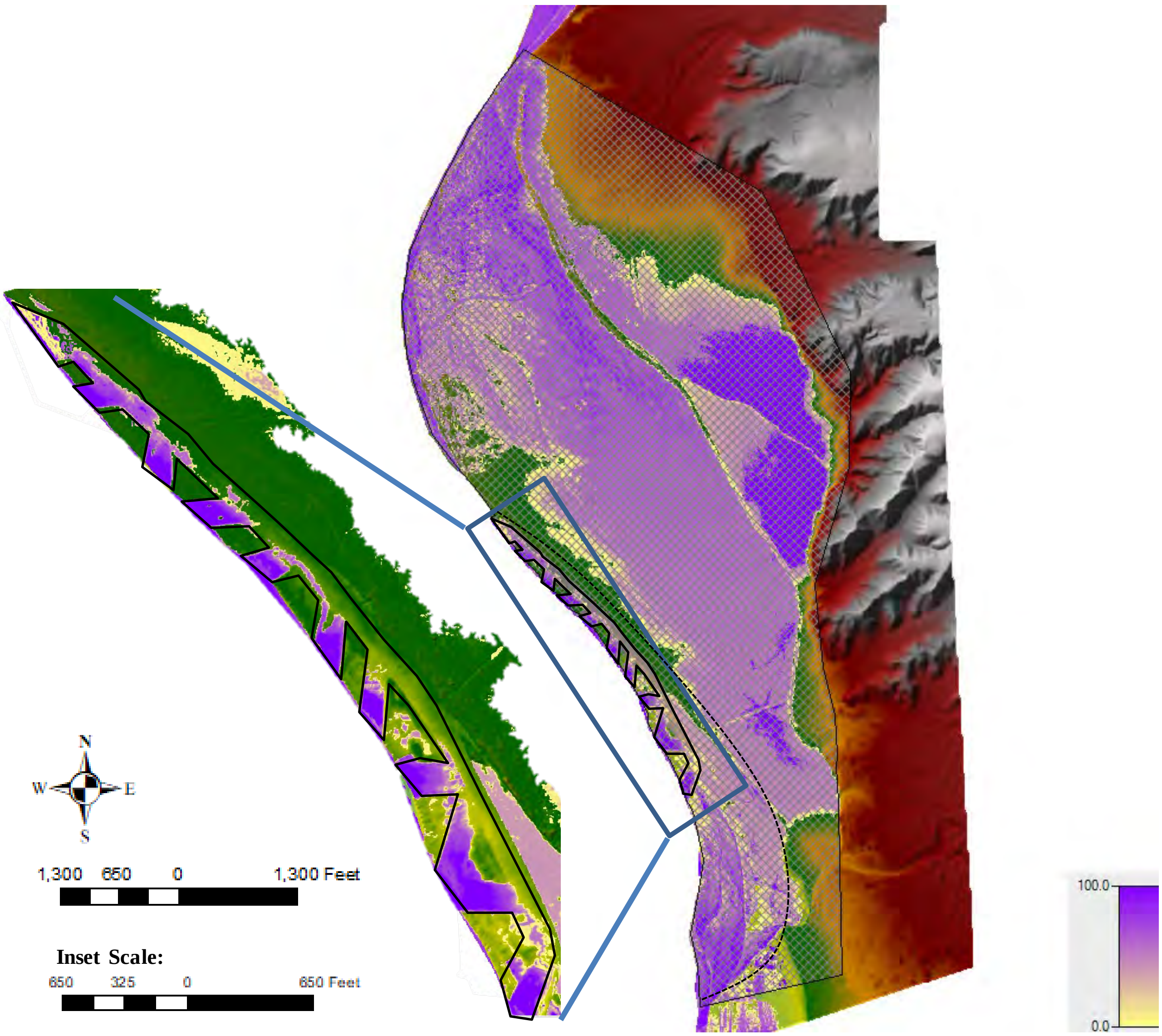


Figure 20. Percent time inundated map for RM 93. Inset is the excavated area. Outlined by a dashed line is the terrace in Habitat Hydraulics evaluation.

3.3 RM 99.5

3.3.1 Hydraulic Analysis for RM 99.5

Habitat Restoration Site RM 99.5 consists of four backwater channels that connect. The excavated project area covers an area of 3.5 acres. It was designed by the ISC, with a design inundation starting at 800 cfs (GSA 2020). The 2D area covered 23.3 acres, though only 19.9 acres became inundated at the maximum discharge simulation (7000 cfs). The restoration site shows that some of the embayments are becoming more narrowly channelized in the PR condition relative to the AB condition (Figure 21). The restoration site became fully inundated at 4000 cfs.

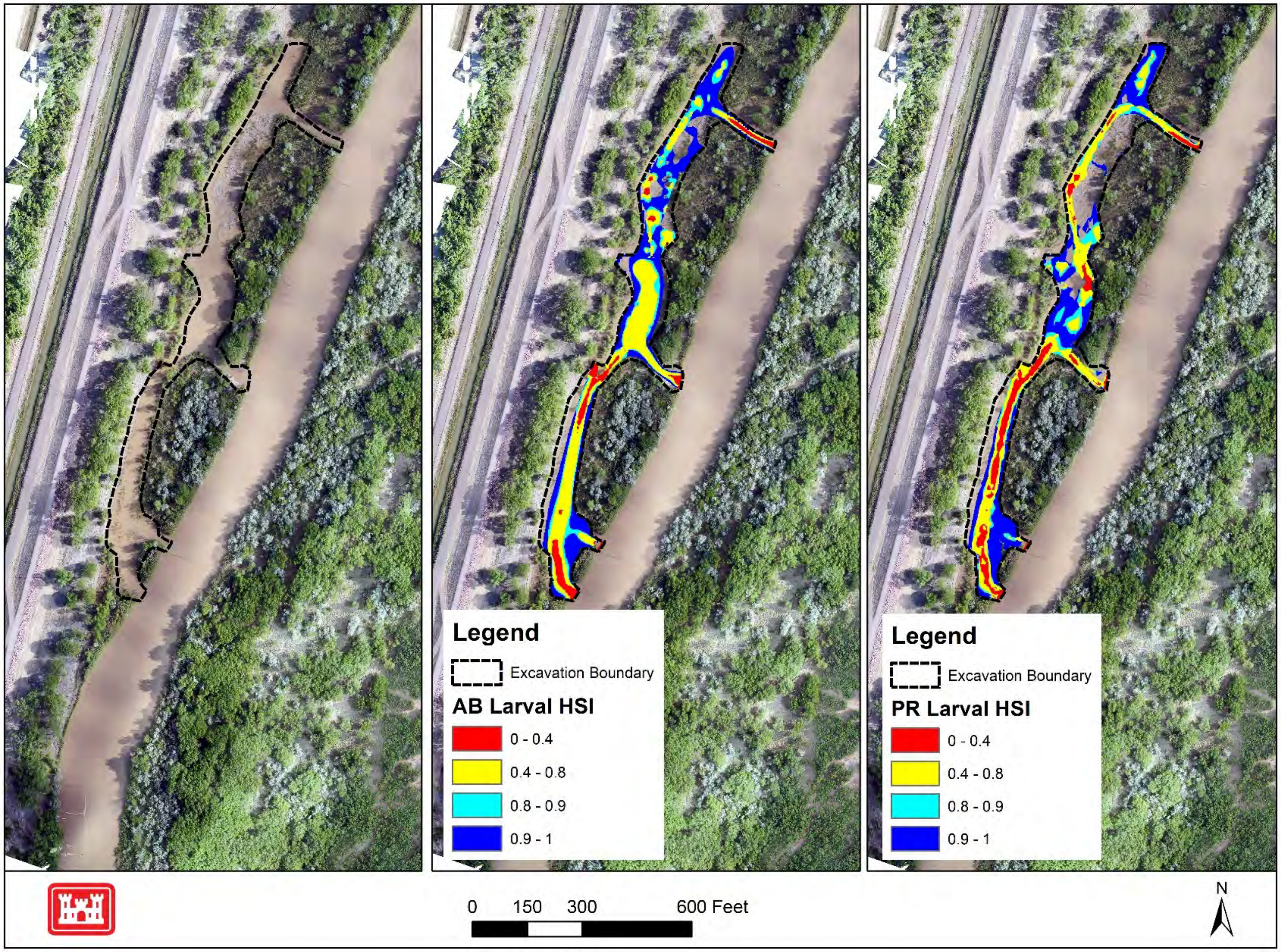


Figure 21. RM 99.5, from left to right: 1) Aerial photograph (GSA 2020) collected at 4130 cfs; hydraulic suitability maps for larval RGSM at for the excavated area at approximately 2800 cfs in 2) the AB condition, and 3) the PR condition.

There were great gains of suitable hydraulic habitat from the non-constructed floodplain once the restoration site extents were exceeded. The lower discharges (1000-3000 cfs) showed decreased suitable habitat for the larval and adult life stages for the silvery minnow following sedimentation from the PR (Figure 22). Though the percent of change at the lower discharges were high, the magnitude of inundated area was not strongly affected due to low areas of inundation.

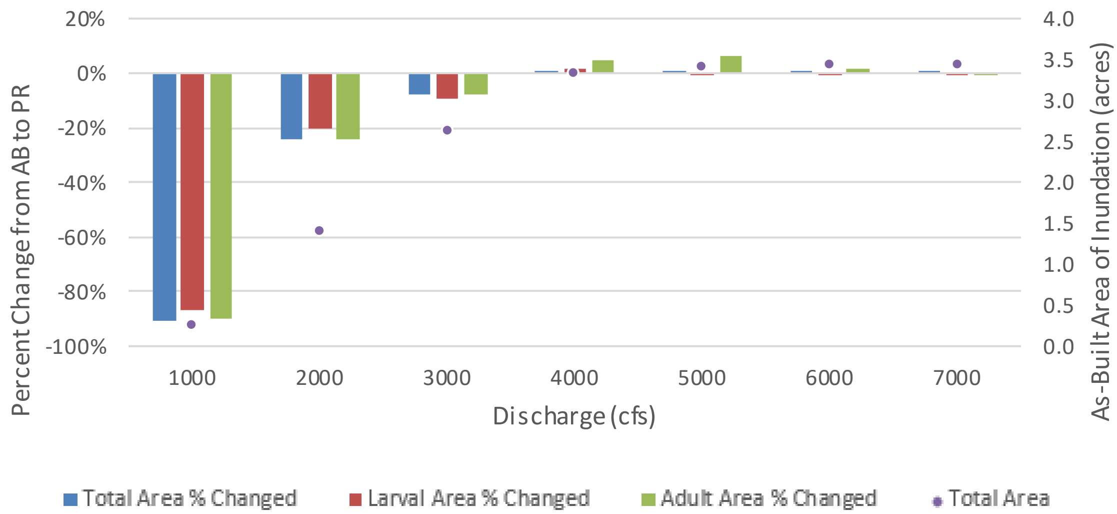


Figure 22. RM 99.5 percent change in inundation areas in the PR and AB suitable hydraulics for larval and adult life stages of RGSM within the restoration construction footprint.

The restoration site shows that areas of suitable hydraulics increase with increasing discharge up to 3000 cfs for the larval life stage, and up to 4000 cfs for the adult life stage (Figure 23). The floodplain surrounding RM 99.5 (called a terrace) was shown to start inundating at 2000 cfs. PR conditions strongly aligned with original, AB areas.

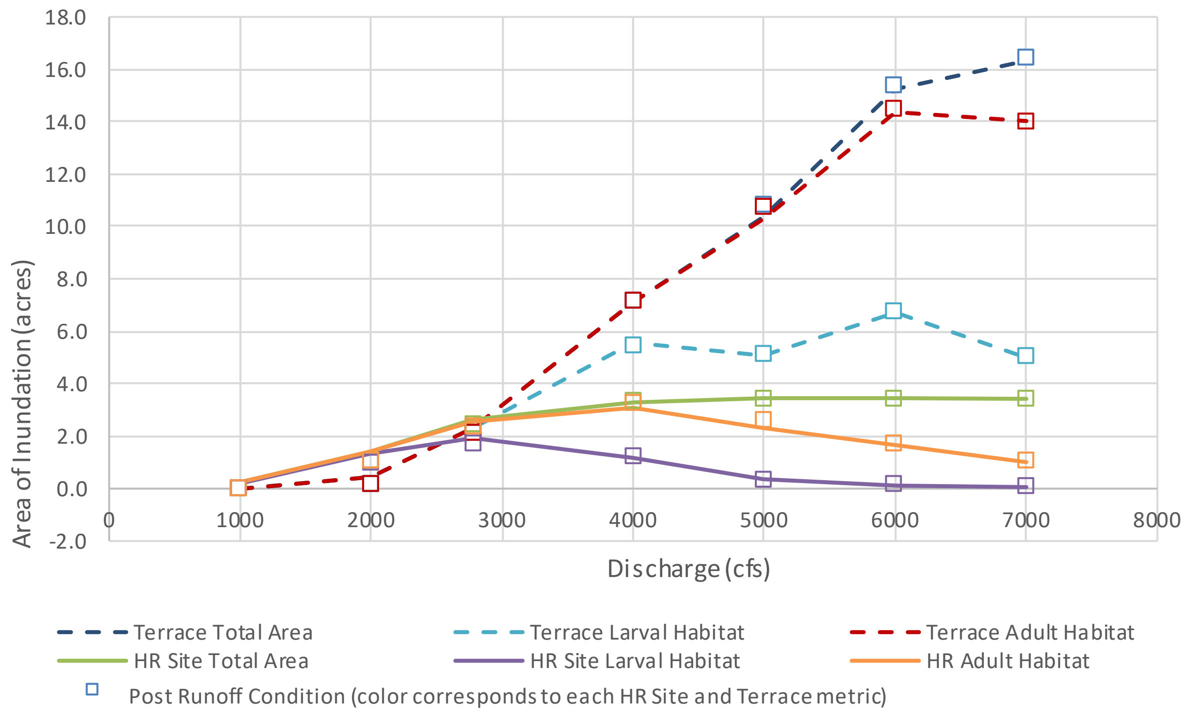


Figure 23. RM 99.5 Areal results for AB (shown as line graphs) and PR (shown as square points) scenarios for adult and larval life stages of the RGSM on constructed habitat restoration (HR) site footprint and the adjacent floodplain (Terrace).

Table 13. Hydraulic suitability areal acreages for the AB terrain for RM 99.5 (corresponds to data presented in Figure 23).

		LARVAL			ADULT		
DISCHARGE (CFS)	**Total Area (ACRES)**	**Velocity (ACRES)**	**Depth (ACRES)**	**Both (ACRES)**	**Velocity (ACRES)**	**Depth (ACRES)**	**Both (ACRES)**
1000	0.2	0.2	0.2	0.2	0.2	0.2	0.2
2000	1.4	1.4	1.3	1.3	1.4	1.4	1.4
2780	2.6	2.3	2.2	1.9	2.6	2.6	2.6
4000	3.3	1.7	2.0	1.2	3.3	3.1	3.1
5000	3.4	0.8	1.0	0.3	3.3	2.4	2.3
6000	3.4	0.6	0.5	0.1	3.1	1.7	1.6
7000	3.4	0.4	0.2	0.1	2.9	1.1	1.0

Table 14. Habitat suitability areal acreages for the PR terrain of RM 99.5

		LARVAL			ADULT		
DISCHARGE (CFS)	Total Area (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)
1000	0.02	0.01	0.02	0.01	0.02	0.02	0.02
2000	1.1	1.0	1.0	1.0	1.0	1.1	1.0
2780	2.4	1.9	2.2	1.7	2.4	2.4	2.4
4000	3.3	1.7	2.2	1.2	3.3	3.2	3.2
5000	3.4	0.8	1.0	0.3	3.3	2.6	2.6
6000	3.4	0.6	0.5	0.1	3.1	1.8	1.7
7000	3.5	0.4	0.2	0.0	2.9	1.1	1.0

3.3.2 Hydrology Analysis for RM 99.5

Hydrology data was paired with hydraulic performance to determine the duration of suitable habitat for each site. For RM 99.5, the area of suitable larval habitat increased by 9% in the average year from the AB to the PR condition. The area of adult habitat decreased by 20%. The PR condition provides 29 acre-days of inundation in an average year for larval fish, and 52 acre-days for adult (Figure 24).

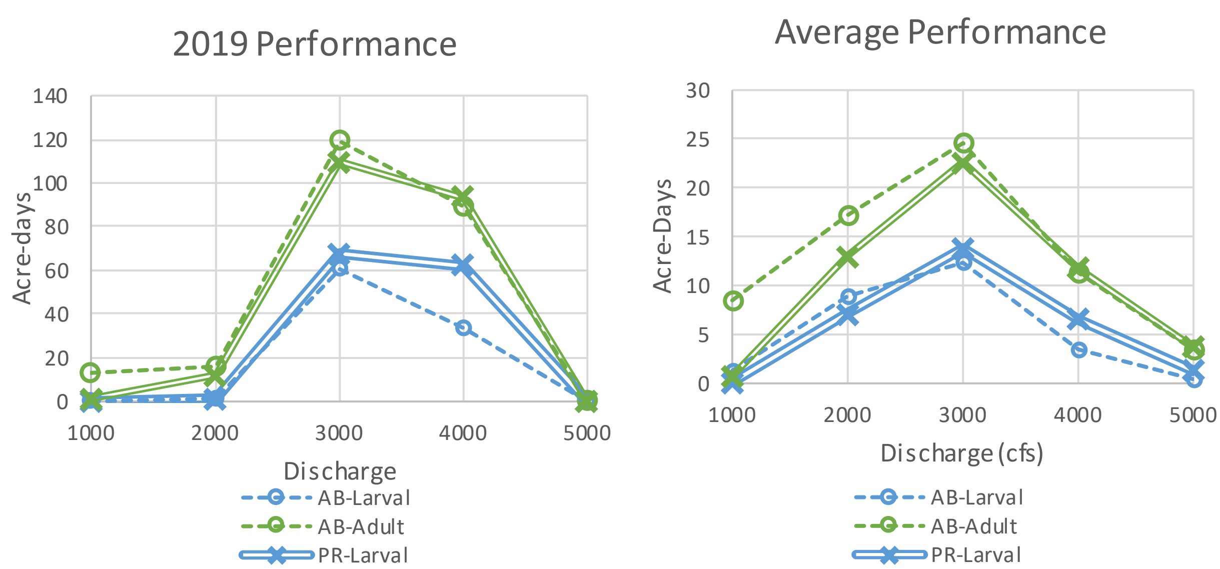


Figure 24. Hydraulic habitat effectiveness curve based on frequency of discharge events from 1000 to 5000 cfs. Note the difference in scale on the y-axis for the two figures.

The percent time inundated map for RM 99.5 showed that the embayments and interior of the restoration site were inundated for a long duration of the 2019 spring runoff (Figure 25). Much of the site was inundated for 85 to 100% of the duration, and the surrounding terrace varied from approximately 40 to 100% duration, with some fringe areas inundated for less than 10% of the season.

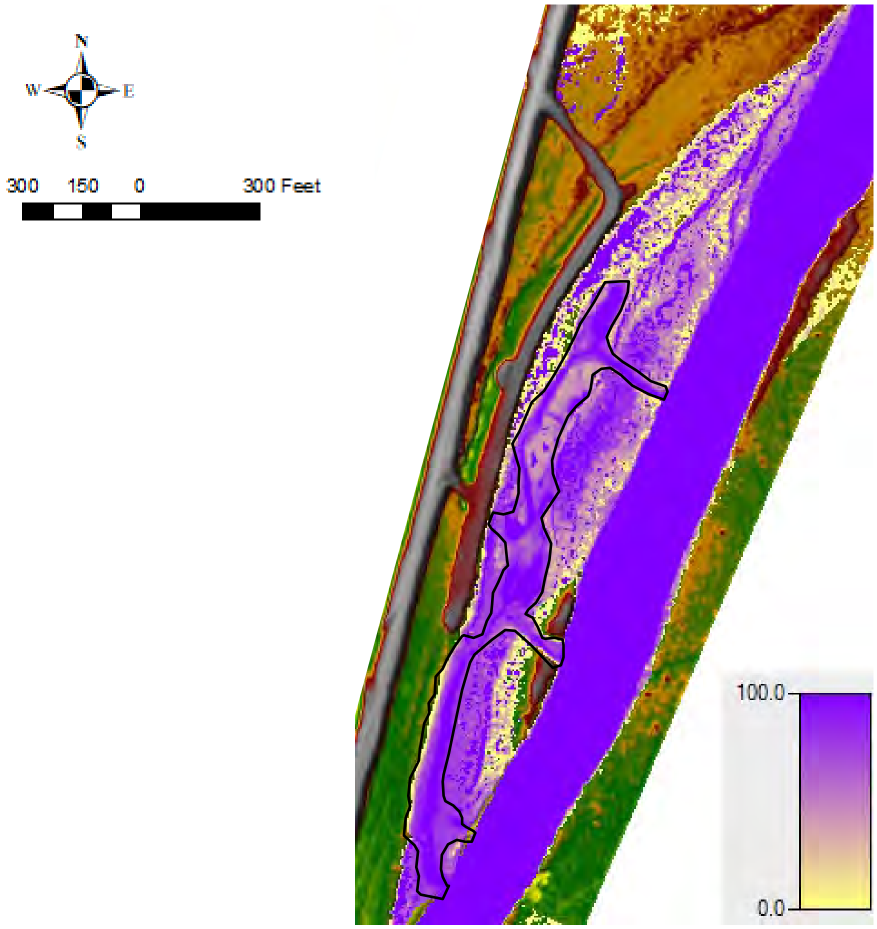


Figure 25. Percent time inundation map for RM 99.5 based on the 2019 Spring hydrograph.

3.4 RM 100

3.4.1 Hydraulic Analysis for RM 100

Habitat Restoration Site RM 100 is a backwater channel that covers an area of 1.4 acres. It was designed by the ISC, with a design inundation starting at 800 cfs (GSA 2020). The 2D area covered 14.7 acres. The restoration site is incised relative to the surrounding floodplain, which is not a lowered terrace relative to its surroundings. This indicates that when higher discharges enter the 2D area, similar hydraulics may be expected in the leveed floodplain area, referred to as a terrace. There is evidence of a natural side channel on the floodplain that enters the 2D area and backwater from northwest of the project site (Figure 26).

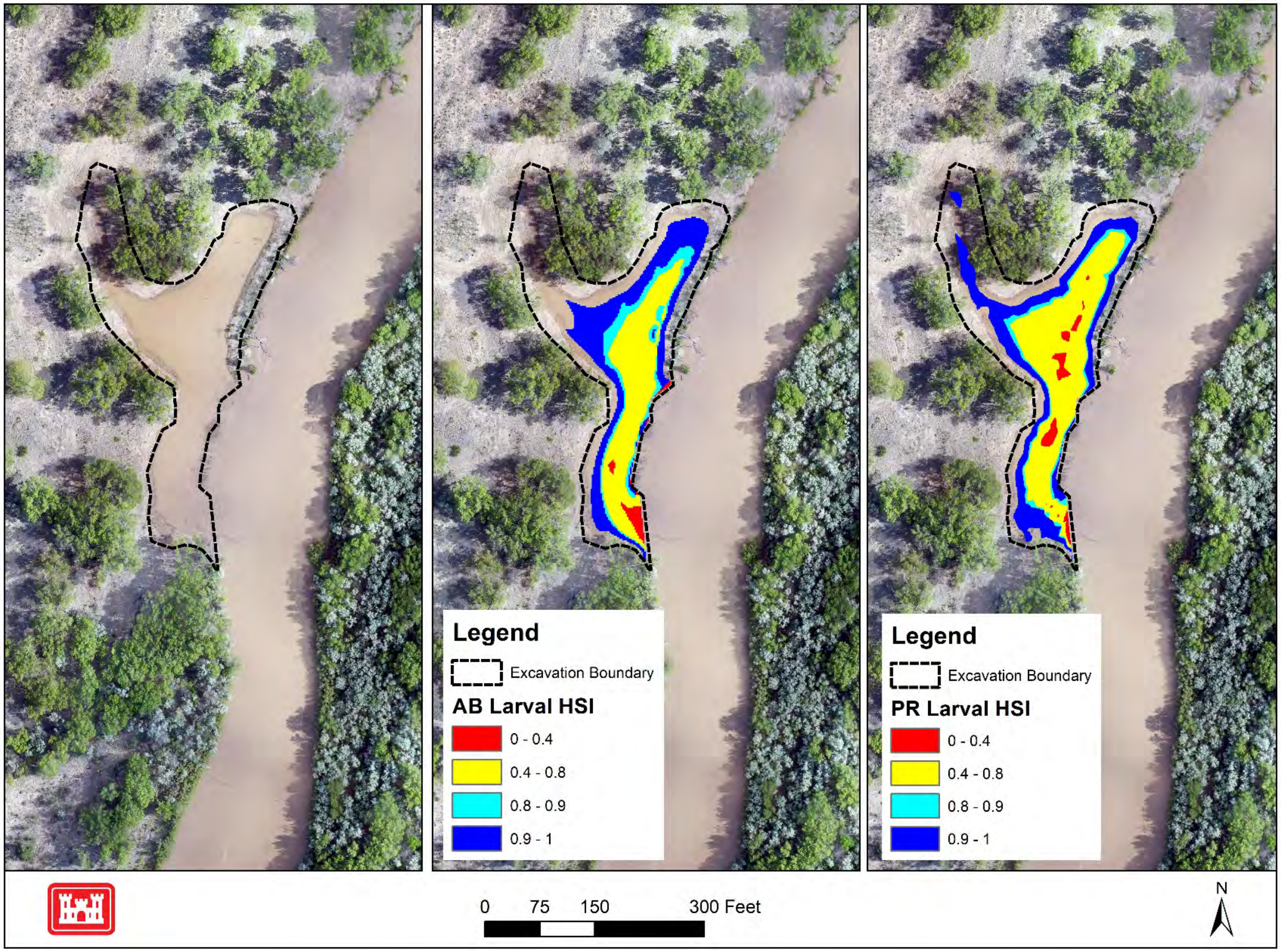


Figure 26. RM 100, from left to right: 1) Aerial photograph (GSA 2020) collected at 4130 cfs; hydraulic suitability maps for larval RGSM at approximately 2800 cfs in 2) the AB condition, and 3) the PR condition.

