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RESEARCH ARTICLE

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Impacts of hydrologic and geomorphic alteration to the availability of shallow, low-velocity habitats in an intensively managed arid-land river

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Abstract

This study seeks better understanding of linkages between channel morphology, streamflow, and aquatic habitat for the effective rehabilitation of imperiled species in rivers subjected to intensive water resource management. We focused on the variability of shallow, low-velocity (SLV) habitat over 50 years for a 56 km reach of the Rio Grande of central New Mexico (Middle Rio Grande). Hydraulic models used topographic data obtained through long-term systematic monitoring between 1962 and 2012 to derive relationships between discharge and SLV habitat availability. We developed a temporally integrated habitat metric (TIHM) to facilitate quantitative comparisons of SLV habitat availability over seasonal hydrologic periods (base flow, spring runoff, and summer low flow) for selected years representative of contemporary discharge variations. Results showed that SLV habitat availability, as captured by TIHM values, decreased on average by 83% over the study period (1962–2012), corresponding to completion of the Cochiti Dam (1973), which profoundly altered flow and sediment regimes. Resulting channel incision and floodplain disconnection, caused shifts in discharge-habitat relationships whereby increases in SLV habitat availability in the modern channel were strictly maximized at the upper range of modeled discharges (200 $m^3 s^{-1}$)—discharges greater than 100 $m^3 s^{-1}$ are infrequent today. Ecological implications of losses to SLV habitat availability include recovery of the federally endangered Rio Grande Silvery Minnow *Hybognathus amarus*.

KEYWORDS
fish conservation, geomorphology, habitat availability, hydraulic modeling, long-term monitoring, river restoration

1 | INTRODUCTION

Variation in the quantity and distribution of riverine habitats over time drives ecosystem processes and influences the abundance and distribution of aquatic organisms. Decreases to the distribution and quantity (i.e., availability) of aquatic habitats needed by certain species can reduce their distribution and abundance over time, potentially causing imperilment, extirpation, or extinction. Exploitation of river systems for human uses has caused widespread changes to the timing and availability of various habitat conditions that have subsequently contributed to declines in aquatic and riparian biodiversity (Dudgeon et al., 2006; Karr et al., 1985; Nilsson et al., 2005; Ward et al., 1999). Understanding how specific habitat conditions change over time in response to anthropogenic impacts (e.g., flow control and channel modifications) is needed to adequately inform and conduct conservation of river ecosystems.

The availability of physical habitat characteristics (i.e., hydraulic parameters) is strongly affected by channel modifications and changes to water and land use. In large, intensively managed rivers, channel morphology is often altered for flood control, water distribution (i.e., irrigation), and navigation among other uses—these modifications are typically associated with changes to the hydraulic environment, such as the loss of shallow, low-velocity habitats (Jacobson & Galat, 2006). Shallow, low-velocity habitats are particularly important to the recruitment of larval and juvenile fishes (Freeman et al., 2001; Love et al., 2016; Pease et al., 2006; Scheidegger & Bain, 1995; Schiemer et al., 2002) and have been associated with the occurrence of imperiled species (Dudley et al., 2024). Additionally, discharge patterns are commonly affected by changes to water and land use over time and flow alterations can further impact the distribution and connectivity of shallow, low-velocity habitats (Bowen et al., 1998; Carlisle et al., 2010; Freeman et al., 2001; Stone et al., 2017). Stream evolution trajectories of alluvial channels vary across a broad range of physiographic settings, and therefore, research is needed to support a better understanding of how changes to streamflow and river-floodplain morphology interact to affect the availability of ecologically important hydraulic conditions in intensively managed rivers (Cluer & Thorne, 2013).

Hydraulic modeling has proven useful in evaluating aquatic habitat characteristics in relation to hydrology, sediment transport, channel morphology, and river management. Determining relationships between streamflow and habitat suitability via hydraulic modeling has been a central component of biological assessments (i.e., Instream Incremental Flow Methodology [IFIM]; Bovee, 1982), and remains a tractable, commonly used approach to investigate habitat dynamics (Nestler et al., 2019; Reiser & Hilgert, 2018). Studies have also used hydraulic models to determine the effects of flow regulation on habitat availability and floodplain connectivity (Bowen et al., 2003; Stone et al., 2017), assess changes between historical and contemporary channel configurations (Erwin et al., 2017; Jacobson & Galat, 2006), and identify tradeoffs between flow and habitat restoration in altered rivers (Anim et al., 2019). Such studies help understand and assess the implications of long-standing hydrologic and geomorphic alterations on aquatic and riparian biota.

In large river systems, studies investigating differences in habitat availability between historical and contemporary conditions are not particularly common and have often been limited to discrete and relatively short study reaches (e.g., <10 river km), hindering comparisons across watersheds and the broad spectrum of geomorphic conditions and human impacts. Furthermore, long-term monitoring of channel morphology is often absent from historical records, limiting inferences regarding the timing, magnitude, and spatial extent of habitat losses. Characterizing changes to habitat availability over time can be useful for river conservation efforts by estimating the approximate scale of habitat loss, determining approximate time frames and rates of geomorphic change, and identifying the dominant factors contributing to habitat loss and degradation. Insights gained from analyses of rivers with long-term, systematic monitoring programs can also be used to evaluate past, present, and future impacts on similar water courses that lack historical records. Restoring ecological integrity in large, intensively managed rivers will require understanding how habitat characteristics, particularly those needed by sensitive species, are affected by anthropogenic impacts.

This study seeks to improve understanding of how changes to hydrology and geomorphology interact to determine the availability of specific hydraulic characteristics at the reach-scale (e.g., >50 river km). We investigated how the availability of shallow, low-velocity (SLV) habitat was affected by channel modifications and changes to water and land use in the intensively managed Rio Grande of central New Mexico (Middle Rio Grande) over 50 years. The study period spans notable hydrologic, geomorphic, and ecological impacts including flood and sediment control (1973), the decline and listing of endemic species under the Endangered Species Act (1990s), and proliferation of nonnative riparian vegetation (post-2000). The objectives of this investigation were to: (1) derive quantitative relationships between discharge and SLV habitat availability across the range of regulated, contemporary discharges for a 50-year period of systematic channel monitoring (1962–2012); (2) quantify and compare SLV habitat availability across seasonal hydrologic periods (i.e., base flow, spring runoff, and summer low flows) for the range of regulated discharges and channel configurations (i.e., historical versus contemporary); and (3) evaluate changes to SLV habitat availability over time in relation to land and water use impacts. Finally, we discuss the ecological implications of these impacts to better inform management approaches that effectively rehabilitate habitats needed to sustain these ecosystems and sensitive aquatic species.

2 | MATERIALS AND METHODS

2.1 | Study area

The Middle Rio Grande is an alluvial river located in central New Mexico, a state of the American Southwest (USA). This reach is bounded upstream by Cochiti Dam and downstream by Elephant Butte Reservoir, about 290 river km. Historically, the Middle Rio Grande was wide and braided with a large floodplain, which mediated variations in streamflow, providing a diversity of aquatic and riparian habitats across the natural flow regime (Medley & Shirey, 2013; Scurlock, 1998). Over the past century, this reach was heavily modified for agriculture, flood control, and urban development; the contemporary channel is largely single-threaded and relatively narrow with channel incision prevalent in several locations (Massong et al., 2006; Richard & Julien, 2003; Swanson et al., 2011). These changes have largely reduced the complexity and availability of aquatic habitats, particularly seasonal connectivity to the floodplain and reduced diversity of hydraulic conditions in the main channel across discharges (Medley & Shirey, 2013; Molles et al., 1998). The flow regime is characterized by peak flows during spring snowmelt runoff (April–June) from mountainous headwaters, low flows during summer (July–September), and relatively stable flows during autumn and winter (October–March), however, interannual and seasonal

