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Abstract

The proliferation of continuous streamflow monitoring and spatial data suitable for hydraulic modeling is increasing opportunities to use hydraulic habitat analysis to inform ecological models. However, species population and streamflow data exhibit high variability, making it challenging to identify hydrologic and hydraulic metrics that effectively correlate with ecological outcomes. Metric selection presents a challenge for informing environmental flow decisions and adaptive management of water infrastructure.

This study applies models to characterize environmental flows with increasing model complexity, including the use of hydraulic models to estimate suitable habitat areas at a given flow. The results are compared to field-measured fish outcomes over the same period using functional data analysis. The variance in model correlation with ecological outcomes aids in identifying the most effective environmental flow parameters while also indicating potential pitfalls from increasing model complexity. This analysis demonstrates techniques that synthesize environmental flows with available habitat analysis and validates the approach.

The case study is based on the Rio Grande silvery minnow (*Hybognathus amarus,* minnow), an endangered fish species in the Middle Rio Grande. Analysis focused on different methods to quantify spring runoff coinciding with the inundation of floodplain nursery habitat necessary for the minnow's larval and juvenile life stages.

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Preface

This study was conducted for Headquarters, US Army Corps of Engineers (USACE) under Funding Account Code U4388857, AMSCO Code 031342, Project SON ENV-1227, "Comparison of Ecological Model Outputs." This study was conducted as part of the Ecosystem Management and Restoration Research program under the direction of Dr. Brook Herman, Program Manager.

The work was performed by the USACE Albuquerque District and the Ecological Resources Branch of the Environmental Process and Engineering Division, Engineer Research Development Center–Environmental Laboratory (ERDC-EL). At the time of publication, Mr. Joseph B. Minter was branch chief; Mr. Mark D. Farr was division chief; and Dr. Jennifer M. Seiter-Moser was technical director. The deputy director of ERDC-EL was Dr. Brandon J. Lafferty, and the director was Dr. Edmond J. Russo.

Data for hydraulic models were provided by the US Bureau of Reclamation. Fish population monitoring by American Southwest Ichthyological Researchers was funded by the US Bureau of Reclamation and the Middle Rio Grande Endangered Species Collaborative Program. Shishir Rao, graduate student from the University of Georgia, contributed to the FDA analysis. Dr. John Hickey provided guidance on setting up the Hydrologic Engineering Center's Ecosystem Functions Model for environmental flows analysis. ERDC technical reviews were provided by Dr. Todd Swannack and Dr. Garrett Menichino.

The commander of ERDC was COL Christian Patterson, and the director was Dr. David W. Pittman.

1 Introduction

The Rio Grande silvery minnow (*Hybognathus amarus*, RGSM) has been a focus of water and ecosystem management since being listed as an endangered species in 1994. Population management efforts include rescuing minnows stranded in channel pools during river drying, conducting population surveys throughout the year, and augmenting populations with hatchery-raised minnows. Habitat restoration has been used to countervail channelization and floodplain narrowing projects of the Rio Grande's main stem with an emphasis on increasing slow-moving nursery habitat. Flow releases from upstream reservoirs are constrained by international compact and authorized use of water within dam operational rules, but flow regulation has been identified as an important leverage point for stimulating minnow reproduction. Research on minnow spawning and movement has informed adaptive management by improving understanding of habitat utilization and potential benefits of flow regulation.

Many factors affect hydrologic flows in the Middle Rio Grande. The volume of water available in the system is typically dictated by two sources: snowpack storage in the headwaters of the watershed and water emitted from meteorological events, notably the summer monsoons. Water availability during the spring runoff is driven by the melting snowpack. The hydrographic variability is high from year to year, which induces significant noise in both streamflow and biological data. Consistent and comprehensive monitoring data representative of intra-and interannual patterns are challenging to collect and analyze in light of this variability.

Local and federal agencies have constructed water delivery projects for agricultural irrigation, municipal water supply, flood risk management and water conveyance to fulfill international and interstate compacts. These projects included channelization, irrigation infrastructure and levee flood protection construction, and flood control dams (Schmidt et al. 2003). Arguably, both river hydraulics and hydrology have been affected by these river engineering projects. Hydrologic trends have been affected by climate and land management, which in turn alter riverine hydrology and sediment transport.

Water management, in combination with a drying and warming climate, has reduced minnow habitat availability (US Fish and Wildlife Service 2010). The minnow is considered an "indicator" fish species of the broader

Middle Rio Grande ecosystem. Fish monitoring was initiated in 1993 to track population trends (Dudley et al. 2019). The interaction of hydrology, sampling methods, and fish catchability produce highly variable fish population data, but two major patterns have emerged. First, reproductive success of the minnow generally increases during larger spring runoff flow (Valdez et al. 2019). Second, the response of the fall population index to floodplain inundation suggests the importance of nursery habitat in minnow life history (Porter and Massong 2002). Environmental flow analyses conducted for the Cochiti Deviation (USACE 2007, 2008, 2009) use these observations as the basis for both active and passive adaptive management (USACE 2019).

The riparian hypothesis (Coutant 2004) provides useful background for understanding the role of inundated floodplain as fish nursery habitat. The riparian hypothesis identifies floodplain habitat inundated by seasonal flow as important fish nursery habitat (Junk et al. 1999). The silvery minnow's early life history and preferred hydraulic habitat has been extensively described (Dudley and Platania 2007; Medley and Shirey 2013; Valdez et al. 2019, 2020). Minnow spawning occurs in conjunction with the rising spring hydrograph (Pease et al. 2006; Widmer et al. 2010; Dudley, Robbins, et al. 2020) and simultaneous inundation of floodplain nursery habitat (Porter and Massong 2002; Fluder et al. 2005; Gonzales et al. 2012; Valdez et al. 2019, 2020). Floodplain hydraulics generally have slower velocities and shallower depths than active channel hydraulics, due to the friction caused by vegetation and the ability of water to spread over greater areas.

In general, water management actions have altered the magnitude, duration, frequency, timing, and rate of change of streamflow and river levels—that is, its flow regime (Poff et al. 1997). In recent years, federal and local agencies invested in habitat restoration and investigated environmental flow strategies to support minnow reproduction. These efforts include regulating water for key seasons of the minnow's life cycle and constructing habitat restoration sites to provide floodplain nursery habitat within the channelized reaches of the Middle Rio Grande. Population and restoration monitoring have been helpful in characterizing minnow habitat created by the frequency, magnitude, and duration of discharge events.

1.1 Background

The water management community is challenged by the ability to identify parsimonious and actionable environmental parameters that support ecosystem processes. This study directly addresses this issue by describing how different resolutions of hydrologic and hydraulic data may be analyzed to inform decisions about fisheries outcomes. Better coupling of physical and ecological modeling tools provides more accurate forecasts of the efficacy of alternative water management strategies. Ultimately, these modeling tools and methods help support the US Army Corps of Engineer's (USACE's) need to balance project purposes such as flood risk management and ecological sustainability.

1.2 Objective

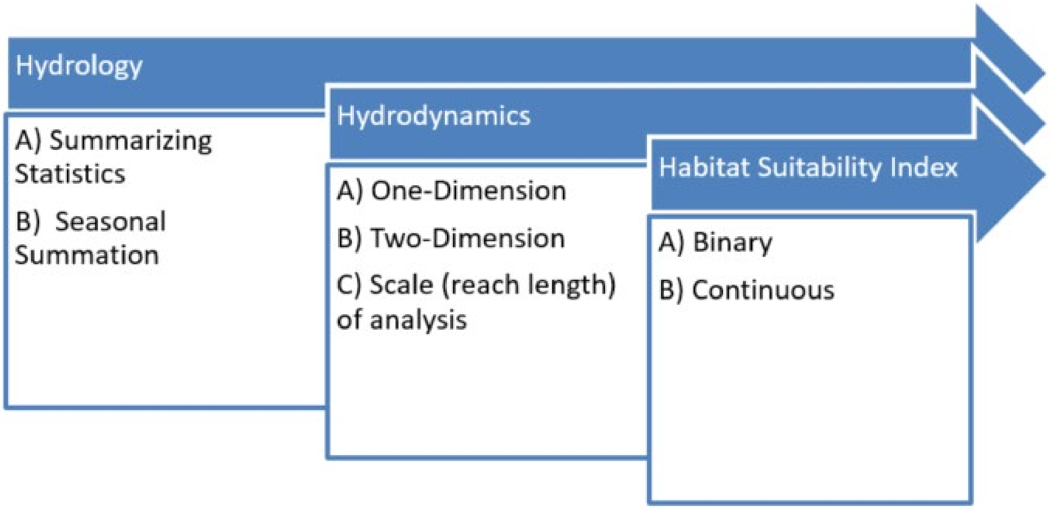
The objective of this work is to assess the accuracy of alternative models for fish population and habitat outcomes in the Middle Rio Grande with a specific focus on the RGSM. Model performance is assessed for multiple hydrologic and hydraulic habitat models based on correlation with fisheries outcomes as well as other factors, such as model complexity and usability.

1.3 Approach

Different levels of hydrologic and hydraulic model complexity were used to quantify available habitat aligned with long-term fish monitoring records. Two seasonal hydrologic time periods, three hydraulic models in varying scale and resolution, and two habitat suitability indices were used as covariates for fish population metrics (Figure 1). The fish population metrics were computed from catch-rates over the year and during the spring runoff season, when fish mature from larvae to free-swimming juvenile.

The result for each model was a streamflow or inundated area representing an environmental flow parameter. The correlation of each model to the fish metric was computed and then compared across model types. Drivers of model performance relative to ecological models for the species are discussed, including how these parameters present alternatives to conventional habitat management.

Figure 1. Increasing complexity of environmental analysis incorporated in this sensitivity analysis.



The analysis informs users on whether increased resolution and scale of hydrologic and hydrodynamic modeling, or pursuing more specific habitat suitability indices, improves predictions of minnow populations. The multitude of combinations also provides the user with options on how to evaluate upcoming water management plans and how hydraulic analysis may be employed for evaluating minnow hydraulic habitat.

2 Methods

2.1 Fish Population Data

The sampling methods and fish catchability produce statistically noisy population data. The fish metrics were calculated from this highly variable data to estimate the population trajectories resulting from environmental trends. Fish population data (2002 to 2018; Dudley et al. 2020) were used for deriving recruitment and population trends (fish metrics) for functional analysis. Fish were collected from April to October using two sizes of seines (3.1 m × 1.8 m with 4.8 mm mesh and 1.2 m × 1.2 m with 1.6 mm mesh) for 20 hauls totaling ~400–600 m^2 (per site visit) at 20 sites. RGSM data include location, habitat type, standard fish length, and age class by individual seine haul (MRGESCP 2020). Age class (0, 1, 2+) was assigned based on standard fish length. The data undergo preliminary review following sampling and a second review prior to release of the annual report (Dudley et al. 2020). The year 2009 was excluded from analysis because sampling was limited to September and October, precluding calculation of recruitment metrics.

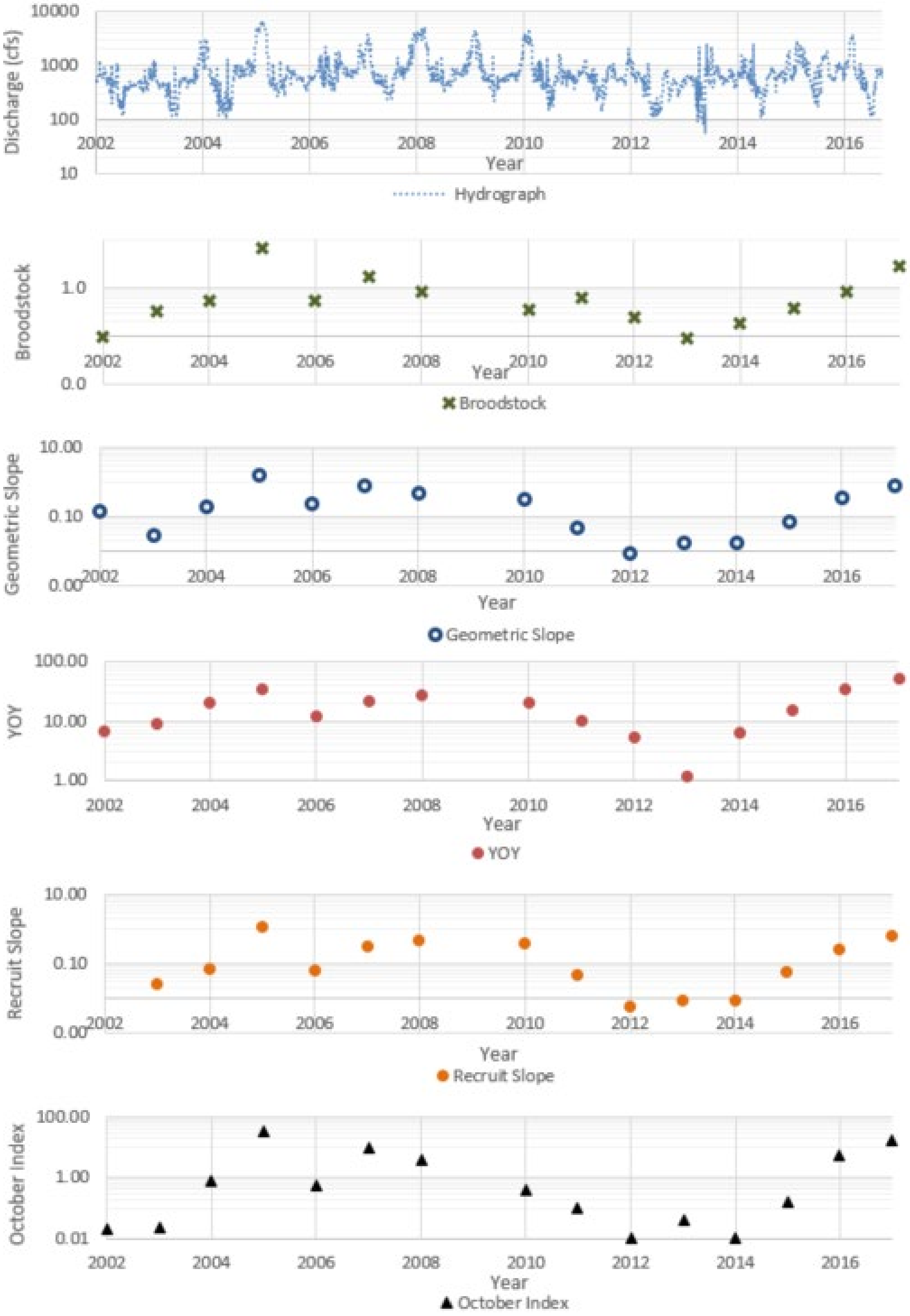
Five fish population metrics (Table 1) were calculated for each sample year using the R statistical software language from the minnow population monitoring dataset (Dudley et al. 2020). Data were parsed into annual cohorts based on estimated age at capture. Cohort catch-per-unit-effort (CPUE; Bonar et al. 2009) was calculated for each site and month from May to October (Table 1; Figure 2) as the number of fish captured per 100 m^2 area sampled, with 0.001 added to each value to support log-transformation of the data.

Table 1. Fish population and recruitment metrics used in the functional analysis (see Table 4).

Fish Metric	Label	Formula	Date range
Broodstock (CPUE)	Broodstock	$100P$	April
Slope to mean (CPUE)	Geometric slope	$lm(\mu\_100P/\mu\_\tau)$	May 1–Aug 9
Young-of-year (CPUE)	YOY	$\frac{100P}{T}$	May 1–Aug 9
Slope of recruit (CPUE)	Recruit Slope	$lm(P \sim T)$	May 1–Aug 9
October index (CPUE)	October index	$100P + 0.001$	October

Where μ_x = average of variable *x*; P= fish population/unit area; T= date range; τ= number of days.

Figure 2. Fish population and recruitment metrics for the period of interest.



The October index (CPUE) calculated from the annual fish sampling at the end of irrigation season is the primary population metric for minnow recruitment and survival (Dudley et al 2020). The percent of seine hauls across the entire sampling effort with at least one RGSM was 37.1% (mean

CPUE =0.28 per 100 m^2, range 0.10–33.33 per 100 m^2 when present). Additional CPUE metrics were calculated for analyzing specific population trends with hydrologic and hydraulic metrics in comparison to the October index. The Broodstock covariate was calculated as the April population (CPUE) prior to spawning. The recruitment metrics were based on young-of-year (YOY) fish collected from May to August. The recruit slope metric is the slope coefficient of the regression line for YOY CPUE from May to August. The mean-slope metric is the slope coefficient from the linear regression model to average CPUE at the average sample date for the May–August samples. The YOY CPUE summarizes the total YOY catch for May to August. After generating these population metrics, it was found that the YOY and geometric slope had very similar distributions to "recruit slope" and were not carried forward in the sensitivity analysis between hydrologic and hydraulic metrics.

2.2 Hydrologic Analysis

The hydrologic data for this study were recorded by the USGS's Albuquerque streamflow gage (No. 08330000). Daily data from 2002 to 2018 were used, corresponding to the period of record for the fish CPUE data. The Hydrologic Engineering Center's Ecosystem Functions Model (HEC-EFM) was used to characterize seasonal streamflow. Though hydrology may be characterized with increasingly complex metrics, these may not necessarily provide meaningful data from an ecological perspective. This study investigates the sensitivity of hydrologic or hydraulic habitat characterization of the spring runoff event relative to annualized fish population metrics.

Streamflow hydrographs in the region are highly variable. The hydrologic analysis summarizes the daily discharge data as an annual spring runoff metric per year. Easily accessed flow statistics, such as the annual maximum, may be a poor representation of the cumulative volume of water for the water year and seasonal phenomena. Annual peak flow does not capture the nature of sustained flows and may overemphasize the peaky nature of semi-arid runoff events. The sensitivity analysis for hydrology tests the following parameters:

- Seasonality—The spring runoff is an important temporal event for minnow reproduction. Different time periods for the "spring season" are evaluated: one well-centered on the typical spring runoff season and a

longer season that may capture early or late runoff events. This differentiates comprehensive seasonal hydrology, which captures early or later than typical spring runoff peaks, and correlates better than a narrower definition of the spring runoff season, when most peak runoff events typically occur.
- Duration—Sample windows of 1, 7, 14, and 21 days reflect various durations of sustained streamflow.
- Statistic—Maximum of the minimum, means of the maximum, means of the minimum values (for each tested duration), and exceedance percentages are different ways to summarize the same season/duration.