The restoration site has a natural berm separating much of the backwater from water entry; however, the berm was compromised during high flows in 2019. Following the recession of flows, the natural berm generated again. This phenomenon was not simulated in the models, due to lack of geotechnical information needed to simulate the feature's sloughing.

From the AB to PR condition, total areas of inundation per discharge increased (Figure 27). The magnitude of suitable habitat also increased. This resulted to 2-15% gains in ideal hydraulic habitat. The gains were most pronounced for 1,000 cfs, where inundated area increased from 0.05 acres to 0.2 acres.

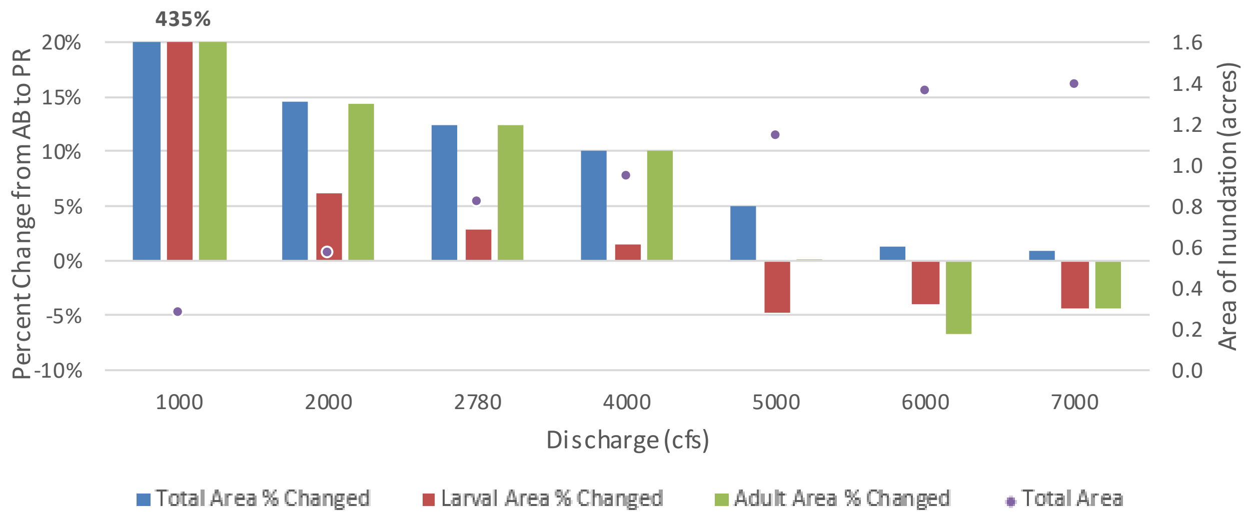


Figure 27. RM 100 percent change in inundation areas in the PR and AB suitable hydraulics for larval and adult life stages of RGSM within the restoration construction footprint.

The small site footprint for RM 100 limits its ability to contribute areas of suitable hydraulic habitat. However, due to the incised nature of the channel relative to the floodplain, this project provides 100% of the available suitable hydraulic habitat from 1000 to 4000 cfs. The site was shown to improve in areas of ideal habitat following the PR condition, but these gains were not significant in terms of absolute acreage. Once the non-constructed surrounding floodplain terrace starts inundating, at 5000 cfs, 100% of the inundated area was shown to be ideal adult hydraulic habitat and at least 85% of the area is ideal larval habitat.

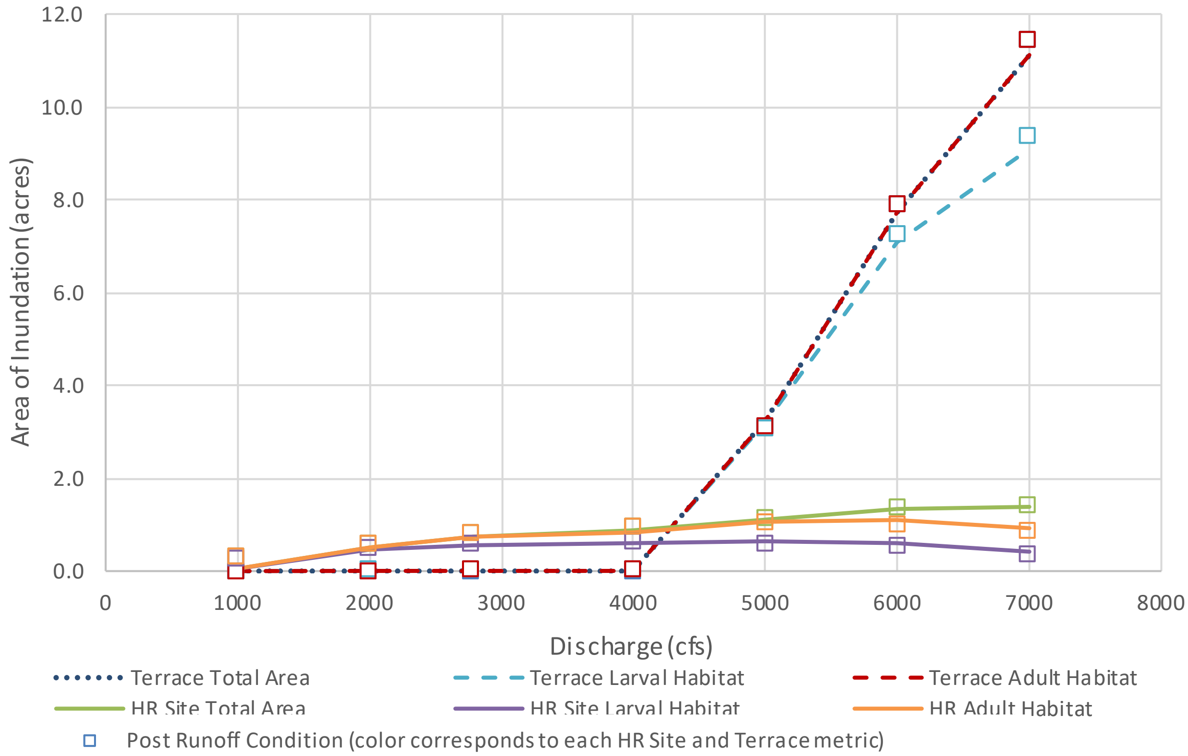


Figure 28. RM 100 Areal results for AB (shown as line graphs) and PR (shown as square points) scenarios for adult and larval life stages of the RGSM on constructed habitat restoration (HR) site footprint and the adjacent floodplain (Terrace).

Table 15. Hydraulic suitability areal acreages for the AB terrain for RM 100 (corresponds to data presented in Figure 28).

		LARVAL			ADULT		
DISCHARGE (CFS)	Total Area (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)
1000	0.05	0.05	0.05	0.05	0.05	0.05	0.05
2000	0.5	0.5	0.5	0.5	0.5	0.5	0.5
2780	0.7	0.7	0.6	0.5	0.7	0.7	0.7
4000	0.9	0.8	0.6	0.6	0.9	0.9	0.8
5000	1.1	1.0	0.7	0.6	1.1	1.1	1.1
6000	1.4	1.1	0.7	0.6	1.4	1.1	1.1
7000	1.4	1.0	0.5	0.4	1.4	0.9	0.9

Table 16. Habitat suitability areal acreages for the PR terrain of RM 100

		LARVAL			ADULT		
DISCHARGE (CFS)	Total Area (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)
1000	0.3	0.3	0.3	0.3	0.3	0.3	0.3
2000	0.6	0.6	0.5	0.5	0.6	0.6	0.6
2780	0.8	0.8	0.6	0.6	0.8	0.8	0.8
4000	0.9	0.9	0.6	0.6	0.9	0.9	0.9
5000	1.1	1.0	0.6	0.6	1.1	1.1	1.1
6000	1.4	1.1	0.6	0.5	1.4	1.0	1.0
7000	1.4	1.0	0.4	0.4	1.4	0.9	0.9

3.4.2 Hydrology Analysis for RM 100

The areas of suitable habitat provided by RM 100 increased by 15% for the larval condition in an average year, and by 52% for the adult condition. In the PR condition, the average year generates 11 acre-days of larval fish habitat and 30 acre-days of adult fish habitat (Figure 29).

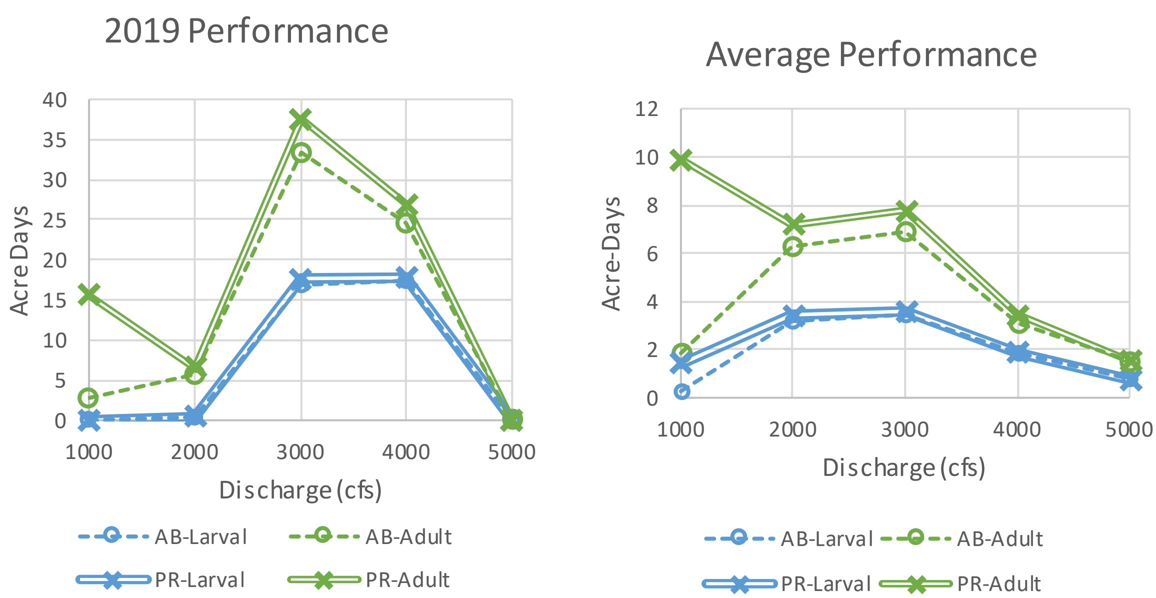


Figure 29. Hydraulic habitat effectiveness curve based on frequency of discharge events from 1000 to 5000 cfs. Note the difference in scale on the y-axis for the two figures.

The percent time inundation for this site from 2019 shows that the near-channel section of the embayment was inundated for most of the runoff (Figure 30). Much of the site was inundated for at least 65% of the runoff's duration. The surrounding floodplain/terrace was also inundated during the spring runoff, though at a lesser degree. Much of this inundation was owed to upstream sheet flow on the floodplain.

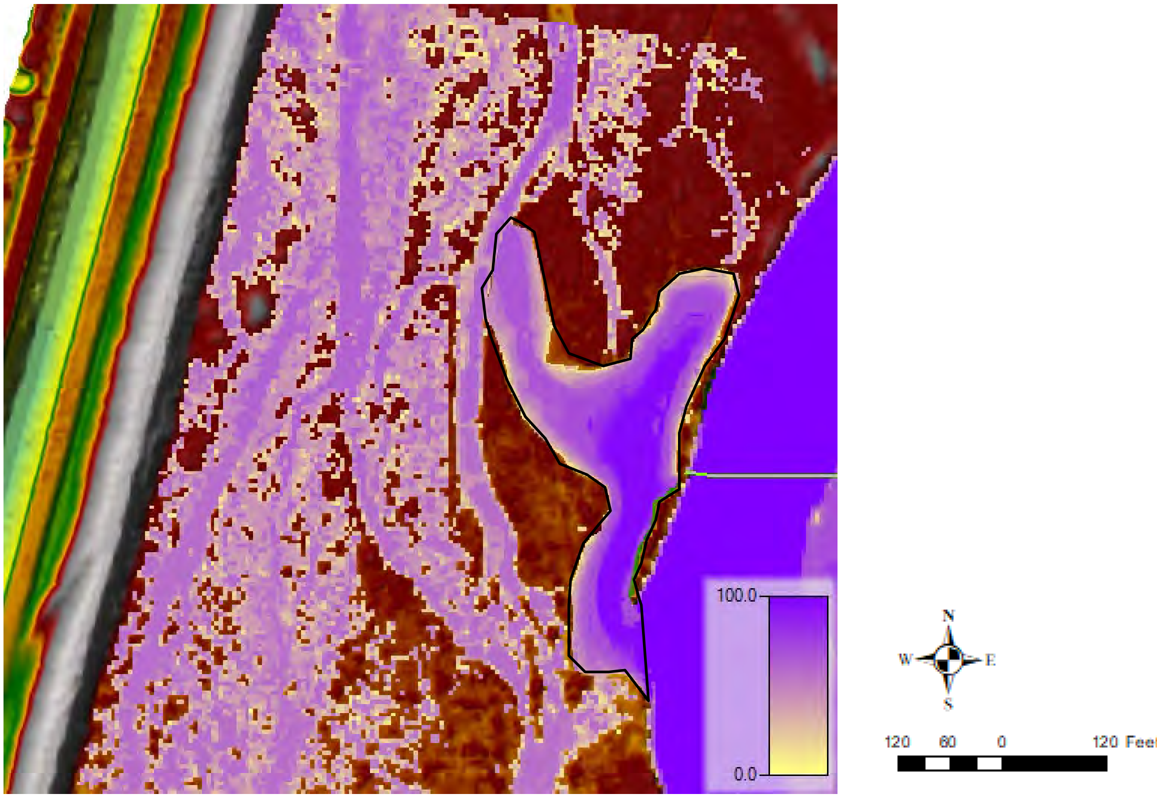


Figure 30. Percent time inundated map from the Spring 2019 hydrograph.

3.5 RM 100.5

3.5.1 Hydraulic Analysis for RM 100.5

Habitat Restoration Site RM 100.5 was a constructed area of 8.2 acres and was designed by the ISC. The design features included two backwater channels with a design incipient inundation of 800 cfs (GSA 2020). According to GSA's 2019 spring runoff monitoring evaluations, the site began inundating at these low discharges and had suitable average velocities throughout the site. The 2D area modeled, including the entire floodplain that could contribute flow to this restoration area, was 41 acres, though only 32 acres was inundated at the maximum simulated discharge. The RM 100.5 Site was mapped based on hydraulic suitability indices to generate a weighted useable area for the AB and the PR terrains (Figure 31).

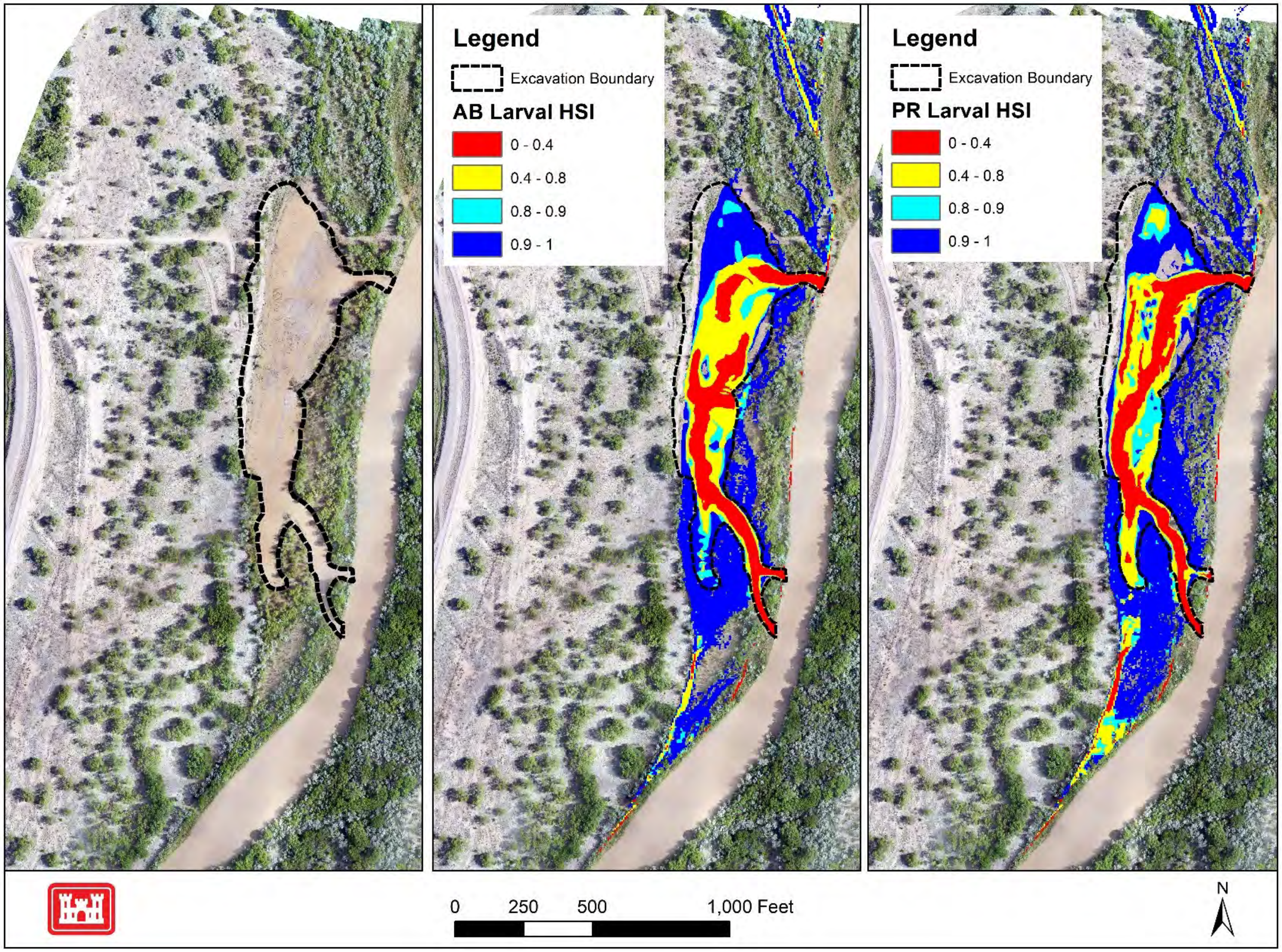


Figure 31. RM 100.5, from left to right: 1) Aerial photograph (GSA 2020) collected at 4130 cfs; hydraulic suitability maps for larval RGSM at 2800 cfs in 2) the AB condition, and 3) the PR condition.

This site was found to generally not have suitable hydraulic areas for the species life stages in its interior, where a higher velocity flow channel connects the upstream inlet to the downstream outlets. Following the sedimentation from the runoff (i.e., the post runoff condition), areas of appropriate hydraulics for larval fish at lower discharges was reduced by as much as 25 percent (Figure 32), as total areas of inundation were reduced in the 1000 to 2780 cfs simulations. , Otherwise, the percent change in area of suitable hydraulics for the restoration site was typically less than 5%.

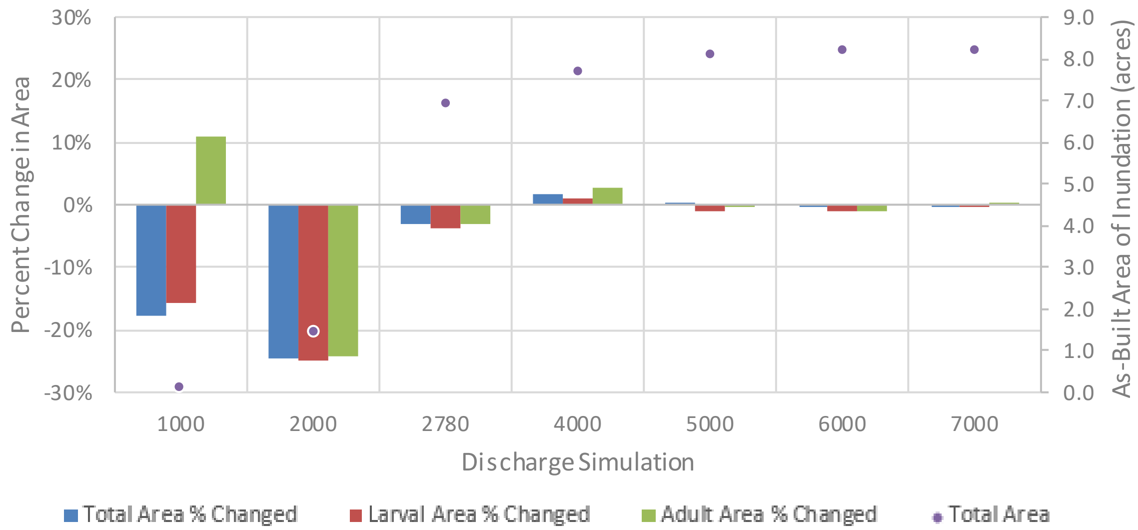


Figure 32. RM 100.5 percent change in inundation areas in the PR and AB suitable hydraulics for larval and adult life stages of RGSM within the restoration construction footprint.

Figure 33 shows that at the lower discharges, 1000 to 2000 cfs, the restoration site provides suitable hydraulics for both the larval and adult life stages of the minnow, whereas the surrounding terrace does not. At 4000 cfs, the terrace provides up to 10 acres of suitable hydraulics for the larval fish. At discharges exceeding 4000 cfs, both the HR site and the terrace generate less larval habitat, due to increasing velocities and depths. Suitable hydraulics for the adult life stage shows a similar decline starting at 5000 cfs. Though total inundation area increased as discharges increased, the physical parameters limited the available hydraulic habitat, and there was shown to be a decreasing trend of available suitable habitat for larval fish starting at 4000 cfs and for adult fish at 3000 cfs on the restoration site.

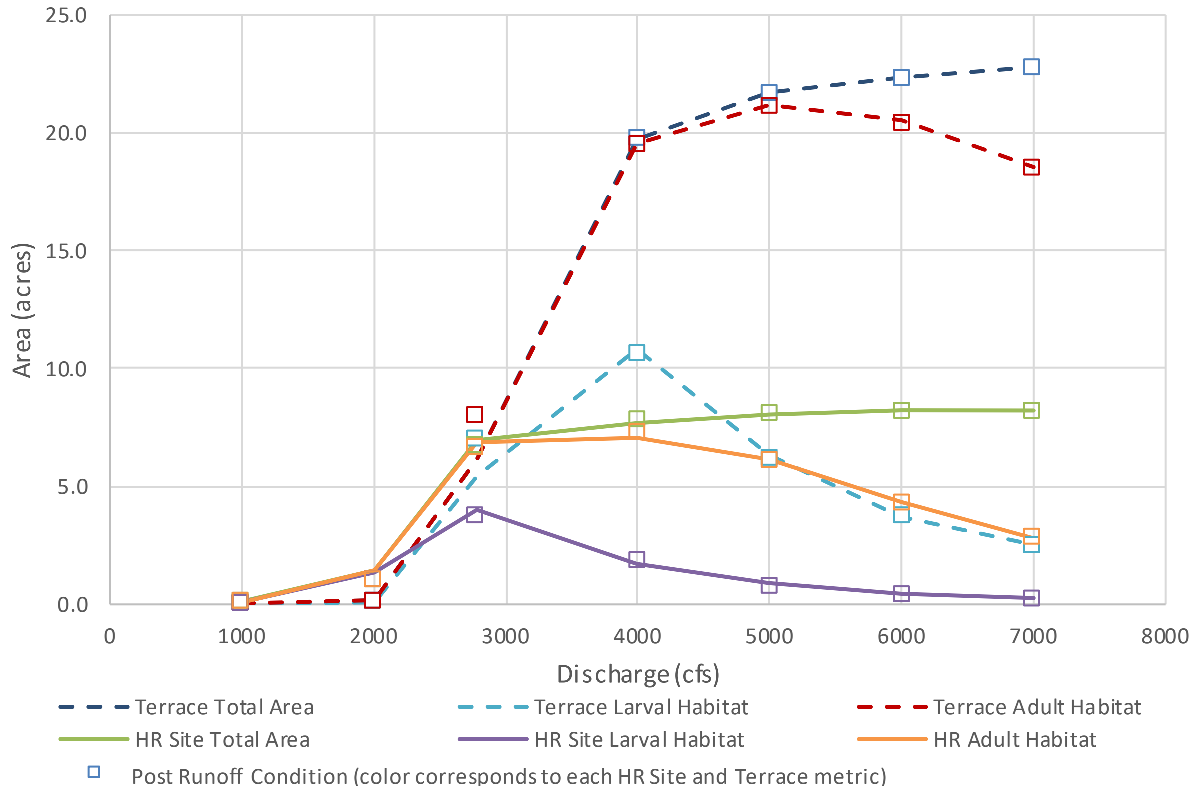


Figure 33. RM 100.5 Areal results for AB (shown as line graphs) and PR (shown as square points) scenarios for adult and larval life stages of the RGSM on constructed habitat restoration (HR) site footprint and the adjacent floodplain (Terrace).

Table 17. Hydraulic suitability areal acreages for the AB terrain for RM 100.5 (corresponds to data presented in Figure 33).

		LARVAL			ADULT		
DISCHARGE (CFS)	Total Area (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)
1000	0.1	0.1	0.1	0.1	0.1	0.1	0.1
2000	1.4	1.4	1.4	1.4	1.4	1.4	1.4
2780	7.0	4.4	6.1	4.0	6.9	6.9	6.9
4000	7.7	2.8	4.3	1.8	7.5	7.2	7.1
5000	8.1	1.7	2.6	0.9	7.6	6.4	6.2
6000	8.2	1.1	1.3	0.5	7.4	4.7	4.4
7000	8.2	0.8	0.7	0.3	7.0	3.1	2.8

Table 18. Habitat suitability areal acreages for the PR terrain of RM 100.5

		LARVAL			ADULT		
DISCHARGE (CFS)	Total Area (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)
1000	0.1	0.1	0.1	0.1	0.1	0.1	0.1
2000	1.1	1.0	1.0	1.0	1.1	1.1	1.1
2780	6.7	4.2	5.7	3.8	6.7	6.7	6.7
4000	7.8	2.8	4.4	1.8	7.7	7.4	7.3
5000	8.1	1.6	2.4	0.8	7.6	6.4	6.1
6000	8.1	1.0	1.2	0.4	7.3	4.6	4.3
7000	8.2	0.4	0.6	0.2	7.0	3.1	2.8

3.5.2 Hydrology Analysis for RM 100.5

For RM 100.5, the hydraulic habitat effectiveness for all life stages of the minnow peaks at 3000 cfs. Though the 4000 cfs discharge generates more habitat for the adult (see Figure 34), the 3000 cfs events are more frequent, both in 2019 and from the average annual frequency from 2000 to 2019. Generally, the PR condition would generate up to 12% more habitat for the adult life stage in the average year during the 3000 cfs flows. There are losses for the larval fish areas and duration, by about 20% from the AB condition at 2000 cfs. The sedimentation and the average year have a net change in acre-days of an increase of 4%, or 5.2-acre days for the larval stage and 11.1 acre-days for the adult stage.