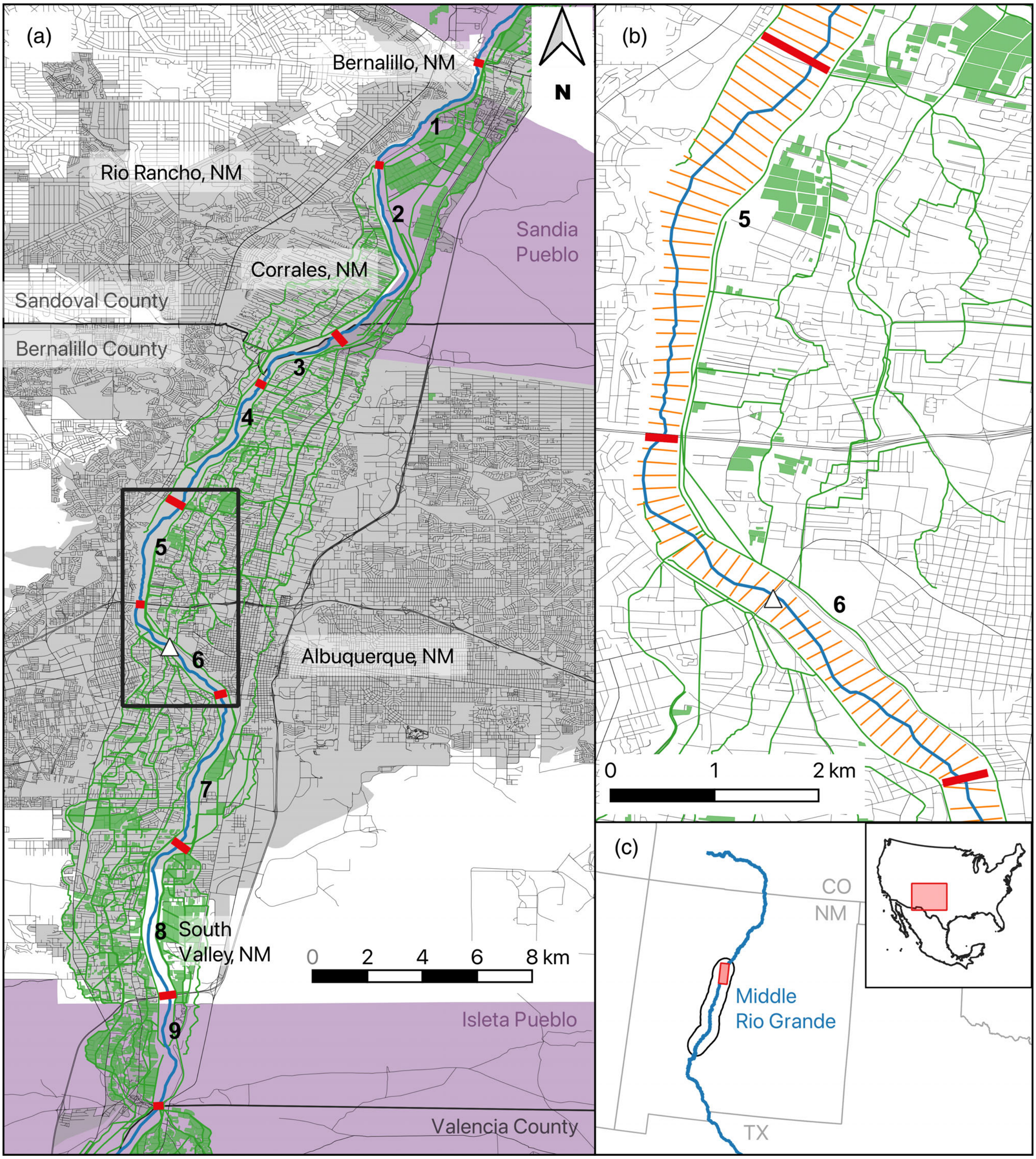

FIGURE 1 (a) Study reach of the Middle Rio Grande including subreach boundaries 1–9 (red), U.S. Geological Survey gaging station No. 08330000 (triangle), irrigation infrastructure and agricultural land (green), urban areas (gray), and tribal lands (purple); (b) two subreaches (5 and 6) selected to show cross-section locations (orange) and spacing (about 150 m); and (c) location of the study reach (red box) and Middle Rio Grande (outline) in the state of New Mexico (USA). [Color figure can be viewed at wileyonlinelibrary.com]

variation in flow conditions is often high. Cochiti Dam regulates peak flows year-round (i.e., flood control) with a maximum discharge of 198 $m^3\ s^{-1}$ (USBR, 2015), and irrigation withdrawals from the Middle Rio Grande typically occur March–October. The Middle Rio Grande contains the extant wild population of the federally endangered Rio Grande Silvery Minnow *Hybognathus amarus* (USFWS, 2003).

This study specifically focused on the reach of the Middle Rio Grande between Bernalillo, NM (US HWY550 bridge crossing) and

Subreach	Boundaries (upstream–downstream)	Cross-sections	Length, km (mi)
1	US550 bridge—siphon crossing	41	6.4 (4.0)
2	–Stormwater outfall	59	9.0 (5.6)
3	–Diversion structure	24	3.9 (2.4)
4	–Montaño bridge	41	6.4 (4.0)
5	–Interstate 40 bridge	31	4.8 (3.0)
6	–Bridge Boulevard bridge	34	5.6 (3.5)
7	–Stormwater outfall	47	7.2 (4.5)
8	–Interstate 25 bridge	48	7.2 (4.5)
9	–Isleta Diversion Dam	34	5.6 (3.5)
Total	–	359	56.1 (35.0)

TABLE 1 Subreach boundaries and selected characteristics for the study reach of the Middle Rio Grande, NM.

the Isleta Diversion Dam (56.1 river km [35.0 mi]; Figure 1). The river corridor is characterized by mixed agricultural and urban land use, including the Albuquerque Metropolitan Area (population ~900,000) and lands of Sandia and Isleta Pueblos. Surface water diversions, irrigation channels, riverside drains, and spoil bank levees were constructed ca. 1930–1950 to increase arable lands, improve soil drainage (i.e., lower water table), and provide flood protection. Sediment control structures, jetty-jacks, were installed at a relatively high density in this reach ca. 1950–1960 to stabilize and aggrade the banks for flood and infrastructure protection. Cochiti Dam (1973) is located about 45 river km upstream of the study reach and was established to provide flood and sediment control for the Middle Rio Grande valley. A low-head concrete diversion dam (i.e., Angostura Diversion Dam) is located approximately 10 river km upstream of the study reach. Confluence with the Jemez River, the largest tributary between Cochiti Dam and the study area, is located approximately 7.5 river km upstream. No major tributaries occur within the study reach, however, irrigation returns and storm water outfalls are present. The study reach was divided into nine subreaches (range 3.9–9.0 river km) for analytical purposes; infrastructure locations (e.g., bridge crossings, storm water outfalls, and diversion dams) were used to delineate subreach boundaries (Table 1).

2.2 | Data collection

2.2.1 | Channel geometry (1962–2012)

The U.S. Bureau of Reclamation (USBR) has systematically collected topographical data along the length of the Middle Rio Grande since 1962. A series of established transects, or cross-sections, are spaced at approximately 150 m (500 ft) intervals normal to the predominant flow; the study area contained 359 cross-sections. River-wide topographical surveys occurred every 10 years since 1962 except for 1982 (i.e., 1962, 1972, 1992, 2002, and 2012). USBR developed channel geometries (i.e., channel-floodplain elevations across transects) for each survey period ($n = 5$). For channel geometries 1962–2002 ($n = 4$), topographical data were obtained by aerial survey and photogrammetric techniques were used to estimate channel-floodplain elevations at established cross-sections. For the 2012 geometry ($n = 1$), topographical data were obtained by LiDAR. To estimate channel elevations below the water surface at the time of the survey, an idealized trapezoidal cross-section was estimated through an iterative process using a hydraulic model (HEC-RAS) and the approximate discharge during the survey (Varyu, 2013). Hence, channel geometries were acknowledged to be a simplified representation of river topography yet were assumed to capture key changes in channel and floodplain morphology over time for the spatial scale of analysis (>55 river km).

2.2.2 | Discharge

Discharge records for two year periods, 2003–2005 and 2016–2018, were selected to variability in contemporary flow conditions (i.e., post-2000). Periods were defined by water year (i.e., 1 October–30 September). Years were selected using mean annual and peak discharge metrics to capture the broad range of seasonal and annual flow conditions that characterize this river reach (Table 2). To illustrate high interannual variability, three-year periods were selected that contained each of the following qualitative flow scenarios: low flow (2003, 2018), moderate flow (2004, 2016), and high flow (2005, 2017). Mean daily discharge for the study area were obtained from the U.S. Geological Survey (gage no. 08330000 Rio Grande at Albuquerque, NM). For analytical purposes, discharge was assumed to be constant throughout the reach.

2.3 | Methods

2.3.1 | Hydraulic modeling

Hydraulic modeling was performed using the Hydrologic Engineering Center River Analysis System (HEC-RAS 6.1; USACE, 2021). Discharges were modeled every 14.2 $m^3\ s^{-1}$ (500 $ft^3\ s^{-1}$) up to 142 $m^3\ s^{-1}$ (5000 $ft^3\ s^{-1}$) with peak discharges of 170 $m^3\ s^{-1}$ and 227 $m^3\ s^{-1}$ (6000 and 8000 $ft^3\ s^{-1}$). Normal depth boundary conditions were considered, slopes ranged 0.0007–0.0009 m/m, and Manning's roughness coefficient (n) was 0.025 in the main channel and 0.100 for overbank areas. These values were precalibrated to measured discharges and the values were kept constant over time for the purpose of comparisons across years. Lateral distributions of flow depth and velocity

TABLE 2 Selected flow metrics for hydrologic periods 2003–2005 and 2016–2018.

