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

Tansy T. Remiszewski[1], Phaedra Budy[1], and William Macfarlane[1]

[1]Utah State University SJ and Jessie E Quinney College of Natural Resources

December 26, 2022

**Abstract**

Widespread hydrologic alterations have simplified in-stream habitats in rivers globally, driving population declines and local 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 habitat changes due to the valley plug. Our results demonstrate that in 2021, the valley plug reach was more diverse than any other stream reach along the SRR, containing 641% more diverse habitat (e.g., pools, riffles, 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 2,800%. 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.

### "Novel Habitat Diversification in the San Rafael River, Utah"

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

Tansy T. Remiszewski[1,2,]11[3]P.O. Box 215, Hardwick, MA 01037[*], Phaedra Budy[2,1], and William W. Macfarlane[1]

[1]*Department of Watershed Sciences & The Ecology Center, Utah State University, 5210 Old Main Hill, Logan, UT, 84322, USA*

[2]*U.S. Geological Survey, Utah Cooperative Fish and Wildlife Research Unit, Utah State University, 5210 Old Main Hill, Logan, UT, 84322, USA*

*Corresponding author

Email: tansyremiszewski@gmail.com

### Acknowledgements

This work was funded primarily by the Bureau of Reclamation and the Bureau of Land Management. The U.S. Geological Survey (USGS) and the Utah Division of Wildlife Resources provided substantive in-kind support including equipment, and additional financial support was provided by The Ecology Center at Utah State University. We thank Gary Thiede for his extensive logistical support, Peter MacKinnon for technical and equipment support, the USU Ecogeomorphology and Topographic Analysis Lab, specifically Cashe Rassmussen, for assistance with experimental design, as well as our many technicians and volunteers who have assisted in both the field and lab. We also thank Timothy Walsworth and Casey Pennock for their analytical support. This study was performed under the auspices of the USFWS ESA Section 10 permit No. TE08832A-1 and USU IACUC protocol No. 10057. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the United States Government.

## Abstract

*Key words: channelization, valley plug, fluvial geomorphology, Colorado River Basin, ecosystem services, native fishes*

Widespread hydrologic alterations have simplified in-stream habitats in rivers globally, driving population declines and local 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 habitat changes due to the valley plug. Our results demonstrate that in 2021, the valley plug reach was more diverse than any other stream reach along the SRR, containing 641% more diverse habitat (e.g., pools, riffles, back-waters) 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 2,800%. 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.

## Introduction

Globally, rivers have been severely altered over the last century due to human population growth, accelerating economic activity, land-use alteration, water development and climate change that have all interrupted fluxes of water, sediment and nutrients (Dynesius and Nilsson, 1994; Ward, Tockner, & Schiemer, 1999; Syvitski, Kettner, Correggiari, & Nelson, 2005), simplified the physical structure of habitats and floodplains (Beechie, Beamer, & Wasserman, 1994; Hohensinner, Jungwirth, Muhar, & Habersack, 2005), and degraded habitat and water quality in river systems by the loading of nutrients and pollutants (Williams, Cook, & Smerdon, 2021). These impacts to watersheds and rivers have altered riverine ecosystems dramatically and, as a result, the freshwater biodiversity of North America has become increasingly threatened. Especially severe impacts of ecosystem stressors can be observed in the dryland systems of the American Southwest where water is scarce relative to demand and there has been a growing urgency over the past few decades amongst managers and stakeholders for a more holistic approach to river management and restoration (Laub, Jiminez, & Budy, 2015).

In arid or semi-arid rivers, reduction in the frequency and/or magnitude of seasonal floods 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 (Vorosmarty et al., 2010; Castle et al., 2014; Udall & Overpeck, 2017). This degradation process is especially prevalent in the arid American Southwest, where four of the 14 fish species native to the Colorado River are considered threatened or endangered under the Endangered Species Act (ESA; Rinne & Minckley 1991; Laub et al., 2015). Remediating threats to the persistence of native biota in Southwest desert rivers will likely require coupled management of flow regimes and active in-channel restoration efforts in order to preserve and maintain crucial habitat (Propst, Gido, & Stefferud, 2008; Pennock, Ahrens, McKinstry, Budy, & Gido, 2021).

The San Rafael River (SRR), a tributary of the Green River in the Colorado River Basin (CRB), is representative of many desert river systems, in that an altered flow regime, fish passage barriers, degraded habitat, and nonnative fish and vegetation have combined to synergistically alter ecosystem processes and threaten the persistence of native communities (Macfarlane et al., 2017; Olden & Poff, 2005; Stromberg, Beauchamp, Dixon, Lite, & Paradzick, 2007). In an attempt to mitigate degradation, an adaptive restoration and monitoring plan was developed (Laub, Jiminez, & Budy, 2013), and there have been a few small-scale restoration projects that include the installation of beaver dam analogs (BDAs) and post-assisted log structures (PALS), as well as tamarisk removal (Keller, Laub, Birdsley, & Dean, 2015). However, mitigation goals in the SRR have tended to focus on reach-scale restoration, and the potential role of valley plugs and avulsions in restoration-conservation efforts had not been previously considered. Additionally, restoration efforts are challenged by the large spatial extent of degraded habitat (> 64 km), the lack of adequate funding for system-wide restoration and, most recently, by pervasive drought and the over-allocation of water within the watershed.

In July 2010, a severe rain event caused flash-flooding in Cottonwood Wash, a tributary of the SRR (Lyster, 2018). This rain event coincided with low flows and reduced sediment transport capacity in the SRR, resulting in the deposition of a valley plug at the confluence with Cottonwood Wash. The term 'valley plug' was coined by Happ, Rittenhouse and Dobson (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-thread channel that began at the confluence with Cottonwood Wash and rapidly expanded upstream (Lyster, 2018). Root masses of invasive species such as tamarisk ( *Tamarix ramosissima* ) 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. Water retention further facilitated expansion of this wide, shallow and heterogenous reach of river, which appeared to be contributing to dramatic habitat diversification within the system and, as of 2021, had continued to expand upstream.

The SRR valley plug offered a unique opportunity to examine the impacts of potential large-scale innovative restoration actions in a historically degraded desert tributary system. We predicted that the resulting rapid geomorphic change contributed to both habitat diversification and increased floodplain inundation, and was actively creating opportunities for native fish persistence. Our research objective was to determine if the valley plug had contributed to both an increased diversity of habitat types and an improved capacity for water retention against a background of otherwise extremely simplified and degraded desert river habitat. To address these aims, we calculated straightforward metrics of habitat diversity utilizing on-the-ground habitat sampling, as well as manual landscape feature digitization using Google Earth and drone-collected orthomosaic imagery.

## Methods

### 2.1. Study Area

The SRR is located in south-central Utah and is a tributary of the Green River in the upper CRB (Figure 1). Like many desert river tributaries in the arid southwestern United States, the SRR has experienced a number of anthropogenic perturbations like dams, diversions and intensifying climate shifts. These impacts have significantly altered its natural hydrograph of high-magnitude, long-duration spring snowmelt-driven floods and short-duration, monsoon-driven floods in late summer and early fall (Webb & Betancourt, 1990; Fortney, Schmidt, & Dean, 2011; Laub et al., 2013). The presence of reservoir and water-diversion systems upstream on the SRR's three tributaries causes the SRR to be one of the most overallocated basins in Utah, where these reservoirs can hold back all spring runoff with exception to those years with abundant snowfall and snowmelt (Fortney et al., 2011). Another significant impact to the SRR riverscape includes the invasion of nonnative tamarisk and Russian olive (*Elaeagnus angustifolia* ), which has contributed to vertical accretion of fine sediments, enhanced streambank stabilization, channel narrowing and planform simplification (Manners, Schmidt, & Scott, 2014). The loss of a natural flow regime, as well as the invasion of nonnative vegetation, has caused the SRR to change from heterogenous, diverse and multi-threaded system to a highly aggraded, simplified and homogenous riverscape (Walker & Hudson, 2004; Pennock et al., 2021;). Specifically, between 1938 and 2009, the system has narrowed 83% in the lower 90 km, and the floodplain has vertically accreted between 1.0 and 2.5 m (Fortney et al., 2011). Reduced flow and exacerbated channel simplification have also collectively altered habitat for native and endemic fishes, significantly reducing the quality and availability of complex habitat required for spawning, feeding, resting and rearing necessary for their persistence (Bottcher, Walsworth, Thiede, Budy, & Speas, 2013; Walsworth, Budy, & Thiede, 2013).