From the combination of these parameters, there are 20 different discharge values representing the spring runoff and 8 probability of exceedance values for each year of this analysis (2002–2018).

2.3 Hydraulic Analysis

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) 5.0 was used to generate hydraulic parameters that are useful in characterizing minnow habitat. The hydrodynamic modeling is used to characterize relationships between streamflow and hydraulic conditions within inundated areas in a test reach of the Middle Rio Grande. The hypothesis is that some characteristic of the streamflow (hydrology) as it is affected by Middle Rio Grande topography (hydraulics) contributes to the life experience of the species. Channelization and reduction of floodplain areas have reduced slow-moving, shallow areas that were characteristic of the Rio Grande before large-scale engineering development. It is posited that as streamflow increases to flood stages, the areal availability of slow-moving and shallow habitat increases, and it is these areas of suitable habitat that drive minnow success. Therefore, quantification of areas of suitable hydraulic conditions may enable better prediction of minnow population data than streamflow alone.

One-dimensional (1D) and 2D modeling was conducted in HEC-RAS. The objective in comparing these is to determine if there are appreciable differences in the correlation of population metrics with areas of suitable habitat. Areas of inundation that conform to the hydraulic habitat suitability criteria for RGSM (discussed in Section 2.4) are quantified per discharge simulation. An eco-value curve is created by plotting areas of inundation and suitable habitat areas for the minnow larval and adult life stages relative to streamflow. These eco-value curves are input into HEC-EFM and paired with the characterizations of spring-runoff hydrology to generate habitat provision at annual, seasonal, and daily timescales. These habitat summary metrics are compared to the annualized fish population metrics.

This project aims to compare the usefulness of different modeling approaches relative to field-measured species proliferation. One advantage of 1D modeling is that it may be conducted over greater river lengths than 2D modeling. The resolution of information required for 1D modeling is also less demanding and expensive to gather. However, the results of a 1D model are averaged over the cross section and over each floodplain, therefore local hydraulics such as the slow-moving and shallow edge habitat and in-channel islands are simplified and sometimes lost when averaged. 2D modeling is better at delineating edge habitat, but also requires more detailed topographic data and land cover information.

Table 2 lists the three hydrodynamic models conducted. Each model is based on 2012 topography.

Table 2. The three-hydraulic based eco-value analyses conducted.

Criteria	Hydraulic Analysis Number 1 (HAN-1R)	Hydraulic Analysis Number 2 (HAN-1S)	Hydraulic Analysis Number 3 (HAN-2S)
Dimension	1D	1D	2D
Extent of Middle Rio Grande	30 mi reach, from Arroyo de la Barranca to Isleta Diversion Dam	10 mi (shorter) reach in Albuquerque	10 mi (shorter) reach in Albuquerque

Results from Hydraulic Analysis Number 2 (HAN-1S) and Number 3 (HAN-2S) (1D and 2D modeling of a 10 mi reach, respectively) have the same extents of a 10 mi reach through Albuquerque. A comparison of these demonstrates how higher hydraulic resolution from the 2D model differ from a 1D method in characterizing annual and seasonal riverine hydraulics.

The 1D model for Hydraulic Analysis Number 1 (HAN-1R) is based on the 2012 aggradation/degradation (agg-deg) data set collected by the Bureau of Reclamation (Reclamation or USBR). Reclamation used fixed-wing airborne lidar to collect this topography data and created 1D cross-sections at designated locations for the entire Middle Rio Grande. The 1D cross-sections were spaced 500 ft apart. Reclamation calibrated the 1D HEC-RAS model to observed water surface elevations and wetted channel widths at the time of the data collection. As part of the calibration process, the bathymetry of the river cross-section is simplified to a trapezoid and should not be used for estimations of water surface elevations at discharges lower than observed at the time of the data collection, which was 600 cubic feet per second (cfs).

The 2012 agg-deg model created by Reclamation has been modified by USACE to better correlate with backwater conditions created by bridges. For HAN-1S, the 1D model from the first analysis was clipped to conform to the 10 mi reach of interest in the Middle Rio Grande. This area of interest intersects with several habitat restoration projects, including the Bosque Restoration Projects (Sites 1A to 1H) that were designed and monitored by USACE.

For HAN-2S, the 2D model, the 2012 lidar dataset from Reclamation was used to derive the digital elevation terrain. The accuracy of this data has a 0.7 root mean square error and a 1.2 ft vertical accuracy at 2 ft contours (Woolpert 2012*b*). The mesh had 25 ft cells, and the diffusion wave equation set was selected. To simulate general channel hydraulics for the bed, field-measured bathymetric cross-sections from 2012 were incorporated in the surface. The transects were georeferenced and used to create a 1D HEC-RAS model and varied from 500 to 5,700 ft apart throughout the 10 mi reach. RAS-Mapper allows users to export a Tagged Image File Format (TIFF) of the cross-sectional geometry for the 1D model, which is interpolated along the river centerline. The TIFF representing the channel bathymetry was overlaid with the original lidar with a smoothed hydrosurface in ArcGIS. The result was compared to the original lidar and aerial imagery.

HEC-RAS 1D rangelines used for bathymetry were moved or corrected to neglect the islands that were not submerged during 2012 lidar data collection. This was an effort to preserve as much of the original lidar as possible and reduce the amount of interpolated data in the final terrain. The original lidar and the clipped bathymetric TIFF were combined as a final surface for 2D hydraulic analysis.

Land cover data for the 2D model are based on Hink and Ohmart (1984, H&O) delineation and classification of various landcover types:

I. Mature and mid-aged trees with shrubby vegetation at all heights
II. Mature and mid-aged trees with little or no shrubby vegetation
III. Intermediate-aged trees with dense shrubby vegetation
IV. Intermediate aged trees with little or no shrubby vegetation
V. Young stands of trees with dense shrubby vegetation
VI. Very young of trees low and/or sparse

A 2005 H&O vegetation dataset was available for the area of interest. A base landcover value was estimated to be analogous to the H&O description type. The landcover values were then calibrated so that the areas of inundation for a 600 cfs event and a 2,000 cfs event simulated in HEC-RAS was similar to the extents shown in aerial photography available for the modeled area at those discharges. Table 3 provides Landcover Manning's *n* values and roughness description for various H&O classifications.

Table 3. Hink and Ohmart (H&O) vegetation classification and calibrated Manning's *n* (roughness coefficient) values per landcover type.

H&O Classification	Landcover Manning's *n*	Roughness Description (Chow 1959)
Channel	0.033	Main Channels, clean, earthen channels (minimum value)
Open Water	0.030	Main Channels, clean, straight, full stage, no rifts or deep pools (normal value)
Type I	0.110	Floodplains, Trees, dense willows, summer, straight (minimum value)
Type II	0.050	Floodplains, Brush, scattered brush, heavy weeds (normal value)
Type III	0.110	Floodplains, Trees, dense willows, summer, straight (minimum value, same as Type I)
Type IV	0.050	Floodplains, Trees, cleared land with tree stumps, no sprouts (high value)
Type V	0.110	Floodplains, Brush, medium to dense brush, in summer (normal value)
Type VI	0.050	Floodplains, Trees, cleared land with tree stumps, heavy growth of sprouts (minimum value)

2.4 Habitat Analysis

The hydraulic analysis segment of this study generates an eco-value curve based on areal inundation, areas of appropriate velocities, appropriate depths, and appropriate habitat (a composite of velocities and depths). Eco-value curves represent the magnitude of available wetted habitat based on the quality of habitat and the area. For the minnow, these are generally areas that are slow-moving and shallow. Suitable depth and velocity qualities for the larval, juvenile, and adult life stages were estimated from Bestgen et al. (2003), Bovee et al. (2008), and Mortensen et al. (2019). These studies are presented as a literature review by Mortensen et al. (2019). Field-data reports with velocities and depths have also been recorded by Valdez et al. (2019, 2020) and Braun et al. (2015).

While the volumes of available water can be estimated with the hydrologic analysis, and the total inundated and overbank inundated areas can be estimated with hydraulic models, the habitat preferences from the literature can be applied to estimate habitat availability in a given season.

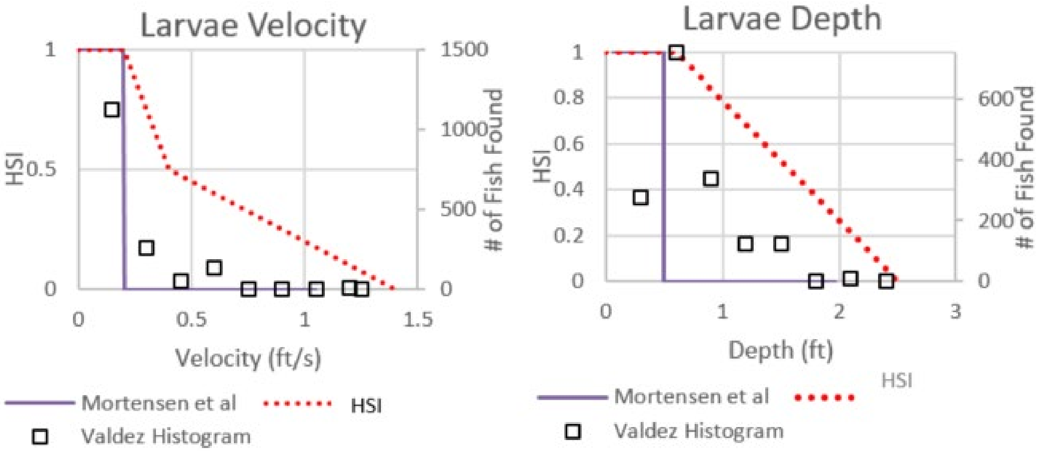
Previous studies observed increasing floodplain inundation was correlated with increased minnow production and therefore computed inundation areas based on Middle Rio Grande geomorphology in 1992, 2002, and 2012 (Gronewold 2010, Harris 2020). For these studies, hydraulic models were used to estimate the surface area of inundation at a given discharge, and then a lookup table was created to relate streamflow with the calculated surface area. These were then cross-referenced to hydrology statistics for the spring hydrograph, typically using the annual maximum flow.

With these same tools, it is possible to characterize the inundated area to specific ranges of hydraulic parameters (e.g., depth and velocity) that relate to species habitat. Given suitable velocity and depth ranges for life stages of the minnow provided by Mortensen et al. (2019) or field-measured hydraulics by Valdez et al. (2019) and Braun et al. (2015), areas of suitable hydraulics can also be quantified at each discharge from the hydrodynamic modeling results.

It is assumed that velocity and depth are influential factors in aquatic suitability for the species even though other factors such as landcover and substrate likely also contribute to minnow habitat and influence the field-measured populations. Landcover is implicitly included in the hydraulic modeling as it affects the friction losses. These data are input as a Manning's *n* land cover map for the modeled area. Channel substrate is not a defined layer in the model but may be implicit in the hydraulic results as velocities and depths culminate as shear forces that affect sediment transport.

Mortensen et al. (2019) summarize hydraulic parameters as a binary analysis: ideal or nonideal habitat characteristics. The suitable hydraulics identified by Mortensen are well-centered around the most frequent hydraulics where RGSM are captured, whereas Valdez et al. (2019) and Braun et al. (2015) report fish captured outside these "ideal" habitat parameters (Figure 3). The field-measured data were used to generate a hydraulic habitat curve. Both the binary generalization (binary method from Mortensen 2019) and the continuous hydraulic habitat curves (continuous method shown as "HSI"—that is, habitat suitability index—in Figure 3) are used to transform the hydraulics from the 1D and 2D models into a habitat suitability score. Comparing these determines the impact on delineating suitable hydraulic areas based on most preferred hydraulic habitat types (binary) or with a graduated HSI score that includes conditions where fewer fish are found (continuous).

Figure 3. Comparison of the binary (Mortensen) and continuous (based on Valdez data) hydraulic habitat suitability indices (HSIs) for larvae silvery minnow used in this study.



ArcGIS was used to process hydraulic modeling results from HEC-RAS models into areal quantities or weighted useable areas (WUAs) of appropriate hydraulics for minnow at larval and adult life stages at various discharge simulations. The hydraulic models delineate the depths and velocities spatially, and the HSIs were applied to translate these areas into a score varying from 0 (least ideal) to 1 (most preferred). The HSI was multiplied by the area it covered to generate a WUA.

Total inundation, areas of suitable habitat depths, and areas of suitable habitat velocities from the hydraulic models are translated into eco-value curves for use in HEC-EFM. Eco-value curves are an index relationship between the discharge and a variable. In this case, the variable is based on areas of inundation that meet the depth and velocity criteria suggested by biological research on the minnow.

Once calibrated, the 1D and 2D models simulated the following discharges: 2,000 cfs, 3,000 cfs, 4,000 cfs, 5,000 cfs, 6,000 cfs, and 7,500 cfs. The bathymetric terrain was superimposed for the 10 mi area of interest and then for HAN-1S and HAN-2S: 500 cfs and 1,000 cfs discharges were also simulated. The processing of the results for the 1D and 2D simulations required different methods and are described in the following sections.

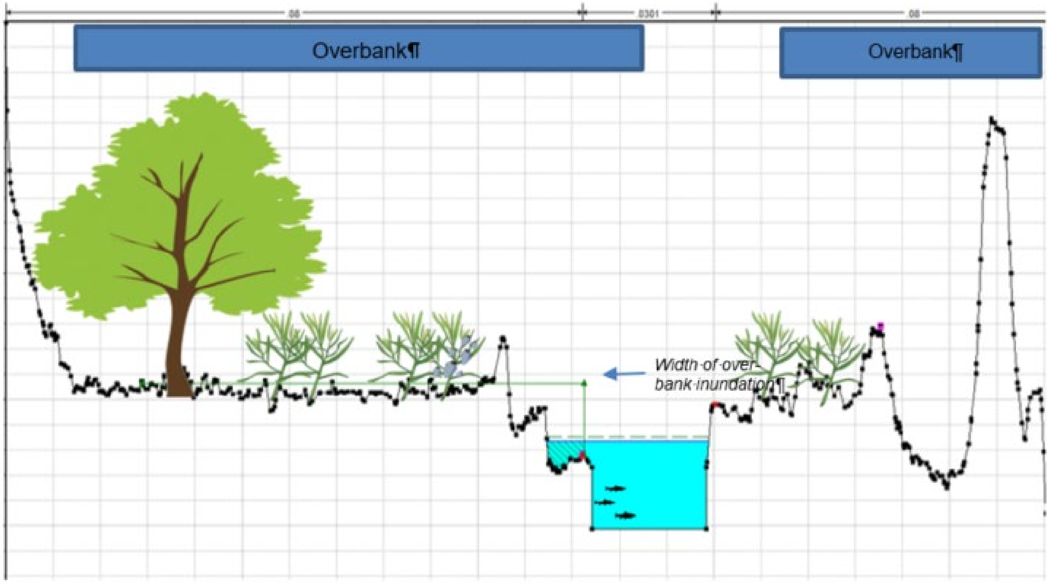
For 1D hydraulic modeling in HEC-RAS, only the binary method was applied. Tabulated data, representing averaged hydraulics per cross-section, are available from 1D simulations. See Figure 4 for a schematic of the 1D HEC-RAS cross-section. Per cross-section, the following variables were extracted directly from the HEC-RAS output and placed in an Excel document:

- Q Total (cfs): Total flow in cross section
- SA Total/Left/Right (acres): Surface area for the total cross-section / left overbank / right overbank measured cumulatively from the bottom of the reach
- Vel (Chan/Left Overbank/Right Overbank): Average velocity of flow in the main channel / left overbank / right overbank
- Hydr Depth (Channel/L /R): Hydraulic depth for the main channel / left overbank/ right overbank (flow area/top width of active flow)

Post-processing of the surface area (SA) is necessary. HEC-RAS generates an SA per cross-section, which represents a cumulative SA from the bottom of the reach. In order to determine the SA per cross-section, the cross-section’s cumulative SA is subtracted from preceding SAs.

The cross-sections are filtered by whether the overbank or channel velocities met the minnow hydraulic criteria. For the area of inundation values, the total surface area was tabulated for each discharge, and the overbank surface area was found by summing the SA Left and SA Right for the topmost cross-section.

Figure 4. Schematic of a Hydrologic Engineering Center's River Analysis System (HEC-RAS) cross-section and the areas of overbank inundation.



Areas of suitable velocity and suitable depth were delineated by using a number filter in Excel. Once a cross-section was identified to have suitable depth or velocity, the cross-sectional areas corresponding to that filtered criteria were summed, giving a cumulative surface area of appropriate hydraulic conditions per discharge. This was done for the adult and larval criteria for velocities, depths and combined velocities and depths.

For simulations of 500 to 1,000 cfs, the flow was found to be confined to the main channel, so the main channel values for the velocity, depth, and surface area were used. It was found that the larval criteria were exceeded in the main channel at these discharges, so no areas were tabulated. For 2,000 cfs, flow was found in both the main channel and the overbank, though the main channel values still exceeded the larval criteria. For the adult criteria tabulation, surface areas that met the hydraulic parameter criteria in the main channel and surface areas that met the criteria in the overbank were summed. For 3,000 cfs and greater, only overbank areas were suitable for the larval and adult habitat criteria.

Two-dimensional modeling with HEC-RAS allows for the export of simulation result rasters of velocity and depth based on underlying terrain. For the eight discharges simulated, velocity and depth rasters of the stable model outputs (hydraulics are not varying with time) were exported as TIFFs. In ArcGIS, the areas of suitable depth and velocity for the larval and adult life stage were generated using Boolean raster analysis for the Mortensen (2019) generalization of most ideal hydraulic habitat. If the raster cell was within the ideal habitat parameter range, it was given a value of 1; if not, 0. This is conducted with the “Less Than” and the “Greater Than” spatial analysis tools.

For the hydraulic habitat curve (i.e., the continuous suitability model from Valdez et al. 2019), the weighted overlay tool was used to translate depth and velocity rasters to a hydraulic suitability index varying from 0 to 1.

For both methods, the suitable depth and the suitable velocity areas were then multiplied together, so that if the cell was more suitable for both depth and velocity parameters, it would have the value closer to 1 (for the binary method, the value would be 1). The reasoning for multiplying these, versus summing both with equal weight, is because depth and velocity are assumed to be mutually inclusive for suitable minnow habitat. A location with ideal depth but poor velocity would have a 0 value. The result was achieved with the “Times” spatial analysis tool. It would be expected that as more monitoring data collecting fish presence and hydraulic conditions are evaluated, this method of summarizing hydraulic habitat can be more refined.

