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Expansive, positive changes to fish habitat diversity following the formation of a valley plug in a degraded desert river

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Abstract

Widespread hydrologic alterations have simplified in-stream habitats in rivers globally, driving population declines and extirpations of many native fishes. Here, we examine how rapid geomorphic change in a historically degraded desert river has influenced habitat diversification and ecosystem persistence. In 2010, a large reach of the degraded and simplified lower San Rafael River (SRR), Utah, was impacted by the formation of a valley plug and began to shift from a homogenous, single-thread channel to a complex, multi-threaded riverscape. We combined field measurements and drone-collected imagery to document changes in fish habitat due to the valley plug. Our results demonstrate that in 2021, the affected reach was more diverse than any other stream reach along the SRR, containing 641% more diverse habitat (e.g., pools, riffles, and backwaters) than what was measured in 2015. The plug reach also retained water for periods beyond what was expected during seasonal drying, with the total extent of inundation within the riverscape increasing by over 2800%. Since the formation of the valley plug, riparian habitat has increased by 230% and channel networks have expanded to more than 50 distinct channels throughout the zone of influence. Our results provide evidence of successful self-restoration in a formerly highly degraded reach of desert river, and encourage new methods of desert river restoration. We aim to inform the use of large-scale, disruptive restoration actions like intentional channel occlusions, with the goal of mitigating the impacts of simplification and increasing habitat persistence in the face of exacerbated aridity in the desert Southwest.

KEYWORDS
channelization, Colorado River basin, ecosystem services, fish habitat complexity, fluvial geomorphology, native fishes, stream restoration, valley plug

1 | INTRODUCTION

In arid and semi-arid rivers, an increasing appropriation of streamflow in addition to widespread climate shifts have led to a reduction in the frequency and/or magnitude of seasonal floods, which often induces a shift from a braided or anastomosing to a meandering single-thread channel, decreases channel width, causes valley alluviation, and is often accompanied by changes in riparian vegetation communities which favor domination by nonnative taxa (Castle et al., 2014; Udall & Overpeck, 2017; Vorosmarty et al., 2010). This habitat degradation process is especially prevalent in the arid American Southwest, where four of the 14 fish species native to the Colorado River Basin (CRB) are considered threatened or endangered under the Endangered Species Act, in part due to degraded habitat (ESA; Laub et al., 2015; Rinne & Minckley, 1970). Remediating threats to the persistence of native biota in Southwest desert rivers will likely require coupled

management of flow regimes and in-channel restoration efforts to re-create, preserve, and maintain crucial habitat (Propst et al., 2008).

In the past decade, river restoration efforts globally have coincided with the development of theoretical channel evolution models that offer a holistic view of the riverscape, targeting the importance of floodplains for ecological productivity and river dynamics (Beechie et al., 2010; Flitcroft et al., 2022; Woelfle-Erskine et al., 2012). These models are designed to classify the sequence of evolutionary changes a stream undergoes after disturbance and help us conceptualize what constitutes a 'healthy' river corridor by focusing on changes in channel and floodplain spatial heterogeneity (Brown et al., 2018; Hinshaw et al., 2022). Cluer and Thorne (2014) built upon existing channel evolution models by adding a 'Stage-0' evolutionary phase, which is assumed to reflect conditions prior to anthropogenic modification and is defined as a pre-channelization phase in which the stream has a high degree of lateral connectivity with an unconfined, multi-threaded and anastomosing network of channels. Stage-0 is now more broadly used to describe valley-scale, process-based stream restoration projects that aim to maximize planform complexity at base flows and facilitate the development of dynamic wetland-stream complexes that are self-sustaining and resilient to external perturbations (Schneider et al., 2022; Wohl et al., 2015, 2022).

Given the novelty of Stage-0 restoration, restoration methods are often site-specific and lack a cohesive methodology; however, there are a few common tools used that often seek the same aims: valley-scale projects with process-based outcomes that are intended to be self-forming and self-sustaining (Schneider et al., 2022). The most common methods include (1) the Geomorphic Grade Line (GGL) restoration method which restores depositional valleys to a common grade that then self-adjusts to natural geomorphic processes over time (e.g., Powers et al., 2019); (2) installation of human-made beaver dam analogs (BDAs) and post-assisted log structures (PALS; e.g., Wheaton et al., 2019); (3) beaver reintroduction, potentially augmented by BDAs and PALS (e.g., Doden et al., 2022); and (4) barrier removal projects coupled with land use changes (e.g., Montanio, 2011). The success of a Stage-0 restoration project is typically evaluated by post-project monitoring that identifies whether the physical objectives of Stage-0 have developed. These metrics can include elevated water tables, aggradation of the incised channel, an increase in habitat diversity, and the retention of large woody debris (LWD; Ciotti et al., 2021; Perle, 2019; Scott & Collins, 2019).

Recent studies reporting occurrences of endangered 'big river' fish species (e.g., flannelmouth sucker *Catostomus latipinnis*, razorback sucker *Xyrauchen texanus*, and Colorado pikeminnow *Ptychocheilus lucius*) in smaller tributary systems of the CRB have sparked an interest in the role of tributary habitat in larger river networks (Bottcher et al., 2013; Fresques et al., 2013; Wick et al., 1991). The use of this habitat is largely dependent on the size of the tributary, its proximity to mainstream rivers, and the availability of wetted habitat; however, prior studies have identified that tributary systems can offer unique habitat conditions that are crucial to the life history stages of native fish (i.e., spawning, refugia, and maturation; Cathcart et al., 2015; Datry et al., 2014; Osborne & Wiley, 1992). Although these tributary

systems are increasingly being recognized as key habitat for native fishes, they are often excluded from management plans and are not consistently designated critical habitat for recovery under the ESA (Laub et al., 2015). This is likely due to the remote nature of these tributary systems, their small size, uncertain political standing, and a dearth of data regarding their contributions to populations of endangered species or critical habitat. Thus, ongoing restoration efforts within these tributary systems are frequently on the reach-scale and therefore impact only small portions of these stream networks (Keller et al., 2014; Laub et al., 2015). Since meaningful restoration actions within the arid, desert river tributary networks of the CRB can be difficult to achieve, they hold significant potential for broad-scale experimental restoration actions.

In our study, we evaluate the decade-long evolution of a degraded desert river tributary of the American Southwest to Stage-0 conditions following the natural formation of a depositional valley plug. We hypothesized that the valley plug had facilitated the successful restoration of high-quality habitat for native fishes at the reach-scale, and that this was measurable by quantifying (a) an increased diversity of habitat types and (b) increased habitat persistence in the face of exacerbated seasonal drying. Based on our results, we suggest the tributary systems of the upper CRB could be excellent candidates for broad-scale restoration actions that target Stage-0 results. We also suggest that the successful evolution of a historically degraded desert river into a 'Stage-0' system that provides crucial spawning, rearing, and maturation habitat for native fishes can be measured through relatively simple metrics of diversity.