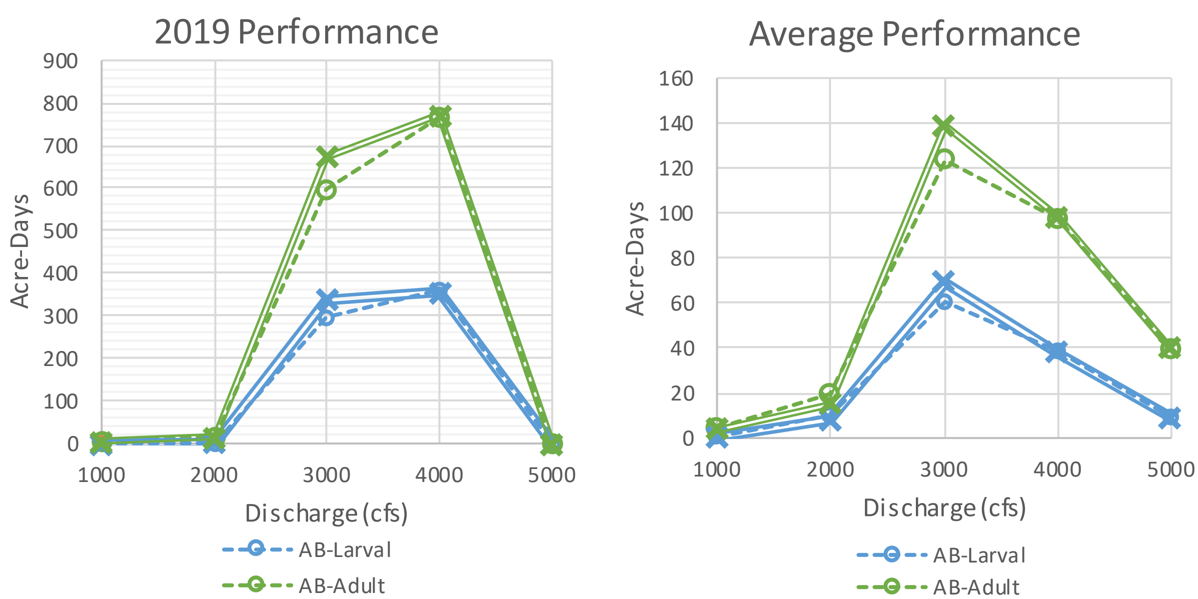


Figure 34. Hydraulic habitat effectiveness curve based on frequency of discharge events from 1000 to 5000 cfs. Note the difference in scale on the y-axis for the two figures.

According to the 2019 spring runoff simulation, the embayments entering RM 100.5 were inundated 100% of the time (Figure 35). Much of the interior of the restoration feature was inundated approximately 65% of the duration. The upstream terrace showed a similar duration of inundation, though there were more fringe areas that experienced 30% duration or less.

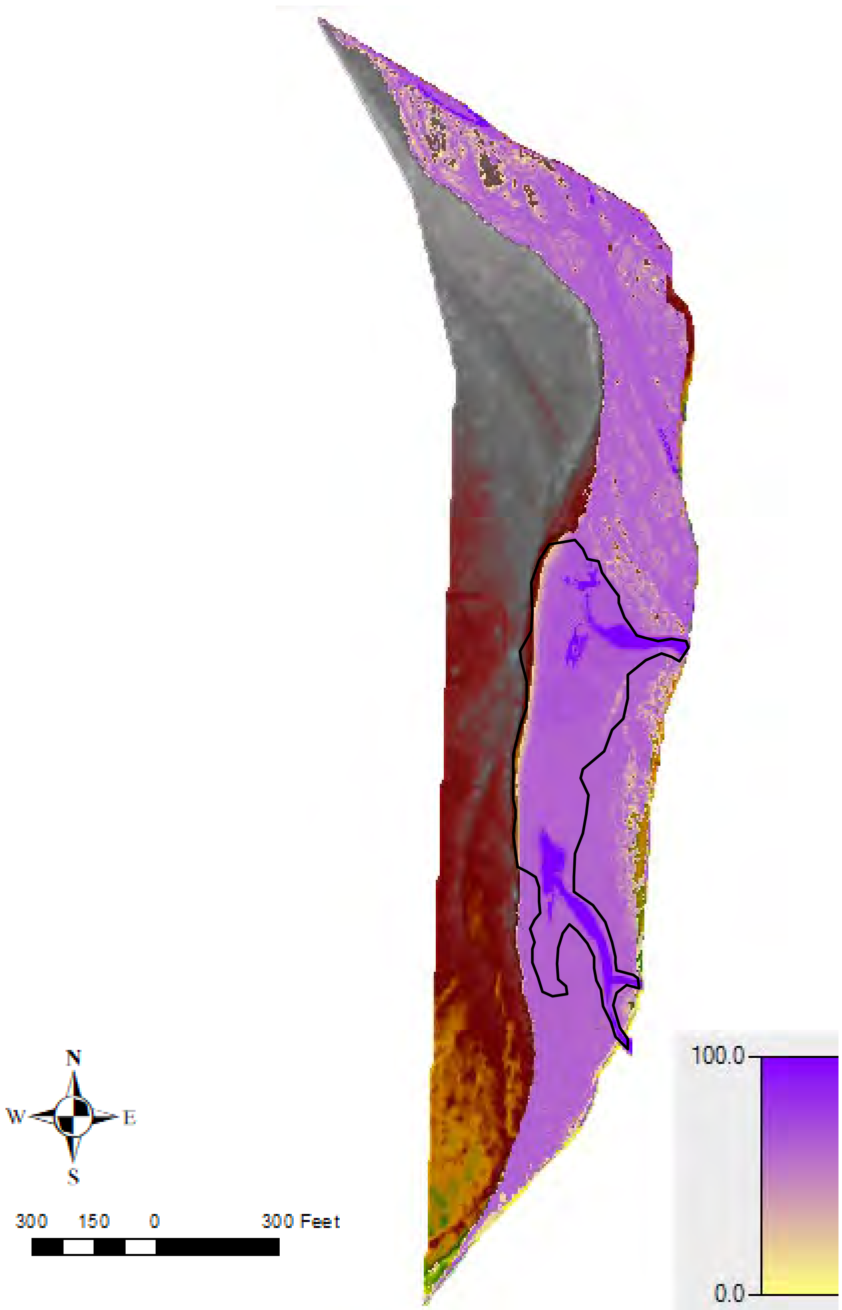


Figure 35. Percent time inundation mapping for RM 100.5 from the 2019 spring runoff hydrograph.

Generally, the losses of larval habitat areas are from deposition and disconnection from a velocity area in the northwest corner of the restoration site (Figure 36). These observations are generated by the hydraulic modeling only and highlight areas that should be monitored in the field. It appears that the sediment deposition and scouring patterns connects flow from both the upstream and downstream excavated inlets at 2000 cfs.

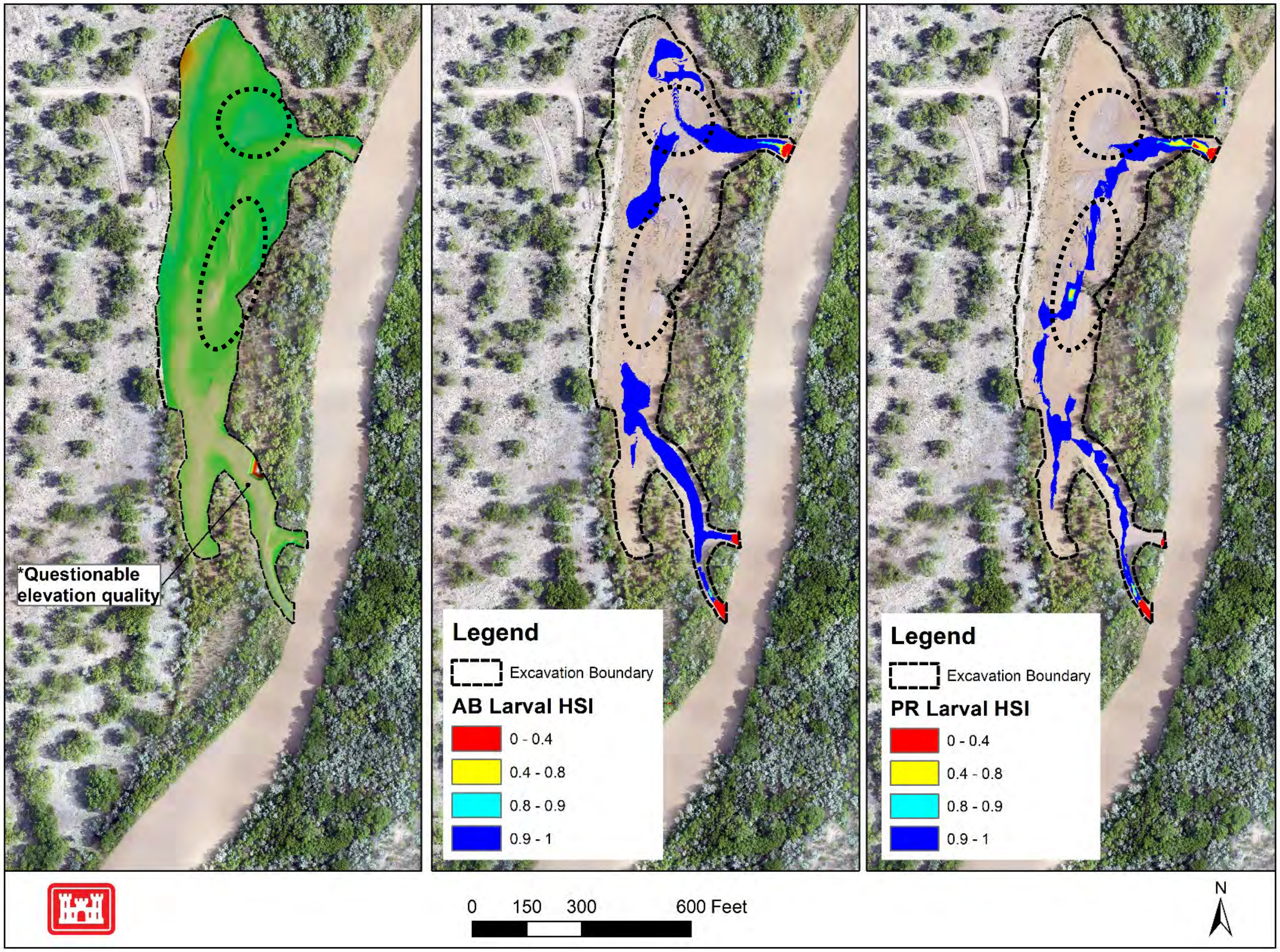


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Figure 36. Figures showing the larval hydraulic habitat losses. 1) PR terrain, with blockages circled; 2) AB results at 2000 cfs; 3) PR results at 2000 cfs. Overlain aerial photography collected by GSA in May 2019.

3.6 RM 103

3.6.1 Hydraulic Analysis for RM 103

RM 103 features backwaters that connect to side-channels. The site was designed by the Bureau of Reclamation and had an inundating design discharge of 300 cfs. The site is unique in that the surrounding terrace is completely inaccessible to inundating flows (Figure 37). Therefore, any hydraulic habitat at this location is contributed by the excavated restoration footprint. Generally, the site does not generate a high proportion of suitable hydraulics per the inundated area, indicating that flows through the site are too fast and deep to meet habitat suitability criteria.

Following sedimentation of the 2019 runoff, the areas of suitable larval habitat generally decreased by 20-50% (Figure 38). Though the total area of inundation increased, both velocities and depths exceeded conditions suitable for the larval life stage. For the adult life stage, 1000-2000 cfs generated more areas of suitable habitat following sedimentation**.**

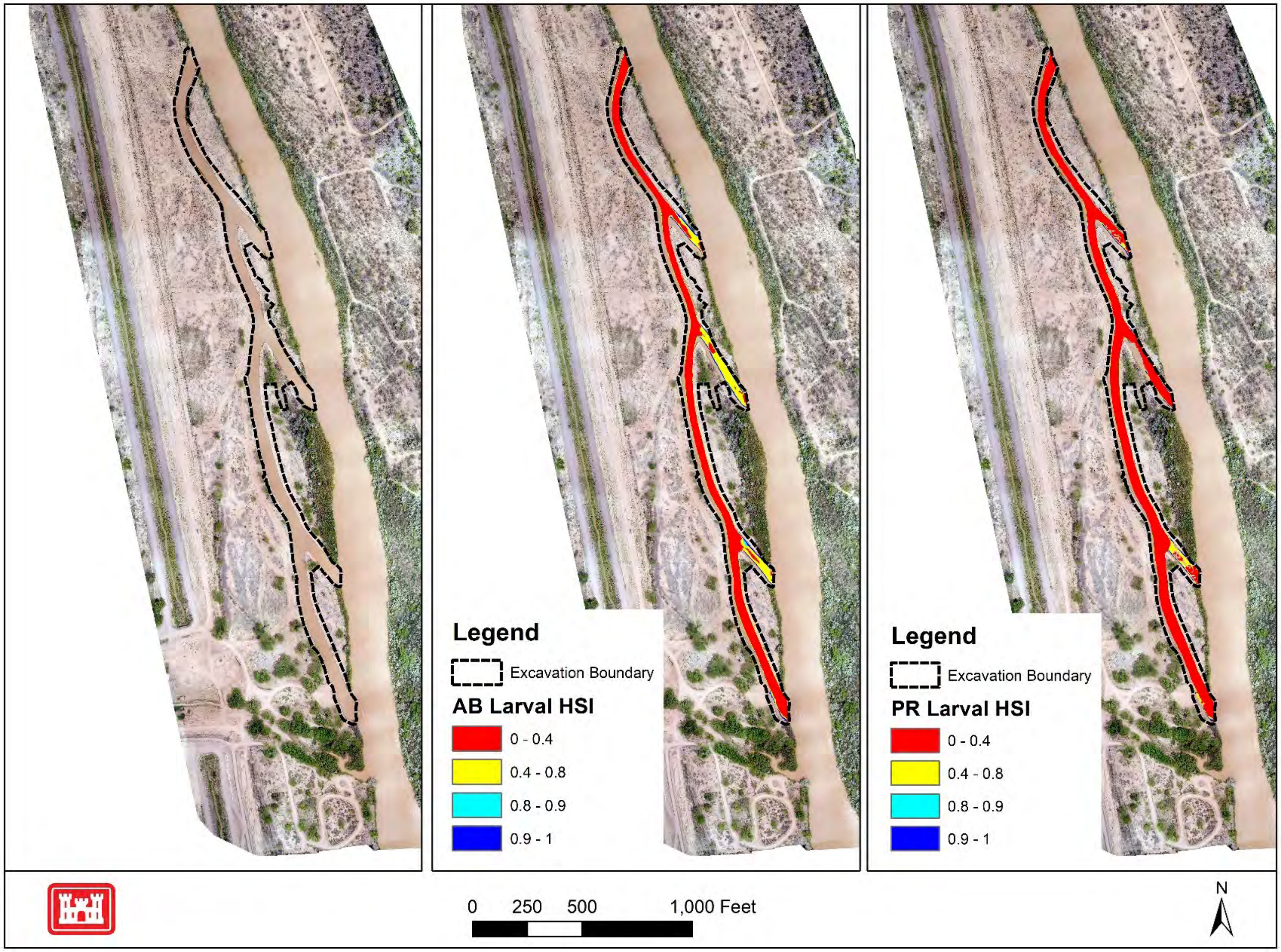

Figure 37. RM 103, from left to right: 1) Aerial photograph (GSA 2020) collected at 4130 cfs; hydraulic suitability maps for larval RGSM at 2800 cfs in 2) the AB condition, and 3) the PR condition.

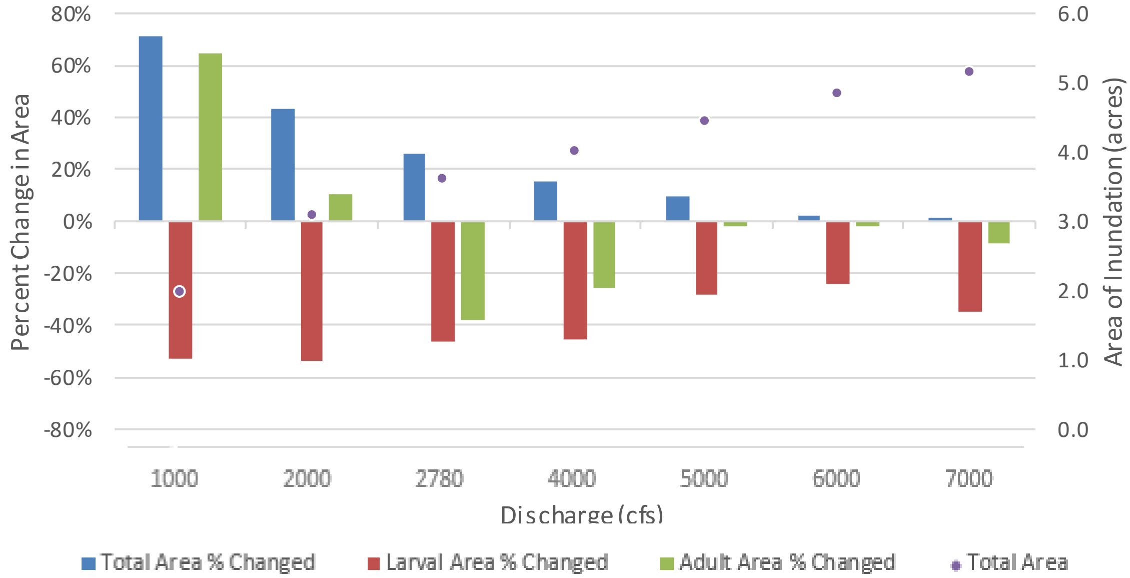

Figure 38. RM 103 percent change in inundation areas in the PR and AB suitable hydraulics for larval and adult life stages of RGSM within the restoration construction footprint.

Noted during the evaluation is that though the excavated area of the project is over 10 acres, the maximum inundated area is 5.2 acres (Figure 39). The site contributes the most hydraulic habitat at lower discharges, from the 1000 to 3000 cfs bins. Available larval habitat decreases with increasing discharge.

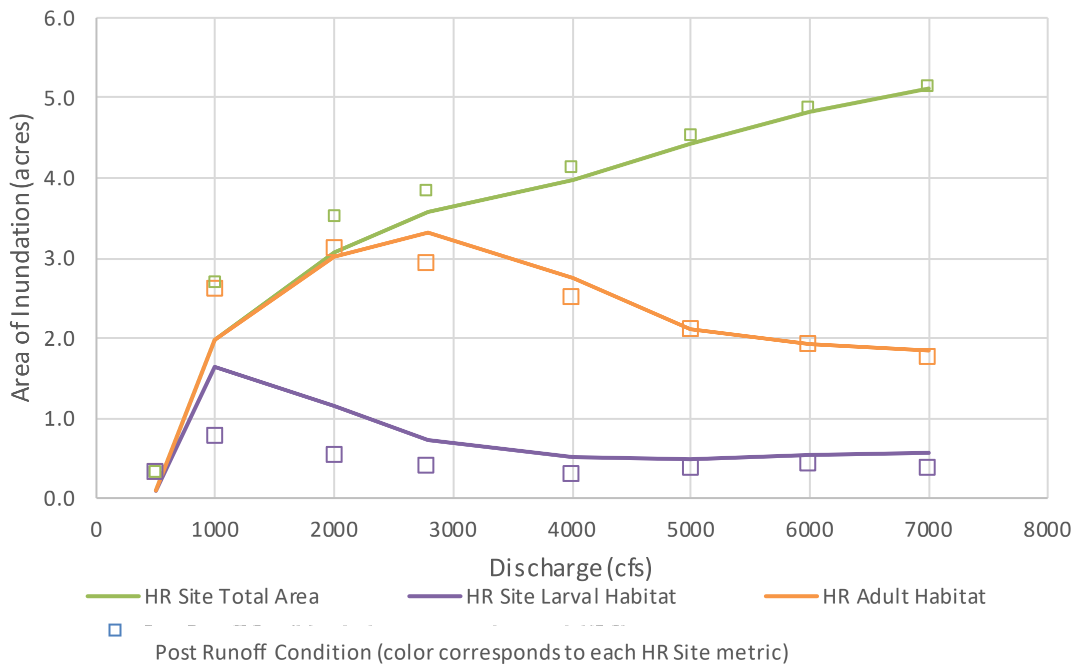

Figure 39. RM 103 Areal results for AB (AB- shown as line graphs) and PR (PR- shown as square points) scenarios for adult and larval life stages of the RGSM on constructed habitat restoration (HR) site footprint.

Table 19. Hydraulic suitability areal acreages for the AB terrain for RM 103 (corresponds to data presented in Figure 39).

		LARVAL			ADULT		
DISCHARGE (CFS)	Total Area (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)
500	0.1	0.1	0.1	0.1	0.1	0.1	0.1
1000	2.0	1.9	1.7	1.6	2.0	2.0	2.0
2000	3.1	2.6	1.4	1.2	3.1	3.0	3.0
2780	3.6	1.9	1.1	0.7	3.5	3.4	3.3
4000	4.0	1.3	1.2	0.5	3.0	3.7	2.7
5000	4.4	1.1	1.2	0.5	2.3	4.0	2.1
6000	4.8	1.1	1.3	0.5	2.1	4.3	1.9
7000	5.1	1.1	1.4	0.6	1.9	4.5	1.8

Table 20. Habitat suitability areal acreages for the PR terrain of RM 103

		LARVAL			ADULT		
DISCHARGE (CFS)	Total Area (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)
500	0.3	0.3	0.3	0.3	0.3	0.3	0.3
1000	2.7	1.5	1.3	0.8	2.6	2.7	2.6
2000	3.5	1.5	1.1	0.5	3.1	3.5	3.1
2780	3.8	1.3	0.8	0.4	3.0	3.7	2.9
4000	4.1	1.1	0.7	0.3	2.6	3.9	2.5
5000	4.5	1.1	0.7	0.4	2.2	4.1	2.1
6000	4.9	1.1	1.0	0.4	2.1	4.4	1.9
7000	5.1	1.0	1.0	0.4	1.9	4.5	1.8

3.6.2 Hydrology Analysis for RM 103

The RM 103 site shows bimodal effective performance in the 2019 with both 1000 and 3000 cfs contributing the most inundation suitable for the adult life stage of the minnow (Figure 40). For the larval life stage, the site is most effective at 3000 cfs. The site has shown decreased performance following sedimentation in 2019, except at 1000 cfs for the adult life stage.

In an average year, the lower discharges provide more effective habitat area. The average year would generate 11.5 acre-days of suitable hydraulic habitat for the larval life stage, which decreased by 51% from the AB condition. For the adult life stage, the PR condition generates 170 acre-days of suitable hydraulic habitat. This is an increase of 13% of hydraulic habitat in the average year from the AB condition.

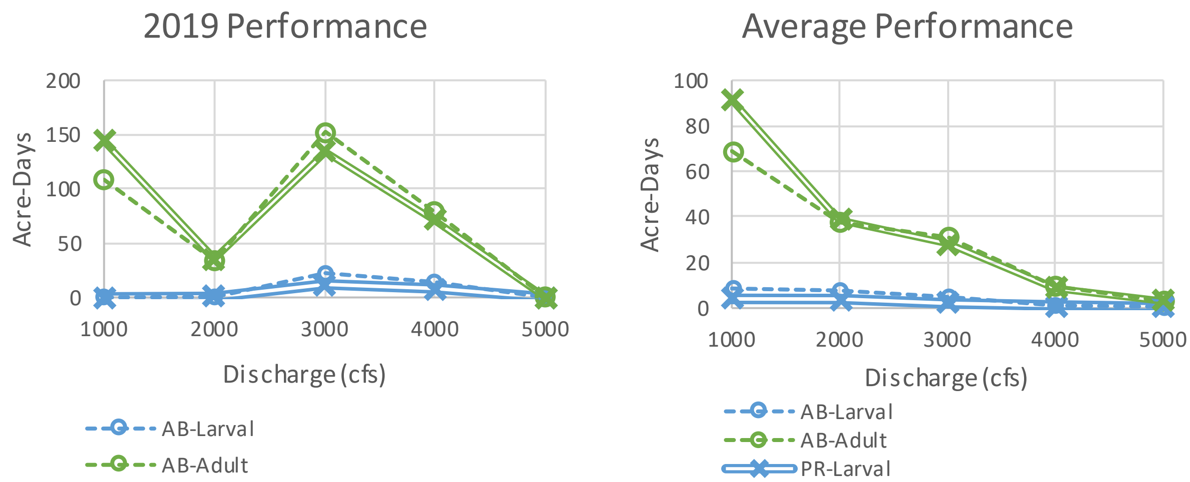

Figure 40. Hydraulic habitat effectiveness curve based on frequency of discharge events from 1000 to 5000 cfs. Note the difference in scale on the y-axis for the two figures.

