DISSERTATION

FORM AND FUNCTION: QUANTIFYING GEOMORPHIC HETEROGENEITY AND DRIVERS IN DRYLAND NON-PERENNIAL RIVER CORRIDORS

Submitted by

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ABSTRACT

FORM AND FUNCTION: QUANTIFYING GEOMORPHIC HETEROGENEITY AND DRIVERS IN DRYLAND NON-PERENNIAL RIVER CORRIDORS

Non-perennial rivers, including intermittent rivers and ephemeral streams, comprise the majority of drainage networks globally. However, ephemeral streams remain understudied compared to perennial counterparts, and the majority of extant studies focus on in-channel dynamics. Floodplains along perennial streams are known to host a high density of ecosystem functions, including the attenuation of downstream fluxes and provision of habitat to diverse flora and fauna. These functions are thought to be correlated to geomorphic heterogeneity, and studies of floodplain heterogeneity are emerging on perennial rivers. Here, I extend the conceptualization of floodplain function and heterogeneity commonly focused in perennial watersheds to dryland, ephemeral streams.

Based on a synthesis of current literature identifying ephemeral stream floodplain characteristics in drylands, a set of floodplain styles emerge dependent on confinement and the presence of channelized flow. Functions related to attenuation and storage are typically concentrated in unconfined and channeled floodplains. The temporary storage of sediment and sub-surface water in ephemeral stream floodplains make them hotspots for biogeochemical cycling and hosts to richer, denser, and more diverse vegetation communities compared to surrounding uplands. Many functions of ephemeral stream floodplains are also found in perennial counterparts, but flashy flow regimes and high sediment loads in ephemeral streams can potentially impact rates and magnitudes of comparable processes and functions.

Similar to perennial rivers, the diverse physical and ecological functions in ephemeral stream floodplains are thought to be related to spatial geomorphic heterogeneity. Although studies on the characteristics and drivers of geomorphic heterogeneity exist for perennial streams, similar studies in ephemeral streams are lacking. Geomorphic heterogeneity was therefore quantified along with potential drivers – including metrics related to geomorphic context and proxies for flood disturbance – to understand underlying processes in ephemeral river corridors. Geomorphic units were mapped in 30 unconfined river corridors within six non-perennial watersheds in Utah and Arizona, U.S. 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, channel change and sediment storage times. Although heterogeneity positively correlated with metrics for morphology and disturbance (i.e., channel change and storage), statistical models suggest that morphologic context, particularly floodplain 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 non-perennial rivers with greater geomorphic heterogeneity may be resilient to changes in flood disturbance frequency or magnitude, but future studies investigating long-term temporal heterogeneity are needed.

The lack of direct flux observations could also be restricting insight into how floods interact with large wood and vegetation, which are known to have complex relationships with geomorphic heterogeneity in perennial rivers. In the absence of flood observations, a hydro-morphodynamic model was developed to investigate changes to channel and floodplain

morphology due to wood and vegetation in an ephemeral river corridor in southeastern Arizona, U.S. Three scenarios were modeled: the actual configuration of the river corridor; an experiment in which jams were removed; and an experiment in which vegetation was removed. Both large wood and vegetation effectively confined flow to the main, unvegetated channel, which became wider and deeper over the course of a single moderate flood. When isolating the impact of large wood, model results show that wood increases the magnitude of channel change created by vegetation, resulting in ±0.1 to 0.3 m of additional scour or aggradation. The simulated removal of vegetation resulted in more channel change than the removal of wood alone, partially because vegetation occupies a much greater area within the stream corridor than large wood. I propose a conceptual framework in which large wood could mediate sedimentation as well as the recruitment and growth of vegetation in ephemeral streams, contributing to the evolution of ephemeral stream morphology over time.

Due to the ubiquity of dryland ephemeral streams, results of this research have the potential to influence watershed management globally. Wide, unconfined ephemeral stream floodplains and riparian forests could be targets for protection and restoration similar to current efforts in perennial rivers. Particularly in the context of future climate and land use changes, understanding the natural character, function, and heterogeneity of ephemeral stream floodplains highlights their physical and ecological importance in dryland landscapes.

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DEDICATION

I dedicate my dissertation to all the women that taught me the importance of education and adventure – especially my mother, Eileen.

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CHAPTER 1: INTRODUCTION

Over 50% of all rivers by length globally are considered to be non-perennial, yet research on intermittent rivers and ephemeral streams is limited compared to perennial counterparts (Levick et al., 2008; Messager et al., 2021). Existing literature on ephemeral streams largely focuses on the main channel, primarily investigating sediment transport (e.g., Reid and Laronne, 1995; Billi, 2011) and to a lesser extent, flow generation (e.g., Hammond et al., 2020; Shanafield et al., 2021) and hydrologic connectivity (e.g., Jaeger and Olden, 2012; Boulton et al., 2017). However, on perennial rivers, floodplains are known hotspots for ecosystem functioning, including storage of sediment, water, and solutes (Wohl, 2021) and nutrient cycling (Bellmore and Baxter, 2014; Hauer et al., 2016). These functions tend to be concentrated in river corridors (including the floodplain as well as the main channel and hyporheic zone [Harvey and Gooseff, 2015]) that are geomorphically heterogenous, meaning that they have a greater number, diversity, and evenness of geomorphic units. Geomorphic units are landforms or features formed by a given set of processes (e.g., point bars or backswamps) (Fryirs and Brierley, 2022; Scott et al., 2022).

Similar research examining structure and function in ephemeral stream floodplains is lacking yet could have important implications for drylands in particular, where the percentage of the drainage network that is non-perennial can exceed 80% by length (Levick et al., 2008). Although floodplains may share many characteristics in common along perennial and ephemeral rivers, ephemeral streams are characterized by more stochastic and extreme flood regimes (Leopold and Miller, 1956; Hassan, 1990; Farquharson et al., 1992; Knighton and Nanson, 1997), higher sediment loads (Langbein and Schumm, 1958; Laronne & Reid, 1993), and sparser vegetation communities (Stromberg et al., 2005), all of which may impact the magnitude and extent of processes and functions in ephemeral stream floodplains. The following research is therefore aimed at expanding recognition and understanding of ephemeral stream floodplains in drylands. Chapter 1 synthesizes previous literature that has defined, mapped, and characterized dryland ephemeral stream floodplains, particularly their unique hydrologic, geomorphic, and biotic features and functions on the landscape. Recognizing that floodplain functions may be tied to geomorphic heterogeneity, Chapter 2 incorporates direct observations of geomorphic units and potential drivers of their density, diversity, and evenness in unconfined, ephemeral river corridors across the southwestern U.S., similar to prior research in perennial watersheds (e.g., Wheaton et al., 2015; Wohl and Iskin, 2019; Scott et al., 2022).

Geomorphic heterogeneity and, more generally, the morphology of floodplains – perennial or non-perennial – is likely driven by a combination of sediment, water, and organic matter inputs largely from floods as well as the broader geomorphic context (e.g., floodplain shape and size, grain size, etc.) and the existing vegetation, which are both influenced by and moderators of said inputs (Wohl, 2016). Particularly, complex feedbacks exist between vegetation, organic matter, and processes of sedimentation and erosion that shape the ephemeral river corridor (e.g., Hooke et al., 2005), which likely cannot be elucidated by static observations during dry conditions. In the absence of flood observations, Chapter 4 employs morphodynamic modeling to understand and isolate the impact of large wood and vegetation on river corridor morphology during moderate to large flash floods in an ephemeral stream.

By synthesizing and adding to direct and indirect observations of process and function in ephemeral stream floodplains, this work holds the potential to influence management across large swathes of drylands influenced by non-perennial rivers as well as motivate future work focused on ephemeral stream floodplains as distinct and disproportionately functional landforms.

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CHAPTER 2: REDEFINING THE EPHEMERAL STREAM FLOODPLAIN: IDENTIFICATION AND IMPORTANCE OF FLOOD ZONES IN DRYLANDS

2.1. Introduction

Floodplains, broadly defined as the variably inundated area adjacent to a river, are disproportionately functional landforms. In perennial rivers, variable flow drives transient storage of sediment, water, and nutrients within floodplains (Wohl, 2021), which supports varied habitat, biotic productivity, and nutrient cycling (Bellmore and Baxter, 2014; Hauer et al., 2016). As such, floodplains are known to be watershed-scale hotspots of biodiversity (Ward et al., 1999; Tockner et al., 2010), biogeochemical reactions (Appling et al., 2014), and terrestrial carbon storage (Wohl et al., 2012; Sutfin et al., 2016; Lininger et al., 2019). While floodplains only cover approximately 1.4% of the global terrestrial land surface, they provide more than 25% of terrestrial ecosystem services (Tockner and Stanford, 2002). Higher concentrations of ecosystem services are thought to occur in unconfined and spatially heterogenous river corridors, (Bellmore and Baxter, 2014; Wohl, 2021), where floodplains are comprised of a mosaic of geomorphic units which allow for variability in inundation frequency, water depth, and ecosystem processes (e.g., Appling et al., 2014; Helton et al., 2014). Floodplains are known to occur across a variety of flow regimes, including ephemeral streams and intermittent rivers, yet the majority of floodplain research has concentrated on perennial reaches, even in dryland environments (e.g., see papers in Carling and Petts, 1992; Wohl, 2021). Additionally, research on non-perennial rivers, including ephemeral streams, has largely focused on the main channel (Graf, 1988; Cooke et al., 1993; Thornes, 1994; Knighton and Nanson, 1997; Tooth, 2000; Reid and Frostick, 2011). Here, I aim to extend our conceptualization of floodplains as highly functional landforms to rivers with ephemeral flow regimes.

In the absence of a perennial channel, the boundaries and functions of a floodplain are harder to distinguish from that of the channel. The boundary between channel and floodplain may be bankfull in ephemeral streams with well-defined banks, but the floodplain may encompass the entire river or valley corridor in reaches with unchanneled flow such as floodouts (e.g., Tooth, 2000). Ephemeral stream floodplains potentially have a large global footprint, given the prevalence of ephemeral streams across biomes. Over 50% of river networks globally are expected to go dry for at least part of the year (Messager et al., 2021), with arid and semi-arid drylands expected to have an even greater percentage of ephemeral channels (Levick et al., 2008). The number and density of ephemeral streams are also expected to increase due to climate change and aridification in drylands and other susceptible ecoregions (Arnell and Gosling, 2013; Reynolds et al., 2015).

Ephemeral stream floodplains, particularly in drylands, develop under distinctly different hydrologic and morphologic conditions than floodplains along perennial rivers. Ephemeral stream hydraulics are characterized by unsteady, nonuniform flow during stochastic flash floods (Leopold and Miller, 1956; Hassan, 1990; Glancy and Williams, 1994) that are subject to downstream transmission losses due to infiltration of flow into the channel bed and floodplain (Thornes, 1977). These conditions can lead to spatially variable sediment transport and deposition, meaning that floodplain morphology and stratigraphy can vary markedly through space (McKee et al., 1967; Patton and Schumm, 1981). Despite relatively low rates of precipitation and high evaporative demand leading to stochastic and sometimes limited streamflow, the unique disturbance regime in drylands could potentially both develop and disrupt ecosystem functions and services in the ephemeral stream floodplain (Renard and Keppel, 1966; Fisher et al., 1982; Hjalmarson, 1984)

Given the unique processes and geographic ubiquity of ephemeral streams, understanding the extent and importance of adjacent floodplains is vital to managing and protecting dryland ecosystems. Here, I highlight the importance of dryland, ephemeral floodplains as functional landforms by: (1) revisiting the definition and form of floodplains along ephemeral streams; (2) reviewing the hydrologic, geomorphic, and biotic characteristics and functions of ephemeral stream floodplains; (3) discussing changes that are likely to affect ephemeral river floodplains in future; and (4) identifying gaps in knowledge of ephemeral river floodplains. By emphasizing the scientific understanding of the boundaries and functions, I hope to highlight the importance of preserving the natural disturbance regime in ephemeral stream floodplains.

2.2. Identifying and Classifying Ephemeral Stream Floodplains

Ephemeral stream river corridors – defined as the channel, floodplain, and hyporheic zone – take a variety of forms in drylands globally (Figure 2.1). This variability in shape can be classified into several floodplain styles, which emerge from studies that have delineated and characterized ephemeral stream floodplains across regions. However, in order to map and study the ephemeral stream floodplain as a unique landform, they must first be defined in theory.

2.2.1. Defining the Ephemeral Stream Floodplain

One means of defining the ephemeral stream floodplain is differentiating it from the active channel. The active channel is a geomorphic landform created by fluvial processes (i.e., erosion and deposition) and is commonly defined by a break in bank slope that typically coincides with the lower limit of permanent vegetation (Hedman and Osterkamp, 1982; Wohl et al., 2016). This definition can hold true in ephemeral stream channels, with the exception that active channels may include vegetation – particularly seedlings – which may temporarily colonize otherwise unvegetated channel surfaces between flows (e.g., Graeme and Dunkerley, 1993; Shaw and Cooper, 2008). In ephemeral streams with a defined bankfull level – or point at which overbank flow occurs – the floodplain can be defined as the channel-adjacent area above bankfull. However, in many ephemeral streams, particularly those that are incised, the bankfull level can be difficult to determine or distinguish from the active channel (Hedman and Osterkamp, 1982). In these settings, the active channel can be delineated using a change in vegetation density or slight topographic rises that indicate the demarcation between channel and floodplain within the river corridor.

Figure 2.1. Examples of dryland ephemeral stream river corridors – and more specifically, floodplains – globally. Clockwise from upper left, Arizona (U.S.), Spain, Namibia, and Chile.

Although determining the active channel can differentiate the near-channel floodplain boundary, the lateral extent of the ephemeral stream floodplain can be determined using hydrologic, geomorphic, and biotic characteristics (Table 2.1), similar to past studies in predominantly perennial rivers (Wolman and Leopold, 1957; Wolman and Miller, 1960; Junk et al., 1989; Graf, 1988; Nanson and Croke, 1992; Moody et al., 1999; Dunne and Alto, 2013).

Table 2.1. Definitions of the ephemeral stream floodplain.

Category	Definition	Example Citations
Hydraulic	The flooded area during a given recurrence-interval flow; can vary widely for ephemeral stream floodplains depending on chosen flow	Wolman and Leopold (1957); Graf (1988)
Genetic	Sediments outside of the active channel fluvially deposited under the contemporary flow regime	Nanson and Croke (1992)
Topographic	Low-lying areas adjacent to the active channel differentiated from the uplands by a slope break; commonly closely related or equated to the genetic floodplain on ephemeral streams	Graf (1988); Bagstad (2006)
Vegetative	Area adjacent to the active channel characterized by xeroriparian and riparian plant species	Lichvar et al. (2009); Manning et al. (2022)

Hydrologically, the floodplain is defined as the area adjacent to the channel that is likely to be inundated due to a given recurrence interval flood, including both bedrock and alluvial surfaces (e.g., Wolman and Leopold, 1957; Graf, 1988). Ephemeral streams in dryland regions are typically characterized by high intensity and localized floods which occur more stochastically through time and space than in perennial networks (Pilgrim et al., 1988; Knighton and Nanson, 1997). Factors such as antecedent moisture, rainfall intensity, and rainfall location can significantly impact runoff generation in ephemeral streams. For example, Morin et al. (2006) found that peak discharge in Walnut Gulch Experimental Watershed in southeastern Arizona, U.S., varied by a factor of two for storms just a few kilometers apart. High runoff variability in ephemeral watersheds results in rare floods with annual recurrence intervals of 50 to 100 years that are much larger than the mean annual flood compared to perennial watersheds (Lane, 1982; Farquharson et al., 1992; Zaman et al., 2012). Global discharge data compiled for rainfall-dominated ephemeral streams consistently found extreme slopes and skewness for regional flood frequency curves (Farquharson et al., 1992). Consequently, hydrologically defined floodplains along ephemeral streams exhibit large variability in extent depending on the defining flood recurrence interval.

Geomorphically, the ephemeral stream floodplain can be defined as the sediment and landforms deposited adjacent to the channel under the current hydrologic regime. Termed the genetic floodplain, this definition encompasses only alluvial surfaces (Nanson and Croke, 1992). The genetic floodplain differentiates between active floodplain surfaces which are continually evolving under the current regime (e.g., Williams, 1978) and inactive floodplains, including fluvial terraces which were created under a prior regime and are no longer subject to active processes (Leopold et al., 1964). Inactive floodplains may still be considered as part of the hydraulic floodplain and may be inundated during high magnitude, low frequency floods. In ephemeral streams, the delineation of the genetic floodplain can be complicated, particularly given large interannual flow variability (Croke et al., 2016). For example, the active floodplain is expected to be inundated every 1.5 to 2 years in perennial streams, coinciding with the return interval of flows that determine the bankfull height (Wolman and Leopold, 1957). Yet in arid ephemeral streams, high discharge variability can result in low frequencies of overbank deposition, particularly given that overbank flow may occur for less than 1% of the year (Reid et al., 1998). Therefore, sediment deposited during floods with 10- to 20-year recurrence intervals or longer could still be considered the genetic floodplain in river corridors with high flow variability like ephemeral streams (Croke et al., 2016). Commonly, the geomorphic or genetic floodplain extent is delineated based on topographic indicators, such as a slope break leading up to the adjacent uplands or terraces (e.g., Graf, 1988; Bagstad et al., 2006).

In addition to hydraulic and geomorphic definitions, vegetation has also been used to determine the extent of the ephemeral stream floodplain. Vegetation is denser and larger in riparian areas near dryland, ephemeral streams due to the association with runoff (Lichvar et al., 2009; Clerici et al., 2013; Hamada et al., 2016; Manning et al., 2020). Additionally, different plant guilds are typical of riparian versus upland regions largely due to changes in moisture and disturbance frequency (Stromberg and Merritt, 2015). Typically, vegetation is used to map the extent of the riparian area, but the presence of xero-riparian plants throughout the river corridor can distinguish the floodplain from adjacent uplands (Manning et al., 2020).

The metrics used to delineate ephemeral stream floodplains largely match those historically used to map floodplains along perennial rivers (Graf, 1988; Nanson and Croke, 1992). However, ephemeral streams have unique flow variability, sediment regimes, and vegetative characteristics that introduce challenges to mapping the floodplain extent. Still, the floodplain definitions highlighted here (Table 2.1) have all been used to map the extent of the ephemeral stream floodplain in practice.

2.2.2. Methods for Delineating the Ephemeral Stream Floodplain

Although hydraulic, geomorphic, and biotic indicators have all been used to determine the ephemeral stream floodplain extent, perhaps the most common method is by estimating inundation. The emphasis on mapping the hydraulic floodplain is largely due to an interest in understanding flood risk along dryland ephemeral streams (e.g., Camarasa-Belmonte and Soriano-Garcia, 2012; Korichi et al., 2016; Betancourt-Suarez et al., 2021; Mazer et al., 2021).

However, other studies have delineated the hydraulic floodplain (or the riparian zone) to aid in channel classification (e.g., Levick et al., 2018) as well as to examine the hydrologic function of ephemeral streams (e.g., Maxwell et al., 2021). Commonly, the hydraulic floodplain is delineated by artificially inundating a digital elevation model (DEM) of the ephemeral stream river corridor. A key challenge of this method is determining a depth or discharge at which to model the floodplain, particularly given limited gage data for ephemeral streams (Costigan et al., 2017). Prior mapping studies have used both a fixed stage – for example, Levick et al. (2018) used a stage depth of 3 m based on the average depth of riparian plant roots to capture all riparian vegetation whose roots are likely tapping into the channel baselevel during flow – and variable stage to determine floodplain extents. Variable stage estimates have used direct measurements of streamflow (e.g., Pacheco-Guerrero et al., 2017), rainfall-runoff relationships (e.g., Maxwell et al., 2021), and regional flood frequency analyses (e.g., Nardi et al., 2006) to estimate an inundation depth throughout the river corridor. However, using discharge estimates to map the floodplain extent may limit studies to areas with existing streamflow or precipitation instrumentation.

With the lack of hydrological instrumentation and observations to aid in mapping floodplains along ephemeral streams, there is an increasing interest to use remote sensing-based approaches to determine floodplain extents. However, given the stochastic nature of ephemeral stream runoff, capturing floods in imagery – particularly, capturing cloud-free imagery during or immediately following flooding – is difficult (e.g., Rowberry et al., 2011; Li et al., 2018). Despite these limitations, floodplain mapping from satellite-based imagery has been possible in larger (> 20 m width) dryland ephemeral river corridors, typically using reflectance in near infrared or short-wave infrared bands to identify flooded pixels (Li et al., 2021; Betancourt-

Suarez et al., 2021; Wang and Vivoni, 2022). On smaller channels, drone-based imagery has been used to delineate ephemeral river corridors and floodplain extents (e.g., Hamada et al., 2016; Andreadakis et al., 2020), typically using topographic and vegetative indices during periods of low to no-flow rather than the presence of water during flooding. Compared to satellite-based imagery, drone imagery has a finer pixel resolution but more limited spatial extent, making it less feasible for large areas (Hamada et al., 2016).

At the reach scale, ephemeral stream floodplain extents have also been delineated in the field using topographic surveys and vegetative indicators. An increase in slope leading to a higher terrace or upland surface has commonly been used to topographically define the lateral extent of the ephemeral stream floodplain both in the field (e.g., Patton and Boison, 1986; Bagstad et al., 2006; Ringrose et al., 2014; Reynolds and Shafroth, 2017; Scamardo et al., in review) and using contour maps (e.g., Maxwell et al., 2021). Additionally, the presence of riparian vegetation has been used to determine the transition from floodplains to uplands (e.g., Levick et al., 2018; Manning et al., 2020; Reynolds and Shafroth, 2017). For example, Levick et al. (2018) noted that creosote (*Larrea tridentata*) typically marks the division between the riparian area and adjacent uplands for ephemeral streams in the Mojave Basin in southern California, U.S., giving one example of how upland indicator species can be used to determine the transition out of the river corridor.

There is no single, consistently applied definition or criteria for designating the floodplain boundaries of ephemeral streams. The current methods used for delineating ephemeral stream floodplains in practice span the variability in floodplain definitions (see Section 2.1), and the specific definition used varies in relation to the purpose of the designation (e.g., natural hazards versus mapping of vegetation communities).

2.2.3. *Floodplain Styles on Ephemeral Streams*

Similar to perennial streams, ephemeral stream floodplains take a variety of forms due to variations in confinement, grain size, slope, vegetation, and channel characteristics. Four main styles of floodplain forms are described along ephemeral streams in: unconfined floodplains, confined floodplains, inset floodplains, and unchanneled floodplains or floodouts (Figure 2.2).