2 | METHODS

2.1 | Study area

The San Rafael River (SRR; Figure 1), a tributary of the Green River in the CRB, is representative of many desert river systems in that an altered flow regime, fish passage barriers, degraded habitat, and non-native species have combined to synergistically alter ecosystem processes and threaten the persistence of native fish communities (Macfarlane, Gilbert, et al., 2017; Macfarlane, McGinty, et al., 2017; Olden & Poff, 2005; Stromberg et al., 2007). The presence of reservoir and water-diversion systems upstream on the SRR's three tributaries results in the SRR being one of the most overallocated rivers in Utah, where these reservoirs can hold back nearly all spring runoff with the exception of those years with abundant snowfall and snowmelt (Fortney et al., 2011). Another significant impact on the SRR riverscape includes the invasion of nonnative tamarisk (*Tamarix ramosissima*) and Russian olive (*Elaeagnus angustifolia*) which have contributed to vertical accretion, enhanced streambank stabilization, channel narrowing, and planform simplification (Manners et al., 2014). The loss of a natural flow regime, invasion of nonnative vegetation, and the encroachment of upland vegetation into the floodplain have changed the SRR from a historically diverse and multi-threaded system to a highly aggraded, simplified, and homogenous riverscape (Fortney
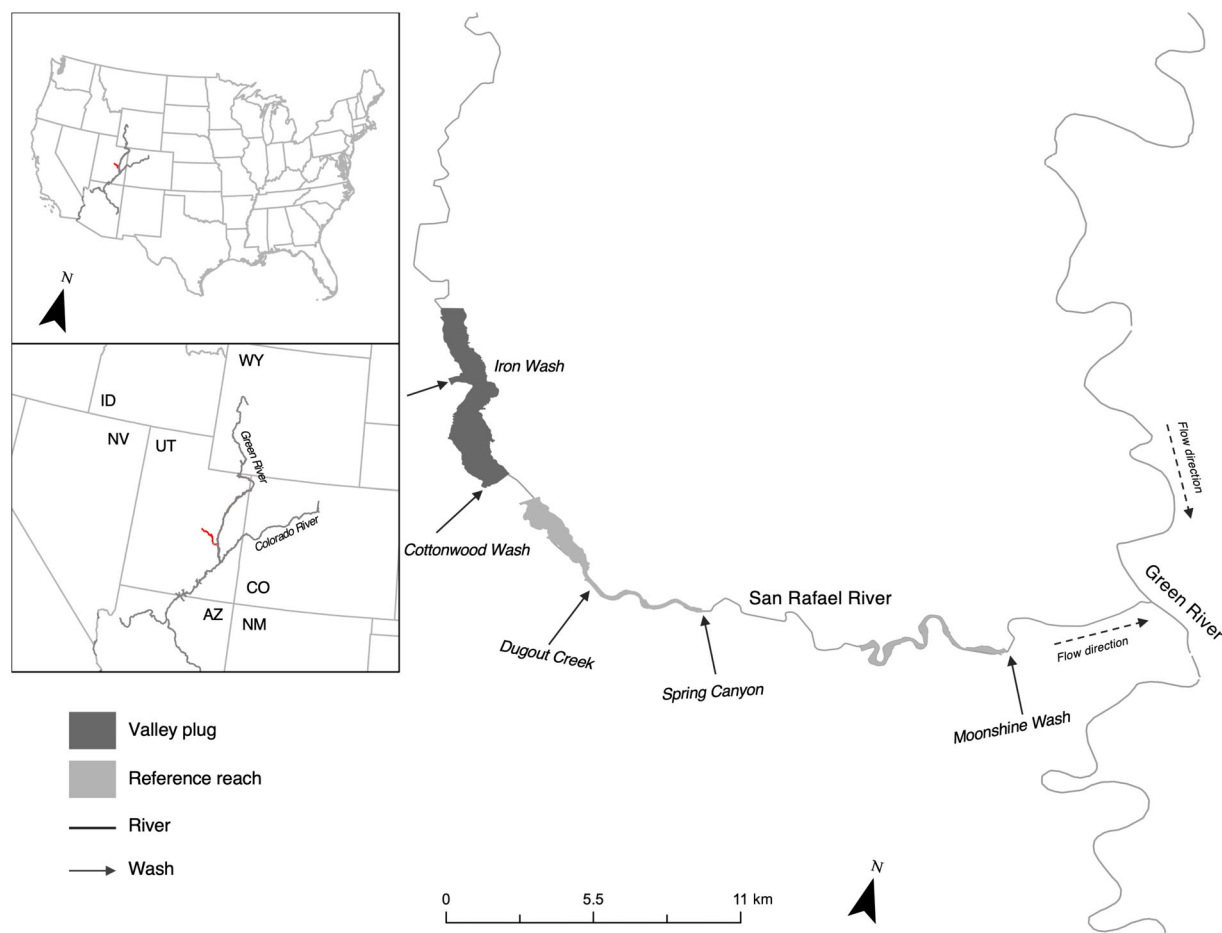
FIGURE 1 Map of the lower San Rafael River and the study area region showing regions of remote mapping: the valley plug and reference reaches. Boundary reaches (or areas) are defined as regions located at upstream and downstream of the expanding valley plug. Confluence junctions are shown, and the Colorado River and Green River are highlighted on the subset map.

et al., 2011; Pennock et al., 2021; Walker & Hudson, 2004). These impacts have also significantly reduced the quality and availability of key spawning, feeding, resting, and rearing habitats that are crucial to the persistence of native and endemic fishes (Bottcher et al., 2013; Walsworth et al., 2013).

In July 2010, a severe rain event caused flash-flooding in Cottonwood Wash, a tributary of the SRR (38.758386°, −110.325490°; Lyster, 2018). This rain event coincided with low flows and reduced sediment transport capacity, resulting in the deposition of a valley plug at the confluence with Cottonwood Wash. The term 'valley plug' was coined by Happ et al. (1940) to describe the processes and deposits resulting from an occluded canal or river channel. The initial plug, stretching from 400 m downstream of Cottonwood Wash confluence to 450 m upstream of Cottonwood Wash confluence, blocked the flow of water in the main river channel and brought water levels to above floodplain elevation (Utah State University Water Research Laboratory, 2010). As a result, the SRR underwent rapid avulsion and transitioned from a single-thread channel to a multi-threaded channel network that began at the confluence with Cottonwood Wash and rapidly expanded upstream (Lyster, 2018). Root masses of invasive species were believed to have stabilized floodplain soils, preventing

the upstream migration of channel headcuts and causing water to remain at near-floodplain levels for nearly a year. These extended periods of inundation appeared to further facilitate the diversification of this affected reach of the river which, as of 2021, had continued to expand upstream.