RM 103 showed consistently high durations of inundation for the 2019 spring runoff event (Figure 41). The interior of the restoration site is dominantly 100% inundated for the duration, though approximately 24 feet of all channel cross-sections varied from 8 to 91%

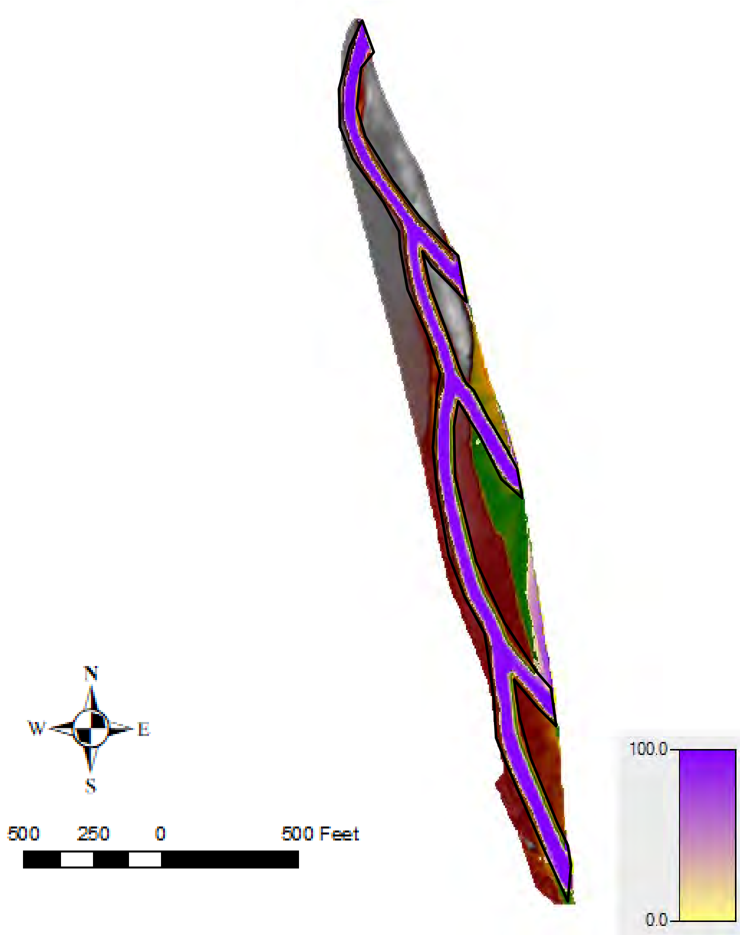

Figure 41. Percent time inundated for the 2019 Spring runoff for RM 103.

3.7 RM 104.5

3.7.1 Hydraulic Analysis for RM 104.5

RM 104.5 is a regraded arroyo confluence. The excavated area for the site is 3.2 acres. At 3000 cfs, presented in Figure 42, the Natural Breaks visualization causes the AB and PR condition to look identical. A gradation is in this instance to show small changes in the site's suitable hydraulics. Generally, the velocity for the site was highly preferable, but water depths precluded high ratings in HSI. (Note that light blue areas in these figures corresponds with HSI = 0.5). The positive changes in the sites had to do with sedimentation, which decreased water depths.

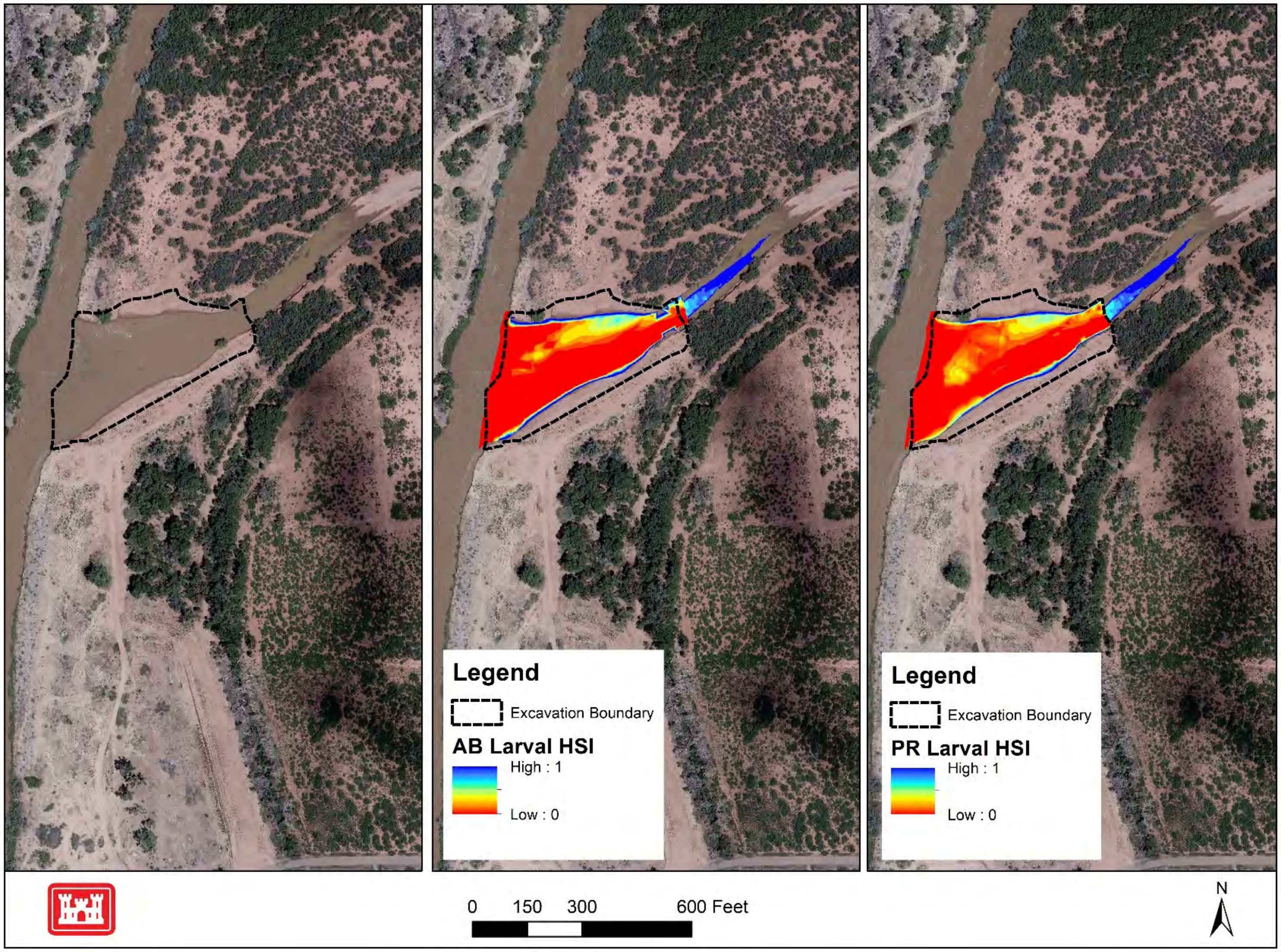

Figure 42. RM 104.5, from left to right: hydraulic suitability maps for larval RGSM at 3000 cfs in 1) the AB condition, and 2) the PR condition. ArcMap aerial base map used as background photography. Note different color scheme for HSI relative to other HSI maps in this report.

The sedimentation experienced at the site strongly affected the 1000 cfs area of inundation by approximately 30% (Figure 43). From discharges 2000 to 4000 cfs, there were some gains in suitable hydraulics for larval and adult life stages. The total inundated area for these discharges after sedimentation varied less than 5% from the AB condition.

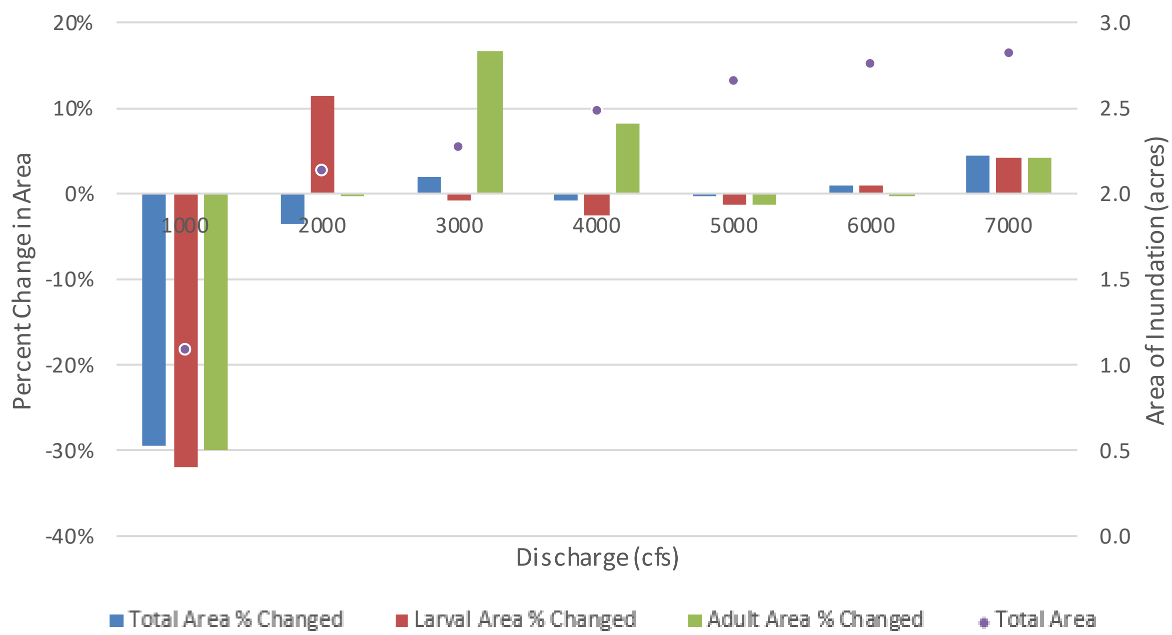

Figure 43. RM 104.5 percent change in inundation areas in the PR and AB suitable hydraulics for larval and adult life stages of RGSM within the restoration construction footprint.

The excavated area was the dominant contributor to suitable hydraulic habitat. This may be owed the site being immediately adjacent to the Rio Grande and the evaluated terrace being further upstream in the arroyo. The site showed the best performance for the larval life stages at 1000 and 2000 cfs (Figure 44). For adults, the area contributing to ideal hydraulics was highest at 2000 cfs.

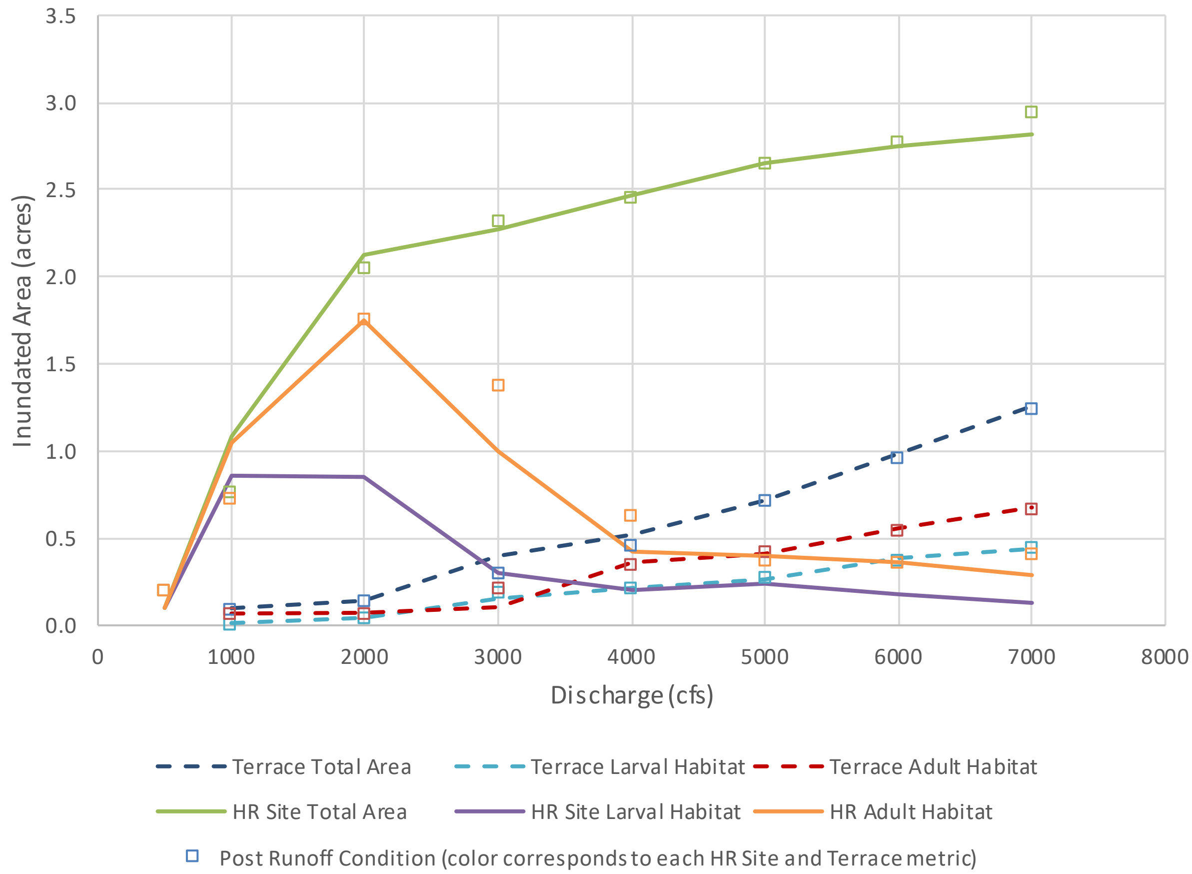

Figure 44. RM 104.5 Areal results for AB (AB- shown as line graphs) and PR (PR- shown as square points) scenarios for adult and larval life stages of the RGSM on constructed habitat restoration (HR) site footprint and the adjacent floodplain (Terrace).

Table 21. Hydraulic suitability areal acreages for the AB terrain for RM 104.5 (corresponds to data presented in Figure 44).

		LARVAL			ADULT		
DISCHARGE (CFS)	Total Area (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)
500	0.1	0.1	0.1	0.1	0.1	0.1	0.1
1000	1.1	0.9	1.0	0.9	1.1	1.1	1.1
2000	2.1	1.8	0.9	0.8	2.0	1.8	1.7
3000	2.3	2.0	0.3	0.3	2.2	1.0	1.0
4000	2.5	2.2	0.2	0.2	2.4	0.4	0.4
5000	2.7	2.3	0.2	0.2	2.5	0.4	0.4
6000	2.7	2.4	0.2	0.2	2.6	0.4	0.4
7000	2.8	2.5	0.1	0.1	2.7	0.3	0.3

Table 22. Habitat suitability areal acreages for the PR terrain of RM 104.5

		LARVAL			ADULT		
DISCHARGE (CFS)	Total Area (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)
500	0.2	0.1	0.2	0.1	0.2	0.2	0.2
1000	0.8	0.6	0.6	0.5	0.7	0.7	0.7
2000	2.0	1.8	1.1	1.1	2.0	1.8	1.7
2780	2.3	1.2	0.6	0.3	2.1	1.4	1.4
4000	2.4	1.2	0.2	0.1	2.1	0.7	0.6
5000	2.6	2.3	0.2	0.2	2.6	0.4	0.4
6000	2.8	2.4	0.2	0.2	2.7	0.4	0.4
7000	2.9	2.5	0.3	0.2	2.8	0.4	0.4

3.7.2 Hydrology Analysis for RM 104.5

The effective habitat discharge for RM 104.5 generally showed improvement following sedimentation from the AB to PR condition, with an exception at the 1000 cfs discharge for the adult life stage (Figure 45). For an average year, 2000 cfs was the most effective discharge for creating habitat for the larval life stage of the minnow. The site contributes approximately 12.7 acres-days of larval habitat on an average year, which is a 4% decrease from the AB condition. The average performance for adult life stage is 56.1 acres, or a 20% decrease from the AB condition.

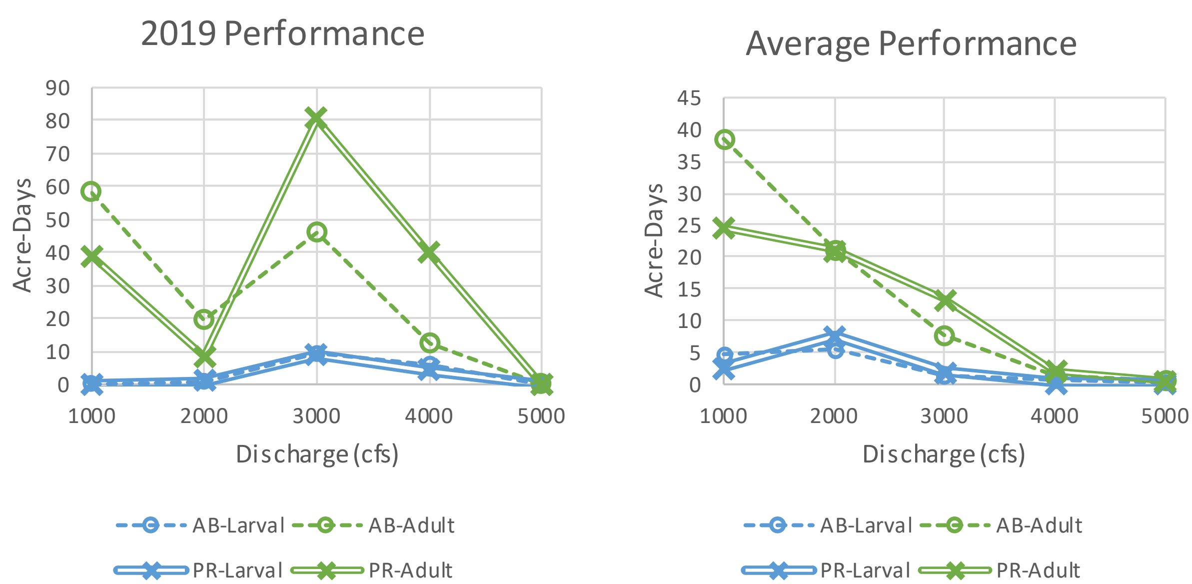

Figure 45. RM 104.5 percent change in inundation areas in the PR and AB suitable hydraulics for larval and adult life stages of RGSM within the restoration construction footprint.

According to the Percent Time Inundated evaluation for the AB condition, RM 104.5 was consistently inundated during the 2019 spring runoff (Figure 46). Most of the excavated area experienced inundation for the duration of the spring runoff hydrograph. On the top right corner of the restoration area in the following figure, the AB condition showed some higher elevations than the rest of the site. In reviewing the post-sedimentation condition in 2019, it is likely that given a similar hydrology, this area of lower inundation duration will expand due to sedimentation (also affecting hydraulics, shown in Figure 42). This location corresponds to approximately 30% duration.

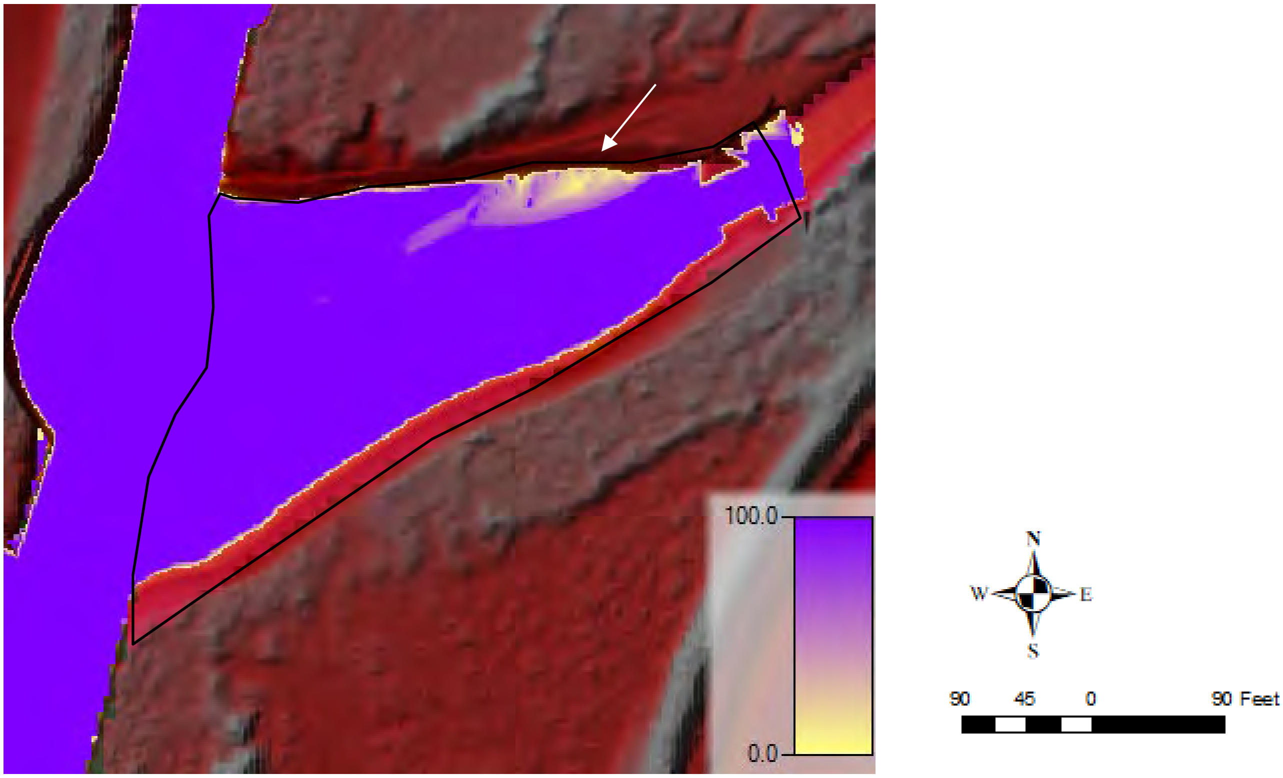

Figure 46. Percent time inundated for the 2019 spring runoff for RM 104.5. Area in discussion indicated with an arrow.

3.8 RM 112

3.8.1 Hydraulic Analysis for RM 112

Habitat Restoration Site RM 112 was a constructed area of 1.5 acres and was designed by the ISC. The design is one backwater channel that reconnects to a high flow channel intersecting the surrounding terrace. The site has a design inundation beginning at approximately 800 cfs (GSA 2020). According to GSA's 2019 spring runoff monitoring evaluations, the site was inundated at 1300 cfs and had average suitable velocities throughout the site. The 2D area modeled, including the entire contributing floodplain, for this restoration area was 8.7 acres, though only 3.2 acres was inundated at the maximum simulated discharge. The hydraulic analyses were based on the indices described in Section 1.2.2. The RM 112 Site was mapped based on hydraulic suitability indices to generate a weighted useable area for the AB and the PR terrains (Figure 47).

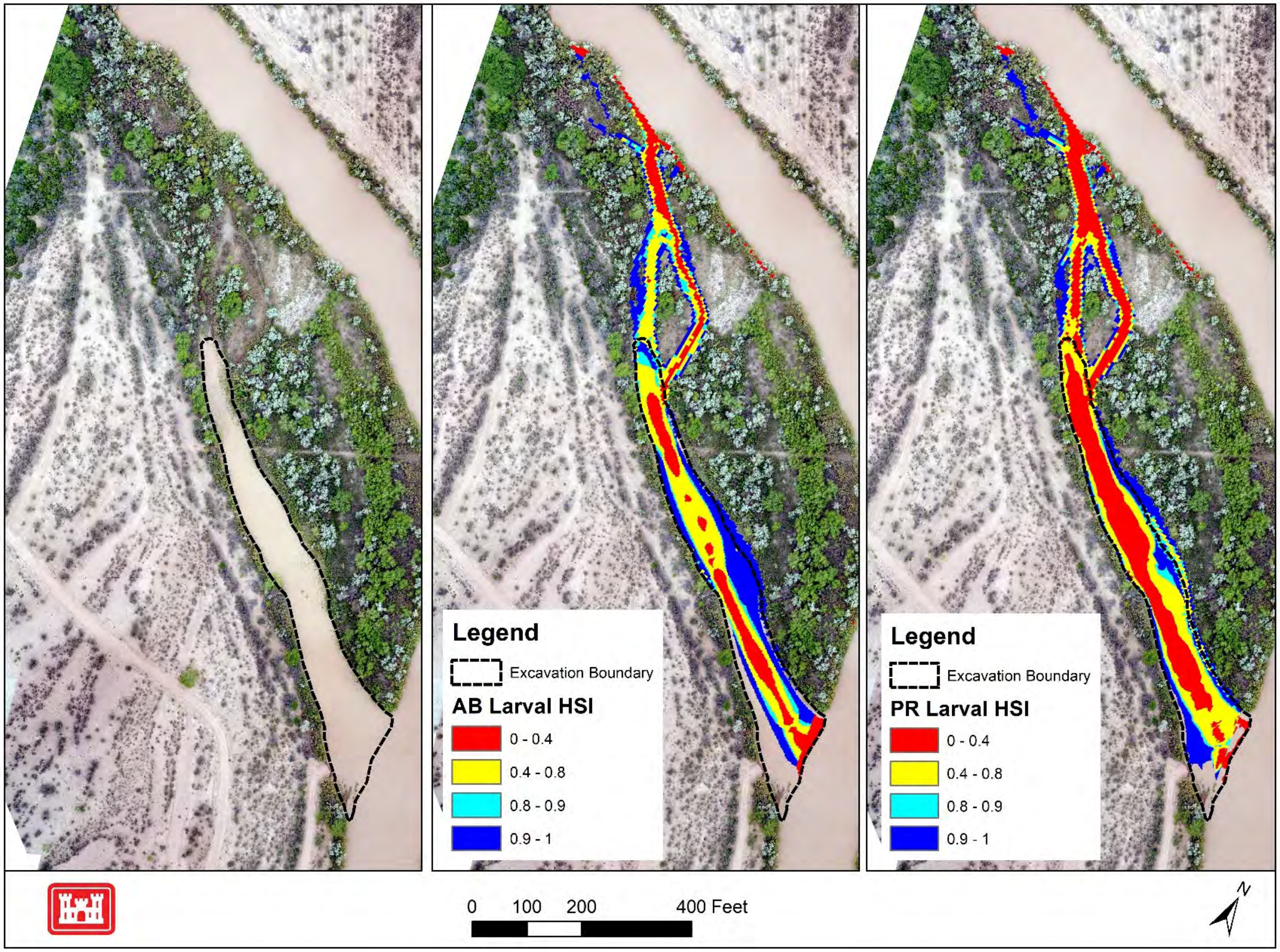

Figure 47. RM 112, from left to right: 1) Aerial photograph (GSA 2020) collected at 4130 cfs; hydraulic suitability maps for larva RGSM at 3000 cfs in 2) the AB condition, and 3) the PR condition.