Unconfined floodplains form where channels and channel lateral migration are not laterally restricted by bedrock or terraces, thus allowing for broad alluvial deposition from multiple, mobile channels. In perennial streams, unconfined floodplains are typically those where the ratio of floodplain width to active channel width is greater than or equal to approximately four (e.g., Beechie et al., 2006; Hall et al., 2007), although other metrics have been proposed, such as the percentage of stream length touching bedrock (e.g., O'Brien et al., 2019). Similar definitions can be used for ephemeral stream floodplains. Floodplain boundaries are typically marked topographically by a slight rise to a higher surface or generally by the transition from fluvial to colluvial or aeolian processes. Classically, braided channels are thought to be the dominant ephemeral stream planform in drylands owing to abundant bedload, high stream power, highly variable discharges, and erodible banks due to a lack of vegetation (Graf, 1988; Tooth, 2000). Floodplains along braided channels include unvegetated bars which separate fluvial channels as well as higher, vegetated surfaces that are inundated less frequently (Figure 2.2; Graf, 1988; Nanson and Croke, 1992). Although the prevalence of braided planforms and unvegetated floodplains seems intuitive for ephemeral streams, anastomosing rivers are also common in drylands, forming extensive floodplains stabilized by limited vegetation (Gibling et al., 1998; Tooth and Nanson, 1999; Ringrose et al., 2014; Dunkerley, 2013). Compared to humid anastomosing rivers, ephemeral anastomosing rivers and floodplains are characterized by higher stream power and sparser yet crucial vegetation that stabilizes otherwise coarse, sandy bars (Nanson and Knighton, 1996; North et al., 2007). Anastomosing planforms typically occur in low gradient, coarse bedload ephemeral streams, with vegetated, tear-shaped islands making them distinct from braided channel floodplains (Tooth and Nanson, 1999). Ephemeral anastomosing floodplains generally form due to vertical accretion from overbank flows that create distinctive features such as levees and crevasse splays (Gibling et al., 1998; Tooth, 2005), which can connect with migrating headcuts on the floodplain to create new anabranch channels (Li et al., 2015). Extensive ephemeral stream floodplains occur along anastomosing rivers, particularly in drylands of Africa and interior Australia, where anastomosing floodplains can extend up to 70 km wide, accumulating up to 40 m thick of unconsolidated sediment (Gibling et al., 1998; Ringrose, 2014).

Single-threaded meandering and straight ephemeral streams can also create characteristic floodplains in drylands (Figure 2.2). Although thought to be rarer in arid regions (Graf, 1988) due to a lack of vegetation needed to stabilize the banks (Tal and Paola, 2007; Gibling et al., 2014), single-threaded streams can form floodplains characterized by lateral accretion during low to moderate flows and substantial vertical accretion during rare, high magnitude floods (e.g., McKee et al., 1967; Friedman and Lee, 2002). Unlike perennial rivers where single thread, meandering channels are common in low gradient reaches with cohesive banks, meandering in ephemeral streams is thought to be driven by bank instability leading to bank collapse and forced lateral migration in low gradient to steep reaches (Billi et al., 2018). Given the presence of both lateral and vertical accretion, common features in these floodplains include levees, point bars, and chute cutoffs (Pickup, 1991; Reid and Frostick, 2011; Billi et al., 2018).

Overall, lower stream powers in unconfined ephemeral stream floodplains result in thicker alluvium (Sutfin et al., 2014) and more diverse topography, leading to more heterogenous inundation across the river corridor compared to other styles of channeled floodplains. As such, unconfined, depositional reaches along ephemeral streams are thought to be more resistant to changes during flooding (Sutfin et al., 2014) compared to confined reaches.

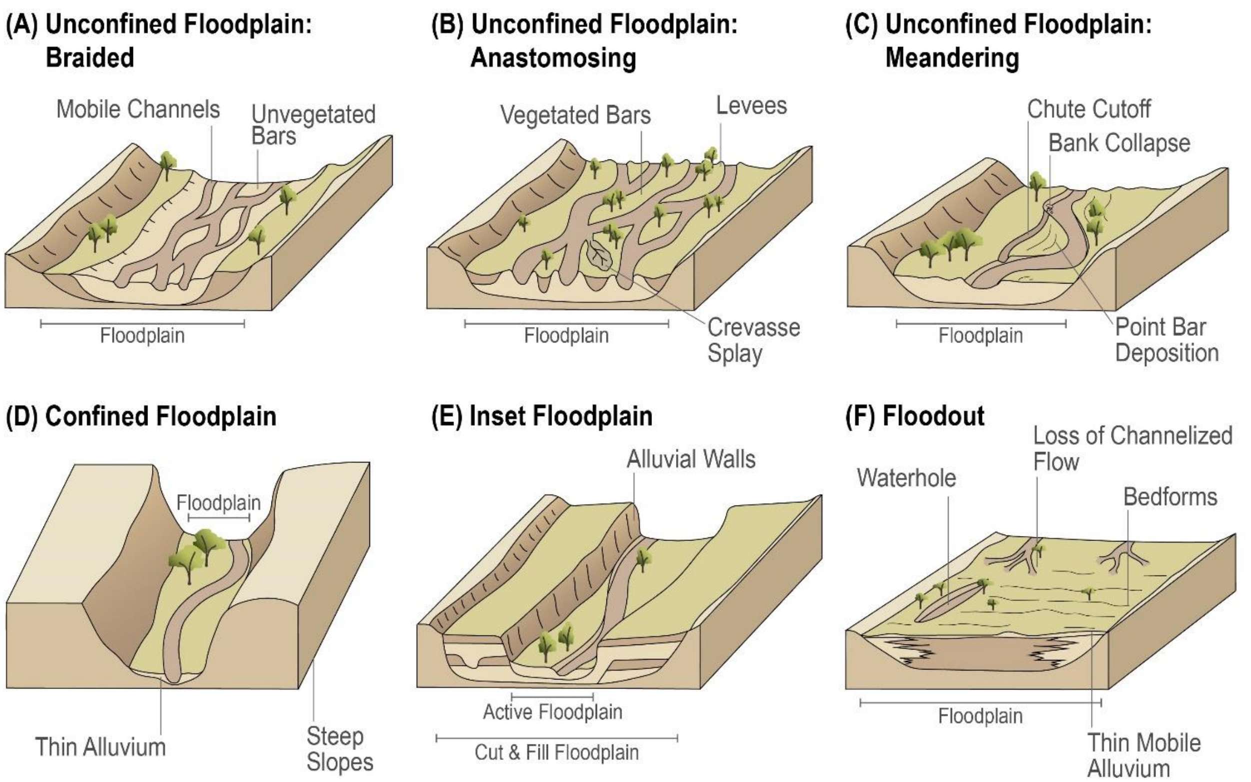

Figure 2.2. Common ephemeral stream floodplain styles: (A) Unconfined, braided floodplains; (B) unconfined, anastomosing floodplains; (C) unconfined, meandering floodplains; (D) confined floodplains; (E) inset floodplains; and (F) unchanneled floodplains or floodouts.

Confined floodplains tend to form in areas restricted by bedrock or terraces and are common in high gradient headwaters of dryland ephemeral streams (Merritt and Wohl, 2003; Sutfin et al., 2014; Jaeger et al., 2017; Rabanaque et al., 2022). Sediment supply is limited by production from bedrock erosion, leading to thinner alluvium (sometimes as little as 10 – 20 cm) compared to unconfined floodplains (Figure 2.2D; Sutfin et al., 2014; Jaeger et al., 2017). Typically, confinement of flow to a narrow, single-thread channel causes greater scour in confined floodplains (Merritt and Wohl, 2003), resulting in river corridors that are more sensitive to change during flooding (Sutfin et al., 2014). Alluvial floodplains can also be completely absent along bedrock-confined ephemeral streams, and the presence or absence of floodplains can oscillate, depending on river corridor width (Sutfin et al., 2014; Rabanaque et a., 2022).

Similar to confined floodplains are inset floodplains, which develop adjacent to incised alluvial channels. Discontinuous, incised channels have been extensively reported in the southwestern U.S. (Cooke and Reeves, 1976; Bull, 1997), where they are commonly termed arroyos and are thought to develop due to a range of environmental and anthropogenic conditions, including climate change (Leopold and Snyder, 1951; Hereford, 2002), land use (Cooke and Reeves, 1976), and the crossing of intrinsic thresholds (Schumm and Hadley, 1957). Similar channels have been reported in drylands globally, particularly in Australia and Africa (Mackel, 1973; Erskine and Melville, 1983). As channels are actively cutting and disconnecting from their original floodplain, an active floodplain may be absent, but as channels begin to refill or aggrade, a temporary inset floodplain may form (Hereford, 1986). Inset floodplains are confined by the boundaries of the incised channel walls, typically resulting in narrow, single-thread channels (Figure 2.2; Gellis et al., 2017), although braiding can exist (Friedman et al., 2015). Unlike bedrock-confined floodplains that commonly have limited sedimentation, inset floodplains can have substantial aggradation driven by upstream erosion (Schumm and Hadley, 1957; Bull, 1997) deposited via lateral accretion during overbank flows (Figure 2.2; Hereford, 1986). Over time, as channels incise, develop inset floodplains, and fill, a broader floodplain can develop that takes the stratigraphic appearance of the cut-and-fill floodplain described by Nanson and Croke (1992).

Finally, in contrast to floodplains formed adjacent to channels, unchanneled floodplains or floodouts are also common along dryland, ephemeral streams. Two types of floodouts exist: (1) intermediate floodouts where the channel distributes upstream but re-forms downstream, and (2) terminal floodouts where unchanneled floods spread and ultimately dissipate (Pickup, 1991; Tooth, 1999; Tooth, 2000). Although floodouts – in particular, terminal floodouts – contain many of the same characteristics of other evaporative landforms (e.g., playas, vleis, and other ephemeral lentic systems), they can be differentiated by the presence of directional and downgradient flow, despite being unchanneled. Floodouts form because of a downstream decrease in discharge in dryland ephemeral streams due to barriers to flow or significant changes toward less confinement (Tooth, 1999; Tooth and McCarthy, 2007; McCarthy et al., 2011) that result in infiltration, evaporation, and the loss of sediment transport in the channel. Inundation occurs in floodouts due to flooding from upstream alluvial channels or localized heavy rainfall. Although no continuous channel exists on floodouts, they can contain waterholes (Tooth, 1999) and wetlands that can retain water for longer than the rest of the surface (Figure 2.2; Tooth and McCarthy, 2007; Tooth et al., 2012). Floodouts are typically characterized by fairly shallow, diffuse flows with limited sediment transport except during rare, large sheetfloods, which can deposit substantial sediment that can form ripple and dune-like bedforms in the direction of down-gradient flow across the floodplain (Figure 2.2F; Pickup, 1991; Patton et al., 1993; Tooth, 1999). Fluctuations in flow through time can result in interfingered coarse and fine sediments within unchanneled floodplain stratigraphy (Tooth & McCarthy, 2007; Tooth et al., 2002).

Floodouts are characterized by a general down-gradient decrease in the ratio of coarser sands and gravels to fines (Tooth, 1999).

Ephemeral stream floodplains can vary between these four categories through space (Stanley et al., 1997; Tooth and Nanson, 1999; Ringrose et al., 2014) as well as time (Hereford et al., 1984; Gellis et al., 2017) due to fluctuations in boundary conditions such as lithology and climate, which can drive changes in sediment delivery, grain size, and discharge. Longitudinally, confined floodplains tend to dominate bedrock headwaters, whereas unconfined and unchanneled floodplains are more common along downstream reaches (Pickup, 1991; Sutfin et al., 2014; Jaeger et al., 2017). Floodplains can also alternate spatially between styles; for example, inset floodplains commonly repeat in sequence with unconfined or unchanneled floodplains throughout a watershed (e.g., Schumm and Hadley, 1957; Wakelin-King & Webb, 2007). Through time (typically centuries to millennia), incised channels in which inset floodplains form can fill, and new floodplains can develop within the now unconfined river corridor (Gellis et al., 2017).

Generally, floodplain styles along ephemeral streams overlap substantially with those on perennial rivers (e.g., Nanson and Croke, 1992), and floodplains along perennial rivers have also been found to vary in style both spatially and temporally (e.g., Benda et al., 2004; Morais et al., 2016). One exception to the similarities with perennial rivers are floodouts, which are a floodplain style unique to ephemeral stream systems. Given differences in aggradational processes and alluvium depth, the style of floodplain along a given reach of ephemeral stream can indicate and impact the types of hydrologic, geomorphic, and biotic functions present.

2.3. Hydrologic Characteristics and Functions of Ephemeral Stream Floodplains

Similar to those along perennial rivers, ephemeral stream floodplains allow for the attenuation of streamflow due to decreased velocities and temporary water storage (Figure 2.3; Hassan, 1990; Bull et al., 2000; Kemp, 2010; Scamardo et al., 2022). Although few studies have explicitly examined floodplain attenuation in flashy, ephemeral stream settings, confined channels distinctly lacking floodplains (including actively incising arroyos) show evidence of higher flood stages and faster flood peaks (Hassan, 1990; Bull, 1996; Dick et al., 1997; Bull et al., 2000; Sutfin et al., 2014). By comparison, flows move slower through reaches with alluvial floodplains and exhibit lower peak stage heights (Bull, 1996; Bull et al., 2000). Flow attenuation in ephemeral stream floodplains is typically associated with lower stream powers in wider river corridors and decreased velocity with overbank flows (Sutfin et al., 2014). Additionally, vegetation can increase riparian and floodplain roughness, thus further decreasing flow velocities when streamflow exceeds the channel banks (Merritt and Wohl, 2003; Hooke et al., 2005; Scamardo et al., 2022).

Discharge in ephemeral streams also attenuates downstream due to transmission losses in alluvial reaches (Renard et al., 1964; Thornes, 1977; Murphey et al., 1977; Goodrich et al., 1997). Transmission losses are attributed to infiltration into unsaturated sediments, direct evaporation of streamflow, and transpiration from riparian vegetation (Renard et al., 1964). The majority of studies have focused on direct transmission losses from the ephemeral stream channel, but floodplains may play an outsized role in water storage and uptake during flow events (Figure 2.3). For example, Knighton and Nanson (1994) found that transmission losses increased from 60% to 90% when flows exceeded the channel capacity and flowed onto the floodplain in Coopers Creek, QLD, Australia. Additionally, Lane et al. (1971) found that transmission losses in Walnut Gulch, AZ, U.S. were unpredictably high for a flow that exceeded the channel capacity.

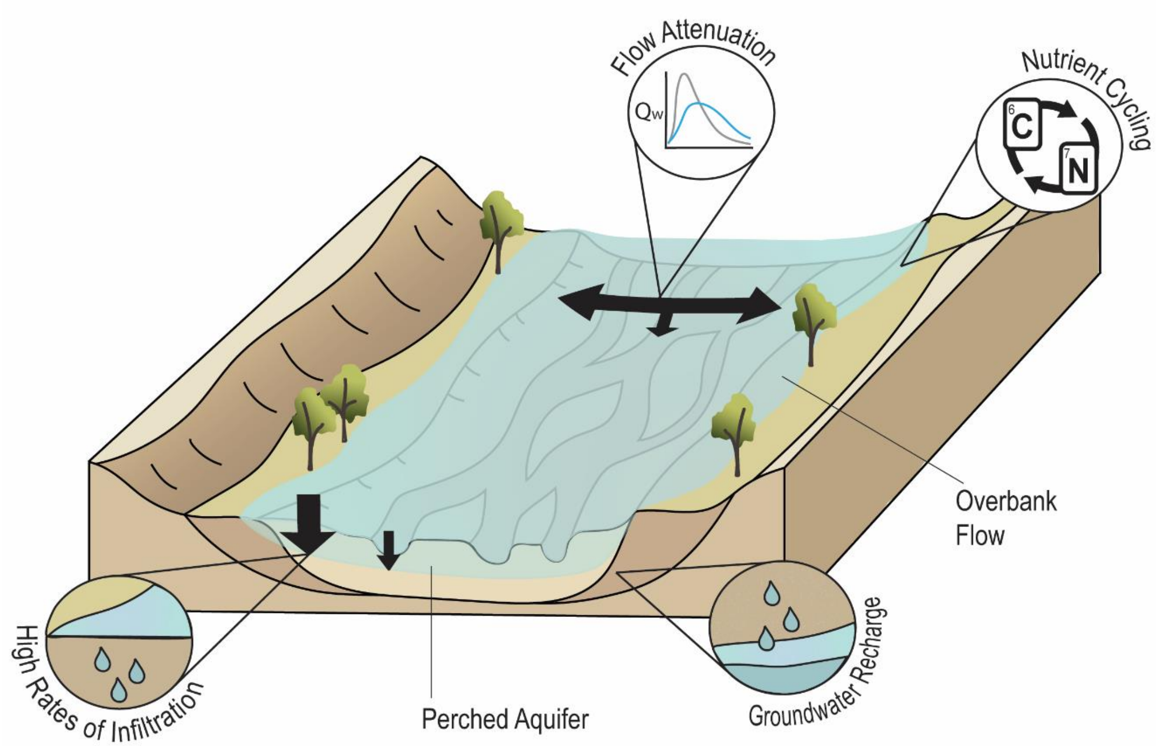

Figure 2.3. Common hydrologic functions of ephemeral stream floodplains include (A) attenuation of high flows and temporary surface water storage, (B) nutrient cycling through respiration and denitrification, (C) high rates of infiltration into shallow aquifers, and (D) groundwater recharge. Floodplains can also influence water quality by increasing salt concentrations and contributing excess nutrients to downstream flows.

Higher transmission losses in the floodplain versus the channel may be attributed to decreased stages and velocities on floodplains leading to high evaporative losses, particularly in arid to hyper-arid drylands (Shanafield and Cook, 2014; Kampf et al., 2016). Additionally, higher vegetation densities on the floodplain could account for greater water uptake via roots (Kampf et al., 2016). Increased transmission losses have also largely been attributed to high rates of infiltration in the floodplain compared to the channel (Knighton and Nanson, 1994; Knighton and Nansonkrau, 2002), which could be due to larger infiltration footprints, decreased streamflow velocities, or lower antecedent moisture, particularly in unconfined reaches. The shallow subsurface below ephemeral stream floodplains is characterized by both vertical infiltration from overbank inundation as well as lateral infiltration from channel banks (Burt et al., 2002; Shanafield et al., 2012; Kampf et al., 2016). More work is needed to determine the relative contribution of vertical infiltration across the floodplain compared to lateral, channel inputs (Shanafield and Cook, 2014), but even in the absence of concentrated channel flow (i.e., floodouts), infiltration across the ephemeral stream floodplain is thought to be high (Villanueve et al., 2015).

Because rates of infiltration are expected to be higher on the floodplain than the active channel, ephemeral stream floodplains in particular could be hotspots for groundwater recharge (Figure 2.3). Following storms and subsequent streamflow in ephemeral channels, two types of alluvial aquifers can form below the riparian and floodplain surface: (1) pocket aquifers where the alluvium is bound by impermeable bedrock (e.g., Renard et al., 1964), and (2) shallow perched aquifers where fine-grained or confining layers may be present (e.g., Rassam et al., 2006; Villanueve et al., 2015; Kampf et al., 2016). Both shallow aquifer types can fluctuate seasonally and from storm-to-storm based on variations in vertical inputs from overbank flooding and lateral inputs from the hillslopes and channel (Burt et al., 2002; Shanafield et al., 2012) as well as variations in vegetation cover and transpiration (Schilling et al., 2021). Rates of infiltration into the shallow water table peak shortly after inundation in the river corridor, with higher infiltration rates associated with river corridors that experience more frequent flows (Schilling et al., 2020). Following initial formation, this perched aquifer can persist for days (e.g., Rassam et al., 2006) to months (e.g., Villanueve et al., 2015), and can eventually dry after the water has recharged to a deeper, regional aquifer, been lost to evaporation or evapotranspiration, or recharged back into the ephemeral stream (Renard et al., 1964; Rassam et al., 2006; Costelloe et al., 2007; Schilling et al., 2021). For example, Villanueve et al. (2015) found that 25% of the perched aquifer following streamflow along the Woodforde River in central Australia recharged the regional aquifer, with the remaining infiltrated water used by riparian and floodplain plants.

Floodplains along ephemeral rivers create the same hydrological functions as those along perennial rivers – primarily, attenuation of peak flows and infiltration and associated groundwater recharge. In dryland environments, the saturation regime of ephemeral stream floodplains is unique, characterized by a lower inundation frequency than the active channel, but greater saturation frequency than the vast, surrounding uplands. Given the flashy nature of flood peaks in ephemeral rivers and the importance of infiltration as a source of recharge to floodplain aquifers, these hydrologic functions are arguably even more important in ephemeral rivers than in perennial rivers.

2.3.1. Biogeochemical Functions of Ephemeral Floodplains

The delivery and storage of solutes and nutrients are closely related to the flow of water through the landscape, and particularly into the surface and subsurface of the floodplain and riparian zone. Following flooding, concentrations of nitrogen (nitrate and ammonium) increase in riparian groundwater reservoirs along dryland ephemeral streams (Marti et al., 2000; Harms et al., 2009). Ephemeral stream floodplains are recognized as nitrogen sinks; for example, incised arroyo floodplains can have over 100 times higher volumes of nitrate compared to surrounding uplands (Linhoff and Lunzer, 2021). Ephemeral stream floodplains can therefore also be hotspots of denitrification, emitting both NO and N_2O following flow pulses (Figure 2.3; Marti et al., 2000; Harms and Grimm, 2012). Flow pulses can also contribute organic material to the floodplain, which can cause the emission of CO_2 and CH_4 shortly following inundation (Figure

2.3; Harms and Grimm, 2012; von Schiller et al., 2014). Antecedent moisture impacts the emission of gases from ephemeral stream floodplains, so that successive floods during the wet season are less likely to cause a large gas emission compared to individual flows during the dry season (Harms and Grimm, 2012). Nitrogen loss is also a factor of groundwater drainage rates, and low head gradients from the riparian area to the channel – particularly in low-gradient, unconfined ephemeral stream floodplains – can increase nitrate removal (Rassam et al., 2006; Woodward et al., 2009). The process of denitrification in ephemeral stream floodplains is likely limited by water availability. In Indian Bend Wash, Arizona, U.S., irrigated floodplains were found to release more nitrogen than non-irrigated floodplains, both releasing less nitrogen than saturated lake sediments. However, given the spatial footprint of floodplains compared to temporary lakes, floodplains removed approximately 2.5 times as much nitrogen as lake sediments (Roach and Grimm, 2011). Floodplains that receive more frequent or seasonal flows likely release more nitrogen, and denitrification rates in ephemeral stream floodplains are generally lower than perennial streams. Once floodplains are saturated, however, the onset of denitrification in ephemeral stream floodplains occurs more rapidly than along perennial streams (Fellows et al., 2011). Additionally, compared to surrounding uplands, ephemeral stream floodplains harbor moisture for longer, thus extending the timeframe over which biogeochemical processes such as denitrification can occur (Collins et al., 2014).

The impact on solutes and nutrients of water flow over and through the ephemeral stream floodplain can affect downstream water quality. Denitrification and organic matter storage can improve downstream water quality (e.g., Rassam et al., 2006). Additionally, water dispersal across the floodplain during overbank flow can decrease major ion concentrations in surface and groundwater resources, which also serves to improve the quality of downstream discharge and groundwater recharge (Ghazavi et al., 2012). However, ephemeral stream floodplains can also be a source of salt during overbank floods, thus increasing downstream salinity discharge (Costelloe et al., 2005), which is a major concern in dryland regions (Peck and Hatton, 2003).

Consequently, ephemeral stream floodplains are both sources and sinks of nutrients and moderators of water quality to downstream perennial rivers. Although rates of processes like respiration and denitrification can be limited and discontinuous compared to perennial counterparts, the tenuous association with water in ephemeral stream floodplains makes them important hotspots of biogeochemical cycling in dryland environments.