### 2.2. Sample Design

We conducted a preliminary field study in 2020 where we selected six 300 m sample reaches that were representative of: a) the historically degraded habitat found in the lower SRR, b) boundary habitat located along the edges of the valley plug and c) habitat located within the valley plug. Each of the three habitat types were represented by two of the six sample reaches. In each reach, we measured mesohabitat composition by estimating the area of geomorphic units within each reach (i.e., glide-runs, pools, backwaters, riffles and large wood accumulation) and calculated percent-area of each type.

In analysis of geomorphic change over time, as well as habitat persistence in the form of floodplain inundation, we used modified methods from the Riverscape Inundation Mapper tool (RIM; Bartelt, 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. The digitization of visible features from high-resolution orthoimagery is a widely used method in landscape analysis (e.g., Carbonneau, Fonstad, Marcus, & Dugdale, 2012; Carbonneau et al., 2020; Donovan et al., 2019; Green, Hagon, Gómez, & Gregory, 2019), and we used the approach to examine geomorphic change resulting from the valley plug and the persistence of this feature over time.

To establish a baseline of geomorphic condition in the lower 90 km of the SRR, we chose two degraded and laterally-confined or partly-confined reference reaches, one upstream of Spring Canyon and the other upstream of Moonshine Wash (Figure 1). Selection of these reference reaches was access-limited due to a lack of roads and the rugged terrain of the region. The selected reaches were similar in length to the valley plug (7.36 km) and were intended to represent simplified and degraded habitat, offering context for metrics of change within the valley plug. For each reference reach, 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 equally spaced segments, 4) quantified the metrics from each segment and 5) calculated measurements of variance for each site (see Table 2). We repeated these data capture methods over two time periods: 2009 and 2015, chosen because these time steps allowed us to examine significant change over time pre- and post- valley plug formation. We then repeated these data capture methods for the Cottonwood Wash valley plug over three time periods: 2009 (pre-valley plug), 2015 and 2021.

#### 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 20 mph. 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 (June 6, 2009, and April 2, 2015; Maxar Technologies, State of Utah, USDA/FPAC/GEO; ˜0.15m resolution) to capture conditions prior to 2021 and for our reference reaches: Moonshine Wash and Spring Canyon.

We collected UAV imagery on September 23, 2021. Flows for the UAV imagery were a maximum of 0.40 and a minimum of 0.30 cms. Historic imagery flows were a maximum of 8.10 and a minimum of 7.14 cms for 2009, and a maximum of 0.26 and a minimum of 0.12 cms for 2015. Flows were measured at US Geologic

Survey (USGS) gauge #09328500 San Rafael River near Green River, Utah.

2.2.2. Site Characterization and Mapping

To contextualize baseline conditions for the SRR, as well as the relative impact of the Cottonwood Wash valley plug, we mapped valley bottom extents (Fryirs, Wheaton, & Brierly, 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 active floodplain and could plausibly flood in the contemporary flow regime (Wheaton, Bennett, Bouwes, Maestas, & Shahverdian, 2019). We used multiple lines of evidence to delineate the valley bottom margins for the study reaches including satellite imagery, Digital Elevation Models (DEMs) and field observations of the surrounding landscape. We assumed the valley bottom extents are constant in order to establish a consistent basis for normalization (Bartelt, 2021). Next, we interpolated a valley bottom center line and used this to characterize valley bottom or site length. We calculated integrated valley bottom width for target sites by dividing 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 (described in greater detail below; Wheaton et al., 2015).

We also conducted a slope analysis for the valley plug and each of the reference reaches. The following equation was used to calculate the slope of the valley centerline

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

*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.

2.2.3. Mapping Inundation

For each survey, 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 inundation area uncertainty for each survey based on the resolution of the imagery used to digitize survey features. This procedure resulted in two separate buffered polygons representing 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 (free-flowing) to more lentic (ponded, but still flowing). 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 inundated area by the valley bottom area which gave us 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 (a proxy for habitat complexity), we used the Shannon's Evenness Index (also referred to as Shannon Equitability or Shannon Evenness) 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 Shannon's Evenness Index value is calculated as follows:

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

*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, overflow) and dry conditions.

2.4.4. Mapping Tier 1 and Tier 2 Geomorphic Units

Wheaton et al. (2015) defines the primary tier 1 geomorphic units that comprise the riverscape or valley bottom as the river's floodplain and channel(s). In our study, we used the presence of upland plant species as an indicator of floodplain activity vs. inactivity. Within these classifications, we defined active 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 diversified habitat and were visible at 1:450 zoom (e.g., confluences, diffluences, riffles and woody debris structures; Palmer et al., 2009; Horan, Kershner, Hawkins, & Crowl, 2000). We classified large wood 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 these within the riverscape through visual estimation via digital imagery. When possible, we confirmed the presence and form of tier 2 geomorphic units through on-the-ground field surveys.

2.4.5. Mapping Riparian and Upland Vegetation

We mapped upland and riparian vegetation in ArcGIS, using the same method described earlier where the presence of upland species was used as an indicator of floodplain activity vs. inactivity. A visual estimate was taken of the boundary between upland and riparian vegetation and a polygon was drawn around each respective vegetation type in order to calculate area. Non-vegetated river channels were not included in our survey. We conducted these measurements for each of our survey years for both the valley plug and our reference reaches.

*2.4.6.* ***Pebble Counts***

In addition to habitat composition mapping, in each reach we examined substrate composition by conducting pebble count surveys (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.

## Results

We first explore results for individual sites that were sampled as part of a 2020 on-the-ground field study. Next, we demonstrate the results for reference reaches selected within the lower SRR to set a baseline for degradation in the lower river. Lastly, we report the summary results for the valley plug, including site specific results for geomorphic units and inundation.

3.1. 2020 Field Study

Our results demonstrate the wash habitat feature is more physically diverse than any other river segment along the lower SRR with wash and boundary habitat reaches containing 17% more unique geomorphic units (e.g., pools, riffles, backwaters) on average than reference reaches, with 70% of primary wash 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 2). Our reference sites contained >800 $m^2$ of riffle habitat and only a very small area (<7 $m^2$) of large woody debris (Figure 2A). 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 large woody debris and a very small section (4 $m^2$) of backwater habitat. On average, boundary habitat contained >1,100% 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 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 2B).

### 3.2. Reference Reach Delineation

For both reference reaches, imagery for 2009 (pre-valley plug) was collected in August when flows were at 8.07 cms, and imagery for 2015 was collected in July when flows were at 0.26 cms. The slope of our Spring Canyon reach was .0015 (Table 1). The valley bottom measured 2.26 $km^2$, of which ˜5% (112,676 $m^2$) 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% (85,199 $m^2$) 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 ˜1,577% more inundated habitat in 2015 (Figures 3A and 3B). The valley plug also contained ˜0.67 $km^2$ more riparian habitat as compared to the Spring Canyon reference reach in 2009, and 0.7 $km^2$ more riparian habitat in 2015 (Figures 4A and 4B).

We found that the Moonshine Wash reference reach had a slope of .0016 (Table 1), with ˜75,227 $m^2$ of inundated habitat in 2009, occupying ˜6% (75,227 $m^2$) of its 1.13 $km^2$ valley bottom. In 2015, inundation was reduced to ˜5% (60,556 $m^2$) of the valley bottom. The valley plug contained 54% more inundated habitat as compared to the Moonshine Wash reference reach in 2009, and ˜2,259% more inundated habitat in 2015 (Figures 3A and 3C). We observed an increase in the number of geomorphic units found in the Moonshine Wash reference reach, containing 43 riffles and 27 large woody debris structures in 2015, compared to zero in 2009. Riparian habitat did not change significantly between 2009 and 2015 in the Moonshine Wash reach, and the valley plug contained an average 0.7 $km^2$ (Figures 4A and 4C) more riparian habitat than the Moonshine Wash reach during both 2009 and 2015.

