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Drivers of Geomorphic Heterogeneity in Unconfined Non-Perennial River Corridors

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Key Points:

- Geomorphic heterogeneity, morphology, and flood disturbance proxies were characterized in 30 floodplains along ephemeral streams
- River corridor width had a stronger influence on diversity metrics than proxies for flood disturbance
- Geomorphic heterogeneity in non-perennial river corridors is similar to values previously measured in perennial watersheds

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

River corridors along non-perennial stream networks provide diverse physical and ecological functions that are thought to be related to the spatial and temporal variability of geomorphic units, also known as geomorphic heterogeneity. While studies on the characteristics and drivers of geomorphic heterogeneity have been developed in perennial streams, similar studies in ephemeral streams are lacking. Given the ubiquity of non-perennial streams globally, we aim to answer questions regarding the magnitude and drivers of geomorphic heterogeneity in ephemeral river corridors as well as how geomorphic unit assemblages reflect processes related to flood disturbance. Geomorphic units were mapped in 30 unconfined river corridors within six non-perennial watersheds in Utah and Arizona, USA. Landscape heterogeneity metrics—Shannon's Diversity Index, Shannon's Evenness Index, and patch density—were used to quantify geomorphic heterogeneity within each reach. Additionally, variables that potentially constrain or drive heterogeneity were quantified, including floodplain shape, grain size, large wood abundance, and proxies for flood disturbance. While heterogeneity positively correlated with metrics for morphology and disturbance, statistical models suggest that morphologic context, particularly river corridor width, was a more important predictor for estimating geomorphic heterogeneity. Still, geomorphic units reflected aggradation processes indicative of a range of flood energies, suggesting a strong tie between heterogeneity and disturbance. Results suggest that geomorphic heterogeneity may be resilient to changes in flood disturbance frequency or magnitude, but future studies investigating long-term temporal heterogeneity are needed.

Plain Language Summary

Rivers and floodplains that flow only temporarily are common in dry environments and support important habitat and other ecosystem functions in deserts. These functions are thought to be tied to the variability of physical forms, such as elevation and sediment grain size, within the river and floodplain. However, physical variability or diversity is understudied in dry, temporary rivers. Here, we measured the range and potential factors that influence physical variability in 30 temporary rivers and floodplains in Utah and Arizona, USA. Potential controlling or influencing factors, including the size of the floodplain as well as evidence of flooding, were also measured in each study area. Results show that river corridor width—not estimates of flooding—has the most important control on physical variability, where wider river corridors have a greater diversity of patches. Results suggest that physical diversity and associated functions may be resilient to future changes in flooding due to climate change.

1. Introduction

Fluctuations in watershed-scale boundary conditions such as climate and geology can drive variability in processes that create diverse, functional landforms or geomorphic units within river corridors, including within the channel and floodplain (Figure 1, Brierley & Fryirs, 2000; Fryirs & Brierley, 2022). This resulting geomorphic heterogeneity—or spatial and temporal variability of geomorphic units—is increasingly being quantified by geomorphologists in order to investigate connections between morphology and floodplain function in fluvial settings (D. N. Scott et al., 2022). Greater river corridor heterogeneity commonly corresponds to greater attenuation of sediment, water, and solute fluxes (Wohl, 2016, 2021), including organic carbon (Bellmore & Baxter, 2014; Wohl et al., 2018), and greater habitat diversity, which can lead to greater biodiversity (Bellmore & Baxter, 2014; Bendix & Hupp, 2000; Greene & Knox, 2014; Luck et al., 2010; M. L. Scott et al., 2003; Wyżga et al., 2012). Although river corridors can also be naturally homogenous, naturally heterogeneous reaches are hotspots of such functions (e.g., storage and attenuation, Wohl (2021)). Most studies quantifying geomorphic heterogeneity in the context of process and function have been conducted in perennial rivers. We start to broaden

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this understanding by examining river corridor geomorphic heterogeneity in non-perennial river corridors of the southwestern United States.

Similar to perennial rivers, floodplains along non-perennial river networks, including intermittent rivers and ephemeral streams, host diverse functions. Non-perennial floodplains store water (Jacobson et al., 1995; Simmers, 2003), sediment (Jaeger et al., 2017; Sandercock & Hooke, 2011), and organic material (Jacobson et al., 1999; Wohl & Scamardo, 2022) on the landscape. In drylands, floodplains adjacent to non-perennial streams tend to have greater biomass and higher productivity (R. L. Scott et al., 2014) as well as greater plant species diversity (Sabo et al., 2005) and evenness (Stromberg et al., 2017) compared to surrounding uplands. Dryland, non-perennial floodplains can support the majority of riparian habitat on a landscape, providing important wildlife migratory corridors (Fonseca & List, 2013; Sánchez-Montoya et al., 2016). Broadly, non-perennial river corridors host a high diversity of invertebrate and vertebrate fauna (Sánchez-Montoya et al., 2017; Stubbington et al., 2017). Distribution patterns of flora and fauna associated with non-perennial river corridors can be affected by spatial heterogeneity in biogeochemical conditions during wetting and drying phases (Claret & Boulton, 2003; von Schiller et al., 2017) as well as spatial variability in erosion and sedimentation (Bendix & Hupp, 2000). Despite literature suggesting that spatial heterogeneity could be tied to floodplain function in non-perennial streams, the framework and quantification of geomorphic-unit heterogeneity has rarely been applied to non-perennial river corridors.

Discussion continues on how to delineate geomorphic units and subsequently quantify heterogeneity in river corridors (e.g., Belletti et al., 2017; Fryirs & Brierley, 2022; McGarigal et al., 2009; Minár & Evans, 2008; D. N. Scott et al., 2022; Scown et al., 2015b; Wheaton et al., 2015). Geomorphic units are commonly identified by changes in topography, substrate, or vegetation (D. N. Scott et al., 2022), which has allowed for the mapping of in-channel and floodplain geomorphic units via field-based surveying (e.g., Moir & Pasternack, 2008; Wohl & Iskin, 2019), remote analyses (e.g., Bizzi & Lerner, 2012; Roux et al., 2015; Williams et al., 2020), and numerical modeling (e.g., Carbonneau et al., 2020; Wyrick et al., 2014). After geomorphic units are delineated, landscape ecology metrics are commonly used to quantify the diversity of units (i.e., patches) within a river corridor (Cadenasso et al., 2006; D. N. Scott et al., 2022). Although quantifying geomorphic heterogeneity relies on assessing river form, the concept is rooted in understanding processes that are typically less feasible to measure directly (Brierley & Fryirs, 2016; Fryirs & Brierley, 2005), particularly in intermittent rivers and ephemeral streams which are generally data-poor (e.g., Borg Galea et al., 2019).

Underlying processes (e.g., erosion and sedimentation) associated with sediment and water fluxes during disturbances like flash floods are hypothesized to drive the formation and heterogeneity of geomorphic units within the ephemeral river corridor. Flash floods in ephemeral streams are characterized by high suspended load (e.g., Reid & Frostick, 2011) and bedload (e.g., Laronne & Reid, 1993; Stark et al., 2021), which can drive the formation of new geomorphic units through deposition (Figure 1). The disturbance regime—largely flood frequency, magnitude, and duration—therefore potentially exerts a first order control on heterogeneity in ephemeral river corridors. Although ephemeral channels and other geomorphic units may be stable when subject to small to moderate flood magnitudes, large floods are known to widen channels, activate bars, and deposit new units across the floodplain (e.g., Friedman & Lee, 2002; Hassan & Egozi, 2001; Hooke, 2016). However, extreme floods in ephemeral streams can also provoke incision (Graf, 1988; Rhoads, 1990; Schick, 1974), thus disconnecting the channel-floodplain system and potentially limiting the formation and evolution of future units. As the frequency of large magnitude events increases, ephemeral river corridors may be continually impacted by the formation and destruction of geomorphic units (Rhoads, 1990). Conversely, as the frequency of large events decreases, channels may narrow and floodplain units may be created or expanded (e.g., Friedman & Lee, 2002; Patton & Schumm, 1981; Schumm, 1961), either diversifying or homogenizing the river corridor. Subsequently, the direction and magnitude of change in heterogeneity due to flash flood frequency and magnitude is relatively unknown. Other aspects of the natural flow regime—for example timing and intensity—may also impact heterogeneity, but these aspects are difficult to constrain in ungauged watersheds. Although topographic changes may influence heterogeneity over the course of a single flood, changes can also lag, so that the present-day heterogeneity was created by sediment and water fluxes decades prior (Panin et al., 1999; Thoms, 2006).