2.4. Geomorphic Characteristics and Functions of Ephemeral Floodplains

Ephemeral stream floodplains can be moderators of sediment fluxes to downstream ephemeral and perennial habitats and sediment dynamics within the floodplain can drive the creation of diverse and functional landforms (Figure 2.4). Similar to perennial streams, the geomorphic character of and subsequent processes within ephemeral stream floodplains can vary downstream. Schumm (1977) outlined three zones in relation to relative elevation and catchment position, which reflect sediment movement and storage throughout a watershed: (1) the production zone is characterized by net erosion and supplies sediment to the channel; (2) the transfer zone is dominated by sediment transport through the system; and (3) the deposition zone is characterized by net sediment accumulation (Figure 2.4A). Although confined floodplains may occur in the production zone, floodplain widths and subsequent deposition tend to increase with drainage area in ephemeral streams, so that unconfined floodplains and floodouts are more common in the deposition zone (Tooth, 1999; Shaw et al., 2008; Ringrose et al., 2014; Sutfin et al., 2016; Jaeger et al., 2017). Unconfined floodplains can also exist in the transfer zone but alternate through time between storing and evacuating sediments (e.g., Graf, 1987).

Sediment dynamics in ephemeral stream floodplains are driven by high rates of sediment transport during floods (Langbein and Schumm, 1958; Laronne & Reid, 1993), which can result in significant overbank deposition (Tooth, 1999). Sediment deposition is expected to be higher in reaches with distinct channel banks where decreased velocities and increased hydraulic roughness on the floodplain encourage sediment aggradation during overbank flows. Although un-channeled floodplains are characterized by low flow energy and associated increased sediment deposition, aggradation is most prominent where channels terminate, with limited aggradation occurring across the majority of the un-channeled floodplain zone (Tooth, 1999). Nonetheless, deposition that does occur within floodouts during large sheetflow events can create fields of fluvial bedforms like dunes and ripples, thus impacting the general morphology of the floodplain (Figure 2.1; Pickup, 1991; Patton et al., 1993; Tooth, 1999). In contrast, ephemeral stream floodplains with distinct active channels and banks can be subject to high rates of overbank deposition, sometimes totaling meters in thickness during a single flood (McKee, 1966; Patton and Schumm, 1981; Friedman and Lee, 2002; Greenbaum and Bergman, 2006). Extreme floods tend to be more important for sediment deposition in ephemeral stream floodplains than along perennial streams. In contrast to river corridors that exhibit regular annual flooding, the sediment flux in ephemeral stream floodplains may be dominated by individual large floods (e.g., Patton, 1988; Pickup, 1991). However, smaller floods can still rework floodplain sediments, influencing sediment deposition and morphology on a finer scale and eventually bringing the river corridor back to pre-flood topography (Friedman and Lee, 2002, Greenbaum and Bergman., 2006).

Similar to perennial streams, fine-grained deposition can occur on the floodplain, with increased fining farther from the channel (Figure 2.4B; Schumm, 1961; Laronne and Reid, 1993; Malmon et al., 2004). Particularly in drylands, fine-grained sediments can travel as silt- to sand-sized aggregates that can deposit and disaggregate on the floodplain, leaving behind a layer of

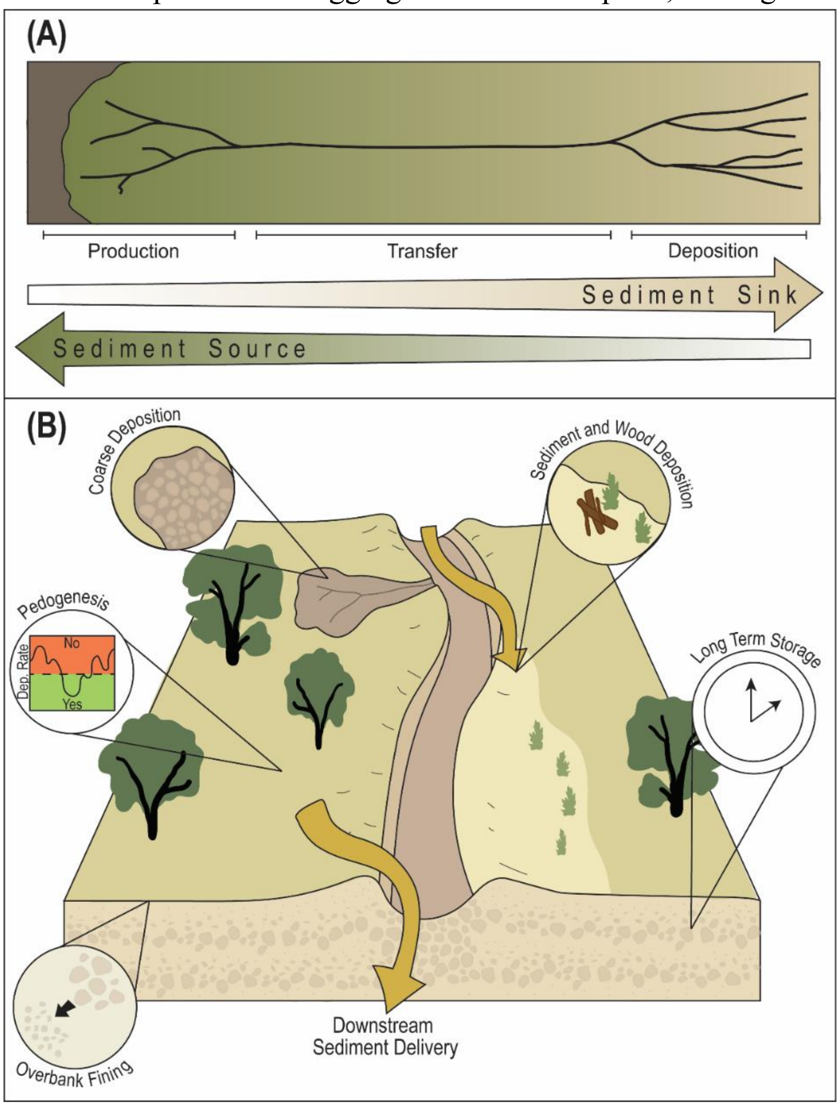

Figure 2.4. Common geomorphic characteristics and functions of ephemeral stream floodplains. (A) Floodplains act as both a source (erosion) and sink (deposition) of sediments depending on location within the channel network. (B) Erosion and deposition drive multiple characteristics and functions, including pedogenesis, overbank fining and general grain size variability, storage times, and the delivery of sediment to downstream reaches.

fine-grained mud deposition (e.g., Wakelin-King & Webb, 2007). Fluvial transport can reinstate mud aggregates, which can travel as bedload along the floodplain, creating ripples, scours, and discontinuous clay layers (Gibling et al., 1998; Wakelin-King and Webb, 2007). Coarse deposition is also common to ephemeral stream floodplains in individual features like crevasse splays (e.g., Tooth, 2005), general overbank deposition during large floods (e.g., Greenbaum & Bergman, 2006), or where channels are reworking coarse-grained deposits such as debris flows (e.g., Wohl and Pearthree, 1991). Deposition rates are generally non-linear in ephemeral stream floodplains, given the stochastic nature of flow. However, annually averaged aggradations rates can commonly be higher than 0.5 cm/year, thus limiting pedogenesis and the formation of well-developed soils on dryland ephemeral stream floodplains (Figure 2.4B; Daniels, 2003).

Along with volumes and fluxes of sediment deposition, floodplain sediment storage is a factor of time (Figure 2.4B). Because active floodplains can aggrade quickly along ephemeral streams, large amounts of sediment may be stored for only short time periods. For example, Patton and Boison (1986) found, using dendrochronology and radiocarbon dating, that the most recent 5 m of floodplain sediment in Harris Wash, UT, U.S. were deposited over only the last 150 years. They distinguished this modern deposition from buried floodplain deposits that could be stored on the timescale of thousands of years if not subject to large floods and erosion (Patton and Boison, 1986; Graf, 1987). A number of studies have looked at sediment storage through the cycle of inset or cut-and-fill floodplains in the southwestern U.S., finding that sediment can be stored on timescales of thousands of years, but can also be eroded over the course of just decades (Friedman et al., 2015; Townsend et al., 2019; Kemper et al., 2022). In this manner, ephemeral stream floodplain storage in channeled floodplains may be cyclical, with sediment stored for significant periods of time before evacuating over relatively short timescales. By contrast, storage in floodouts may be longer and subject to less cyclical change. For example, Tooth (1999) found that floodouts along the Sandover-Bundey and Woodforde Rivers in central Australia can store sediment for more than 10,000 years, compared to upstream channeled floodplains that stored sediment less than half as long.

Closely tied to sediment deposition and storage in ephemeral stream floodplains can be the erosion and evacuation of sediment from the floodplain (Figure 2.4B). Given the lack of vegetative ground cover and the abundance of fine-grained material along dryland ephemeral streams, overbank flows can remobilize floodplain sediment, thus significantly increasing downstream suspended sediment fluxes (Gibling et al., 1998; Alexandrov et al., 2002). Erosion and scour can provide sediment for deposition over short distances (10^0 km) downstream within the same catchment (Schumm and Parker, 1973; Bull, 1997; Greenbaum and Bergman, 2006) or many kilometers away along downstream perennial rivers (Goodrich et al., 2018; Kemper et al., 2022).

The supply of sediment and subsequent storage and redistribution on the ephemeral stream floodplain can create diverse landforms and unique geomorphic units. Lateral and vertical accretion and subsequent erosion on the floodplain drive the creation of geomorphic units, paralleling geomorphic diversity found in perennial river floodplains (Rabanaque et al., 2021; Scamardo et al., in review). Along anastomosing and meandering ephemeral streams, levees commonly build in the riparian area and subsequent crevasse splays and avulsions can create topographic complexity (Tooth, 2005). Bedload movement over the floodplain can serve to create heterogeneity through the formation of ripples and dunes (Williams, 1971; Tooth, 1999; Wakelin-King and Webb, 2007). Additionally, large wood inputs along ephemeral stream floodplains can create geomorphic heterogeneity by influencing sediment deposition and causing avulsions (Dunkerley, 2014; Scamardo et al., 2022). Large wood is mainly deposited on the floodplain instead of the active ephemeral stream channel due to the flashiness of flow and abundance of trapping locales, such as woody vegetation (Greenbaum and Bergman, 2006; Wohl et al., 2018; Wohl and Scamardo, 2022). The creation of unique geomorphic units and complex topography can drive variations in inundation across the floodplain, thus allowing diverse habitats to form.

Sediment dynamics in ephemeral streams can lead to the formation of weak soil horizons within the floodplain (Figure 2.4B). After sediment has been delivered, a lack of subsequent disturbance can allow for pedogenic development if aggradation rates remain below roughly 0.5 cm/year (Daniels, 2003). Soils that form within ephemeral stream floodplains are typically poorly developed, commonly lacking a transition between the A and C horizons. Still, due to the presence of weak soils and seasonal water availability, ephemeral stream floodplains have been used for agriculture and farming for centuries (e.g., Huckleberry, 2015).

Ultimately, ephemeral stream floodplains can strongly influence sediment budgets within a river network, analogous to perennial river floodplains (e.g., Noe et al., 2022). However, the moderating effect of at least transient floodplain storage may be particularly important in ephemeral watersheds, given the higher concentration of suspended sediment carried by flashy, ephemeral flows.

2.5. Biotic Characteristics and Functions of Ephemeral Floodplains

Another main function of ephemeral stream floodplains is the provision of habitat for a range of plants and animals that are uniquely adapted to high variability in flow recurrence (Figure 2.5;

Datry et al., 2017). Ephemeral stream floodplains receive less frequent disturbance than the active channel but a greater range of saturation than the uplands. Consequently, floodplain vegetation species can have greater niche widths, representing more generalists, than the channel or the surrounding hillslopes (Bloss and Brotherson, 1979). Vegetation species within ephemeral stream floodplains can grade from upland to xeroriparian or riparian depending on position within the network as well as the degree of confinement (Bloss and Brotherson, 1979; Shaw and Cooper, 2008; Santos, 2010), and ephemeral stream floodplains typically have greater volumes of vegetation and abundance of species compared to uplands (Figure 2.5; Stromberg et al., 2017; Manning et al., 2020). Ephemeral stream floodplains tend to have sparser vegetation cover favored by more mesic species compared to floodplains adjacent to perennial flow (Stromberg et al., 2005). Still, although species richness and diversity can be low in ephemeral stream floodplains compared to perennial during average or drought conditions (Stromberg et al., 2009; Katz et al., 2012), plant diversity and year-round richness in ephemeral reaches can parallel perennial reaches during wet years. Without a permanent water source to sustain dense canopies, open patches of bare mineral soil can be seasonally occupied by a larger number of annual plant species, resulting in high species richness (Stromberg et al., 2009).

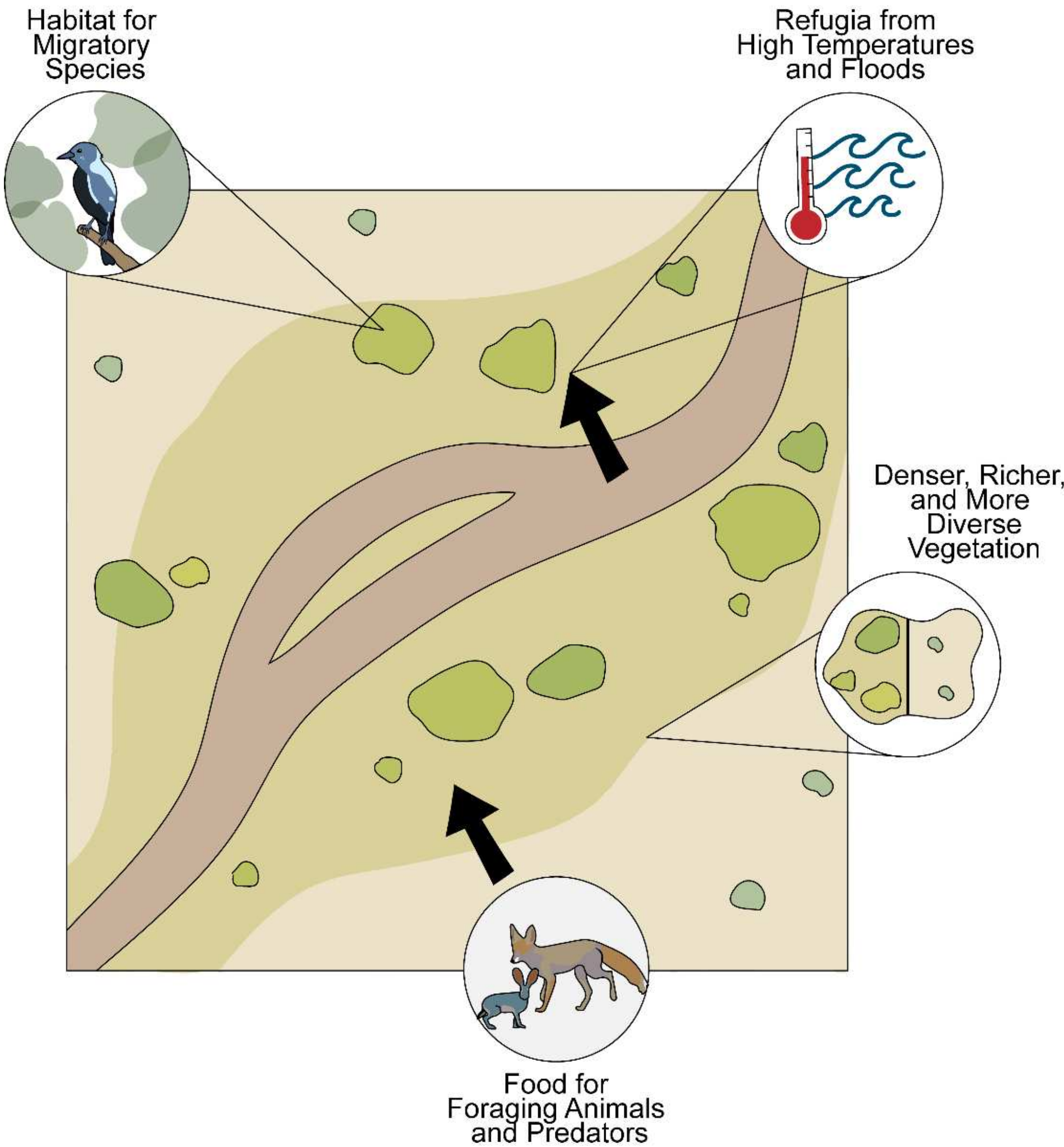

Figure 2.5. Common biotic functions of ephemeral stream floodplains include: denser riparian vegetation representing greater species richness and diversity than surrounding uplands; habitat for a range of migratory species; food for a range of foraging and predatory species; and refuge from high temperatures between flows and inundation during flow in the active channel.

Vegetation communities in ephemeral stream floodplains are sustained by seasonal or perched aquifers. Perched and fluctuating water tables recharged by flow events can sustain many of the same productive riparian phreatophytes (i.e., woody plants that rely on groundwater resources) commonly found along perennial dryland rivers (Scott et al., 1999; Friedman and Lee, 2002; Stromberg and Merritt, 2016). For dryland riparian vegetation, the variably saturated conditions created by the rise and fall of temporary groundwater resources can provide optimal conditions for root water uptake (Schilling et al., 2021). Following the cessation of streamflow, temporary floodplain aquifers and saturated soils can sustain ephemeral stream floodplain vegetation for months (Schilling et al., 2014; Pettit and Froend, 2018; Schilling et al., 2021). However, the distribution of species and plant growth is strongly influenced by depth to the water table (Stromberg et al., 1993; 1996; Busch and Smith, 1995) as well as other abiotic factors, such as sediment distribution (e.g., Zimmerman et al., 1999).

Vegetation assemblages, as well as the intermittent access to surface and subsurface water resources, impact the abundance and diversity of desert fauna (Figure 2.5). In drylands of the southwestern U.S., for example, approximately 80% of all animals use riparian resources and habitats, and over 50% of breeding bird species nest chiefly in riparian areas (Krueper, 1995). Riparian vegetation is utilized by migrating species, such as birds and a range of mammals (Skagen et al., 1998; Mac Nalley et al., 1999; Hilty et al., 2006; Carlisle et al., 2009; Santos et al., 2011, Fonseca and List, 2013), predators of those species (e.g., Nilson et al., 1999), and foraging species, such as elephants and giraffes in the African savannah (e.g., Viljoen, 1989; Skinner and Chimimba, 2005) and mesocarnivores in the Mediterranean (e.g., Rosalino and Santos-Reis, 2008). A range of invertebrates similarly inhabit ephemeral stream floodplains, relying on organic material and vegetation for habitat, food, and shade (O'Toole et al., 2016; Steward et al., 2022).

The role of ephemeral stream floodplains and their vegetation as refuge is important for biota both during and between periods of in-channel flow (Figure 2.5). When channels are dry, sediment temperatures can exceed 60ºC, and shade provided by floodplain vegetation can provide lower temperature refuge to invertebrates (Holm and Edney, 1973), mammals (Owen-

Smith, 1992), and amphibians (Rojas-Ahumada and Menin, 2010). When channels are inundated but floodplains are not, floodplains can provide refuge for terrestrial species (Langhans and Tockner, 2014; Sanchez-Montoya et al., 2017). During overbank inundation, large wood accumulations, coarse particulate organic matter (Wohl and Scamardo, 2022), and vegetation in the floodplain may provide stable refugia for otherwise transported biota such as macroinvertebrates (e.g., Chester and Robson, 2011). Overall, floodplains can support species assemblages that are distinct, and occasionally richer, than the ephemeral stream channel (Steward et al., 2011; Steward et al., 2012).

Although the provisioning of habitat for a range of unique flora and fauna is also a function of perennial floodplains (e.g., Hauer et al., 2016), the ubiquity of ephemeral stream floodplains makes them particularly important for dryland plants and animals. Additionally, although species richness, density, and diversity may be lower than perennial river floodplains during dry conditions and years, flows and wet seasons in ephemeral streams can allow for unique flora and fauna to thrive. As such, preserving the natural flow regime is especially important for maintaining the biotic function of ephemeral stream floodplains.

2.6. The Future of Ephemeral Floodplains

Ephemeral stream floodplains currently supply a wide range of ecosystem functions, and given proper management, will continue to do so in the future. However, natural floodplains are disappearing globally as floodplain ecosystems and functions are increasingly threatened by human development, pollution, climate change, and more (Tockner and Stanford, 2002). Although most studies have focused on perennial floodplain degradation, similar stressors are increasingly impacting ephemeral stream floodplains (Field and Lichvar, 2007; Chiu et al., 2017). The future of ephemeral stream floodplains therefore includes a number of natural and anthropogenic threats as well as the potential for restoration and adaptive management.

2.6.1. Climate Change

A primary threat to ephemeral stream floodplains in drylands is increasing aridification and changing flow regimes expected under climate change. The greatest continental warming over the past 100 years has occurred in hot drylands, and precipitation has variably increased and decreased in drylands globally (Huang et al., 2017). Future models suggest that even regions that have seen precipitation increases over the past decades, like the southwestern U.S., will be subject to future drying (Seager et al., 2007; Prein et al., 2016), characterized by fewer yet more extreme rainfall events (Garfin and Lenart, 2007; Dominguez et al., 2012). Although hydrologic extremes are regarded as the norm in ephemeral streams, changing climate conditions may impact ecosystem functions, particularly those related to vegetation. As regional water tables decline and flow becomes increasingly intermittent, floodplain plant species diversity decreases, with species compositions typically shifting from pioneer wetland species to drought-tolerant shrubs (Stromberg et al., 2007; Stromberg and Boudell, 2013). Nonetheless, vegetation species may remain resilient as viable seeds in soil seed banks that can be remobilized and germinated during rare but intense floods (e.g., Stromberg et al., 2013). Given limited studies on the ecological impacts of drought and aridification in ephemeral streams and their floodplains, the true impact of climate on riparian communities is still relatively unknown (Sarremejane et al., 2022). Changing flow regimes could also impact morphology, potentially causing stream incision akin to arroyo incision of the southwestern U.S. (e.g., Cooke and Reeves, 1976; Water and Haynes, 2001), which could lead to disconnectivity with the current floodplain and the formation of future inset floodplains.

As a secondary effect of increasing temperatures and decreasing precipitation, drylands could be subject to increased wildfire frequency and severity (Middleton and Sternberg, 2013). Following wildfires, ephemeral streams can exhibit higher peak stages (McLin et al., 2001) and increased sediment loads (Canfield et al., 2005; Malmon et al., 2007) during floods. Combined with increases in flood magnitudes, higher stages and sediment fluxes following fire could expand floodplain areas along dryland ephemeral streams and impact morphology, thus increasing connectivity in ephemeral stream floodplains.

Understanding the impact of climate change on ephemeral streams could also have importance for perennial river floodplains, which may be subject to drying and the loss of flow permanence (e.g., Reynolds and Shafroth, 2017). Compared to perennial streams, the impact of climate change on ephemeral stream floodplains may be relatively better known – for example, the impact of climate on arroyo cycling and floodplain disconnectivity has been extensively studied. However, studies on climate impacts have again largely focused on the active channel, and future work is needed to understand the impact to floodplain morphology and ecology.