The attribute table for each of the resultant rasters provides a count of the cells that have the value 0 to 1. The count of cells is then multiplied by the cell size (25 square ft, a 5 ft by 5 ft cell), and then units are converted to acres to be comparable to the 1D parameter outputs. For the 2D outputs, the adult hydraulics are based on the total suitable areas (including the active channel); for the larvae, field monitoring is usually conducted on the floodplain only. It would be an assumption to conclude that appropriate hydraulics measured in the floodplain is also applicable in the active channel. The area of suitable hydraulic habitat for the larval fish was computed in two ways: total suitable area (including discharges confined to the active channel from 500 to 1,000 cfs) and the overbanking suitable area excluding the active channel were used as eco-value curves.

In addition, summarizing the hydraulic habitat for a given year was computed in two ways. A seasonal eco-value summary was computed as a summation of the daily discharge and corresponding WUA of that discharge. For the adult life stage, this was an annual eco-value summation and the hydraulic requirements of adult minnow. For the larval life stage, the hydrology was summed based on the spring runoff time period. The eco-value summation, as a single value, was computed for each year from 2002 to 2018. Finally, using the results from the hydrologic characterizations, the many ways to summarize the spring runoff season as a single streamflow (e.g., minimum discharge during the 14-day runoff peak) were transformed into an area of suitable habitat to determine whether spatial hydraulics correlates more with fish population characterizations.

2.5 Functional Analysis

A functional (data) analysis framework was used to evaluate each combination of fish and environmental metrics that correspond to production of YOY minnows. Four linear models (Table 4) were formulated to evaluate the correlation of each fish population metric with environmental flow metrics. Two models log-transformed the environmental parameters ($\log_{10}$ [environmental metric]), and two models added the April broodstock fish metric as a covariate (+ broodstock) with the environmental metric. Each linear model was executed with all combinations of fish and environmental metrics calculating R^2 and Akaike information criterion (AIC) values. This resulted in 960 total candidate models (i.e., 4 linear models × 4 fish metrics × 60 environmental metrics). The model results for each of the four fish metrics were sorted by R^2 values to identify which environmental metrics had a higher correlation and lower AIC score. The environmental metrics with higher correlations (R^2) with the fish metrics are assumed to indicate important parameters for recruitment (Figure 5).

Table 4. Models evaluated for functional analysis.

Model	Formula
Linear model	Fish metric $\approx$ 0 + (environmental metric)
Log-transform model	Fish metric $\approx$ 0 + $\log_{10}$ (environmental metric)
Linear model with broodstock	Fish metric $\approx$ 0 + (environmental metric) + broodstock
Log-transform model with broodstock	Fish metric $\approx$ 0 + $\log_{10}$ (environmental metric) + broodstock

Figure 5. Functional analysis model results organized by the fish metrics and sorted by the statistical results of performance metrics.

Fish Metric

- Mean-slope:Slope to mean recruit CPUE (May to August
- YOY: Young-of-year CPUE (May to August)
- Recruit slope: Slope of recruit CPUE (May to August)
- October Index: Annual index CPUE (October)
- Broodstock: April CPUE as covariate in two models

Hydraulic and Hydrologic Metric (H&H)

- Seasonal statistical hydrology (durations, minimums, etc.)
- Seasonal summation hydrology
- 1D/2D hydraulics using binary or continuous method hydrology
- Linear relationship or $\log_{10}$ transformed metric

Performance Metric

- R^2: Fit of correlation of the fish metric and the H&H metric
- AIC: In-sample prediction error

3 Results

3.1 Hydrologic Covariates

Throughout a single season, the Middle Rio Grande streamflow varies temporally without a consistent rate of change or hydrograph shape. The system is subject to outside influences: the volume of snowpack, the operational constraints imposed by water users, and the temperature effects on generating the spring runoff. This gives rise to very noisy data, which presents challenges when trying to make year-to-year comparisons.

The fish population data are similarly noisy. Therefore, this study seeks to untangle relationships between surface water runoff characteristics and fish population metrics using R^2 correlations. Results presented focus only on the linear model with the hydrologic and hydraulic metrics, as these performed better than when "broodstock" covariate was applied and the $\log_{10}$ regression analysis.

The hydrologic results only use the USGS daily discharge data record, with no reference to spatial or hydraulic analysis. The purpose is to demonstrate the sensitivity of hydrologic parameters: duration, season, and frequency, and the magnitudes to which single-value spring-runoff summarizations vary. The following matrix shows the combinations of variables evaluated (Figure 6).

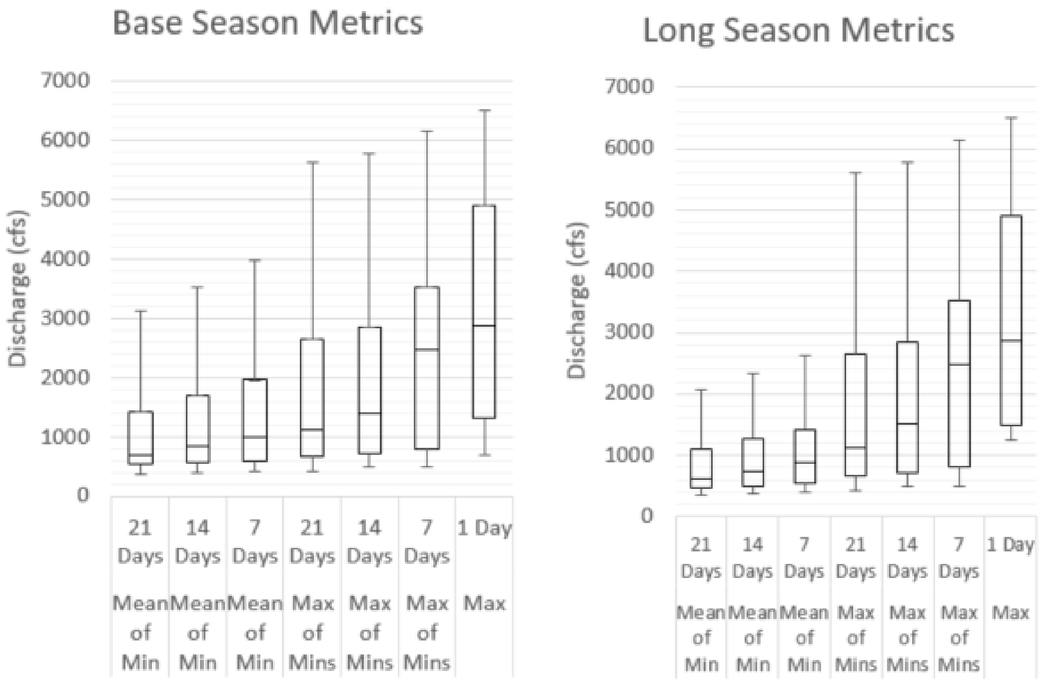
Figure 6. List of the three variables tested for sensitivity and the alternative values for each variable.

Box plots were generated for the hydrologic metrics (Figure 7, Figure 9, and Figure 10). There was not much difference between the base season and the long season analysis. A quartile plot of the years of interest demonstrates that the distribution of the results is very similar (Figure 7).

This indicates that the “base season” hydrology is well-centered on the typical months of the spring runoff. This result may vary for other watersheds or further downstream in the Rio Grande watershed.

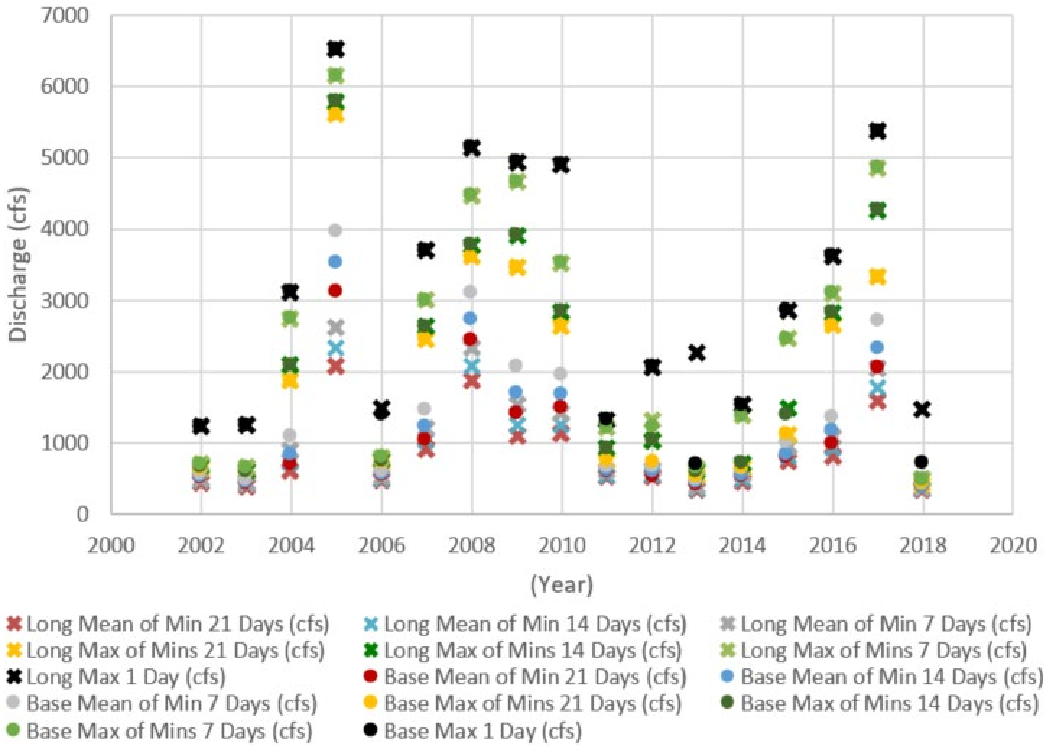
The mean of minimum metric had less variance than the maximum of minimum metric. As the duration observed increased, so did the variance.

Figure 7. Base and long season hydrologic metrics based on quartiles with whiskers representing the Figure 8 maximum and minimum values.



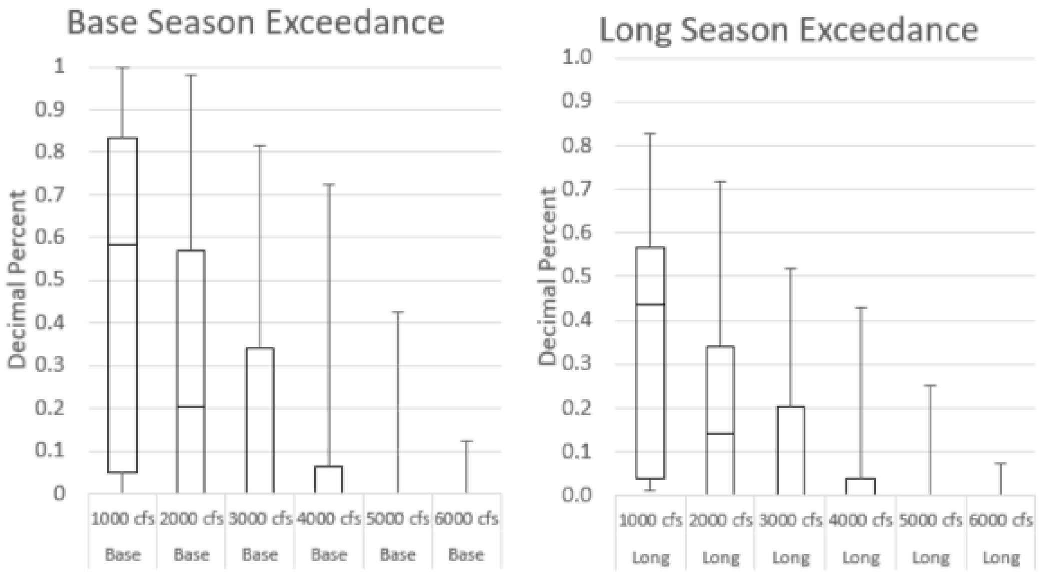
The year-by-year data are presented in Figure 8, and the differences between the base and long seasons can be observed. The mean of minimums metric stands out for all durations, with the longer season attenuating the discharge. The maximum 1-day event is higher for the long season in two instances for the 17-year time frame.

Figure 8. Year-by-year hydrologic metrics.



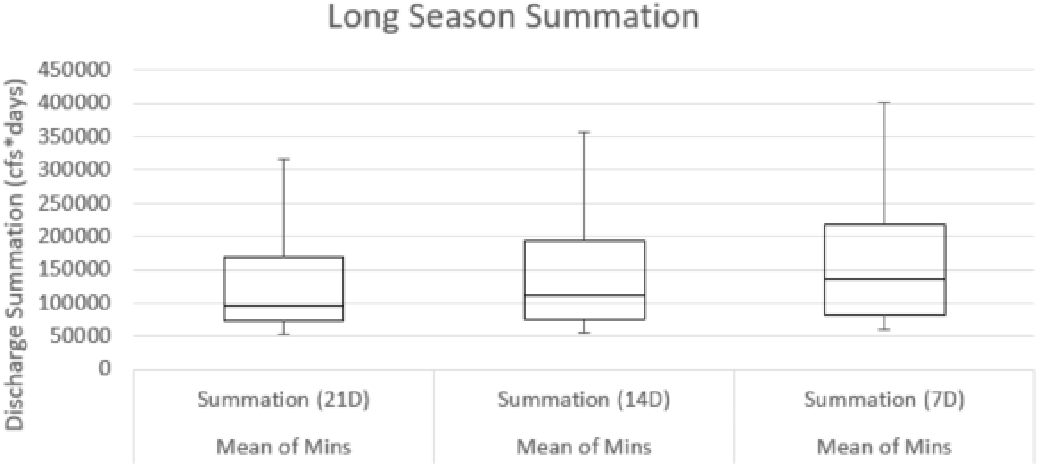
In addition, exceedance frequencies were calculated for the years. These are presented as a decimal percent. This analysis further demonstrates how the long season attenuates the higher discharges of the spring runoff. The base season is well-centered on the spring runoff event.

Figure 9. Base and long season percent exceedance.



A summation of the discharges for varying durations is presented in Figure 10. This hydrologic parameter represents how averaging the minimum discharge for a 7-, 14-, and 21-day duration simplifies the seasonal hydrology. The long season is used in this example. It is found that the longer the duration, the more attenuated the summation for that year becomes. This is again from the averaging effects and the longer time period. The base season was carried forward for evaluation with fish population metrics, discussed in Section 3.3.

Figure 10. Long season summation of the mean of minimums for varying durations.



3.2 Hydraulic and Habitat Covariates

This section demonstrates how 1D and 2D modeling affects quantification of suitable hydraulic habitat, including the differences between the binary method (which delineates only the most ideal habitat) and the continuous method (which delineates habitat quality based on the density of minnows found per hydraulic measurement, in a gradation from 0 to 1). Similar to the preceding section, the performance of the hydraulic characterizations is compared to fish population metrics on an annual basis in Section 3.3 to determine whether any of these methods are more useful in correlating riverine conditions to conditions that benefit minnow success.

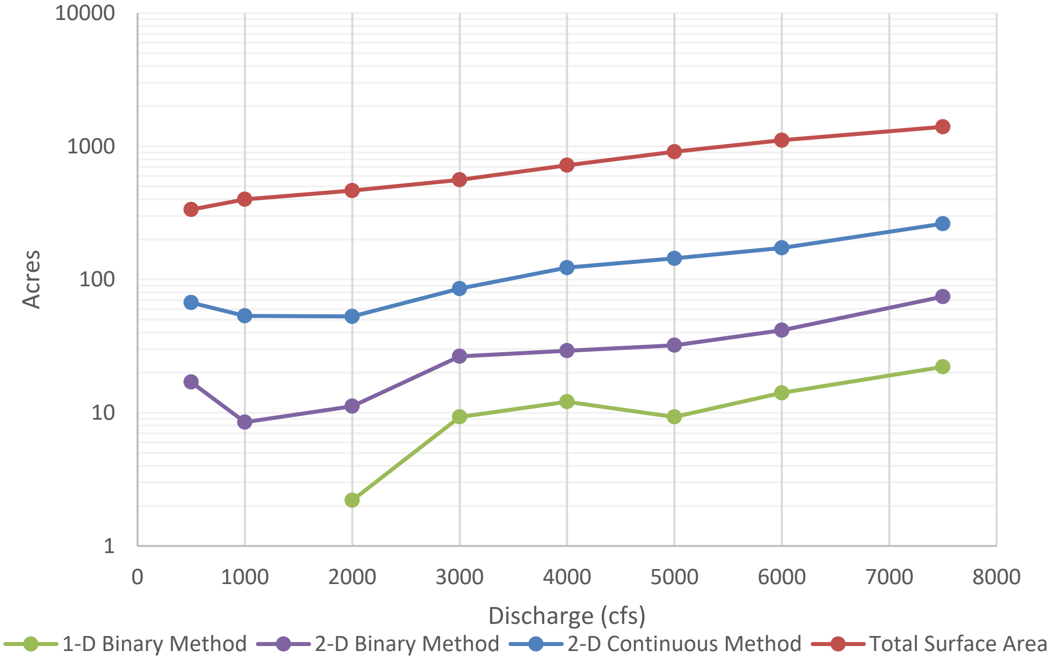
Figure 11 and Figure 12 shows the different methods of hydraulic habitat quantification relative to each other. Total surface areas for the 1D (HAN-1S) and 2D (HAN-2S) covering the same reach had very similar magnitudes of inundation throughout the series of tested discharges. The difference between areal inundations for the two models increased as discharges increased, particularly at 6,000 and 7,000 cfs. The magnitude of difference at 2,000 cfs was 4 acres (0.0062 mi^2) and increased up to 270 acres difference at 7,000 cfs (0.4 mi^2 for the 10 mi reach).

The differences in estimated areas of suitable hydraulics was much more pronounced between the 1D and 2D models (Figure 11) by an order of magnitude (10^1) between the 1D HSI results and the 2D continuous HSI results. Increased areas of appropriate hydraulics are associated with increased model dimensionality. The larval habitat is associated with edge habitat: shallower and slower waters, which is accounted for in the 2D modeling results but lost in the averaging of 1D cross-sectional hydraulics.