Fluxes associated with flood disturbances are additionally influenced by morphologic context—including river corridor width, location within the watershed, and dominant grain size—in ephemeral watersheds (Figure 1) (Boulton et al., 2017; Goodrich et al., 1997; Jaeger & Olden, 2011; Murphey et al., 1977). For example, downstream changes in river morphology due to transmission losses and changing downstream flood regimes (e.g., Goodrich et al., 1997; Murphey et al., 1977) can influence the spatial structure of vegetation communities

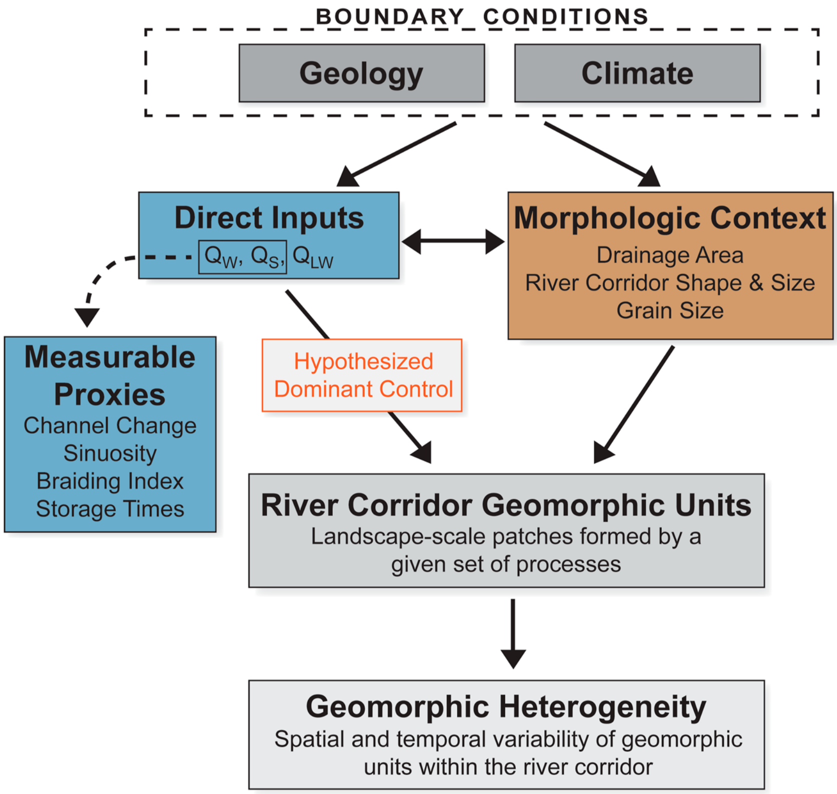

Figure 1. Framework showing the drivers of geomorphic units which in turn influence metrics of geomorphic heterogeneity. Individual geomorphic units can vary in spatial extent from 10^0 to 10^4 m^2. We hypothesize that direct inputs of discharge (Q_w), sediment flux (Q_s), and large wood loads (Q_{lw}) during flood disturbances are the dominant control on the type and diversity of geomorphic units in non-perennial river corridors. However, morphologic context—including the drainage area, river corridor shape and size (including confinement) and grain size—could also influence heterogeneity.

(Shaw & Cooper, 2008), thus suggesting that geomorphic heterogeneity could similarly be influenced by network position. Additionally, river corridor width can mediate floodplain heterogeneity, with unconfined floodplains tending to be areas of high heterogeneity in perennial rivers (e.g., Bellmore & Baxter, 2014; Stanford & Ward, 1993; Wohl et al., 2018, 2022). Greater heterogeneity in unconfined, perennial reaches is often attributed to increased channel mobility (e.g., Wohl et al., 2018), decreased stream power (e.g., Thompson & Croke, 2013), or biota (e.g., Dunkerley, 2014; Polvi & Wohl, 2012; Scamardo et al., 2022) that thrive with more accommodation space. Similar processes could be driving heterogeneity in non-perennial streams, where river corridor width is known to oscillate throughout a network (Pelletier & DeLong, 2004). Additionally, sediment cohesion may influence landform development on floodplains (Nanson & Croke, 1992; Schumm, 1960), where finer grained floodplains may be more resistant to the development and evolution of geomorphic units. Although drivers known to influence floodplain heterogeneity in perennial streams are present in ephemeral watersheds, studies connecting disturbance and morphologic context to geomorphic heterogeneity in non-perennial streams are lacking.

Given that non-perennial streams comprise the majority of global river networks (Messager et al., 2021) and are projected to increase in extent with climate change (Reynolds et al., 2015), understanding the magnitude and drivers of geomorphic heterogeneity in non-perennial river corridors can improve our understanding of ecosystem function in watersheds worldwide. Here, we quantify geomorphic heterogeneity along dryland non-perennial river corridors in three study regions within the southwestern U.S. in order to understand the spatial variability of geomorphic diversity. From these surveys we ask: (a) how do processes in non-perennial streams influence geomorphic units? and (b) what drives geomorphic heterogeneity in dryland non-perennial river corridors? Based on the existing literature, we hypothesize that disturbance (primarily in the form of flash floods) over decadal to centennial timespans will drive the development and diversity of geomorphic units, and that morphologic context will be a secondary influence on heterogeneity.

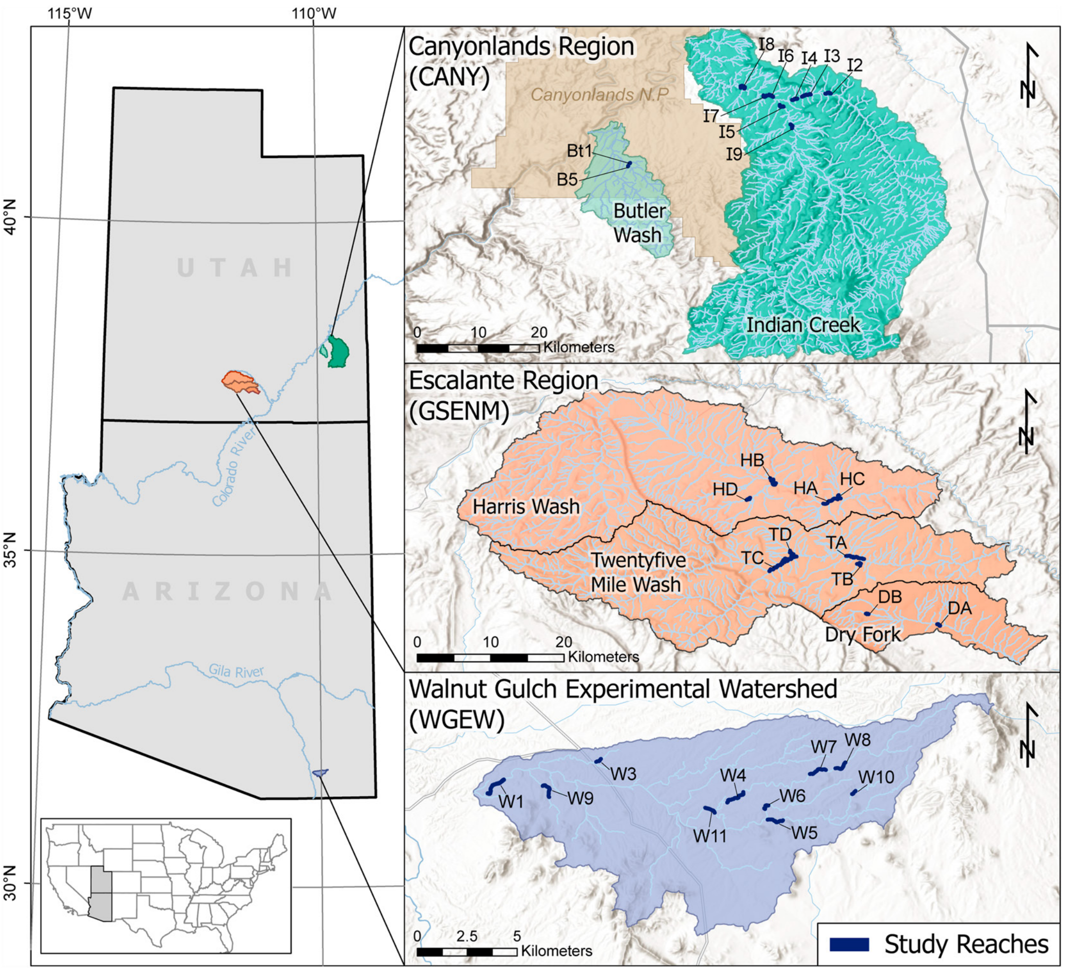

Figure 2. Map of study sites in CANY, GSENM, and Walnut Gulch Experimental Watershed, including both broader location in the southwestern U.S. as well as position within each watershed. Two-digit codes represent naming schemes used in surveying and analysis.

2. Study Sites

In order to understand the degree and drivers of geomorphic heterogeneity in non-perennial river corridors, geomorphic units and potential drivers were mapped in 30 unconfined reaches—often called beads (Stanford et al., 1996; Wohl et al., 2018)—across six watersheds in three geographic regions in the southwestern U.S.: the Canyonlands and Escalante regions of Utah and Walnut Gulch Experimental Watershed in Arizona (Figure 2, Table 1). We defined beads as having a floodplain width at least three times greater than average channel width. Reaches were chosen to have consistent unconfinement while also representing a range of potential drivers to heterogeneity.

Most of the studied watersheds are subject to anthropogenic land use through livestock grazing. Other human practices historically common throughout the southwestern U.S., such as vegetation chaining (e.g., Redmond et al., 2013) and brush management (e.g., Archer et al., 2011), may have impacted the morphologic or vegetative character of some of the studied river corridors, but these practices have not been explicitly recorded or observed within the areas of interest.