2.6.2. Land Use Change

Historically and pre-historically, ephemeral stream floodplains have been altered for human use for agriculture (Huckleberry, 2015). In the southwestern U.S., for example, ephemeral stream floodplains comprise only a limited proportion of the landscape (1-2%) but were disproportionately important sites for agriculture for indigenous peoples (Nials et al., 2011). Anthropogenic water diversion from ephemeral streams was common across the southwestern U.S. to supplement overbank flows (Norton et al., 2002). Floodplain types and dynamics have influenced agriculture along ephemeral streams for millennia, particularly considering that incision into the floodplain and long periods without overbank flows may have caused agricultural decline (Huckleberry and Billman, 1998; Finley et al., 2023). In addition to crop farming, ephemeral stream floodplains are also utilized for the grazing and watering of livestock (Levick et al., 2008).

Approximately 38% of the global population lives in drylands (Huang et al., 2017). Consequently, dryland ephemeral streams and their floodplains are subject to development and urbanization. Urbanization can result in channelization, which can confine floods to the active channel (Ortega et al., 2014) and limit groundwater-surface water interactions (Grimm et al., 2004), potentially impacting vegetation communities. Consequently, urban ephemeral stream floodplains are subject to decreased vegetation density, volume, and richness (Hutmacher et al., 2014). Increased impervious cover with development can also increase total runoff volume and peak discharges in ephemeral streams (Almousawi et al., 2020). Combined with urban effluent returns, increased runoff can result in previously ephemeral streams turning perennial, thus impacting the disturbance regime (Hassan and Egozi, 2001). Alternatively, increased runoff can lead to channel destabilization and scour (Chin and Gregory, 2001; Ortega et al., 2014), thus further disconnecting the floodplain. Disconnectivity and the loss of the natural flow regime on urban ephemeral stream floodplains can result in the loss of function, such as the loss of nutrient storage and cycling (e.g., Grimm et al., 2004).

Development also commonly comes with the building of roads, which may traverse and bisect ephemeral stream floodplains. Roads can act as a barrier to species movement through the floodplain and channel and can alter downstream water delivery (Duniway and Herrick, 2011). Roads can obstruct sheetflow, thus causing ponding of water upstream of the road and limiting water resources downstream so that upstream vegetation cover can increase while downstream vegetation cover declines (Shaw, 2023). Alternatively, roads and low water crossings can consolidate runoff from impervious cover, thus increasing water in the downstream channel and adjacent floodplain, resulting in an opposite pattern of floodplain vegetation change (Shaw, 2021). Without adaptive management, the impact of roads and human development can last for decades. For example, on U.S. military lands in the Mohave Desert, road berms from military practices during World War II still impacted the morphology of ephemeral streams and their floodplains more than 50 years later (Nichols and Bierman, 2001).

Beyond urbanization, human-related land use changes such as alternative energy development (e.g., Lovich and Ennen, 2011; Grippo et al., 2015), water diversion and damming (e.g., Patton and Schumm, 1981; Belmar et al., 2013), and gravel mining (e.g., Calle et al., 2017; Sanchis-Ibor et al., 2017) within ephemeral river corridors can impact the delivery of sediment, water, and nutrients to floodplains. Solar energy development is becoming increasingly economically viable in drylands where solar radiation is high. Construction related to solar energy zones and solar farms can result in the in-filling of ephemeral streams, grading and compaction of floodplains and removal of vegetation, as well as the depletion of groundwater for water-intensive solar technologies (Lovich and Ennen, 2011; Grippo et al., 2015), effectively removing ephemeral stream floodplains and/or severely limiting functions related to hydrology and ecology. Dams across ephemeral stream corridors can trap sediment, water, and nutrients, as they can on perennial streams, as well as increase the number of annual zero-flow days (Patton and Schumm, 1981; Westerhoff and Anning, 2000; Neave et al., 2009), thus limiting overbank flows and hampering floodplain habitat (Belmar et al., 2013). However, immediately upstream of channel-spanning obstructions such as dams, artificially saturated floodplains can develop with denser vegetation than surrounding riparian areas (Hamdan and Stromberg, 2016; Hamdan and Schmeckle, 2016), at the expense of downstream floodplain habitat. Gravel mining within the ephemeral river corridor can also limit the extent of ephemeral stream floodplains, as channel incision and widening effectively disconnect and remove floodplain area, which may take decades to recover following cessation of mining activities (Sanchis-Ibor et al., 2017).

Changing land use and associated impacts are not unique to ephemeral stream floodplains (e.g., Krause et al., 2008; Rajib et al., 2021), but floodplains along ephemeral streams tend to receive lower protection from development and land use change than perennial river floodplains (Bren, 1993; Nadeau and Rains, 2007; Fritz et al., 2017; Fesenmeyer et al., 2021). As a result, increasing population growth in drylands will likely disproportionally impact ephemeral stream floodplains.

2.6.3. Invasive Species

Characteristics of ephemeral stream floodplains, such as water stress and high disturbance frequencies (e.g., Quinn and Holt, 2008; Coffman et al., 2010), make them prone to colonization by invasive and introduced species. Invasive plant species such as tamarisk (spp. *Tamarix*) and Russian olive (*Elaeagnus angustifolia*) in the southwestern U.S., Acacia, Arundo, and Eucalyptus in the Mediterranean and South Africa, and Rubus and Acacia in Chile (Stella et al., 2013) can outcompete native vegetation and have cascading physical and ecological impacts (e.g., Zale et al., 1989; Reynolds and Cooper, 2009). For example, tamarisk and Russian olive can negatively impact native bird species that rely on native species such as cottonwood (spp. *Populus*) for higher quality stopover habitat, cavity nesting, and prey (Shafroth et al., 1995; Walker, 2008). On the other hand, tamarisk has also been shown to be utilized by endangered songbird species, thus providing important potential habitat (Sogge et al., 2008).

Invasive species can thrive at higher densities than native species, thus increasing floodplain roughness, which can decrease flood power (Birkeland, 2013) on ephemeral stream floodplains. Floodplain stabilization associated with invasive species encroachment can cause the narrowing and incision of ephemeral stream channels (Cadol et al., 2011; Weiting et al., 2023), thus altering the sediment regime and ultimately disconnecting channels and floodplains in ephemeral settings. Invasive species can additionally alter canopy dynamics and organic matter inputs, which can impact invertebrates and cascading food webs (e.g., Going and Dudley, 2008).

Although invasive vegetation is an issue facing perennial river floodplains in drylands, streamflow regime is a strong determinant of riparian vegetation structure, and non-perennial flow regimes can lead to a dominance of introduced species (Stromberg et al., 2007). By impacting riparian vegetation communities and associated physical processes, invasive species have the potential to impact multiple, connecting ecosystem functions in ephemeral stream floodplains.

2.6.4. Restoration and Adaptive Management

Given a range of stressors, restoration and adaptive management of ephemeral stream floodplains can potentially help regain or protect desirable functions. Restoration is more common within the ephemeral stream channel itself, including grade-control structures such as gabions, trincheras, one-rock dams, jetty jacks, hay bales, and brush piles (Miller and Borland, 1963; Gellis et al., 1995; Gellis et al., 2001; Norman et al., 2022). However, in-channel structures can aggrade the channel, decrease flow velocities, and increase connectivity with floodplains (Debano and Schmidt, 1990; Streeton et al., 2013; Norman et al., 2022), thus improving or preserving a suite of floodplain functions in ephemeral streams. For example, one-rock dams (ORDs) can decrease peak flow velocities, spread flood waters, and increase infiltration into the shallow subsurface below the floodplain (Debano and Schmidt, 1990; Norman et al., 2021), resulting in increased riparian cover, albeit of both native and non-native varieties (Wilson and Norman, 2023). Aggradation associated with in-channel structures like rock retention structures and ORDs can facilitate the formation of, at a minimum, an inset floodplain or at maximum connection with the former floodplain, particularly in actively incising ephemeral streams (Streeton et al., 2013). The removal of anthropogenic structures like dams can also facilitate floodplain connectivity by allowing for the natural flow and sediment regime to reach floodplain surfaces (e.g., Neave et al., 2009)

Direct restoration of the floodplain surface in ephemeral stream corridors has often taken the form of introduced and invasive species removal and biocontrol (Stromberg et al., 2007; Jaeger and Wohl, 2011; Kennard et al., 2016; Wieting et al., 2023). However, although invasive vegetation can narrow the active channel and homogenize the floodplain, removal in ephemeral streams can cause bank widening but commonly does not shift the river corridor back to a more heterogeneous planform (e.g., braided river) within the first few years of restoration (e.g., Jaeger and Wohl, 2011). Instead, longer timescales (i.e., decades) may be needed to see change on the floodplain following vegetation removal (Wieting et al., 2023). Removal and biocontrol of invasive species (e.g., tamarisk and the Tamarisk beetle) can also reduce bird species on ephemeral stream floodplains, because tamarisk die-back can decrease prey availability and alter microclimates (e.g., Mahoney et al., 2022).

In the absence of direct restoration action, adaptive management of ephemeral stream corridors can result in the rehabilitation of ecologic, hydrologic, and biotic processes. For example, the installation of road culverts, instead of low-water crossings, increases conveyance of water and sediment, decreases scour, and helps reconnect downstream floodplains in urbanizing areas (Chin et al., 2017). Fencing to exclude livestock from grazing in ephemeral stream floodplains can benefit vegetation, which Krueper et al. (2003) found increased the species diversity of birds after just four years in the San Pedro Riparian National Conservation Area, AZ, U.S.

Similar to perennial river corridors, stream restoration and adaptive management projects in ephemeral streams can help restore floodplains by creating lateral connectivity, the conveyance of natural flows, and habitat for native species. However, the timescale over which ephemeral stream floodplains respond to restoration is likely longer than in perennial rivers. Although in-channel restoration in perennial rivers may be able to divert even baseflows onto the floodplain, ephemeral streams require a runoff event (which may be sparse and sporadic in nature) to create change. More studies are needed to fully understand the impact of restoration projects on the long-term functioning of ephemeral stream floodplains. The majority of ephemeral stream restoration literature focuses on the impact to channels and monitoring studies on the floodplain have primarily examined biotic indicators rather than geomorphic or hydrologic change. Additional monitoring studies have the potential to support future restoration endeavors on ephemeral streams, which may be increasingly needed in the face of changing climate regimes and increasing populations.

2.7. Remaining Questions for Ephemeral Stream Floodplains

Although significant advances have been made in our understanding of their boundaries and functions, further research is still needed to better manage ephemeral stream floodplains in a landscape context. How do ephemeral stream floodplains respond to disturbances of different magnitudes? How will changing disturbance regimes in the future affect ephemeral stream floodplains in drylands? These questions require interdisciplinary answers, and further investigations of how hydrological, geomorphological, biogeochemical, and ecological functions interact on ephemeral stream floodplains are needed. Questions focused on the functioning of ephemeral stream floodplains also remain within specific disciplines. Uncertainties exist about the relative importance of vertical overbank versus lateral bank infiltration, the timing and cycling of floodplain sediment storage, and the impact of drought on riparian and floodplain vegetation.

Particularly important to elucidating some of these remaining questions is the need for better mapping and monitoring of ephemeral stream floodplains. Although research has begun to remedy the under-mapping of ephemeral stream channels (Hamada et al., 2016; Messager et al., 2021), future studies are needed to map the extent and location of ephemeral stream floodplains at regional to global scales, similar to recent efforts on perennial rivers (e.g., Nardi et al., 2019). The lack of monitoring of ephemeral stream floodplains is related to the stochastic nature of flow (Shanafield et al., 2021). Emerging solutions for monitoring variably inundated systems globally may help address the challenges of stochastic flow on ephemeral stream floodplains (e.g., Constantz et al., 2001; Noto et al., 2022), and additional monitoring is needed even during no-flow periods (Datry et al., 2016). Given the current and future abundance of ephemeral streams, more concentrated efforts are needed to understand the importance of natural and shifting inundation regimes in ephemeral stream floodplains globally.

2.8. Conclusions

By reviewing the body of literature on floodplains along ephemeral streams, differences and commonalities with perennial river floodplains are emphasized. Ephemeral stream floodplains host unique processes and functions compared to their channels and surrounding uplands. Functions parallel those commonly cited in perennial river floodplains, including attenuation of flows, cycling of nutrients, storage of sediment, and provisioning of unique habitat for indicator species. However, stochastic flow, high sediment loads, and stark differences in vegetation density and diversity compared to surrounding landscapes moderate the rates and magnitudes of processes within ephemeral stream floodplains and highlight the importance of their functions within dryland environments. Given the ubiquity of ephemeral streams in drylands, commonly comprising more than 80% of the total stream network, ephemeral stream floodplains are hotspots of many processes vital to dryland ecosystems. However, as on perennial rivers, changing climate, land use, management, and invasive species all threaten the functioning of ephemeral streams. Future research is needed to understand many of the general functions within ephemeral stream floodplains and their interactions, as well as on the impact of future stressors.

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CHAPTER 3: DRIVERS OF GEOMORPHIC HETEROGENEITY IN UNCONFINED, DRYLAND NON-PERENNIAL RIVER CORRIDORS

3.1 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 (Figure 3.1; 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 (Scott et al., 2022). Greater river corridor (including the channel and floodplain) heterogeneity commonly corresponds to greater attenuation of sediment, water, and solute fluxes (Wohl, 2016; Wohl, 2021), including organic carbon (Bellmore & Baxter, 2014; Wohl et al., 2018), and greater habitat diversity, which can lead to greater biodiversity (Bendix & Hupp, 2000; Scott et al., 2003; Luck et al., 2010; Wyzga et al., 2012; Bellmore & Baxter, 2014; Greene & Knox, 2014). Although river corridors can also be naturally homogenous, naturally heterogeneous reaches are hotspots of these 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. I start to broaden this understanding by examining river corridor geomorphic heterogeneity in non-perennial rivers 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 (Sandercock and Hooke, 2011, Jaeger et al., 2017), 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 (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, 2012; Sanchez-Montoya et al., 2016). Broadly, non-perennial river corridors host a high diversity of invertebrate and vertebrate fauna (Sanchez-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., Minar & Evans, 2008; McGarigal et al., 2009; Wheaton et al., 2015; Scown et al., 2015; Belletti et al., 2017; Fryirs & Brierley 2022; Scott et al., 2022). Geomorphic units are commonly identified by changes in topography, substrate, or vegetation (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., Wyrick et al., 2014; Carbonneau et al., 2020). 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; 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, 2005; 2016), particularly in intermittent rivers and ephemeral streams which are generally data-poor (e.g., Borg Galea et al., 2019).

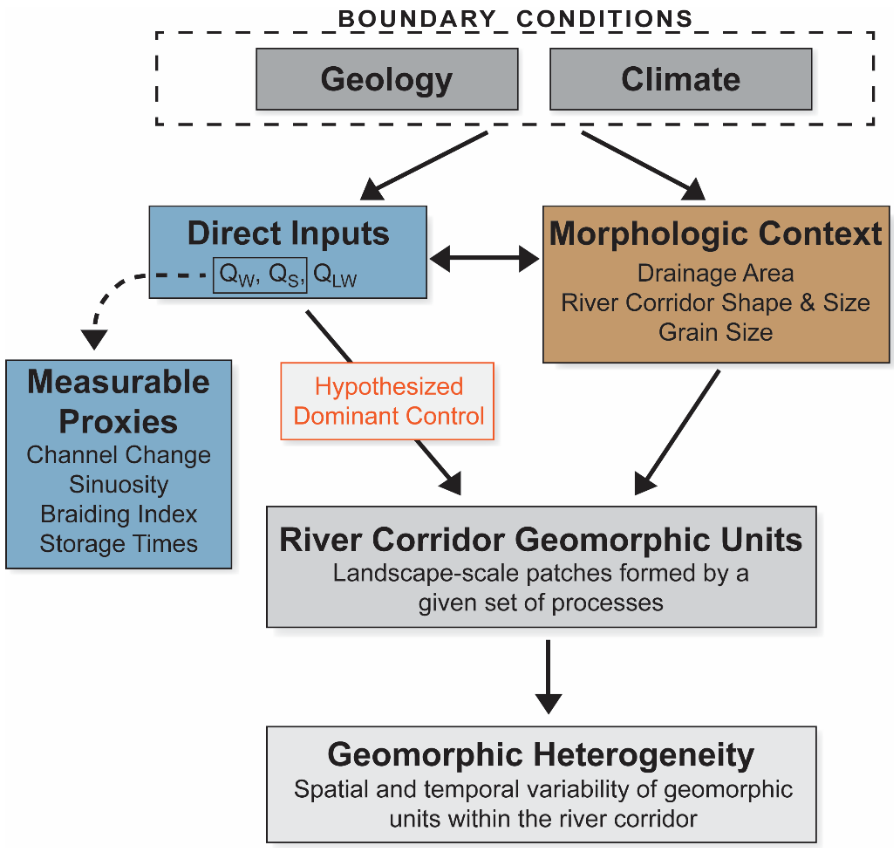

Figure 3.1. Framework showing the drivers of geomorphic units which in turn influence metrics of geomorphic heterogeneity. Individual geomorphic units can vary in spatial extent from 10^0 to 10^4 square meters. I hypothesize that direct inputs of discharge (Q_w), sediment flux (Q_s), and large wood loads (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.

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 and Frostick, 2011) and bedload (e.g., Reid and Laronne, 1995; Stark et al., 2021), which can drive the formation of new geomorphic units through deposition (Figure 3.1). 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., Hasan and Egozi, 2001; Friedman and Lee, 2002; Hooke, 2016). However, extreme floods in ephemeral streams can also provoke incision (Schick, 1974; Welsch, 1977; Rhoads, 1990), 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., Schumm, 1961; Patton and Schumm, 1981; Friedman and Lee, 2002), 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 – timing and intensity – may also impact heterogeneity, although 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 (Thoms, 2006; Panin et al., 1999).

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 3.1). (Murphey et al., 1977; Goodrich et al., 1997; Jaeger & Olden, 2011; Boulton et al., 2017). For example, downstream changes in river morphology due to transmission losses and changing downstream flood regimes (e.g., Murphey et al., 1997; Goodrich et al., 1997) can influence the spatial structure of vegetation communities (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., Stanford & Ward, 1993; Bellmore & Baxter, 2014; Wohl et al., 2018; Wohl et al., 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., Polvi & Wohl, 2012) 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 (Schumm, 1960; Nanson & Croke, 1992), 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, 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, I quantified 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, the following questions were posed: (1) how do processes in non-perennial streams influence geomorphic units? and (2) what drives geomorphic heterogeneity in dryland non-perennial river corridors? Based on the existing literature, I 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.

3.2.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 3.2, Table 3.1). Beads were defined 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.

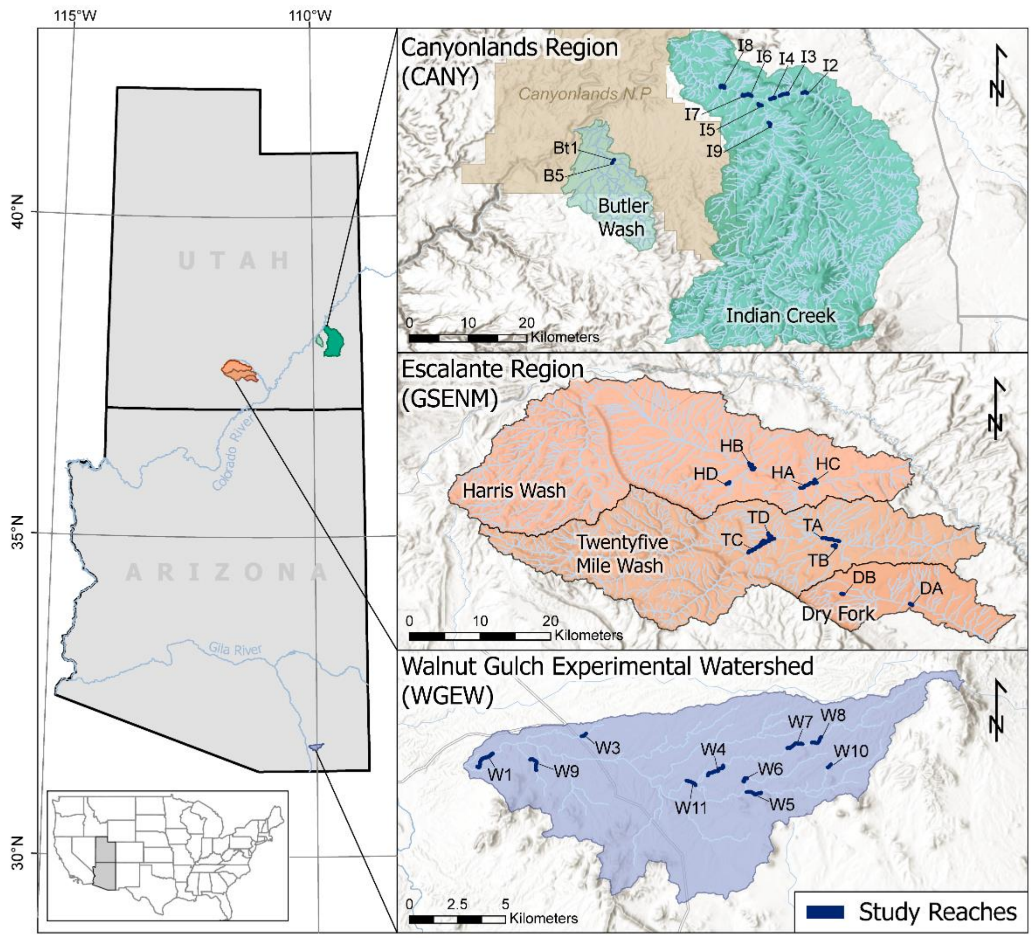

Figure 3.2. Map of study sites in CANY, GSENM, and WGEW, including both broader location in the southwestern U.S. as well as position within each watershed. Two-digit codes represent naming schemes used in surveying and analysis.

3.2.1. *Canyonlands Region, Utah (CANY)*

Indian Creek and Butler Wash are non-perennial tributaries to the Colorado River in southeastern Utah (Figure 3.2) 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 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).

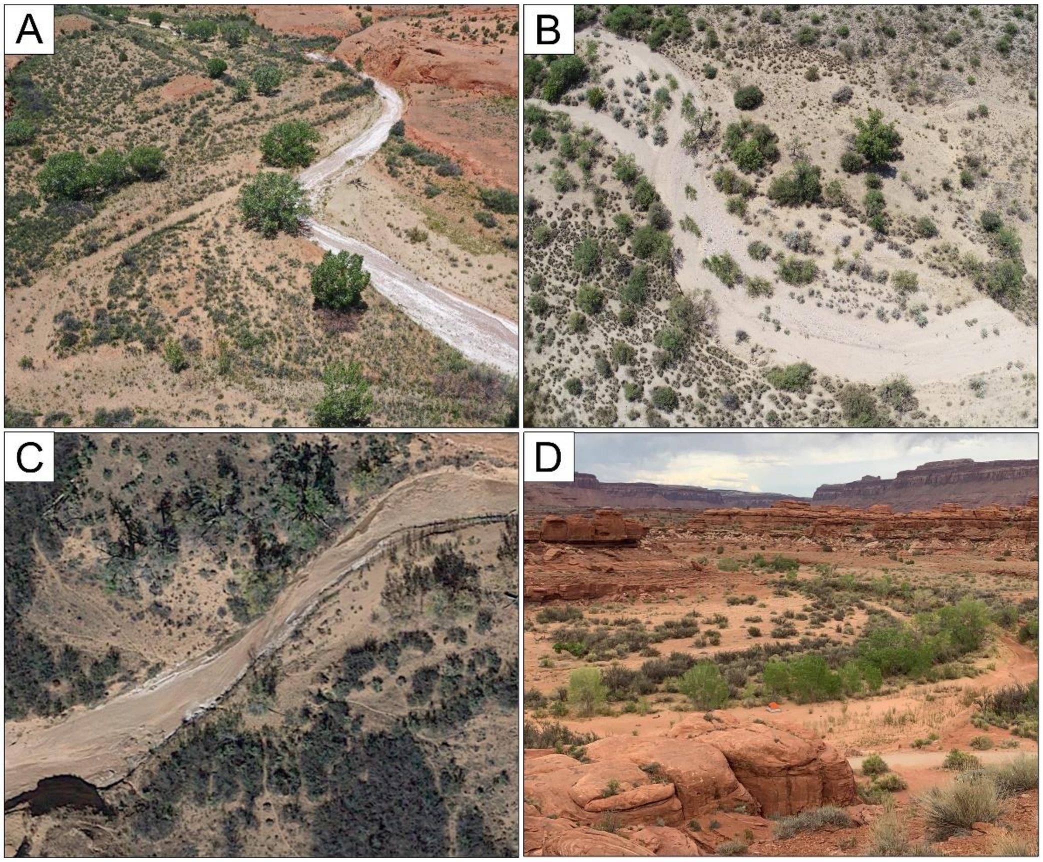

Figure 3.3. Aerial imagery and site photos showing representative floodplain study sites in Grand Staircase Escalante National Monument (A), Walnut Gulch Experimental Watershed (B), and Indian Creek in the Canyonlands Region (C & D). Dominant geomorphic unit types shown are main channel, shrub floodplain, 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).