The observed differences in suitable area and model dimensionality are attributed to the higher resolution of information provided by 2D terrain and hydraulic computations. Conversely, the 1D model had a single water surface and averaged hydraulics generated for each cross-section.

The continuous (weighted useable area) method has a wider envelope of appropriate depths and velocities than the binary method, and therefore quantities of habitat from the continuous HSI are greater than those estimated from the binary method.

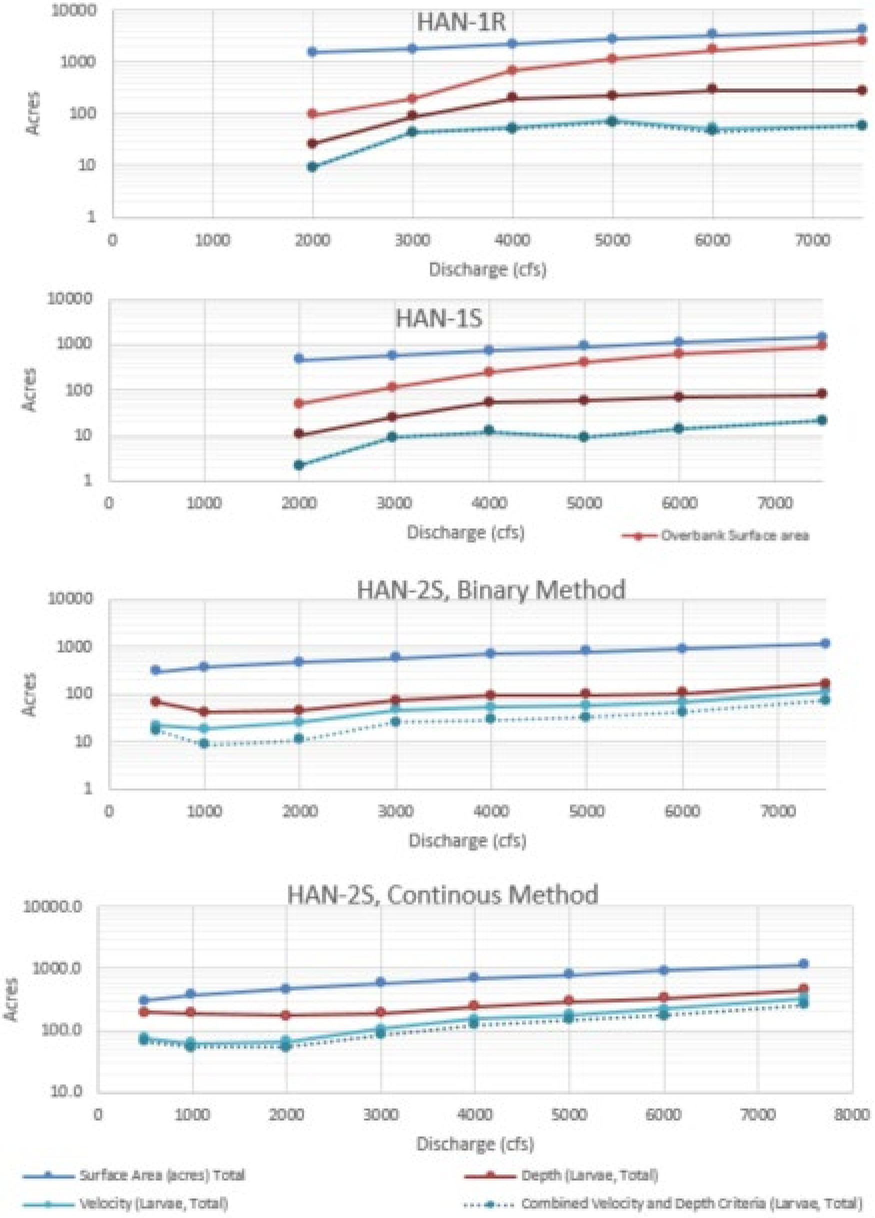
Figure 11. Areas of suitable hydraulics (combined velocity and depth) for the larval life stage of minnow as effected by model dimensionality and hydraulic characterization methods.



For the 1D models (HAN-1R and HAN-1S), while the surface area and overbank areas increase with discharge, the areas of appropriate depths plateau at approximately 6,000 cfs. In the longer-reach model (HAN-1R), areas of suitable velocities also plateau at around 5,000 cfs (Figure 12). This is attributed to the layout of the Rio Grande relative to leveed infrastructure. Though more water is available, the flow remains confined to the channelized river or leveed areas and is unable to spread and expand suitable habitat areas. For the 1D models, suitable velocities are the limiting factor in determining habitat. If the velocity is appropriate at a cross-section, it is likely that the depth is also suitable, but the opposite is not true.

In comparing the 30 mi reach (HAN-1R) and the 10 mi reach larval results (HAN-1S), it was found that though the 10 mi reach is inset of the larger reach, the habitat eco value curves are not proportional (Figure 12). This indicates that local differences may affect the hydraulic habitat availability results.

Figure 12. Eco-value curves for the 1D and 2D hydrodynamic models.



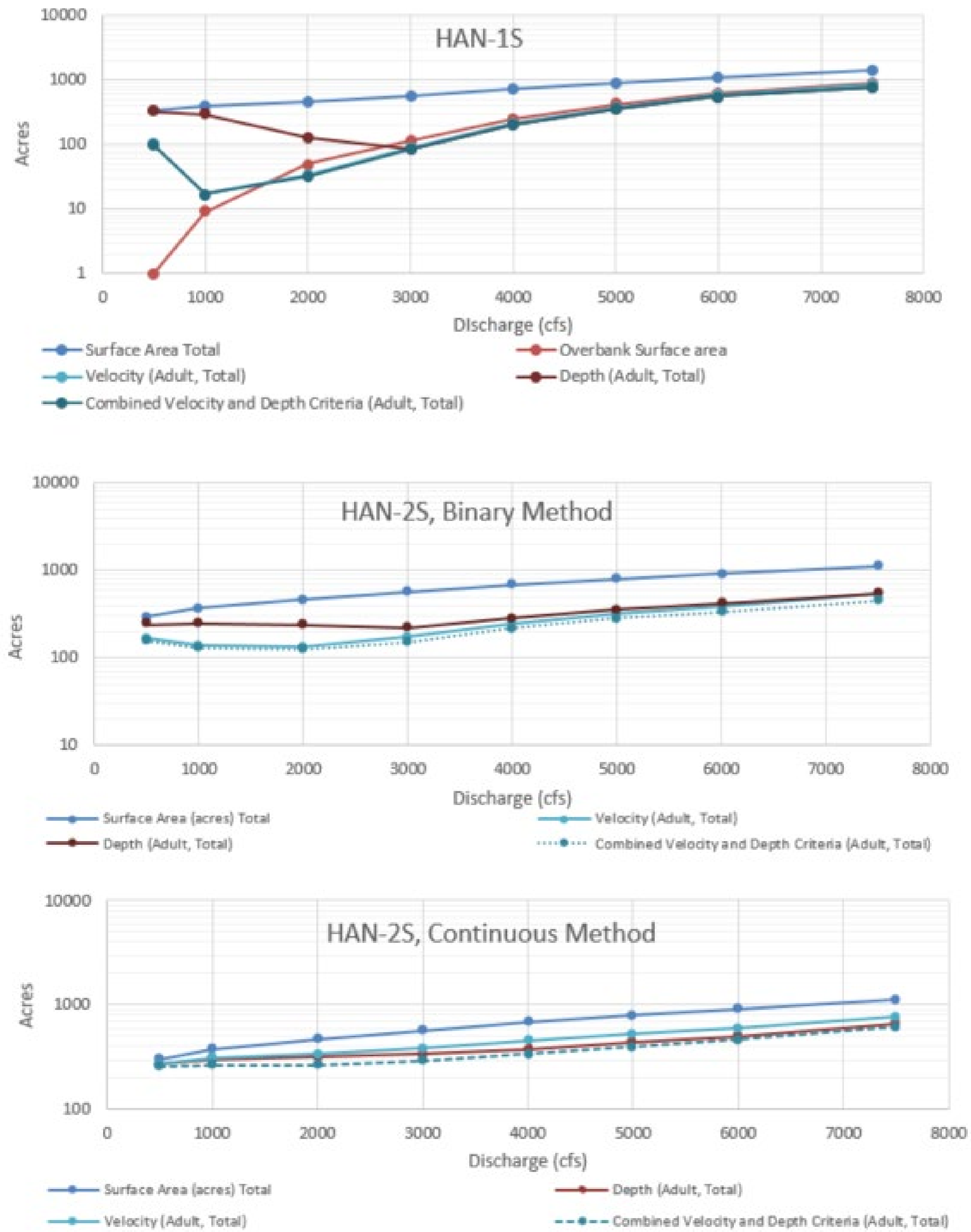
Between HAN-1S and HAN-2S, the difference between the areas of suitable velocities had a root-mean-square difference of 76 acres, meaning that the discrepancies between the 1D and 2D analysis varied by an average of 76 acres from one another. This is substantial, considering that 1D analysis of areas of suitable velocities does not exceed 25 acres in total. For the areas of suitable depth and combined velocity/depth, the root-mean-square difference was 50 acres and 28 acres, respectively. This is attributed to the 1D averaging of hydraulics across cross-sections and the ability for the 2D method to account for edge habitat and the changes of hydraulics over mid-channel bars.

For the adult habitat eco-value curves (shown in Figure 13), the active channel contains areas of suitable velocities and depths at lower discharges. However, as discharges increase, so do active channel velocities and depths, reducing the area of suitable habitat. Once the river begins to overbank, suitable hydraulics are found in the overbank areas only. The hydraulic parameters for adults are met in nearly all the overbank areas in the 1D analysis. In the active channel, the question of appropriateness of using hydraulics as a habitat indicator becomes more uncertain. Though the hydraulics may be ideal in some locations, the active channel has less vegetation for food and cover.

The results for the 2D adult minnow analysis show that flows increasing from 500 cfs do not see a drop in suitable depths observed in the 1D evaluation. This is likely due to the discretization of cell-by-cell hydraulics and the ability to quantify suitable edge habitat, which is averaged over in the 1D cross-section.

For both larval and adult life stages, the areas of suitable velocities from the continuous HSI evaluation were greater than those estimated by the binary method. For the adult, change was up to 150% more suitable velocity area (for 3,000 cfs) with an average increase of 90%. For the suitable depth areas, the average change was an increase of 30%. Overall, this culminated to an approximately 70% increase in suitable areas for both criteria, the maximum change for 2,000 to 4,000 cfs.

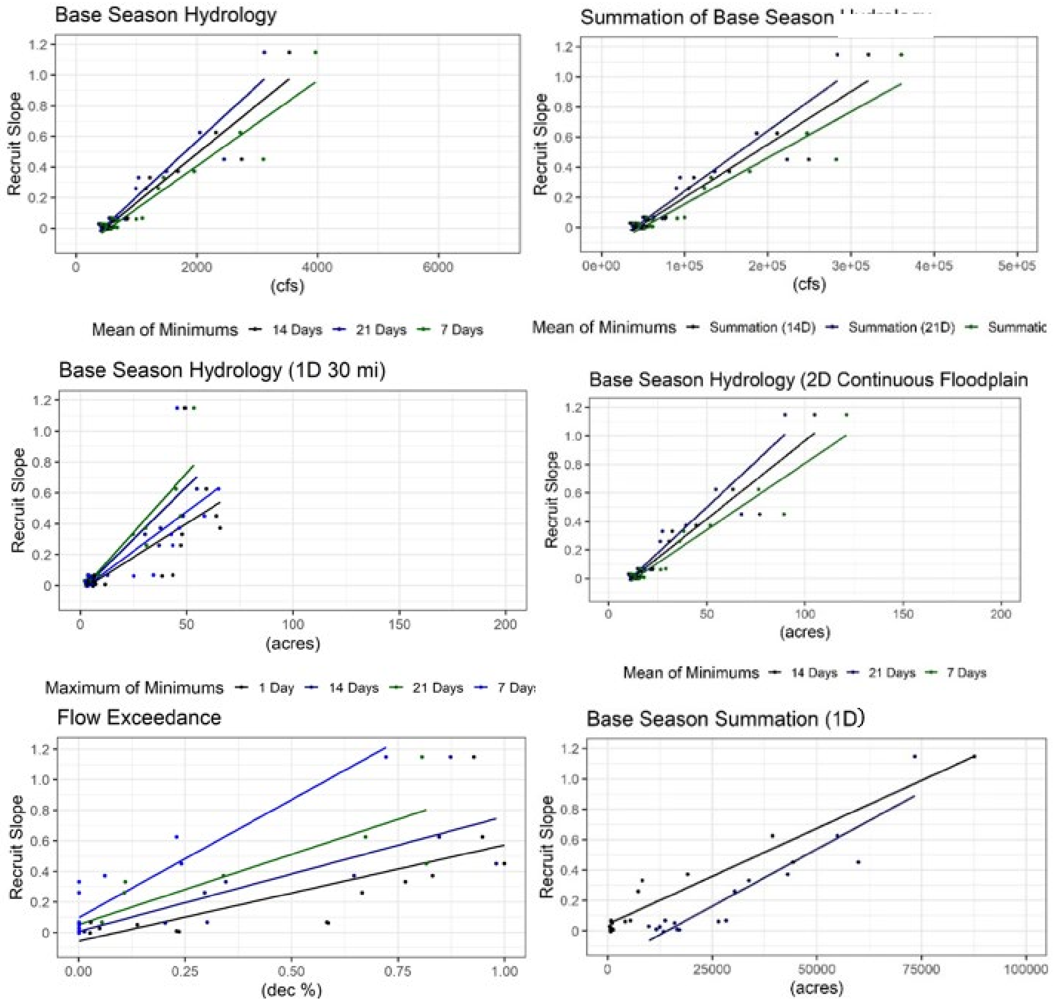
Figure 13. Eco-value curves for adult minnow.



3.3 Comparison of Ecological Models

The various hydrologic, hydraulic, and habitat eco-value curves were used to generate single-value characterizations of the spring runoff or annual hydrographs. These characterizations were correlated to fish population metrics on an annual basis through a linear regression analysis. The resulting R^2 values are presented throughout this section to show which eco-values curves correlated best with fish population data from 2002 to 2018. The eco-value summaries for 2002 to 2018 had various magnitudes of variance. This was owed to the units of the eco-value—for example, percentages in flow exceedance, discharge, acres of inundation—for various time frames: seasonal summation, durational hydrology varying from 7 to 21 days. Examples of the linear regression are shown in Figure 14. All plots are presented in Appendix A.

Figure 14. Examples of the eco-value summaries for years 2002–2018 versus recruit slope.

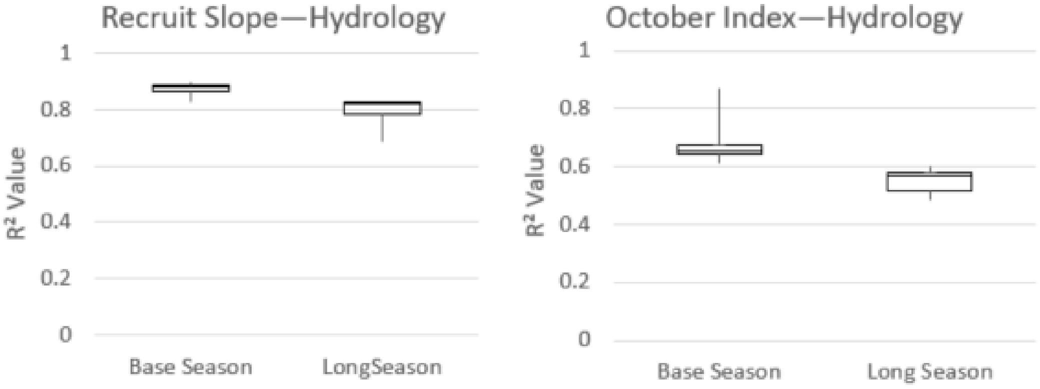


The degree of variance provided by each eco-value summary may affect the goodness of fit in a linear regression. Generally, the linear regressions had a positive relationship between the eco-value and the recruit slope. The year 2005 was an outlier among the dataset, with the highest recruit slope around 1.1 units. The linear regression plots (Figure 14 and Appendix A) can be observed for correlation with both the majority low recruitment years and 2005.

The first comparison is hydrology. Percent exceedance and discharge durations were computed based on two seasons: base (April–June) and long season (March–July). The objective was to identify whether a comprehensive seasonal hydrology—which captures early or later than typical spring runoff peaks—would correlate better than a narrower definition of the spring runoff season, when most peak runoff events typically occur. As discussed in Section 3.1, the longer seasons attenuated the magnitude of mean discharge and the duration of the percent exceedance.

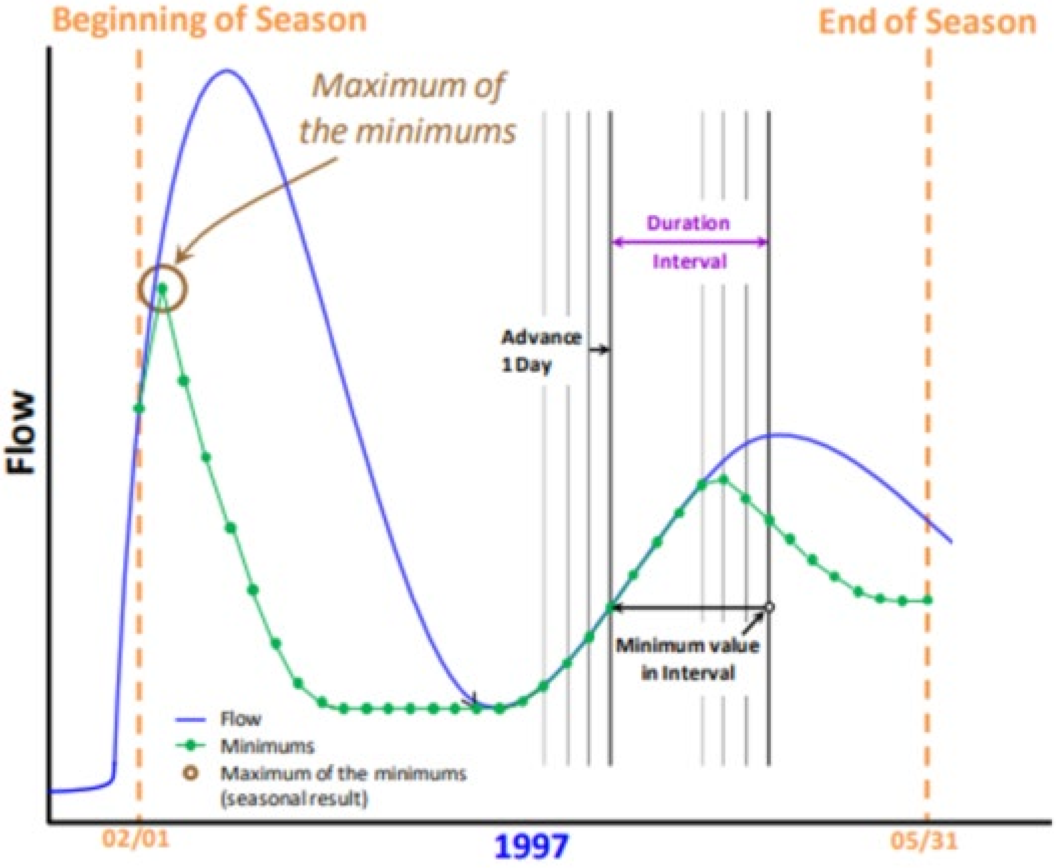
The base season performed slightly better than the longer season (Figure 15), though the medians of the metric correlations were within 0.05. The recruitment metric for fish population is based on data collected in May to August, and the base season (April to June) correlates better than the long season (March to July). This correlation indicates that most of the recruitment is well-centered on the April–June base season.