2.2 | Study design

Fortney et al. (2011) conducted an extensive analysis of geomorphic change within the SRR beginning in the mid-1800s through the present day, and our definition of 'complexity' in the SRR is based on these historic 'Stage-0' pre-modification accounts (Figure 2). In the early 20th century, the lower SRR was observed as a multithreaded stream-wetland complex with wide (10–40 m), shallow (≥0.25 m) channels that were bordered by abundant grass, sedges, and wetlands, suggesting the water table was near the surface in much of the valley (Fortney et al., 2011). Native fishes that historically used the SRR for spawning, rearing and maturation (e.g., bluehead sucker *Catostomus discobolus*, flannelmouth sucker *Catostomus latipinnis*, and roundtail chub *Gila robusta*) are often found in stream reaches that have a
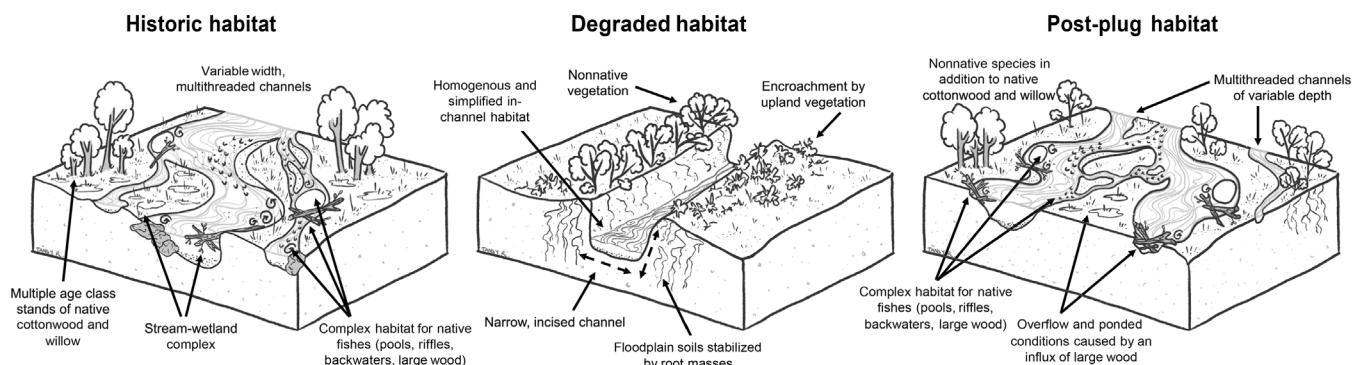
FIGURE 2 A conceptual model of the San Rafael River showing (a) historic conditions, (b) simplified conditions, and (c) post-plug conditions.

diverse mosaic of pool and riffle habitats, as well as in relatively deep, low-velocity habitats often associated with LWD or other forms of cover (Bezzerides & Bestgen, 2002). Their abundance in the SRR in the early 20th century suggests ample presence of their preferred 'complex' habitat (McAda et al., 1980; Vanicek et al., 1970). Thus, utilizing historic accounts of the system as a baseline for diversification, we define 'complex' as an expansive stream-wetland complex containing diverse and complimentary habitat types suitable for native fishes. On the other hand, we define 'simplified habitat' within these desert tributaries as the historically degraded and homogenous habitat that characterizes much of the river system in the present day. Specifically, the river has narrowed to occupy a single channel, the existing channel of the SRR has narrowed and deepened, the floodplain has aggraded, backwaters and other off-channel habitats have filled with sediment, and the channel is now dominated primarily by low-velocity, sandy run, or glide habitat (Laub, 2013; Laub et al., 2018).

We characterize the degree of simplification in the SRR by quantifying both overall complexity as well as temporal variability. We quantify complexity via the following metrics: (1) valley bottom extent; (2) inundation; (3) vegetation; (4) more traditional geomorphic complexity metrics as they relate to complex fish habitat (confluences, diffluences, pools, riffles, backwaters, and LWD); and (5) the Shannon's Evenness Index (SHEI) which has more traditionally been used to describe ecologic diversity (Maddock et al., 2008; Wyrick & Pasternack, 2014). Our selection of these metrics is based on previous studies of the SRR (and similar tributaries of the upper CRB) which identified complexity metrics crucial to the survival and persistence of native and endemic fishes (e.g., Bottcher et al., 2013; Walsworth et al., 2013), prior research that identified that the encroachment of upland shrubs in desert tributary systems serves as a prominent indicator of riparian habitat degradation (e.g., Macfarlane, Gilbert, et al., 2017; Macfarlane, McGinty, et al., 2017), the definition of tier 1 and tier 2 geomorphic units by Wheaton et al. (2015); described in greater detail below), and modified methods from the Riverscape Inundation Mapper tool (RIM; Bartelt, 2021).

These complexity metrics (valley bottom extent, inundation, vegetation, geomorphic units, SHEI) allowed us to describe the valley bottom of our study area at a given point in time; however, a fully functioning

valley bottom likely changes through time, necessitating that temporal analysis also be a key part of monitoring geomorphic complexity within our study area. For this reason, we selected three time periods (2009, 2015, and 2021) that had suitable imagery available and were representative respectively of pre-valley plug conditions, 5 years post-plug formation, and 11 years post-plug formation. To establish a baseline of simplification in the lower 90 km of the SRR, we established two reference reaches in addition to the valley plug reach, one upstream of Spring Canyon and the other upstream of Moonshine Wash (Figure 1). The selected reaches were similar in length to the valley plug (7.36 km) and were intended to represent the historically degraded habitat of the SRR, offering context for metrics of change within the valley plug. Notably, the selection of reference reaches was access-limited due to a lack of roads and the rugged terrain of the region, and we could not access the most degraded reaches for field work.

To analyze changes to geomorphic complexity over time within the valley plug and each of our reference reaches, we followed a five-step process where we (1) acquired basemap imagery; (2) digitized features that represent: (a) valley bottom extent, (b) inundation, (c) geomorphic units, and (d) riparian and upland vegetation; (3) split the valley bottom and metrics into 13 intervals that were (a) of similar area and (b) of equal spacing (≤0.6 km) given the shape and size of the valley bottom; (4) quantified the metrics from each segment; and (5) calculated measurements of variance for each site over our three time periods (2009, 2015, and 2021; see Table 2). We also conducted field-based surveys of geomorphic complexity in six sample reaches representative of (a) the historically degraded habitat found in the lower SRR, (b) the boundary habitat located along the edges of the valley plug, and (c) the habitat located within the valley plug. Each of the three habitat types was represented by two of the six sample reaches.

2.2.1 | Imagery acquisition

We acquired basemap imagery for the digitization of the valley plug in 2021 with an unmanned aerial vehicle (UAV; DJI Mavic 2 Pro) outfitted with a Hasselblad L1D-20c camera (20MP 1″ sensor), or from available high-resolution aerial photos. For 2021 imagery collected by UAV, we collected imagery at flight heights ranging from 300 to

350 m at 32 kmh. We post-processed imagery in DroneDeploy (dronedeloy.com) to produce 2 cm resolution orthomosaic images (e.g., Carbonneau et al., 2020; Oakland, 2020). We also used historic imagery from Google Earth (6 June 2009, and 2 April 2015; Maxar Technologies, State of Utah, USDA/FPAC/GEO; ∼0.15 m resolution) to capture conditions prior to 2021 and for our reference reaches: Moonshine Wash and Spring Canyon.