Water Year	Flow Scenario	Annual	Oct–Mar (base flow)			Apr–Jun (spring runoff)			Jul–Sep (low flow)		
		Mean ± SD	Mean ± SD	Min	$d<5$ m^3 s^{-1}	Mean ± SD	Max	$d>60$ m^3 s^{-1}	Mean ± SD	Min	$d<5$ m^3 s^{-1}
2003	Low	12.1 ± 4.7	11.1 ± 3.0	3.3	11	16.8 ± 4.7	35.7	0	9.4 ± 3.2	3.3	17
2004	Moderate	19.4 ± 17.9	14.8 ± 8.0	3.3	23	40.3 ± 17.9	88.3	20	7.8 ± 4.3	2.9	30
2005	High	44.7 ± 51.2	19.8 ± 8.0	4.0	16	123.2 ± 51.2	184.3	79	16.6 ± 11.5	7.7	0
2016	Moderate	26.6 ± 19.3	24.0 ± 12.4	4.7	6	44.7 ± 25.9	102.8	26	14.0 ± 4.8	6.3	0
2017	High	37.0 ± 38.0	21.8 ± 19.2	3.1	25	90.8 ± 33.8	151.8	76	13.9 ± 4.9	8.6	0
2018	Low	17.0 ± 10.6	22.3 ± 12.1	9.6	0	13.2 ± 2.1	20.6	0	10.2 ± 6.4	2.6	23

Note: Discharge units (mean, maximum, and minimum values) are m^3 s^{-1} and *d* represents the number of days meeting the specified flow thresholds. Mean daily discharge obtained from USGS 08330000 Rio Grande at Albuquerque, NM.

were estimated by subdividing cross-sections—25 subsections were assigned to the main channel and 10 subsections for each overbank (45 total); mean depth and velocity were output for each subsection (Figure 2). Ineffective flow areas and computational levees were implemented locally on a case-by-case basis (i.e., by cross-section) to correct for the inaccurate distribution of water into disconnected low-lying areas as modeled discharges were increased.

2.3.2 | Discharge-habitat relationships

Depth and velocity criteria were selected to classify shallow, low-velocity (SLV) habitat from hydraulic modeling outputs. SLV habitat was defined as 1–50 cm deep and 0–30 cm/s velocity. These habitat criteria were selected to represent habitats that could be occupied by small-bodied fishes, such as the Rio Grande Silvery Minnow, given biophysical performance of this species and its occurrence in the wild (Bestgen et al., 2010; Dudley et al., 2024). These hydraulic criteria were previously selected by an expert panel for habitat modeling of juvenile Rio Grande Silvery Minnow (Bovee et al., 2008), and are comparable to those used in recent hydraulic modeling studies to classify SLV habitat in other rivers (Anim et al., 2019; Bowen et al., 2003).

Hydraulic modeling outputs and SLV habitat criteria were used to derive quantitative relationships between discharge and SLV habitat availability for the range of modeled discharges (0–227 m^3 s^{-1} [0–8000 ft^3 s^{-1}]). To calculate SLV habitat availability, the cumulative width meeting habitat criteria at each cross-section was summed, multiplied by cross-section spacing, and normalized by reach length for all modeled discharges as shown in Equation (1):

$$H_Q = \sum_{i=1}^{n} X_i \times \frac{s}{L} \tag{1}$$

where H_Q is SLV habitat availability at discharge Q, X is the total channel width meeting habitat criteria at a cross-section, n is the number of cross-sections (359), s is cross-section spacing (150 m), and L is reach length. Conceptually, SLV habitat availability (ha km^{-1}) represents an equivalent width of available habitat for the reach (e.g., 1.0 ha km^{-1} = 10 m).

Variability in discharge-habitat relationships was expressed by the 10th and 90th percentiles of subreach modeling outputs ($n = 9$) at each modeled discharge. Habitat availability values between modeled discharges were assumed to be linear (e.g., between 14.2 and 28.3 m^3 s^{-1} [500 and 1000 ft^3 s^{-1}] as shown in Equation (3)); habitat availability was assumed to be zero when discharge equals zero.

2.3.3 | Temporally integrated habitat metric

A temporally integrated habitat metric (TIHM) was developed to quantify SLV habitat availability over time for specified hydrologic periods. The following hydrologic periods were selected to represent

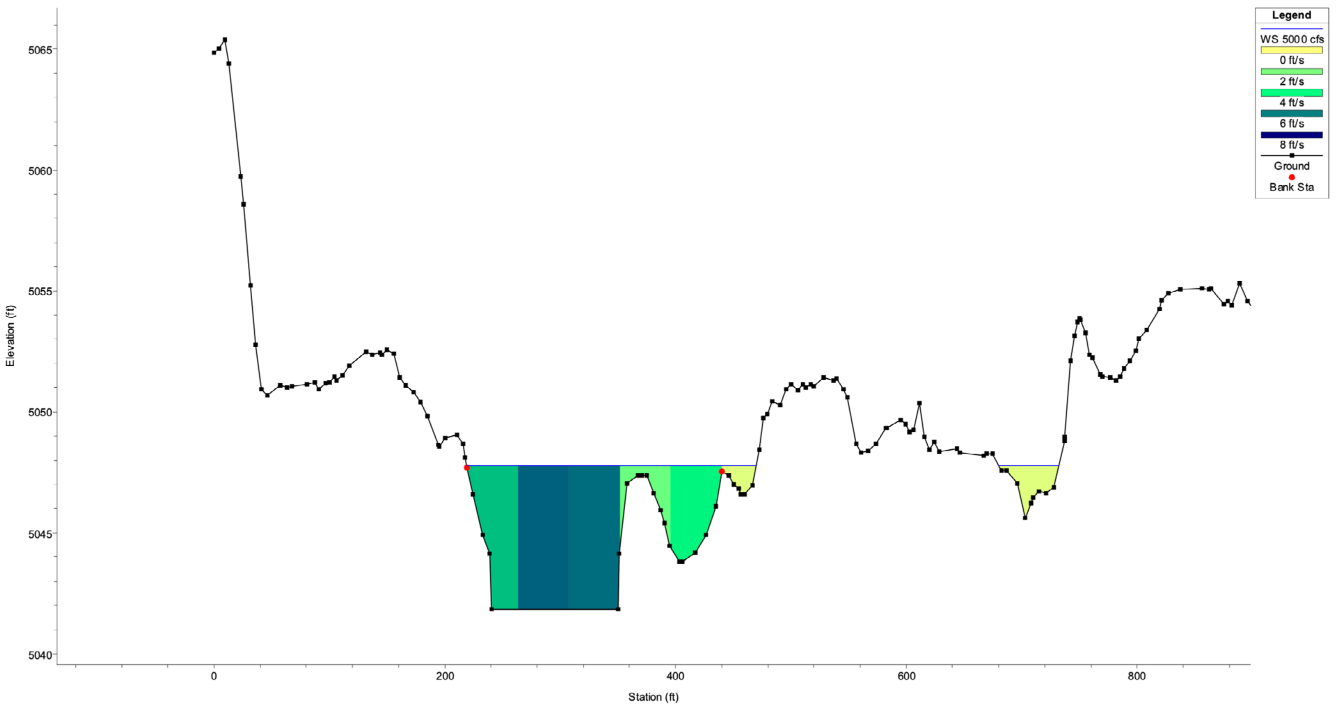

FIGURE 2 Example HEC-RAS output showing predicted lateral depth and velocity distributions for a sample cross-section at 142 $m^3\ s^{-1}$ (5000 $ft^3\ s^{-1}$). Velocity is represented by a color gradient with increasing velocity from lighter to darker. U.S. Customary units are shown due to software conventions. [Color figure can be viewed at wileyonlinelibrary.com]

seasonal streamflow patterns: 1 April–30 June (spring runoff), 1 July–30 September (summer low flow), and 1 October–31 March (base flow). This approach provided a basis to compare variations in SLV habitat availability attributed strictly to temporal changes in channel morphology.

Conceptually, TIHM was defined as the integral of habitat availability over time for each seasonal period as shown in Equation (2):

$$\mathrm{TIHM} = \int_{t0}^{t1} H(t)dt \tag{2}$$

where $H(t)$ is habitat availability as a function of time, t_0 is the time at the beginning of the seasonal period (e.g., April 1), t_1 is the time at the end of the seasonal period (e.g., June 30), and dt is differential time.