### 3.3. Valley Plug Inundation

The valley plug reach of river measured as 5.5 $km^2$(7.36 km) with a slope of .0016 (Figure 5; Table 2). We collected and analyzed imagery from 2009 (pre-valley plug) which showed that at moderate flow (8.07 cms), 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 spring of 2015 from Google Earth during a low flow period (0.26 cms). Inundation increased from 2.1% to 26% (1,428,893 $m^2$) of the valley bottom (Figure 6A). Of that total inundated area, 7.1% (101,889 $m^2$) was free-flowing and 92.9% (1,327,004 $m^2$) was overflowing. Integrated wetted width increased to 194.1 m from 15.8 m. In analysis of the 2021 drone-collected imagery when flows were at 0.40 cms, 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 observed 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 cms in 2009 versus 0.40 cms in 2021), and a decrease in inundation was expected. Even with these dramatic differences in flow, we observed that ponded and overflow area increased over 11 years by 2,846.4%. We also observed that changes to the diversity of inundation types were reflected in an increase of the average Shannon's Evenness Index value from an average of 0.007 in 2009 to 0.057 in 2021 (Figure 6B). All measured metrics of change from 2009 to 2021, along with site-specific constants are summarized in greater detail in Table 2.

### 3.4. Valley Plug Geomorphic Units and Vegetation Survey

We found that the valley plug underwent a 641% increase in more diverse geomorphic units from 2015 to 2021 (Figure 7). Specifically, we observed a 657% increase in confluences, a 371% increase in diffluences, an ˜861% increase in large woody debris structures and a 225% increase in riffle habitat. The riparian zone increased >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 $km^2$ 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.

## Discussion

The results of this study indicate the introduction of a channel occlusion and the subsequent hydrologic and geomorphic responses of the riverscape have initiated expansive, positive changes to habitat diversity. Prior research identified that valley plugs can have negative ecosystem implications including various land-use challenges and alterations to both floodplain and sedimentation dynamics (Shields Jr., Knight, & Cooper, 1999; Pierce & King 2008; Fore, Alford, Blackwood, & Blanchard, 2019); however, we observed that in the SRR, the valley plug has facilitated a positive return to near-historic conditions. Accounts of the SRR valley during the early 20th century describe abundant cottonwoods, willows, sedges, and wetlands suggesting the water table was near the surface in much of the valley, similar to what we have seen over the past decade with the evolution of the valley plug (Fortney et al., 2011). Early surveys of the lower SRR also observed a highly sinuous, braided system with multiple low flow channels within the wide active channel (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 $19^{\mathrm{th}}$and early $20^{\mathrm{th}}$ century condition of the SRR, where 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. Valley Plug Persistence and Expansion

We believe that the valley plug has been able to persist and expaFnd over the past decade due to the SRR being largely a low gradient system in the lower 90 km, with a wide and less rugged valley bottom than other tributaries of the basin (Fortney et al., 2011). Due to this low gradient, the SRR is also a fairly low velocity river with exception to seasonal flooding, and the wide valley bottom offers the river a greater opportunity to meander if given floodplain access. The lack of consistent high velocity flows and the wide, relatively flat valley bottom likely offered the perfect landscape for the valley plug to persist. When a large magnitude flash flooding event resulted in a channel occlusion in June of 2010, the ensuing flooding likely drained much less quickly than it would have in a higher gradient system, allowing the valley plug to evolve and expand.

In addition to its gradient, the SRR has a densely vegetated floodplain, consisting primarily of non-native tamarisk (Macfarlane et al., 2017). Though colonization by nonnative vegetation often carries negative consequences, dense root masses could be a significant contributor to the persistence of the valley plug by maintaining the near-floodplain water surface levels of the newly formed channels and preventing the upstream migration of channel headcuts. Beaver are also prevalent in this system, both presently and were prior to the development of the valley plug, and their presence has been associated with valley plug maintenance and expansion. Prior research monitoring the success of translocated beavers in Utah desert river tributaries, including the SRR, identified that river reaches containing beaver populations experienced a greater density of dams and woody debris structures (Doden, Budy, Avgar, & Young, 2022). Many translocated beavers, as well as resident beaver populations, in the SRR were located within the valley plug itself, where they were known to contribute to drought-specific resilience in this system. This is due to the fact that, even at low flows, beaver dams will continue to pond water, which we directly observed during the summer of 2021 (Bartelt, 2021; personal observation, 2021). We surmise that ecosystem engineering by beaver facilitated an increase of inundated area, thereby extending water residence times during increasingly dry periods and continually expanding the available area for geomorphic change to occur as well as refugia for fishes.

### 4.3 Inundation Patterns and Diverse Habitat Structures as a Driver of Complexity

Our use of ponded, overflow and free-flowing as the delineated inundation types is based on known physical changes occurring as a result of structural forcing through changes in channel morphology, the presence of large wood, and increased beaver activity (Naiman, Johnston, & Kelley, 1988; Johnson, Renik, Windels, & Hafs., 2018; Bartelt, 2021). Variable inundation types can be considered a direct metric of habitat complexity, due to the habitat forming processes that accompany changes in flow. Our conclusions are supported by the flood pulse concept proposed by Junk, Bayley and Sparks (1989), wherein floodplains are characterized as being periodically flooded by lateral overflow of the main course of a river, forming a mosaic of lotic habitats that consist of channels and lentic features, along with the seasonally inundated floodplain (Girard, Fantin-Cruz, Loverde de Oliveira, & Hamilton, 2010). Combined seasonal flood pulses and the spatially variable physical structures they produce result in a spatiotemporally variable mosaic of habitat-forming structures, flow paths and inundation hydroperiods (Junk et al., 1989; Mertes, 1997; Poff et al. 1997). This variability inherent to the flood pulse concept is a key driver of ecological complexity that is often most apparent in the biotic and abiotic responses of the surrounding ecosystem. We found this to be especially prevalent in our riverscape, where a diverse distribution of inundation types and complex geomorphic units throughout our target reach of river support research that highlights the relationship between inundation patterns, channel mobility and habitat diversity (e.g., Tiegs, O'Leary, Pohl, & Munill, 2005; Hohensinner Jungwirth, Muhar, & Schmutz, 2014; Chone & Biron, 2016).

We considered substrate type as one potential metric of habitat diversity in our analyses of wash, reference and boundary habitat based on limited pebble count surveys. We observed that reference reaches contained more diverse substrate types than boundary habitat; however, we want to emphasize that our reach selection was limited by access in an incredibly remote region of south-central Utah. As a result, we were limited to reference reaches where access was often correlated with factors in the surrounding landscape that often affect substrate in these desert rivers (e.g., tributary junctions, anthropogenic structures and proximity to the confluence with the Green River; Walsworth et al., 2013), and these impacts likely had significant effects on channel morphology, habitat condition and geomorphic complexity. We suggest that the remainder of degraded habitat along the lower SRR, where these factors are not as prevalent, would experience less diversity in substrate type.

4.3. Diversity Metrics in Boundary Habitat

Our discovery of geomorphically-complex boundary habitat was especially significant in the discussion of landscape mosaics as a measure of riverscape complexity. We defined boundary habitat in this study as habitat found along the edges of the upstream-expanding valley plug. Overall, we found this habitat to be the most complex, containing all of the geomorphic units we had identified as metrics of diversity (pools, riffles, backwaters and large woody debris structures; Bottcher, 2009) as well as the most diverse array of inundation types. These findings support our initial suggestions that: 1) boundary habitat is the most diverse within this system (Remiszewski, 2022) and 2) the valley plug has contributed to ecosystem habitat diversity, especially when compared to our simplified and degraded reference reaches. Especially significant is the presence of pool habitat, as prior studies have identified that the lower SRR is incredibly pool limited (Walsworth, 2011).

Pool habitat offers refugia from predation for native fishes, as well as thermal refugia during increasingly hot summer months (Murphy, Pavlova, Thompson, Davis, & Sunnucks, 2015). Direct observation demonstrated pools are frequently the only wetted portions of the lower SRR during seasonal drying and, during spot sampling that occurred simultaneously with seasonal drying in the SRR, the only fish remaining for many kilometers of the lower SRR were captured in pools below habitat features such as beaver dams and BDAs (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 river offering persistent habitat for fishes during drought. Additionally, the large quantities of large woody debris found in boundary reaches 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).

4.4. Riparian Vegetation as an Indicator of Habitat Persistence

A large base of research points to drought as the major driver of shrinking vegetated zones in arid and semiarid systems (e.g., Stromberg et al., 2007; Garssen, Verhoeven, & Soons, 2014; Andersen, 2016); however, further research indicates the role of ephemeral wetlands in ecosystem persistence in the face of extreme drought (Leigh, Sheldon, Kingsford, & Arthington. 2014; Sandi et al., 2020). The presence of dryland wetlands allows arid or semiarid 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, the presence of riparian vegetation reduces the rates of evaporation, contributing to water retention in dryland systems (Rodrigues, Gomes Costa, Raabe, Medeiros, & Carlos de Araújo, 2021).