2.1. Canyonlands Region, Utah (CANY)

Indian Creek and Butler Wash are non-perennial tributaries to the Colorado River in southeastern Utah (Figure 2) in the Canyonlands region of the Colorado Plateau. Although headwaters to Indian Creek in the Abajo Mountains can be perennial, all chosen study sites in this region are ephemeral, flowing only after sufficient precipitation, which typically occurs in the late summer. All sites in CANY were ungauged. Vegetation near the washes

Table 1
Study Site Watershed Characteristics

Region	Watersheds	Number of study sites (n)	Drainage area[a] (km^2)	Average river corridor width (m)	Average elevation[a] (m a.s.l.)	Average annual precipitation[a] (mm)
Canyonlands (CANY)	Indian Creek	8	1,110	116	1,990	400
	Butler Wash	2	16.2	30	1,720	260
Escalante (GSENM)	Harris Wash	4	605	102	1,910	270
	Twenty-five Mile Wash	4	465	170	1,880	270
	Dry Fork	2	85	65	1,615	230
Walnut Gulch Experimental Watershed (WGEW)	Walnut Gulch	10	153	67	1,415	370

[a]Calculated using the downstream-most study site as a drainage outlet in StreamStats (U.S. Geological Survey, 2019).

predominantly consists of riparian species, including Fremont cottonwood (*Populus fremontii*) and netleaf hackberry (*Celtis reticulata*), although non-native shrub species such as tamarisk (*Tamarix* spp.) are common on floodplains in Indian Creek (Figure 3).

Land management varies between the two watersheds. Butler Wash is located within Canyonlands National Park and are managed by the U.S. National Park Service. To that end, grazing is excluded from Butler Wash, whereas Indian Creek—which is managed privately and by the U.S. Bureau of Land Management—is subject to livestock grazing, although some reaches may be more difficult for livestock or wildlife to access for grazing due to canyon walls. Only minor infrastructure and human alterations (e.g., buildings, bridges) exist along Indian Creek through the study area.

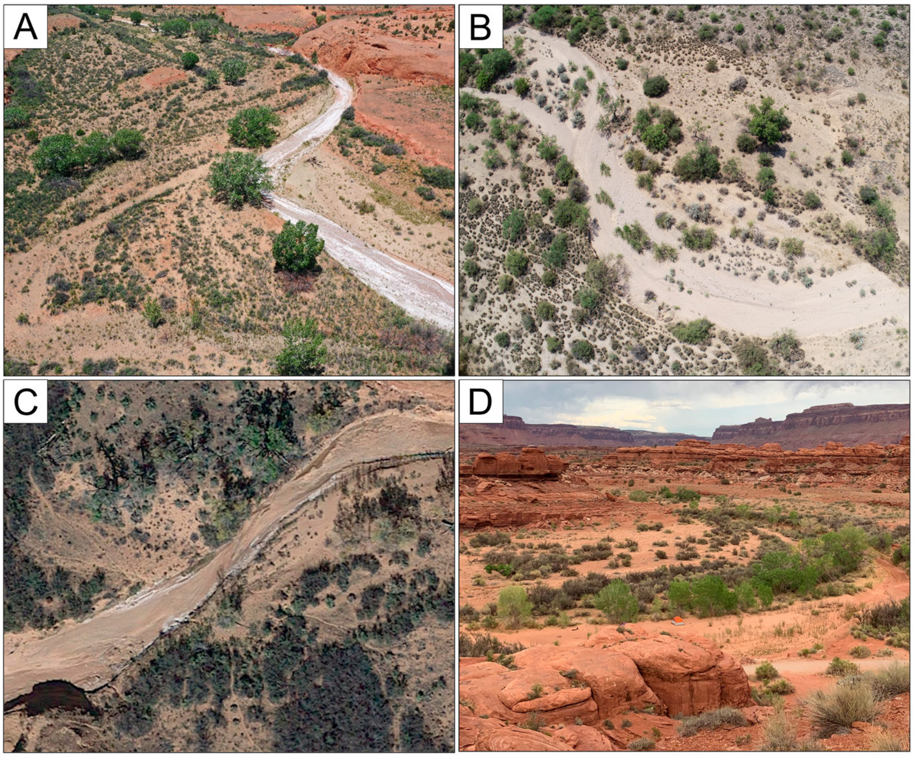

Figure 3. Aerial imagery and site photos showing representative floodplain study sites in Grand Staircase Escalante National Monument (a), Walnut Gulch Experimental Watershed (b), and Indian Creek in the Canyonlands Region (c, d). Dominant geomorphic unit types shown are main channel, shrub floodplain, and riparian forest (a); main channel, shrub longitudinal bars, and shrub floodplain (b); main channel, herbaceous point bars, and shrub floodplain (c), and shrub floodplain and riparian forest (d) (see Section 3.1).

2.2. Escalante Region, Utah (GSENM)

Twenty-five Mile Wash, Harris Wash, and Dry Fork Coyote Gulch are ephemeral tributaries to the Escalante River in south-central Utah (Figure 2, Table 1). All sites are ungauged, but streamflow is common in the spring and late summer following seasonal precipitation. River corridor width can vary dramatically between unconfined alluvial reaches and confined bedrock slot canyons. Vegetation in unconfined river corridors generally consists of greasewood (*Sarcobatus vermiculatus*), big sagebrush (*Artemisia tridentata*), and Mormon tea (*Ephedra cutleri* and *E. viridis*), with riparian bands of cottonwoods (*Populus spp.*) (Figure 3). Invasive species, including tamarisk (*Tamarix* spp.) and Russian olive (*Elaeagnus angustifolia*), also persist within and near ephemeral channels.

2.3. Walnut Gulch Experimental Watershed, Arizona (WGEW)

Walnut Gulch Experimental Watershed (WGEW) is an ephemeral tributary to the San Pedro River in southeastern Arizona (Figure 2). River corridor vegetation in Walnut Gulch primarily consists of herbaceous shrubs—including Mormon tea (*Ephedra trifurca*), snakeweed (*Gutierrezia sarothrae*), creosote bush (Larrea tridentata), and white-thorn acacia (*Acacia constricta*)—and grasses, such as black grama (*Bouteloua eriopoda*) and blue grama (*Bouteloua gracilis*). Riparian corridors can host a variety of woody tree species, including Arizona walnut (*Juglans major*), mesquite (genus *Prosopis*), and netleaf hackberry (*Celtis reticulata*) (Figure 3). Since 1959 CE, the U.S. Department of Agriculture Agricultural Research Service has maintained a series of in-channel critical depth flumes to record water depth and discharge (Smith et al., 1981), which typically occurs during summer monsoonal rains. Additionally, much of WGEW is used by private landowners for livestock grazing, and urban development has occurred within the watershed at the town of Tombstone, AZ.

3. Materials and Methods

3.1. Delineating Geomorphic Units

Previous studies have used a range of field and computationally based methods to delineate geomorphic units (Wheaton et al., 2015; Wohl & Iskin, 2019). Here, we used a combined field- and GIS-based mapping approach to delineate geomorphic units within each river corridor for the year in which we surveyed. Field surveys were conducted in 2020 CE for sites in GSENM and WGEW and 2021 CE for sites in CANY. At each site, transects were randomly designated perpendicular to the main valley trend using a random point generator along the channel thalweg. The number of transects varied by floodplain reach, so that all reaches had a minimum of five transects, but the maximum distance between transects did not exceed 200 m. Along each transect, the boundary between river corridor and upland surfaces and the boundaries between individual geomorphic units were surveyed using a handheld Garmin eTrex GPS unit (3-m horizontal accuracy). The river corridor boundary was determined based on topography and vegetation; slope breaks up to higher surfaces with upland vegetation were generally used to determine the floodplain limit. Within the river corridor, geomorphic unit boundaries were placed at measurable changes in topography (i.e., height above the channel), convexity, or surface grain size. Typically, changes in geomorphic character indicative of transitioning from one geomorphic unit to another were accompanied with changes in vegetation cover type (e.g., unvegetated, herbaceous, shrub, or forest). The association between geomorphic units and cover type is likely due to feedbacks between morphology and vegetation (Gurnell, 2014; Latterell et al., 2006; Osterkamp et al., 2012). Deposition and the formation of new geomorphic units can provide opportunities for seedlings to establish (Cooper et al., 2003; Kemper et al., 2022; M. L. Scott et al., 1996), and the evolution of an individual geomorphic unit over time can be matched with the succession of vegetation (e.g., Corenblit et al., 2009; Friedman & Lee, 2002). Conversely, the presence of different vegetation cover can dictate sediment deposition and flow dynamics (Corenblit et al., 2007; Gurnell, 2014), thus aiding in the formation and evolution of new units. Given the close linkage between geomorphic units and vegetation, units were primarily distinguished based on topography and surface grain size, and secondarily differentiated by vegetation cover type (unvegetated, herbaceous, shrub, or forested), similar to previous geomorphic unit classifications (e.g., Wheaton et al., 2015).

Units were therefore classified under an overarching group—floodplain surface, channel, bar, levee, bench, backswamp, riparian, or relict—which were further divided into classes of geomorphic units by both grain size and vegetation cover (Table S1 in Supporting Information S1). The same naming conventions and geomorphic unit classes were used for all three regions, although the specific species that comprises each vegetation cover type differed between regions. Additionally, climatic differences between regions exist so that woody tree species are less common in WGEW compared to GSENM or CANY.