RM 112 would benefit from data collection on the surrounding terrace, as the 2012 LiDAR dataset shows that the side channels upstream of the constructed site inundates at 1000 cfs. The 2012 LiDAR also shows that the restoration site profile does not connect smoothly with the upstream terrain. The restoration site required higher roughness coefficients than other modeled restoration sites to simulate the low velocities measured on the site ('n' = 0.14, which conforms to a "sluggish ineffective reach" (Chow, 1959)).

This site is generally channelized, connecting to an upstream side channel at higher flows. The areas of suitable hydraulics are generally at the channel edges, which have shown contraction on the downstream side following the 2019 spring runoff event. Following the sedimentation from the runoff, areas of appropriate hydraulics for larval fish at 1000 cfs was greatly reduced (Figure 48). This is due to deposition at the confluence of the embankment and the channel, creating a natural levee separating the restoration site from inundation.

A comparison was made between the suitable hydraulics surrounding the habitat restoration site, on the floodplain terrace connected to, but outside the constructed footprint (referred to as "terrace" in subsequent figures) and the constructed restoration site (referred to as habitat restoration site or "HR"). Figure 49 shows that the terrace contributes less area of suitable hydraulics than the restoration site from 1000 cfs to 4000 cfs. The areas of inundation are very low for this site, with the footprint of the project being only 1.5 acres and the maximum terrace inundation just exceeding 5.2 acres.

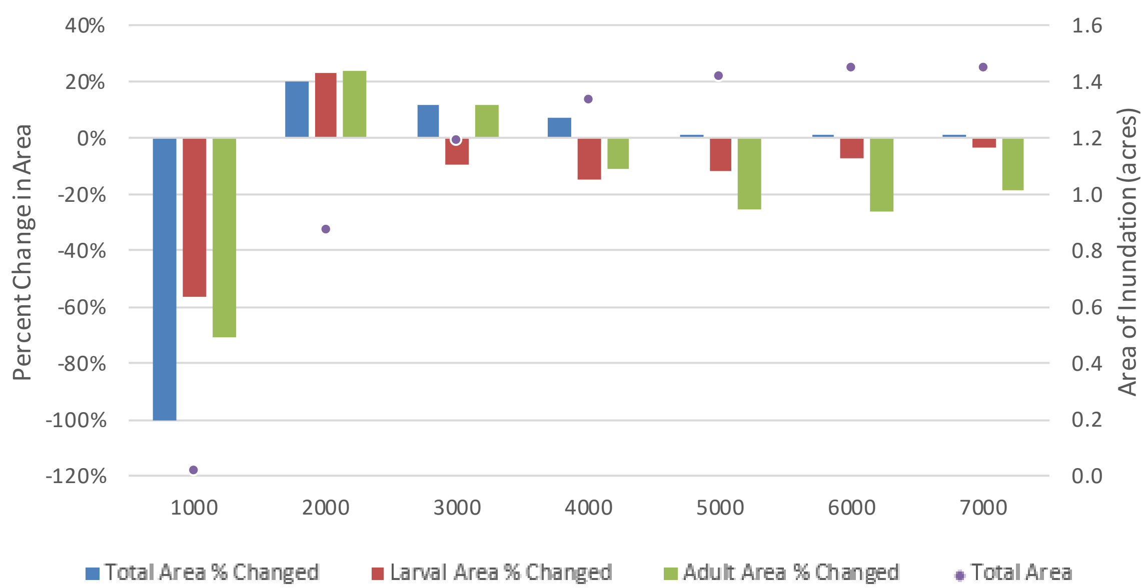

Figure 48. RM 112 percent change in inundation areas in the PR and AB suitable hydraulics for larval and adult life stages of RGSM within the restoration construction footprint.

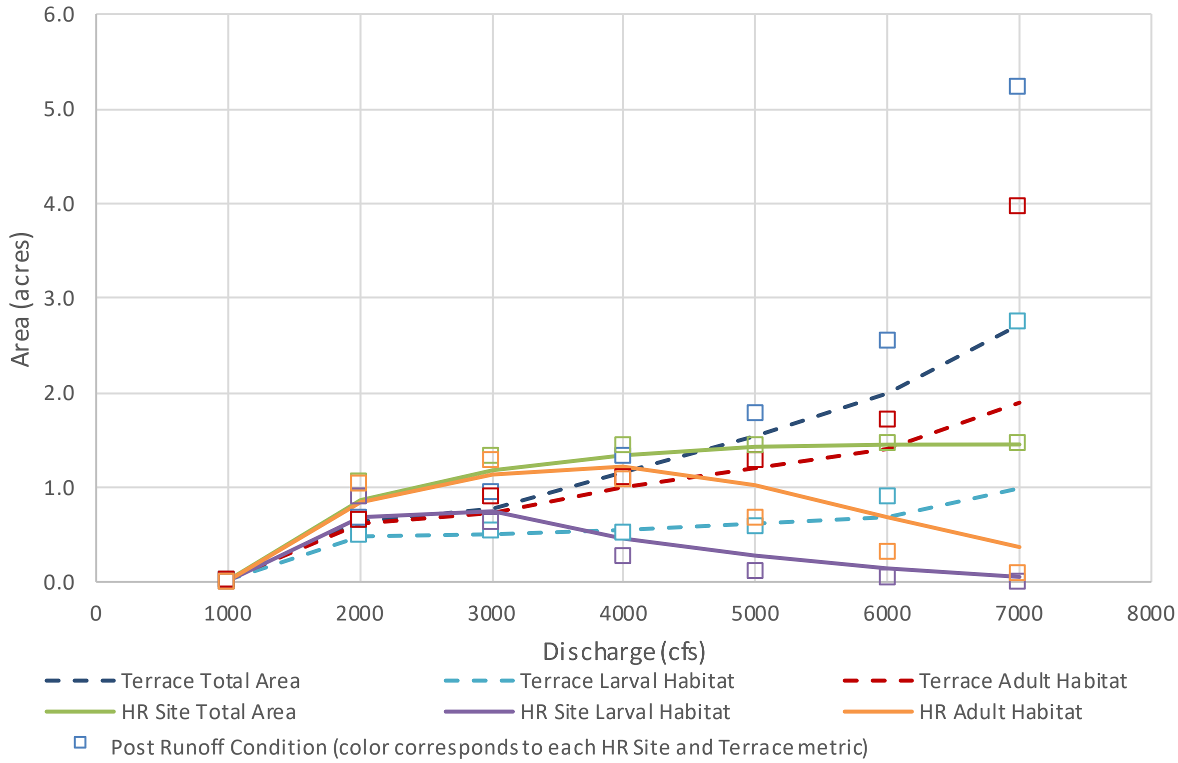

Figure 49.RM 112 Areal results for AB (shown as line graphs) and PR (shown as square points) scenarios for adult and larval life stages of the RGSM on constructed habitat restoration (HR) site footprint and the adjacent floodplain (Terrace).

For this site, suitable depth was more prevalent than suitable velocity areas for the larval criteria. For the adult life stage, the depth hydraulic criteria would become a limiting factor as discharges increased. For the terrace, inundation area increased as discharges increased, and the suitable hydraulic areas also increased. For the restoration site, the available areas of suitable hydraulics peaked at 2000 cfs for the larval, and at 3000 cfs for the adult criteria.

Table 23. Hydraulic suitability areal acreages for the AB terrain for RM 112 (corresponds to data presented in Figure 49)

		LARVAL			ADULT		
DISCHARGE (CFS)	**Total Area (ACRES)**	**Velocity (ACRES)**	**Depth (ACRES)**	**Both (ACRES)**	**Velocity (ACRES)**	**Depth (ACRES)**	**Both (ACRES)**
1000	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2000	0.2	0.2	0.2	0.2	0.2	0.2	0.2
3000	1.2	0.9	0.9	0.7	1.1	1.2	1.1
4000	1.3	0.8	0.7	0.5	1.3	1.3	1.2
5000	1.4	0.7	0.4	0.3	1.4	1.1	1.0
6000	1.5	0.6	0.2	0.1	1.4	0.7	0.7
7000	1.5	0.6	0.1	0.1	1.4	0.4	0.4

Table 24. Habitat suitability areal acreages for the PR terrain of RM 112

		LARVAL			ADULT		
DISCHARGE (CFS)	**Total Area**	**Velocity (ACRES)**	**Depth (ACRES)**	**Both (ACRES)**	**Velocity (ACRES)**	**Depth (ACRES)**	**Both (ACRES)**
1000	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2000	0.1	0.1	0.1	0.1	0.1	0.1	0.1
3000	1.3	1.0	0.8	0.6	1.3	1.3	1.3
4000	1.4	0.7	0.5	0.3	1.4	1.1	1.1
5000	1.4	0.6	0.2	0.1	1.4	0.7	0.7
6000	1.5	0.5	0.1	0.0	1.4	0.4	0.3
7000	1.5	0.4	0.0	0.0	1.4	0.1	0.1

3.8.2 Hydrology Analysis for RM 112

For RM 112, the hydraulic habitat effectiveness for the larval and adult life stage of the minnow peaks at 3000 cfs (Figure 50). The PR condition would generate up to 15% more areas of suitable hydraulics for the adult life stage in the average year at 3000 cfs. However, at lower and higher discharges, the sedimentation has decreased the amount of available area generated by as much as 20%. Due to sedimentation, the net change in larval habitat over the whole season is 28%. For adult habitat, the sedimentation causes an increase of acre-days by 1%, or 0.2 acre-days.

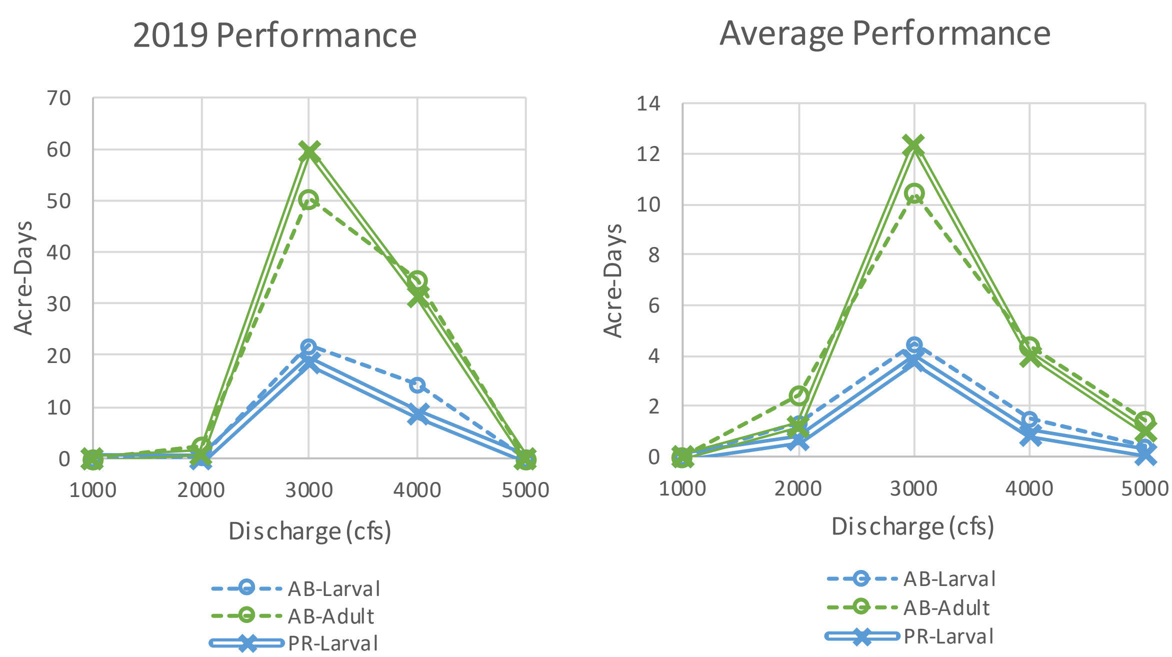

Figure 50. Hydraulic habitat effectiveness curve based on frequency of discharge events from 1000 to 5000 cfs. Note the difference in scale on the y-axis for the two figures.

The percent time inundation mapping for RM 112 indicates that the excavated area of the site was inundated about 65% of the time for the 2019 spring runoff simulation (Figure 51). The side channels upstream from the restoration site had longer durations, from approximately 70 to

100%. The restoration site's confluence with the Rio Grande experienced up to 100% inundation for the spring runoff hydrograph.

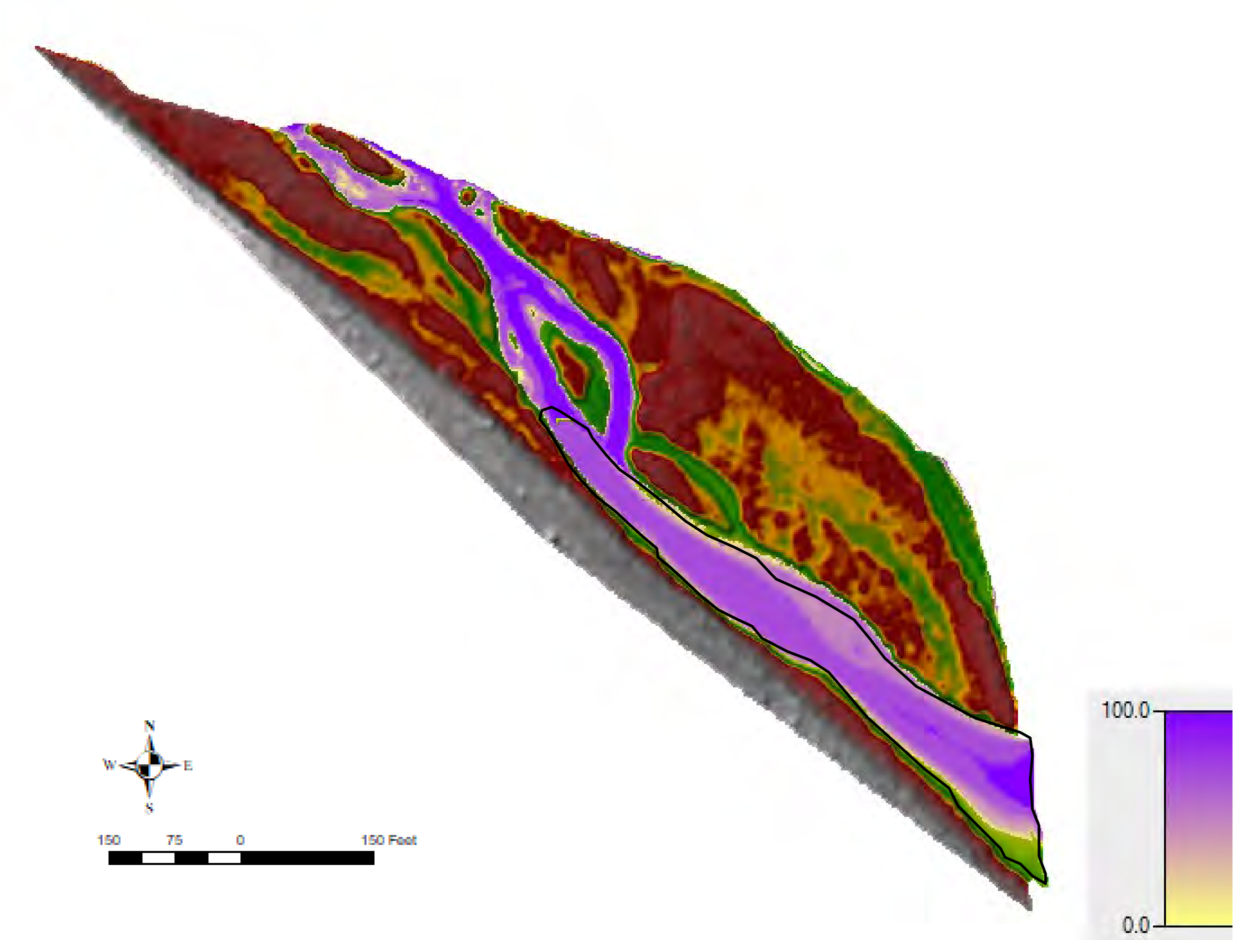

Figure 51. The percent time inundated for RM 112.

The loss of habitat area is from the generation of a natural levee at the confluence of the habitat restoration site and the Rio Grande. This deposition may have been facilitated by the shear forces occurring within channelized sections of the restoration site (Figure 52). The backwater effects from the river's confluence then shows a reduction in shear right at the confluence, which results in the natural levee formation.

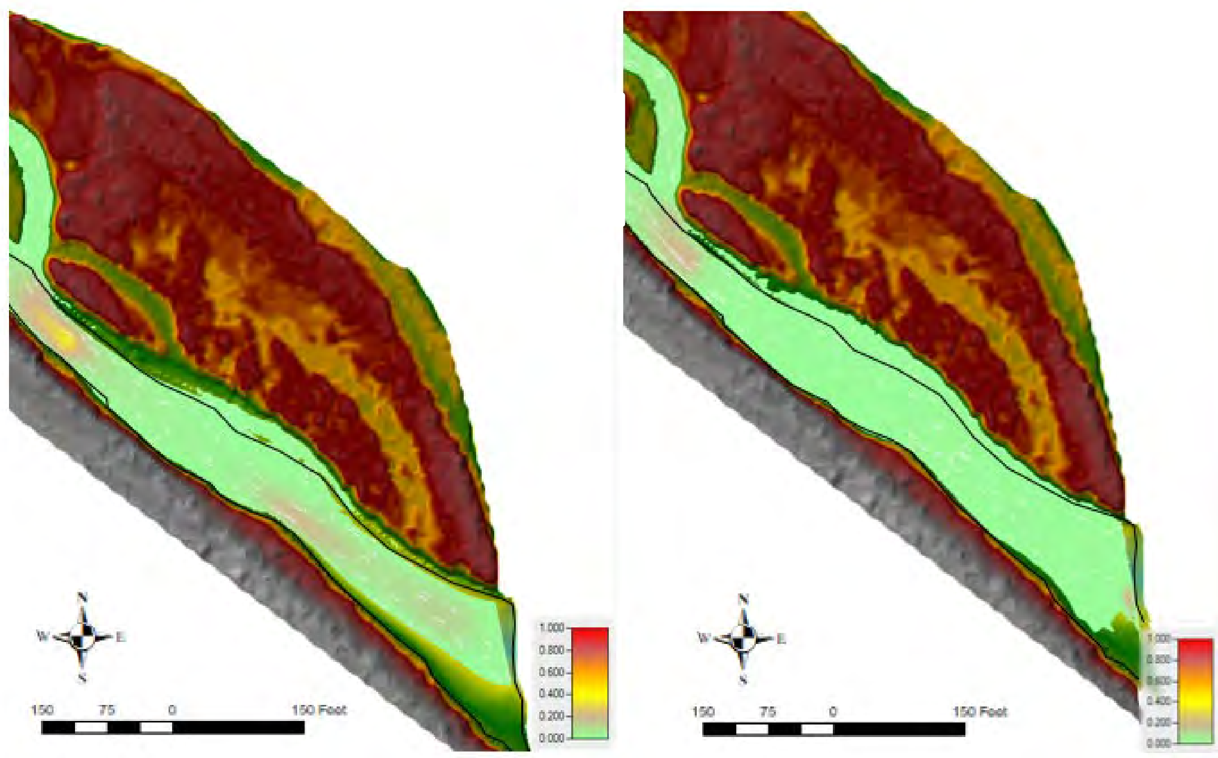

Figure 52. Shear stress (psf) plots of AB (left) and PR (right) hydraulics at 3000 cfs. Particle tracing is overlain.

3.9 RM 114

3.9.1 Hydraulic Analysis for RM 114

Habitat Restoration Site RM 114 was a constructed area of 1.7 acres and was designed by the ISC. The design features two backwater inlets that connect to a single backwater channel. The terrace inundates downstream of the RM 114 site and is also well-connected on the upstream side at higher discharges. The site has a design inundation beginning at approximately 800 cfs (GSA 2020).

According to GSA's 2019 spring runoff monitoring evaluations, the site was inundated at 1300 cfs and had suitable average velocities throughout the site. The 2D area modeled, including the entire contributing floodplain (referred to as terrace) was 31.6 acres, though only 18 acres was inundated at the maximum simulated discharge.

The deposition that had occurred at the confluence of the two inlets appears to affect site hydraulics (Figure 53 and Figure 54). At discharges below 1000 cfs, the site is shown to experience less inundation. Once water enters the site, the velocities in the PR condition at the confluence of the two inlets causes the location to be less suitable for larvae, but the deposition has also reduced the storage volume, increasing the area of inundation in the backwater. The surrounding terrace provides more area of suitable habitat hydraulics than the HR site starting at 2000 cfs.

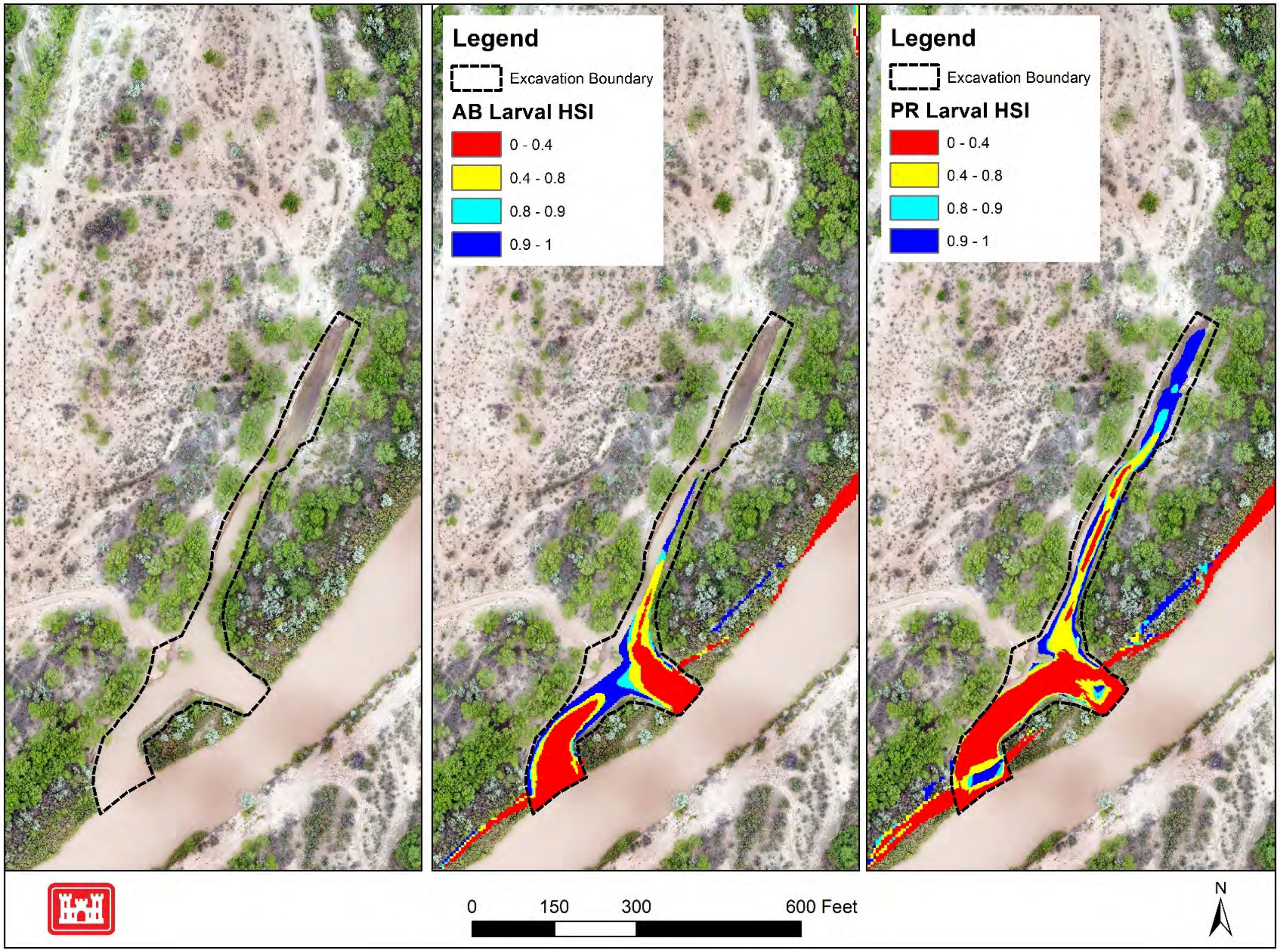

Figure 53. RM 114, from left to right: 1) Aerial photograph collected at 4130 cfs (Reclamation collection); hydraulic suitability maps for larval RGSM at 2780 cfs in 2) the AB condition, and 3) the PR condition.

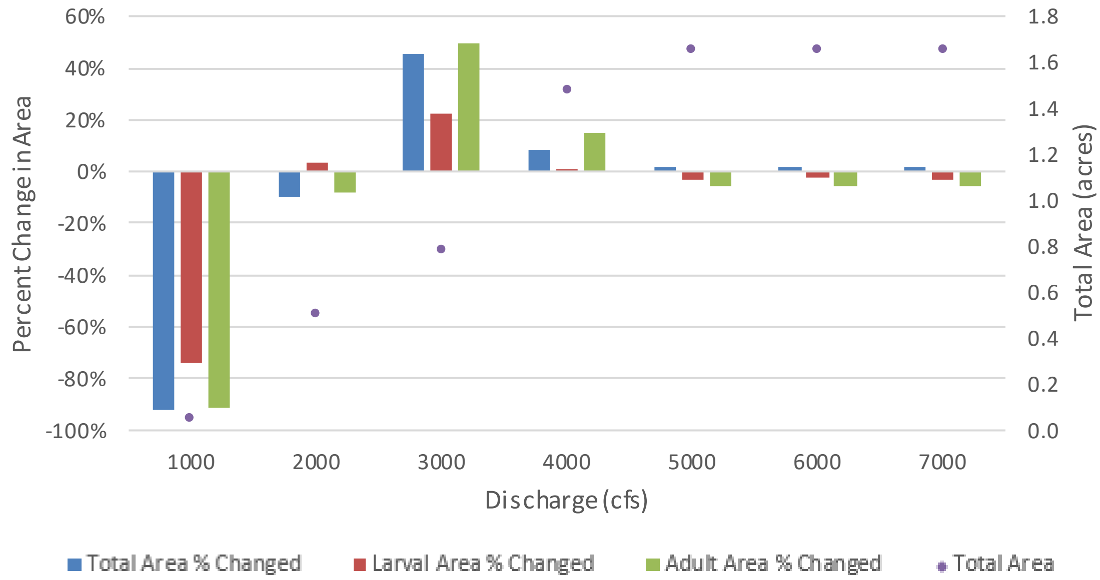

Figure 54. RM 114 percent change in inundation areas in the PR and AB suitable hydraulics for larval and adult life stages of RGSM within the restoration construction footprint.