Habitat availability (ha km^{-1}) was estimated at a daily time step using the derived discharge-habitat relationships and mean daily discharge. Mean daily habitat availability (H_{Qt}) was calculated by linear interpolation of discharge-habitat curves between modeled discharges (e.g., between 14.2 and 28.3 $m^3\ s^{-1}$) as shown in Equation (3):

$$H(t) \cong H_{Q_t} = mQ_t + b \tag{3}$$

where m is the slope between modeled discharges, Q_t is the mean daily discharge at time t during the seasonal hydrologic period, and b is the intercept of the line between modeled discharges.

Functionally, the TIHM was approximated by a finite sum of mean daily habitat availability values (i.e., Riemann sum) over each hydrologic period as shown in Equation (4):

$$\mathrm{TIHM} \cong \sum_{T=t0}^{t1} H_{Q_t} \times \Delta T \tag{4}$$

where $\Delta T = 1$ day. TIHM values are reported as 10^2 ha d km^{-1}. TIHM values represent an index of habitat availability and are not meant to be a precise quantifier of habitat (Reiser & Hilgert, 2018). The metric is nevertheless useful for comparative purposes.

TIHM values were used to evaluate the interactions of hydrology and geomorphic change over time on habitat availability. Because the influence of discharge on habitat availability metrics was expected to be high, hydrologic conditions were isolated to assess the relative influence of geomorphic changes on seasonal habitat metrics over time. Discharge records for two periods, 2003–2005 and 2016–2018, were used to represent variability in seasonal and annual streamflow (Section 2.2.2). These data served as inputs for each survey period (i.e., 1962, 1972, 1992, 2002, and 2012) to facilitate hydrologically equivalent comparisons of SLV habitat availability, as captured by the TIHM, over a 50-year period.

3 | RESULTS

3.1 | Channel morphology 1962–2012

Channel cross-sections and aerial imagery indicated substantial changes to channel morphology over time (Figure 3). Temporal trends were generally characterized by decreased width, increased depth, and decreased slope, however, the magnitude of these changes varied spatially. Upstream subreaches tended to show greater change in width and depth relative to downstream subreaches, with accretion of floodplain surfaces present in downstream subreaches. Estimated bed elevations were generally similar between 1962 and 1972 with the largest magnitude of change occurring between 1972 and 1992; bed elevations 1992–2012 were similar with relatively minor variations over time except for the upstream-most subreach, which degraded about 2 m between 1992 and 2012 (Figure 3). In 2012, bed elevations showed a transition from degradation to aggradation occurring around 32 river km (20 mi) from the upstream boundary and continuing for the remainder of the study reach.

3.2 | Discharge-habitat relationships 1962–2012

Discharge-habitat relationships were estimated for each channel geometry (1962, 1972, 1992, 2002, and 2012) for discharges ranging 0–212.4 $m^3 s^{-1}$. Trends in discharge-habitat relationships were similar for channel geometries 1962 and 1972 with habitat availability increasing with increasing flow up to about 125 $m^3 s^{-1}$ (Figure 4). For 1962 and 1972, SLV habitat availability peaked at 24.3 ha km^{-1} at discharges of 113 $m^3 s^{-1}$ (4000 $ft^3 s^{-1}$) and 142 $m^3 s^{-1}$ (5000 $ft^3 s^{-1}$), respectively. Trends in discharge-habitat relationships were also similar for channel geometries 1992, 2002, and 2012 with relatively lower magnitude increases in SLV habitat availability with increasing discharge across the range of modeled discharges. For 1992, 2002, and 2012, SLV habitat availability peaked at 227 $m^3 s^{-1}$ (8000 $ft^3 s^{-1}$), the highest modeled discharge, and ranged 11.6–16.9 ha km^{-1}.

Changes in SLV habitat availability over time showed distinct temporal trends. Channel geometry for 1972 showed relatively minor losses to SLV habitat availability across discharges (0–150 $m^3 s^{-1}$) from 1962. The greatest changes to SLV habitat availability were recorded between 1972 and 1992 with relatively large losses across the range of modeled discharges; the greatest loss (19.3 ha km^{-1}) occurred at 113 $m^3 s^{-1}$ (4000 $ft^3 s^{-1}$). Discharge-habitat relationships appeared relatively stable between 1992, 2002, and 2012 with some losses to SLV habitat availability recorded at high flows in 2002 (>125 $m^3 s^{-1}$) and slight increases across discharges in 2012 (0.4–2.6 ha km^{-1}).

3.3 | Selected hydrologic conditions

The selected hydrologic periods, water years 2003–2005 and 2016–2018, collectively contained a broad range of annual and seasonal flow conditions representative of contemporary hydrology for the study reach (Table 2). Seasonal periods corresponding to spring runoff (1 April–30 June) were the most variable across selected water years as represented by mean and peak flow metrics; mean and low-flow metrics for base flow (1 October–31 March) were less variable, with summer low flow (1 July–30 September) showing the least variability across selected water years. Metrics corresponding to the duration and magnitude of flow conditions were consistent with qualitative flow descriptors (i.e., low, moderate, and high flow) for annual and spring runoff periods but varied for base flow and low-flow periods across selected years; mean seasonal discharges were consistent with flow descriptors when averaged by flow scenario. On average, mean discharge during high-flow years was 56% and 95% greater than moderate and low-flows years, respectively. For spring runoff periods, high-flow years were 86% and 151% greater than moderate and low-flow years, respectively–for base-flow periods, high-flow years were on average 7% and 22% greater than moderate and low-flow years, respectively–and for low-flow periods, high-flow years were on average 33% and 44% greater than moderate and low-flow years, respectively.

3.4 | Temporally integrated habitat metrics

A total of 90 TIHMs were calculated to quantify and compare habitat availability by seasonal period and channel geometry for the selected hydrologic periods, 2003–2005 and 2016–2018 (Table 3). TIHM values (10^2 ha d km^{-1}) ranged 1.12–19.9 for spring runoff (1 April–30 June), 0.81–7.45 for summer low flow (1 July–30 September), and 1.88–19.6 for base flow (1 October–31 March). TIHM values corresponding to spring runoff periods were consistent with flow scenario classifications (low, moderate, and high) but varied for summer low flow and base flow periods. TIHM values consistently showed decreases in habitat availability across flow scenarios and seasonal hydrologic periods over the study period 1962–2012 (Figure 5). On average, TIHM values decreased 83% between 1962 and 2012 across all seasonal periods and selected flow periods; percent decreases 1962–2012 were marginally lower for spring runoff periods in 2005 and 2017 (i.e., high flow years), with decreases of 73% and 79%, respectively. TIHM values were positively related to mean discharge across survey periods and seasonal periods with pronounced decreases in magnitude between 1962–1972 and 1992–2012 survey periods (Figure 6).

4 | DISCUSSION

This study used hydraulic models to quantify changes to the availability of shallow, low-velocity (SLV) habitat in the Middle Rio Grande over a 50-year period. The largest magnitude changes in SLV habitat availability occurred between 1972 and 1992, coinciding with the completion of Cochiti Dam (1973), which is located about 45 river km upstream of the study reach. The magnitude of change over time for the most recent survey periods (1992–2012) was much less pronounced. Due to the lack of intermediate survey data (i.e., between 1972 and 1992) and coarse temporal resolution of channel-floodplain measurements (i.e., 10-year intervals), the exact timing and rate of change in SLV habitat availability were not possible to determine. Nonetheless, long-term systematic surveys of the Middle Rio Grande provided a basis for assessing impacts of historical and recent