We collected UAV imagery on 23 September 2021. Flows for the UAV imagery were a maximum of 0.40 and a minimum of 0.30 m^3/s, with seasonal averages. Historic imagery flows were a maximum of 8.10 and a minimum of 7.14 m^3/s for 2009, and a maximum of 0.26 and a minimum of 0.12 m^3/s for 2015. All flows represent low to moderate flow conditions for the SRR and were measured at US Geologic Survey (USGS) gauge #09328500 SRR near Green River, Utah.

2.3 | Data analysis

2.3.1 | Site characterization

To contextualize habitat condition for the SRR, as well as the relative impact of the valley plug, we utilized modified methods from the RIM Tool (Bartlet, 2021). Based on these methods, we conducted relatively rapid and manual digitization of landscape features to analyze readily available (e.g., Google Earth) and easily acquirable (e.g., consumer-grade drones) high-resolution aerial imagery. We mapped valley bottom extents (Fryirs et al., 2015) to provide a basis for normalization. The valley is defined as the area between the adjacent hillslopes (Wheaton et al., 2015), and the valley bottom is the area that contains the active channel(s) and could plausibly flood in the contemporary flow regime (Wheaton et al., 2019). We used multiple lines of evidence to delineate the valley bottom margins for the study reaches including satellite imagery, Digital Elevation Models (DEMs; dated to 2009, 2016, and 2018) and field observations of the surrounding landscape. We assumed the valley bottom extents are constant to establish a consistent basis for normalization (Bartlet, 2021). Next, we bisected the valley bottom polygon with a center line and used this to characterize the valley bottom or site length. We calculated the integrated valley bottom width for target sites by dividing the valley bottom area by site length. For each data capture event, we digitized features representing tier 1 and tier 2 geomorphic units, as well as inundation extent and type (Wheaton et al., 2015).

In addition, we conducted a slope analysis for the valley plug and each of the reference reaches. Slopes were computed from 10-m DEMs and the following equation was used to calculate the slope of the valley centerline

$$m = \frac{\text{rise}}{\text{run}} = \frac{y_1 - y_2}{x_1 - x_2},$$

where y_1 is the elevation at x_1, which is the upstream end of the valley centerline and y_2 is the elevation at x_2, which is the downstream end of the valley centerline.

2.3.2 | Mapping geomorphic units as an indicator of complexity

Wheaton et al. (2015) define the primary tier 1 geomorphic units that comprise the riverscape or valley bottom as the river's contemporary floodplain and channel(s). In our study, we visually inferred the boundary between the low-lying floodplain and upland hillslopes or terraces. Within these classifications, we defined the contemporary floodplain as a polygon shapefile in Esri ArcGIS. Similarly, we mapped primary and secondary channels as a polygon feature class.

We defined tier 2 geomorphic units as the depositional or erosional instream features that contribute to complex fish habitat (pools, backwaters, riffles, and LWD; Bottcher et al., 2013; Horan et al., 2000; Palmer et al., 2009). We measured all units during the sampling of our six field reaches. In addition to habitat composition mapping, in each reach we examined substrate composition by conducting pebble count surveys in each of our six field sites (Potondy & Hardy, 1994). For each 300 m reach, we collected 20 substrate samples at 30 m intervals along a cross-channel transect for a total of 200 samples per reach.

During imagery analysis via ArcGIS, we mapped only those features that were visible at 1:450 zoom (riffles and LWD) and added confluences and diffluences as an additional metric of habitat diversity (Benda et al., 2004; Duncan et al., 2009). We classified LWD structures as those found both in- and out-of-channel that fell within a zone of inundation, and riffles as clear changes in flow visible on the channel surface. We identified confluences and diffluences as channel breaks and joins stemming from the active channel or former active channel. We mapped LWD, riffles, confluences, and diffluences as points through visual estimation via digital imagery and conducted a total count of each metric within the study area. When possible, we confirmed the presence and form of tier 2 geomorphic units through on-the-ground field surveys.

2.3.3 | Mapping inundation extents as a proxy for habitat diversification

Changes in inundation due to structural forcing from channel-spanning structures (e.g., LWD, beaver dams) can often initiate planform change when water from the main channel flows across the floodplain, leading to the formation of secondary channels and inducing a shift from a single-threaded to multi-threaded channel network (Bartlet, 2021). Based on this assessment, we used inundation as a metric of complexity where changes in flow indicate the potential for habitat diversification. Imagery for use in the analysis of inundation was collected during 2009, 2015, and 2021 during low to moderate flow conditions. Valley plug imagery was analyzed during all three time periods: 2009, 2015, and 2021. For our reference reaches, we only analyzed 2009 and 2015 imagery.

We mapped inundation by digitizing a polygon around the wetted edge visible in the aerial imagery. We inferred visible boundaries

where vegetation or shadows obscured the water's edge. We estimated uncertainty in the inundation area through the addition of 2 ± 10 m buffered polygons which represented the upper and lower bounds of maximum and minimum inundation within the valley bottom.

We delineated each inundation survey polygon into three flow-type classes on a continuum from more lotic to more lentic. We defined these classes as follows: (1) free-flowing—not obstructed by river channel or by a channel-spanning structural element, (2) overflow—flow that is spilling over active channel boundaries and onto the floodplain or otherwise exposed in-channel surfaces (e.g., bars, benches, and/or ledges), and (3) ponded—structurally forced backwater creating a pond or pool upstream of a channel-spanning structural element (e.g., a beaver dam; Wheaton et al., 2015). Once inundation types were classified, we used these data to derive the total area of each inundation type. We then divided the inundated area by the valley bottom area, which provided the percent of both total inundation and each inundation type, allowing for comparison of inundation across reaches. We also estimated the integrated wetted width by dividing the total inundated area by the valley bottom length.

To characterize the diversity of inundation types, we used SHEI to calculate a value for each site and survey, a metric frequently used to describe spatial heterogeneity (e.g., Laurel & Wohl, 2019; Wyrick & Pasternack, 2014). The SHEI value is calculated as follows:

$$\text{SHEI} = \frac{-\sum_{i=1}^{m}(P_i * \ln P_i)}{\ln v},$$

where P_i is equal to the proportion of the valley bottom occupied by each inundation type i and v is equal to the number of inundation types present in the valley bottom. In our study, v was equal to four to include the three inundation types (free-flowing, ponded, and overflow) and dry conditions.

2.3.4 | Mapping riparian vegetation as an indicator of habitat persistence

We mapped riparian and upland vegetation utilizing ArcGIS where riparian vegetation presence was used as our primary indicator of water retention. We utilized visual estimates to infer the boundary between riparian and upland vegetation and a polygon was drawn around each respective vegetation type to calculate area. Percent bare ground was visually uniform in riparian and upland zones; thus, we did not remove any bare ground from our area estimates. We did not include non-vegetated river channels in our survey. Imagery for use in the analysis of vegetation was collected in 2009, 2015, and 2021. We analyzed valley plug imagery during all three time periods: 2009, 2015, and 2021. For our reference reaches, we only analyzed 2009 and 2015 imagery.