Figure 15. Box and whisker plot showing the quartiles, maximum, and minimum R^2 values for the hydrologic metrics against fish population metrics recruit slope and October index.



The best performing hydrology metrics were associated with longer durations: 21 days and 14 days. The mean of minimums for the peak discharge or the maximum of the minimum flows for the durations (see Figure 16 for schematic) had similar R^2 correlations, per duration, for all durations evaluated.

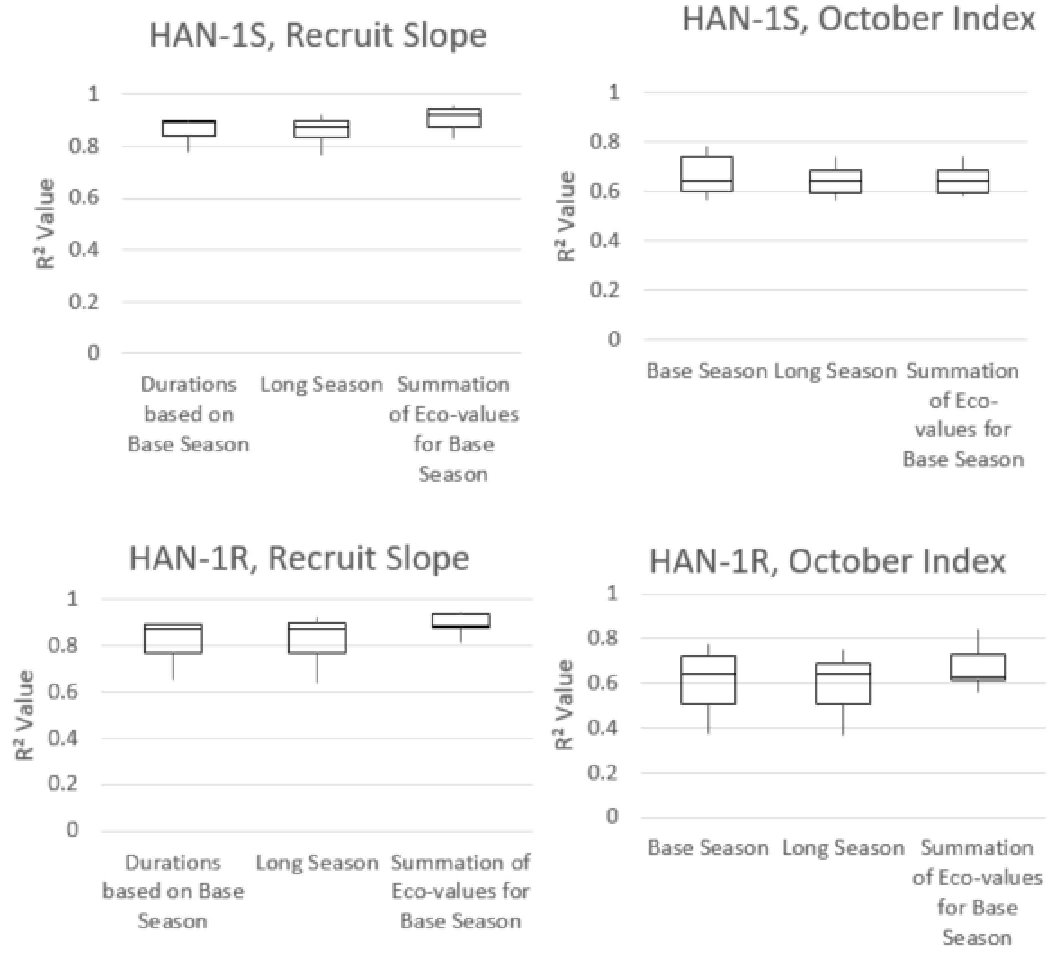
Figure 16. Schematic demonstrating the calculation of the “maximum of minimum flows” of a given duration. Modified from Hickey (2020).



The 1D hydraulic evaluation featured two different scales of hydraulic models: 10 mi (HAN-1S) and 30 mi (HAN-1R). The objective in comparing these is to determine if there are appreciable differences in the correlation of population metrics with areas of suitable habitat. The 1D models were evaluated with the binary HSI method.

For recruit slope, the base season durations performed slightly better than the long season, but the summation (daily eco-values summed) for the base season performed better than any habitat quantification based on duration (e.g., 21-day minimum peak flow). This may mean that the summation of the entire season reflects habitat availability better than assessing durations specific to the species life cycle. This could be due to the observation that spawning may occur multiple times throughout the spring runoff season. HAN-1S and HAN-1R performed very similarly when compared to the fish population metrics, though HAN-1R showed more variance in the results (Figure 17). The highest correlations to the recruit slope metric for HAN-1S were the total surface area (R^2 = 0.958) and the overbank suitable velocity (R^2 = 0.945) eco-value curves. For the HAN-1R, the longer reach, the best performing metric was the overbanking surface area (R^2 = 0.944) and the overbanking suitable depth (R^2 = 0.935). It was found for 1D that the suitable depth and velocities eco-value curves performed better than when both were combined, which indicates that the method to combine the two hydraulic criteria can be improved for approximations of available habitat in 1D.

Figure 17. Correlation performance for the 1D hydraulic habitat evaluations. Box and whisker represent quartiles, minimum, and maximum values.

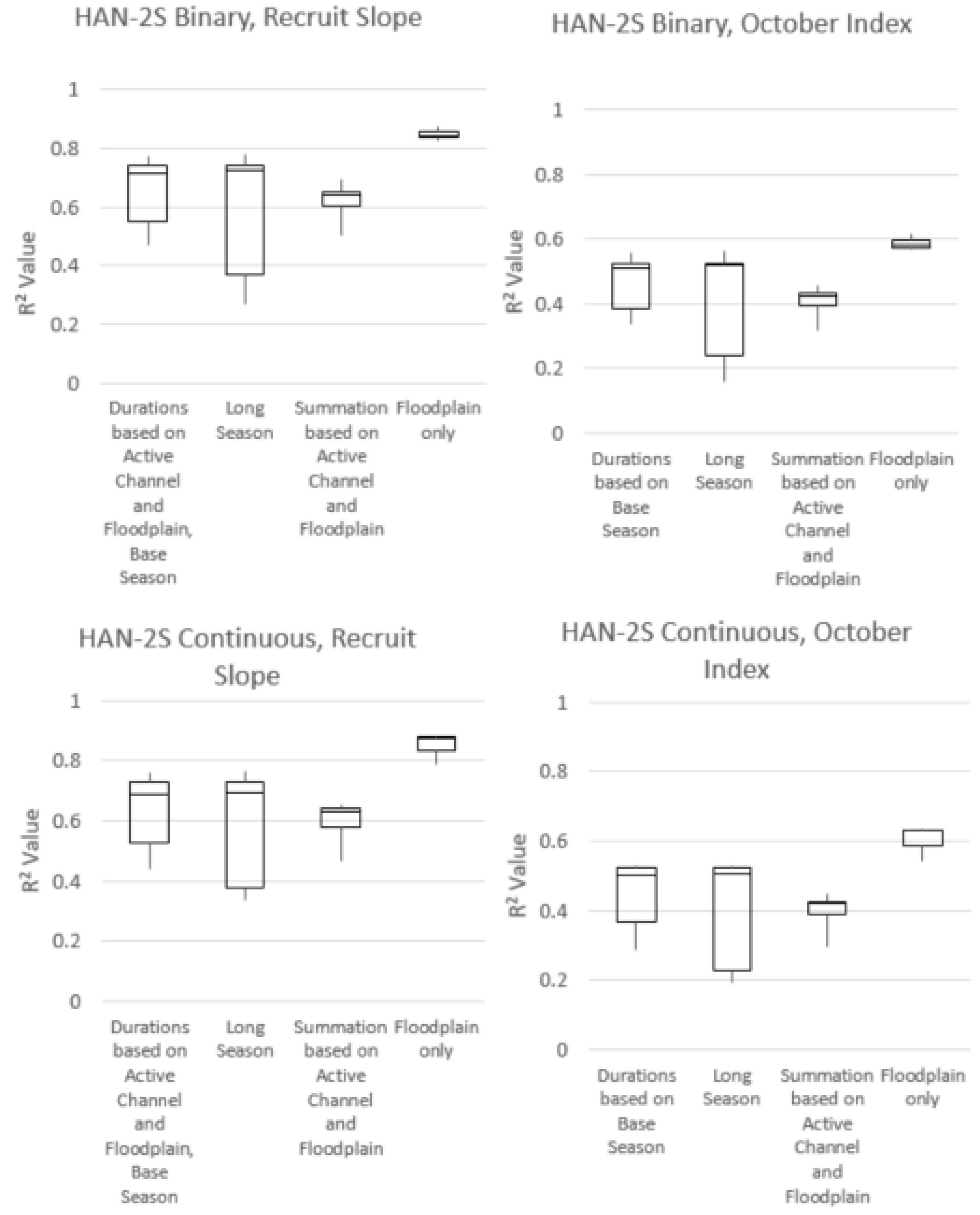


The 1D results for the October index showed less correlation than the recruit slope. The best performing metric was the summation of overbank surface areas for the duration of the base season, with an R^2 of 0.842.

The 2D Hydraulic evaluation featured two different HSI quantification methods: binary and continuous. In addition, the scope of hydraulics evaluated varied: total surface area or floodplain surface areas. This evaluation was to determine the impact on delineating suitable hydraulic areas based on most preferred hydraulic habitat types (binary) or with a graduated HSI score that includes conditions where fewer fish are found (continuous). The Total and Floodplain evaluation tests the applicability of the larval minnow HSI in the active channel, though most fish-monitoring activities are conducted on inundated floodplains.

It was found that the floodplain hydraulic habitat was much more correlated with both the recruit slope and the October index than total area estimations (Figure 18). This result demonstrates that the larval HSI for minnow does not apply well to the active channel area. It also demonstrates that adding areas that are outside typical habitat zones to the ecovalue curves may produce less correlation with species recruitment. Including the active channel may incorrectly assume some hydraulically appropriate areas are utilized as rearing habitat.

Figure 18. Correlation performance for the 2D hydraulic habitat evaluations. Box and whisker represent quartiles, minimum, and maximum values.



The 60 hydrologic and hydraulic metrics produced similar trends across the fish metrics, though the R^2 ranking varied between the fish metrics. The recruitment slope metric (R^2 =0.369–0.958) performed better than the YOY (R^2 =0.296–0.878), mean-slope (R^2 =0.383–0.869), or October index (R^2 =0.217–0.842) parameters in the linear model. The R^2 statistics are used as performance indicators for variable trend data metrics with a small sample size (~20 years). The reliability of these relationships should improve with additional samples. The slightly higher R^2 values for the recruitment slope metric with hydrologic and hydraulic metrics support its use as the primary fish metric for minnow production. The overlap of higher-ranked environmental metrics (the 14- and 21-day maximum of minimum flow) between the recruitment slope and October index supports using functional analysis for identifying environmental flow magnitude and duration (see Table 5 and Table 6). The maximum-minimum flow magnitudes for the 14- and 21-day durations are classified as suitable, intermediate, and insufficient flow for minnow production in the current Rio Grande environment (Table 7).

Table 5. High-performing recruitment slope and October index correlations with hydrologic metrics.

Recruitment Slope	Recruitment Slope R^2	Recruitment Slope AIC	October Index (CPUE)	October Index R^2	October Index AIC
Base season, 21-day maximum of minimum, cfs	0.897	−16.09	Long season, exceedance, 4,000 cfs, percent	0.870	87.68
Long season, 21-day maximum of minimum, cfs	0.891	−15.30	Base season, exceedance, 4,000 cfs, percent	0.870	87.75
Base season, 14-day mean of minimums, cfs	0.887	−14.67	Base season, 21-day maximum of minimum, cfs	0.684	101.06
Base season, 14-day summation of means, cfs	0.887	−14.67	Long season, 21-day maximum of minimum, cfs	0.680	101.26
Base season, 14-day maximum of minimum, cfs	0.884	−14.32	Base season, 14-day maximum of minimum, cfs	0.672	101.62
Base season, 7-day mean of minimums, cfs	0.883	−14.19	Long season, 14-day maximum of minimum, cfs	0.670	101.71
Base season, 7-day summation of means, cfs	0.883	−14.19	Base season, 14-day mean of minimums, cfs	0.652	102.51
Long season, 14-day maximum of minimum, cfs	0.882	−14.09	Base season, 14-day summation of means, cfs	0.652	102.51
Base season, 21-day mean of minimums, cfs	0.879	−13.72	Base season, 7-day mean of minimums, cfs	0.647	102.73
Base season, 14-day summation of means, cfs	0.879	−13.72	Base season, 7-day summation of means, cfs	0.647	102.73
Long season, exceedance, 4,000 cfs, percent	0.857	−11.14	Base season, 21-day mean of minimums, cfs	0.643	102.88
Base season, exceedance, 4,000 cfs, percent	0.856	−11.04	Base season, 21-day summation of means, cfs	0.643	102.88

Table 6. High-performing recruitment slope and October index correlations with hydraulic metrics.

Recruitment Slope	Recruitment Slope R^2	Recruitment Slope	October Index (CPUE)	October Index R^2	October Index AIC
Base season summation, total surface area, 1D 10 mi reach, acres	0.958	−29.7	Base season, chance exceedance for 4,000 cfs, percentage	0.87	87.8
Base season summation, overbank velocity criteria for larvae, 1D 10 mi reach, acres	0.945	−25.6	Long season, chance exceedance for 4,000 cfs, percentage	0.87	87.7
Base season summation, overbank surface area, 1D 30 mi reach, acres	0.944	−25.4	Base season summation, overbank surface area, 1D 30 mi reach, acres	0.842	90.6
Annual summation, overbank surface area, 1D 30 mi reach, acres	0.943	−25.2	Base season summation, total surface area, 1D 10 mi reach, acres	0.815	93.0
Base season summation, overbank depth criteria for larvae, 1D 30 mi reach, acres	0.935	−23.1	Annual summation, overbank surface area, 1D 10 mi reach, acres	0.795	94.5
Base season summation, overbank depth criteria for larvae, 1D 10 mi reach, acres	0.923	−20.4	Base season summation, overbank velocity criteria for larvae, 1D 10 mi reach, acres	0.785	95.3
Long season, 14-day mean of minimum discharge, 1D 30 mi reach, total area, acres	0.921	−20.0	Base season, 21 day mean, 1D 10 mi reach, acres	0.78	95.6
Long season, 14-day mean of minimum discharge, 1D 10 mi reach, total area, acres	0.918	−19.6	Base season, 21 day mean, 1D 30 mi reach, acres	0.778	95.7
Base season, 21-day maximum of minimum discharge, 2D 10 mi floodplain, continuous method, acres	0.907	−17.7	Base season, 14 day mean, 1D 10 mi reach, acres	0.756	97.1

Table 6 (cont.). High-performing recruitment slope and October index correlations with hydraulic metrics.

Recruitment Slope	Recruitment Slope R^2	Recruitment Slope	October Index (CPUE)	October Index R^2	October Index AIC
Base season, 14-day mean of minimum discharge, 2D 10 mi floodplain, continuous method, acres	0.906	−17.4	Long season, 14 day mean, 1D 30 mi reach, acres	0.75	97.5
Base season, 7-day mean of minimum discharge, 2D 10 mi floodplain, binary method, acres	0.906	−17.6	Base season, 14 day mean, 1D 30 mi reach, acres	0.741	98.0
Long season, 7-day mean of minimum discharge, 1D 30 mi reach, acres	0.903	−17.0	Long season, 14 day mean, 1D 10 mi reach, acres	0.741	98.1

Table 7. Comparison of maximum-minimum flow and fish metrics for 2002–2018.