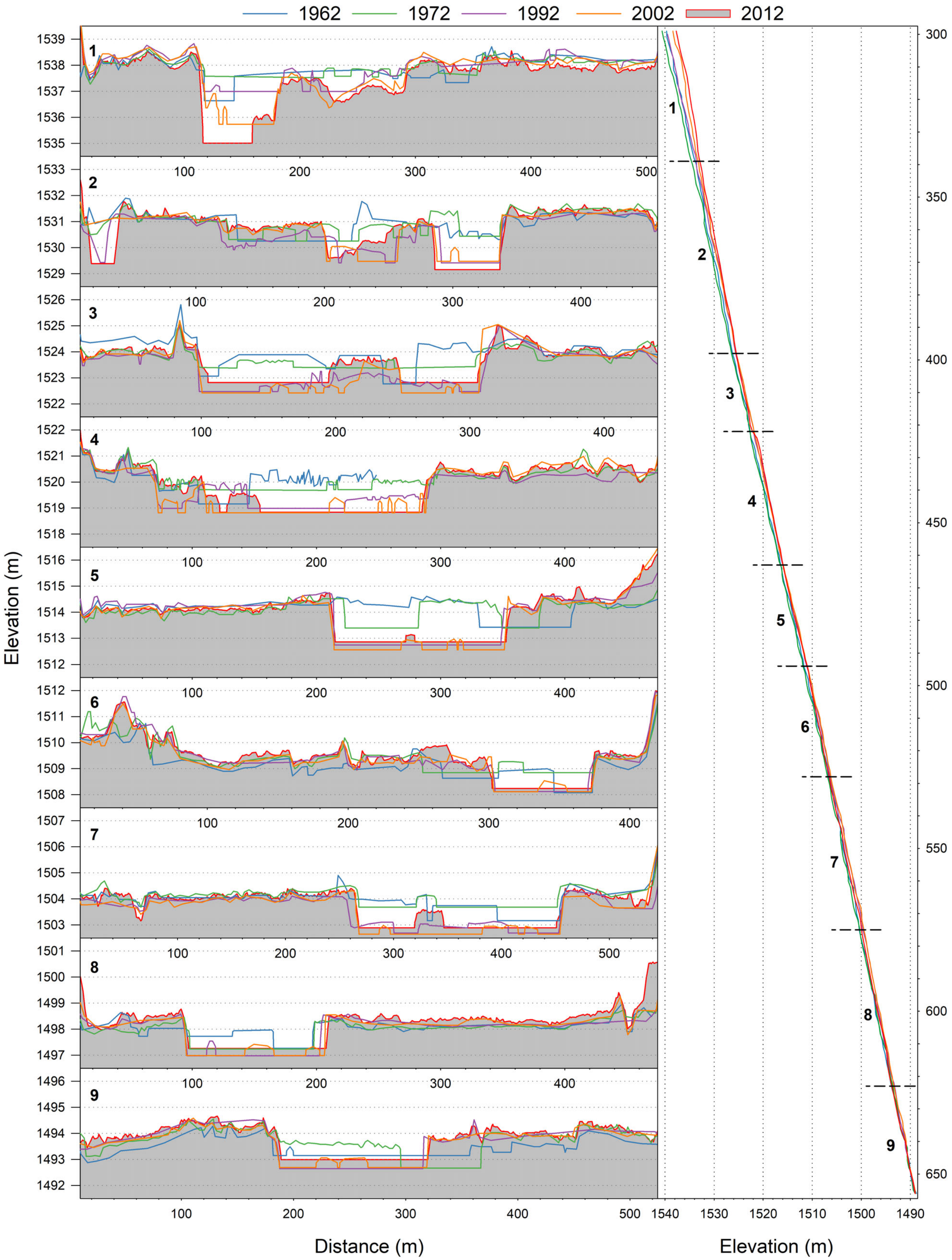

FIGURE 3 Channel-floodplain elevations at established cross-sections located near subreach midpoints (left) and longitudinal profile for the study reach (right) 1962–2012. Panels are arranged upstream to downstream from top to bottom (1–9). Solid lines represent channel-floodplain elevations 1962, 1972, 1992, and 2002; gray shaded areas represent channel-floodplain elevations in 2012. For the longitudinal profile, bed elevations were averaged across every three cross-sections. Vertical datum is NAVD 88. [Color figure can be viewed at wileyonlinelibrary.com]

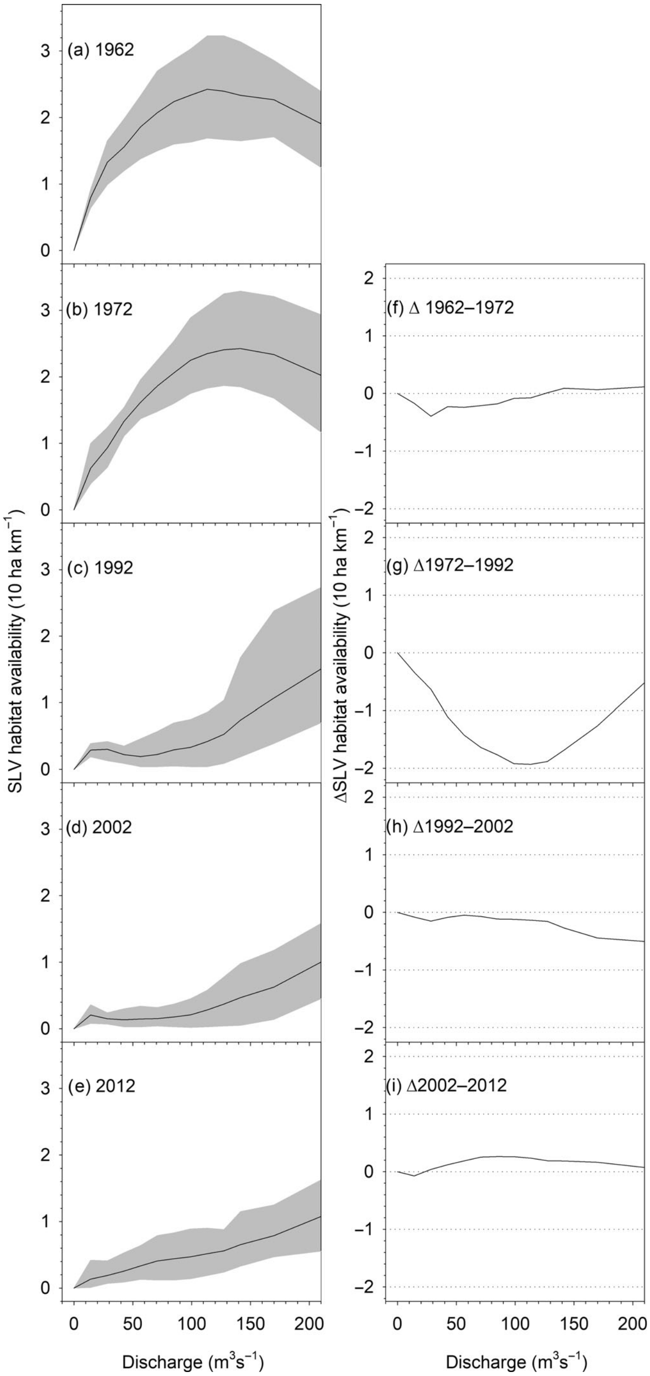

FIGURE 4 Discharge-habitat relationships derived via hydraulic modeling (left column; a–e) and change from previous survey (right column; f–i). For panels (a–e), solid lines represent mean SLV habitat availability normalized by reach length; shaded areas represent 10th–90th percentile ranges based on subreach modeling variability ($n = 9$). For panels (f–i), solid lines represent change in mean habitat availability between consecutive survey periods.

geomorphic changes that is often unavailable. Cochiti Dam, which serves as flood and sediment control for the Middle Rio Grande, initiated downstream channel adjustments that have included decreased bed elevation (i.e., degradation), channel width, and channel migration rates due to reductions in peak flows and sediment supply (Massong et al., 2006; Richard et al., 2005; Richard & Julien, 2003). It is worth noting that decreasing peak flows and engineering measures contributed to relatively high rates of channel narrowing prior to the study period (Swanson et al., 2011), and therefore, our historical reference data (i.e., 1962 and 1972) included these preceding impacts. The effects of Cochiti Dam were captured in our discharge-habitat relationships 1992–2012, which indicated reduced hydraulic diversity in the channel, increased bankfull discharge, and reduced floodplain connectivity. The cumulative impact of these changes was shown to have reduced SLV habitat availability across the range of modeled discharges, which are representative of contemporary hydrological variability (i.e., flow-regulated). The derivation of discharge-habitat relationships and use of habitat metrics (i.e., TIHM) allowed for retrospective analysis of seasonal habitat conditions in relation to morphodynamic changes over the study period (1962–2012).

The development of a TIHM facilitated quantitative comparisons of habitat availability, over a 50-year period, across a broad range of contemporary hydrologic conditions. Our results highlighted the importance of seasonal flow magnitudes on SLV habitat availability, particularly spring runoff April–June, the most variable seasonal flow period based on selected flow metrics. For our historical reference datasets (e.g., 1972), channel morphology mediated the flow regime by providing SLV habitat across a range of low to moderate flows, with strong increases in SLV habitat availability related to moderate and high spring runoff (Figure 7a,b). By comparison, contemporary channel morphology (e.g., 2002) minimally provided SLV habitat across low to moderate flows, and exceptionally high flows (e.g., 2005 spring runoff) produced only marginal increases in SLV habitat availability relative to historical reference data (Figure 7a,c). These survey periods corresponded to a shift from a relatively wide and braided planform to a largely single-threaded, incised channel (Figure 8). These changes to channel morphology when compounded over seasonal periods, resulted in up to an order of magnitude difference between habitat availability metrics (i.e., TIHM values) for the respective hydrologic periods.

