Received: 6 December 2023 | Revised: 20 May 2024 | Accepted: 24 May 2024

DOI: 10.1002/eco.2681

RESEARCH ARTICLE

WILEY

Hydraulic analysis for assessing environmental flow selection and ecological model formulation

Aubrey Harris[1] | Michael Porter[2] | S. Kyle McKay[3] | Anjali Mulchandani[4] | Mark Stone[5]

[1]US Army Corps of Engineers, Engineer Research and Development Center, Environmental Laboratory, Albuquerque, New Mexico, USA

[2]US Army Corps of Engineers, Sacramento District, Albuquerque, New Mexico, USA

[3]US Army Corps of Engineers, Engineer Research and Development Center, Environmental Laboratory, New York, New York, USA

[4]Civil Engineering Department, University of New Mexico, Albuquerque, New Mexico, USA

[5]Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, Nebraska, USA

Correspondence

Aubrey Harris, US Army Corps of Engineers, Engineer Research and Development Center, Environmental Laboratory, Albuquerque, NM, USA.

Email: aubrey.e.harris@usace.army.mil

Funding information

Engineer Research and Development Center; U.S. Army Corps of Engineers, Grant/Award Number: SON-ENV-1227

Abstract

Ecosystem management depends on transforming qualitative observations (e.g., slow-moving shallow conditions provide nursery refugia for silvery minnow larvae) into management actions to increase habitat quantity or improve habitat quality. To be effective, decision metrics that are developed for management objectives should be validated with field observations. Model assumptions, precision and parameter importance can be refined by comparing the fidelity of selected parameters computed as habitat quality metrics and the correlation of these metrics to real-world observations. Validated environmental metrics are more credible for management and can be compatible with ecosystem monitoring and project design processes. In this study, streamflow monitoring data and hydraulic modelling are used to quantify fish habitat extent for 15 years of spring runoff. The spring runoff event coincides with larval maturation to a free-swimming juvenile phase for the silvery minnow, a critical period in Rio Grande habitat management. Different methods to estimate habitat availability (i.e., hydrology statistics, inundation extents based on hydraulic modelling and areal habitat availability based on different formulations of a habitat suitability index curve) were used to test the efficacy of different metrics relative to species population monitoring. This analysis finds that flow–ecology relationships based on hydraulic modelling or hydrology statistics are both effective and highly correlated to larval production. The investigation shows how seasonal hydrologic characterization and hydraulic discretization have varying levels of correlation with seasonal fish production. This study demonstrates how hydraulic modelling data and hydrologic characterization of riverine environments can be used to validate or develop conceptual ecological models.

KEYWORDS

endangered species, environmental flows, habitat hydraulics

1 | INTRODUCTION

Managing water for environmental objectives (i.e., environmental flows) requires basic understanding of the response of an ecosystem to changes in streamflow (i.e., flow–ecology relationships). Environmental flows can be translated directly to adaptive management actions such as change in water operations that improve species success (Berthot et al., 2021). However, the efficacy of these actions depends on the reliability of how changes in flow magnitude, duration, frequency, timing and rate of change of streamflow (i.e., a 'flow regime'; Poff, 1997) affect ecosystem functions such as water quality, in-stream hydraulics, aquatic populations and energy sources.

Year-to-year variability of both species prevalence and streamflow presents challenges in identifying flow targets. For instance, fish populations are inherently variable in response to environmental conditions (Guy & Brown, 2007), and population data can vary with fish density and capture efficiency based on gear type (Bonar et al., 2009; Widmer et al., 2012). Similarly, flow regimes can be summarized by hundreds of metrics (Olden & Poff, 2003), many of which vary significantly through time or may only be available at a narrow set of gage locations. Given these uncertainties, the link between hydrology and ecosystem processes can be challenging to define and much more so when trying to create a parsimonious model with outputs that are clear enough to guide management action.

Hydrologic, hydraulic and habitat analyses are fundamental to environmental flow methods. For instance, techniques such as flow regime analysis using the Indicators of Hydrologic Alteration (IHA) have become standard tools for practitioners (Richter et al., 1997). Similarly, hydraulic habitat analysis using methods such as Physical Habitat Simulation (PHABSIM) (Milhous & Waddle, 2012) has provided a repeatable framework to characterize how streamflows affect species and justify environmental flow decisions. While comprehensive field measurement of habitat is infeasible, the scalability of hydraulic habitat modelling facilitates extension of spatial domains and temporal windows, ultimately increasing available datasets supporting environmental flows (Masarei et al., 2021).

While increasing the complexity of ecological models can be useful, identifying the most tractable and sufficiently specific model is a necessary step in efficient analysis (Larsen et al., 2016). Hydraulic models have been used to link streamflow to available habitat at resolutions varying from coarse (e.g., river reach) to micro-habitat (e.g., sub-cross-section) scale (Tharme, 2003). Advancements in data availability and computational efficiency have provided advanced insights of connections between discharge and physical habitat availability (Berthot et al., 2021; Pisaturo et al., 2021). Conversely, these advancements can lead to overparameterization and overfitting, which negatively affect model performance (Cox et al., 2006).

This study's objective was to evaluate the effectiveness of varying resolutions of environmental flow modelling approaches in predicting species response. Specifically, we use a case study on the Rio Grande (New Mexico, USA) and examine the role of multiple levels of detail in hydrologic and hydraulic models on predicting population trends for the Rio Grande Silvery Minnow (*Hybognathus amarus*, RGSM). In doing so, we investigated how increasing model complexity can improve or degrade correlation with species population trends. Seasonality of peak snowmelt, hydraulic models of varying dimensionality and four approaches of hydraulic habitat discretization were analysed as covariates for fish population metrics (Figure 1). The analysis identifies how increased data resolution and specificity in habitat criteria affect metric correlation to RGSM population growth or decline.

2 | MATERIALS AND METHODS

Fish population monitoring data were used as a means test to the performance of several hydrologic and hydraulic habitat metrics.