We demonstrated the valley plug and resulting overflow from the main channel into the valley bottom allowed the riparian zone to increase substantially over 12 years. 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 experienced an increased capacity for water retention beyond what is typical during drying. We observed from imagery collected in 2021 that the system was retaining overflow inundation well into the expanded riparian zone through late-August, prior to summer monsoon flooding. Given what is known about the importance of riparian vegetation, as well as dryland wetland systems in arid and semiarid 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.

4.5. Conclusion

The results of this study indicate that the addition of large amounts of sediment to the lower SRR at Cottonwood Wash facilitated the occlusion of the main river channel, encouraged bank destabilization, promoted beaver dam building, allowed for channel avulsion and aided in riparian wetland expansion across the entire valley bottom that resulted in complex habitat that has benefitted native and imperiled fishes (Remiszewski, 2022). We also suggest that an increased area of inundation has enhanced the capacity of this riverscape to retain water for periods longer than expected during extended drought. Traditional stream restoration approaches are typically too expensive and small in size to match what has taken place naturally on the SRR (Skidmore & Wheaton, 2022). This realization has led us to believe that in order to promote large-scale, habitat-forming and ecologically beneficial restoration in desert river tributaries, there needs to be an increased emphasis on large-scale, process-based approaches to restoration (Wohl, 2019; Ciotti, Mckee, Pope, Kondolf, & Pollock, 2021; Skidmore & Wheaton, 2022). If intentional process-based restoration actions were taken on the scale of channel occlusions and valley plugs, we would likely see the creation and maintenance of additional complex habitat, further improving the recruitment and persistence of the native and endangered fishes of the Upper CRB, and contributing to resiliency and refugia in the face of worsening climate change (Fairfax & Whittle, 2020).

**References**


Andersen, D.C. (2016). Climate, streamflow, and legacy effects on growth of riparian Populus

angustifolia in the arid San Luis Valley, Colorado. *Journal of Arid Environments*, 134, 104–121.

Balian, E., Segers, H., Lévêque, C., & Martens, K. (2008). The Freshwater Animal Diversity Assessment: An overview of the results.*Hydrobiologia* , 595, 627–637. Bartelt, K. (2021). Valley Bottom Inundation Patterns in Beaver-Modified Streams: A Potential Proxy for Hydrologic Inefficiency. MS Thesis, Utah State University, Logan, UT. Barnett, T.P., & Pierce, D.W. (2009). Sustainable water deliveries from the Colorado River in a changing climate. *PNAS* , 106(18).

Beechie, T., Beamer, E., & Wasserman, L. (1994). Estimating Coho Salmon Rearing Habitat and

Smolt Production Losses in a Large River Basin, and Implications for Habitat Restoration. *North American Journal of Fisheries Management,* 14(4), 797–811.

Bellmore, J.R., & Baxter, C.V. (2014). Effects of geomorphic process domains on river ecosystems: A comparison of floodplain and confined valley segments. *River Research and Applications* , 30(5). Benke AC. (1990). A perspective on America's vanishing streams.

*Journal of the North*

*American Benthological Society*, 977–988.

Bottcher, J.L. (2009). Maintaining population persistence in the face of an extremely altered hydrograph: implications for three sensitive fishes in a tributary of the Green River, Utah. M.S. Thesis, Utah State University, Logan, UT. Bottcher, J.L., Walsworth, T.E., Thiede, G.P., Budy, P., & Speas, D.W. (2013). Frequent Usage

of Tributaries by the Endangered Fishes of the Upper Colorado River Basin: Observations from the SRR, Utah. *North American Journal of Fisheries Management*, 33(3), 585–594.

Bouwes, N., Weber, N., Jordan, C.E., Saunders, W.C., Tattam, I.A., Volk, C., Wheaton, J.M., &

M.M. Pollock, M.M. (2016). Ecosystem experiment reveals benefits of natural and simulated beaver dams to a threatened population of steelhead (*Oncorhynchus mykiss*). *Scientific Reports*, 6.

Carbonneau, P., Fonstad, M.A., Marcus, W.A., & Dugdale, S.J. (2012). Making riverscapes real. *Geomorphology* , 137(1), 74-86. Carbonneau, P. E., Belletti, B., Micotti, M., Lastoria, B., Casaioli, M., Mariani, S., Marchetti, G.,

& Bizzi, S. (2020). UAV-based training for fully fuzzy classification of Sentinel-2 fluvial scenes. *Earth Surface Processes and Landforms*, 45(13), 3120–3140.

Castle, S.L., Thomas, B.F., Reager, J.T., Rodell, M., Swenson, S.C., & Famiglietti, J.S. (2014).

Groundwater depletion during drought threatens future water security of the Colorado River Basin. *Geophysical Research Letters,* 14(16), 5904–5911.

Chone, G., & Biron, P.M. (2015). Assessing the Relationship Between River Mobility and

Habitat. *River Research and Applications*, 32(4), 528–539.

Ciotti, D.C., Mckee, J., Pope, K.L., Kondolf, G.M., & Pollock, M.M. (2021). Design Criteria for

Process-Based Restoration of Fluvial Systems. *BioScience*, 71(8), 831–845.

Cluer, B., & Thorne, C.R. (2014). A Stream Evolution Model Integrating Habitat and

Ecosystem Benefits. *River Research and Applications,* 30(2).

Cushman, R.M. (1985). Review of ecological effects of rapidly varying flows downstream from hydroelectric facilities. *North American Journal of Fisheries Management* , 5, 5330–339.

Dauwalter, D.C., Sanderson, J.S., Williams, J.E., & Sedell, J.R. (2011). Identification and Implementation of Native Fish Conservation Areas in the Upper Colorado River Basin. *Fisheries* , 36(6).

Doden, E., Budy, P., Avgar, T., & Young, J.K. (2022). Movement Patterns of Resident and

Translocated Beavers at Multiple Spatiotemporal Scales in Desert Rivers.*Frontiers in Conservation Science*, 3, 112–127.

Dynesius, M., & Nilsson, C. (1994). Fragmentation and Flow Regulation of River Systems in the Northern Third of the World. *Science* , 26, 753–762. Dudgeon, D. (2000). Conservation of freshwater biodiversity in Oriental Asia: constraints, conflicts, and challenges to science and sustainability. *Limnology* , 1, 237–243. Donovan, M., Belmont, P., Notebaert, B., Coombs, T., Larson, P., & Souffront, M. (2019). Accounting for uncertainty in remotely sensed measurements of river planform change. *Earth-Science Reviews* , 193, 220–236.

Fairfax, E., & Whittle, A. (2020). Smokey the Beaver: beaver-dammed riparian corridors stay

green during wildfire throughout the western United States.*Ecological Applications*, 30, 8.

Fore, J.D., Alford, A.B., Blackwood, D.C., Blanchard, T.A. (2019). Linking fish trait responses to in-stream habitat in reconstructed valley-plugged stream reaches of the Coastal Plain, U.S.A. *Restoration Ecology*, 27(6), 1483–1494.

Fortney, S.T., Schmidt, J.C., & Dean, D.J. (2011). Establishing the geomorphic context for wetland and restoration of the SRR (NRCS Cooperative Agreement #68-3A75-4-155). Intermountain Center for River Rehabilitation and Restoration, Logan, Utah. Fryirs, K., Wheaton, J.M., & Brierley, G.J. (2015). An approach for measuring confinement and assessing the influence of valley setting on river forms and processes. *Earth Surface Processes and Landforms* , 41(5), 701–710. Garssen, A.G., Baattrup-Pedersen, A., Voesenek, L.A., Verhoeven, J.T., & Soons, M.B. (2015). Riparian plant community responses to increased flooding: a meta-analysis. *Global Change Biology* , 21(8).

Garssen, A.G., Verhoeven, J.T.A., & Soons., M.B. (2014). Effects of climate-induced increases

in summer drought on riparian plant species: a meta-analysis.*Freshwater Biology*, 59(5), 1052–1063.

Girard, P., Fantin-Cruz, I., Loverde de Oliveira, S.M., & Hamilton, S.K. (2010). Small-scale spatial variation of inundation dynamics in a floodplain of the Pantanal (Brazil). *Hydrobiologia* , 638, 223–233.

Giraud, R., & McDonald, G. (2013). Damaging debris flows prompt landslide inventory

mapping for the 2012 Seeley fire, Carbon and Emery counties, Utah. Survey Notes (Utah Geologic Survey), 45(3), 1–3.