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 by the U.S. Bureau of Land Management and private landowners – 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.

3.2.2. 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 3.2, Table 3.1). 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 3.3). Invasive species, including tamarisk (*Tamarix* spp*.)* and Russian olive (*Elaeagnus angustifolia*), also persist within and near ephemeral channels.

3.2.3. Walnut Gulch Experimental Watershed, Arizona (WGEW)

Walnut Gulch Experimental Watershed (WGEW) is an ephemeral tributary to the San Pedro River in southeastern Arizona (Figure 3.2). 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 3.3). Since 1959 CE, instrumentation on the watershed has been managed by the U.S. Department of Agriculture Agricultural Research Service, which maintains 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.

Table 3.1. Study Site Watershed Characteristics. Metrics (drainage area, average elevation, and precipitation) were calculated from the downstream-most study site in each watershed.

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	1110	116	1990	400
	Butler Wash	2	16.2	30	1720	260
Escalante (GSENM)	Harris Wash	4	605	102	1910	270
	Twentyfive Mile Wash	4	465	170	1880	270
	Dry Fork	2	85	65	1615	230
Walnut Gulch Experimental Watershed (WGEW)	Walnut Gulch	10	153	67	1415	370

[a] Average watershed precipitation calculated using the downstream-most study site as a drainage outlet in StreamStats (USGS, 2019).

3.3 Materials and Methods

3.3.1. 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, a combined field- and GIS-based mapping approach is used to delineate floodplain geomorphic units for the year surveyed. Field surveys were conducted in 2020 CE for sites in GSENM and WGEW and 2021 CE for sites in CANY. At each site, floodplain 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, both the boundary between river corridor and upland surfaces and the boundary 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., bare, herbaceous, shrub, or forest). The association between geomorphic units and cover type is likely due to feedbacks between morphology and vegetation (Osterkamp et al., 2012; Gurnell, 2014). Deposition and the formation of new geomorphic units can provide opportunities for seedlings to establish (Scott et al., 1996; Cooper et al., 2003; Kemper et al., 2022), and the evolution of an individual geomorphic unit over time can be matched with the succession of vegetation (e.g., Friedman and Lee, 2002; Corenblit et al., 2009). 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 (Appendix A). 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. 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 3.4). 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 3.2). 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 $\leq$ 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.

Table 3.2. Source and acquisition dates of imagery and digital elevation models used to delineate geomorphic units.

Region	Layer Type	Study Site(s)	Source	Acquisition Date
Canyonlands (CANY)	Aerial Imagery	All	USDA NAIP RGB	08/2018
	Digital Elevation Model	I2, I3, I4	USGS 1/3 Arc Second (n39w110)	09/2020
		I5	USGS 1-meter (x61y423)	05/2020
		I6, I7, I8	USGS 1-meter (x61y424)	05/2020
		I9	USGS 1-meter (x62y423)	05/2020
		B5, Bt1	USGS 1-meter (x59y422)	05/2020
Grand Staircase-Escalante National Monument (GSENM)	Aerial Imagery	TA, HA, HB, HC	Drone Flight	06/2020
		HD, TB, TC, TD, DA, DB	USDA NAIP RBG	07/2018
	Digital Elevation Model	TA, HA, HB, HC	Drone Flight	06/2020
		HD	USGS 1-meter (x46y417)	10/2019
		TB, TC, TD	USGS 1-meter (x46y416)	10/2019
		DA	USGS 1-meter (x48y415)	10/2019
		DB	USGS 1-meter (x47y415)	10/2019
Walnut Gulch Experimental Watershed (WGEW)	Aerial Imagery	W1	Drone Flight	08/2020
		W3, W4, W5, W6, W7, W8, W9, W10, W11	WGEW 10-cm	2018
	Digital Elevation Model	All	WGEW 1-m	09/2015

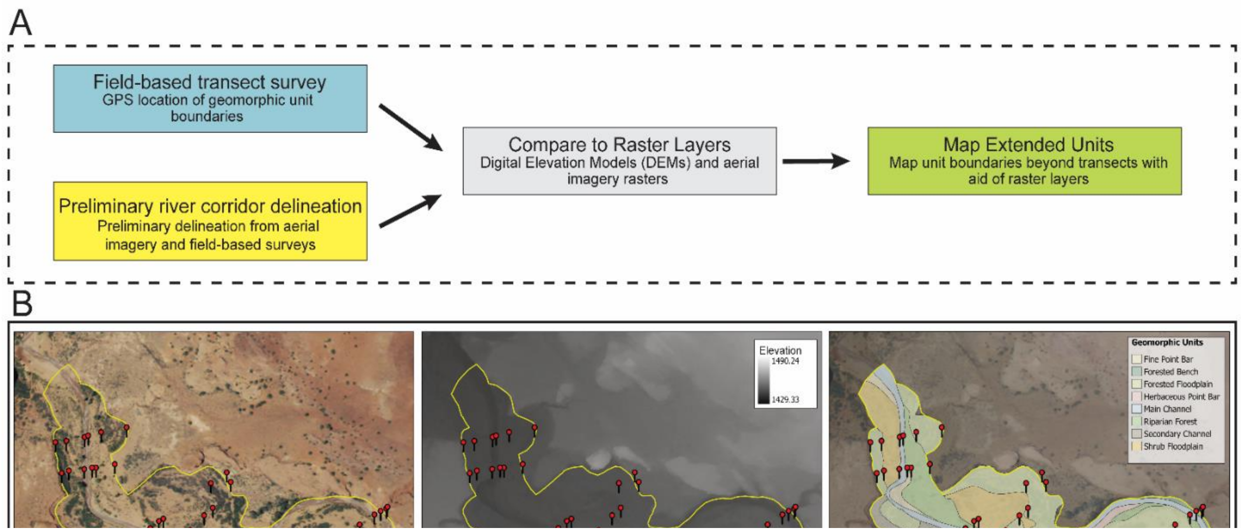

Figure 3.4. Workflow for delineating geomorphic unit based on a combined field and remote sensing approach. (A) digital workflow used for all studied reaches. (B) Example of survey and delineation from CANY Reach I5.

3.3.2. 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:

$$Patch\ Density = \frac{Total\ Number\ of\ Patches}{River\ Corridor\ Area\ (ha)} \quad \text{[Eq. 3.1]}$$

Patch density indicates the richness of patches on a landscape without considering the diversity of unit descriptions (i.e., unit class). To consider the diversity of geomorphic unit classes, Shannon's Diversity Index (SHDI) was calculated:

$$SHDI = -\sum_{i=1}^{m}(P_i \cdot \ln P_i) \quad \text{[Eq. 3.2]}$$

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). To look at how evenly the river corridor area is distributed between the present classes, Shannon's Evenness Index (SHEI) was calculated:

$$SHEI = \frac{-\sum_{i=1}^{m}(P_i \cdot \ln P_i)}{\ln m} \qquad \text{[Eq. 3.3]}$$

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.

3.3.3. Measuring Potential Driving Factors

Based on prior studies in perennial streams, I measured potential driving factors of geomorphic heterogeneity indicative of both morphologic context and disturbance regime at each study bead. In the field, 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 < 3 phi (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 and 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.

$$GC = \frac{Floodplain\ Perimeter}{2\sqrt{\pi \cdot Area}} \quad \text{[Eq. 3.4]}$$

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/).

Multiple metrics were used to estimate flood disturbance. Because most sites were ungauged, channel planform and metrics for channel change were used as proxies for flood disturbance and input rates. First, I 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 (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 and Schmidt, 2002; Hooke, 2015; Schook et al., 2017; Walker et al., 2020; Kemper et al., 2022). 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 3.5). 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:

$$\%\ Overlap = \frac{Overlap\ Area\ between\ Modern\ and\ Historical}{Historical\ Channel\ Area} \qquad \text{[Eq. 3.5]}$$

$$\%\ Channel\ Area\ Change = \frac{Modern\ Channel\ Area}{Historical\ Channel\ Area} \qquad \text{[Eq. 3.6]}$$

Channel change over 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, I 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 3.6). 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. The channel change analysis was used as a proxy for disturbance given that metrics of channel movement via imagery can be measured at all sites unlike direct flood measurements.

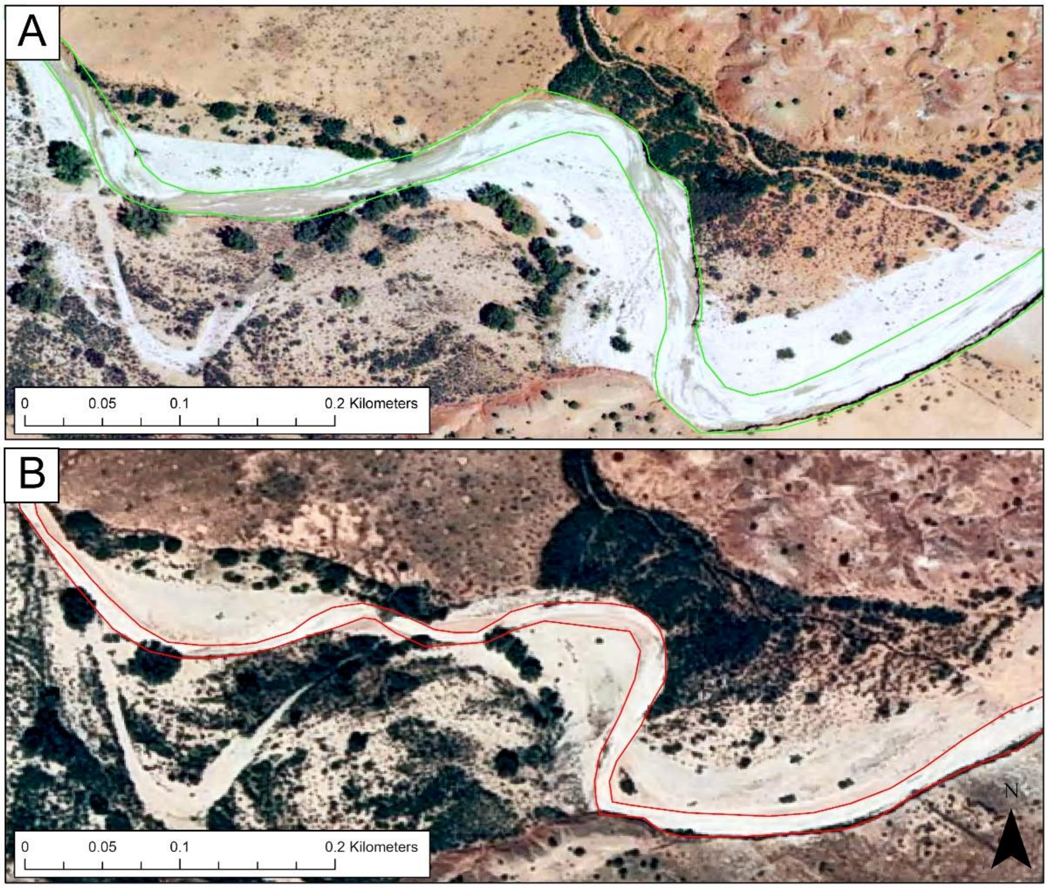

Figure 3.5. Example of channel change analysis in GSENM Reach TA. (A) Modern mapped channel from 2020 with NAIP imagery from 2018. (B) Historical mapped channel with NAIP imagery from 2011.

As a secondary proxy for channel change and disturbance, sediment residence time was 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 (Summa-Nelson & Rittenour, 2012; Harvey et al., 2011; Hayden-Lesmeister & Rittenour, 2014). To reduce the potential of sampling partially bleached sediments, I targeted plane-bed and ripple cross-bedded lithofacies, which likely represent less flashy and turbid depositional environments (Summa-Nelson & Rittenour, 2012). To minimize the effect of partial bleaching, I 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 Appendix B).

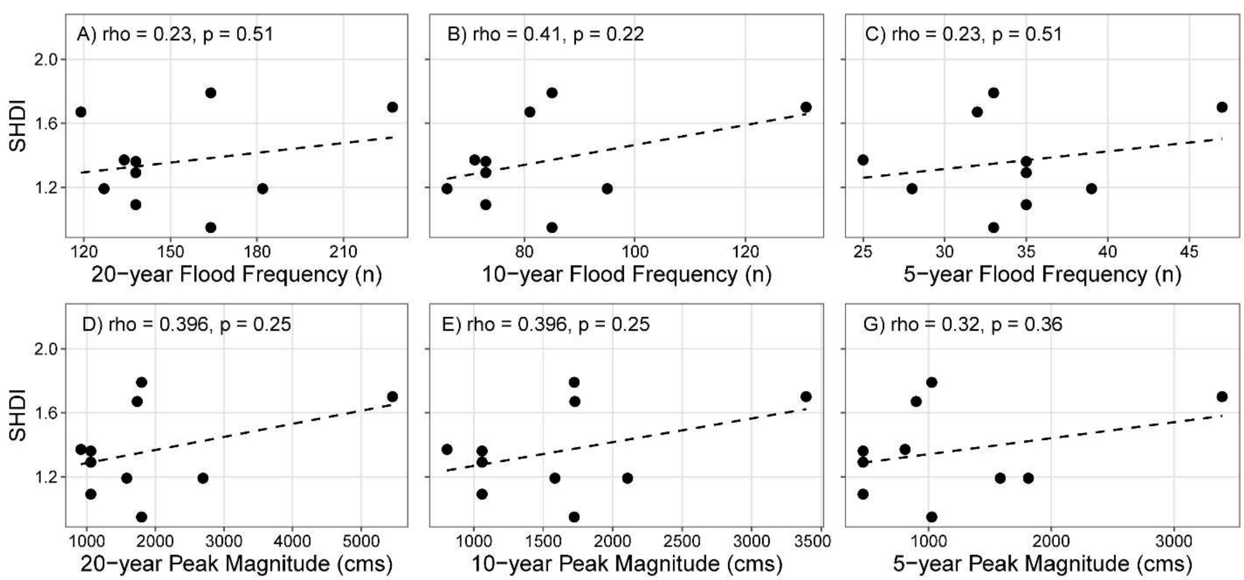

Figure 3.6. Relationship between flood frequency and peak flood magnitude over a 20-, 10-, and 5-year period for study sites in Walnut Gulch Experimental Watershed, Arizona. Relationships show trends, but given small sample sizes, are not significant.

Nine OSL samples were collected from exposed banks in Twentyfive 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 for both calculating 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 and Wintle, 2000) (see Appendix B). 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., Thoms, 2006; Panin et al., 1999).

3.3.4. Statistical Analyses

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 3.7).

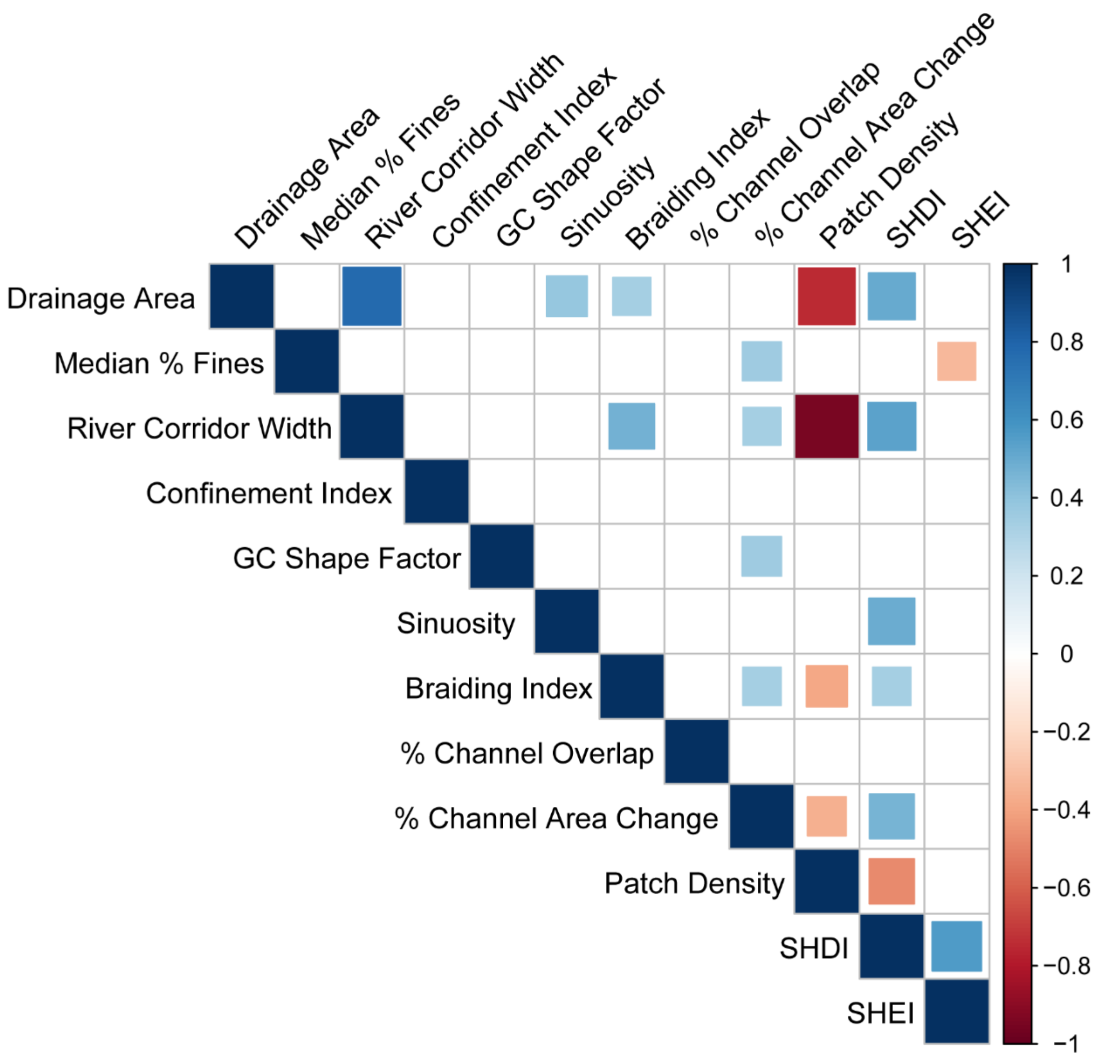

Figure 3.7. Correlation matrix for heterogeneity metrics (Patch Density, SHDI, and SHEI) and all potential driving factors. Color indicates strength and direction of correlation. Correlations with $p > 0.1$ are not shown.

To better understand the relative importance of potential driving factors on heterogeneity, I built multiple linear regression 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, Twentyfive Mile Wash C (TC), was identified as an outlier and excluded from regressions using the entire dataset (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), TC was included due to small sample sizes.

3.4 Results

3.4.1. 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, including 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 3.8, Appendix A).

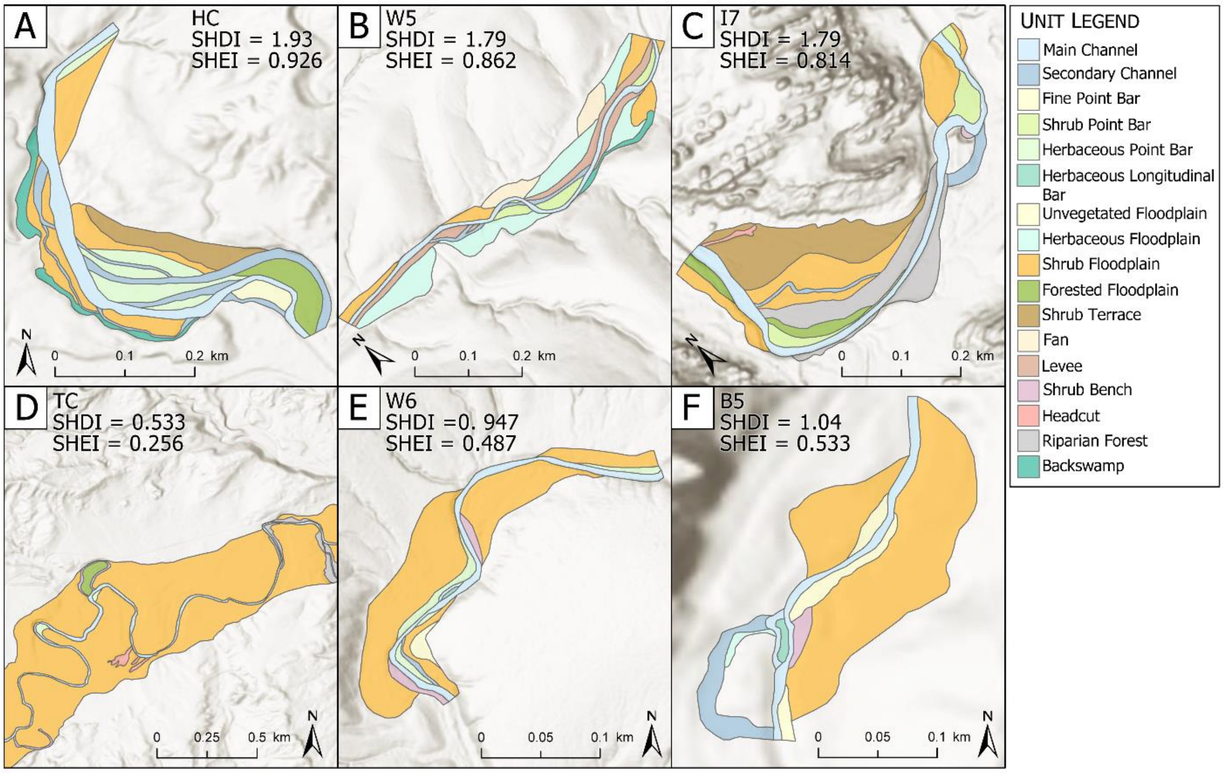

Figure 3.8. Subset of study beads showing geomorphic unit maps representative of high and low values of Shannon's Diversity Index (SHDI) and Shannon's Evenness Index (SHEI) across study regions: GSENM (A & D), WGEW (B & E), and CANY (C & F).