Transects with point measurements of unit boundaries were overlain on aerial imagery and topography (digital elevation models [DEMs]) in order to delineate the extent of geomorphic units between survey transects (Figure S1 in Supporting Information S1). Aerial imagery came from three sources, depending on location: the USDA National Agriculture Imagery Program (NAIP, 0.6-m resolution) for partial sites in Utah, original drone surveys for partial sites in GSENM and WGEW (0.3-m resolution), and imagery surveys by Walnut Gulch Experimental Watershed (1-m resolution) (Table S2 in Supporting Information S1). Drone surveys were used in lieu of other imagery in reaches where the most current, available imagery did not match the current position of the main channel. DEMs were obtained from the USGS 3D Elevation Program (1-m resolution) or drone surveys. Using the survey transects, aerial imagery, and DEMs, geomorphic units within each river corridor were delineated and assigned a description (i.e., geomorphic unit class) in ArcGIS Pro 2.9.3. Minimum unit size was 1-m so that units ≤1-m in any horizontal dimension were not differentiated. Once delineated, the surface area of each unit was calculated in order to make comparisons between unit types and calculate heterogeneity metrics.

3.2. Quantifying Geomorphic Heterogeneity

Using the unit maps, geomorphic heterogeneity was quantified with various landscape ecology metrics housed in the *landscapemetrics* package in R (Hesselbarth et al., 2019). Three landscape metrics were calculated: patch density, Shannon's diversity index (SHDI), and Shannon's evenness index (SHEI). Patch density is the number of geomorphic units (patches) normalized by the total area of the river corridor:

$$\text{Patch Density} = \frac{\text{Total Number of Patches}}{\text{River Corridor Area (ha)}} \tag{1}$$

Patch density indicates the richness of patches on a landscape without considering the diversity of unit descriptions (i.e., unit class). To consider diversity, we calculated SHDI:

$$\text{SHDI} = -\sum_{i=1}^{m}(P_i \cdot \ln P_i) \tag{2}$$

Where P_i is the proportion of the area within the river corridor classified as class i. SHDI is a diversity metric originally developed in ecology to measure biodiversity by accounting for both the number of classes as well as the abundance of each class (Shannon & Weaver, 1949). To study landscapes, SHDI has been modified to look at river corridor area instead of species. High values of SHDI indicate a high proportion of unique classes, whereas a value of zero represents a river corridor with only one patch type. While SHDI indicates the diversity of classes, it is still influenced by patch richness (count). The SHEI was therefore calculated to look at how evenly the river corridor area is distributed between the present classes:

$$\text{SHEI} = \frac{-\sum_{i=1}^{m}(P_i \cdot \ln P_i)}{\ln m} \tag{3}$$

where m is the total number of classes within a given river corridor. SHEI is the ratio (range from 0 to 1) between actual SHDI and the potential maximum SHDI for a given site based on the number of classes present.

Theoretically, the chosen heterogeneity metrics account for floodplain area or size, meaning that metrics should be broadly comparable across reaches and regions, as long as the minimum unit size remains the same. Additionally, while patch density only measures the count of geomorphic units, both SHDI and SHEI account for proportional area within unit classes.

3.3. Measuring Potential Driving Factors

Potential driving factors of geomorphic heterogeneity indicative of both morphologic context and flood disturbance regime were measured at each study bead (see Table S3 in Supporting Information S1). Shallow sediment cores (30 cm depth) were randomly taken across the river corridor (minimum of 10, maximum of 18 per site).

Sediment cores were processed for texture using the hydrometer method if the sample was mostly <3Φ (0.125 mm) or sieve analysis for coarser samples. The location and dimensions of large wood pieces and accumulations (i.e., jams) were measured within 20 sites, including all sites in CANY, eight sites in GSENM, and two sites in WGEW, based on accessibility for such surveys. Surveys were used to calculate jam density, or the number of jams per river corridor area. River corridor area was used in lieu of main channel area because the majority of measured LW occurred in the floodplain rather than in the main channel (e.g., Wohl & Scamardo, 2022).

Aerial imagery was used to measure average river corridor width and confinement index (confinement index = total river corridor width/main channel width). River corridor shape was measured using the Gravelius compactness coefficient (GC, Sassolas-Serrayet et al., 2018), which accounts for both corridor width and length.

$$\mathrm{GC} = \frac{\text{Floodplain Perimeter}}{2\sqrt{\pi \cdot \text{Area}}} \tag{4}$$

Higher values of the GC coefficient represent elongated corridors, where values approaching 1 represent a perfect circle. Drainage area was measured for each site using the USGS StreamStats application (https://streamstats.usgs.gov/ss/).

Because most study sites were ungauged, multiple metrics—including channel planform and channel change—were used as proxies for flood disturbance and input rates. First, we measured sinuosity and braiding index as proxies for channel mobility and sediment supply. Lateral channel migration can increase geomorphic heterogeneity (e.g., Williams et al., 2020) and, similar to perennial streams, sinuosity can be one static marker to understand mobility potential in ephemeral streams (Billi et al., 2018). Sinuosity was measured by calculating the channel length divided by the straight-line valley bottom length. Additionally, braiding is a common and readily measurable fluvial response to increased sediment supply (Kemper et al., 2023). Braiding index was calculated by averaging the number of channels (including main and secondary) within the river corridor at five random transects. Second, given that ephemeral streams are typically data poor (Borg Galea et al., 2019; Krabbenhoft et al., 2022) and that most sites in this study were ungauged, channel change was used as a proxy for recent flood disturbance. Channel change mapped through aerial imagery and DEMs is a common metric for understanding morphologic impacts of flood frequency, duration, magnitude, and other factors in ephemeral and perennial dryland streams (e.g., Grams & Schmidt, 2002; Hooke, 2015; Kemper et al., 2022; Schook et al., 2017; Walker et al., 2020). In this study, modern mapped main channels were compared to historical main channels delineated from imagery taken approximately one decade prior to sampling: 2011 NAIP imagery for CANY and GSENM (1-m resolution) and 2009 USDA imagery for WGEW (1-m resolution) (Figure S2 in Supporting Information S1). Historical imagery for all sites was collected in the summer months (between June and September), thus representing similar hydrologic and vegetative conditions as the modern surveys. Both percent overlap and percent change in main channel area were calculated between historical channels and surveyed channels:

$$\%\,\text{Overlap} = \frac{\text{Overlap Area between Modern and Historical}}{\text{Historical Channel Area}} \times 100 \tag{5}$$

$$\%\,\text{Channel Area Change} = \frac{\text{Modern Channel Area}}{\text{Historical Channel Area}} \times 100 \tag{6}$$

Channel change over the timeframe of the last decade was investigated due to correlations between flood metrics (namely, magnitude and frequency) and heterogeneity metrics in a limited analysis conducted for WGEW. For sites in WGEW, we identified the in-channel flume closest to each study bead and calculated the discharge frequencies and peaks for the most recent 5-, 10-, and 20-year period. Preliminary analyses indicated that the strongest correlation existed between SHDI and the total flood count and peak flood discharge in the last decade (Figure S3 in Supporting Information S1). Additionally, flood count and peak magnitude weakly correlated with metrics of channel overlap ($\rho = 0.47$, $p = 0.16$ and $\rho = 0.56$, $p = 0.09$, respectively). Statistical significance is likely limited by sample size ($n = 10$) in WGEW alone. We used channel change analysis as a proxy for disturbance because metrics of channel movement via imagery can be measured at all sites unlike direct flood measurements.

As a secondary proxy for channel change and disturbance, sediment residence times were measured in a subset of floodplains using single-grain optically stimulated luminescence (OSL) dating of quartz sand. OSL provides an age estimate for the last time sediments were exposed to light—such as during transport—which resets the luminescence signal (Huntley et al., 1985). After deposition, the luminescence signal accumulates at a rate proportional to the radioactivity of surrounding sediments. OSL ages are the quotient of the lab-derived radiation dose required to replicate the in situ dose and the environmental dose rate of the surrounding sediments (Aitken, 1998). Luminescence dating is ideal for the study sites due to the presence of quartz-rich, sandy exposed banks and limited material suitable for other dating techniques, such as organic material for radiocarbon dating. However, OSL dating of dryland fluvial sediments can be challenging, due to short transport times potentially leading to partial bleaching or incomplete resetting of the luminescence signal, which can result in overestimated depositional ages (Harvey et al., 2011; Hayden-Lesmeister & Rittenour, 2014; Summa-Nelson & Rittenour, 2012). To reduce the potential of sampling partially bleached sediments, we targeted plane-bed and ripple cross-bedded lithofacies, which likely represent less flashy and turbid depositional environments (Summa-Nelson & Rittenour, 2012). To additionally minimize the effect of partial bleaching, we used single grain dating and a minimum age model (Galbraith & Roberts, 2012), which calculates a weighted mean of the lower (younger) end of positively skewed data (see Methods in Supporting Information S1).

Nine OSL samples were collected from exposed banks in Twenty-five Mile Wash (TC), Dry Fork (DB), Harris Wash (HD), and Indian Creek (I3, I4, I7, I9). Samples were collected by pounding opaque metal conduit into targeted sandy strata at a minimum of 1-m depth below the top of the floodplain to minimize cosmogenic dose errors. Due to lithofacies targeting, samples were collected at variable depths below the active floodplain. Representative sediment was collected within a 30-cm radius of the OSL sample to calculate background dose rate and estimating water content. Single-grain OSL measurements were conducted in the Utah State University Luminescence Laboratory following the single-aliquot regenerative-dose method (Murray & Wintle, 2000) (see Methods in Supporting Information S1). Calculated ages were normalized by sampled depth in order to compare storage times and rates between reaches. In the absence of direct sediment transport measurements, storage times may be indicative of historic sediment transport rates that have culminated in the present-day heterogeneity (e.g., Panin et al., 1999; Thoms, 2006).