Green, D.R., Hagon, J.J., Gómez, C., & Gregory, B.J. (2019). Chapter 21 - Using Low-Cost UAVs for Environmental Monitoring, Mapping, and Modelling: Examples from the Coastal Zone, *in* Krishnamurthy, R.R., Jonathan, M.P., Srinivasalu, S., & Glaeser, B. Coastal Management, Academic Press. 465–501.

Happ, S.C., Rittenhouse, G., & Dobson, G.C. (1940). Some principles of accelerated stream and

valley sedimentation. *U.S. Department of Agriculture Technical Bulletin*, 695.

Hohensinner, S., Jungwirth, M., Muhar, S., & Habersack, H. (2005). Historical analyses: A

foundation for developing and evaluating river-type specific restoration programs. *International Journal of River Basin Management,* 3(2), 87–96.

Hohensinner, S., Jungwirth, M., Muhar, S., & Schmutz, S. (2014). Importance of multi- dimensional morphodynamics for habitat evolution: Danube River 1715–2006. *Geomorphology* , 215. Horan, D. L., Kershner, J.L., Hawkins, C.P., & Crowl, T.A. (2000). Effects of habitat area and complexity on Colorado River cutthroat trout density in Uinta Mountain streams. *Transactions of the American Fisheries Society,* 129(6), 1250–1263. Johnson, S.M., Renik, K.M., Windels, S.K., & Hafs, A.W. (2018). A Review of Beaver–

Salmonid Relationships and History of Management Actions in the Western Great Lakes (USA) Region. *North American Journal of Fisheries Management*, 38(6).

Junk, W.J., Bayley, P.B., & Sparks, R.E. (1989). The Flood Pulse Concept in River-Floodplain Systems. *Canadian Journal of Fisheries and Aquatic Sciences* , 106. Keller, D.L., Laub, B.G., Birdsley, P., & Dean, D.J. (2014). Effects of Flooding and Tamarisk

Removal on Habitat for Sensitive Fish Species in the SRR, Utah: Implications for Fish Habitat Enhancement and Future Restoration Efforts. *Environmental Management*, 54, 465–478.

Laub, B.G. (2013). Restoration and Monitoring Plan for Native Fish and Riparian Vegetation on the San Rafael River, Utah. Laub, B.G., Theide, G.P., Macfarlane, W.W., & Budy, P. (2018). Evaluating the Conservation

Potential of Tributaries for Native Fishes in the Upper Colorado River Basin. Fisheries, 43(4), 194–206.

Laub, B., Jimenez, J., & Budy, P. (2015). Application of Science-Based Restoration Planning to

a Desert River System. *Environmental Management*, 55.

Laub, B., Macfarlane, W.W., Walsworth, T.E., Goodell, J., Jimenez, J., Keller, D., Thiede, G.P.,

& Truman, D. (2020). Restoration and monitoring plan for the lower Price River, Utah.

Laurel, D., & Wohl, E. (2019). The persistence of beaver-induced geomorphic heterogeneity and

organic carbon stock in river corridors. *Earth Surface Processes and Landforms*, (44)1, 342–353.

Leigh, C., Sheldon, F., Kingsford, R.T., & Arthington, A.H. (2010). Sequential floods drive

booms and wetland persistence in dryland rivers: A synthesis.*Marine and Freshwater Research*, 61(8), 896–908.

Lyster, S. (2018). SRR Restoration Project Progress Report: Gravel Additions. Unpublished

M.S. thesis, Utah State University, Logan, UT.

Macfarlane, W.W., Gilbert, J.T., Jensen, M.L., Gilbert, J.D., Hough-Snee, N., McHugh, P.A., Wheaton, J.M., & Bennett, S.N. (2017). Riparian vegetation as an indicator of riparian condition: Detecting departures from historic condition across the North American West.*Journal of Environmental Management* , 202, 477–460.

Macfarlane, W.W., McGinty, C.M., Laub, B.G. and Gifford, S.J. (2017), High-resolution

riparian vegetation mapping to prioritize conservation and restoration in an impaired desert river. *Restor Ecol*, 25: 333-341. *https://doi.org/10.1111/rec.12425*

Manners, R.B., Schmidt, J.C., Scott, M.L. (2014). Mechanisms of vegetation-induced channel

narrowing of an unregulated canyon river: Results from a natural field-scale experiment. *Geomorphology,* 211, 100–115.

Mertes, L. (1997). Documentation and significance of the perirheic zone on inundated

floodplains. *Water Resources Research.*

Montgomery, D.L. (1999). Process Domains and the River Continuum. Journal of the American *Water Resources Association* , 35(2).

Murphy, A.L., Pavlova, A., Thompson, R., Davis, J., & Sunnucks, P. (2015). Swimming through

sand: connectivity of aquatic fauna in deserts. Ecol Evol, 5(22), 5252– 5264.

Naiman, R.J., Johnston, C.A., & Kelley, J.C. (1988). Alteration of North American Streams by Beaver. *BioScience* , 38(11), 753–762. Oakland, H.C. (2020). Studying Water from the Air: Using New Measures of Aquatic Habitat to Assess Stream Restoration Outcomes [27739228 M.S.]. University of Maryland, Baltimore County, 173. Olden J.D., & Poff, N.L. (2005). Long-term trends of native and non-native fish faunas in the American Southwest. *Animal Biodiversity and Conservation* , 28, 75–89. Palmer, M., Lettenmaier, D., Poff, N., Postel, S., Richter, B., & Warner, R. (2009). Climate

Change and River Ecosystems: Protection and Adaptation Options.*Environmental Management*, 44, 1053–68.

Pennock, C.A., Ahrens, Z., McKinstry, M., Budy, P., & Gido, K. (2021). Trophic Niches of

Native and Nonnative Fishes along a River-Reservoir Continuum.*Scientific Reports*, 11(1).

Pierce, A.R., & King, S.L. (2008). Spatial dynamics of overbank sedimentation in floodplain

systems. *Geomorphology*, 100, 258–268.

Poff, N., Allan, D.J., Bain, M., Karr, J., Prestegaard, K., Richter, B., Sparks, R., & Stromberg, J. (1997). The Natural Flow Regime: A Paradigm for River Conservation and Restoration. *Bioscience* , 47(11), 769–784.

Potondy, J.P. & Hardy, T. (1994). Use of Pebble Counts to Evaluate Fine Sediment Increase in

Stream Channels. *Journal of the American Water Resources Association*, 30(3).

Pringle, C.M., Freeman, M.C., & Freeman, B.J. (2000). Regional Effects of Hydrologic Alterations on Riverine Macrobiota in the New World: Tropical-Temperate Comparisons: The massive scope of large dams and other hydrologic modifications in the temperate New World has resulted in distinct regional trends of biotic impoverishment. While neotropical rivers have fewer dams and limited data upon which to make regional generalizations, they are ecologically vulnerable to increasing hydropower development and biotic patterns are emerging.*BioScience* , 50(9),807–823 Propst, D.L., Gido, K., & Stefferud, J.A. (2008). Natural flow regimes, nonnative fishes, and native fish persistence in arid-land river systems. *Ecological Applications* , 18(5), 1236– 1252. Pulwarty, R., Jacobs, K., & Dole, R.. (2005). The hardest working river: Drought and critical water problems on the Colorado, in Wilhite, D., ed., Drought and water crises. Science, technology and management. New York, Taylor and Francis Press. p. 249–285.

Remiszewski, T.T. (2022). Extreme, Positive Geomorphic Change in a Historically Degraded

Desert River: Implications for Imperiled Fishes. MS Thesis, Utah State University, Logan, UT.

Rinne, J.N., & Minckley, W.L. (1970). Native Arizona Fishes Part III "Chubs". *Arizona Game and Fish Publication* , 17, 12–19. Rodrigues, I.S., Gomes Costa, C.A., Raabe, A., Medeiros, P.H. & Carlos de Araujo, J. (2021). Evaporation in Brazilian dryland reservoirs: Spatial variability and impact of riparian vegetation. *Science of the Total Environment* , 797. Sandi, S.G., Sacoa, P.M., Rodriguez, J.F., Saintilan, N., Wen, L., Kuczera, G., Riccardi, G., &

Willgoose, G. (2020). Patch organization and resilience of dryland wetlands. *Science of The Total Environment*, 726.

Shields Jr., F.D., Knight, S.S., & Cooper, C.M. (2000). Cyclic perturbation of lowland river

channels and ecological response. *River Research and Applications*, 16(4), 307–325.