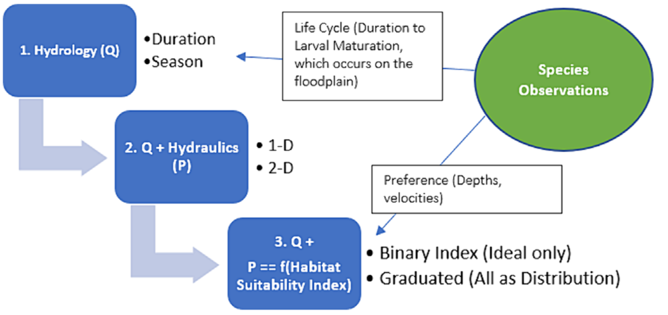

FIGURE 1 Conceptual representation of the study design. On the left, increasing model complexity: (1) hydrologic data as discharge (Q), (2) inundation areas (P) based on Q using different hydraulic models and (3) inundation areas (P) based on Q-provided habitat quality using a hydraulic habitat suitability index. Parameterization of hydrology and hydraulic habitat preference were defined based on field observations of species life cycle requirements and hydraulic preferences.

The spring runoff, a critical period for RGSM population recruitment, was characterized in numerous ways based on conceivable durational and hydraulic habitat requirements for larval fish production. We initially performed analysis based on hydrologic conditions alone. Then, one- and two-dimensional (1D and 2D) hydraulic models were used to estimate total inundation and inundated habitat based on existing models of hydraulic habitat preference. This array of hydrologic and hydraulic metrics was compared to fish population data using statistical correlations to identify the most predictive metrics and model resolutions.

2.1 | Case study location and species

This research was focused on a case study on the Rio Grande (New Mexico, USA), with emphasis on the federally endangered Rio Grande Silvery Minnow (*H. amarus*, RGSM). The RGSM is the remaining species of the native fluvial minnow guild in this river (Remshardt et al., 2003) and occupies 5% of its original range due to channelization and disconnection of the river and its floodplain (Bestgen & Platania, 1991). Population and range losses are common among fish species on fragmented and flow-regulated rivers in part due to changing hydraulics and flow patterns (Dudley & Platania, 2007). For the Rio Grande, such fragmentation was caused by installation of flood control and diversion structures, as well as channelization and levee projects that have reduced the active channel and floodplain widths respectively.

The life history and hydraulic habitat preferences of RGSM have been extensively described (Medley & Shirey, 2013; Valdez et al., 2019, 2021). RGSM spawning occurs in conjunction with the rising spring hydrograph (Dudley, Robbins, et al., 2020; Pease et al., 2006; Widmer et al., 2012), and a larger runoff is associated with increased species spawning success (Valdez et al., 2019). Spring runoff causes floodplain inundation, which creates slow-moving and shallow larval nursery habitat (Fluder et al., 2007; Gonzales et al., 2014; Valdez et al., 2019, 2021). The correlation between autumn RGSM population and the degree of spring floodplain inundation underscores the importance of floodplain nursery habitat in minnow life history (Porter & Massong, 2004).

Conceptually, observations of hydrologic and hydraulic thresholds to support RGSM have already been applied as habitat management actions in this river system. Water management requirements for a short-duration runoff pulse produced drifting eggs but very low numbers of offspring (Dudley, Platania, & White, 2020; Dudley, Robbins, et al., 2020). Following 2004 and 2005, prolonged floodplain inundation was recognized as essential for RGSM production. Water managers are interested in defining essential spring runoff parameters (e.g., magnitude and duration) for successful production of minnow with minimal use of water. Restoration sites have been constructed by transforming banklines and the floodplain to generate shallow-slow-moving habitat at lower flows.

For hydraulic habitat parameterization, Bachus and Gonzales (2017) identified suitable water depths and velocities for larval life stages for RGSM. Valdez et al. (2019) and SWCA (2019, nonpub) have collected monitoring data for RGSM populations including measurements of depth and velocity. We defined habitat preferences as a habitat suitability index (HSI). Velocity and depth were transformed to an HSI value ranging from 0 (inhospitable) to 1 (conditions most utilized by the species).

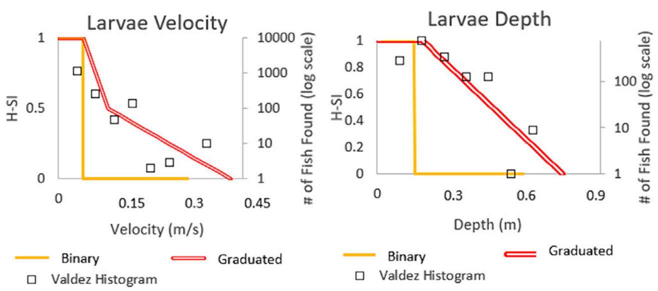

FIGURE 2 Velocity and depth are the hydraulic habitat parameters delineated for RGSM in this study. The HSI (hydraulic habitat suitability index) has a range from 0 to 1, with 1 being the most preferred habitat, 0 being inhospitable. Two HSI schema were used. 'Binary' is based on ideal hydraulic habitat conditions delineated by Mortensen et al. (2019) (solid yellow line). The 'Graduated' (double red line) encloses a histogram of fish counts into equal sized bins based on field measured data from Valdez et al. (2019) (black boxes).

Two HSI were tested. The first was an existing suitability index, referred to in this study as a 'Binary' HSI, that was previously published by Mortensen et al. (2019), delineating the most ideal habitat conditions. A new 'Graduated' HSI was developed based on a histogram of larval fish observations from Valdez et al. (2021), where depth, velocity and number of RGSM were measured during field monitoring. The samples were combined as a frequency analysis in a histogram based on observed velocity and depth conditions. The Graduated HSI is a polyline that envelops the Binary HSI and the field-measured histogram (Figure 2).

2.2 | Fish population metrics

Fish population data (2002 to 2018; Dudley, Platania, & White, 2020) were used for deriving recruitment and population trends (fish metrics) for functional analysis (FA) using linear regression. 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 totalling ~400–600 m^2 (per site visit) at 20 sites. The RGSM monitoring data included location, habitat type, mean fish length and age class by individual seine haul (Dudley, Platania, & White, 2020). The year 2009 was excluded from analysis because sampling was limited to September and October, precluding calculation of spring season recruitment metrics.

Data were parsed into annual cohorts based on estimated age at capture. Catch-per-unit-effort (CPUE) was calculated from May to October, as the number of fish captured per 100-m^2 area sampled, with 0.001 added to each value to support log-transformation when no fish were found. The percentage of seine hauls with at least one silvery minnow was 37.1% (mean CPUE = 0.28 per 100 m^2, range 0.10–33.33 per 100 m^2 when present).