Habitat metrics (TIHM) provided a framework to evaluate SLV habitat availability over ecologically relevant seasonal periods. However, these metrics were representative of only certain flow characteristics (i.e., magnitude and duration) and did not fully capture other flow characteristics that are likely important for ecological responses (e.g., rate of change, threshold effects). Likewise, abiotic factors such as water quality degradation are likely to occur in SLV habitats during summer low flow periods (i.e., elevated water temperature, low dissolved oxygen; Van Horn et al., 2022), which have been associated with fish kills in the Middle Rio Grande (Archdeacon & Reale, 2020). Some studies have implemented thresholds for modeling hydraulic and thermal parameters to incorporate these effects (Anim et al., 2019; Castelli et al., 2012); inclusion of such thresholds was beyond the scope of this study. Future studies should incorporate factors known or suspected to be ecologically relevant as feasible (e.g., bankfull discharge, water quality). Given the availability of geomorphic data for the Middle Rio Grande, our study implemented a tractable modeling approach that facilitated equivalent comparisons

TABLE 3 Temporally integrated habitat metrics (TIHM; 10^2 ha d km^{-1}) calculated by seasonal periods and channel geometries for selected water years.

Water year	Flow scenario	Channel geometry	Temporally integrated habitat metric		
			October–march	April–June	July–September
2003	Low	1962	11.22	7.95	4.81
		1972	8.82	6.04	3.76
		1992	4.07	2.50	1.75
		2002	2.90	1.65	1.25
		2012	1.88	1.27	0.81
2004	Moderate	1962	13.89	13.20	3.89
		1972	10.85	10.98	3.02
		1992	4.45	2.35	1.38
		2002	3.03	1.50	0.97
		2012	2.28	2.28	0.64
2005	High	1962	17.43	19.85	7.45
		1972	12.92	19.64	5.77
		1992	4.64	5.91	2.24
		2002	2.78	3.69	1.53
		2012	2.65	5.28	1.21
2016	Moderate	1962	19.62	14.08	6.89
		1972	15.18	11.65	5.28
		1992	4.68	2.52	2.28
		2002	2.88	1.50	1.55
		2012	3.09	2.42	1.12
2017	High	1962	17.20	19.43	6.89
		1972	13.41	18.29	5.27
		1992	4.50	3.43	2.36
		2002	2.82	2.17	1.64
		2012	2.80	4.07	1.14
2018	Low	1962	18.72	6.68	5.00
		1972	14.57	5.23	3.90
		1992	4.97	2.39	1.70
		2002	3.19	1.69	1.18
		2012	3.00	1.12	0.83

of five survey periods representative of historical and contemporary channel conditions.

The hydraulic models developed for this study provided a moderately complex representation of channel morphology and hydraulic conditions. Application of one-dimensional hydraulic models in combination with relatively coarse spatial resolution were acknowledged to affect modeling accuracy and confidence intervals (i.e., 10th and 90th percentiles) were used to characterize the range of observed modeling variability. However, one-dimensional modeling provided sufficiently consistent results to fulfill our objectives and data availability did not support the potential gain of a two-dimensional hydraulic model (USACE, 2016). Modeling improvements are nevertheless possible pending advancements in data collection (e.g., more detailed channel bathymetry or finer cross-section spacing). Data limitations related to simplified channel bathymetry likely most affected our results at low flows and therefore, our models might have failed to identify local optima in discharge-habitat relationships in this range (<5 m^3 s^{-1}; Bovee et al., 2008). Advances in remote sensing (e.g., LiDAR) are expected to improve modeling accuracy for contemporary and future conditions, and the acquisition of high-resolution spatial data at an increased sampling frequency is recommended, especially during high and low flow periods. The Middle Rio Grande is a mobile, sand-bed river and high-resolution channel bathymetry might only be representative of relatively short periods (1–2 years) yet could be informative of localized geomorphic processes. Additionally, changes in riparian vegetation composition over time have been observed (Petrakis et al., 2017), and recent encroachment of nonnative vegetation (i.e., Salt Cedar *Tamarix* spp., Russian Olive *Elaeagnus angustifolia*) has

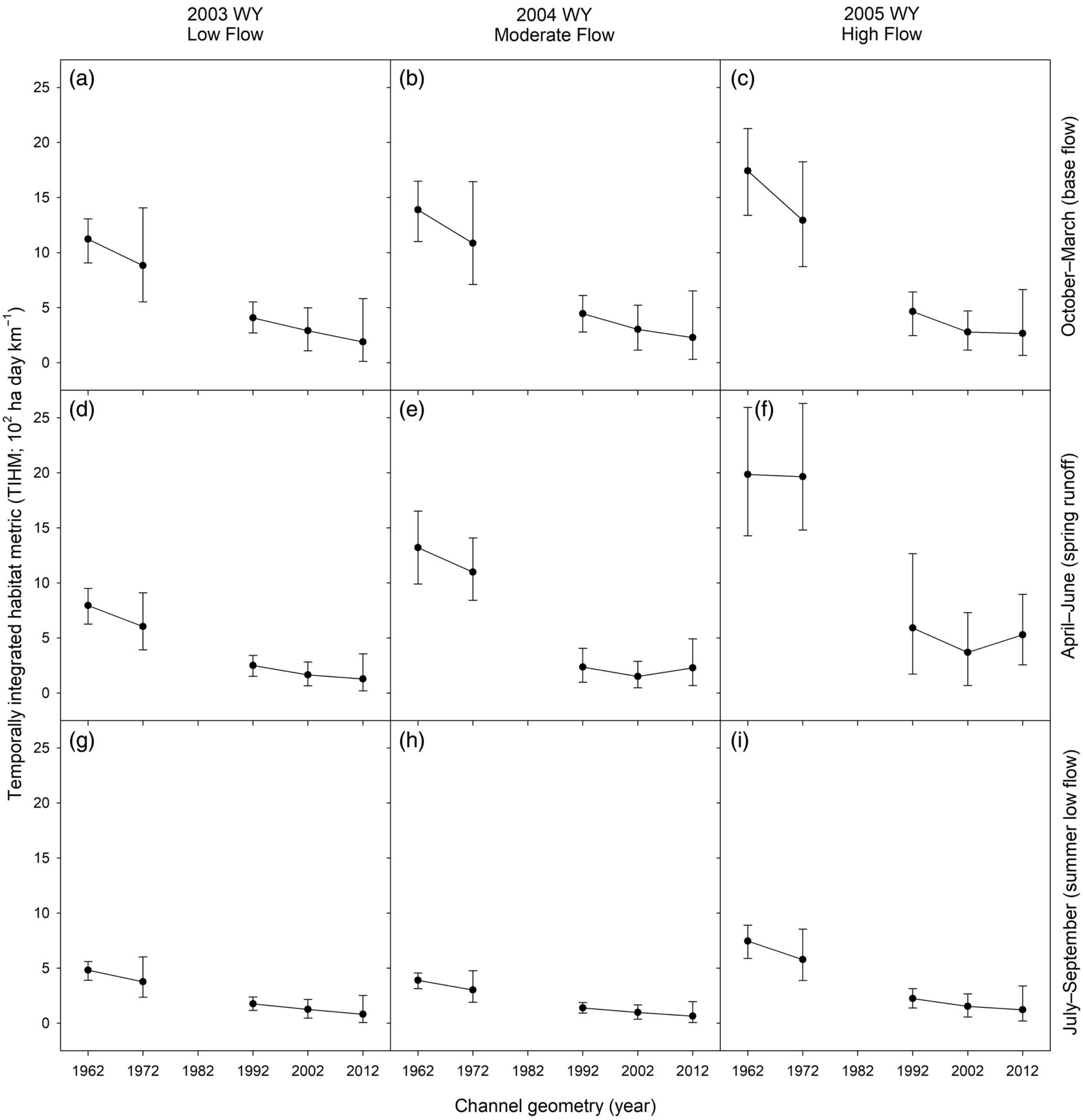

FIGURE 5 Temporally integrated habitat metrics (TIHM) calculated for seasonal hydrologic periods during water years 2003–2005 using channel geometries 1962–2012. Seasonal hydrologic periods were defined as: October–March (base flow; a–c), April–June (spring runoff; d–f), July–September (summer low flow; g–i). Vertical bars represent 10th to 90th percentile ranges in TIHM values based on subreach modeling variability (shown in Figure 4).

influenced channel evolution trajectories (Massong et al., 2010), whereby vegetation colonizes and stabilizes banks, bars, and islands during consecutive low flow years (Figure 8b, d). Incorporating impacts of vegetation remains challenging to implement in hydraulic models. Overall, the applied modeling techniques were deemed reasonable for the relatively broad spatial and temporal scale of the study (>55 river km reach; 50-yr period), and our results appeared consistent with predominant geomorphic trends that have been documented in this reach (Massong et al., 2006; Richard & Julien, 2003; Swanson et al., 2011).