Environmental Flow (Spring Runoff)	21-Day Maximum-Minimum Flow Range Min	21-Day Maximum-Minimum Flow Range Max	14-Day Maximum-Minimum Flow Range Min	14-Day Maximum-Minimum Flow Range Max	Recruitment (Slope) Min	Recruitment (Slope) Max	October Index (CPUE) Min	October Index (CPUE) Max
Suitable flow	2,460	5,610	2,630	5,780	0.26	1.15	0.42	36.83
Intermediate flow	1,130	1,870	1,400	2,100	0.06	0.07	0.15	0.79
Insufficient flow	426	759	499	1,040	0.00	0.07	0.01	0.55

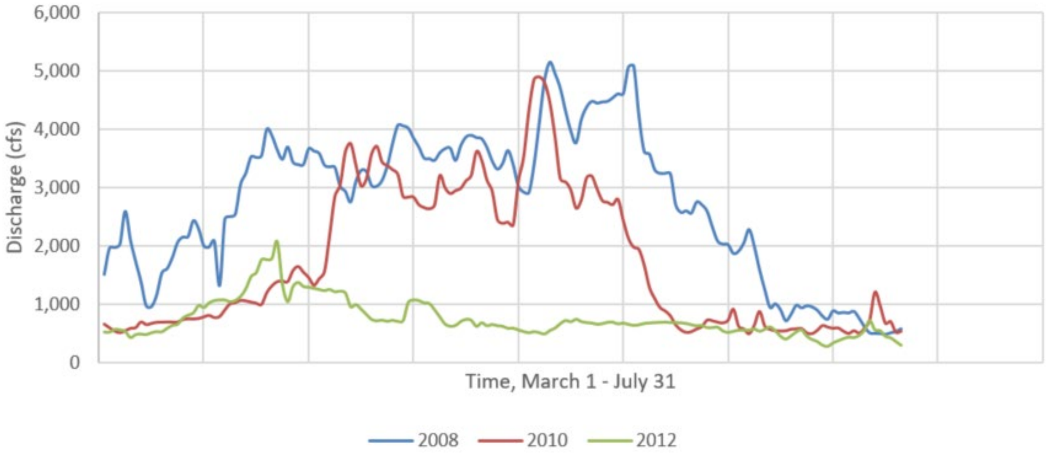
4 Discussion

4.1 Example Application of Fish Models

As stated previously, various external factors culminate into surface water hydrology in the Middle Rio Grande. Some factors are environmental: the spring runoff is dictated by snowpack accumulation and the timing and rate of temperature increase in the spring, and the summer hydrology is strongly affected by monsoon precipitation events. In addition, water managers regulate inflows through the Middle Rio Grande according to irrigators and other water stakeholders, as well as to support endangered species under guidance from biological opinions or assessments. Therefore, the volume of available water any given year is unpredictable, and the shape of the hydrograph is affected by available water, planned releases, and further natural effects of seepage and tributary runoff.

As a case study, hydrographs for three years (Figure 19) are presented: 2008, 2010, and 2012. The year 2008 was a large runoff year, and of the period of record for the USGS gage in Albuquerque, it represents one of the top quartile events. This is an event that, according to the hydrology metrics assessed in this study, occurs once every 4 years. The year 2010 was a median year, and 2012 was a bottom quartile year, which represents the most frequent low-flow years.

Figure 19. Spring hydrograph for the selected case study years.



The highest-performing metrics within this study were selected to show how they vary in characterizing these 3 years (Figure 20). The fish metrics for these same years are shown in Figure 21. For recruit slopes, the best performing metrics for increasingly complex models (hydrology to 2D) are as follows:

- Hydrology only: the 21-day duration maximum of minimums for the base season
- 1D hydraulics: summation of the total surface area for the 10 mi (HAN-1S) reach for the base season.
- 2D hydraulics: the 21-duration maximum of minimums for the base season using the continuous HSI method for the floodplain area

Chronologically from 2008 to 2012, the volume of water during the spring hydrograph decreased. The hydrologic and hydraulic metrics for these years also decreased. The units for these three eco-value metrics varied by orders of magnitude and type (i.e., cfs or acres). The magnitude of difference between the metrics varied for the case studies. Though generally the relative year-by-year quantities follow a similar pattern across metrics, the management opportunities to “elevate” any of these performance metrics vary greatly. Hydrology is strongly affected by precipitation, snowpack, and temperature and is also constrained by water operation authorities at dams. Therefore, even though 2010’s 21-day maximum of minimum discharges is only 1,000 cfs less than 2008’s, the volume of water needed to have 2010 perform similarly to 2008 is 42,000 acre-feet. To increase the 21-day minimum of maximums from 2012 to 2018, 2,500 additional cfs for the 21 days are needed, or approximately 105 acre-feet of water for the spring runoff.

Figure 20. Hydrology and hydraulic metrics for the selected case study years.

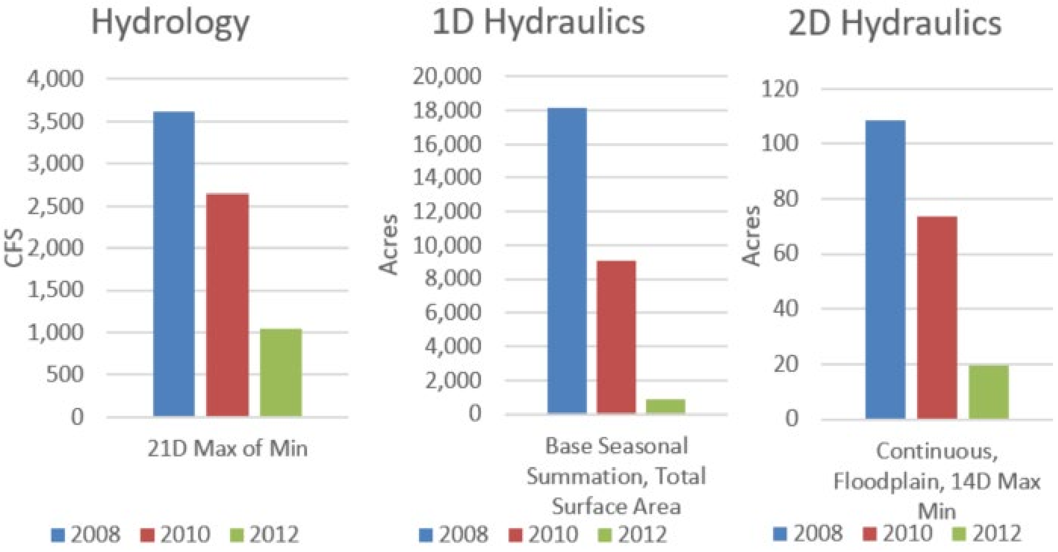
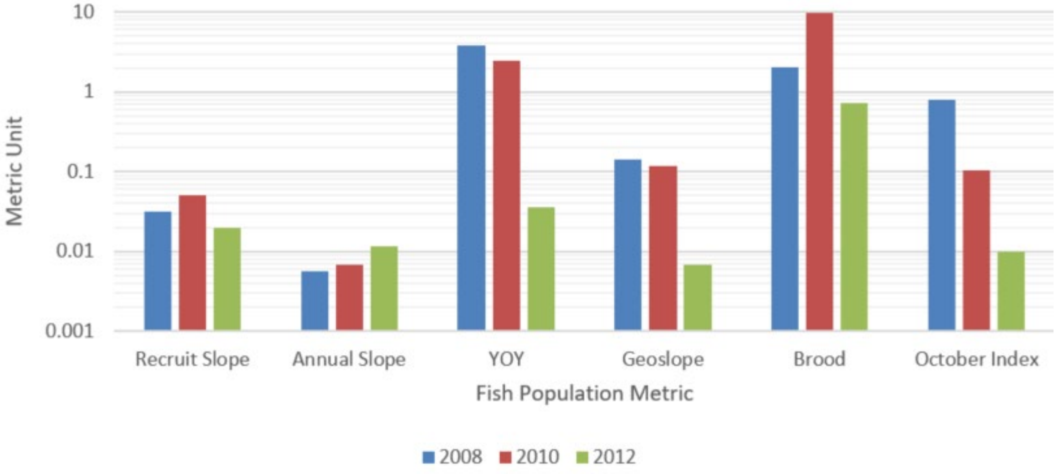


Figure 21. Minnow population metrics for the selected case study years.



The hypothesis that hydraulic habitat is just as correlated as volume of water may increase the variety of restoration approaches available for the RGSM. The 14-day maximum of minimums between 2010 and 2008 has a difference of 1,800 cfs. Perhaps a restoration effort to increase the inundated area at a given discharge, either by creating restoration sites or raising the water surface elevation in the channel with temporary embankments to increase flooding and therefore increase the area of suitable hydraulics, may increase the diversity of opportunities for minnow population restoration.

4.2 Selecting Environmental Metrics

For this study, combinations of fish and environmental parameters with higher R^2 values were considered better indicators of ecological interactions. Correlations with lower R^2 values are indicative of more variable metrics with less effect on RGSM production. (See Appendix A for results.) Generally, the correlations were higher than 0.5, which comes from a foundational observation that hydrology influences minnow success year to year. Hydrology is an influential parameter to the minnow ecosystem function.

The large variety of metrics, with different units of measure and magnitudes, for a relatively small number of years (events) evaluated in this functional analysis produces a broad range of correlation coefficients to fish population metrics. Metrics with stronger relationships (correlation) are indicators for environmental flow parameters that should be validated relative to the biological functions they appear to influence. The metrics varied in units: cubic feet per second over a period of days for the hydrology metrics, percent exceedance for frequency metrics, acres, and acres per season. As the analysis becomes more complex, there is an opportunity to further pinpoint and describe the ecosystem functions that promote the species.

The statistical results will change with the addition of more events. Metrics with stronger relationships should change less than those with weak relationships. If the Middle Rio Grande changes in geometry—with channel narrowing or incision—the hydraulic estimations will be less applicable and need to be revisited. This is a real limitation, particularly in the Rio Grande, as sedimentation trends in both the flood plain and active channel strongly affect hydraulics. The Bureau of Reclamation conducts studies on a decadal basis about river conveyance in the Rio Grande, as necessitated by the magnitude of change in that time frame.

Flow duration appears to be robust across different quantities, particularly the 14-day and 21-day durations. This recurring pattern suggests that variability at the different durations affects the metrics in similar ways.

Fish populations are inherently variable in response to varying environmental conditions (Guy and Brown 2007). Many species have high reproductive potential, increasing the variability of fish numbers (Caldwell et al. 2019; Hatch et al. 2020). Population data for calculating trends varies with fish densities and capture efficiency of gear types (Bonar et al. 2009; Widmer et al. 2010).

Figure 2 illustrates the variability of fish metrics generated from population data. The linear models used in functional analysis evaluates the relationship of the fish metrics to the hydrologic and hydraulic metrics for describing environmental flow. The recruit slope, mean-slope, YOY, October index (fish metrics) have variable responses to spring runoff and sampling conditions producing a broad range of values (Figure 2). Juvenile fish show increasing numbers from May through August as the fish grow and recruit to the seine gear. Mortality begins to offset production later in the summer, beginning a seasonal downward trend. The October index summarizes spring production and subsequent mortality rates.

The recruit slope metric (regression line through the scattered YOY CPUE value) had higher correlations with the hydrologic/hydraulic metrics that were higher than all the parameters evaluated with the mean-slope, YOY, and October index fish metrics.

Initial water management requirements for a short duration runoff pulse produced an abundance of drifting eggs but very low numbers of offspring (Dudley et al. 2020; Dudley, Robbins, et al. 2020). Following 2004 and 2005, prolonged floodplain inundation was recognized as essential habitat for minnow production (USACE 2007, 2008). Water managers are interested in defining the essential spring runoff parameters of magnitude and duration for successful production of minnow with minimal use of water.

4.3 Hydrology

HEC-EFM can pull various hydrologic metrics from online USGS sources. The season of interest for this study was the spring runoff, centered on April through June. Also evaluated was a longer season from March to July. It was found that both these seasons had similar characteristics when seeking the minimum of the peak event. Seasonal summations, summing the hydrology results for every day of the spring runoff, had higher correlations with the fish population metrics.

The duration hydrology, based on characterizing the peak event from 14 to 21 days, showed better correlations than the 7-day characterization. This is validated by the life cycle for the species, which requires a period of inundation to mature to free-swimming survival. In management, the duration hydrology may be easier to act on as the seasonal summation is more subject to net water availability in the system and more constrained by external factors.

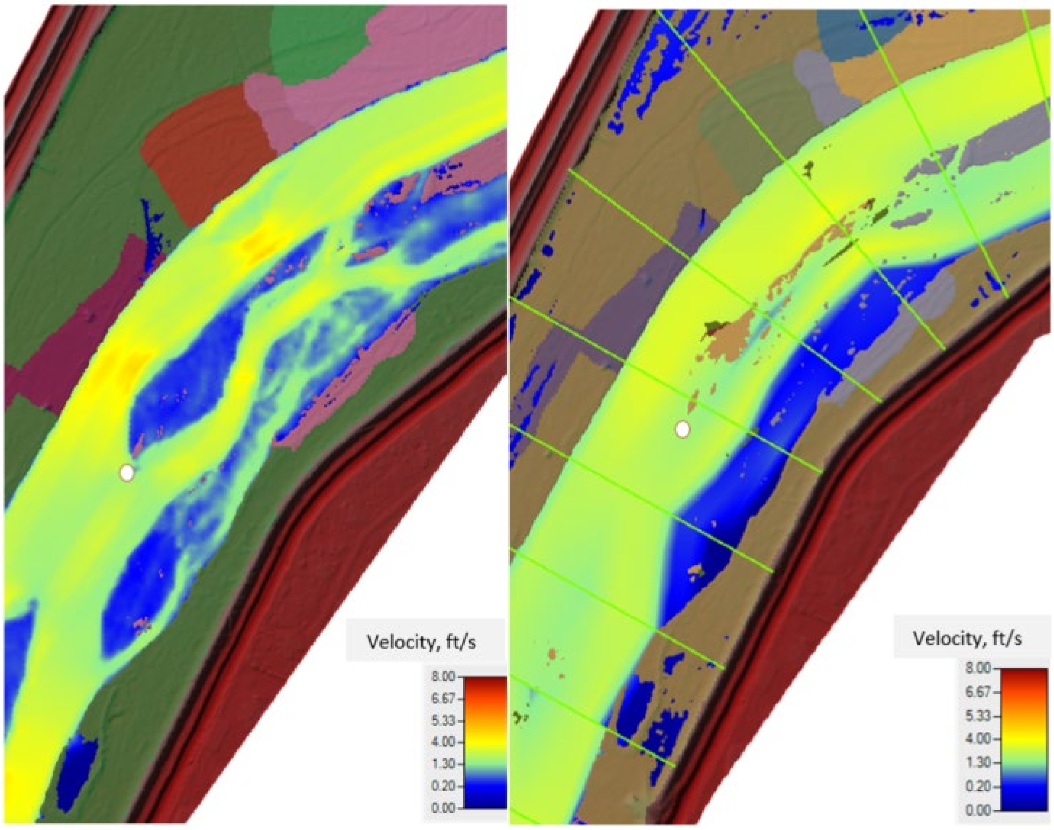
The 4,000 cfs to 6,000 cfs exceedance rates had high correlation with fish population metrics. However, the availability of water is limited, and this discharge target may not be actionable. Continuing to monitor for these high-discharge events and correlate with fish population metrics will be informative, but in this study, the sample size is too small for definitive conclusions.

The hydrology metrics taken as a whole had high variation in performance against the fish population parameters. The minimum correlation values were consistently from the Days Exceeding 1,000 cfs metric. This indicates that the number of days where discharges are around 1,000 cfs does not consistently correlate with the minnow population.

4.4 Hydraulics

There have been investigations on differences between 1D and 2D hydraulics (Benjankar et al. 2014) and how dimensionality effects habitat quantification. The hydraulic analysis was conducted in order to evaluate differences between 1D and 2D hydraulic habitat estimations and how these estimations effect eco-value correlations with minnow metrics (see Figure 22).

Figure 22. 2D (*left*) and 1D (*right*) rendering of 4,000 cfs flow velocities over the same mid-channel bars. White circle shows approximately the same location. H&O land cover shapefile is in the background of both images.



For the minnow, larval hydraulic habitat is characterized as slow-moving and shallow (see Section 2.4). For the Rio Grande, whose active channel has been channelized, it would be anticipated that 2D hydraulics would be more appropriate for computing edge habitat. This is owed to the resolution of 1D hydraulics across the cross-section, which is averaged. 2D, on the other hand, computes cell-by-cell hydraulics. A competing factor for this system's analysis, however, is the resolution at which fish population data are recorded. The CPUE is also an averaging of minnow quantities relative to both numbers of site collections by monitors. In addition, the fish metrics used in this report are averaged over surface areas sampled.

The 1D analysis for both the longer reach (HAN-1R) and shorter reach (HAN-1S) showed that areas of suitable velocities tend to have suitable depth. Areas of suitable depth exceeded areas of suitable velocity. Both the longer reach and the shorter reach performed well when seasonal summations was considered. For the longer reach, the overbank surface area and the larval depth criteria where the best performers. For the shorter reach, the total surface area, the larval depth, and the larval velocity criteria were good performers. The best performing hydraulic criteria were better than the best performing hydrology criteria, indicating that hydraulic information may be useful in characterizing seasonal habitat availability. The seasonal (daily) summations for larger reaches, using surface area as an eco-value curve, was shown to be the best-performing metric to use for describing minnow generation. Taken alone, this metric performed very well for all the fish metrics. This metric would not lend itself well for forecasting or target discharges, as it is sensitive to the daily hydrology and total seasonal volumes. However, this metric may be useful in regional and restoration work planning, as hydraulic engineering tools frequently utilize spatial hydraulic mapping to evaluate alternatives and designed effectiveness.

The seasonal summation component suggests hydrology is a strong driver for the correlation with fish metrics. The relatively low cost of computation presents an opportunity for expanding the scope of the 1D reach further to determine if hydraulic correlations can be improved when incorporating more reaches of the Middle Rio Grande. The Albuquerque reach that was modeled is an area of the Middle Rio Grande where it is transitioning from a wide-braided geomorphology to a single channel. The channel disconnection is increasing to be similar to the upstream 85 mi of the Rio Grande to Cochiti Dam. The disconnection is due to channel incision and vertical accretion of bars and channel banks. Downstream from the modeled reach, the Rio Grande is less laterally stable, with the migration of bends and potential for aggradation and channel avulsion (Makar and AuBuchon 2012). Such potential for diversity in the channel hydraulics may affect which hydraulic computation is a better fit and improve the correlations with fish population metrics.

The shorter 1D reach and the 2D reach covered the same river extent in the Albuquerque reach. Because of the dimensionality of the 2D, the quantification of habitat hydraulics for 2D modeling was higher than those calculated in the 1D model. Also, the 2D results presented divergence in the suitable velocity hydraulics versus velocity and depth combined. This means that there were locations identified where the velocity was appropriate but the depth was not, which was not identified in the 1D model.

Both the 1D and 2D models had great performance metrics measured for the recruit slope when utilizing the seasonal summation with species-specific hydraulics as well as durational hydrology using total surface areas as an eco-value curve.

Relative to the performance metrics, the 2D model performed comparably to the 1D larger reach as long as the analysis extents were confined to the floodplain. This demonstrates the lack of transferability for larval hydraulics into the active channel. The 2D hydraulics outperformed all other metrics in the recruit slope, and also presented very little correlation variation and very high correlation when utilizing the different hydrology durations. This indicates that the 2D hydraulics is a very good tool for forecasting recruitment, with less dependence on what type of hydrology is used in the analysis. This does not imply that hydrology can be neglected but instead shows that the 2D results are very rigorous in characterizing recruitment conditions for minnow. This type of analysis will be more robust as an adaptive management tool as it can use fewer hydrology parameters than the seasonal summation.