Four fish population metrics were calculated for each sample year using the R statistical software language from the RGSM population monitoring dataset (Table 1; Dudley, Platania, & White, 2020). The broodstock covariate is the April population (CPUE) prior to spawning. The recruit slope metric is the slope of young-of-year (YOY) CPUE over time from May to August for each year. The YOY CPUE summarizes the total YOY catch for May–August. The YOY and mean slope had a similar distribution as the slope of recruitment (recruit slope). Recruit slope was carried forward as the fish metric for evaluation against hydrologic and hydraulic metrics.

TABLE 1 Fish population and recruitment metrics considered in the FA.

Fish metric	Label	Formula	Date range
Broodstock (CPUE)	Broodstock	100P	April
Slope to mean CPUE	Mean slope	$\mathrm{lm}(\mu_{100P}/\mu_{\tau})$	May 1–Aug 9
Young-of-year (CPUE)	YOY	$\frac{100P}{T}$	May 1–Aug 9
Slope of recruit (CPUE)	Recruit slope	$\mathrm{lm}(P \sim T)$	May 1–Aug 9

Note: μ_x = average of variable 'x'; P = fish population/unit area; T = date range; τ = number of days: ~ = 'as a function of'.

2.3 | Hydrologic and hydraulic habitat metrics

Daily average discharge data were retrieved from the USGS gage Rio Grande at Albuquerque, NM Gage (08330000). The Hydrologic Engineering Center's Ecosystem Functions Model (HEC-EFM) was used to characterize the spring runoff to create a one-to-one parameter comparison: one hydrologic or hydraulic habitat data point per year compared with one fish population metric that summarizes the spring runoff larval production for that same year (Figure 3). Characterization of hydrology was based on critical spring-runoff habitat conditions for the larval life stage of RGSM: flow during the peak discharge event over 1-, 7-, 14- and 21-day durations according to multiple summarizing statistics (peak, average, minimum). Seasonal summations and discharge frequency (e.g., number of days with streamflow ranging from 25 to 50 cubic meters per second [cms]) were also evaluated as hydrological habitat metrics. Hydrographs from 2002 to 2018 (except for 2009) were evaluated, corresponding with the years when fish data were available.

Seasonality was tested with base and long season periods of observation. The base season was centred on the most typical months of the spring runoff (April to June), while the long season was of a sufficient duration to capture most outlier (early) runoff seasons (March to July) of the sample period. In addition to seasonality, the durational hydrological statistics were determined using HEC-EFM: maximum and average values for the minimum flow of a particular duration for each runoff season. The combinations of hydrologic or hydraulic metrics that were tested against the recruit slope are shown in Table 2.

One-dimensional (1D) and two-dimensional (2D) hydraulic models were created for a 16-km sub-reach of the Rio Grande in Albuquerque, NM using HEC's River Analysis System (HEC-RAS). These models encompass a reach of the Rio Grande that includes several US Army Corps of Engineers (USACE) restoration sites in the Corrales and Albuquerque, NM, area. Bathymetric survey and LiDAR were collected by the US Bureau of Reclamation and represent 2012 conditions. The field measurements included water surface elevations and surveyed channel cross-sections. The result was a detailed and comprehensive topographical dataset appropriate for simulating river hydraulics.

Landcover data were collected in 2005, mapping out main vegetation types, including density and canopy characteristics (based on methods from Hink & Ohmart, 1984). These data were used to define different Manning's roughness coefficients for the hydraulic analyses. Manning's 'n' values were calibrated to a low-flow (~15 cms, corresponding to the US Bureau of Reclamation survey between January 11 and 18, 2012) water surface elevation and areas of inundation during a high-flow event (~150 cms, collected by USACE as aerial photography June 8–10, 2008).

The hydraulic simulations were used to characterize inundated areas and areas of suitable hydraulics for a range of discrete discharges, using two different hydraulic modelling approaches for comparison. The 1D model estimates spatially averaged hydraulic conditions for the

TABLE 2 List of the hydrologic and the hydraulic metrics tested against the fish metric (recruit slope).

Hydrology	Hydraulics for each of the * (asterisked) Hydrology metrics
• Season: Long (April to July); base (May to June) * • Duration (1 to 21 days) * • Flow magnitude (maximum, mean of minimums, minimum of minimums, summation) * • Frequency	• 1D and 2D inundated area • 1D and 2D area with Binary HSI, velocity, depth and composite. • 2D area with Graduated HSI, velocity, depth and composite. • 2D area with Graduated HSI for the floodplain, velocity depth and composite.

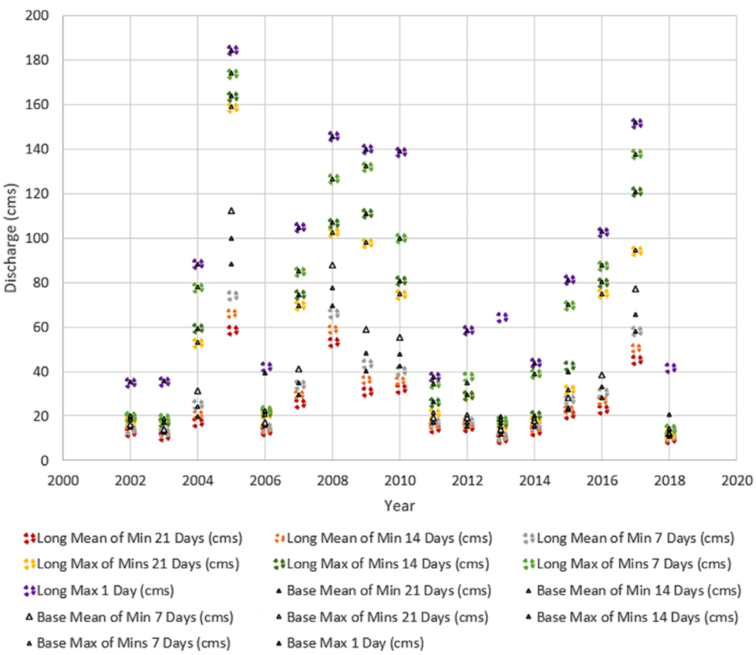

FIGURE 3 Plots of hydrologic metrics for the study period. These were computed with HEC-EFM 'Long' indicating a longer season (capturing outliers occurring in the early spring) and 'Base' season representing the most typical run off. The durations are 1-day duration to 7-, 14- and 21-day durations. The spring pulse is identified with the highest minimum flows for each annual spring flow of each given duration. The mean and the maximum are statistical summaries of these, either the mean minimum flow or the maximum minimum flow.

main-channel cross-section and floodplains. The 2D model provides spatially explicit estimates of hydraulic conditions for cells distributed in a mesh. Though the 1D and 2D models had similar areal inundation patterns, they produced different estimates of 'suitable' habitat area due to their differences in hydraulic computational approach.