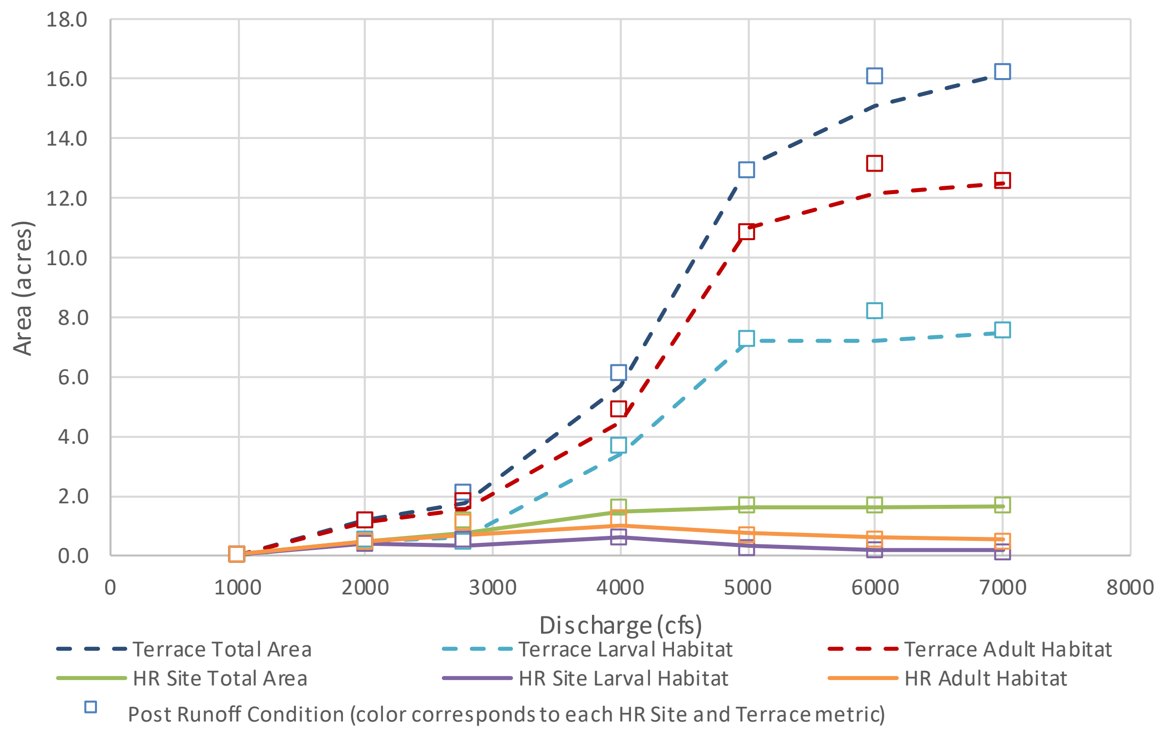

Figure 55. RM 100.5 Areal results for AB (AB- shown as line graphs) and PR (PR- shown as square points) scenarios for adult and larval life stages of the RGSM on constructed habitat restoration (HR) site footprint and the adjacent floodplain (Terrace).

As discharges increased, and the suitable hydraulic areas also increased, particularly on the surrounding floodplain. For the restoration site, the available areas of suitable hydraulics peaked at 4000 cfs for both adult and larval criteria.

Table 25. Hydraulic suitability areal acreages for the AB terrain for RM 114 (corresponds to data presented in Figure 55).

		LARVAL			ADULT		
DISCHARGE (CFS)	Total Area (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)
1000	0.05	0.03	0.05	0.03	0.05	0.05	0.05
2000	0.5	0.5	0.4	0.4	0.5	0.5	0.5
2780	0.8	0.5	0.5	0.3	0.8	0.7	0.7
4000	1.5	1.3	0.6	0.6	1.5	1.0	1.0
5000	1.6	1.5	0.3	0.3	1.6	0.8	0.8
6000	1.6	1.3	0.2	0.2	1.6	0.6	0.6
7000	1.6	1.0	0.2	0.1	1.6	0.5	0.5

Table 26. Habitat suitability areal acreages for the PR terrain of RM 114

		LARVAL			ADULT		
DISCHARGE (CFS)	Total Area (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)	Velocity (ACRES)	Depth (ACRES)	Both (ACRES)
1000	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2000	0.5	0.4	0.4	0.4	0.4	0.4	0.4
2780	1.1	0.6	0.8	0.5	1.1	1.1	1.1
4000	1.6	1.3	0.7	0.6	1.6	1.2	1.2
5000	1.7	1.5	0.3	0.2	1.6	0.7	0.7
6000	1.7	1.2	0.2	0.2	1.6	0.5	0.5
7000	1.7	0.9	0.1	0.1	1.6	0.5	0.4

3.9.2 Hydrology Analysis for RM 114

For RM 114, the hydraulic habitat effectiveness for the adult life stage of the Silvery Minnow peaks at 3000 cfs (Figure 56). The PR condition would generate up to 57% more acre-days of suitable hydraulics for the adult life stage in the average year at 3000 cfs. Otherwise, the difference between the provided habitats from the AB to PR terrains has not changed appreciably. This is owed to the large contribution of the terrace to suitable habitat areas. The net change for the season for larval habitat is an increase by 14% of suitable hydraulic area, or 0.9 acre-days. For the adult life stage, the adult habitat is increased by 7%, or 1.4 acre-days.

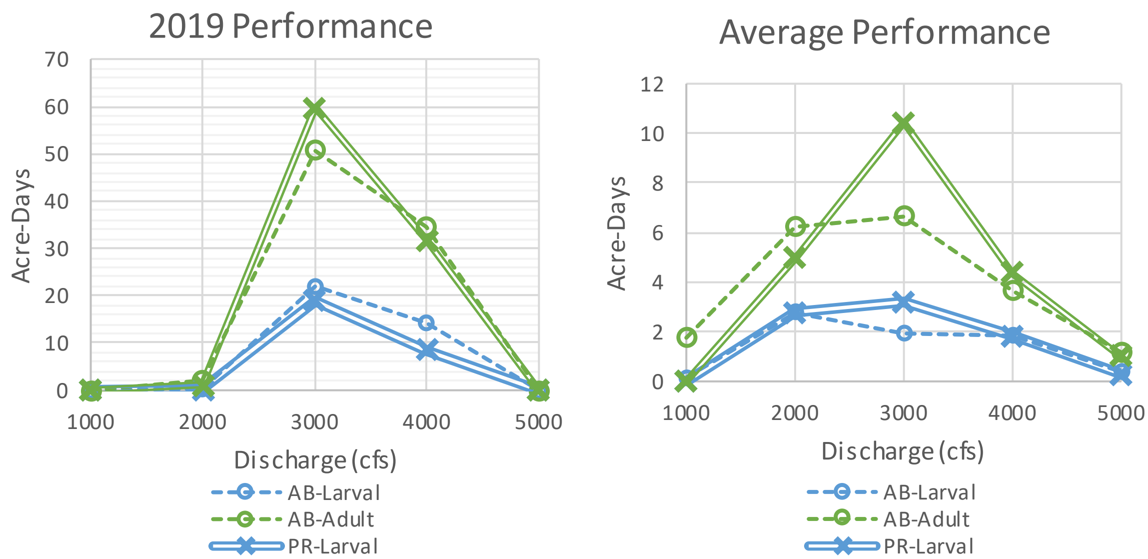

Figure 56. Hydraulic habitat effectiveness curve based on frequency of discharge events from 1000 to 5000 cfs. Note the difference in scale on the y-axis for the two figures.

The percent time inundated for RM 114 is higher than its surrounding terrace of the duration for the 2019 spring runoff simulation (Figure 57). The excavated area near the inflow of the site is around 100%, and gradually reduces to 65% up the embayment. The surrounding terraces is inundated from 45 to 62% of the duration.

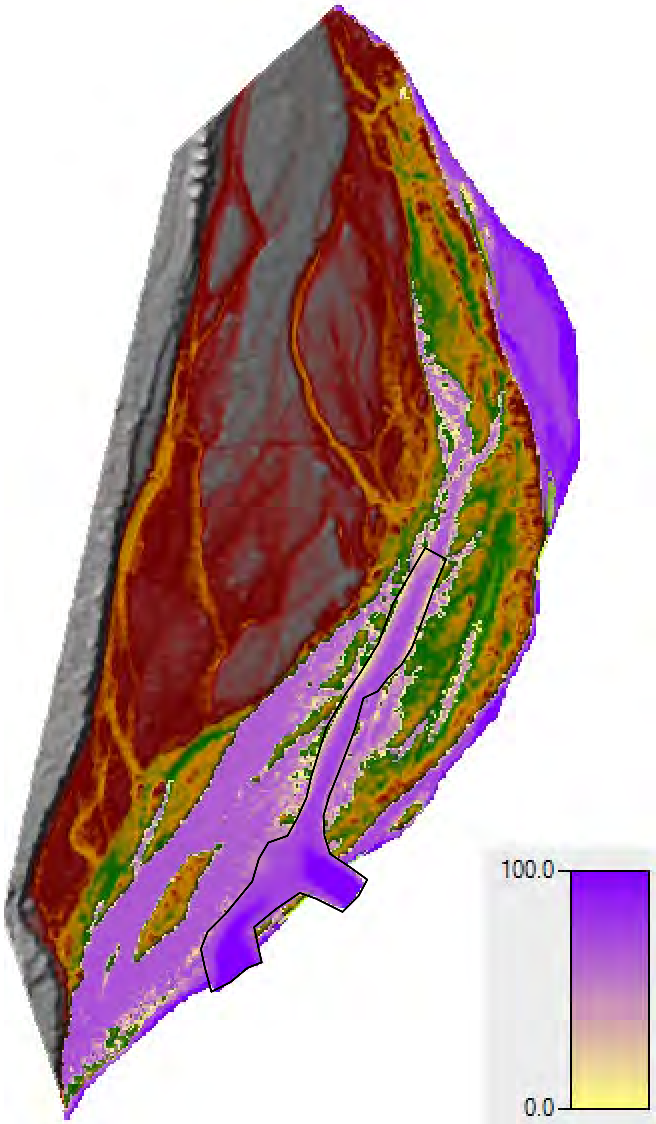

Figure 57. Percent time inundation mapping for RM 114

4 - Conclusions

This report presents a comprehensive method for developing a HSI for Silvery Minnow using field data, applying the HSI to hydraulic modeling results to map preferred habitat, and quantification of site performance with the aid of Rio Grande hydrologic frequencies. The results demonstrate the magnitude of change in hydraulics occurring from sedimentation in (8) San Acacia restoration sites. Also presented are comparisons of the restoration site's contribution to hydraulic habitat relative to surrounding, non-constructed floodplains.

The results show that despite sedimentation on all restoration sites, the suitable hydraulics are not necessarily negatively affected. Three of the eight sites showed slight improvements in suitable hydraulic habitat (RM 99.5, RM 100, RM 114), and 4 of the sites that had negative change, changed by less than 6.4 acre-days (0.01 square miles) -- RM 93, RM 100.5, RM 104.5, and RM 112. Generally, all sites showed decreased performance at 1000 cfs (except RM 100 and RM 103). These losses were attributed to sedimentation, particularly at river interface with the restoration site.

Many of the sites are situated at terraces, or adjacent floodplains that inundate at typical Rio Grande flows. Other sites were situated on highly disconnected locations and are the only contribution of habitat at various flows. The sites most disconnected with the floodplain are Escondida sites (RM 103, RM 104.5). RM 112 and RM 100 are connected to natural side channels. Another notable trend is the channelization of habitat features following sedimentation. Much of the sites vary from barren to lightly vegetated, and it is expected that vegetation encroachment may affect sedimentation and site hydraulics.

One of the benefits of evaluating the 8 restoration sites is so that they may be compared on the basis of their contribution to habitat and performance over typical Rio Grande hydrology. The various scales of restoration sites provide information on how scale affects site performance. Generally, the maximum hydraulic suitable areas for larval life stages were half of the maximum inundated area for each site. This indicates that inundation is a more important criterion for site design than excavated area, because the larger excavated sites (RM 93, RM 103) did not fully inundate, even at higher discharges. RM 99.5 contributed the highest ratio suitable habitat area relative to excavated area. Despite individual site performance, the magnitude of habitat contributions is given at a scale of 8 to 72 acre-days in the PR condition. Relative to the 172 miles of Middle Rio Grande, the largest habitat contributor: RM 93; contributes approximately 0.1 square miles/72.4 acres-days of suitable larval habitat in an average year.

As regional strategies are developed for the Silvery Minnow, it is important to consider the magnitude of these features relative to the system. These sites contribute a great proportion of larval habitat at 1000 cfs relative to the unconstructed floodplain areas, however they are most effective at contributing habitat for larval Silvery Minnow around 3000 cfs. This observation presents opportunities in restoration site design by delimiting site effectiveness via incremental hydrology. Engineers may pursue larger areas of inundation, or in-stream methods to increase water surface elevations entering these sites, as an effort to shift higher levels of performance for lower discharges.

The HSI-curve and the weighted depths and velocities are based on literature review and field-measured data. The HSI results should be compared field observations of fish presence. This process would involve emulating field conditions using a hydraulic model and HSI analysis, and then comparing the mapped HSI results to observations of fish presence in the field. Incremental improvement can be made to the HSI by either adjusting the curve, adjusting the weight of velocity and depth parameters, or adding another habitat parameter (i.e., landcover type, substrate type, shear stress). This validation process strengthens conceptualization of hydraulic habitat requirements for the Silvery Minnow and may also uncover research questions or perspectives on how to apply existing knowledge. This may lead to further hydraulic analysis, such as the depth and shear conditions required for biofilm environments, which contributes a food source for Silvery Minnow life stages.

There are two major challenges that may be addressed with future analysis. Sediment transport strongly influences both the Rio Grande active channel capacity and the flow paths on the restoration sites. Changes in either of these locations may affect inundating discharge volumes and extents. Not only should models be updated as more monitoring data is collected, but sediment transport modeling should be explored to improve forecasting of site weathering and hydraulic habitat trends. Another challenge is the temporal component of hydrology, as the true performance of the site may be affected not only by site hydraulics, but by duration of inundation. The nature of inundation and site hydraulics may strongly affect the Silvery Minnow's experience and survival.

A major benefit of this analysis is quantification of site performance. Magnitudes of hydraulic habitat available throughout a runoff season or over years may be compared and may indicate the life cycle performance for a restoration site. Quantities are better suited for economic analysis for site maintenance than qualitative observations.

4.1 Monitoring Requirements

Calibration and validation data are of utmost importance in developing hydraulic models. In this exercise, the Middle Rio Grande bathymetry and the 1D/2D interface between the Middle Rio Grande and the restoration site strongly effected riverine hydraulics and required significant calibration. The field data collected during monitoring guide the assumptions which make computational hydraulics possible.

To increase the accuracy of the hydraulics calculated in future modeling efforts, the following data should be provided

Current Practices:

- Gather georeferenced water surface elevations in the following locations:
    - At the Rio Grande above and below the restoration site: this provides the energy grade line of water entering and exiting the restoration site.
    - As a profile for the site (at most every 500 feet) at various discharges: this will validate the energy grade throughout the site.
- Record areas of inundation using GPS within and around the restoration site.
- Collect velocity and depth data.
    - Georeferenced measurements, either by following consistent stationing at established rangelines or by collecting accurate location data.
    - At locations where Silvery Minnow are found.
    - Collect field notes about the method of depth measurement.
        - Depths above suspended sediment/silt or "clear water" layer.
        - Depths at the bottom of the water column or "solid ground".

Additional Monitoring Needs:

- Collect topography data.
    - Collect transects of the Rio Grande adjacent to the project sites throughout the spring runoff to evaluate temporal changes in Rio Grande capacity.
    - Since floodplains may be contributing flows to the restoration sites, expand the area of interest for each site to include areas that are likely to be inundated during high-flow events and include that area of interest in the terrain survey efforts.

- Collect qualitative or quantitative geomorphic data to create a more rigorous geospatial conceptual model for Silvery Minnow habitat:
  - Mapping with GPS:
    - Bed material type (silt, sand, small gravel, etc.) within restoration sites.
    - Boundaries of vegetation types.
  - Field notes of change and status of major mesohabitat types over the course of monitoring season:
    - Riffles, channelized areas, shallow waters, the thalweg, submerged sand bars, woody debris.
    - Presence and location of Silvery Minnow and food sources (biofilms).
    - Observations of change: locations to which water is spreading, locations no longer inundated, locations of sedimentation or scour.
  - Collect geo-referenced photographs during inundation events throughout the project area and inundated locations.

4.2 Modeling Recommendations

Sediment transport is a phenomenon that strongly affects the Rio Grande and its surrounding floodplain. Mobilization of the channel bed can change channel conveyance capacity; channel widths may be narrowing or expanding due to prevailing geomorphic trends; vegetation encroachment on channel edges or on sand bars may affect channel roughness. Therefore, for the hydrodynamic modeling approaches to become more robust in the future, it is suggested to expand the scope of modeling analysis to the following items:

- Conduct shear and sediment transport analysis for both the Rio Grande local to these restoration sites and on the restoration sites themselves.
- Conduct paired hydrologic and sediment transport analysis to identify trends; develop forecasting techniques to implement geomorphic evolution in alternatives analysis and restoration site design.
- Deploy modeling engineers to the sites during high flows to collect qualitative data to aid in modeling assumptions and validation.

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Appendix A: Geospatial Analysis for Hydraulic Habitat Suitability Maps

The desired output from this process are figures of weighted useable areas versus discharge to demonstrate how hydraulic habitat varies with discharge. Quantifying the data this way and pairing with hydrology data can be used to create an “effective habitat curve”, similar to “effective sediment discharge curves” which identify the most impactful discharges for geomorphic change. Another way these quantities can be used are in environmental flow analyses like those available in HEC-EFM. This addendum demonstrates how to convert the HEC-RAS data into habitat useable area quantities and maps.

Preprocessing Data for Tool Input

HEC-RAS can export hydraulic data at specified time-steps as a Geospatial Data Abstraction Library Virtual Format (VRT), which is a raster file format supported by ArcGIS. The timestep representing each discharge is selected in HEC-RAS, and Depth and Velocity rasters are exported.

In some cases, the rasters need to be clipped to the restoration site footprint or the 2D area (ArcMap//Extract by Mask Tool), in order to evaluate areas of interest. Areas outside the 2D area do not represent accurate hydraulics and should be removed before evaluation.

General Process

The methods described in the report converts input rasters: depth and velocity; into a habitat suitability index from 0 to 1. For data processing in ArcMap, there are a few data-type conversions that are necessary for data-processing (discussed in Details sub-section of the addendum). The Spatial Analyst module is needed to Reclassify the depth and velocity results to the Larval and Adult suitability curves presented in the report. The depth and velocity HSI’ s are multiplied together to create a hydraulic suitability index (H-SI) for each cell of the raster. The reasoning for multiplication arises from the binary index, where the H-SI equals 0 OR 1. Averaging was not preferred for binary or subsequent evaluations, because it is assumed that hydraulic habitat is inclusive: a site where one of the parameters was ideal and where one of the parameters was inhospitable should be considered inhospitable.

Once the depth and velocity rasters are multiplied, the following information may be derived from the hydraulic suitable map by looking at the raster properties: the cell size, the number of cells, the average raster value for each of the sub-parameter indices (depth and velocity), and the average raster value for the sub-parameters combined. Both adult and larval life stages have different suitability curves, so this process generates (6) suitability rasters: Rasters for the sub-parameters and the product of the two (ArcMap//Times), for adult and larval life stages, are saved for evaluation and mapping.

Details and Key Steps

The data must be in a format that could be utilized by subsequent tools. For example, the H-SI curve varied over a small range of depth and velocity values: the maximum suitable depth for the larvae is 2.4 feet; the maximum suitable velocity for the adult was 3.9 feet per second. However, the Reclassify tool uses integer values. Translating the input floating rasters to integer rasters would over-generalize the data because the fraction would be truncated to a whole number. The inputs were multiplied by 10 (Times) so that reclassifying by integers captured the tenth fraction. The H-SI is an index from 0 to 1, so the reclassification had to be divided by 10 (Divide).

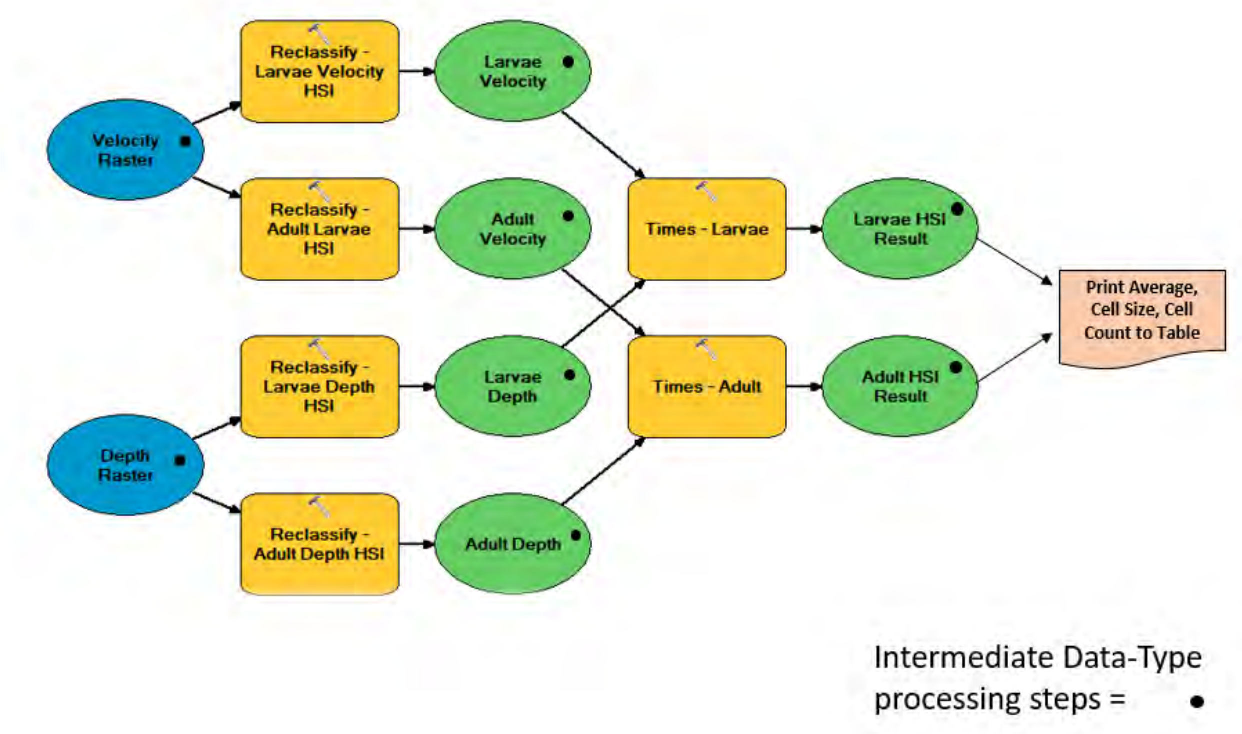


Figure 58. Module Builder representation of the workflow. Intermediate data-type processing involves changing the data to Integer, Float, or Script to be used in subsequent ArcMap Tools.

These are the steps conducted in ArcMap, tools notated by quotation marks:

1. Set -up the environment: Check-out spatial analyst and 3D extensions.
2. Process the depth raster into the "Int" data type (See Reclass Tables section).
    a. Multiply the depth raster by 10 using "Times"
    b. Convert the output to an integer raster using "Int".
    c. "Reclassify" the depth raster into a larval depth HSI (saved as 0_LarDepHSI) and adult depth HSI (0_AduDepHSI) based on respective raster value to H-SI. The Reclass Tables Section shows reclassification bounds based on integer values.
    d. Divide the depth raster into a floating type raster again using "Divide"
3. Process the velocity raster into the "Int" data type (See Reclass Tables section).
    a. "Reclassify" the depth raster into a larval velocity HSI (saved as 0_LarVelHSI) and adult velocity HSI (0_AduVelHSI) based on respective raster value to H-SI using similar process as steps 2a-2d.
4. Finalize the Hydraulic-HSI: find the product ("Times") for the sub-parameters and the larval and adult life stages respectively.
5. Write to an Excel table:
    a. Get Raster Properties for the cell size and each average of the output rasters. This may be collected manually by looking at the raster properties.

b. Calculate Weighted Useable Area:
   i. Calculate inundated area by multiplying cell size and the number of cells in the raster.
   ii. For each discharge, multiply the average raster value for each respective parameter: larval depth, larval velocity, larval habitat suitability, adult depth, etc. This gives the useable area for each parameter.

6. The data may be visualized in several ways, as in this report (Harris, 2021).

Reclass Tables

The "Reclassify" tool works with integer rasters only. The inputs for each of the hydraulic habitat parameters per life stage are shown in the following tables. As demonstrated in the Key Steps workflow, the inputs and outputs are processed with the Raster Math tool "Times" and "Divide" to convert the floating rasters to integer rasters. The following tables correspond to the habitat suitability curves presented in the report.

Table 27. Reclass Tool inputs (gray columns) for the Larval H-SI data processing.