3.4. Statistical Analyses

All statistical tests were performed using R 4.2.0. Simple linear regressions were calculated to understand the relationship between patch density, SHDI, and SHEI and potential driving factors, including: drainage area, river corridor width, confinement index, the GC coefficient, median percent fines (silt and clay), wood jams per area, sinuosity, braiding index, percent channel overlap, and percent channel area change. Sediment residence times (derived from OSL ages) were analyzed separately due to limited site coverage. The relationship between residence time and heterogeneity was tested via linear and non-linear regressions with OSL age normalized by sampling depth. For all statistical tests, an $\alpha = 0.05$ was used for significance; however, given high variability in natural systems, statistical tests with a $p < 0.1$ were considered marginally significant. Correlations between potential driver factors were also considered (Figure S4 in Supporting Information S1).

To better understand the relative importance of potential driving factors on heterogeneity, we built multiple linear regression (MLR) models for patch density, SHDI, and SHEI. Inputs for each heterogeneity model were determined from individual linear regressions, where all potential driving factors with significant linear relationships to a given heterogeneity metric were included in the full model for that metric. Model selection was then performed using the Akaike information criterion corrected for small sample sizes (AICc, Hurvich & Tsai, 1989) using the *dredge* function in the MuMIn R package (Barton, 2022). Additionally, the importance of each modeled variable, or the frequency at which it was included in models during the model selection process, was investigated using the sum of model weights (*sw* function in MuMIn package).

One study bead, Twenty-five Mile Wash C (TC), was identified as an outlier for heterogeneity metrics and excluded from regressions using the entire data set ($n = 30$). Reaches with outliers among potential drivers (including characteristics of morphologic context and proxies for direct inputs) were additionally identified using Dixon tests and removed from regressions (Dixon, 1950). For OSL analyses ($n = 9$), all data were included due to small sample sizes.

4. Results

4.1. Geomorphic Unit Types by Region

The most common geomorphic units by area were low-lying floodplains with shrub vegetation in WGEW and GSENM and forested floodplains in CANY. The second most common class (by area) was channels, includ-

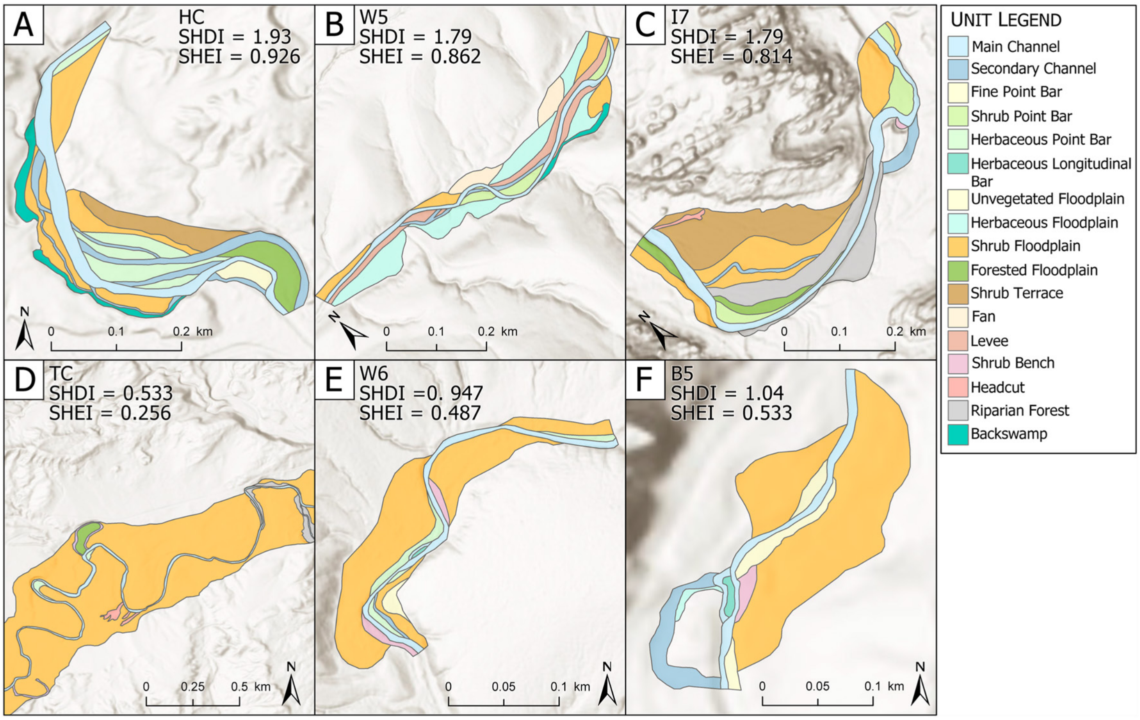

Figure 4. Subset of study beads showing geomorphic unit maps representative of high and low values of Shannon's diversity index and Shannon's evenness index across study regions: (a, d) GSENM, (b, e) WGEW, and (c, f) CANY.

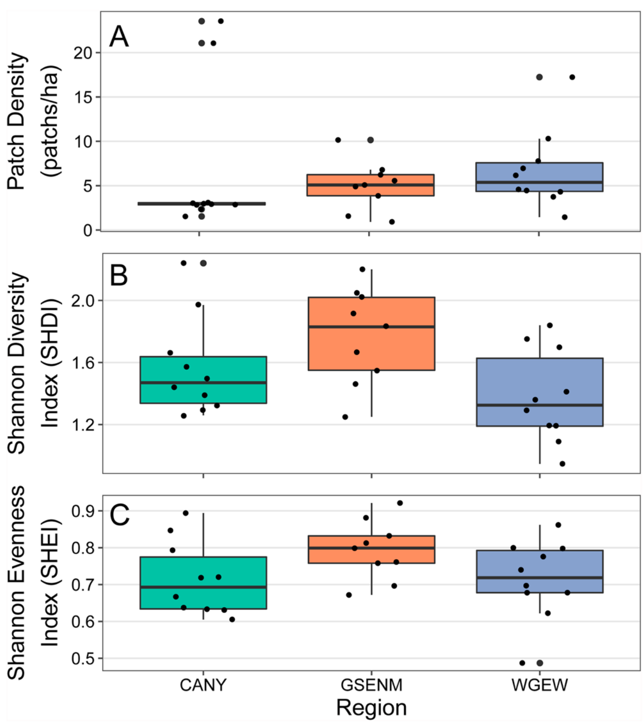

Figure 5. Range of values for heterogeneity metrics (patch density, Shannon's diversity index, and Shannon's evenness index) across study regions.

ing main channels and secondary channels. Point bars, riparian forests, and natural levees were found in all regions. Headcuts that were large enough to be mapped as their own units were only found in select GSENM floodplains. Similar unit types occurred across regions, although WGEW was distinctly lacking forested floodplains, likely due to climatic differences between southern Utah and southern Arizona (Figure 4, Table S1 in Supporting Information S1).

Given the commonality of secondary channels and point bars, we investigated the ratio of these classes by region. In GSENM and CANY, secondary channels occupied less area than point bars within the river corridor (ratio = 0.96 and 0.72, respectively). In WGEW, secondary channels were more common features (by area) than point bars (ratio = 1.6).

4.2. Watershed Scale Trends in Heterogeneity and Potential Drivers

Values for patch density and SHEI varied within watersheds but were not statistically different between watersheds (Figures 5a and 5c). Values for SHDI varied within watersheds as well as between watersheds: watersheds in GSENM had moderately higher diversity values than watersheds in CANY ($p = 0.066$) and significantly higher than WGEW ($p = 0.008$) (Figure 5b). Patch density and SHDI varied significantly with drainage area, where patch density decreased with increasing drainage area ($\rho = -0.75$, $p < 0.0001$) and SHDI increased with drainage area ($\rho = 0.45$, $p = 0.014$) (Figure 6). SHEI did not show a downstream trend ($\rho = 0.09$, $p = 0.63$), suggesting that the range of SHEI (SHEI = 0.487—0.926) is driven by other factors.