Hydraulic metrics were exported from HEC-RAS as raster maps. ArcGIS (Version 10.3) was used to compute the HSI, also as raster maps, for depth and velocity using the Reclassify tool. Field observations indicated that hydraulic habitat conditions were mutually inclusive, meaning both depth and velocity conditions are met when fish are found. Thus, raster multiplication ensured a location had suitable conditions for both parameters as a Composite HSI. The hydrology and hydraulic results were used to translate the spring runoff hydrograph from 2002 to 2018 into habitat quantities (areas) with increasing complexity: hydrology alone, inundation area based on streamflow and suitable hydraulic habitat areas based on streamflow. The habitat quantities were compared to fish population data collected during the same period.

2.4 | Fish population and comparisons with hydrologic and hydraulic metrics

A functional data analysis framework was used to evaluate each combination of fish and environmental metrics corresponding to YOY RGSM production. The recruitment index was compared to all combinations of environmental metrics calculating R^2 and error prediction via Akaike information criterion (AIC) values. This resulted in 100 total candidate models. The model results were sorted by R^2 values to identify which environmental metrics had a higher correlation and lower AIC score. The environmental metrics with higher R^2 with the fish metrics may be conceptually defined as hydrologic or hydraulic parameters relevant to fish production.

Though selecting metrics that can be implemented as management actions may be straightforward (e.g., discharge for a duration), we wanted to determine if hydraulic data produced unique results. Following parameter identification, correlation between the hydraulic/hydrologic habitat metrics and the fish population measurements was evaluated. A Pearson correlation was used to test the degree to which hydraulic and hydrologic metrics correlated with one another. A second Pearson analysis was run to measure individual hydraulic and hydrology metric correlations to fish recruitment.

3 | RESULTS

Inundated area increases with flow, but the area does not increase linearly as discharges increase (Figure 4). In an incised river, the channel conveys bankfull discharges in a narrow, high-velocity channel. Overbanking flow enters the floodplain, expanding inundated areas that are better habitat for RGSM larvae nursery. At very high flows (140 cms), flow becomes constrained by levees, causing increasing discharge to continue increasing inundated area, but the areas of suitable hydraulics reach an asymptote.

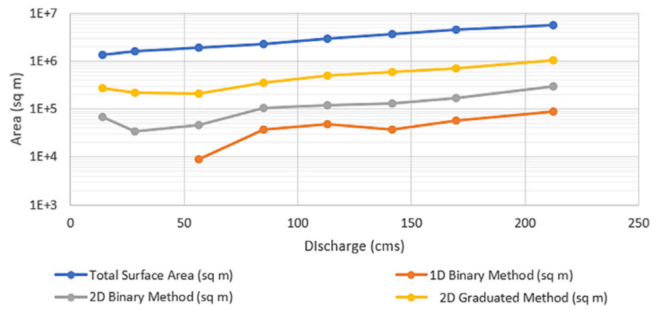

FIGURE 4 Inundated area per discharge curves using 1D and 2D hydraulic models and two habitat suitability index definitions. The total surface area between 1D and 2D were similar and were therefore plotted with one line.

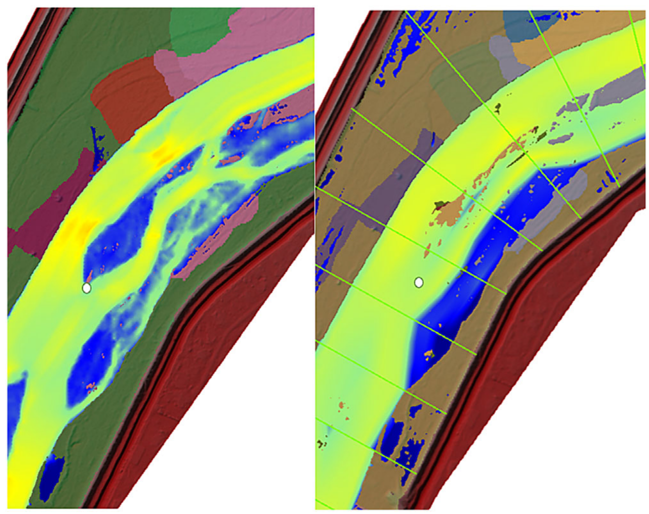

FIGURE 5 2D (left image) and 1D (right) rendering of 11.3-cms flow velocities over the same in-stream islands. White circle shows approximately the same location.

Using a 1D or 2D hydraulic model affects habitat quantification (Benjankar et al., 2015), with the 1D averaging the active channel and overbank areas and 2D having higher resolution throughout the inundated area, including edge habitat (Figure 5). 2D habitat computation constrained to the floodplain performed better than when the 2D habitat computation included active channel areas. For the 1D results, active channel hydraulics were averaged, and no suitable velocity or depth areas were identified in the active channel in the first place. This demonstrates a risk in increasing model resolution and the lack of transferability for suitable hydraulic evaluation: though the active channel may have suitable hydraulics, underlying mesohabitat conditions do not support species recruitment.

The differences in estimated areas of suitable hydraulics were much more pronounced between the 1D and 2D models, by an order of magnitude (10^1) between the 1D HSI results and the 2D Graduated HSI results (Figure 4). The Graduated HSI method had a wider range of suitable depths and velocities than the Binary method, and therefore, quantities of habitat from the Graduated HSI are greater than those estimated from the Binary method.

TABLE 3 Eco-value curves relate discharge to some habitat quantity, in this case: inundated area.

	1D Total area[a]	1D Binary-floodplain[a]	2D Total area	2D Binary
1D Binary-floodplain	0.908^{+}			
2D Total Area	0.997^{+++}	0.912^{+}		
2D Binary	0.945^{++}	0.968^{+++}	0.918^{+}	
2D Graduated	0.986^{+++}	0.952^{++}	0.954^{++}	0.983^{+++}

Note: 1D and 2D hydraulic models are tested, and this table demonstrates how much these eco-value curves correlate with one another.
[a]Correlations for these columns apply to the floodplain only and therefore are compared from 60 to 215 cms only. + (0.90–0.93]; ++ (0.93–0.96]; +++(0.96 or higher).