Skidmore, P., & Wheaton, J.M. (2022). Riverscapes as natural infrastructure: Meeting challenges

of climate adaptation and ecosystem restoration. *Anthropocene*, 38.

Stromberg, J.C., Beauchamp, V.B., Dixon, M.D., Lite, S.J., & Paradzick, C. (2007). Importance

of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in arid southwestern United States.*Freshwater Biology*, 52(4), 651–679.

Syvitsky, J.P.M., Kettner, A.J., Correggiari, A., & Nelson, B.W. (2005). Distributary channels

and their impact on sediment dispersal. *Marine Geology,* 222–223, 74–94.

Tiegs, S.D., O'Leary, J.F., Pohl, M.M., & Munill, C.L. (2005). Flood disturbance and riparian species diversity on the Colorado River Delta.*Biodiversity and Conservation* , 14, 1174– 1194. Tyus, H. M., & Saunders, J.F. (2001). An evaluation of the role of tributary streams for recovery of endangered fishes in the upper Colorado River basin, with recommendations for future recovery actions. University of Colorado at Boulder, Upper Colorado Endangered Fish Recovery Program Final Report, Project Number 101, Boulder, Colorado.

Udall, B., & Overpeck, J. (2017). The twenty-first century Colorado River hot drought and

implications for the future. Water Resources Research, 53(3), 2404–2418.

Van Steeter, M.M., & Pitlick, J. (1998). Geomorphology and endangered fish habitats of the upper Colorado River: 1. Historic changes in streamflow, sediment load, and channel morphology, *Water Resour. Res.* , 34(2), 287– 302. Vorosmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P.,

Glidden, S., Bunn, S.E., Sullivan, C.A., Reidy Liermann, C., & Davies, P.M. (2010). Global threats to human water security and river biodiversity. *Nature*, 467, 555–561.

Walker, C.A., & Hudson, M. (2004). Surveys to determine the current distribution of roundtail chub, flannelmouth sucker, and bluehead sucker in the San Rafael drainage, during 2003. Unpublished report. Utah Division of Wildlife Resources, Salt Lake City, Utah

Walsworth, T.E. (2011). Analysis of food web effects of non-native fishes and evaluation of

restoration potential for the San Rafael River, Utah. MS Thesis, Utah State University, Logan, UT.

Walsworth, T.E, Budy, P., & Theide, G.P. (2013). Longer food chains and crowded niche space: effects of multiple invaders on desert stream food web structure. *Ecology of Freshwater Fish* , 22(3), 439–452.

Ward, J.V., Tockner, K., and Schiemer, F. (1999). Biodiversity of floodplain river ecosystems:

Ecotones and connectivity. *Regulated Rivers: Research and Management*, 15, 125–139.

Webb, R.H., & Betancourt, J. (1990). Climatic variability and flood frequency of the Santa Cruz River, Pima County, Arizona. *Water Supply Paper 2379.*Wegener, M.G., Harriger, K.M., Knight, J.R., & Barrett, M.A. (2017). Movement and Habitat

Use of Alligator Gars in the Escambia River, Florida. *North American Journal of Fisheries Management*, 37(5), 1028-1038.

Wheaton, J.M., Bennett, S.N., Bouwes, N., Maestas, J.D. and Shahverdian, S.M. (Editors). 2019.

Low-Tech Process-Based Restoration of Riverscapes: Design Manual. Version 1.0. Utah State University Restoration Consortium. Logan, UT. DOI: 10.13140/RG.2.2.19590.63049/2.

Wheaton, J.M., Fryirs, K.A., Brierley, G., Bangen, S.G., Bouwes, N., & O'Brien, G. (2015). Geomorphic mapping and taxonomy of fluvial landforms. *Geomorphology* , 248, 273– 295.

Williams, A.P., Cook, B.I., Smerdon, J.E. (2022). Rapid intensification of the emerging

southwestern North American megadrought in 2020–2021. *Nature Climate Change,* 12, 232–234.

Wohl, E. (2019). Forgotten Legacies: Understanding and Mitigating Historical Human Alterations of River Corridors. *Water Resources Research,* 55, 5181–5201.

Wyrick, J. R., & Pasternack, G.B. (2014). Geospatial organization of fluvial landforms in a gravel–cobble river: Beyond the riffle–pool couplet. *Geomorphology* , 213(15), 48–65.

**Data Availability Statement**

Data are available from the authors upon reasonable request.

**TABLE 1.** Results of the reference reach analyses for each year surveyed.

| **Description** | **Description** | **Site** | **Year** | **Year** |
|---|---|---|---|---|
| | | | 2009 | 2015 |
| *Flow at date of imagery (cms)* | *Flow at date of imagery (cms)* | | | |
| max | – | 8.07 | 0.26 | |
| min | | 7.14 | 0.12 | |
| *Valley bottom length constant (km)* | *Valley bottom length constant (km)* | | | |
| | Spring Canyon | 7.36 | 7.36 | |

| **Description** | **Description** | **Site** | **Year** | **Year** |
|---|---|---|---|---|
| | Moonshine Wash | 7.36 | 7.36 | |
| *Valley bottom area constant (km$^2$)* | *Valley bottom area constant (km$^2$)* | | | |
| | Spring Canyon | 2.26 | 2.26 | |
| | Moonshine Wash | 1.14 | 1.14 | |
| *Valley gradient* | *Valley gradient* | | | |
| grade | Spring Canyon | .0015 | .0015 | |
| | Moonshine Wash | .0016 | .0016 | |
| grade in % | Spring Canyon | 0.15 | 0.15 | |
| | Moonshine Wash | .16 | .16 | |
| angle of elevation | Spring Canyon | 9.68 | 9.68 | |
| | Moonshine Wash | 9.55 | 9.55 | |
| *Geomorphic units* | *Geomorphic units* | | | |
| total count | Moonshine Wash | 0 | 70 | |
| | Spring Canyon | 0 | 0 | |
| *Total area inundated (km$^2$)* | *Total area inundated (km$^2$)* | | | |
| | | Spring Canyon | 0.11 | 0.09 |
| | | Moonshine Wash | 0.08 | 0.06 |
| *Percent valley bottom inundated* | *Percent valley bottom inundated* | | | |
| | | Spring Canyon | 5.1 | 3.7 |
| | | Moonshine Wash | 6.6 | 5.3 |

**TABLE 2.** Results of the valley plug inundation metrics (see Table 1) for each year surveyed.

| **Metric** | **Metric** | **Metric** | **Year** | **Y** |
|---|---|---|---|---|
| | | | 2009 | 2 |
| *Flow at date of imagery (cms)* | *Flow at date of imagery (cms)* | *Flow at date of imagery (cms)* | | |
| max | 8.07 | 0.26 | 0.40 | |
| min | 7.14 | 0.12 | 0.28 | |
| *Valley bottom length constant (km)* | *Valley bottom length constant (km)* | *Valley bottom length constant (km)* | | |
| | 7.36 | 7.36 | 7.36 | |
| *Valley bottom width constant (km)* | *Valley bottom width constant (km)* | *Valley bottom width constant (km)* | | |
| mean | 0.78 | 0.78 | 0.78 | |
| min | 0.55 | 0.55 | 0.55 | |
| max | 1.37 | 1.37 | 1.37 | |
| *Valley bottom area constant (km$^2$)* | *Valley bottom area constant (km$^2$)* | *Valley bottom area constant (km$^2$)* | | |
| | 5.5 | 5.5 | 5.5 | |
| *Valley gradient* | *Valley gradient* | *Valley gradient* | | |
| grade | .0016 | .0016 | .0016 | |
| grade in % | .16 | .16 | .16 | |
| angle of elevation | 6.95 | 6.95 | 6.95 | |
| *Geomorphic unit count* | *Geomorphic unit count* | *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 km$^2$)* | *Inundation type (area km$^2$)* | *Inundation type (area km$^2$)* | | |
| free-flowing | 0.12 | 0.1 | 0.1 | |

| **Metric** | **Metric** | **Metric** | **Year** | **Y** |
|---|---|---|---|---|
| overflowing | 0 | 1.33 | 3.3 | |
| ponded | 0 | 0 | 0.02 | |
| dry | 5.38 | 4.07 | 2.07 | |
| *Total inundated area (km$^2$)* | *Total inundated area (km$^2$)* | *Total inundated area (km$^2$)* | | |
| | 0.12 | 1.43 | 3.43 | |
| *% valley bottom inundation* | *% valley bottom inundation* | *% valley bottom inundation* | | |
| | 2.1 | 26 | 62.3 | |
| *% valley bottom inundation by type* | *% valley bottom inundation by type* | *% 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* | *Integrated wetted width* | *Integrated wetted width* | | |
| | | 15.8 | 194.14 | 4 |

## Figure Captions

**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 the 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.

**FIGURE 2.** 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 3.** Total area of inundation for two 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.