4.5 Refining Environmental Flow Requirements for Minnow

The magnitude of spring runoff produces suitable hydraulic habitat along the edge of the river channel and on the inundated floodplain. Hydrologic and hydraulic metrics are autocorrelated. Identifying the hydrologic thresholds where available habitat increases for minnow larvae is necessary to validate results despite these recurring patterns. The change on the descending limb of the hydrograph should coincide with hydraulic habitat suitability for larvae transitioning into the river as juveniles.

Habitat suitability indices using hydraulic metrics allow for areal estimations per flow magnitude. The areal extent of suitable hydraulic habitat is transformed into a function of flow and is a subset of the total inundated area. This subset of suitable habitat area (depth and velocity) is the littoral zone as the river rises with increasing flow volume. The area of suitable habitat begins increasing at flow above 2,000 cfs (Figure 11), indicating that floodplain inundation (Junk et al. 1999) is an important element of larval minnow habitat. The suitable hydraulic habitat for larval minnow increases survival, contributing to the measurable production of juvenile fish at later stages. From a management perspective, identifying lower flows for producing sufficient nursery habitat supports opportunities to increase the frequency of appropriate annual environmental flow. Also, identifying appropriate ways to quantify suitable hydraulics makes 1D and 2D modeling for habitat restoration sites and planning more meaningful. Using hydraulic habitat suitability to estimate appropriate flow magnitude is a bridge between fish nursery habitat requirements and water management objectives. Future research examining the incremental change in suitable habitat area for flows between 500 and 2,000 cfs within each reach would refine magnitude for the lower effective flows.

The functional output of a steady inundation for 14 to 21 days is consistent with the critical period (May 1974) of RGSM development from fertilization to first feeding (~5–7 days, Platania 2000). RGSMs may spawn multiple batches of eggs over a few days, or ovulation may lag following increased flow. Both responses suggest extending the flow duration will increase recruitment following spawning. The EFM mean-minimum and maximum-minimum flows for 14 and 21 days indicate the minimum effective duration is within this range. Monitoring of larval minnow on the floodplain (Valdez et al. 2019; Valdez, Zipper, et al. 2020) suggests that spawning may occur prior to floodplain inundation. The early life history from fertilization to larval mobility is approximately 5 to 7 days depending on water temperature. Larval drift in the river and onto the floodplain needs documentation to further refine minnow requirements for environmental flow leading to successful production.

Timing of spring flow to overlap with greater spawning activity would benefit from focused studies on minnow egg and larval drift. Reproductive monitoring of minnow eggs (Dudley, Robbins, et al. 2020) is inversely related to the higher flow magnitude and duration described in this report and the population data used for the fish metrics (Dudley et al. 2020). The earliest documented minnow spawning occurred on March 31 (Platania and Dudley 1999). Semi-buoyant fish eggs tend to drift in the lower water column (Worthington et al. 2013; Worthington, Brewer, and Farless 2013;

Porter et al. 2021) with better detection at flows that produce few juveniles. Back-calculating hatch dates from larval minnow (Valdez et al. 2019, 2020) provides a useful estimate of successful spawning and larval drift but doesn't provide information on earlier spawning or spawning magnitude.

Future adaptive management studies should (1) improve detection of minnow egg and larval drift for all flow magnitudes and bracket the earliest detections to better define the spawning period, (2) refine the details of minnow early life history on the floodplain for flow duration, (3) quantify hydraulic larval habitat suitability in all reaches at small flow increments (100–200 cfs) to define the lower limits of flow magnitude (< 2,000 cfs at Albuquerque), and (4) increase the scope of the hydraulic habitat analysis to include other reaches. Documenting the initiation of spawning provides flexibility for environmental flow actions to coincide with earlier spring runoff. Similarly, a better understanding of suitable habitat as a function of flow magnitude and duration may increase opportunities for management actions.

5 Conclusions and Recommendations

5.1 Conclusions

This study used the RGSM's larval life stage to demonstrate ecological function modeling with increasing hydrologic and hydraulic habitat complexity (Section 1.3). HEC-EFM and HEC-RAS were used to characterize seasonal streamflow characteristics and hydraulic habitat availability, respectively (Sections 2.2, 2.3). This project aims to compare the usefulness of different modeling approaches relative to field-measured species proliferation. 1D and 2D hydraulic modeling have different advantages based on the scale of effort, available data, and relevant data outputs (Section 2.3).

Knowledge of RGSM's hydraulic habitat preferences and life-cycle milestones were instrumental in scoping these analyses (Section 2.4). However, despite conceptual understanding of RGSM life cycle milestones and preferred habitat conditions, there are many possible combinations of environmental parameters. Functional analysis provides a framework to validate the selection of hydrologically linked metrics while filtering noisy streamflow and population measurements (Section 2.5).

It was found that this analysis approach was helpful in guiding the selection of meaningful metrics, as poorly formulated metrics did not correlate with fish production (e.g., the appropriateness of estimating 2D hydraulic habitat areas in the active channel). The result is identification of the best tools to quantify hydraulic habitat and durational hydrology that are correlated with fish production during the spring runoff (Section 3.3).

Identifying appropriate durations or hydraulic habitat definitions aids in the development of appropriate management actions and verifies that hydraulic habitat is correlated with ecosystem responses (Section 4.2). Some of the metrics, such as the hydrology durations, may be applicable to adaptive management and forecasting as they characterize the spring runoff hydrology into simple terms.

Implementing hydraulics in addition to hydrology improved the correlations for all fish metrics with this exercise. This indicates that the nature of inundation is as important or more important than the volume of streamflow. This may support habitat management approaches to increase inundated areas with appropriate hydraulics, including levee setbacks to increase suitable areas at higher flows or improving floodplain-channel connections at lower flows.

5.2 Recommendations

This approach can be transferred to other river systems, species, or life stages by applying conceptual ecological models to hydrologic and hydraulic habitat indices. Further research is needed to apply this approach to longer time scales that integrate different habitat conditions as life-cycle requirements change.

Adaptive management studies should be used to verify the minimum effective flow magnitude and duration criteria for refining environmental flow criteria for minnow production. Developing better estimates for the broodstock covariate may improve its use for analysis of hydrological and hydraulic metrics.

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Appendix A: R^2 Results for Hydraulic Parameters

Table A-1. Recruit slope.

Flow Metric	7-Day Mean of Minimum	14-Day Mean of Minimum	21-Day Mean of Minimum	1D Maximum	7-Day Maximum of Minimum	14-Day Maximum of Minimum	21-Day Maximum of Minimum
Base Season Hydrology Duration	0.883	0.887	0.879	0.783	0.829	0.884	0.897
Base Season Hydrology Summation	0.883	0.887	0.879	–	–	–	–
Discharge	**1,000 cfs**	**2,000 cfs**	**3,000 cfs**	**4,000 cfs**	–	–	–
Base Season Hydrology Exceedance	0.723	0.828	0.849	0.856	–	–	–
Long Season Hydrology Duration	0.824	0.825	0.819	0.759	0.828	0.882	0.891
Long Season Hydrology Summation	0.824	0.825	0.819	–	–	–	–
Discharge	**1,000 cfs**	**2,000 cfs**	**3,000 cfs**	**4,000 cfs**	–	–	–
Long Season Hydrology Exceedance	0.688	0.788	0.828	0.857	–	–	–
Base Season Hydrology and Larval Habitat Criteria HAN-1R	0.872	0.891	0.887	0.648	0.705	0.831	0.889
Base Season HAN-1S	0.889	0.899	0.892	0.775	0.805	0.876	0.89
Base Season HAN-2S (Binary)	0.579	0.525	0.471	0.775	0.742	0.743	0.717
Base Season HAN-2S (Continuous)	0.557	0.497	0.439	0.762	0.739	0.719	0.687
Base Season HAN-2S (Continuous, Floodplain Only)	0.906	0.906	0.893	0.811	0.843	0.893	0.907
Long Season Hydrology and Larval Habitat Criteria HAN-1R	0.901	0.921	0.87	0.639	0.704	0.831	0.888
Long Season HAN-1S	0.903	0.918	0.866	0.763	0.805	0.876	0.888

Table A-1. Recruit slope (cont.).

Flow Metric	7-Day Mean of Minimum	14-Day Mean of Minimum	21-Day Mean of Minimum	1D Maximum	7-Day Maximum of Minimum	14-Day Maximum of Minimum	21-Day Maximum of Minimum
Long Season HAN-2S (Binary)	0.419	0.323	0.27	0.776	0.742	0.743	0.728
Long Season HAN-2S (Continuous)	0.396	0.356	0.335	0.765	0.739	0.719	0.692
Long Season HAN-2S (Continuous, Floodplain Only)	0.835	0.833	0.821	0.79	0.842	0.892	0.902

Table A-2. Season summation of habitat.

Model Type	Overbank	Total	Depth	Velocity	HHSI
HAN-1R	0.944	0.81	0.935	0.886	0.878
HAN-1S	0.826	0.958	0.923	0.945	0.875
HAN-2S (Binary)	—	0.638	0.828	0.842	0.873
HAN-2S (Continuous)	—	0.638	0.465	0.621	0.652
HAN-2S (Continuous, Floodplain Only)	—	—	0.786	0.877	0.875

Table A-3. October index caption.

Flow Metric	7-Day Mean of Minimum	14-Day Mean of Minimum	21-Day Mean of Minimum	1D Maximum	7-Day Maximum of Minimum	14-Day Maximum of Minimum	21-Day Maximum of Minimum
Base Season Hydrology Duration	0.647	0.652	0.643	0.533	0.601	0.672	0.684
Base Season Hydrology Summation	0.647	0.652	0.643	—	—	—	—
Discharge	**1,000 cfs**	**2,000 cfs**	**3,000 cfs**	**4,000 cfs**	—	—	—
Base Season Hydrology Exceedance	0.465	0.549	0.625	0.87	—	—	—

Table A-3. October index caption (cont.).

Flow Metric	7-Day Mean of Minimum	14-Day Mean of Minimum	21-Day Mean of Minimum	1D Maximum	7-Day Maximum of Minimum	14-Day Maximum of Minimum	21-Day Maximum of Minimum
Long Season Hydrology Duration	0.58	0.579	0.571	0.514	0.6	0.67	0.68
Long Season Hydrology Summation	0.58	0.579	0.571	–	–	–	–
Discharge	1,000 cfs	2,000 cfs	3,000 cfs	4,000 cfs	–	–	–
Long Season Hydrology Exceedance	0.434	0.51	0.603	0.87	–	–	–
Base Season Hydrology and Larval Habitat Criteria HAN-1R	0.7	0.741	0.778	0.371	0.444	0.573	0.642
Base Season HAN-1S	0.728	0.756	0.78	0.579	0.563	0.624	0.642
Base Season HAN-2S (Binary)	0.405	0.368	0.334	0.56	0.525	0.526	0.509
Base Season HAN-2S (Continuous)	0.393	0.339	0.287	0.526	0.522	0.526	0.501
Base Season HAN-2S (Continuous, Floodplain Only)	0.685	0.684	0.692	0.567	0.61	0.678	0.666
Long Season Hydrology and Larval Habitat Criteria HAN-1R	0.738	0.75	0.646	0.365	0.443	0.573	0.641
Long Season HAN-1S	0.734	0.741	0.64	0.569	0.562	0.624	0.642
Long Season HAN-2S (Binary)	0.28	0.204	0.159	0.561	0.525	0.525	0.518
Long Season HAN-2S (Continuous)	0.244	0.212	0.193	0.528	0.522	0.526	0.505
Long Season HAN-2S (Continuous, Floodplain Only)	0.594	0.59	0.575	0.551	0.609	0.677	0.688

Table A-4. October index season summation of habitat.

Model Type	Overbank	Total	Depth	Velocity	HHSI
HAN-1R	0.842	0.564	0.729	0.629	0.614
HAN-1S	0.582	0.815	0.697	0.785	0.607
HAN-2S (Binary)	—	0.419	0.319	0.458	0.426
HAN-2S (Continuous)	—	0.419	0.295	0.446	0.42
HAN-2S (Continuous, Floodplain Only)	—	—	0.54	0.634	0.629

Figure A-1. Hydrology flow exceedance (base season).

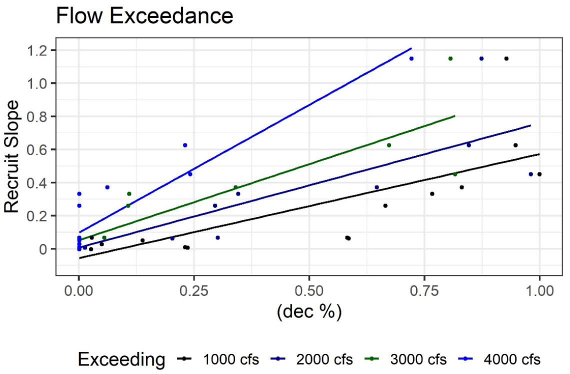


Figure A-2. Hydrology flow exceedance (long season).

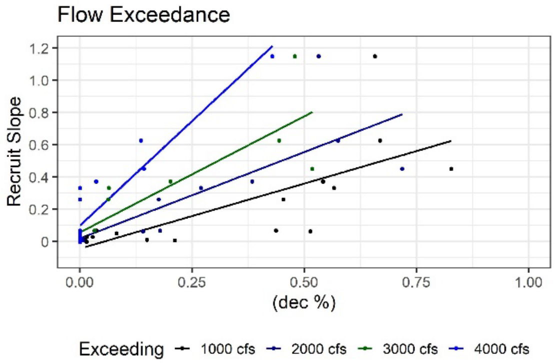


Figure A-3. Base season hydrology.

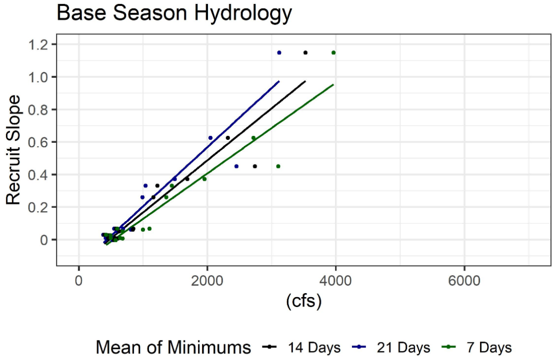


Figure A-4. Long season hydrology.

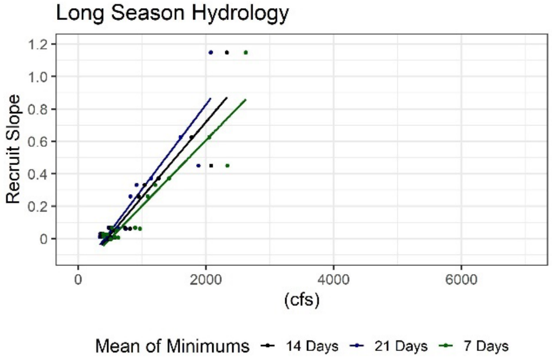


Figure A-5. Summation of base season hydrology.

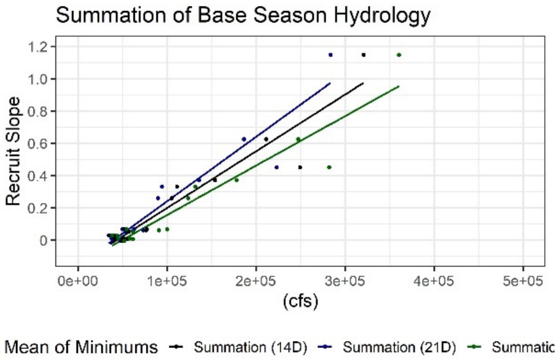


Figure A-6. Summation of long season hydrology.

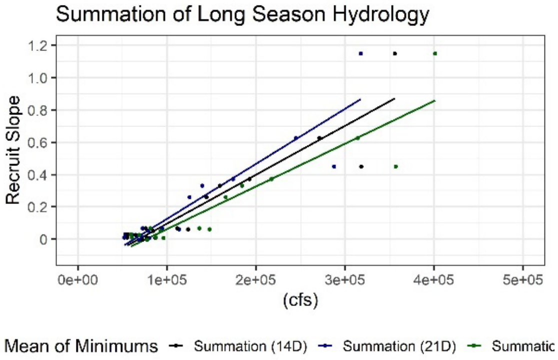


Figure A-7. Hydrology and hydraulics maximum of minimum duration, 1D.

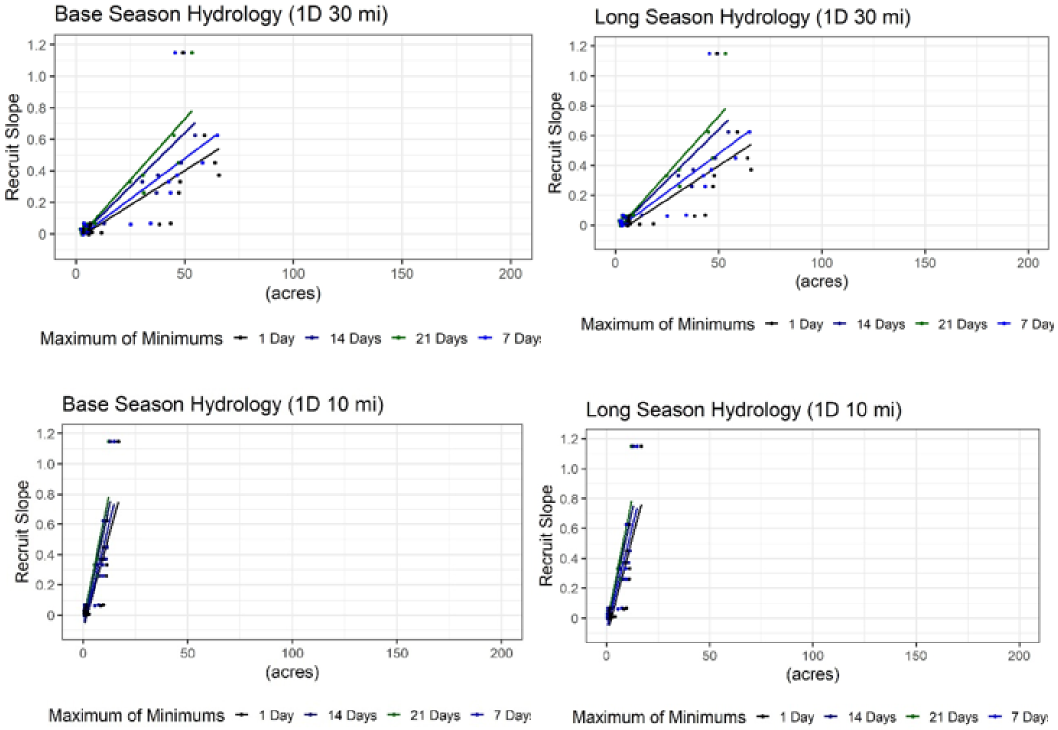


Figure A-8. Hydrology and hydraulics maximum of minimum duration, 2D.