The variance between the metric correlations would be small because underlying hydrology data were common to all parameters. The eco-value curves (habitat quantity as a function of streamflow volume) using habitat areas had a very high correlation with one another (Table 3). 1D Total Area and 2D Total Area had the highest correlation. Total area curves had the least correlation relative to habitat curves. The least correlated eco-value curve was the 1D Total Area relative to the 1D Binary HSI, having a coefficient of determination (R^2) value of 0.91.

3.1 | Functional data analysis

The various hydrologic, hydraulic and habitat eco-value curves were used to generate single-value characterizations of the spring runoff or annual hydrographs. Correlations between these characterizations are presented in Table 4. The parameter results for 2002 to 2018 had different magnitudes of variance. The units of the eco-value (e.g., percentages in flow exceedance, discharge, and acres of inundation) and the various time frame (e.g., seasonal summation and streamflow durations) affected variance in the result distribution.

Conceptually, a maximum of the minimum flow represents the peak runoff's magnitude at a given duration. Between the base and long season hydrology, the maximum of minimum flows is similar. However, when comparing the base and long season mean of minimum metric, the longer season attenuates the peak discharge. The maximum 1-day event is higher for the long season in two instances for the 17-year time frame.

Generally, the linear regressions had a positive relationship between the eco-value and the recruit slope. The base season durations performed slightly better than the long season, though medians of these metric correlations (R^2 values in Table 4) were within 0.05. The highest correlated hydrology metrics were associated with longer durations: 21 and 14 days. The mean of minimums for the peak discharge and the maximum of the minimum flows for the durations had similar R^2 correlations to each other for all durations.

The summation (daily eco-values summed) for the base season had a higher correlation with the fish population metrics than any habitat quantification based on duration (e.g., 21-day minimum peak flow). The highest correlations to the recruit slope metric were the total surface area ($R^2 = 0.958$) and the overbank suitable velocity ($R^2 = 0.945$) eco-value curves. 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.

The consistent trends of increasing duration for environmental metrics (the 14- and 21-day maximum of minimum flow) for recruitment slope support using FA for identifying environmental flow duration. The differences between the maximum intermediate and the minimum suitable flows for the 21- and 14-day maximum-of-the-minimum flow ranges identify flow combinations (duration and magnitude) that require additional data collection to refine a minimum environmental flow for successful minnow recruitment.

3.2 | Pearson correlation

The Pearson correlation results are shown on a quadrant plot, with the mean correlation among hydrologic and hydraulic habitat parameters and the fish population metrics at the origin. Absolute deviation from the mean (MAD) to the fish population metric is on the x-axis; MAD correlation of the hydraulic and hydrologic metrics to each other is on the y-axis (Figure 6). Metrics vary most from the mean plot farther from the origin.

Metrics plotted in Quadrants II and III have a lower correlation with fish population recruitment than those in Quadrants I and IV. Within Quadrant I (no metrics fell in Quadrant IV), items that move farther from the origin on the x-axis are better correlated with fish population recruitment, and items that move farther from the origin on the y-axis have more correlation with hydrologic-based metrics. Therefore, items that are farthest to the right of the origin and further down the y-axis are the most independent metrics with the highest correlation with fish population metrics (see Figure 7 for more examples of variance among characterization of hydrology alone, the season and different habitat suitability indices).

The results are grouped together based on hydrologic metric type (hydrology, 2D Binary, etc.), and the centroids were computed by averaging the MAD x- and y-axis values, respectively. Some metrics could not be evaluated with Pearson correlations. Seasonal summations did not follow a normal distribution, so 1D and 2D results were combined for plotting the centroid in Figure 6. The long season, 14- and 21-day mean values for 2D Binary and Graduated HSIs had the least self-correlation with other metrics and poor performance with the recruit slope. These strongly affected the centroid location. When

TABLE 4 FA results for the tested hydrologic and hydraulic metrics, colour coded to highest correlation (blue) to least correlated (red).

Recruit slope		Mean of minimums			Maximum	Maximum of minimum		
		7-day	14-day	21-day	1D	7-day	14-day	21-day
Base season Hydrology	Duration	0.883	0.887	0.879	0.783	0.829	0.884	0.897
	Summation	0.883	0.887	0.879	--	--	--	--
		28 cms	56 cms	85 cms	113 cms	--	--	--
	Exceedance	0.723	0.828	0.849	0.856	--	--	--
		Mean of minimums			Maximum	Maximum of minimum		
		7-day	14-day	21-day	1D	7-day	14-day	21-day
Long season Hydrology	Duration	0.824	0.825	0.819	0.759	0.828	0.882	0.891
	Summation	0.824	0.825	0.819	--	--	--	--
		28 cms	56 cms	85 cms	113 cms			
	Exceedance	0.688	0.788	0.828	0.857	--	--	--
		Mean of minimums			Maximum	Maximum of minimum		
		7-day	14-day	21-day	1D	7-day	14-day	21-day
Base season Hydrology and larval habitat	1D Binary	0.889	0.899	0.892	0.775	0.805	0.876	0.89
	2D Binary	0.579	0.525	0.471	0.775	0.742	0.743	0.717
	2D Graduated	0.557	0.497	0.439	0.762	0.739	0.719	0.687
	2D Graduated, floodplain	0.906	0.906	0.893	0.811	0.843	0.893	0.907
		Mean of minimums			Maximum	Maximum of minimum		
		7-day	14-day	21-day	1D	7-day	14-day	21-day
Long season Hydrology and larval habitat	1D Binary	0.903	0.918	0.866	0.763	0.805	0.876	0.888
	2D Binary	0.419	0.323	0.27	0.776	0.742	0.743	0.728
	2D Graduated	0.396	0.356	0.335	0.765	0.739	0.719	0.692
	2D Graduated, floodplain	0.835	0.833	0.821	0.79	0.842	0.892	0.902
		Surface area		Larval criteria				
		Overbank	Total	Depth	Velocity	HHSI		
Seasonal summation of habitat	1D Binary	0.826	0.958	0.923	0.945	0.875	--	--
	2D Binary	--	0.638	0.828	0.842	0.873	--	--
	2D Graduated	--	0.638	0.465	0.621	0.652	--	--
	2D Graduated, floodplain	--	--	0.786	0.877	0.875	--	--

only the floodplain is considered (Graduated 2D, Floodplain), the correlation with fish population metrics is greatly improved. This indicates that when the hydraulic HSI is applied to the active channel, there is less correlation with fish production. The 1D hydraulic results already filtered out the active channel area, as average channel hydraulics in these locations exceeded ideal hydraulic habitat conditions.