Given significant relationships between drainage area and diversity metrics (i.e., patch density and SHDI), we investigated downstream trends in

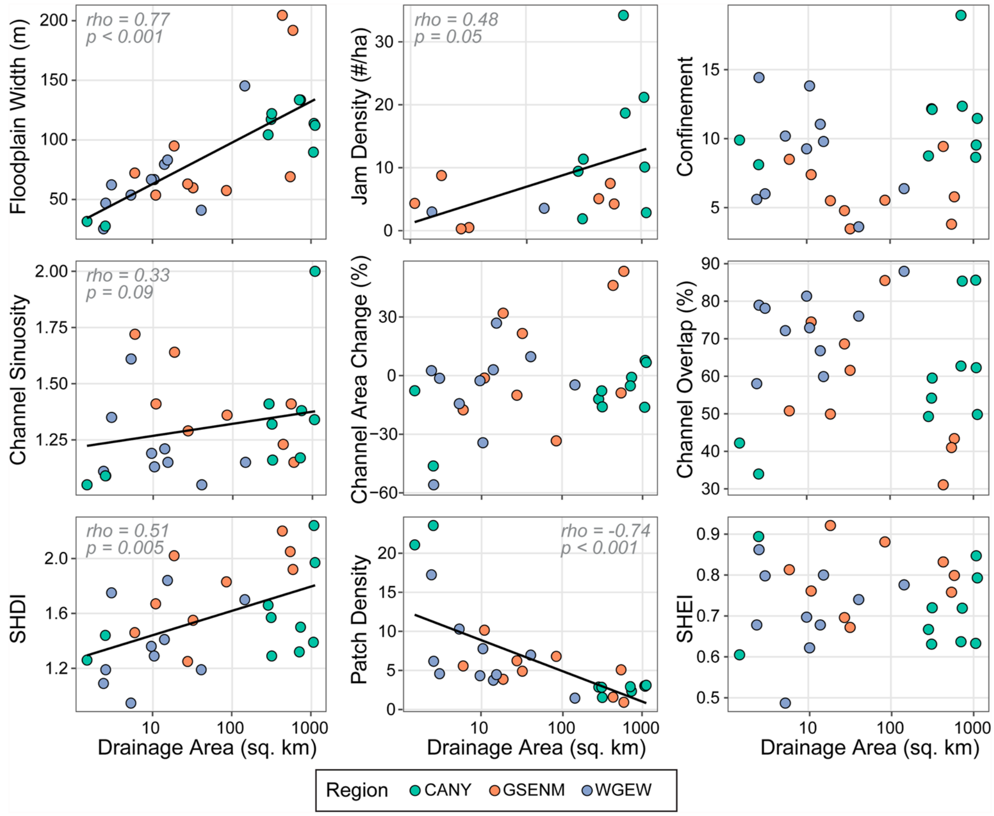

Figure 6. Linear relationships between drainage area, other potential driving factors, and diversity metrics.

other potential driving factors (Figure 6). Floodplain area (ρ = 0.765, p < 0.0001) and river corridor width (ρ = 0.772, p < 0.001) both increased downstream. However, confinement index did not correlate to drainage area (ρ = 0.096, p = 0.62). Channel sinuosity increased with drainage area (ρ = 0.38, p = 0.04), but other drivers indicative of channel mobility (including metrics of channel change) did not exhibit significant downstream trends (Figure 6).

4.3. Correlations Between Heterogeneity and Potential Drivers

Initial linear regressions highlighted significant relationships between heterogeneity and potential drivers. SHEI exhibited a weak correlation with median percent fines (Figure S5 in Supporting Information S1). As floodplains became finer grained, evenness decreased (ρ = −0.33, p = 0.08).

Patch density inversely correlated to river corridor width, where wider floodplains were less patchy per unit area (ρ = −0.94, p < 0.001) (Figure 7). Additionally, patch density was inversely correlated to metrics of channel mobility, including braiding index (ρ = −0.39, p = 0.04) and percent change in channel area (ρ = −0.35, p = 0.06) (Figure 7). Increased channel area over the past decade was predominantly driven by channel widening within the study beads, whereas decreased channel area was typically associated with channel narrowing by vegetation encroachment, although some reaches experienced meander cutoff. Therefore, higher values of patch density were found in cases of channel narrowing.

Opposite to patterns with patch density, SHDI significantly increased as river corridor width increased (ρ = 0.53, p = 0.003) and as braiding index increased (ρ = 0.34, p = 0.08) (Figure 8). Additionally, SHDI increased as channel sinuosity increased (ρ = 0.49, p = 0.006). A significant relationship existed between percent channel area change and SHDI, where river corridors with channels that widened over a decade exhibited higher unit diversity (ρ = 0.46, p = 0.01).

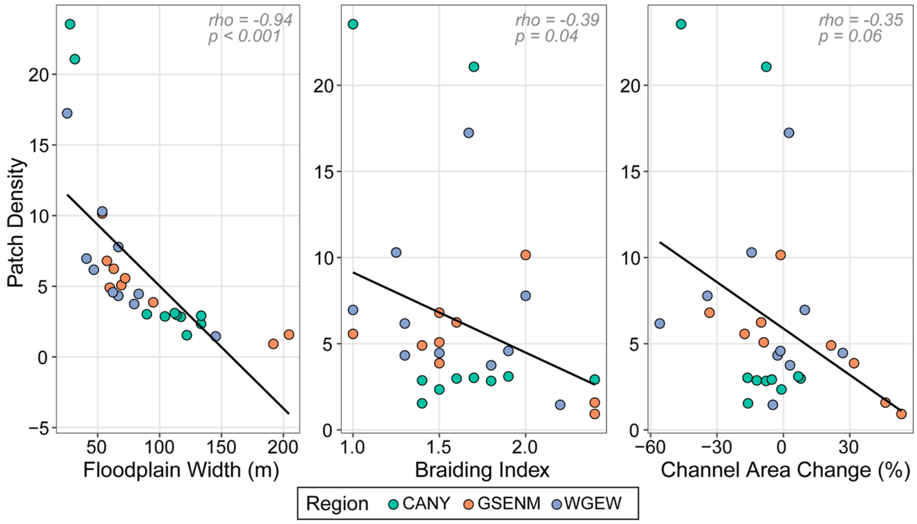

Figure 7. Significant relationships between patch density and potential driving factors.

Relationships between OSL ages and metrics of heterogeneity were tested separately, given the limited site selection. Although results are limited, sample depths normalized by OSL age (sample depth/OSL age) were significantly related to SHEI. OSL ages sampled between 1 and 2 m below the active floodplain surface varied in age between 0.5 and 0.8 ka, ranging from 4.04 to 1.29 m/ka when normalized by depth. A non-linear relationship was found between normalized ages and SHEI, where peak diversity was found at moderate normalized ages ($R^2 = 0.77$, $p = 0.02$, Figure 9). Given the limited sample size, the correlation between diversity and normalized OSL ages should still be considered weak.

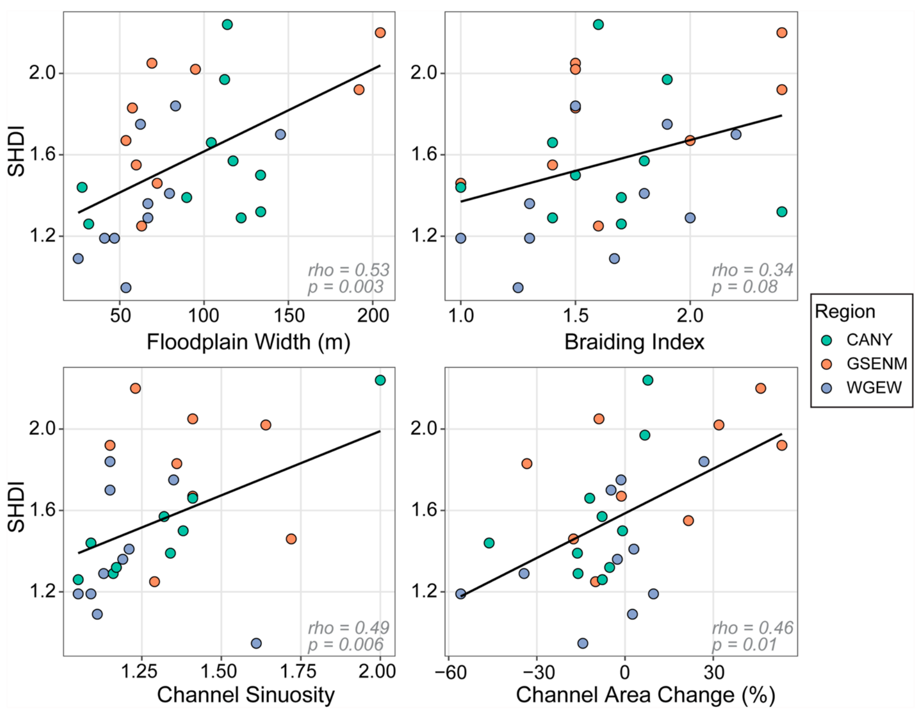

Figure 8. Significant relationships between Shannon's diversity index and potential driving factors.

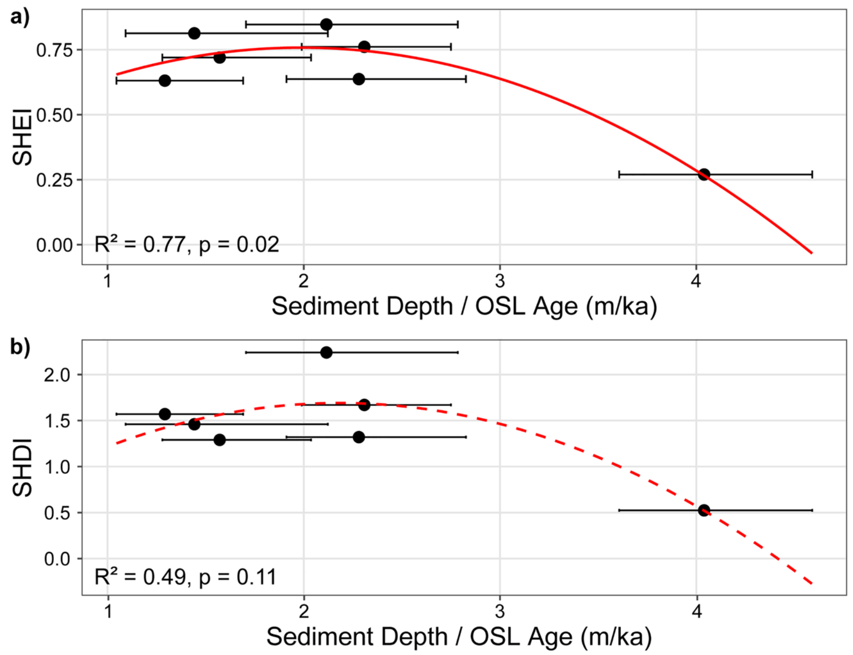

Figure 9. Plots of optically stimulated luminescence (OSL) ages normalized across sampling depth (sediment depth) compared to heterogeneity metrics: (a) Shannon's Evenness Index and (b) Shannon's Diversity Index. Error bars represent age errors from the OSL analysis.