Given the commonality of secondary channels and point bars, the ratio of these classes were investigated 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).

3.4.2. Watershed scale trends in heterogeneity and potential drivers

Values for patch density and SHEI varied within watersheds but were not statistically different between watersheds (Figure 3.9a & c). 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 3.9b). 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 3.10). 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.

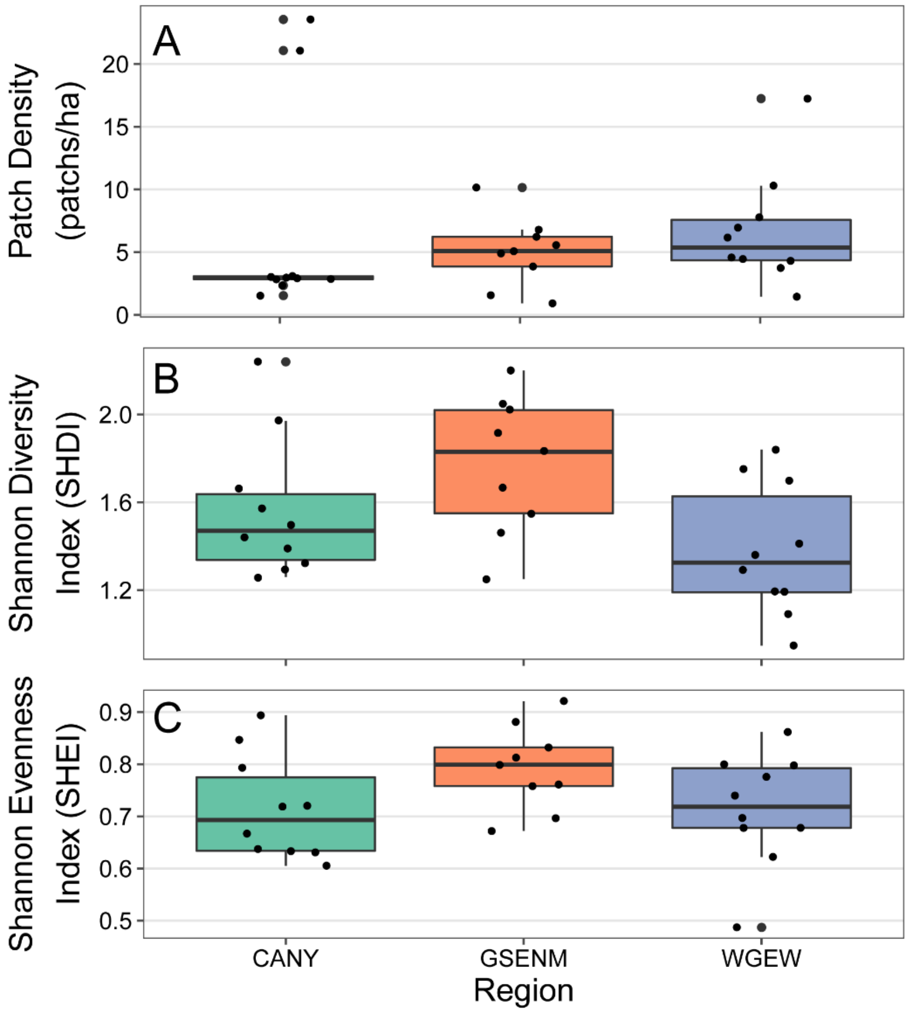

Figure 3.9. Range of values for heterogeneity metrics (patch density, SHDI, and SHEI) across study regions.

Given significant relationships between drainage area and diversity metrics (i.e., patch density and SHDI), I investigated downstream trends in other potential driving factors (Figure 3.10). Floodplain area (rho = 0.765, p <0.0001) and river corridor width (rho = 0.772, p < 0.001) both increased downstream. However, confinement index did not correlate to drainage area (rho = 0.096, p = 0.62). Channel sinuosity increased with drainage area (rho = 0.38, p = 0.04), but other drivers indicative of channel mobility (including metrics of channel change) did not exhibit significant downstream trends (Figure 3.10).

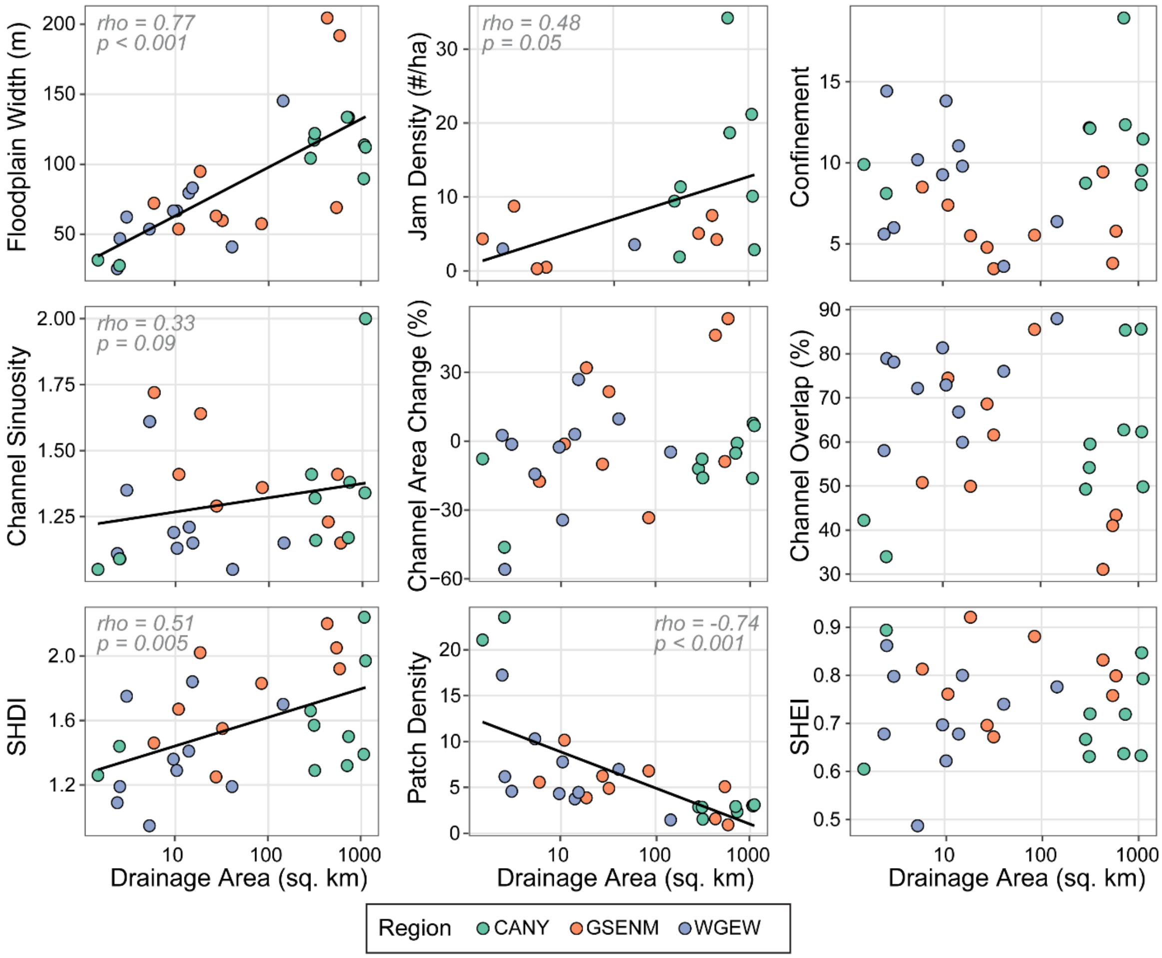

Figure 3.10. Linear relationships between drainage area, other potential driving factors, and diversity metrics.

3.4.3. 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 3.11). As floodplains became finer grained, evenness decreased (rho = -0.33, p = 0.08).

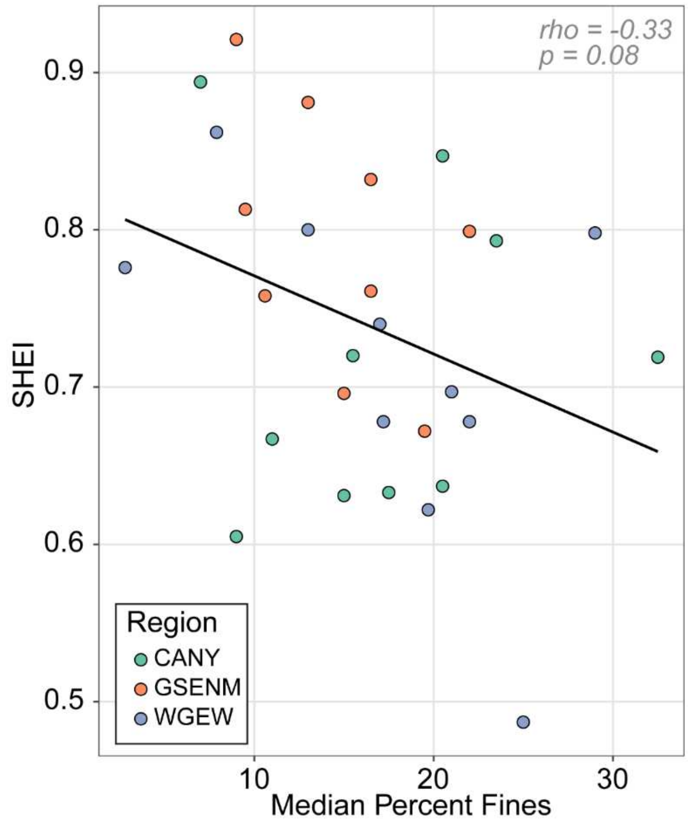

Figure 3.11. Moderately significant relationship between Shannon's Evenness Index (SHEI) and median percent fines.

Patch density inversely correlated to river corridor width, where wider floodplains were less patchy per unit area (rho = -0.94, p < 0.001) (Figure 3.12). Additionally, patch density was inversely correlated to metrics of channel mobility, including braiding index (rho = -0.39, p = 0.04) and percent change in channel area (rho = -0.35, p = 0.06) (Figure 3.13). 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.

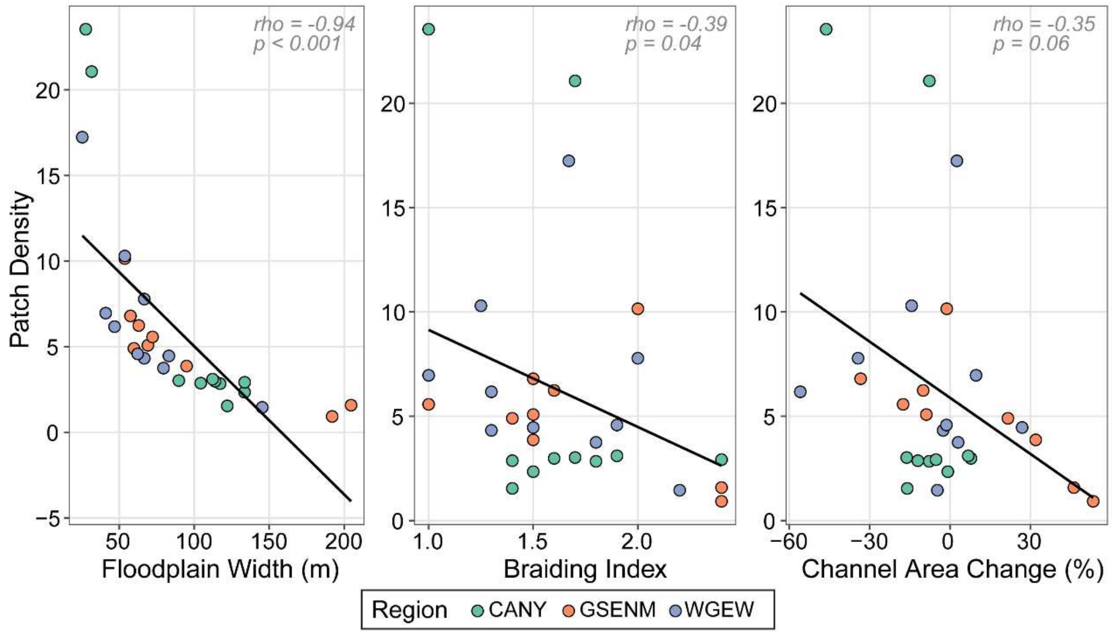

Figure 3.12. Significant relationships between patch density and potential driving factors.

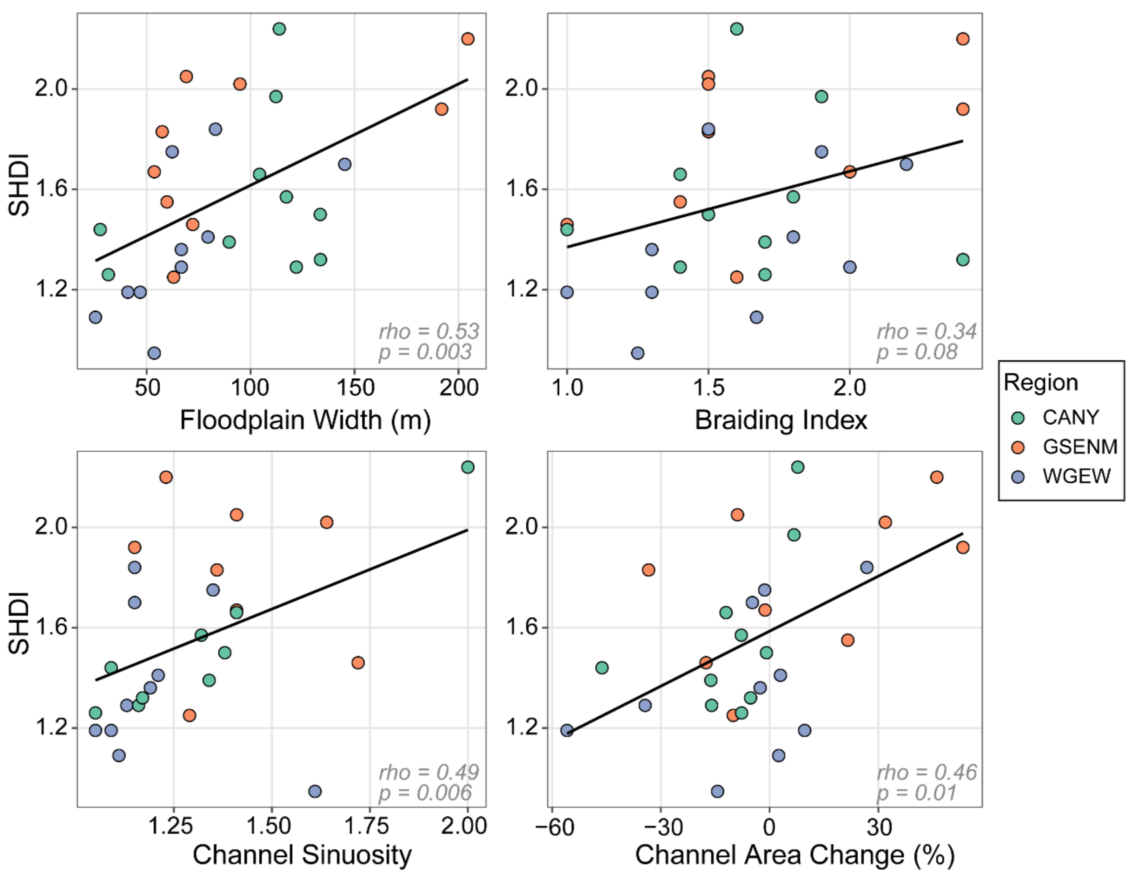

Figure 3.13. Significant relationships between Shannon's Diversity Index (SHDI) and potential driving factors.

Opposite to patterns with patch density, SHDI significantly increased as river corridor width increased (rho = 0.53, p = 0.003) and as braiding index increased (rho = 0.34, p = 0.08) (Figure 3.13). Additionally, SHDI increased as channel sinuosity increased (rho = 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 (rho = 0.46, p = 0.01).

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 SHDI. 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 m/ka to 1.29 m/ka when normalized by depth. A non-linear relationship was found between normalized ages and SHDI, where peak diversity was found at moderate normalized ages (R^2 = 0.72, p = 0.035, Figure 3.14). Given the limited sample size, the correlation between diversity and normalized OSL ages should still be considered weak.

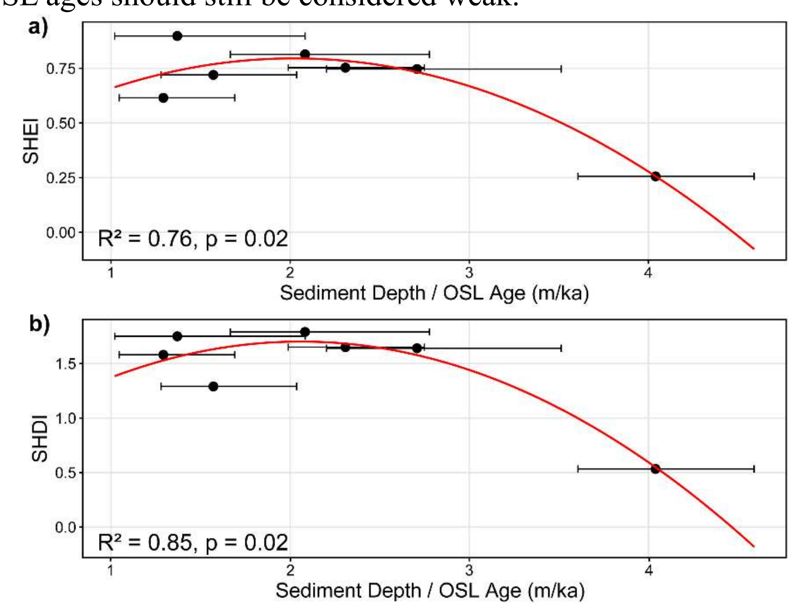

Figure 3.14. Plots of OSL ages normalized across sampling depth (sediment depth) compared to heterogeneity metrics: Shannon's Evenness Index (a) and Shannon's Diversity Index (b). Error bars represent age errors from the OSL analysis.

3.4.4. Relative Importance of potential drivers

Potential drivers that significantly varied with metrics of heterogeneity were included in multiple linear regression (MLR) models for each metric to determine relative importance. Based on the correlation between river corridor width and drainage area (Figure 3.10), I 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 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 change 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 3.3). The sum of weights simply represents the fraction of fitted models that included the variable of interest during model selection.

Given limited relationships between SHEI and predictors, a full MLR was not built. Instead, the median percent fines was recognized as the most important (and only) variable for estimating SHEI (Table 3.3).

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 3.3).

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 (including frequency, magnitude, and disturbance).

Table 3.3. 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 (-) Braiding index (-) % Channel area change (-)	River Corridor width [1.0] Drainage area [0.93] Drainage area: River Corridor width [0.92]
Shannon's Diversity Index (SHDI)	Drainage area (+) River Corridor width (+) Sinuosity (+) Braiding index (+) % Channel area change (+)	River Corridor width [0.65] % Channel area change[0.62] Drainage Area [0.49]
Shannon's Evenness Index (SHEI)	Median percent fines (-)	Median percent fines [*n/a*]

3.5. Discussion

3.5.1. 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 3.8). Spatial variations in specific stream power during floods can influence floodplain aggradation and erosion, which in turn affects the formation of geomorphic units within the river corridor (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 3.8, Appendix). Abandoned channels 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 across studied sites. First, CANY and GSENM beads tend to represent larger catchment areas than WGEW (Figure 3.10), 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 (Patton & Schumm, 1981; Graf, 1983). 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. Therefore, 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 3.8). 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 forest 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 3.9). Although this may indicate that floodplain evolution and geomorphic diversity are largely unaffected by invasive species encroachment, previous studies have noted the influence of invasive species on channel planform and migration, which can affect the development of geomorphic units (Graf, 1978; Hereford, 1984; Birken & Cooper, 2006; Walker et al., 2020). 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 & Spence, 2011), including removal of tamarisk in our specific study sites (HA and HC) in 2019 CE. Geomorphic units that developed during tamarisk colonization may still exist in GSENM floodplains but may currently be 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., Stevens et al., 1995; Merritt and Cooper, 2000; Grams and Schmidt, 2002) 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.

3.5.2. 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 (Thorp et al., 2008; Scown et al., 2016). 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 flood power will decrease, which limits the construction of floodplain features (Magilligan, 1992; Fagan and Nanson, 2004). 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 energy flux. Steeper stage-discharge relationships in narrower reaches could also 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, I found that as river corridor width increased, unit diversity increased (Figure 3.13). 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 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 3.3). 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 recently 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., Harris, 1987; Bendix & Hupp, 2000). 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. I interpret increased channel area as indicating higher flood frequency, magnitude, and/or duration over the decade analyzed, suggesting that higher frequencies of disturbance do 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 flash flood regime. However, the secondary effect of disturbance proxies also implies that ephemeral river corridors could be sensitive to changes in disturbance regimes over time. Ephemeral streams are likely sensitive to change, given their high erodibility (Graf, 1988). 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 diversity. Luminescence ages highlighted variations in sediment accumulation over centennial timescales across study beads, which had an impact on geomorphic unit diversity (Figure 3.14). 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 diversity 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 3.14). 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 diversity in this bead. 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 (Thoms, 2006; Panin et al., 1999). While TC evidently experienced high sediment loads at times over the past 500 years, this is not evidence that high sedimentation rates exist today. In fact, 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 to 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; Mackel, 1973), sporadic sediment influxes due to complex channel response could influence floodplain development in non-perennial river corridors worldwide.

3.5.3. Comparing Heterogeneity across Environments

Comparing heterogeneity metrics across mapping projects and environments can be complicated. Differences in mapping resolution (Wheaton et al., 2015; Scown et al., 2015) and criteria for defining geomorphic units (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; Yarnell et al., 2006; Wheaton et al., 2015; Williams et al., 2020), which are difficult to compare to floodplain-scale studies. However, comparing complexity of floodplains along non-perennial streams to perennial systems could elucidate both similarities and uniqueness in process and function between environments. I 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, 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; Scott et al., 2022).

3.6 Conclusions

Geomorphic heterogeneity in non-perennial beads across the southwestern U.S. was influenced by floodplain 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, individual unit types 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. As with perennial rivers, more research is needed to understand the best metrics for monitoring and interpreting heterogeneity. Still, geomorphic heterogeneity may be a useful metric for monitoring river corridors, including those that are non-perennial, and ecosystem function in the future, particularly as disturbance regimes change under a changing climate.