3 | RESULTS

First, we demonstrate the results for our simplified reference reaches to set a baseline for degradation in the lower river. Next, we report the summary results for the valley plug, including site-specific changes in geomorphic complexity, inundation, and riparian vegetation.

3.1 | Delineation of simplified reference habitat

For both reference reaches, imagery for 2009 (pre-valley plug) was collected in August when flows were at 8.07 m³/s, and imagery for 2015 was collected in July when flows were at 0.26 m³/s. The slope of our Spring Canyon reach was 0.0015 (Table 1). The valley bottom measured 2.26 km², of which ~5% (112,676 m²) was inundated by free-flowing river in 2009. The river rerouted and cut off an >800 m stretch of river between 2010 and 2012, and in 2015 ~3%

TABLE 1 Results of the reference reach imagery analyses for each year surveyed. Valley bottom length and valley bottom area are constant at each reach for both time periods.

| Description	Site	Year	
		2009	2015
Flow at date of imagery (m³/s)			
Max	–	8.07	0.26
Min		7.14	0.12
Valley bottom length constant (km)			
	Spring Canyon	7.36	
	Moonshine Wash	7.36	
Valley bottom area constant (km²)			
	Spring Canyon	2.26	
	Moonshine Wash	1.14	
Valley gradient			
Grade	Spring Canyon	0.0015	
	Moonshine Wash	0.0016	
Grade in %	Spring Canyon	0.15	
	Moonshine Wash	0.16	
Angle of elevation	Spring Canyon	9.68	
	Moonshine Wash	9.55	
Geomorphic units			
Total count	Moonshine Wash	0	70
	Spring Canyon	0	0
Total area inundated (km²)			
	Spring Canyon	0.11	0.09
	Moonshine Wash	0.08	0.06
Percent valley bottom inundated			
	Spring Canyon	5.1	3.7
	Moonshine Wash	6.6	5.3

(85,199 m²) of the valley bottom was inundated. We found that the valley plug contained 3% more inundated habitat as compared to the Spring Canyon reference reach in 2009 and had ~1577% more inundated habitat in 2015 (Figure 3a,b). The valley plug also contained ~0.67 km² more riparian habitat as compared to the Spring Canyon reference reach in 2009, and 0.7 km² more riparian habitat in 2015 (Figure 4a,b).

We found that the Moonshine Wash reference reach had a slope of 0.0016 (Table 1), with ~75,227 m² of inundated habitat in 2009,

occupying ~6% (75,227 m²) of its 1.13 km² valley bottom. In 2015, inundation was reduced to ~5% (60,556 m²) of the valley bottom. The valley plug contained 54% more inundated habitat as compared to the Moonshine Wash reference reach in 2009, and ~2259% more inundated habitat in 2015 (Figure 3a,c). We observed an increase in the number of geomorphic units found in the Moonshine Wash reference reach, containing 43 riffles and 27 LWD structures in 2015, compared to zero in 2009. Riparian habitat did not change significantly between 2009 and 2015 in the Moonshine Wash reach, and
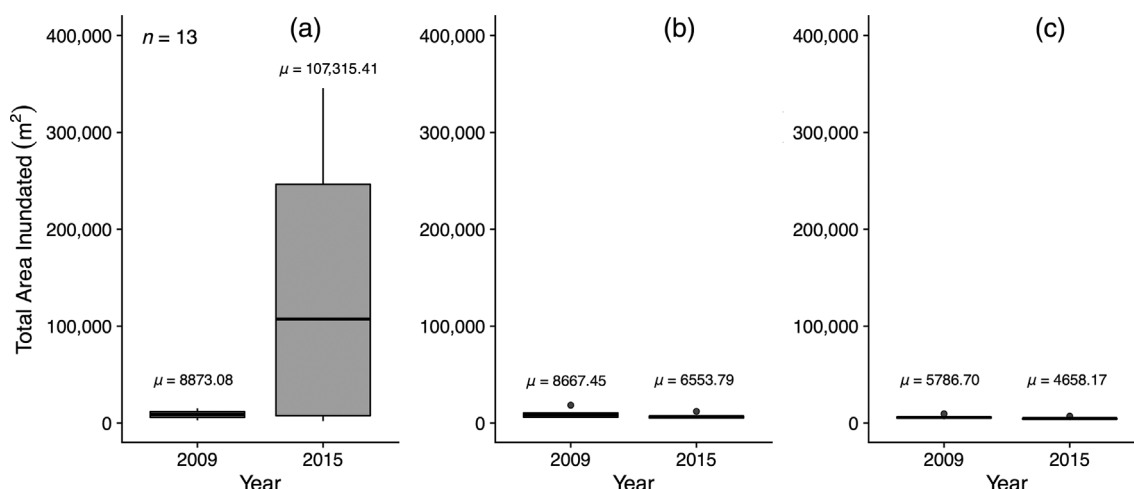
FIGURE 3 Total area of inundation for 2 years, 2009 and 2015. Measurements were calculated for (a) the valley plug and two reference reaches: (b) Spring Canyon and (c) Moonshine Wash. The lower extent of the boxplots represents the bottom quartile (25%), the line represents the median, and the upper extent of the box represents the upper quartile (75%). The whiskers extend to the minimum and maximum values, within the 1.5 interquartile range, and outliers are represented by points.
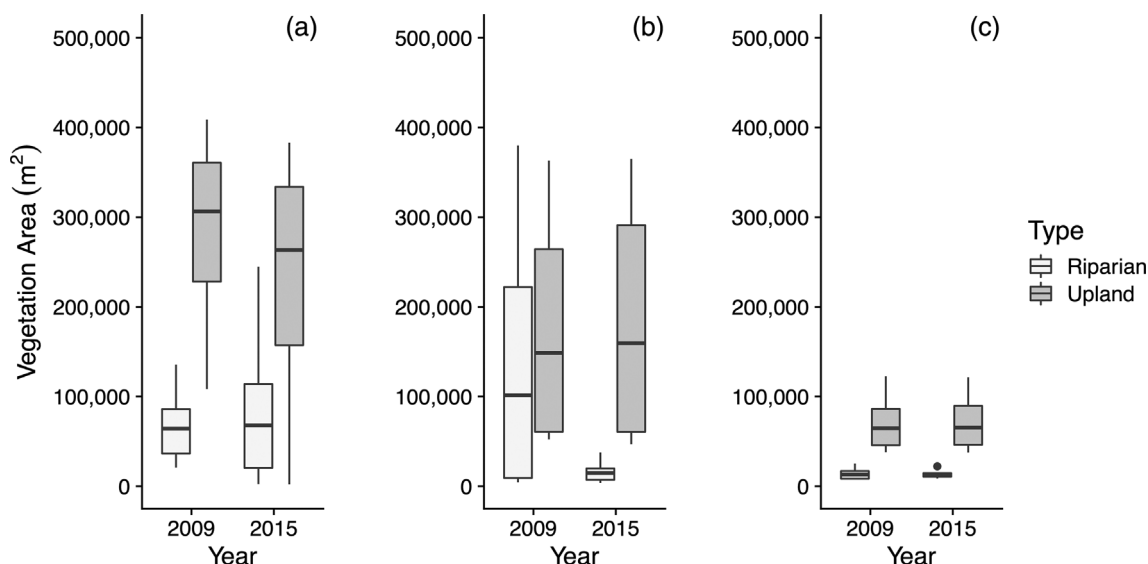
FIGURE 4 Areas for upland (dark shading) and riparian (light shading) vegetation collected via drone and historic imagery for two time periods, 2009 and 2015. Measurements were calculated for (a) the valley plug and two reference reaches: (b) Spring Canyon and (c) Moonshine Wash. The box represents the 25%, median, and 75%. The whiskers extend to a maximum of 1.5 interquartile range, and outliers are represented by points.
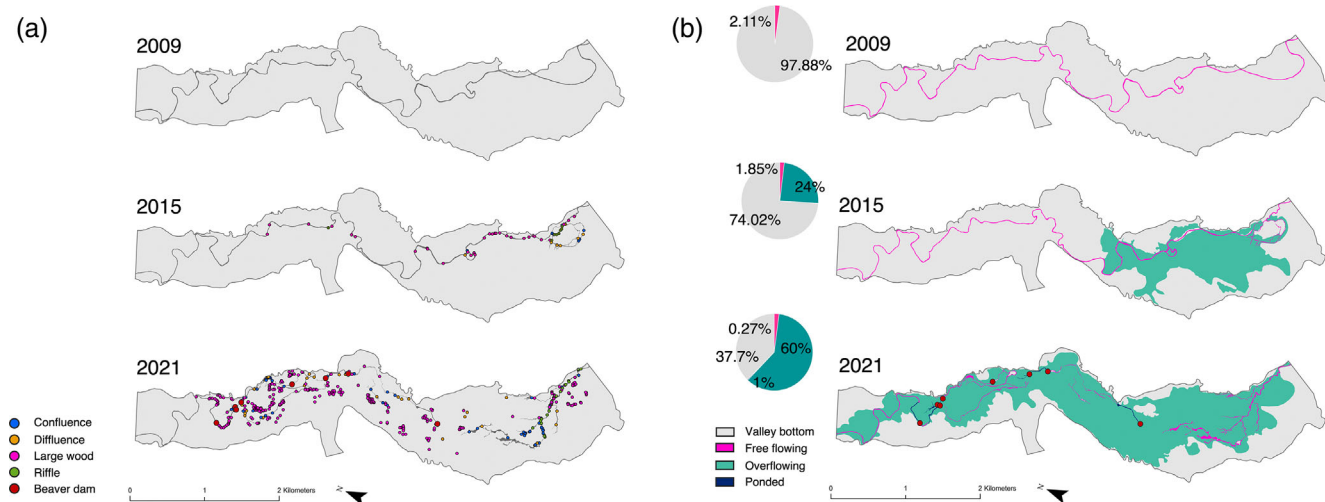
FIGURE 5 (a) Map of geomorphic units (e.g., confluences, diffluences, large woody debris, and riffles) for three time periods: 2009, 2015, and 2021 upstream of Cottonwood Wash within the valley plug. The imagery was collected in the same reach of the river for all 3 years.
(b) Riverscape inundation mapping results for imagery collected in 2009, 2015, and 2021. [Color figure can be viewed at wileyonlinelibrary.com]