4.4. Relative Importance of Potential Drivers

Potential drivers that significantly varied with metrics of heterogeneity were included in MLR models for each metric to determine relative importance. Based on the correlation between river corridor width and drainage area (Figure 6), we included the interaction between river corridor width and drainage area for all full models that included river corridor width. The full MLR model for SHDI included sinuosity, braiding index, percent channel area change, drainage area, river corridor width, and the interaction between width and drainage area as predictor variables. The best-fit model included river corridor width and percent channel area change as the sole independent variables for estimating SHDI. Using the sum of model weights (sw), the most important variables were river corridor width (sw = 0.65), percent channel area change (sw = 0.62), and drainage area (sw = 0.49) (Table 2). The sum of weights simply represents the fraction of fitted models that included the variable of interest during model selection.

Table 2
Correlations With and Importance of Driving Variables by Heterogeneity Metric

Response variable	Potential driving variables (correlation direction)	Top importance [sw]
Patch density	Drainage area (−)	River corridor width [1.0]
	River corridor width (−)	Drainage area [0.93]
	Braiding index (−)	Drainage area: River corridor width [0.92]
	% Channel area change (−)	
Shannon's Diversity Index (SHDI)	Drainage area (+)	River corridor width [0.65]
	River corridor width (+)	% Channel area change [0.62]
	Sinuosity (+)	Drainage area [0.49]
	Braiding index (+)	
	% Channel area change (+)	
Shannon's Evenness Index (SHEI)	Median percent fines (−)	Median percent fines [*n/a*]

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Given limited relationships between SHEI and predictors, a full MLR was not built. Instead, the median percent fine was recognized as the most important (and only) variable for estimating SHEI (Table 2).

The full MLR model for patch density included braiding index, percent channel area change, river corridor width, drainage area, and the interaction between the width and drainage area. Based on model selection, the best-fit model includes river corridor width as the sole independent variable. River corridor width was the most important variable (sw = 1.0), followed by drainage area (sw = 0.93) and the interaction between river corridor width and drainage area (sw = 0.92) as the next most selected variables during model selection (Table 2).

Model results indicate that morphologic context and flood regime influence geomorphic heterogeneity in non-perennial river corridors. However, contrary to our hypothesis, morphologic context has a stronger influence on heterogeneity than proxies for flood disturbances.

5. Discussion

5.1. Inferring Processes and Condition in Non-Perennial River Corridors

The morphology and description of geomorphic units in the study beads are indicative of processes of channel change and disturbance in ephemeral streams (Figure 4). The formation of geomorphic units within river corridors is affected by spatial variations in specific stream power during floods, which can influence floodplain aggradation and erosion (Nanson & Croke, 1992). In non-perennial streams, substantial overbank deposition during moderate to large, high-energy floods can result in geomorphic units primarily formed through vertical accretion, such as natural levees and avulsed channels (Hereford, 1984; Nanson & Croke, 1992). Evidence of vertical accretion is present at many of the study sites, including units that represent backswamps, natural levees, and abandoned channels (Figure 4, Table S1 in Supporting Information S1). Avulsed, secondary channels indicative of vertical accretion outnumbered laterally accreted point bars in WGEW, but lateral accretion units dominated in CANY and GSENM. In flash flood-dominated systems, lateral accretion is typically indicative of lower energy floods (Nanson & Croke, 1992), suggesting that the studied CANY and GSENM beads are experiencing lower stream power on average than the WGEW beads.

Two justifications could explain potential differences in stream power indicated by accretion patterns across studied sites. First, CANY and GSENM beads tend to represent larger catchment areas than WGEW (Figure 6), and flood energy tends to dissipate downstream in dryland ephemeral catchments. Therefore, there may be a threshold at which dominant accretion processes change in non-perennial streams, with upstream (small drainage area) floodplains dominated by vertical accretion and downstream (large drainage area) floodplains dominated by lateral accretion. Second, ephemeral streams oscillate between incised, cut channels (termed arroyos in the southwestern U.S.) that are entrenched in place and dominated by vertical accretion, and filled, wide channels that are able to migrate laterally (Graf, 1983; Patton & Schumm, 1981). Our floodplains represent a continuum of cut and fill, ranging from TC (GSENM), which is a true arroyo with banks 2–3 m high throughout the reach, to beads with varying lengths and heights of discontinuous entrenched banks. Given the spatial variability in entrenchment, differences in flood energy over drainage area is a more likely explanation for the differences in dominance by lateral versus vertical accretion units across study reaches. However, disconnectivity by channel incision can still impact the creation of geomorphic units, as is evident by TC, which was an outlier in both number and diversity of units within the river corridor (Figure 4). Overall, discussions of flood energy would benefit from direct observations of streamflow and calculations of stream power in the studied areas.

Geomorphic units also reflect anthropogenic processes within the study sites. The most common geomorphic unit in the CANY region was forested floodplain surfaces dominated by tamarisk, which is an invasive species introduced to the region in the late 1800s CE to early 1900s CE (Christensen, 1962). Although the dominance of broad, invasive patch types may contribute to lower patch density in CANY, the presence of invasive species within the region has limited apparent impact on diversity or evenness of geomorphic units (Figure 5). Although this may indicate that floodplain evolution and geomorphic diversity are largely unaffected by invasive species encroachment, previous studies have shown the influence of invasive species on channel planform and migration (Birken & Cooper, 2006; Graf, 1978; Hereford, 1984; Walker et al., 2020), which in turn can affect the heterogeneity of geomorphic units (Figures 7 and 8). As an alternative explanation, the lack of impact on SHDI and SHEI could also be indicative of past processes in GSENM and WGEW. In GSENM, widespread removal of invasive tamarisk and Russian olive has been conducted by local restoration groups since 2009 CE (Tuhy

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& Spence, 2011), including removal of tamarisk in certain study sites (HA and HC) in 2019 CE. Geomorphic units that developed during tamarisk colonization may still exist in GSENM floodplains but may be currently dominated by native shrub species left in the wake of invasive species removal. Anthropogenic alterations such as invasive species introduction and removal as well as large perturbations such as flow regulation (e.g., Grams & Schmidt, 2002; Merritt & Cooper, 2000; Stevens et al., 1995) may impact geomorphic heterogeneity in non-perennial river corridors for decades, particularly given punctuated change associated with infrequent and stochastic flows. While quantifying anthropogenic alterations can be difficult, these alterations likely have an impact—potentially increasing or decreasing the number of units—on geomorphic heterogeneity that may not be captured in other drivers measured here.

5.2. Linking Correlations to Drivers of Heterogeneity in Non-Perennial Streams

Morphologic context had a stronger influence on geomorphic heterogeneity than proxies for flood disturbance in the selected, unconfined sites across the southwestern U.S. Similar to perennial streams, wider river corridors or beads are areas of higher geomorphic diversity in ephemeral watersheds. Floodplain width exerted the dominant control on geomorphic heterogeneity in the study rivers, which has been found for other complexity metrics in dryland floodplains (Scown et al., 2016; Thorp et al., 2008). Scown et al. (2016) suggested that strong correlations between complexity and river corridor width are evidence of the long-held belief in geomorphology that "the valley rules the stream" (Hynes, 1975; Schumm, 1977; Van Appledorn et al., 2019). The inverse correlation between river corridor width and patch density is likely due to dissipation of flood energy at larger floodplain sizes. As floodwaters are able to spread in increasingly larger floodplains, both the magnitude (stage) and unit stream power will decrease, which limits the construction of floodplain features (Fagan & Nanson, 2004; Magilligan, 1992). As found by Scown et al. (2016), the magnitude of correlation between patch density and river corridor width sharply wanes at larger widths (approximately 75 m or wider in this study), likely representing a threshold in the rate of change in power. Additionally, steeper stage-discharge relationships in narrower reaches could result in the same number of patches in a smaller floodplain area, thus increasing patch density. In addition to influences on flood energy, river corridor width can potentially impact disturbance frequency. As distance from the channel increases, the likelihood of disturbance decreases and reworking by floods becomes less frequent (Konrad, 2012), thus limiting the potential for high patch density at floodplain edges. However, we found that as river corridor width increased, unit diversity increased (Figure 8). High diversity in wide floodplains suggests that, although distal units likely have long residence times, the processes involved in formation and evolution of these units contribute to a diversity of form and habitat in ephemeral floodplains.