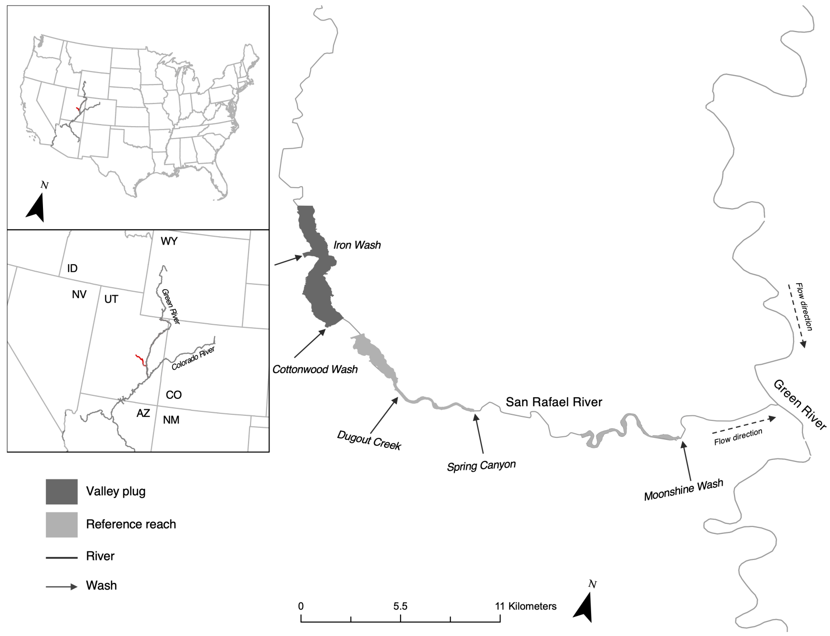
**FIGURE 4.** Areas for upland (dark shading) and riparian (light shading) vegetation collected via drone and historic imagery for two time periods, 2009 and 2015. Measurements were calculated for A) the valley plug and two reference reaches: B) Spring Canyon and C) Moonshine Wash. The box represents the 25%, median, and 75%. The whiskers extend to a maximum of 1.5 interquartile range, and outliers are represented by points.

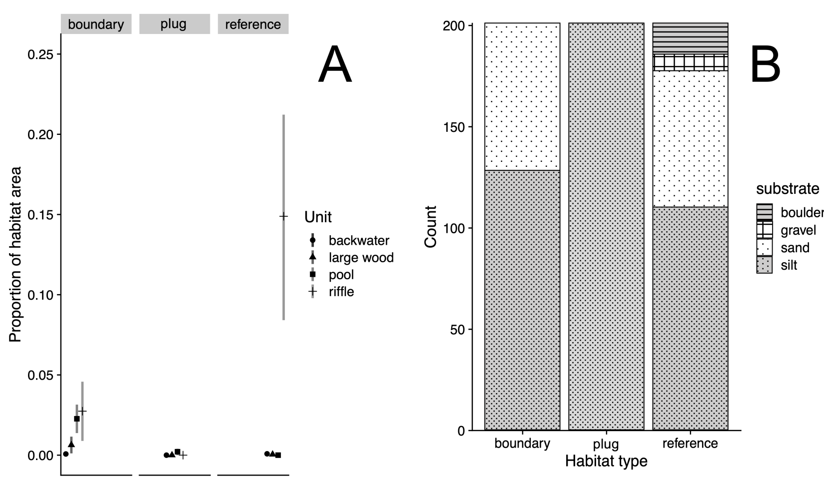
**FIGURE 5.** Riverscape inundation mapping results for imagery collected in 2009, 2015 and 2021. Imagery was collected in the same reach of river for all three years, located upstream of Cottonwood Wash, and in the valley plug.

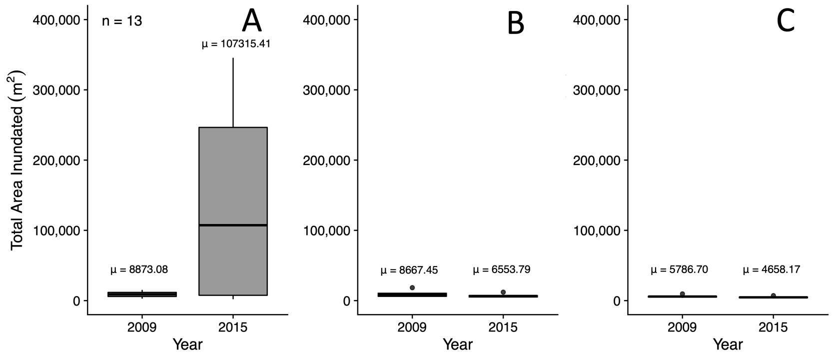
**FIGURE 6.** (A) Percent valley bottom inundation for three time periods: 2009, 2015 and 2021 for the reach upstream of Cottonwood Wash within the valley plug. (B) Shannon Evenness Index values for total inundation area (m$^2$) calculated for 2009, 2015 and 2021 surveys upstream of Cottonwood Wash within the valley plug. For each box represents the 25%, median and 75%. The whiskers extend to a maximum of 1.5 interquartile range.

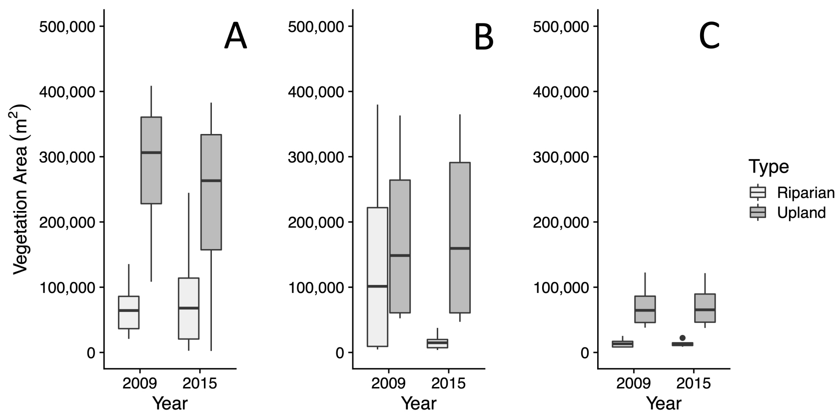
**FIGURE 7.** Map of geomorphic units (e.g., confluences, diffluences, large wood and riffles) for three time periods: 2009, 2015 and 2021 upstream of Cottonwood Wash within the valley plug.

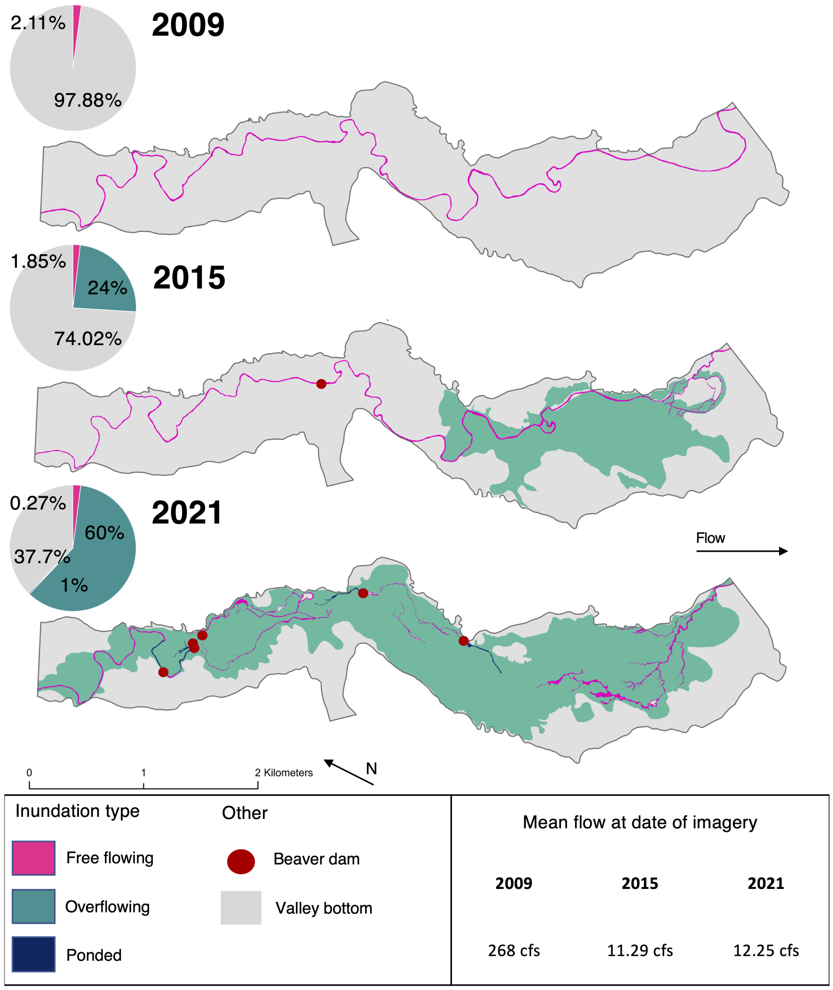
**FIGURE 8.** Map of vegetation types for three time periods: 2009, 2015 and 2021 upstream of Cottonwood Wash within the valley plug. Vegetation types are split into riparian and upland.