Velocity	(Raster) Velocity as Integer	H-SI Value	(Reclass) H-SI as Integer
0	0	1	10
0.1	1	1	10
0.2	2	1	10
0.3	3	0.75	8
0.4	4	0.50	5
0.5	5	0.45	5
0.6	6	0.40	4
0.7	7	0.35	4
0.8	8	0.30	3
0.9	9	0.25	3
1	10	0.20	2
1.1	11	0.15	2
1.2	12	0.10	1
1.3	13	0.05	1
1.4	14	0.00	0

Depth	(Raster) Depth as Integer	H-HSI Value	(Reclass) H-SI as Integer
0	0	1	10
0.1	1	1	10
0.2	2	1	10
0.3	3	1	10
0.4	4	1	10
0.5	5	1	10
0.6	6	1	10
0.7	7	0.95	9
0.8	8	0.89	9
0.9	9	0.84	8
1	10	0.79	8
1.1	11	0.74	7
1.2	12	0.68	7
1.3	13	0.63	6
1.4	14	0.58	6
1.5	15	0.53	5
1.6	16	0.47	5
1.7	17	0.42	4
1.8	18	0.37	4
1.9	19	0.32	3
2	20	0.26	3
2.1	21	0.21	2
2.2	22	0.16	2
2.3	23	0.11	1
2.4	24	0.05	1
2.5	25	0.00	0

Table 28. Reclass Tool inputs (gray columns) for the Adult H-SI data processing.

Velocity	(Raster) Velocity as Integer	H-SI Value	(Reclass) H-SI as Integer
0	0	1	10
0.1	1	1	10
0.2	2	1	10
0.3	3	1	10
0.4	4	1	10
0.5	5	1	10
0.6	6	1	10
0.7	7	1	10
0.8	8	1	10
0.9	9	1	10
1	10	1	10
1.1	11	1	10
1.2	12	1	10
1.3	13	1	10
1.4	14	0.96	10
1.5	15	0.93	9
1.6	16	0.89	9
1.7	17	0.85	9
1.8	18	0.81	8
1.9	19	0.78	8
2	20	0.74	7
2.1	21	0.70	7
2.2	22	0.67	7
2.3	23	0.63	6
2.4	24	0.59	6
2.5	25	0.56	6
2.6	26	0.52	5
2.7	27	0.48	5
2.8	28	0.44	4
2.9	29	0.41	4
3	30	0.37	4
3.1	31	0.33	3
3.2	32	0.30	3
3.3	33	0.26	3
3.4	34	0.22	2
3.5	35	0.19	2
3.6	36	0.15	1
3.7	37	0.11	1
3.8	38	0.07	1
3.9	39	0.04	0
4	40	0.00	0

Depth	(Raster) Depth as Integer	H-HSI Value	(Reclass) H-SI as Integer
0	0	1	10
0.1	1	1	10
0.2	2	1	10
0.3	3	1	10
0.4	4	1	10
0.5	5	1	10
0.6	6	1	10
0.7	7	1	10
0.8	8	1	10
0.9	9	1	10
1	10	1	10
1.1	11	1	10
1.2	12	1	10
1.3	13	1	10
1.4	14	1	10
1.5	15	1	10
1.6	16	1	10
1.7	17	1	10
1.8	18	1	10
1.9	19	1	10
2	20	1	10
2.1	21	0.92	9
2.2	22	0.83	8
2.3	23	0.75	8
2.4	24	0.67	7
2.5	25	0.58	6
2.6	26	0.50	5
2.7	27	0.42	4
2.8	28	0.33	3
2.9	29	0.25	3
3	30	0.17	2
3.1	31	0.10	1
3.2	32	0.10	1
3.3	33	0.10	1
3.4	34	0.10	1
3.5	35	0.10	1
3.6	36	0.10	1
3.7	37	0.10	1
3.8	38	0.10	1
3.9	39	0.10	1
4	40	0.10	1
4.01	40.1	0	0

Recommendations

Developing a Python Script or Module can reduce the likelihood of error. The process only requires two raster datasets as input, and the User can use a script to automate several steps of data processing: data type conversion, various reclassification steps, and raster algebra. The script is presented as an example of the data processing workflow. The script is functional and can be set up with a user interface like the one shown below. If the script is set up as a Tool, multiple raster datasets may be run in "Batch".

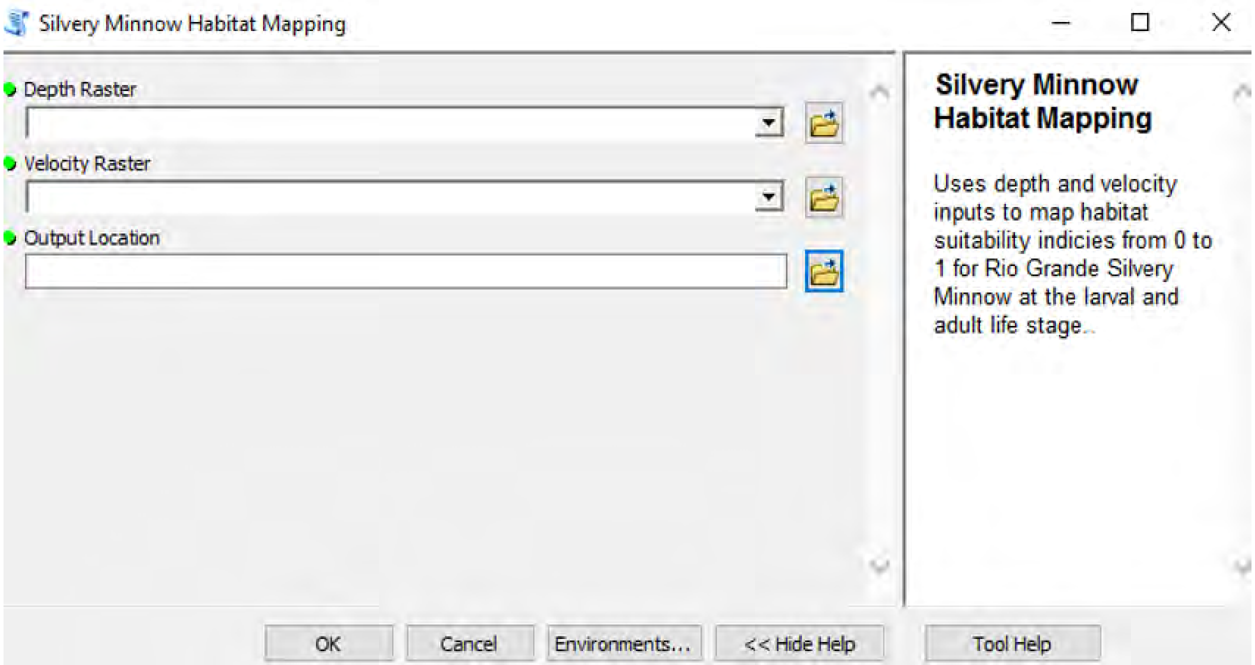


Figure 59. Example User Interface using two inputs and an output location for H-SI processing.

Example Script

```
#Set-up the environment
import arcpy, os, platform
from datetime import datetime as dt
from arcpy import env
from arcpy.sa import *

arcpy.CheckOutExtension("spatial")
arcpy.CheckOutExtension("3D")

# Set-up variables
Do = 10
```

```
Undo = 0.1
depth_raster  = arcpy.GetParameterAsText(0)
velo_raster = arcpy.GetParameterAsText(1)
path = arcpy.GetParameterAsText(2)  + "\\"
env.workspace = path
arcpy.env.overwriteOutput  = True

arcpy.AddMessage("Inputs  are valid..")
arcpy.AddMessage("Executing  Habitat Suitability Index...")
# Process
# the depth raster..
depth_times  = Times(Do, depth_raster)
depth_int  = Int(depth_times)
arcpy.AddMessage("Processing  depth  raster...")

# .. for larvae
larva_depInt  = Reclassify(depth_int,  "Value",
                           "0 6 10;7 8 9;9 10 8;11 12 7;13 14 6;15 16 5;17 18 4;19 20 3;21 22 2;23 24 1;25
10000 0")
larvadepHSI  = Times(Undo, larva_depInt)
larvadepHSI.save(path  + "0_LarDepHSI")

# .. for adults
adult_depInt  = Reclassify(depth_int,  "Value",
                           "0 20 10;21 9;22 23 8;24 7;25 6;26 5;27 4;28 29 3;30 2;31 40 1;41 10000 0")

adultdepHSI  = Times(Undo, adult_depInt)
adultdepHSI.save(path  + "0_AduDepHSI")

# the velocity raster..
velo_times = Times(Do, velo_raster)

velo_int = Int(velo_times)
arcpy.AddMessage("Processing  velocity raster...")
```

```
# .. for larvae
larva_velInt = Reclassify(depth_int, "Value", "0 2 10;3 8;4 5 5;6 7 4;8 9 3;10 11 2;12 1;13 10000 0")

larvavelHSI = Times(Undo, larva_velInt)
larvavelHSI.save(path + "0_LarVelHSI")

# .. for adults
adult_velInt = Reclassify(depth_int, "Value",
                    "0 14 10;15 17 9;18 19 8;20 22 7;23 25 6;26 27 5;28 30 4;31 33 3;34 35 2;36 38
1;39 10000 0")

adultvelHSI = Times(Undo, adult_velInt)
adultvelHSI.save(path + "0_AduVelHSI")

# Finalize HHSI analysis
AduHHSI = Times(adultvelHSI, adultdepHSI)
AduHHSI.save(path + "00_AduHHSI")

LarHHSI = Times(larvavelHSI, larvadepHSI)
LarHHSI.save(path + "00_LarHHSI")
arcpy.AddMessage("Finalizing analysis...")

# Write to table
# Create output table, with date as the name of the text file; open in append mode.
#Suggest changing tablePath to a location on the User’s drive, so that Batch analysis is appended
to a single text file.

now = dt.now()
date = now.strftime("%d%b%y")
tablePath = path + date + ".txt"

# convert the Raster to a shapefile so that its cells may be counted, count
out_path = path + "Ras_Point.shp"
countRas = arcpy.RasterToPoint_conversion(depth_int, out_path)
countResult = arcpy.GetCount_management(countRas)
scount = str(countResult)
```

```
# get properties from pre-processing results
cellSize = arcpy.GetRasterProperties_management(larvadepHSI, "CELLSIZEX")
gcellSize = cellSize.getOutput(0)
cellSize = float(gcellSize) ** 2
scellSize = str(cellSize)

larDep = arcpy.GetRasterProperties_management(larvadepHSI, "MEAN")
slarDep = larDep.getOutput(0)

larVel = arcpy.GetRasterProperties_management(larvavelHSI, "MEAN")
slarVel = larVel.getOutput(0)

larHHSI = arcpy.GetRasterProperties_management(LarHHSI, "MEAN")
slarHHSI = larHHSI.getOutput(0)

aduDep = arcpy.GetRasterProperties_management(adultdepHSI, "MEAN")
saduDep = aduDep.getOutput(0)

aduVel = arcpy.GetRasterProperties_management(adultvelHSI, "MEAN")
saduVel = aduVel.getOutput(0)

aduHHSI = arcpy.GetRasterProperties_management(AduHHSI, "MEAN")
saduHHSI = aduHHSI.getOutput(0)

arcpy.AddMessage("Printing export table...")

# write data as a row in the table
file = open(tablePath, "a")
file.write(
    depth_raster + ", " + velo_raster + ", " + path+ ", " + scount + ", " + scellSize + ", " + slarDep + ", " + slarVel + ", " + slarHHSI + ", " + saduDep + ", " + saduVel + ", " + saduHHSI + ",\n")
file.close()
```

The result of this code are several rasters showing the spatial distribution of H-SI and a comma separated file containing quantities that can be used for effective habitat curves, H-SI vs. discharge relationship figures and other quantitative analysis.

Appendix B: 1D Modeling Adjustments

Methodology for 1D Modeling Adjustments in Section 2.1.1

Appendix Table 1. Approximate adjustments of the 2012 1D model to match water surface elevations observed in 2019.

LINE (PROJECT)	1-D CORRECTION FROM 2012 TO 2019
SA-1215 (RM 114, RM 112)	Narrowed channel by 20 feet; Bed lowered by 1.4 feet.
SO-1327 (RM 103, RM 104.5)	Bed lowered by 2.3 feet
SO-1346 (RM 99.5, RM 100.5)	Narrowed channel by 20 feet; Bed lowered by 1.3 feet
(RM 100)	No narrowing: Bed lowered by 0.4 feet
SO-1414 (RM 93)	Bed lowered by 0.13 feet
SO-1420 (RM 93)	Bed lowered by 1.5 feet to account for widening by approximately 85 feet.

Appendix C: 2D Modeling Options

RM 93

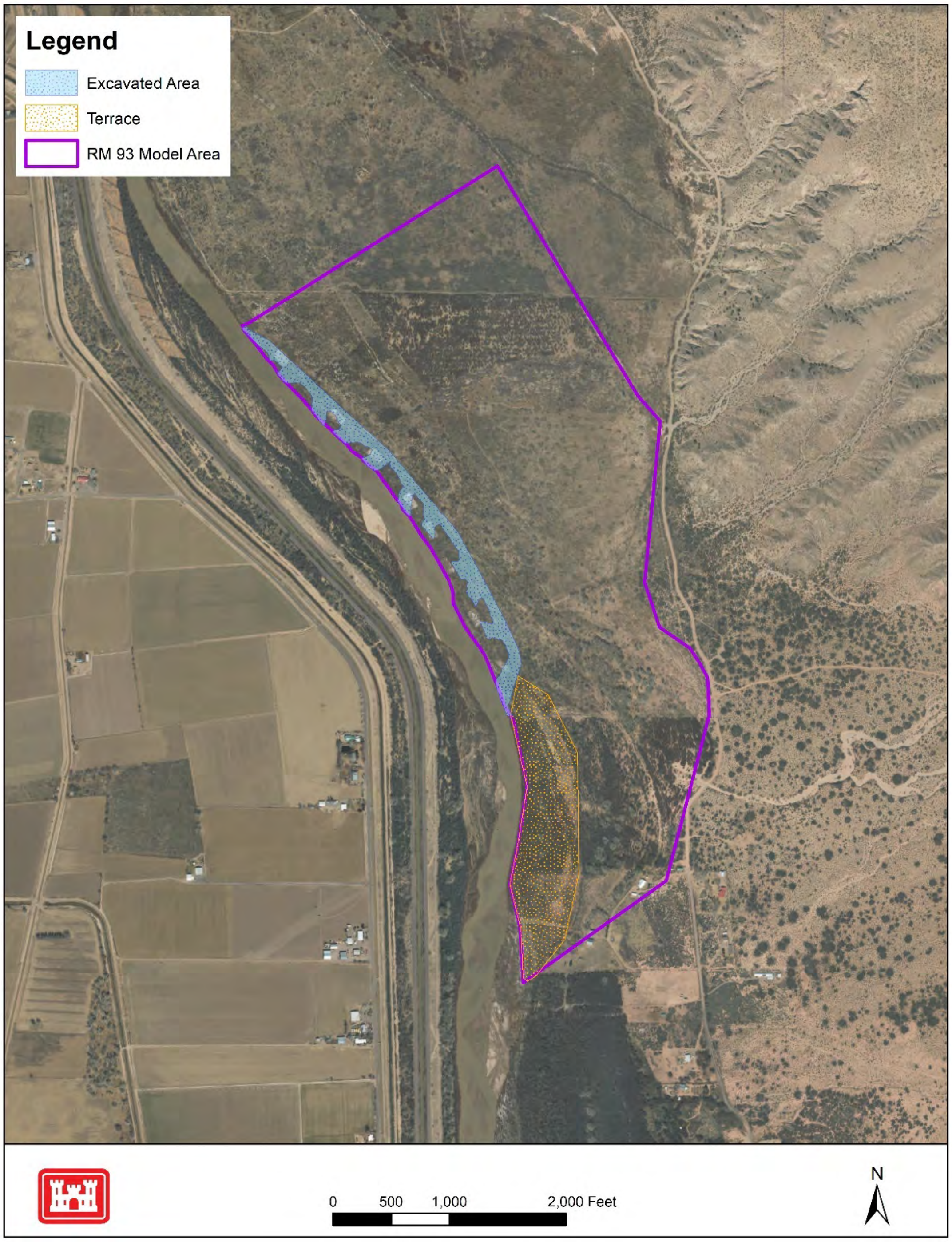


Figure 60. Extents of the 2D model area, the RM 93 excavated area (HR site) and the area evaluated as a "terrace".

2D Area:

- Cell size = 10 ft square
- Default Manning's 'n': 0.06

Landcover:

- Barren = 0.02
- Sparse Scrub-shrub = 0.06

Lateral Structure:

- RS 319000: Weir Equation, Left overbank, Use Velocity as 2D Boundary, Weir width = 0; Coefficient = 0.2; Height = Zero Height.

Unsteady Computation Options:

- General: 30 warm-up time steps, with a time step of 0.05 hours. Lateral structure flow stability = 2;
- 2D Flow Options: 2 hrs initial conditions time, ramp up factor of 80%, 50 time slices. Boundary condition volume checked.
- 1D/2D: 5 iterations between 1D and 2D
- Advanced time step control: 0.75 minimum Courant, 5 as maximum Courant. Use the Courant Method.

RM 99.5

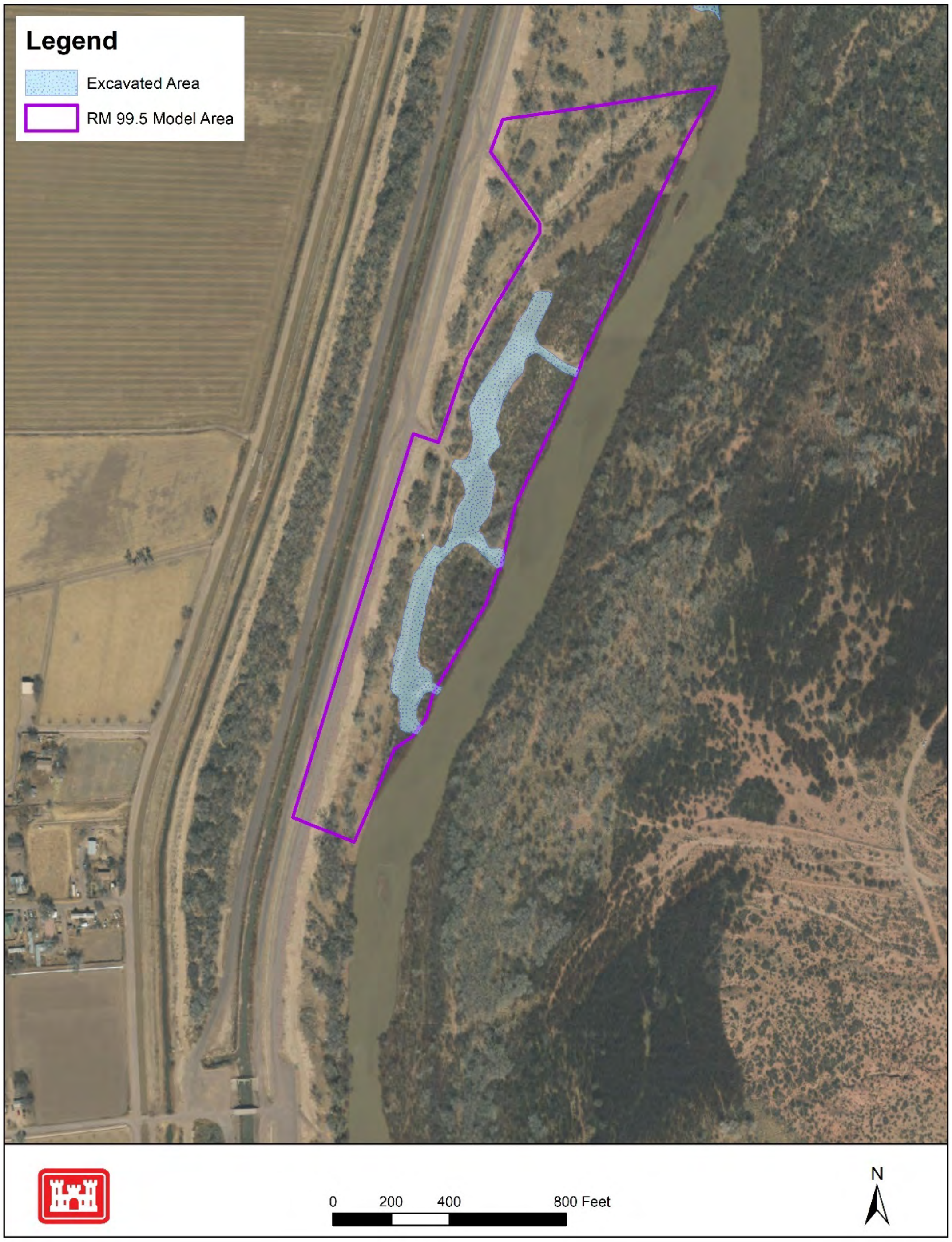


Figure 61. Extents of the 2D model area (evaluated as the adjacent floodplain or "terrace" – geomorphic terrace shown as well) and the RM 99.5 excavated area (HR site).

2D Area:

- Cell size = 15 ft square
- Default Manning's 'n': 0.08

Landcover:

- Barren = 0.03
- Dense Willows = 0.15
- Grasses = 0.03
- Sparse Scrub-shrub = 0.06

Lateral Structure:

- RS 349000: Weir Equation, Right overbank, Use Velocity as 2D Boundary, Weir width = 0; Coefficient = 0.2; Height = Zero Height.

Unsteady Computation Options:

- General: 100 warm-up time steps, with a time step of 0.01 hours. Lateral structure flow stability = 2;
- 2D Flow Options: 2 hrs initial conditions time, ramp up factor of 80%, 30 time slices. Boundary condition volume checked.
- 1D/2D: 5 iterations between 1D and 2D
- Advanced time step control: 0.75 minimum Courant, 3 as maximum Courant. Use the Courant Method.

RM 100

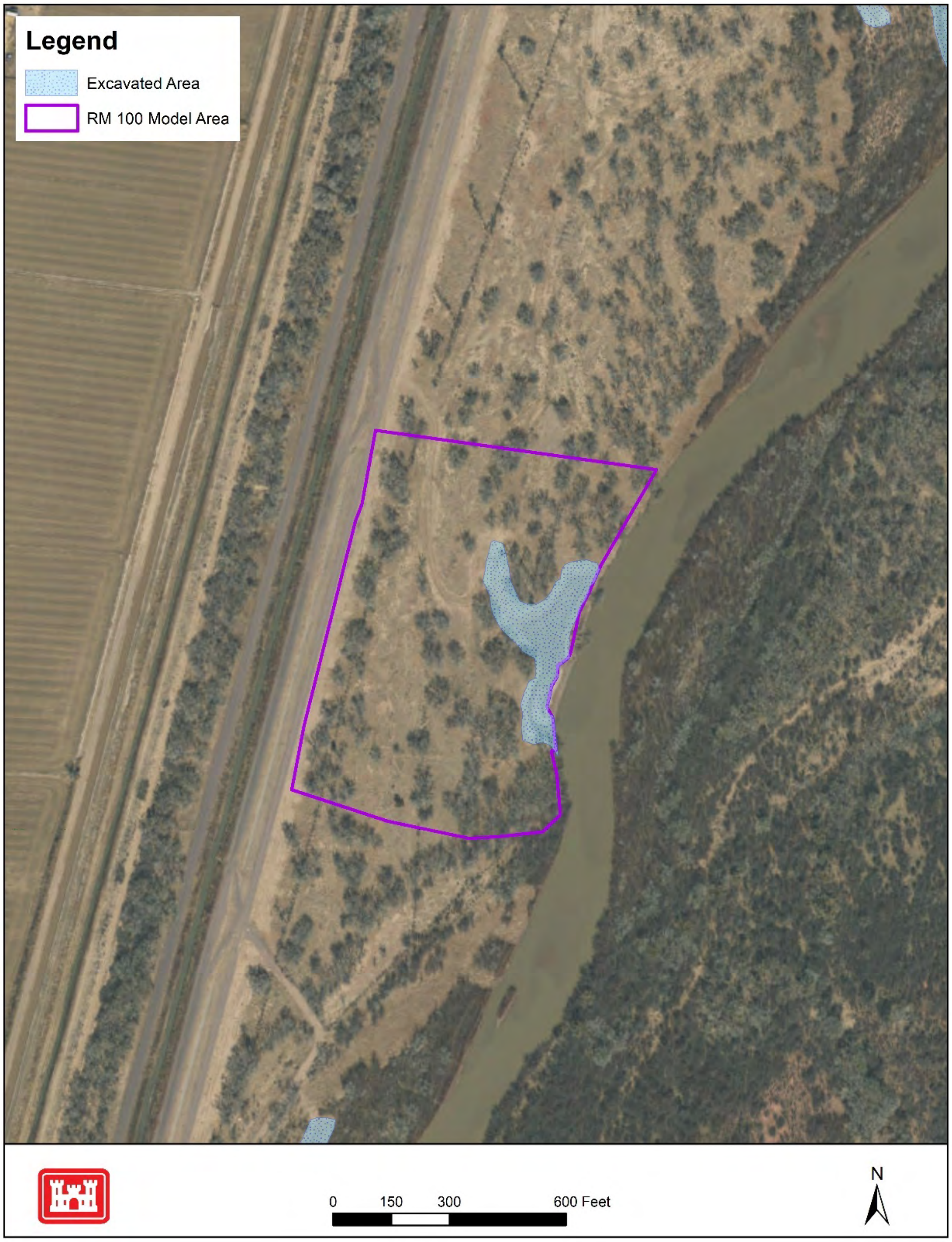


Figure 62. Extents of the 2D model area (evaluated as the adjacent floodplain or "terrace") and the RM 100 excavated area (HR site).

2D Area:

- Cell size = 15 ft square
- Default Manning's 'n': 0.08

Landcover:

- Barren = 0.03
- Dense Willows = 0.15
- Grasses = 0.03
- Sparse Scrub-shrub = 0.06

Lateral Structure:

- RS 350900: Weir Equation, Right overbank, Use Velocity as 2D Boundary, Weir width = 0; Coefficient = 0.35; Height = Zero Height.