3.7. References

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CHAPTER 4: MODELING THE RELATIVE MORPHODYNAMIC INFLUENCE OF VEGETATION AND LARGE WOOD IN A DRYLAND EPHEMERAL STREAM, ARIZONA, USA[1]

4.1. Introduction

The ecologic and geomorphic influence of organic matter accumulations has been readily established in perennial rivers (Montgomery et al., 2003; Gurnell, 2013; Ruiz-Villanueva et al., 2016; Scott and Wohl, 2017; Wohl, 2017; Swanson et al., 2021). Large wood (LW; >10 cm in diameter and 1 m in length) and coarse particulate organic matter (CPOM; > 1 mm in diameter) can significantly impact the morphology and function of river corridors (including the channel, floodplain, and hyporheic zone (Harvey and Gooseff, 2015)). In-channel LW pieces and accumulations (i.e., jams) can increase hydraulic resistance (Curran and Wohl, 2003; MacFarlane and Wohl, 2003), which lowers local and reach-averaged velocity (Shields and Smith, 1992; Manners et al., 2007). As a result, LW can pond water (Gurnell et al., 2005; Klaar et al., 2009) and sediment upstream of jams (Bilby, 1981; Nakamura and Swanson, 1993; Faustini and Jones, 2003; Short et al., 2015). Sedimentation can aggrade the channel and encourage secondary channels to form on the floodplain (Abbe and Montgomery, 2003; Montgomery and Abbe, 2006). Channel-spanning LW jams can transform reaches from homogeneous, single-threaded channel planforms to multi-threaded planforms with a greater diversity of channel widths and depths (Wohl, 2011). Sedimentation downstream of individual LW pieces and jams can form new islands or stabilize pre-existing islands (Gurnell et al., 2005). In reaches with erodible banks and substrate, LW can cause bank and bed scour (Keller and Swanson, 1979), which can encourage

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lateral channel migration (Nakamura and Swanson, 1993; Lassettre et al., 2008). Although understudied compared to in-channel wood, LW on perennial floodplains can cause high sedimentation rates and spatially heterogeneous deposition during overbank flow (Jeffries et al., 2003). LW jams buried on floodplains can create hard points that resist erosion and promote avulsion and multi-threaded planforms (Collins et al., 2012). LW can be deposited in association with vegetation (e.g., Lininger et al., 2021), thus creating similar increases in roughness, but the body of literature outlining the geomorphic effects of LW establishes that jams play a distinct role in shaping channels and floodplains in perennial river corridors.

In contrast, the effects and benefits of LW and CPOM in streams with ephemeral flow regimes are relatively understudied (Wohl, 2017), particularly in dryland regions where flow is predominantly controlled by high-intensity, irregular storms. A limited number of studies have quantified the volume of LW and CPOM in dryland ephemeral streams in Australia (Graeme and Dunkerley, 1993; Dunkerley, 2014), the Mediterranean (Galia et al., 2018; Galia et al., 2019; Galia et al., 2020), Africa (Jacobson et al., 1999) and the southwestern United States (Wohl et al., 2018; Wohl and Scamardo, 2022). Most studies found that LW was present but at lower volumes than in perennial rivers, and that LW and CPOM accumulations were commonly associated with existing vegetation in the ephemeral channel and floodplain (Dunkerley, 2014; Galia et al., 2020; Wohl and Scamardo, 2022). Despite the growing recognition of LW in ephemeral channels, the impact that LW and CPOM accumulations have on ephemeral stream channel morphology is still poorly constrained and, given common trapping locations, entangled with the geomorphic effect of vegetation. LW jams have rarely been observed during a flow event due to the infrequency and brevity of discharge in dryland ephemeral channels. The current understanding of how LW jams alter hydraulics during flow is based on sediment deposition patterns around jams post-flood. Significant sediment deposition has been found downstream of LW jams (Jacobson et al., 1999; Dunkerley, 2014; Galia et al., 2018), suggesting potential decreased velocity or eddying behind stable jams during flash floods. Jacobson et al. (1999) found that recent sediment accumulations acted as 'nursery bars' that could develop into elongate islands if not removed by subsequent high flows. Due to sedimentation and flow deflection, LW jams may create multi-threaded planforms in ephemeral channels (Graeme and Dunkerley, 1993; Dunkerley, 2014). However, despite some evidence that LW accumulations can affect flow paths, sedimentation, and channel morphology in dryland ephemeral streams, evidence for physical effects from LW accumulations can be unclear. Galia et al. (2018), for example, noted sediment deposition downstream from LW jams but found no scour, temporary dammed pools, or evidence of flow deflection around LW jams, suggesting that LW accumulations may have limited physical effects. As in perennial streams, LW deposition can be correlated to vegetation density in ephemeral streams (e.g., Wohl and Scamardo, 2022), because stable vegetation provides ample trapping locales for LW and CPOM. Vegetation similarly increases roughness along ephemeral channels, which can lead to sediment deposition (Nepf, 1999) and the creation or maintenance of braided planforms (Graeme and Dunkerley, 1993; Wende and Nanson, 1998). Therefore, the question remains, how do LW jams influence channel morphology in ephemeral rivers and how does the influence of LW compare to that of vegetation?

Given the difficulty of obtaining direct measurement during infrequent and short-duration flash floods, I approach this question using indirect methods. Our primary objective is to numerically model reach-scale morphological changes during a flash flood in an ephemeral stream using three scenarios: a calibrated model representing the actual configuration of the river corridor; a numerical experiment in which jams are removed; and a numerical experiment in which vegetation is removed. This allows us to compare the modeled geomorphic changes associated with the presence of LW versus those associated with vegetation and thus infer the relative importance of LW and vegetation in channel change during a flood. Given the correlation between the trapping of wood and presence of vegetation, I do not intend to contrast the morphological influence of both factors, but rather to compare. I hypothesize that LW jams and vegetation will result in similar spatial patterns and magnitudes of changes in morphology, such as increased sedimentation on the floodplain and the formation of braided channels. However, I expect floodplain sedimentation and channel erosion to be greater with the inclusion of jams than without. I use two-dimensional hydro-morphodynamic models to simulate and isolate the influence of LW jams and vegetation in an ephemeral stream in southeastern Arizona.

4.2. Study Site

Walnut Gulch Experimental Watershed (WGEW) encompasses ~150 km^2 of the semi-arid transition zone between the Sonoran and Chihuahuan deserts in southeastern Arizona (Figure 4.1). Headwaters to Walnut Gulch start in the Dragoon Mountains and Tombstone Hills, eventually joining the San Pedro River as an ephemeral tributary. Runoff events in Walnut Gulch predominantly occur due to late summer monsoon rainfall. Bedrock in the headwaters of WGEW is primarily highly erodible Gleeson Quartz Monzonite, soft tuffs of the lower S O Volcanics Group, and sandstones and limestones of the Bisbee and Naco Groups (Osterkamp, 2008). Lowland hillslopes are underlain by the Gleeson Road Conglomerate, while river corridors are composed of late Holocene alluvium.

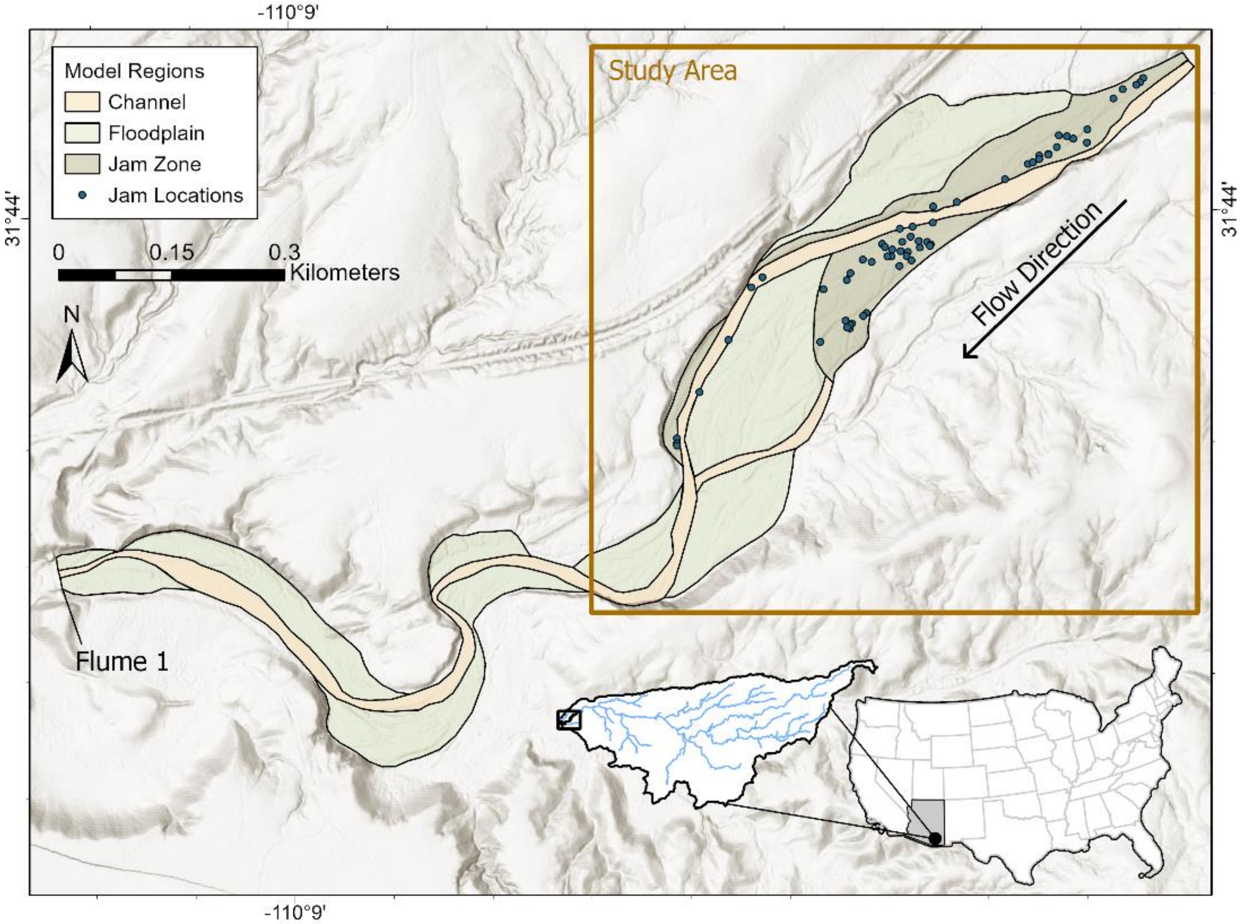

Figure 4.1. Site map of the study area (box) and modeled area (colored regions) in Walnut Gulch Experimental Watershed, Arizona. Surveyed jam locations are indicated with points.

WGEW has been managed by the U.S. Department of Agriculture Agricultural Resources Service (USDA-ARS) since 1959. The experimental watershed was initially created to investigate the influence of upland conservation on downstream water supply. Accordingly, a series of in-channel flumes have been maintained in WGEW since the 1950s to record temporary flows. A total of 11 critical-depth flumes, specially designed to withstand intense flash floods in the watershed, record water depth and discharge of all runoff events that produce flow above a minimum threshold stage (0.003 m at small flumes, 0.015 m at large flumes) (Smith et al., 1981).

Currently, flow depth is recorded using a potentiometer and converted to discharge using a known stage-discharge relationship developed for each flume.

The following study focuses on a ~ 2.3 km reach of WGEW immediately upstream of Flume 1, the downstream-most and largest flume in WGEW (Figure 4.1). The reach is separated into two parts: the upstream-most 1.1 km, termed the study reach, and the downstream-most 1.2 km. The study reach is unconfined (average floodplain width = 115.3 m) with an anastomosing planform, while the downstream reach is more confined (average floodplain width = 46.5 m) with a single channel. The field study and interpretation of the results are limited to the study reach, but combined, the two reaches form the modeled area. The main ephemeral channel through the modeled area is largely unvegetated and consists of fine sand to medium gravel, with an average channel width of 18.1 m and average gradient of 0.01 m/m. Bedforms are not evident throughout the reach. Occasional bedrock outcrops ~ 5 – 10 m in length occur on outer meander bends in the downstream reach, but otherwise, bedrock outcrops or large (> 0.5 m) boulders are rare in the channel. Approximately 31% of the floodplain is vegetated with Arizona walnut (*Juglans major*), mesquite (genus *Prosopis*), and netleaf hackberry (*Celtis laevigata*) as well as shrubs such as Mormon tea (*Ephedra nevadensis*) and rabbitbrush (genus *Chrysothamnus*) (Figure 4.2). Ground cover of grasses and sedges is limited.

Figure 4.2. Oblique aerial image of the upstream portion of the study area, showing a sparsely vegetated floodplain, multiple channels, and outcropping bedrock. Reach and floodplain boundaries are highlighted with a dashed yellow line. Camera angle is looking upstream.

4.3. Methods

4.3.1. Field Data Collection

A comprehensive survey of all LW and CPOM jams within the study area was conducted in August 2020. Surveys were completed by walking the extent of the study reach and documenting the location of all jams larger than 0.5 m in two principal directions (length, width, height) using a handheld Garmin GPS (accuracy ± 3m). I chose to include CPOM accumulations meeting the size requirement due to the prevalence of woody accumulations that did not meet the definition of LW, but still likely persist for years (Wohl & Scamardo, 2022). The longevity of LW and CPOM accumulations has not explicitly been monitored in WGEW, but occupation of jams by packrats and colonization by vegetation suggests that some of the surveyed jams had persisted for multiple seasons. Additionally, wood decay rates in dryland floodplains are low, on the order of decades to centuries, suggesting that non-mobilized wood surveyed in the floodplains would persist from year-to-year (Anderson et al., 2016). Moving from upstream to downstream in the reach, I walked a series of perpendicular transects across the floodplain and channel to capture all jams. In addition to location, I measured the bounding dimensions and estimated porosity within those bounds by visually approximating the volume of void space within the jam volume (Livers et al., 2020). The occurrence and size of all LW pieces were measured within each surveyed jam and it was noted whether jams were trapped on vegetation. Finally, the location of the jam was categorized into one of four geomorphic units: main channel, secondary channel, floodplain, or bar.

Sediment cores were collected at randomly generated point locations in the channel and floodplain within the study area to characterize grain size in the reach. Eight cores were collected in the channel and ten cores were collected on the floodplain. Cores were taken to a depth of 20 cm using a slide-hammer corer, and sediment extracted from the cores was sieved for grain size. Cores were unconsolidated and not vertically stratified post-collection; however, no armoring or noticeable vertical variation in grain sizes were noted.

4.3.2. Modeling Domain Set-Up

SRH-2D, a two-dimensional depth-averaged hydro-morphodynamic model (Lai, 2010), was used to simulate a specific runoff event that occurred on 28 July 2017, starting at 6:20 P.M. with a peak discharge of ~ 96 m^3/s (Appendix C Figure C1). The 2017 event represents the largest flow recorded in the decade prior to the 2020 wood survey and has an 8-year recurrence interval based on the period of record at Flume 1. Given the magnitude and recurrence interval of the runoff event, I expect all surveyed jams to have been deposited prior to or at the front of the 2017 flood.

Model pre- and post-processing was performed using SMS 13.1 software (Aquaveo, commercial surface-water model system, https://www.xmswiki.com/wiki/SMS:SMS). A computational mesh was created by specifying the number of bounding nodes on the floodplain, channel, and jam zone boundaries. The boundaries between the floodplain and channel zones were determined from field mapping and aerial imagery. The jam zones are identified as areas of concentrated jam deposition, and boundaries were determined by the field-based wood survey (Figure 4.1). The model boundaries and mesh were extended beyond the study reach to include Flume 1, to take advantage of a known outflow for model calibration. In total, the mesh contained 52,959 quadrilateral and triangular elements with an average element length of 3.1 m. Mesh element shape and size were chosen based on the need for an accurate solution while balancing increasing computational demands. Channel areas were modeled using quadrilateral elements with an average cell size of 2.5 m in the downstream and lateral directions, while floodplain areas were modeled using triangular elements with an average cell size of 2.5 m near the channel and 5.0 m near the model boundaries. The decision to vary mesh resolution across the domain was made to increase accuracy in places of expected high change, such as the channel and surrounding jam zones, while balancing computational efficiency.

Elevation was assigned to the mesh using a 1-m resolution digital elevation model (DEM) derived from airborne laser swath mapping (Heilman et al., 2008) in WGEW in 2015. I assume that minor floods between 2015 and 2017 minimally changed topography, so that the 2015 DEM represents pre-flood morphology. Sediment characteristics within the mesh domain were estimated from the sieved sediment cores taken from the bed and floodplain of the study reach. The channel was modeled with D_{16} = 0.5 mm, D_{50} = 1.85 mm, and D_{84} = 8.8 mm, representing medium sand to fine gravel. The floodplain and jam zones were modeled with D_{50} = 0.7 mm and D_{84} = 1.6 mm, representing coarse sand.

4.3.3. Hydrodynamic Set Up and Calibration

An unsteady hydrodynamic model was developed using the hydrograph from the July 2017 runoff event in SRH-2D, which solves the depth-averaged St. Venant equations using an implicit scheme (Lai, 2010). Discharge was measured at the downstream end of the reach at Flume 1. I used an iterative process to infer an inlet hydrograph based on the outlet hydrograph. Initially, the outlet hydrograph was used as an inlet hydrograph, and the modeled outlet hydrograph was compared to the measured outlet hydrograph. The difference between the modeled and measured outlet hydrographs at each timestep was then added to the inlet hydrograph until the lowest root mean square error (RMSE) was achieved between the modeled and measured outlet hydrographs. RMSE was determined by calculating the error between the modeled and measured outlet hydrograph at each time step, in order to capture error in the magnitude and timing of discharge. Hydrograph calibration was conducted using Manning roughness values of n = 0.036 for the channel, n = 0.06 for the floodplain, and n = 0.09 for the jam zone, based on previously published values in Walnut Gulch (Bunch and Forbes, 2019; Michaelides et al., 2018) and additive methods for calculating roughness (Cowan, 1956). The flow outlet was modeled as a supercritical boundary to mimic the conditions immediately upstream of the critical-depth flume. For all runs, the initial bed condition was set to dry in order to mimic the conditions prior to the runoff event.

4.3.4. Roughness Parameterization and Sensitivity Analysis

Post-hydrograph calibration, model sensitivity to surface roughness was tested by varying Manning's n values in the channel, floodplain, and jam zone within a reasonable range. Previous studies in other reaches of WGEW estimated roughness values of n = 0.027 in the channel (Bunch and Forbes, 2019) and of n = 0.056 on the floodplains and hillslopes (Michaelides et al., 2018). Although published roughness values were not estimated for the study and modeled reach, they provide context for developing a reasonable range of roughness values. A range of roughness values for the channel was determined using the additive method of Cowan (1956),

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m \qquad \text{(Eq. 4.1)}$$

where n_b is a base roughness value of a straight, uniform, smooth channel in natural materials, n_1 is a correction factor for surface irregularities, n_2 is a value accounting for fluctuations in cross-section shape, n_3 is a value estimating obstructions, n_4 accounts for roughness of vegetation, and m is a correction factor for meandering. A base value of $n_b = 0.025$ for coarse sand bed channels was used. The channel through the model reach is fairly uniform, with minor vegetation and obstructions. Therefore, the lower limit of channel roughness was determined to be the base value, while the upper limit of channel roughness was estimated to be n = 0.036 based on moderate irregularities, moderate cross-section variability, negligible obstructions, and small amounts of vegetation.

Reasonable roughness values for the floodplain were estimated using Equation 1 adjusted for floodplains (Arcement and Schneider, 1989). The floodplain along Walnut Gulch is characterized by minor to moderate topographic irregularities (rises and sloughs) and minor to moderate brushy vegetation. A lower limit of roughness in the floodplain was determined to be n = 0.042, based on minor irregularities, negligible obstructions, and small amounts of vegetation. An upper limit of n = 0.063 was chosen, representing moderate irregularity, minor obstructions, and moderate amounts of vegetation.

Roughness for the modeled jam region, or region where the majority of jams were accumulated, was determined based on the calibrated roughness for the floodplain, given that jams were mostly accumulated in vegetated floodplain areas. In perennial systems, increasing the surface roughness value within a model is a common approach to modeling jams (Addy and Wilkinson, 2019). Accordingly, based on the floodplain roughness value, the effect of obstructions (n_3) was increased to minor or appreciable (n = + 0.01 – 0.03). This increased roughness accounts for the added obstruction within the cross-section created by LW and CPOM accumulations.

Sensitivity to roughness was tested by adjusting Manning's n values for each model region within the range of realistic n-values and then comparing the RMSE of the measured and modeled hydrographs (Appendix C Figure C2). The sensitivity analysis was conducted to determine how important relative uncertainty in roughness values is on the results of the hydrodynamic model. Roughness values used in the hydrograph calibration were chosen from within the reasonable range of values for each model region, based on site characteristics and previously published values determined upstream in the catchment. However, roughness was not explicitly calibrated due to limited available data, given that stage measurements were only conducted in one location – Flume 1 – during the duration of the flow.

4.3.5. Morphodynamic Set Up and Calibration

Following the hydrograph calibration, the hydrodynamic model was then coupled with a mobile bed morphodynamic model in SRH-2D. I modeled bedload transport using both the

Engelund and Hansen (1972) total load and Meyer-Peter and Müller (1948) bedload transport equations to test output sensitivity to transport equations. Both equations have been used to successfully and accurately model sediment transport and morphodynamic change in sand to gravel bed ephemeral channels (Lotsari et al., 2018; Scott, 2006). Adaptation length was modeled using the Philips-Sutherland saltation length formula, which is recommended for sand bed channels (Lai, 2020). Active layer thicknesses between 1.0 and 3.0 times the D_{90} thickness were tested to calibrate sediment transport. Sediment concentration at the inlet was estimated by calculating the transport capacity across the upstream boundary.

Six model runs were developed to calibrate the sediment equation and active layer thickness (Appendix C Table C1). Resulting erosion and sedimentation from each model run were compared to a DEM of difference (DoD) for the reach between 2015 and 2018 created using the Geomorphic Change Detection Software (Wheaton et al., 2010). Although smaller flows before and after the 2017 runoff event likely changed topography within the reach, the 2017 runoff event marks a large flood during this period, and likely created a significant amount of channel change during the time of interest. Output rasters of modeled erosion and sedimentation were compared to the DoD using RMSE (Appendix C Figure C3, C4). The Engelund-Hansen sediment transport equation with an active layer twice the thickness of the D_{90} produced the lowest error and was therefore used as the calibrated model for comparisons.

4.3.6. Numerical Experiments

Our analysis compares three morphodynamic modeling simulations: a baseline (calibrated) model including channel, vegetation, and jam zones; a model without jams, and a model without jams or vegetation. Based on the roughness sensitivity analysis, the baseline model used Manning's n values of 0.036 for the channel zone, 0.06 for vegetation zones, and 0.09 for jam zones. In the second simulation, the additional roughness of jams was removed by assigning a Manning's n value of n = 0.06 to the jam zones instead of n = 0.09; that is, jam zones were treated as floodplain zones in the model. In the third simulation, the roughness of vegetation was artificially removed by assigning a roughness value of n = 0.036 to both the floodplain and jam zones; that is, the entire domain was modeled using the channel roughness. Beyond roughness, all parameters of the experimental runs matched those of the calibrated model. Experimental runs were compared to the calibrated run, and were not validated or calibrated, given that the conditions being modeled were not present in the reach during the 2017 runoff event.

4.4. Results

4.4.1. Jam Characteristics

A total of 61 jams were surveyed within the study area. The average volume of LW and CPOM per jam was 0.97 m^3, with the largest jam having a wood volume of 18.48 m^3 (Table 4.1). A total wood volume of 67.1 m^3 was recorded in the study reach, which covered 120.3 m^2 or ~0.1% of the total study area. Jams were largely deposited on vegetation (91% of all jams) outside of the channel region. Approximately 94% of the measured jams were found within the denoted 'jam regions' in the model, with the remaining 6% located in the channel wrapped around mid-channel vegetation (Figure 4.3B). I observed coarse sediment deposition associated with jams (Figure 4.3).