Long-term monitoring of the Middle Rio Grande has established this river as a valuable case study to better understand impacts to floodplain connectivity associated with intensive water management and river engineering. Adair (2016) reconstructed a digital elevation

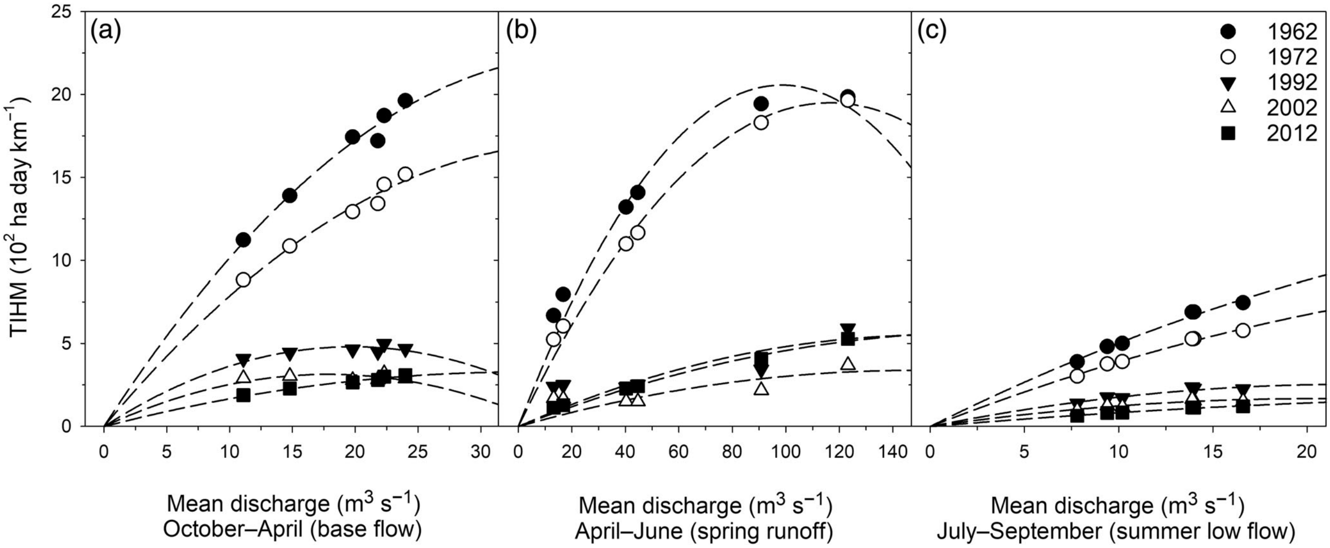

FIGURE 6 Relationships between mean discharge and temporally integrated habitat metrics (TIHM) for seasonal hydrologic periods 2003–2005 and 2016–2018: (a) October–April (base flow), (b) April–June (spring runoff), and (c) July–September (summer low flow). Symbols represent channel geometries (survey periods), and dashed lines represent 2nd-order polynomial regressions for each channel geometry—all relationships are assumed to pass through the origin (i.e., habitat availability equals zero when discharge equals zero).

model for a section of our study reach ca. 1918 (35 river km), prior to major channelization efforts (i.e., levee construction and bank armoring ca. 1950), and illustrated large-scale reductions (~80%) to the spatial extent of flooding compared to modern channel configurations (i.e., post-2010) for a range of pre-development flood discharges (142–566 $m^3\ s^{-1}$). Stone et al. (2017) generated a two-dimensional model for a 32 km reach of our study area using LiDAR elevation data (2010) to assess spatial patterns in inundation duration and frequency associated with flow regulation at Cochiti Dam (1974–2003). Including our analyses, these studies consistently showed profound reductions to floodplain connectivity associated with the cumulative impacts of hydrologic and geomorphic alteration of the Middle Rio Grande. Hydraulic modeling has revealed similar changes to floodplain connectivity and SLV habitat availability in the Missouri River basin (Bowen et al., 2003; Erwin et al., 2017; Jacobson & Galat, 2006), further highlighting the linkages between discharge, channel morphology, and habitat availability in regulated rivers. Our study contributes to a greater understanding of how geomorphic changes over 50 years have affected hydraulic conditions for a range of regulated discharges and the development of habitat metrics provides an additional measure by which managers can assess the seasonal availability of certain physical habitat parameters.

The conservation of riparian and aquatic species in large, heavily modified river ecosystems will depend on informed management of important flow and habitat characteristics, such as SLV habitat availability and floodplain connectivity. In the Middle Rio Grande, the federally endangered Rio Grande Silvery Minnow *Hybognathus amarus* is most frequently encountered in shallow, low-velocity habitats (Dudley et al., 2024), and long-term monitoring has demonstrated that its distribution and abundance are positively related to seasonal discharge conditions, primarily elevated and prolonged flows during spring (i.e., floodplain inundation, persistence of nursery habitats). Conservation of this endemic fish species exemplifies the challenges associated with balancing water use and development with wildlife conservation in the American Southwest. For the foreseeable future, highly variable precipitation, projected declines in runoff, and consumptive water use will continue to limit the water available to achieve ecological flow targets (i.e., spring flooding and instream flows during summer) on an annual or semi-annual basis (Blythe & Schmidt, 2018; Prein et al., 2016), the frequency likely needed for short-lived fishes such as Rio Grande Silvery Minnow (Horwitz et al., 2018). Our findings showed that increases in SLV habitat availability in the modern channel (Figure 4) are strictly maximized at the upper range of modeled discharges (200 $m^3\ s^{-1}$). By contrast with historical channel morphology, this suggests that flow manipulations of low to moderate magnitude would only marginally increase habitat availability for Rio Grande Silvery Minnow. At present, moderate to high magnitude discharges (>100 $m^3\ s^{-1}$) occur infrequently in the Middle Rio Grande and flood control facilities are managed to limit discharge to less than 200 $m^3\ s^{-1}$ (USBR, 2015, 2023). Despite these challenges, the joint implementation of floodplain restoration and managed spring runoff appears to contribute to positive population responses given sufficient flow magnitude and duration (Valdez et al., 2019). This suggests that increased SLV habitat availability at higher flows can still stimulate ecological processes even though our habitat metrics showed large reductions relative to historical geomorphic conditions (Figure 5). In addition to traditional restoration approaches (e.g., floodplain and side channel construction), the application of engineered structures to reduce water velocities and bank erosion has also been explored for the study area (Kinzli & Myrick, 2010). The study reach is located near the upstream boundary of the species' current range, where losses to habitat availability and floodplain connectivity