the valley plug contained an average of 0.7 km^2 (Figure 4a,c) more riparian habitat than the Moonshine Wash reach during both 2009 and 2015.

3.2 | Valley plug geomorphic complexity

From our analyses of orthomosaic imagery, we found that the valley plug underwent a 641% increase in more diverse geomorphic units from 2015 to 2021 (Figure 5a; Table 2). Specifically, we observed a 657% increase in confluences, a 371% increase in diffluences, an ∼861% increase in LWD, and a 225% increase in riffle habitat. Our field-based survey demonstrates that the valley plug is more physically diverse than any other river segment along the lower SRR with plug and boundary habitat reaches containing 17% more unique geomorphic units (e.g., pools, riffles, and backwaters) on average than reference reaches, with 70% of primary plug habitat comprised of diverse habitat. We found that boundary habitat was the most complex, containing a combined greater diversity of geomorphic units and substrate composition when compared to sampled reference and valley plug reaches (Figure 6). Our reference sites contained >800 m^2 of riffle habitat and only a very small area (<7 m^2) of LWD (Figure 6a). Reaches within the valley plug itself were composed of only a small area of pool habitat (16 m^2). In contrast, the boundaries of the valley plug contained >123 m^2 of pool habitat, 149 m^2 of riffle habitat, >34 m^2 of LWD, and a very small section (4 m^2) of backwater habitat. On average, boundary habitat contained >1100% more pool habitat than the other reaches. Based on the results of pebble counts, we found that boundary sites contained a mixture of silt and sand substrate, with 64% of the substrate comprised of silt. In comparison, reference sites were more complex than anticipated, containing >54% silt substrate, >33% sand, >4% gravel, and 7% boulder. Valley plug reaches were comprised entirely of silt (Figure 6b).

3.3 | Valley plug inundation extents

The valley plug reach of the river measured as 5.5 km^2 (7.36 km) with a slope of 0.0016 (Figure 5b; Table 2). We collected and analyzed imagery from 2009 (pre-valley plug) which showed that at moderate flow (8.07 m^3/s), the SRR's inundation was contained entirely within a single free-flowing primary channel (integrated wetted width = 15.8 m). The inundated area was measured to be 116,292 m^2 or 2.1% of the valley bottom.

We collected imagery for the spring of 2015 from Google Earth during a low flow period (0.26 m^3/s). Inundation increased from 2.1% to 26% (1,428,893 m^2) of the valley bottom (Figure 7a). Of that total inundated area, 7.1% (101,889 m^2) was free-flowing and 92.9% (1,327,004 m^2) was overflowing. The integrated wetted width increased to 194.1 m from 15.8 m. In an analysis of the 2021 drone-collected imagery when flows were at 0.40 m^3/s, we observed a 45% (1,997,523 m^2) increase in total inundated area, with 62.3% (>3,426,416 m^2) of the valley bottom inundated. Of this 62.3%, 3.2% (>110,528 m^2) of inundation was free-flowing, 96.3% (3,300,537 m^2) was overflowing and 0.5% (>15,350 m^2) was ponded. We observed a 700% increase in the number of active channels and a visible increase in beaver activity with eight new and intact beaver dams actively ponding water.