Evenness was also dictated by morphologic context more than direct proxies for disturbance. Decreased evenness (SHEI) with increased median fines suggests that finer grained (i.e., more cohesive) floodplains are more resistant to the creation of new units and that individual units may be larger or tend to cluster in specific classes, which follows previous evolution models for non-perennial dryland streams (e.g., Schumm, 1960).

Although relationships between morphologic context and heterogeneity are intuitive and supported by past research, results may be influenced by the lack of direct measurements for flood disturbance regimes. The use of channel change as a proxy for flood disturbance relies on past relationships between morphologic changes and flood frequency, magnitude, and duration, but potentially ignores other driving factors of channel mobility or stability, such as vegetation or bank cohesion (e.g., Hooke, 2016). Subsequently, channel change may be capturing not just differences in disturbance between reaches but also other confounding factors. The absence of direct measurements for flow frequency, magnitude, and duration also limits our understanding of the specific aspect or aspects of the flow regime that influences heterogeneity in non-perennial river corridors. However, in the absence of more robust gauging networks on non-perennial streams (Krabbenhoft et al., 2022), channel change analysis is one readily measurable proxy for potential flood disturbances in ungauged watersheds. Additionally, metrics of channel change—namely, percent channel overlap—did show a weak correlation with flood count and peak magnitudes in WGEW, the one gauged basin in the study.

Without direct measurements, proxies for flood disturbance (decadal percent channel overlap and percent channel change) were secondary drivers for determining geomorphic heterogeneity (Table 2). Patch density and SHDI both had significant relationships with metrics of channel change potentially indicative of disturbance frequency, magnitude, and/or duration. Patch density decreased in channels that widened over time, likely due to recent increased area within a single patch: the main channel. River corridors where channels narrowed over time represent near-channel corridors that have experienced vegetation colonization and encroachment, which can help support the creation of new patches (e.g., Bendix & Hupp, 2000; Harris, 1987). However, unit diversity in narrowing channels was low, indicating that new patches might represent similar successional vegetation stages or that unique patches that would form in the presence of flash floods are absent. We interpret increased channel area as indicating higher flood frequency, magnitude, and/or duration over the decade analyzed, suggesting that higher frequencies of disturbance lead to higher geomorphic diversity in non-perennial river corridors.

The dominance of river corridor width in models created to describe geomorphic heterogeneity in the study beads suggests that floodplain heterogeneity in non-perennial river corridors is more sensitive to changes in morphology than changes in flood regime. Ephemeral streams have long been perceived as sensitive to flood disturbance, given high erodibility (Graf, 1988). However, our work suggests that this sensitivity should be viewed through a broader lens of river corridor morphology, which mediates disturbance processes such as floods. However, the true interaction between disturbance and heterogeneity may be better identified by tracking geomorphic units and heterogeneity metrics through time as well as through space. If individual large flows or suites of smaller flows can notably alter geomorphic unit assemblages in a river corridor, tracking the creation and evolution of units following flows of different magnitudes and frequencies would directly elucidate that process. Because non-perennial streams are characterized by unpredictable flow, long-term (i.e., decadal) studies are needed in the future to truly represent temporal change in heterogeneity.

In the absence of robust temporal studies, sediment dating methods emphasized the importance of long-term processes in shaping geomorphic unit heterogeneity. Luminescence ages highlighted variations in sediment accumulation over centennial timescales across study beads, which had an impact on geomorphic unit evenness (Figure 9). Floodplains that have been accumulating sediment at intermediate rates over the last ~500—800 years corresponded to the highest metrics of geomorphic heterogeneity, which mirrors prior ecological studies in non-perennial streams that suggest relatively intermediate levels of disturbance create the highest diversity (Lite et al., 2005). Low sedimentation rates would limit the creation of new surfaces while high sedimentation rates would potentially overwhelm the system. Although the majority of measured sites cluster at slightly increasing levels of evenness with increasing accumulation rates, the floodplain with the lowest heterogeneity values also had the youngest depositional ages (i.e., highest sediment depth/OSL age) (Figure 9). The largest accumulation rate was experienced in GSENM bead TC where sediment buried ~2 m below the floodplain surface was deposited ~500 years ago. Here, high rates of sediment deposition—likely combined with channel incision—have resulted in an entrenched channel (i.e., arroyo) with limited potential to connect with the current genetic floodplain. Limited lateral connectivity and reworking of geomorphic units have likely contributed to low geomorphic evenness. While data are limited, results begin to suggest that high rates of accumulation may aid in floodplain disconnectivity, thus influencing river corridor heterogeneity.

Although luminescence ages provide some context for sedimentation over the past centuries, modern sediment yields are not monitored or available in these catchments. Previous studies suggest floodplain surface complexity can lag changes in sediment yields by decades (Panin et al., 1999; Thoms, 2006). While TC evidently experienced high sediment loads at times over the past 500 years, this is not evidence that high sedimentation rates exist today. Instead, patterns in sediment deposition rates and subsequent floodplain evolution are likely impacted by patterns of cutting and filling common to dryland non-perennial streams. Regionally, channels were actively cutting between 1200 and 1400 CE (Townsend et al., 2019), which corresponds to ages of sediment deposition (~500–800 years before present) measured in the studied floodplains. Subsequently, regional trends and complex response in channels likely have an impact on general floodplain development and geomorphic unit evolution in dryland non-perennial river corridors. Given that studies have identified cut and fill processes globally (e.g., Erskine, 1986; Mäckel, 1974), sporadic sediment influxes due to complex channel response could influence floodplain development in non-perennial river corridors worldwide.

5.3. Comparing Heterogeneity Across Environments

Comparing heterogeneity metrics across mapping projects and environments can be complicated. Differences in mapping resolution (Scown et al., 2015a; Wheaton et al., 2015) and criteria for defining geomorphic units (D. N. Scott et al., 2022) can alter both the value and meaning of landscape metrics such as SHDI, SHEI, and patch density. Many previous studies that identify geomorphic units and calculate landscape-scale diversity indices have focused on in-channel habitat (e.g., Thomson et al., 2001; Wheaton et al., 2015; Williams et al., 2020; Yarnell et al., 2006), which are difficult to compare to river corridor-scale studies. However, comparing complexity of river corridors along non-perennial streams to perennial systems could elucidate both similarities and uniqueness in process and function between environments. We identified a subset of heterogeneity studies that used similar methods (field-surveys paired with remotely sensed layers) at similar resolutions (approximately 1-m) as our study for comparison. Marston et al. (1995) calculated an SHDI of 1.98 for a 40-km stretch of the 100-year floodplain along the Ain River in France. Laurel and Wohl (2019) found a median SHDI of 1.45 and median SHEI of 0.808 for beaver meadows (both active and abandoned) along perennial streams in Rocky Mountain National Park in Colorado, USA. Finally, D. N. Scott and Collins (2019) calculated a SHEI of 0.85 for a restored reach of Deer Creek in Oregon, USA. In general, our study found similar values of SHDI (median = 1.57 for all sites) and SHEI (median = 0.747 for all sites) as these studies in perennial rivers. Maximum SHDI and SHEI values in our study were 2.22 and 0.926, respectively, indicating that non-perennial river corridors can exhibit similar and potentially even higher levels of complexity than perennial river corridors. Similarities between non-perennial and perennial river corridors also supports that hydrologic regime may be a less important driver of geomorphic heterogeneity.

Although these comparisons are limited, they provide an indicator by which to contextualize the importance of non-perennial river corridors. High geomorphic complexity in non-perennial river corridors reflects the structural potential to support high biodiversity and storage of sediment, water, and nutrients, similar to perennial river floodplains. Moving forward, heterogeneity could provide a metric for monitoring the geomorphic condition of non-perennial streams and for tracking geomorphic change, similar to the use of geomorphic heterogeneity metrics to monitor perennial river corridors (Fryirs & Brierley, 2022; D. N. Scott et al., 2022).

6. Conclusions

Geomorphic heterogeneity in non-perennial beads across the southwestern U.S. was influenced by river corridor morphology more than proxies of flash flood disturbance. However, potential drivers measured in this study only represent ~30% of the variability in geomorphic heterogeneity across floodplains, suggesting that other factors—such as specific vegetation feedbacks or short-term variations in water and sediment fluxes—may be influencing the creation and diversity of geomorphic units in non-perennial streams. For example, unit classes and abundance also reflect processes related to deposition and lateral channel migration during flash floods as well as anthropogenic processes such as invasive vegetation introduction and removal. Although results are likely limited due to a lack of direct flood disturbance measurements which are difficult to collect during temporary inundation, this study provides context for spatial geomorphic heterogeneity and potential drivers in non-perennial streams. Future studies tracking geomorphic units and flood disturbance within a given study site over years to decades may better elucidate the relationship between disturbance and heterogeneity. Compared to perennial river corridors, non-perennial river corridors had similar values of heterogeneity, emphasizing the potential importance of non-perennial river corridors for providing ecosystem functions. Geomorphic heterogeneity may be a useful metric for monitoring non-perennial river corridors and ecosystem function in the future, particularly as disturbance regimes change under a changing climate.

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Data Availability Statement

Data used in the study are available at Dryad via https://doi.org/10.5061/dryad.nk98sf7x4 with a Creative Commons Zero license. Data archived at this DOI include the raw field survey data used to differentiate geomorphic units and calculate heterogeneity, reach data used to calculate statistical models, and the Optically Stimulated Luminescence data (Scamardo, 2023).

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