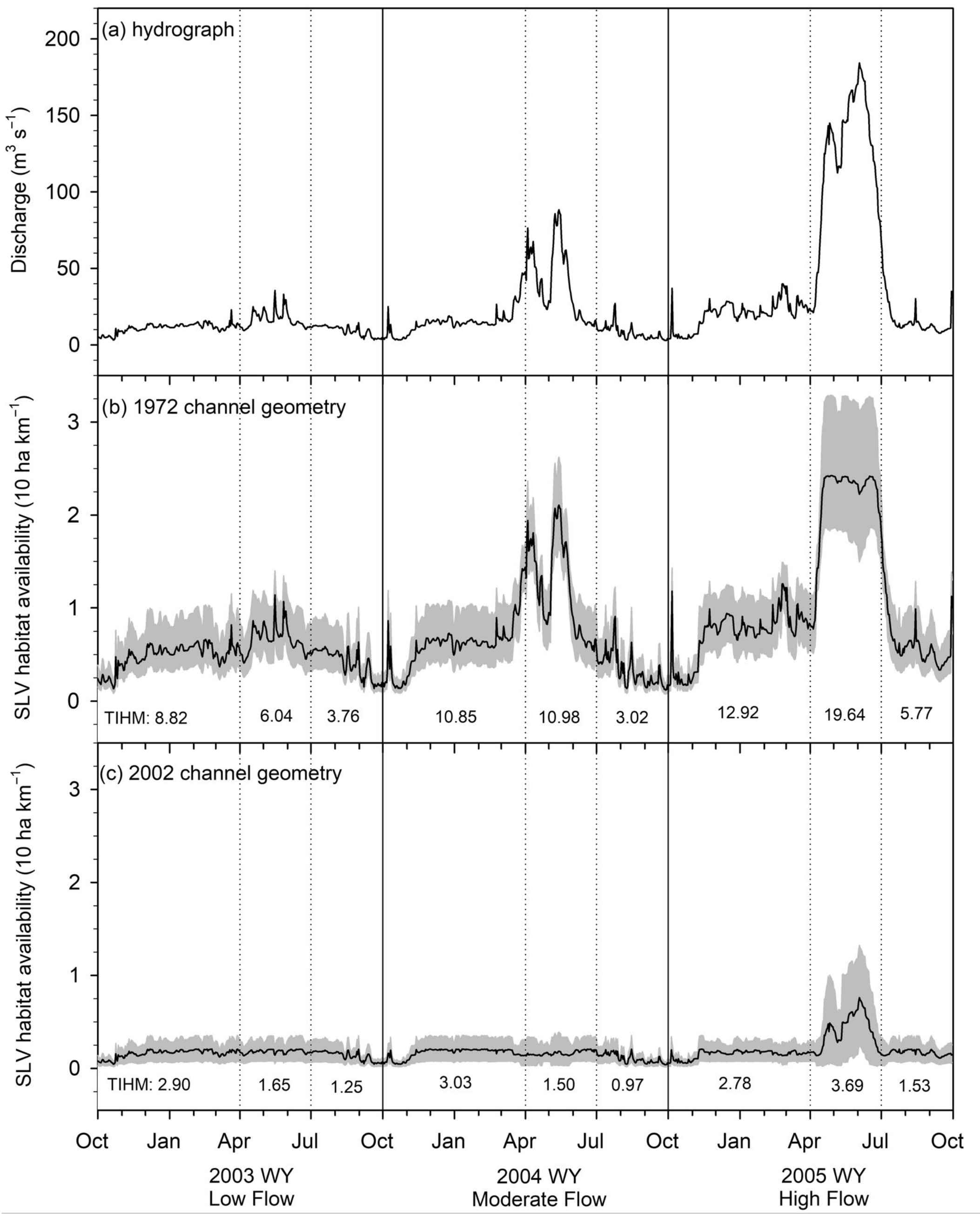

FIGURE 7 (a) mean daily discharge for the Rio Grande at Albuquerque, NM (USGS 08330000) for water years 2003–2005, (b) mean daily SLV habitat availability for water years 2003–2005 estimated using 1972 channel geometry; (c) mean daily SLV habitat availability for water years 2003–2005 estimated using 2002 channel geometry. Solid vertical lines represent water year (WY) and dotted vertical lines represent seasonal hydrologic periods (October–March [base flow], April–June [spring runoff], July–September [summer low flow]); shaded areas (panels b and c) correspond to 10th–90th percentile ranges shown in Figure 4. Values in panels (b) and (c) correspond to temporally integrated habitat metric values (TIHM; 10^2 ha d km^{-1}) for the respective seasonal periods.

are high relative to downstream (Massong et al., 2006). Recent research suggests restoration of larval fish habitat (i.e., SLV habitat) to be more effective in upstream reaches of the Middle Rio Grande for recovery of Rio Grande Silvery Minnow (Yackulic et al., 2022), which might be related to spatially distinct morphodynamic trends (e.g., upstream degradation versus downstream aggradation). Overall, successful conservation strategies will need to consider the dynamic interactions between streamflow, channel morphology, and hydraulic conditions to sustainably manage SLV habitats and the ecological benefits they provide.

Management approaches that increase floodplain connectivity are also expected to be important for other critical ecosystem processes such as recruitment of native vegetation (e.g., Rio Grande cottonwood *Populus deltoides wislizeni*; Howe & Knopf, 1991), riparian

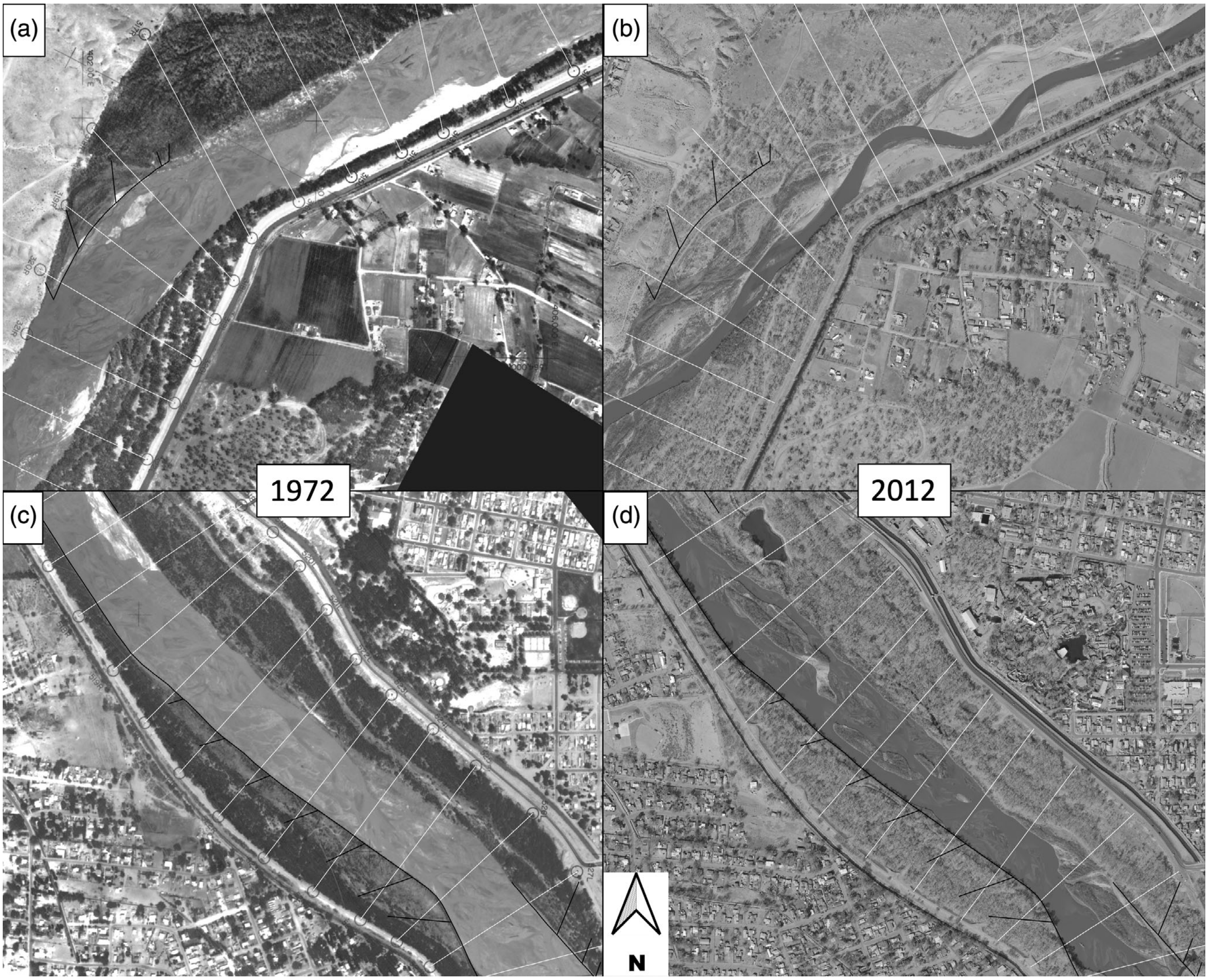

FIGURE 8 Aerial imagery of pre-dam (1972) and contemporary (2012) channel planforms at two locations in the study area. Panels (a) and (b) are located 3 km downstream of the study boundary (subreach 1); panels (c) and (d) are located about 2 km downstream of the Central Ave. Bridge (subreach 6). White lines represent channel cross-sections spaced at 150 m intervals and black lines represent approximate locations of bank stabilizing structures (i.e., jetty jacks) installed prior to 1962.

habitat creation for threatened or endangered bird species (e.g., Southwestern willow flycatcher, Yellow-billed Cuckoo), and ecosystem productivity (Kennedy & Turner, 2011; Yarnell et al., 2010). Based on our modeling results, the potential spatial scale of habitat restoration required to achieve pre-dam levels of SLV habitat availability might be substantial (10–20 ha km^{-1}), however, the scale needed to achieve desired ecological outcomes is unclear and might be considerably lower. Consideration of prevailing hydrologic and geomorphic processes and their constraints on habitat formation (e.g., peak flows and sediment load) will be central to the long-term success and sustainability of habitat restoration efforts (Beechie et al., 2010; Biron et al., 2014; Florsheim et al., 2008; Grabowski et al., 2014; Meitzen et al., 2013; Opperman et al., 2009). For example, operation of the sediment retention pool at Jemez Canyon Dam (1953), located approximately 7.5 km upstream of the study area, was modified in 2001 to allow passage of suspended and bed sediments (USACE, 2013). While increasing SLV habitat availability is expected to enhance some ecological functions, certain biological responses (e.g., fish abundance) might be related to additional factors and complex interactions with species' life histories (Nestler et al., 2019; Reiser & Hilgert, 2018). Addressing the impacts of long-standing water resource developments on habitat and biodiversity losses will remain challenging; our study explored methods for assessing habitat change over time related to historical impacts and emphasizes the importance of specific hydraulic conditions for conservation of riparian ecosystems.

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CONFLICT OF INTEREST STATEMENT

The authors have seen and agree with the contents of this article, have no relevant financial or non-financial interests to disclose and have no conflicts of interest relevant to the content of this article.

DATA AVAILABILITY STATEMENT

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

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