Although the total surface area of free-flowing inundation decreased from 2009 to 2021, flows were dramatically different between these two time periods (8.07 m^3/s in 2009 vs. 0.40 m^3/s in 2021) and a decrease in inundation was expected. Even with these differences in flow, we observed that ponded and overflow area increased over 11 years by 2846.4%. We also observed that changes to the diversity of inundation types were reflected in an increase of the average SHEI value from an average of 0.007 in 2009 to 0.057 in 2021 (Figure 7b). All measured metrics of change from 2009 to 2021,

TABLE 2 Results of the valley plug imagery analyses (see Table 1) for each year surveyed. Valley bottom length, valley bottom width, and valley bottom area are constant for all three time periods.

Metric	Year		
	2009	2015	2021
Flow at date of imagery (m³/s)			
Max	8.07	0.26	0.40
Min	7.14	0.12	0.28
Valley bottom length constant (km)		7.36	
Valley bottom width constant (km)			
Mean		0.78	
Min		0.55	
Max		1.37	
Valley bottom area constant (km²)		5.5	
Valley gradient			
Grade		0.0016	
Grade in %		0.16	
Angle of elevation		6.95	
Geomorphic unit count			
Confluences	0	7	53
Diffluences	0	7	33
Channels	0	8	56
Riffles	0	8	26
Beaver dams	0	0	6
Large woody debris	0	31	281
Inundation type (area km²)			
Free-flowing	0.12	0.1	0.1
Overflowing	0	1.33	3.3
Ponded	0	0	0.02
Dry	5.38	4.07	2.07
Total inundated area (km²)	0.12	1.43	3.43
% Valley bottom inundation	2.1	26	62.3
% Valley bottom inundation by type			
Free-flowing	0.02	0.02	0.02
Overflowing	0	0.24	0.60
Ponded	0	0	0
Integrated wetted width	15.8	194.14	465.55

Note: Valley bottom length, valley bottom width, valley bottom area, and valley length are constant for all three time periods.

along with site-specific constants are summarized in greater detail in Table 2.

3.4 | Valley plug riparian expansion

The riparian zone increased by >5% between 2009 and 2015, occupying ~16% of the valley bottom (Figure 8). Between 2015 and 2021, riparian vegetation increased by >238%, occupying ~55% of the

valley bottom. In total, the riparian zone increased by 2.2 km² or by >258% after the arrival of the 2010 sediment pulse and corresponding plug. The amount of upland vegetation in the valley bottom shrank by ~96% between 2009 and 2021.

4 | DISCUSSION

We hypothesized the valley plug facilitated the successful restoration of high-quality, complex habitat for native fishes in a desert river tributary of the American Southwest, and the results of this study indicate that the introduction of a channel occlusion and the subsequent hydrologic and geomorphic responses of the riverscape did in fact initiate expansive, positive changes to habitat complexity and persistence. Prior research identified that valley plugs can have negative ecosystem implications including various land-use challenges and alterations to both floodplain and sedimentation dynamics (Fore et al., 2019; Pierce & King, 2008; Shields et al., 2000); however, we observed that in the SRR, the valley plug has facilitated a positive return to near-historic conditions at reach level (~7.36 km). We also observed that variable inundation types can be considered a direct metric of habitat complexity due to the habitat-forming processes accompanying changes in flow. We found this to be especially prevalent in boundary reaches which we defined as habitat found along the edges of the upstream-expanding valley plug (Supplementary Material Appendix 1.1). This habitat in particular contained a diverse distribution of inundation types and complex geomorphic units, and our findings contribute to research that highlights the relationship between inundation patterns, channel mobility, and habitat diversity (e.g., Chone & Biron, 2015; Hohensinner et al., 2014; Tiegs et al., 2005; Supplementary Material Appendix 1.2).

Our discovery of the presence of complex pool habitat as a result of the valley plug is especially significant as prior studies have identified that the lower SRR is extremely pool-limited (Walsworth, 2011). Pool habitat offers refugia from predation for native fishes, as well as lower velocity and thermal refugia during increasingly hot summer months (Murphy et al., 2015). Direct observation demonstrated pools are frequently the only wetted portions of the lower SRR during seasonal drying. During spot sampling that occurred simultaneously with seasonal drying in the SRR in dry years, the only fish remaining for many kilometers of the lower SRR were captured in pools below habitat features such as beaver dams and BDAs (Dan Keller, Utah Division of Wildlife Resources, personal communication, 2021). The presence of large quantities of pool habitat within boundary sites, compared to other habitat types, means that these are some of the only reaches of rivers offering persistent, suitable, and wetted habitat for fishes during drought. Additionally, the large quantities of habitat-forming LWD found throughout the valley plug offer rare and vital refugia for both adult and larval native fishes, ensuring the persistence of spawning and rearing habitat in an otherwise extremely habitat-limited system (Bottcher et al., 2013; Walsworth et al., 2013).