Still, the variation between these metrics, either in correlation with the recruit slope or with the hydrographic metrics, is very small. While Figure 6 presents the centroid of the metrics grouped by type (i.e., 1D, 2D and Hydrology), looking at a single hydrologic condition (i.e., 14-day duration) demonstrates how increasing model complexity affects correlation with the fish population metric (Figure 8a). Differences between the long and base season hydrology were minimal but impacts of the hydraulic habitat accounting method showed 'migration' within the quadrant plot. Of these, the increasing dimensionality of the model increased correlation with the recruit slope. Among a given hydraulic metric (i.e., long season and 2D Graduated Floodplain; Figure 8b), whether the duration was summarized by the mean flow of the peak event or the maximum flow at a given duration affects correlation with the fish population metric. Maximum flows and increasing durations showed better correlation and therefore may be most robust relative to larval RGSM recruitment.

4 | DISCUSSION

For this study, a multimethod approach was used to evaluate correlation between different characterizations of spring runoff and larval minnow response. FA and Pearson correlations were applied to identify the independence of hydrologic and hydraulic metrics from each other and their correlation with fish population. These determine

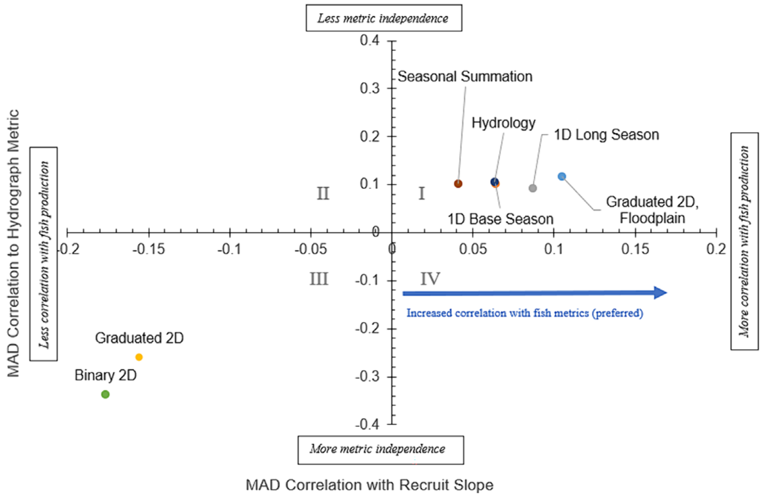

FIGURE 6 Centroids of the parameter results are plotted with absolute deviation from the mean (MAD). The origin is the average metric independence (y-axis) and average correlation with fish production (x-axis). Items in Quadrant I correlate more with all metrics than average, and items moving right on the x-axis have increasing correlation with the fish production metric.

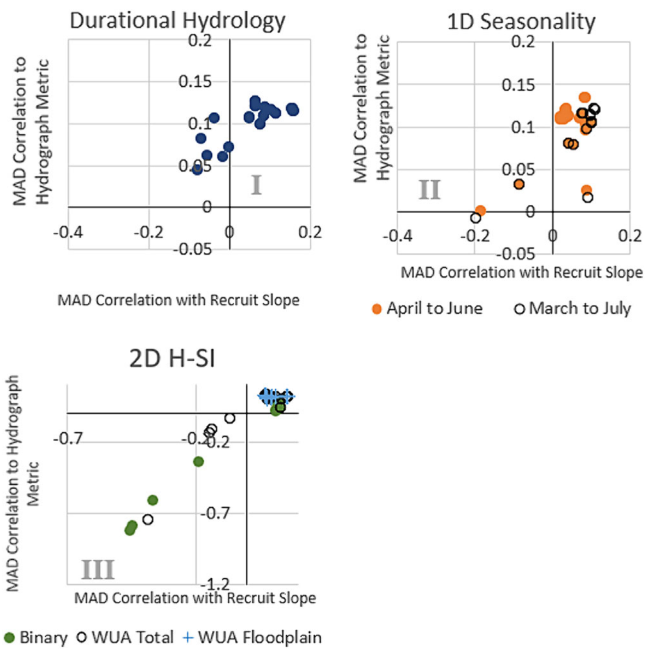

FIGURE 7 Plots for the different hydrological metric self-correlation (e.g., 1-, 7- and 14-day durations in the first plot; different definitions of long or short season in the second, 2D HSI at different durations in the third plot) and recruit slope correlation results. Quadrant number shown in grey. Demonstrates the amount of clustering and scatter for each of the metric types, which are otherwise summarized as a centroid in Figures 6 and 8. (WUA = Graduated HSI).

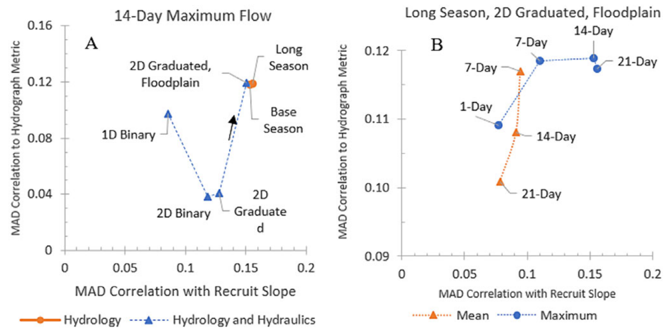

FIGURE 8 The impact of model complexity can be visualized as a migration from the mean/origin (left figure, 14-day maximum flow habitat contributions based on different eco-value curves). (a) The hydrology metrics (circle) do not have much variation from one another and are grouped tightly on the plot. The hydraulic habitat metrics show greater variance. 2D migrates to the right of 1D and the origin, indicating stronger correlation with fish metrics. The 2D Binary and 2D Graduated are more independent (moving down the y-axis) relative to the 1D Binary and 2D Graduated floodplain because these incorporate suitable hydraulics in the active channel. (b) The impacts of hydrology durations are shown. The environmental flow metric: mean of the minimums for the duration (triangles); showed little migration relative to the fish population metric via the x-axis, showing the mean gives the same level of correlation with RGSM production. The maximum of the minimums (circles) shows greater variation, with longer durations correlating more with the fish population metric.

whether these differing characterizations of hydrology were unique from one another. Many of the correlations from the FA were higher than 0.5, which demonstrates that regardless of characterization approach, spring runoff hydrology is an influential parameter to RGSM production. Streamflow is a driving factor for all the hydrograph metrics; it affects the magnitude at a particular duration and areas of inundation. However, streamflow, whether for a season or over several years, is a noisy dataset, with varying rates of increase, recession and duration.