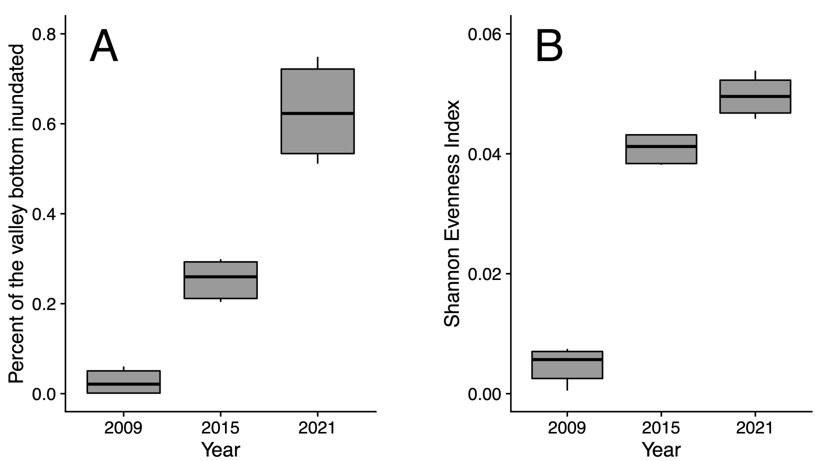

ID
WY
NV
UT
Green River
Colorado River
CO
AZ
NM
Iron Wash
Cottonwood Wash
Dugout Creek
Spring Canyon
San Rafael River
Moonshine Wash
Green River
Flow direction
Flow direction
Valley plug
Reference reach
River
Wash
0
5.5
11 Kilometers
N

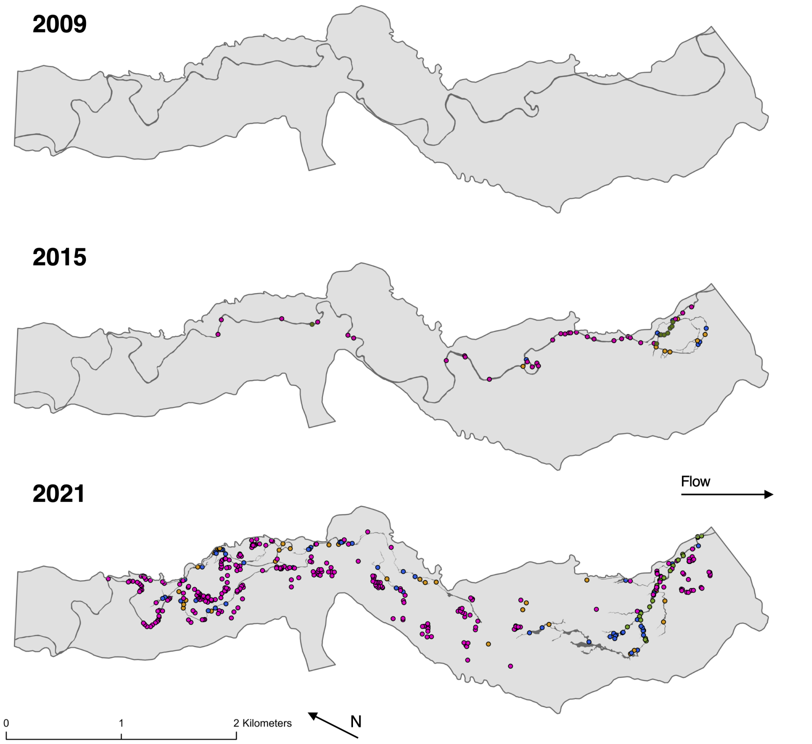

A
B
boundary
plug
reference
Proportion of habitat area
0.25
0.20
0.15
0.10
0.05
0.00
Unit
backwater
large wood
pool
riffle
Count
200
150
100
50
0
substrate
boulder
gravel
sand
silt
Habitat type


n = 13
A
B
C
Total Area Inundated (m²)
μ = 8873.08
μ = 107315.41
μ = 8667.45
μ = 6553.79
μ = 5786.70
μ = 4658.17
Year


A
B
C
Vegetation Area (m²)
Year
Type
Riparian
Upland

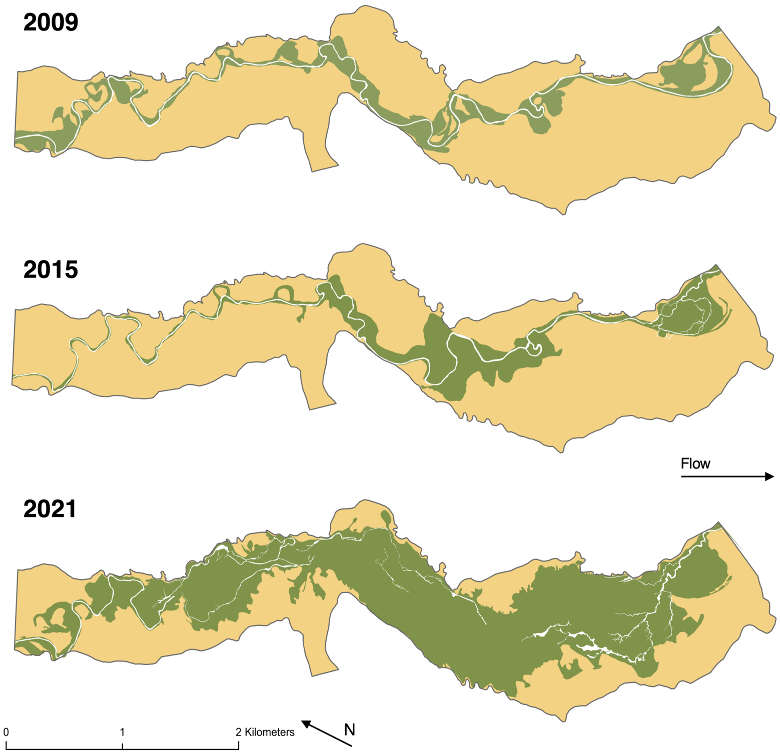

2009
2.11%
97.88%
2015
1.85%
24%
74.02%
2021
0.27%
60%
37.7%
1%
Flow
0
1
2 Kilometers
N
Inundation type
Free flowing
Overflowing
Ponded
Other
Beaver dam
Valley bottom
Mean flow at date of imagery
2009
2015
2021
268 cfs
11.29 cfs
12.25 cfs


A
Percent of the valley bottom inundated
0.0
0.2
0.4
0.6
0.8
2009
2015
2021
Year
B
Shannon Evenness Index
0.00
0.02
0.04
0.06
2009
2015
2021
Year




**Geomorphic units**
- Confluence
- Diffluence
- Large wood
- Riffle

| | Confluences | Diffluences | Large wood | Riffle |
|---|---|---|---|---|
| 2009 | 0 | 0 | 0 | 0 |
| 2015 | 7 | 7 | 31 | 8 |
| 2021 | 53 | 33 | 281 | 26 |




Vegetation type

Upland

Riparian

| Vegetation type | 2009 (km$^2$) | 2015 (km$^2$) | 2021 (km$^2$) |
|---|---|---|---|
| Upland | 4.55 | 4.5 | 2.32 |
| Riparian | 0.85 | 0.9 | 3.05 |