We demonstrated the valley plug and resulting overflow from the main channel into the valley bottom allowed the riparian zone to
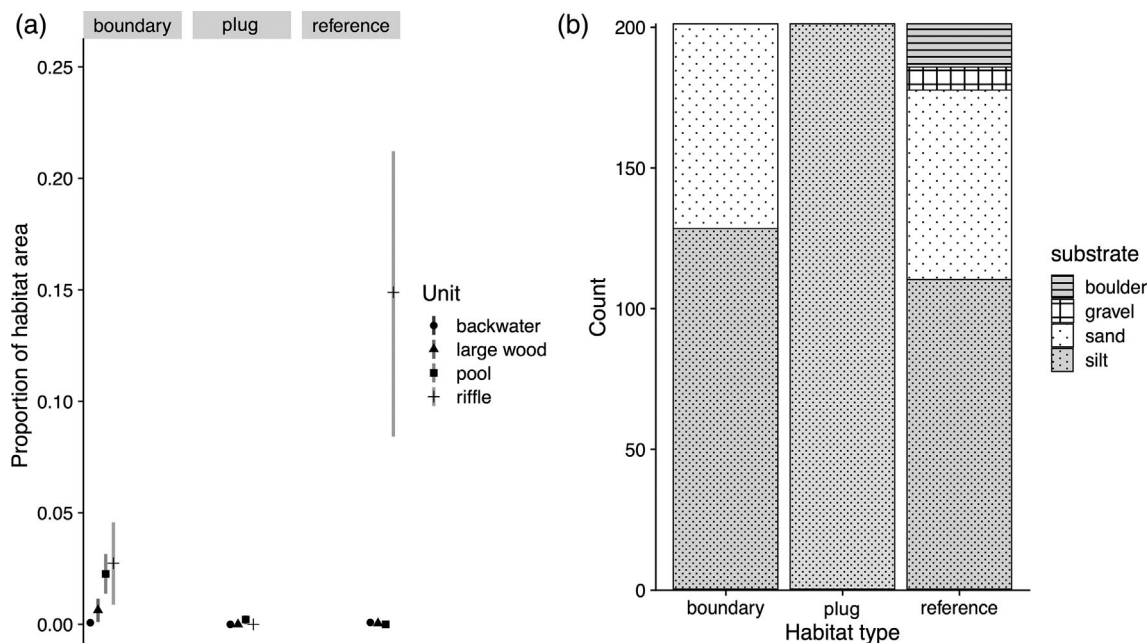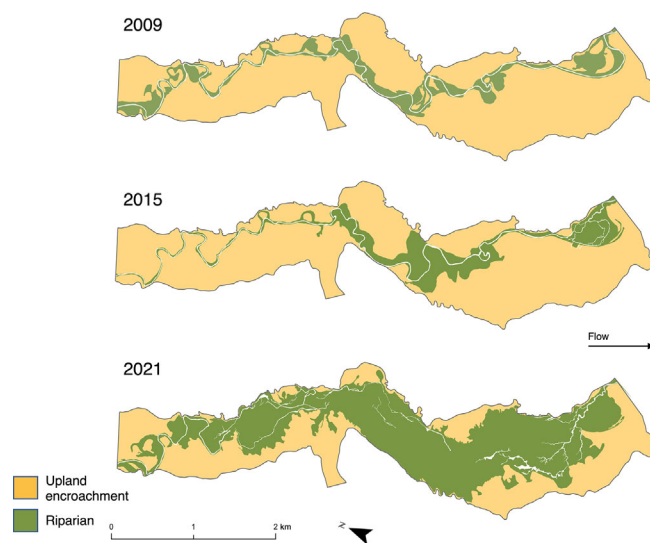
FIGURE 6 Proportion of geomorphic units within each habitat type as a metric of habitat diversity (a) and substrate types by count for the three habitat types (b).
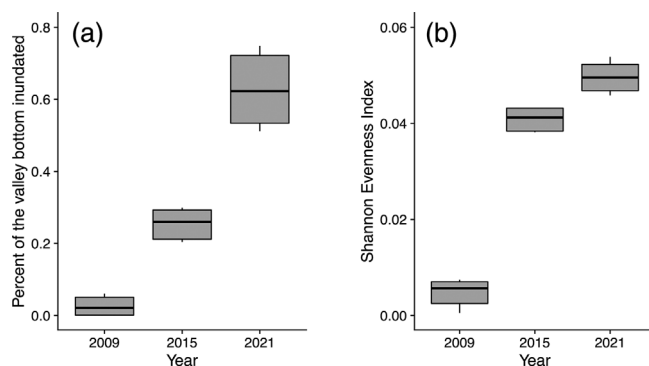
FIGURE 7 (a) Percent valley bottom inundation for three time periods: 2009, 2015, and 2021 for the reach upstream of Cottonwood Wash within the valley plug. (b) Shannon Evenness Index values for total inundation area (m^2) calculated for 2009, 2015, and 2021 surveys upstream of Cottonwood Wash within the valley plug. Each box represents 25%, median, and 75%. The whiskers extend to a maximum of 1.5 interquartile range.

FIGURE 8 Map of vegetation types for three time periods: 2009, 2015, and 2021 upstream of Cottonwood Wash within the valley plug. Vegetation types are split into riparian and upland encroachment. [Color figure can be viewed at wileyonlinelibrary.com]

increase substantially over 11 years, recolonizing areas of upland encroachment and potentially contributing to habitat persistence in the face of exacerbated regional drying. A large base of research points to drought, in combination with over-allocation of developed water, as the major driver of shrinking vegetated zones in arid and semi-arid systems (e.g., Andersen, 2016; Garssen et al., 2014; Stromberg et al., 2007). Nonetheless, further research indicates the role of ephemeral wetlands in ecosystem persistence in the face of extreme drought (Leigh et al., 2010; Sandi et al., 2020). The presence of dryland wetlands allows arid or semi-arid riverscapes to exist as isolated refugia during periods of extreme drought, with low flow

channels providing short-term connections between otherwise isolated sections of the river network. Additionally, riparian vegetation presence reduces the rates of evaporation, contributing to water retention in dryland systems (Rodrigues et al., 2021).

Though we cannot make a definitive claim that this system has experienced increased resilience, visual estimates and delineation of the riverscape demonstrate the valley plug has facilitated an increased capacity for water retention beyond what is typical during drying.

From imagery collected in 2021, we observed the system was retaining overflow inundation well into the expanded riparian zone through late-August, prior to summer monsoon flooding. Prior research monitoring the success of translocated beavers in the SRR suggests that ecosystem engineering by beavers has also facilitated extended water residence times (Doden et al., 2022). Given what is known about the importance of dryland wetland systems in arid and semi-arid regions, it is logical to suggest that this valley plug is contributing to habitat persistence in the face of amplified drought in the American Southwest (Sandi et al., 2020; Stromberg et al., 2007).

The use of intentional channel occlusions in systems like the SRR have not been previously explored as a restoration practice; therefore, there have been limited attempts made to quantify restoration success in highly simplified desert river streams at the scale we observed (Doden et al., 2022; Laub et al., 2020; Macfarlane, Gilbert, et al., 2017; Macfarlane, McGinty, et al., 2017). By utilizing historic accounts of the SRR, we were able to compare the evolution of this system over time to a straightforward baseline of Stage-0 condition. Additionally, our use of relatively simple metrics of complexity (valley bottom extent, inundation, vegetation, geomorphic units, and SHEI) allowed us to easily quantify the extensive changes this system underwent. Historic accounts of the SRR valley during the early 20th century describe a highly sinuous and braided stream-wetland complex with abundant native cottonwoods, willows, and sedges, suggesting the water table was near the surface in much of the valley similar to what we have observed over the past decade with the evolution of the valley plug (Fortney et al., 2011). Taking these early observations into account, we conclude the conditions surrounding the valley plug are very similar to the historic late 19th and early 20th century condition of the SRR, and that the river has shifted from a Stage III degraded riverscape to the anastomosing grassed wetland or Stage-0 of the nine-stage Stream Evolution Model identified by Cluer and Thorne (2014).

4.1 | Conclusion

The results of this study indicate that the addition of large amounts of sediment to the lower SRR at Cottonwood Wash facilitated a valley plug that encouraged bank destabilization, promoted beaver dam building, allowed for channel avulsion, and aided in riparian-wetland expansion that resulted in complex habitat that has benefitted native and imperiled fishes (Remiszewski, 2022). We also suggest that the resulting increased area of inundation has enhanced the resiliency of this riverscape to drying during exacerbated drought. Traditional stream restoration approaches are typically too expensive, small in size, and much less dynamic than what has taken place naturally on the SRR (Skidmore & Wheaton, 2022). This realization has led us to believe that to facilitate the historic, Stage-0 stream-wetland conditions of Southwestern desert river tributaries, there would need to be an increased emphasis on valley-scale, process-based approaches to restoration (Ciotti et al., 2021; Skidmore & Wheaton, 2022;

Wohl, 2019). If intentional process-based restoration actions were taken on the valley-plug scale, we would likely see the creation and maintenance of additional complex habitat, further improving recruitment and persistence of the native and endangered fishes of the Upper CRB and contributing to ecosystem resilience in the face of worsening climate change (Fairfax & Whittle, 2020).

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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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.