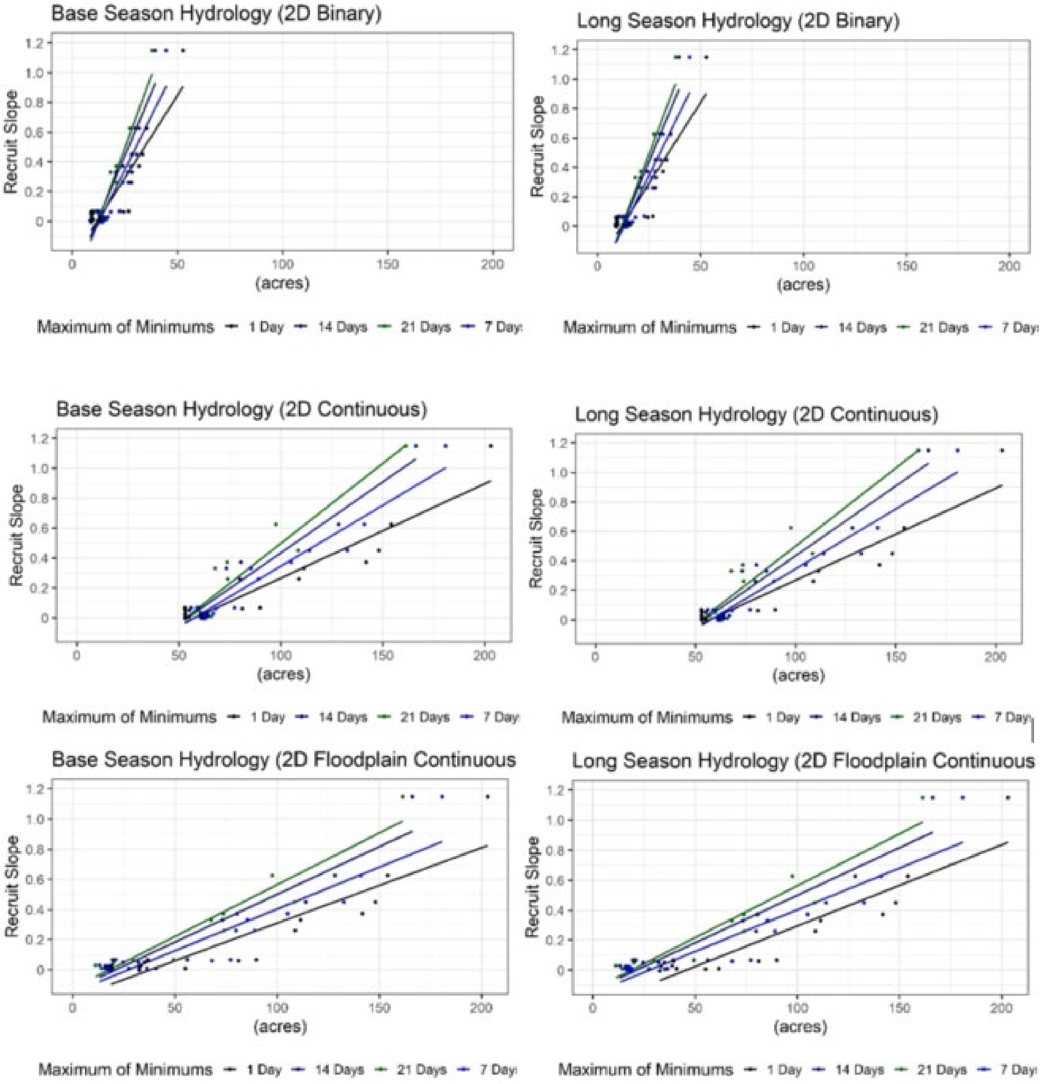
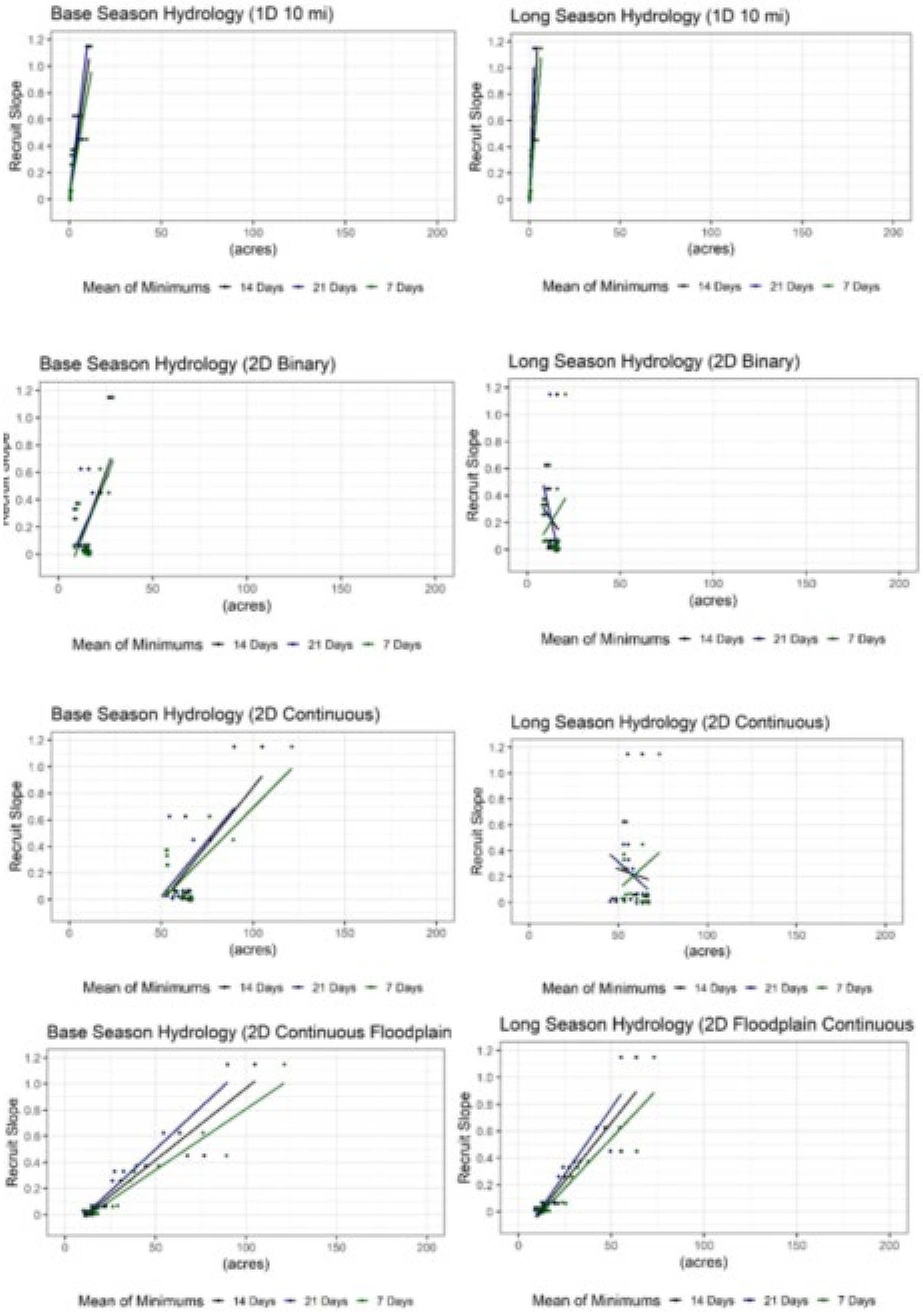


Figure A-9. Hydrology and hydraulics mean of minimum duration.



Base Season Hydrology (1D 10 mi)

Long Season Hydrology (1D 10 mi)

Base Season Hydrology (2D Binary)

Long Season Hydrology (2D Binary)

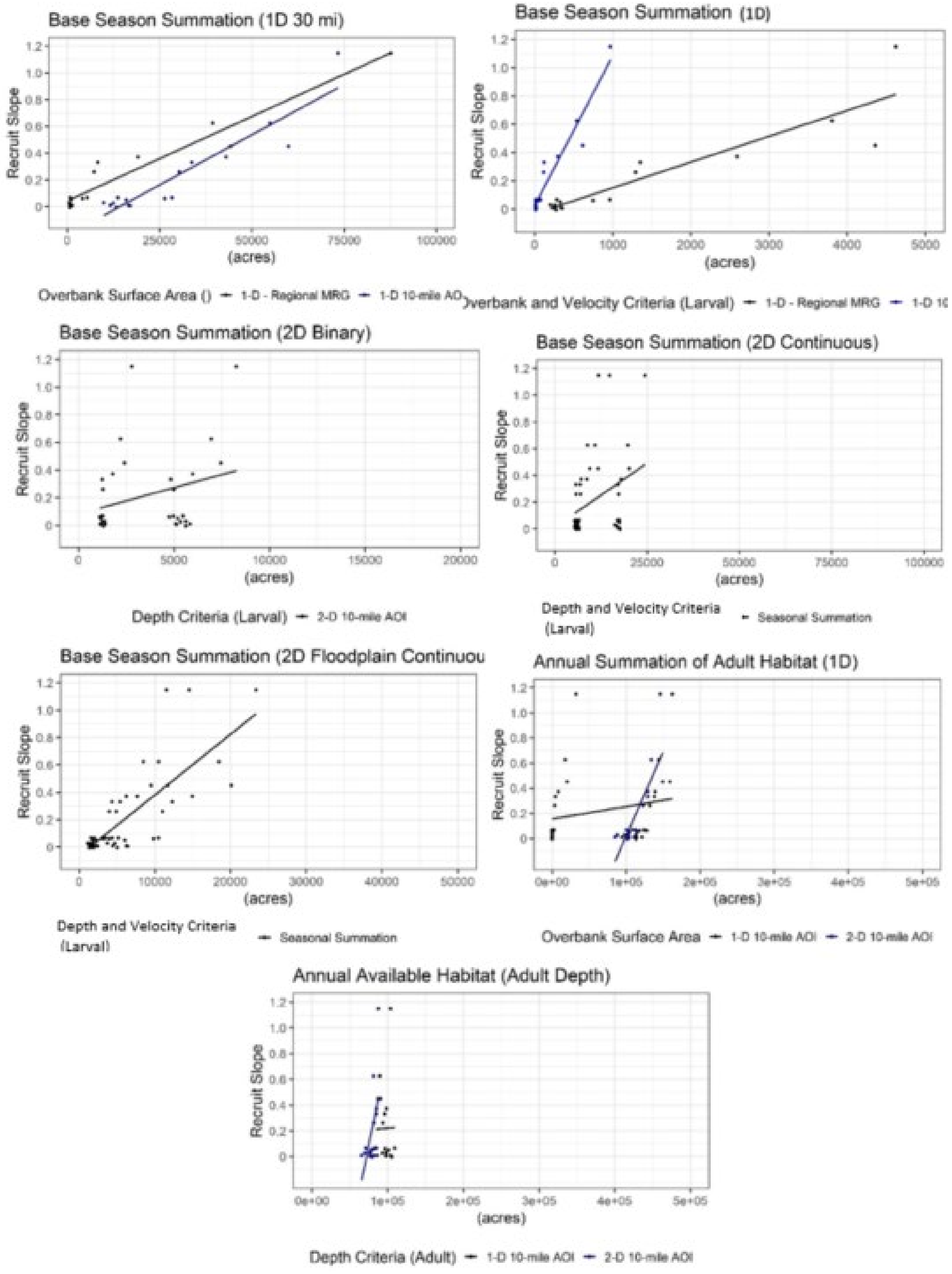
Base Season Hydrology (2D Continuous)

Long Season Hydrology (2D Continuous)

Base Season Hydrology (2D Continuous Floodplain

Long Season Hydrology (2D Floodplain Continuous

Figure A-10. Hydrology and hydraulics seasonal summation.



Appendix B: Quality Assurance Steps for the Hydraulic Models

This section discusses the quality assurance methods to quantify potential sources of error and their magnitude. Generally, the differences between the simulated and observed hydraulic conditions fall within the scope of typical limitations in data collection, hydraulic modeling applicability, and uncertainty. The following describes the quality assurance methods showing different reference data sets used to triangulate the best possible model. Several quality assurance methods were reviewed to quantify potential errors. The 1D river channel area (bank to bank) was compared to the lidar hydro-surfaced area at 600 cfs. The HEC-RAS inundated area covered a 250-acre domain, whereas the lidar-collected data had an inundated area of at 600 cfs covered 330 acres. When inspecting the HEC-RAS inundated area to the lidar, differences were attributed to divided flow in side channels, which may not be typically captured in a 1D hydraulic model.

For the 2D model, the interpolated terrain was evaluated with field-measured data. Reclamation collected Acoustic Doppler Current Profiler (ADCP) data of longitudinal profile of the area of interest in 2012. The ADCP data provide bed elevations and water surface elevations. Error analysis for the bed interpolated from HEC-RAS was conducted by generating a raster of the ADCP data points and comparing the raster to the 2D interpolated terrain with the Minus spatial analysis tool in ArcGIS. For the Albuquerque reach (the same area as HAN-1S and HAN-2S), the mean difference was 0.41 ft, with a standard deviation of up to 3.4 ft. The most significant error was found at side-channel confluences and outside meandering bends. Generally, the upstream portion of the reach showed ADCP bathymetry exceeding the HEC-RAS interpolated bed and the lower portion of the reach the opposite.

The 2D model's channel roughness was calibrated to match the aerial inundation areas and the water surface elevations measured by the ADCP data at approximately 600 cfs (Table 3). Channel roughness from Manning's *n* 0.017, 0.025, and 0.033 were tested. The roughness of 0.017 had the least mean absolute error throughout the reach, with a mean difference of 0.5 ft and a standard deviation of 1.4 ft. Uncertainties in the evaluation are attributed to (1) the number of data points available for ADCP comparison, (2) bumpiness of the water surface elevation possible from waves or other disturbance during data collection, and (3) in some places, ADCP data collection did not overlap the extents of the 2D estimation, greatly increasing the error.

Field-surveyed rangelines also recorded the water surface elevation at approximately 600 cfs throughout the reach. These surveys are less frequent than the ADCP data but more accurate as they are collected by licensed surveyors at set locations. Twenty-four rangelines are present throughout the reach. Of these, 7 rangelines are within 1 mi of an inflatable baffle diversion structure, whose operations are unknown relative to the field-measured data. It was noted that the magnitude of error in the HEC-RAS model was highest near this diversion structure. When a Manning's *n* roughness for 0.033 was simulated, the root-mean-square error was 0.3 ft.

Finally, the HEC-RAS 2D model was validated with a roughness calibration at a higher discharge. In 2008, Quickbird imagery is available at approximately 6,000 cfs for visual assessment. The original 1D HEC-RAS was also run at 6,000 cfs to generate a polygon of inundated area. The extents for the area of interest were approximately 774 acres. The 2D roughness was calibrated within a range of potentially allowable values based on H&O land cover descriptions and Chow (1959). Five roughness scenarios, navigating the minimum to maximum roughness values, were simulated in HEC-RAS 2D. It was found that using the minimum roughness was closest to generating a similar area of inundation as found in the simulation. For 6,000 cfs, the calibrated roughness generated 920 acres of inundation. This constitutes as 18% "error"; however, the dependence on visual assessment through vegetation may decrease the certainty of the validation data. Upon inspection of the areas of inundation surrounding the bridges and diversion structures, the model appeared to show inundation of approximately 0.3 ft depth in areas where no water was visible from the aerial imagery. Bridges were not simulated in the 2D model and assumed to be implicit during calibration of the water surface elevations at 600 and 6,000 cfs.

Abbreviations

ADCP	Acoustic Doppler Current Profiler
Agg-deg	Aggradation/degradation
cfs	cubic feet per second
CPUE	catch-per-unit-effort
H&O	Hink and Ohmart
HAN-1R	Hydraulic Analysis Number 1
HAN-1S	Hydraulic Analysis Number 2
HAN-2S	Hydraulic Analysis Number 3
HEC-EFM	Hydrologic Engineering Center's Ecosystem Functions Model
HEC-RAS	Hydrologic Engineering Center's River Analysis System
HSI	Habitat suitability index
RGSM	Rio Grande silvery minnow
SA	Surface area
TIFF	Tagged Image File Format
USACE	US Army Corps of Engineers
USBR	US Bureau of Reclamation
USGS	US Geological Survey
WUA	Weighted useable area
YOY	Young of year

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14. ABSTRACT

The proliferation of continuous streamflow monitoring and spatial data suitable for hydraulic modeling is increasing opportunities to use hydraulic habitat analysis to inform ecological models. However, species population and streamflow data exhibit high variability, making it challenging to identify hydrologic and hydraulic metrics that effectively correlate with ecological outcomes. Metric selection presents a challenge for informing environmental flow decisions and adaptive management of water infrastructure.

This study applies models to characterize environmental flows with increasing model complexity, including the use of hydraulic models to estimate suitable habitat areas at a given flow. The results are compared to field-measured fish outcomes over the same period using functional data analysis. The variance in model correlation with ecological outcomes aids in identifying the most effective environmental flow parameters while also indicating potential pitfalls from increasing model complexity. This analysis demonstrates techniques that synthesize environmental flows with available habitat analysis and validates the approach.

The case study is based on the Rio Grande silvery minnow (Hybognathus amarus, minnow), an endangered fish species in the Middle Rio Grande. Analysis focused on different methods to quantify spring runoff coinciding with the inundation of floodplain nursery habitat necessary for the minnow's larval and juvenile life stages.

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