Unsteady Computation Options:

- General: Lateral structure flow stability = 2;
- 2D Flow Options: 2 hrs initial conditions time, ramp up factor of 80%, 20 time slices. Boundary condition volume checked.
- 1D/2D: 5 iterations between 1D and 2D
- Advanced time step control: 0.75 minimum Courant, 3 as maximum Courant. Use the Courant Method.

RM 100.5

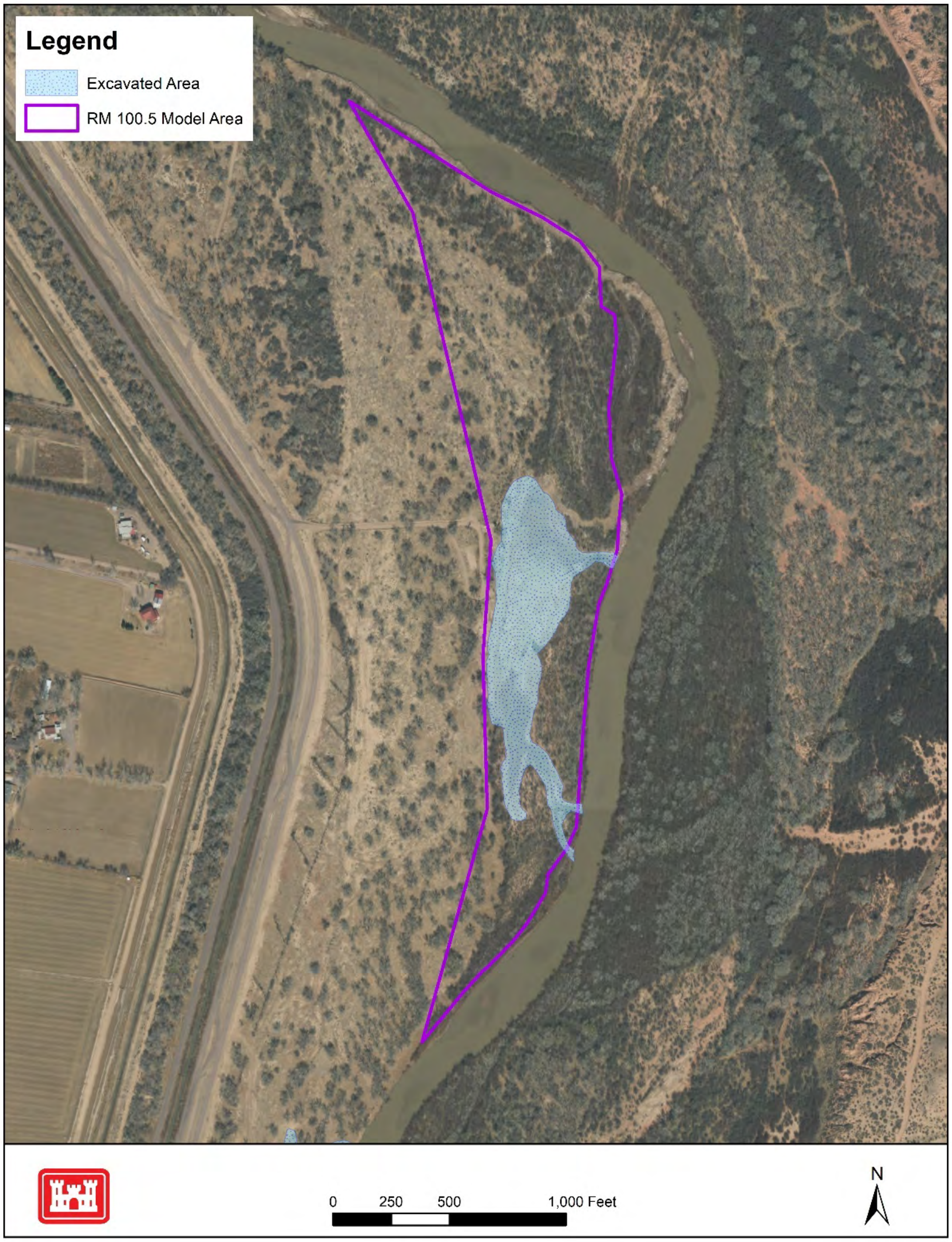


Figure 63. Extents of the 2D model area (evaluated as the adjacent floodplain or "terrace") and the RM 100.5 excavated area (HR site).

2D Area:

- Cell size = 10 ft square
- Default Manning's 'n': 0.08

Landcover:

- Barren = 0.03
- Dense Willows = 0.15
- Grasses = 0.05
- Sparse Scrub-shrub = 0.06

Lateral Structures:

- RS 355500: 2D Equation Domain, Next to right bank station, Use Velocity as 2D Boundary.
- RS 352600: 2D Equation Domain, Next to right bank station, Use Velocity as 2D Boundary
- RS: 352070: Weir Equation, Next to right bank station, Use Velocity as 2D Boundary, Weir width = 0; Coefficient = 0.5; Height = Zero Height.
- RS 351000: 2D Equation Domain, Next to right bank station, Use Velocity as 2D Boundary

Unsteady Computation Options:

- General: 20 warm-up time steps, with a time step of 0.1 hours. Lateral structure flow stability = 2;
- 2D Flow Options: 2 hrs initial conditions time, ramp up factor of 80%, 20 time slices. Boundary condition volume checked.
- 1D/2D: 5 iterations between 1D and 2D
- Advanced time step control: 0.75 minimum Courant, 5 as maximum Courant. Use the Courant Method.

RM 103

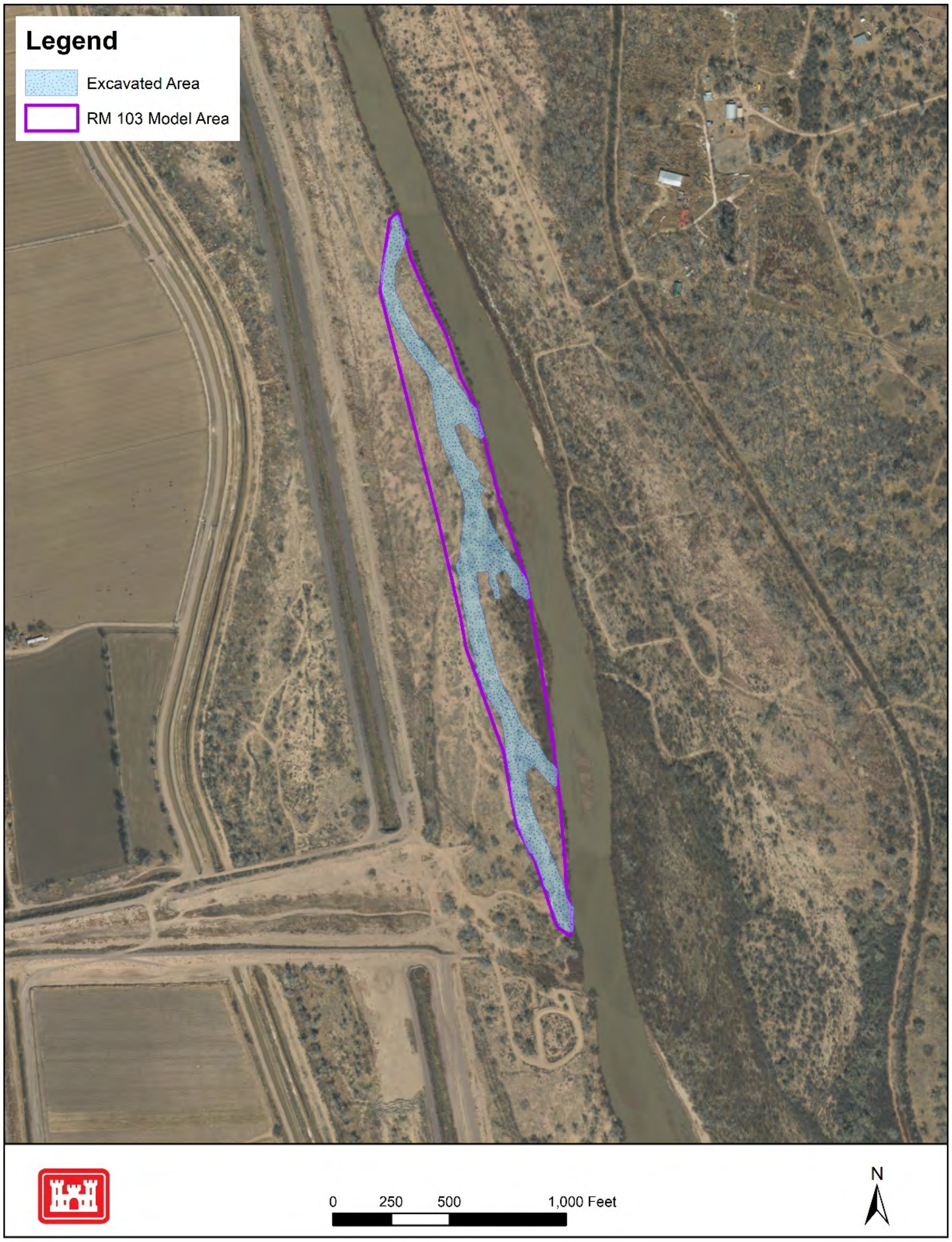


Figure 64. Extents of the 2D model area (evaluated as the adjacent floodplain or "terrace") and the RM 103 excavated area (HR site).

2D Area:

- Cell size = 10 ft square
- Default Manning's 'n': 0.038

Landcover:

- Not needed due to incised nature of the site.

Lateral Structure:

- RS 365335: Weir Equation, next to Right Bank Station, Use Velocity as 2D Boundary, Weir width = 0; Coefficient = 0.2; Height = Zero Height.

Unsteady Computation Options:

- General: 100 warm-up time steps, with a time step of 0.01 hours. Lateral structure flow stability = 2;
- 2D Flow Options: 2 hrs initial conditions time, ramp up factor of 80%, 20 time slices. Boundary condition volume checked.
- 1D/2D: 5 iterations between 1D and 2D
- Advanced time step control: 0.75 minimum Courant, 3 as maximum Courant. Use the Courant Method.

RM 104.5

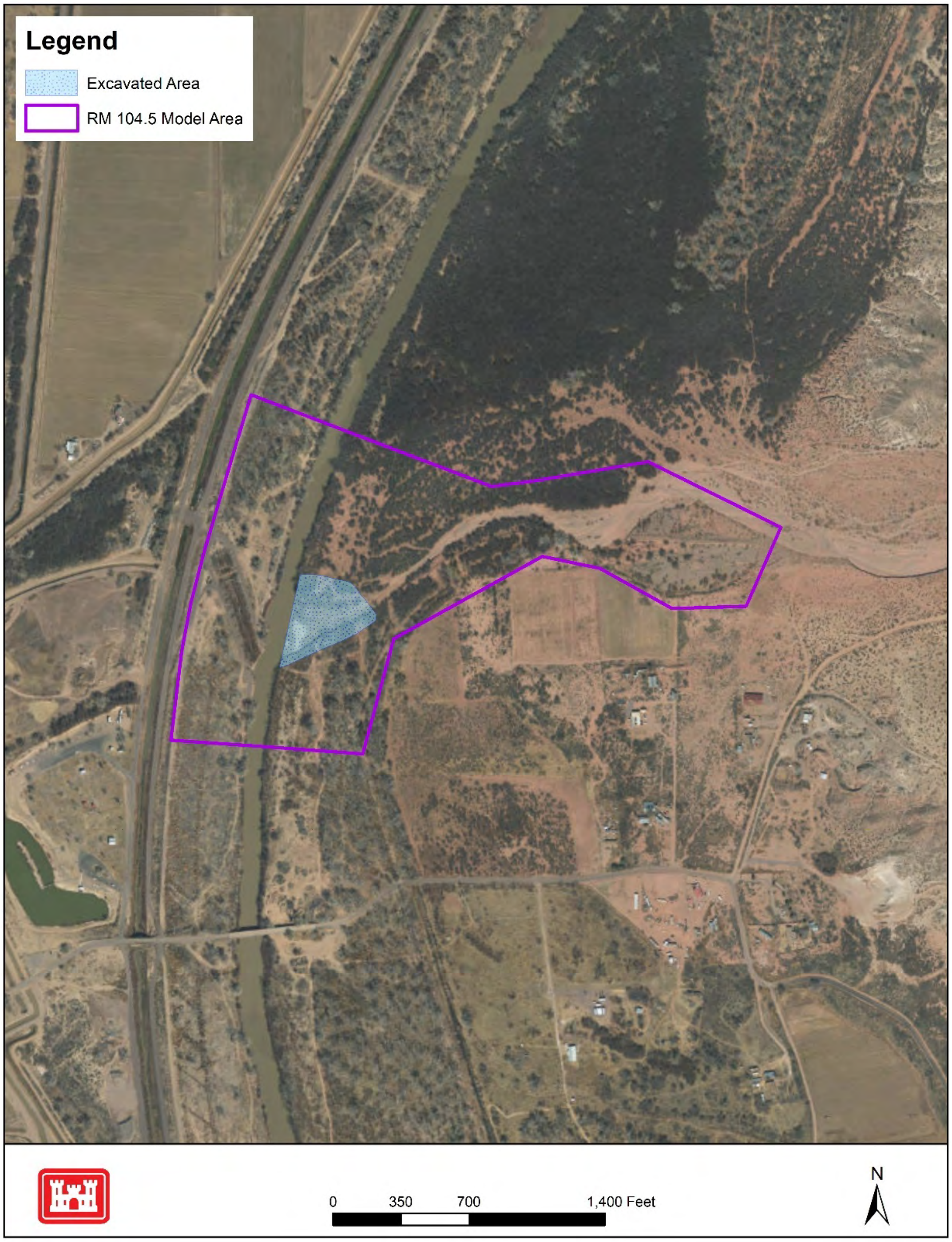


Figure 65. Extents of the 2D model area and the RM 104.5 excavated area (HR site). Areas excluding the Rio Grande channel were evaluated as a "terrace".

2D Area:

- Cell size = 10 ft square in project area; 40 ft square outside project
- Default Manning's 'n': 0.06

Landcover:

- Active channel = -0.035
- Arroyo excavated area = 0.025
- Embayment area = 0.08

Lateral Structure:

- None utilized. Fully 2D

Unsteady Computation Options:

- General: 100 warm-up time steps, with a time step of 0.01 hours. Lateral structure flow stability = 2;
- 2D Flow Options: 2 hrs initial conditions time, ramp up factor of 80%, 20 time slices. Boundary condition volume checked.
- 1D/2D: Not utilized
- Advanced time step control: 0.9 minimum Courant, 2 as maximum Courant. Use the Courant Method.

RM 112

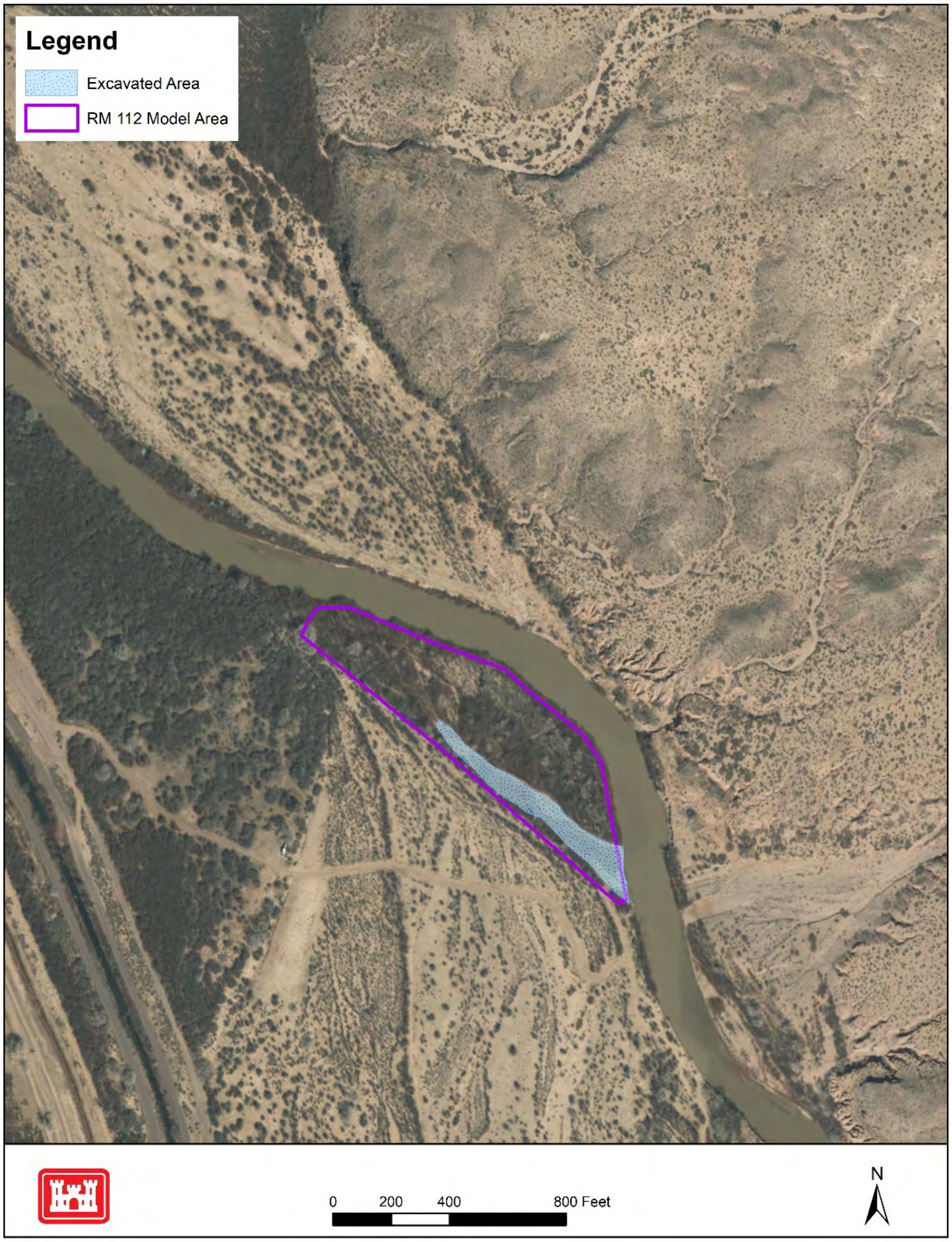


Figure 66. Extents of the 2D model area (evaluated as the adjacent floodplain or "terrace") and the RM 112 excavated area (HR site).

2D Area:

- Cell size = 10 ft square
- Default Manning's 'n': 0.08

Landcover:

- Barren, "sluggish, ineffective areas" = 0.14

Lateral Structures:

- RS 409900: Weir Equation, Next to right bank station, Use Velocity as 2D Boundary, Weir width = 0; Coefficient = 0.1; Height = Zero Height.
- RS: 408200: Weir Equation, Next to right bank station, Use Velocity as 2D Boundary, Weir width = 0; Coefficient = 0.25; Height = Zero Height.

Unsteady Computation Options:

- General: 20 warm-up time steps, with a time step of 0.01 hours. Lateral structure flow stability = 2;
- 2D Flow Options: 4 hrs initial conditions time, ramp up factor of 80%, 20 time slices. Boundary condition volume checked.
- 1D/2D: 5 iterations between 1D and 2D
- Advanced time step control: 0.75 minimum Courant, 3 as maximum Courant. Use the Residence Time.

RM 114

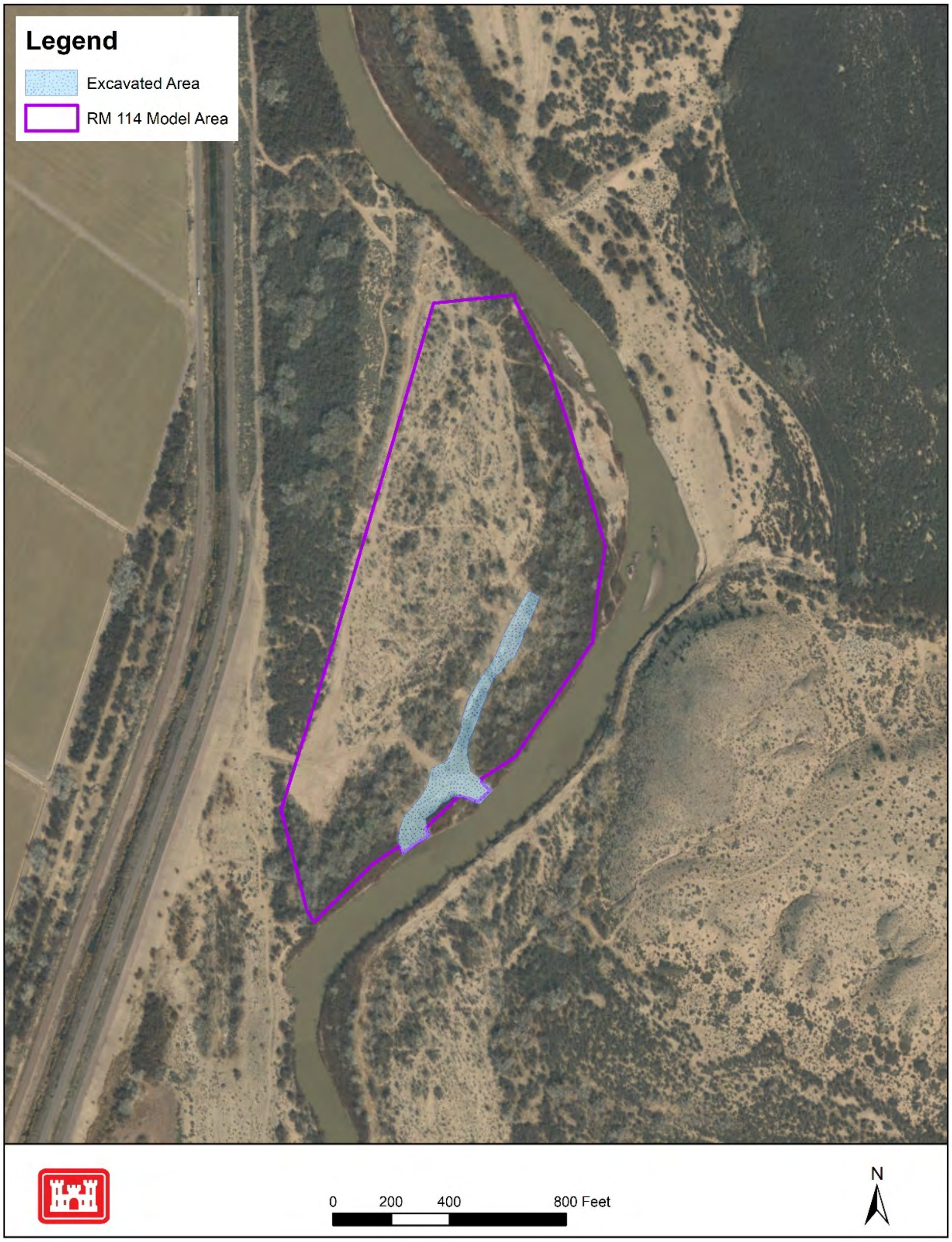


Figure 67. Extents of the 2D model area (evaluated as the adjacent floodplain or "terrace") and the RM 114 excavated area (HR site).

2D Area:

- Cell size = 10 ft square
- Default Manning's 'n': 0.08

Landcover:

- Barren = 0.03

Lateral Structures:

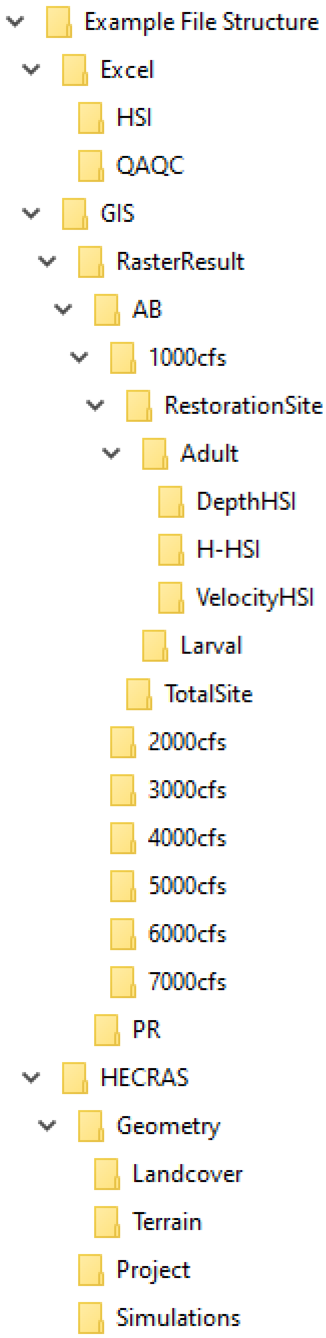
- RS 420600: Normal 2D Equation, Next to right bank station, Use Velocity as 2D Boundary,
- RS: 418000: Weir Equation, Next to right bank station, Use Velocity as 2D Boundary, Weir width = 0; Coefficient = 0.5; Height = Zero Height.

Unsteady Computation Options:

- General: 20 warm-up time steps, with a time step of 0.01 hours. Lateral structure flow stability = 2;
- 2D Flow Options: 4 hrs initial conditions time, ramp up factor of 80%, 20 time slices. Boundary condition volume checked.
- 1D/2D: 5 iterations between 1D and 2D
- Advanced time step control: 0.75 minimum Courant, 3 as maximum Courant. Use the Residence Time.

Appendix D: File Management

The following folder structure is an example and demonstrates all of the data utilized and generated in this analysis.



Naming convention:

- *AB: As-built terrain*
- *PR: Post-runoff terrain*

<u>HEC-RAS folder</u> contains: HEC-RAS project files; terrains and landcover; the naming convention for simulations:

Terrain (As-Built or Post-Runoff)-Discharge (in cfs)

(e.g. AB-4000)

<u>Excel folder</u> contains results from raster analysis; quality assurance and quality control data, such as the hydraulic quality assurance analysis based on field-measured points. These data were generated using a Python Script described in Appendix A.

<u>GIS folder</u> contains the raster hydraulic habitat suitability results, using the same naming convention as HEC-RAS simulations.

Naming convention:

Depth HSI or dep: Results of the depth HSI analysis for larval and adult life stage respectively.

Velocity HSI or vel: Results for the velocity HSI for larval and adult life stage.

HHSI or HSI: the results of compositing the depth and velocity HSI.