It was found that the floodplain hydraulic habitat computed using velocity and depth results from both 1D and 2D modelling approaches was more strongly correlated with the recruit slope than total inundated area from the same simulations. Additionally, it was found that applying the larval HSI for RGSM to the active channel area did not correlate well with fish population metrics. This demonstrates that adding areas that are outside typical habitat zones to the eco-value curves may produce a less effective model.

Given the observation that hydraulic habitat area is more effective than total inundated area, at a certain threshold increasing discharge does not linearly increase fish production. Instead, higher discharges may have negative effects on fish production. This trend may be attributed to the river planform and surrounding flood control infrastructure which restricts areas of inundation. Flows are confined between levees, leading to increasing depths and velocities.

Hydraulic models confirm these field observations. If the river's morphology drives how the hydrology manifests as hydraulic conditions, then it is possible that suitable hydraulics are an important and unique component of species life cycle requirements. Metrics that correlate best with fish population and less among the other metrics may present dimensions of fish habitat that have not yet been prioritized in restoration management. 2D analysis will be more flexible as a tool for adaptive management, as it can be used directly in alternative analysis, design criteria and performance measurement. Hydrologic metrics, such as seasonal summation, are much more difficult to incorporate in a project planning process. While allocating water for instream benefits is strongly limited by resource scarcity, targeting an increase in suitable hydraulic areas may support a different habitat management approach. A suitable hydraulics approach would aim to increase areas that conform to higher scores in the HSI which has now been delineated.

From a management perspective, identifying lower streamflow conditions capable of producing sufficient nursery habitat supports opportunities to increase the frequency of an appropriate annual environmental flow. Also, identifying appropriate ways to quantify suitable hydraulics makes 1D/2D modelling 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.

5 | CONCLUSIONS

Environmental flow analyses based on hydrologic and hydraulic data sources generate a multitude of candidate statistics. Fish population trends are strongly affected by day-to-day streamflow, which may present challenges in identifying better statistical hydrologic metrics. FA provides a framework to validate the impacts of reducing noisy data into hydrologic or hydraulic habitat metrics by identifying those that correlate with species-specific processes, in this case, with species production during the spring runoff.

The methods provided in this study may be applied to other river systems and other species types. This study demonstrates how life cycle requirements for biota can be parameterized and tested as hydraulic and hydrologic habitat criteria. Increasingly complex models generate a multitude of available habitat estimations. With species monitoring data, it was possible to evaluate whether increasing complexity improves the ecological conceptual model.

Assessing the hydraulic habitat parameterization allows for further use of hydraulic modelling as an ecosystem management tool. The HSI for depth and velocity can be applied to restoration site design or site performance monitoring, to quantify suitable habitat abundance. Hydraulic modelling can be used to forecast available habitat at a range of flows. When field measurements are available, observations of habitat quality can validate hydraulic habitat model performance.

Future research includes assessing the applicability of hydraulic habitat on a restoration-site scale and implementing the reach-wide environmental flow analyses for evaluating adaptive management alternatives. This approach may also be tested with other species in different watersheds, as species-specific processes influence the relevance of hydraulic modelling dimensionality and hydrologic discretization.

AUTHOR CONTRIBUTIONS

Aubrey Harris: Conceptualization; methodology; formal analysis; investigation; data curation; writing—original draft; writing—review and editing; visualization. **Michael Porter:** Conceptualization; methodology; validation; formal analysis; data curation; writing—review and editing. **S. Kyle McKay:** Conceptualization; writing—review and editing; project administration; funding acquisition. **Anjali Mulchandani:** Writing—review and editing; supervision. **Mark Stone:** Writing—review and editing; supervision; project administration.

ACKNOWLEDGEMENTS

This work is an expansion of analysis to be published as an ERDC Technical Report with Jonathan AuBuchon as a co-author. This study was funded in part by the U.S. Army Corps of Engineers' Engineer Research and Development Center's Ecosystem Management and Restoration Research Program under grant number SON-ENV-1227, 'Comparison of ecological model outputs:' and the Engineer Research and Development Center's Aquatic Nuisance Species Research Program, 'Next Generation Ecological Modeling'. Ongoing work by the Middle Rio Grande Endangered Species Collaborative Program, including data collection and formulation of conceptual ecological models, was critical in supporting this analytical framework. Data for hydraulic models were provided by US Bureau of Reclamation. Fish population monitoring by American Southwest Ichthyological Researchers was funded by the U.S. Bureau of Reclamation and the Middle Rio Grande Endangered Species Collaborative Program. Conversations with Eric Gonzales and Jennifer Bachus (USBR Albuquerque office) and Richard Valdez (SWCA) was a great help in defining the ecological model as it relates to hydrology and physical habitat. Dr John Hickey provided guidance on use of HEC-EFM for environmental flows analysis.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Aubrey Harris https://orcid.org/0000-0003-1228-4453

REFERENCES

Bachus, J., & Gonzales, E. (2017). *Technical note—Habitat targets for BDA realignment pilot modeling analysis*. *U.S.* Bureau of Reclamation, Albuquerque Area Office, Environment and Lands Division. 3 p.

Benjankar, R., Tonina, D., & McKean, J. (2015). One-dimensional and two-dimensional hydrodynamic modeling derived flow properties: Impacts on aquatic habitat quality predictions. *Earth Surface Processes and Landforms*, *40*(3), 340–356. https://doi.org/10.1002/esp.3637

Berthot, L., St-Hilaire, A., Caissie, D., El-Jabi, N., Kirby, J., & Ouellet-Proulx, S. (2021). The use of wetted perimeter as habitat proxy to assess environmental flows in Southern Quebec Rivers (Canada). *Ecological Indicators*, *132*, 108283. https://doi.org/10.1016/j.ecolind.2021.108283

Bestgen, K. R., & Platania, S. P. (1991). Status and conservation of the Rio Grande silvery minnow. *Hybognathus amarus*. *The Southwestern Naturalist*, *36*(2), 225. https://doi.org/10.2307/3671925

Bonar, S., Hubert, W., & Willis, D. (2009). *Standard methods for sampling North American freshwater fishes*. American Fisheries Society.

Cox, G. M., Gibbons, J. M., Wood, A. T. A., Craigon, J., Ramsden, S. J., & Crout, N. M. J. (2006). Towards the systematic simplification of mechanistic models. *Ecological Modelling*, *198*(1–2), 240–246. https://doi.org/10.1016/j.ecolmodel.2006.04.016

Dudley, R., Platania, S., & White, G. (2020). Rio Grande silvery minnow population monitoring during 2019. In *Report to the US Department of the Interior*. Bureau of Reclamation. Report and supporting data available at. Retrieved from. http://apps.usgs.gov/MRGESCP/data/

Dudley, R., Robbins, T., Platania, S., & White, G. (2020). Rio Grande silvery minnow reproductive monitoring during 2020. In *Report to the US Department of the Interior*. Bureau of Reclamation. Report available at. Retrieved from. http://apps.usgs.gov/MRGESCP/data/

Dudley, R. K., & Platania, S. P. (2007). Flow regulation and fragmentation imperil pelagic-spawning riverine fishes. *Ecological Applications*, *17*(7), 2074–2086. https://doi.org/10.1890/06-1252.1

Fluder, J., Porter, M. D., & McAlpine, B. (2007). Analyzing floodplain and aquatic nursery habitat of the Rio Grande silvery minnow at different hydrologic flows. In *Third international symposium GIS/spatial analyses in fishery and aquatic sciences*, 2005 *(August 22–26), Shanghai, CN* (pp. 387–398). Fishery-Aquatic GIS Research Group.

Gonzales, E. J., Tave, D., & Haggerty, G. M. (2014). Endangered Rio Grande silvery minnow use constructed floodplain habitat. *Ecohydrology*, *7*(4), 1087–1093. https://doi.org/10.1002/eco.1438

Guy, C., & Brown, M. (2007). *Analysis and interpretation of freshwater fisheries data*. American Fisheries Society. https://doi.org/10.47886/9781888569773

Hink, V., & Ohmart, R. (1984). *Middle Rio Grande biological survey*. *Developed for USACE*, Contract No. DACW47-81-C-0015.

Larsen, L. G., Eppinga, M. B., Passalacqua, P., Getz, W. M., Rose, K. A., & Liang, M. (2016). Appropriate complexity landscape modeling. *Earth-Science Reviews*, *160*, 111–130. https://doi.org/10.1016/j.earscirev.2016.06.016

Masarei, M. I., Erickson, T. E., Merritt, D. J., Hobbs, R. J., & Guzzomi, A. L. (2021). Engineering restoration for the future. *Ecological Engineering*, *159*, 106103. https://doi.org/10.1016/j.ecoleng.2020.106103

Medley, C., & Shirey, P. (2013). Review and reinterpretation of Rio Grande silvery minnow reproductive ecology using egg biology, life history, hydrology, and geomorphology information. *Ecohydrology*, *6*(3), 491–505.

Milhous, R., & Waddle, T. (2012). *Physical habitat simulation (PHABSIM) software for windows*. United States Geological Survey Fort Collins Science Center.

Mortensen, J., Dudley, R., Platania, S., & Turner, T. (2019). *Rio Grande silvery minnow habitat synthesis*. American Southwest Ichthyological Researchers.

Olden, J. D., & Poff, N. L. (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications*, *19*(2), 101–121. https://doi.org/10.1002/rra.700

Pease, A. A., Justine Davis, J., Edwards, M. S., & Turner, T. F. (2006). Habitat and resource use by larval and juvenile fishes in an arid-land river (Rio Grande, New Mexico). *Freshwater Biology*, *51*(3), 475–486. https://doi.org/10.1111/j.1365-2427.2005.01506.x

Pisaturo, G. R., Folegot, S., Menapace, A., & Righetti, M. (2021). Modelling fish habitat influenced by sediment flushing operations from an Alpine reservoir. *Ecological Engineering*, *173*, 106439. https://doi.org/10.1016/j.ecoleng.2021.106439

Poff, N. L. (1997). Landscape filters and species traits: Towards mechanistic understanding and prediction in stream ecology. *Journal of the North American Benthological Society*, *16*(2), 391–409. https://doi.org/10.2307/1468026

Porter, M., & Massong, T. (2004). *Progress report—Contributions to delisting Rio Grande silvery minnow: Egg habitat identification*. US Army of Engineers. Albuquerque, NM.

Remshardt, W., Smith, J., & Hoagstrom, C. (2003). *Fishes of the main stem Rio Grande; Bernalillo to Fort Craig, New Mexico*. June 1999 *through June 2001* [Final report]. Prepared for US Army Corps of Engineers and City of Albuquerque.

Richter, B., Baumgartner, J., Wigington, R., & Braun, D. (1997). How much water does a river need? *Freshwater Biology*, *37*(1), 231–249. https://doi.org/10.1046/j.1365-2427.1997.00153.x

SWCA. (2019). Fish community monitoring in the Middle Rio Grande in the San Acacia Reach. Prepared for NM Interstate Stream Commission [unpublished].

Tharme, R. E. (2003). A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications*, *19*(5–6), 397–441. https://doi.org/10.1002/rra.736

Valdez, R. A., Haggerty, G. M., Richard, K., & Klobucar, D. (2019). Managed spring runoff to improve nursery floodplain habitat for endangered Rio Grande silvery minnow. *Ecohydrology*, *12*(7), 1–18. https://doi.org/10.1002/eco.2134

Valdez, R. A., Zipper, S. A., Kline, S. J., & Haggerty, G. M. (2021). Use of restored floodplains by fishes of the Middle Rio Grande, New Mexico, USA. *Ecohydrology*, *14*(2), 1–19. https://doi.org/10.1002/eco.2262

Widmer, A. M., Fluder, J. J., Kehmeier, J. W., Medley, C. N., & Valdez, R. A. (2012). Drift and retention of pelagic spawning minnow eggs in a regulated river. *River Research and Applications*, *28*(2), 192–203. https://doi.org/10.1002/rra.1454

How to cite this article: Harris, A., Porter, M., McKay, S. K., Mulchandani, A., & Stone, M. (2024). Hydraulic analysis for assessing environmental flow selection and ecological model formulation. *Ecohydrology*, e2681. https://doi.org/10.1002/eco.2681