4.4.2. Sensitivity to Roughness

The model was most sensitive to roughness adjustments in the channel region, compared to the floodplain and jam zones (Appendix C Figure C3). RMSE ranged from 6.01 to 8.64 m^3/s (2.62 m^3/s range) when roughness in the channel region was varied (range of n = 0.025 – 0.036), compared to a 1.4 m^3/s range when floodplain roughness was varied (range of n = 0.042 – 0.063), and 0.9 m^3/s range when the jam zone roughness was varied (range of n = 0.07 – 0.09). Generally, RMSE was lower as roughness increased, but overall, the model is only mildly sensitive to uncertainty in roughness, as is indicated by small ranges of RMSE (1.0 – 2.0 m^3/s) relative to the magnitude of peak discharge (~90 m^3/s).

Table 4.1. Jam characteristics within the study reach.

Characteristic	Value
Total number of Jams	61
Jams per hectare	4.1
Number of Jams with LW	19
Median Volume	0.51 m^3
Standard Deviation of Volume	2.4 m^3
Max Volume	18.48 m^3
Proportion in Channel	0.06
Proportion in Secondary Channel	0.16
Proportion in Floodplain	0.67
Proportion on Bar	0.11
Proportion with Vegetation	0.91

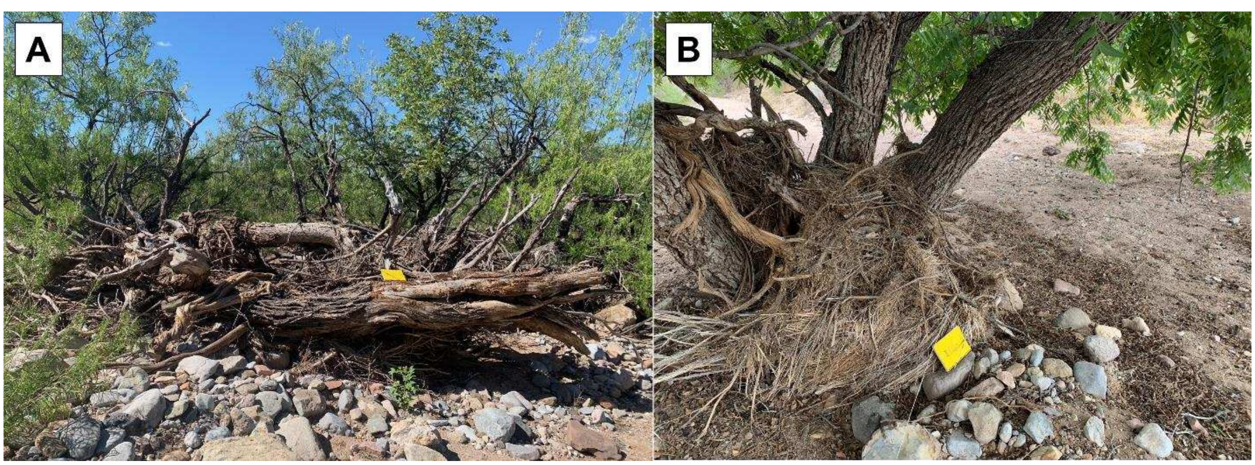

Figure 4.3. Examples of LW jams in Walnut Gulch Experimental Watershed. Flow is into the image (A) and from right to left (B).

4.4.3. Modeled Hydrologic Characteristics

The modeled flash flood peaked 2 hours after the start of the flood, similar to the measured runoff that occurred in the reach (Appendix C Figure C1). At the runoff peak, the calibrated hydro-morphodynamic model (including jams and vegetation) showed inundation across the majority of the floodplain, with high velocities confined to the main channel (Figure 4.4A). Average velocity in the channel was 2.46 m/s, compared to average velocities of 0.86 m/s and 0.93 m/s in the floodplain and jam regions, respectively (Table 4.2). The total wetted area at the peak discharge was ~182,200 m^2 (87% of total area).

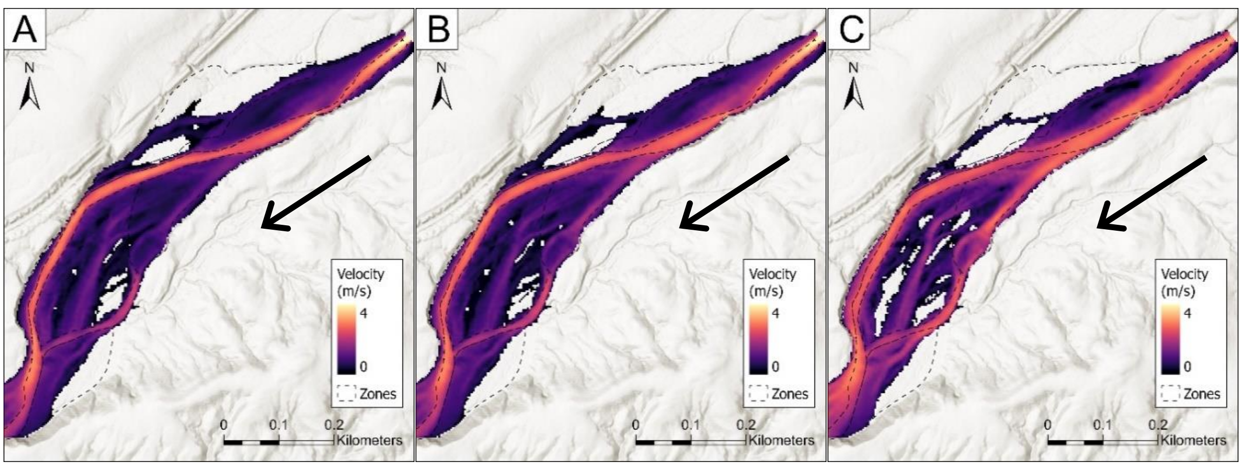

Figure 4.4. Velocity at peak discharge (timestep = 2 hours) for the calibrated jam model (A), the no-jam experiment (B), and the no-vegetation experiment (C). Arrow indicates direction of flow.

Artificially removing the roughness of jams resulted in minimal change to hydrologic conditions during the modeled runoff event (Figure 4.4B). In the experiment excluding jam roughness, ~ 179,900 m^2 (86% of total area) of floodplain and channel were inundated. High velocity flow was still mostly confined to the channel, with an average velocity of 2.46 m/s, compared to average velocities of 0.85 m/s and 1.19 m/s in the floodplain and jam regions, respectively (Table 4.2). Velocity distributions and inundation are very similar to the modeled run with jams.

In contrast, the no-vegetation experiment resulted in a larger change in hydrologic conditions (Figure 4.4C). Average velocity at peak inundation in the channel was 2.37 m/s, and average velocities in the floodplain and jam zones were 1.16 m/s (35% higher than the calibrated model) and 1.62 m/s (74% higher than the calibrated model), respectively (Table 4.2). Higher velocities in the floodplain and jam zones were also accompanied by higher standard deviations in velocity compared to the calibrated run and no-jam experiment, reflecting concentrated high-velocity areas in side-channels on the floodplain and jam zones. Higher floodplain velocities were coupled with a slightly smaller inundated area of 173,500 m^2 (83% of total area).

Table 4.2. Mean velocity and standard deviation of velocity in each model region at peak discharge (t = 2 hours) for each modeled scenario. Percent change in mean velocity is calculated based on the calibrated jam model.

Model Region	Scenario	Mean Velocity (m/s) [% Change]	Standard Deviation (m/s)
Channel	Jams	2.46	0.63
	No Jams	2.46 [+0%]	0.61
	No Veg	2.37 [-0.1%]	0.43
Floodplain	Jams	0.86	0.46
	No Jams	0.85 [-0.1%]	0.47
	No Veg	1.16 [+35%]	0.66
Jam Region	Jams	0.93	0.46
	No Jams	1.19 [+28%]	0.54
	No Veg	1.62 [+74%]	0.77

4.4.4. Modeled Erosion and Deposition

Significant deposition occurred at the upstream boundary of the model in all scenarios, likely due to the calculation of sediment supply in the absence of a known sediment discharge which results in significant entrainment and subsequent deposition at the upstream boundary. The upstream-most 150 m (~10 channel widths) of the modeling domain were excluded from sediment volume calculations, to ensure entrance effects were not skewing results. Entrance effects appear to only influence the upstream-most ~100 m of the modeled reach. However, by excluding the upstream-most 150 m, it can be ensured that sediment transport has equilibrated, and entrance effects are not skewing results. As with changes in hydrologic characteristics, changes in morphology over the course of the runoff event were similar between the calibrated model and the no-jam experiment (Figure 4.5A). Jams in the calibrated model resulted in more channel erosion (on the order of 0.1 m) and more (0.1 – 0.3 m) floodplain deposition (Figure 4.6A & B). However, volumes of eroded and deposited sediment were comparable between the calibrated model and no-jam experiment (Table 4.3). The volume of eroded and deposited sediment was calculated for each run by comparing the final bed configuration (t = 8 hours) to the initial bed elevation. Net change in sediment storage was similar between the calibrated model and no-jam experiment, with one notable exception being that the calibrated model resulted in more deposition in the jam zone than the no-jam experiment (Table 4.3).

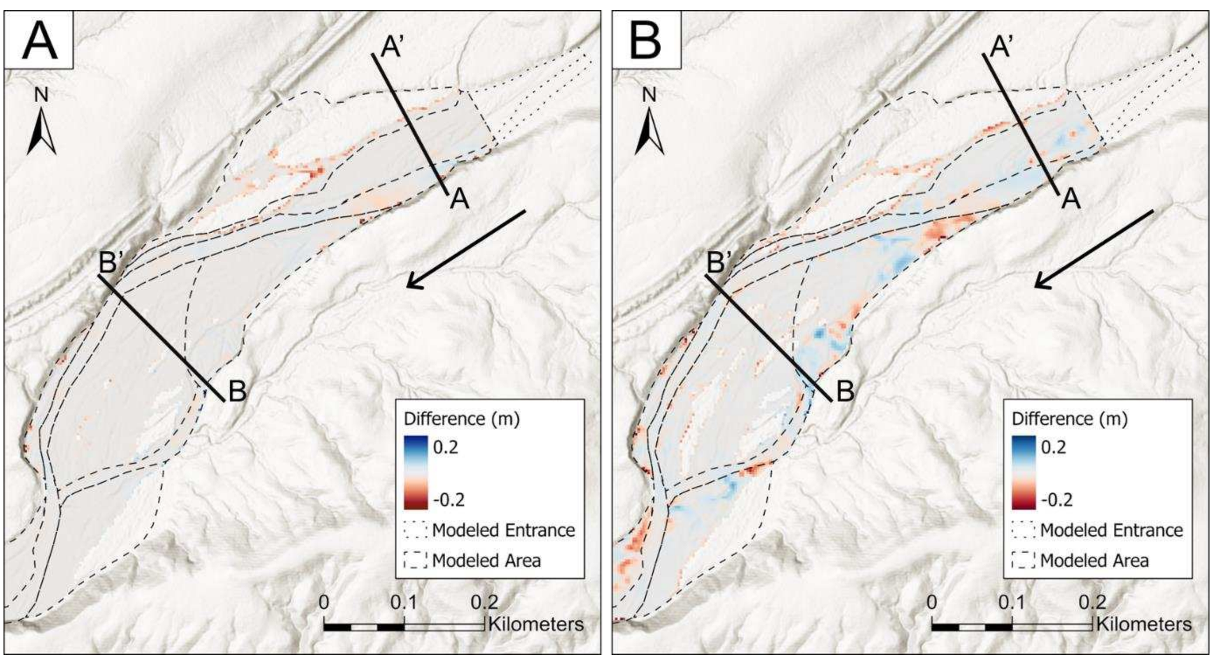

Figure 4.5. Differences in elevation at peak discharge (timestep = 2 hours) between the calibrated jam model and no-jam experiment (A) and no-jam experiment and no-vegetation experiment (B). Negative values indicate erosion with the removal of jams (A) or vegetation (B). Negative values indicate erosion with the removal of jams (A) or vegetation (B). Arrow indicates direction of flow.

Table 4.3. Total volume of erosion, deposition, and net change in each model region for each modeled scenario as well as the percentage of the study area in each region experiencing erosion or deposition. Values reflect final model configuration (t = 8 hours).

Model Region	Scenario	Erosion (m^3)	Deposition (m^3)	Erosion (% Area)	Deposition (% Area)	Net Change (m^3)
Channel	Jams	-474	208	59	39	-266
	No Jam	-456	180	54	45	-276
	No Veg	-416	250	51	48	-165
Floodplain	Jams	-39	235	24	45	+196
	No Jam	-36	235	20	47	+199
	No-Vegetation Experiment	-178	358	22	39	+180
Jam Region	Jams	-72	331	32	66	+260
	No Jam	-47	282	31	66	+235
	No Veg	-241	484	36	58	+244

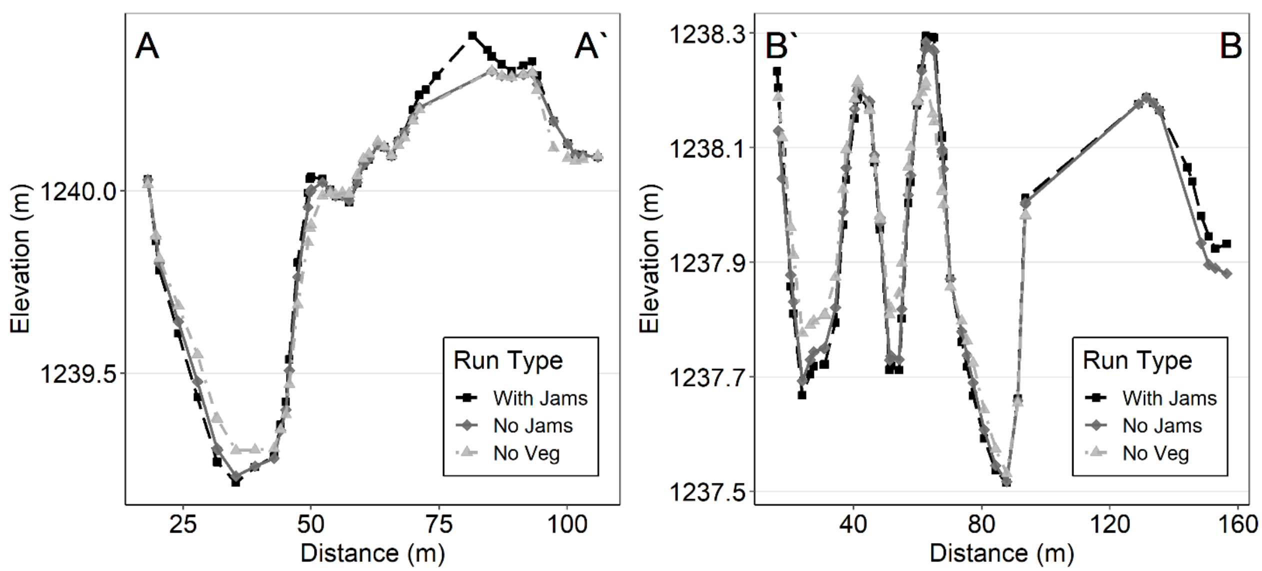

Figure 4.6. Elevation cross-sections at peak runoff (timestep = 2 hours) at two locations within the study area. Cross-section locations are shown in Figure 4.5.

In contrast, the differences between the no-jam experiment and the no-vegetation experiment are larger (Figure 4.5B). The removal of vegetation resulted in less net channel erosion and less net floodplain deposition compared to the vegetated runs (calibrated model and no-jam experiment; Table 4.3). Higher volumes of erosion outside the channel in the no-vegetation experiment were also coupled with higher rates of deposition, resulting in comparable net change to the vegetated experiments, despite greater sediment instability (Table 4.3). High rates of deposition are likely due to a higher calculated sediment flux in the no-vegetation experiment (Figure 4.7), which may be a result of increased sediment mobility due to higher velocities in the jam and floodplain regions of the model (Table 4.2). Overall, the no-vegetation experiment resulted in shallower and slightly narrower channels and lower floodplains than the vegetated scenarios (Figure 4.6).

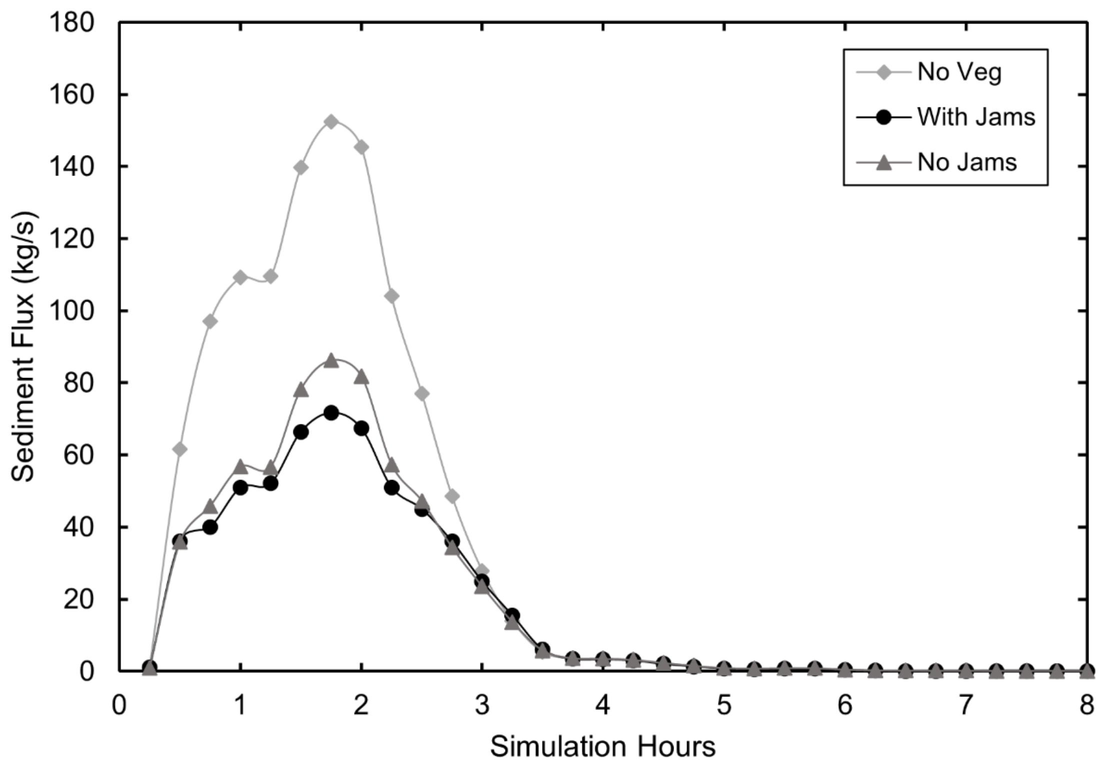

Figure 4.7. Time series of sediment flux at cross-section A-A' for the calibrated model (with jams), no-jam experiment (no jams), and no-vegetation experiment (no veg).

4.5. Discussion

4.5.1. Patterns of Erosion and Deposition with LW and Vegetation

Vegetation and LW worked in tandem to effectively confine flow, resulting in high velocity in the main channel in the calibrated jam scenario. However, the basic template of channel change – wider and deeper channels – is likely driven by the roughness of vegetation in the Walnut Gulch study reach, based on the more substantial changes between the vegetated scenarios and the no-vegetation experiment (Figures 4.5 & 4.6). The additional roughness of jams on top of vegetation resulted in minor (±0.1- 0.3 m) enhancement of floodplain deposition and channel scour while still resulting in similar post-flood topography (Figure 4.6).

Although the inclusion of jams still resulted in net sediment storage in the floodplain and throughout the reach, the added roughness of jams resulted in increased erosion in the channel (Table 4.3). The effect of jams increasing sediment transport and scour due to flow concentration has been shown in prior field (Keller and Swanson, 1979; Abbe and Montgomery, 2003) and modeling studies (Cherry and Beschta, 1989; Schalko et al., 2019) for sand-bed perennial rivers. Greater channel erosion was also coupled with greater channel deposition in the calibrated jam model compared to the no-jam experiment, which is consistent with prior studies that document significant deposition upstream of LW accumulations in perennial rivers (Bilby, 1981; Nakamura and Swanson, 1993; Abbe and Montgomery, 2003; Faustini and Jones, 2003; Short et al., 2015). However, the result of net channel erosion even in the calibrated jam model is likely a result of the location of LW in our study area. Only 6% of jams were found in the channel, whereas previous studies have focused on the effect of sediment deposition around in-channel LW. In contrast, our study found the majority (94%) of jams outside of the channel region, where few studies have documented the magnitude of sediment deposition behind or around LW accumulations during floods. For example, in forested perennial streams in England, Jeffries et al. (2003) documented ~ 0.5 m of deposition associated with LW jams, and Sear et al. (2010) measured up to 0.16 m of sedimentation behind LW accumulations annually. Based on these comparisons with humid perennial floodplains, jams in the calibrated model resulted in similar magnitudes of additional sedimentation on the floodplain in Walnut Gulch (Figure 4.6A).

In dryland ephemeral streams, field studies have also found that riparian vegetation can increase in-channel velocity and drive scour in main and secondary channels during large floods (Graeme and Dunkerley, 1993; Wende and Nanson, 1998; Merritt and Wohl, 2003). Therefore, similarities in topography and net erosion/deposition between the two vegetated scenarios (the jam model and no-jam experiment) are expected, given that both LW and vegetation result in similar channel change. The result of vegetation driving channel morphology is also expected, given that vegetation covers ~ 31% of the reach area compared to 0.1% of area covered by jams and that 91% of jams were deposited in association with vegetation.

In the no-vegetation experiment, increased velocity on the floodplain and decreased velocity within the main channel facilitated significant sediment deposition outside of the channel region (Table 4.3). Significant sediment deposition has been recorded in wide or braided perennial and ephemeral dryland streams during high magnitude, long recurrence interval floods due to a loss of transport capacity (e.g., Friedman et al., 1996; Merritt and Wohl, 2003). As roughness values shift in the no-vegetation experiment to mimic those of the channel across the entire reach, there is ample energy available to transport sediment-laden flows into the floodplain where energy dissipates and sediment is deposited, suggesting topography itself is a significant factor influencing sedimentation in ephemeral streams. Smaller magnitude flows that are confined to a single, narrower channel can subsequently erode sediment deposited during larger floods (e.g., Friedman et al., 1996). However, given a decrease in transport capacity in wide, braided ephemeral reaches during large flows, significant amounts of LW and CPOM deposition from upstream vegetated areas in the watershed can be expected. LW and CPOM can trap moisture and stabilize sediment, providing prime locations for seedling establishment (Pettit et al., 2005), thus increasing the vegetated area. Increased vegetation would provide increased LW inputs – due to falling limbs or tree mortality – and create future trapping sites for new LW accumulations. As shown in this study, LW enhances the process of floodplain deposition and channel scour created by vegetation. Therefore, deposition associated with a no-vegetation scenario could eventually lead to channel erosion during floods, as LW facilitates a transition back to a vegetated scenario further stabilized by jams (Figure 4.8).

The scenario of an unvegetated reach and wide, sandy channel is not unfamiliar in Walnut Gulch. Aerial imagery and cross-sectional topographic surveys from the mid-20th century show that the reach upstream of Flume 1 was largely unvegetated, with a much wider channel corridor. Vegetation density has increased throughout the reach since the 1930s, concurrent with a decrease in the magnitude of annual peak discharges and increase in precipitation during non-summer months (Nichols et al., 2002; Nichols et al., 2005).

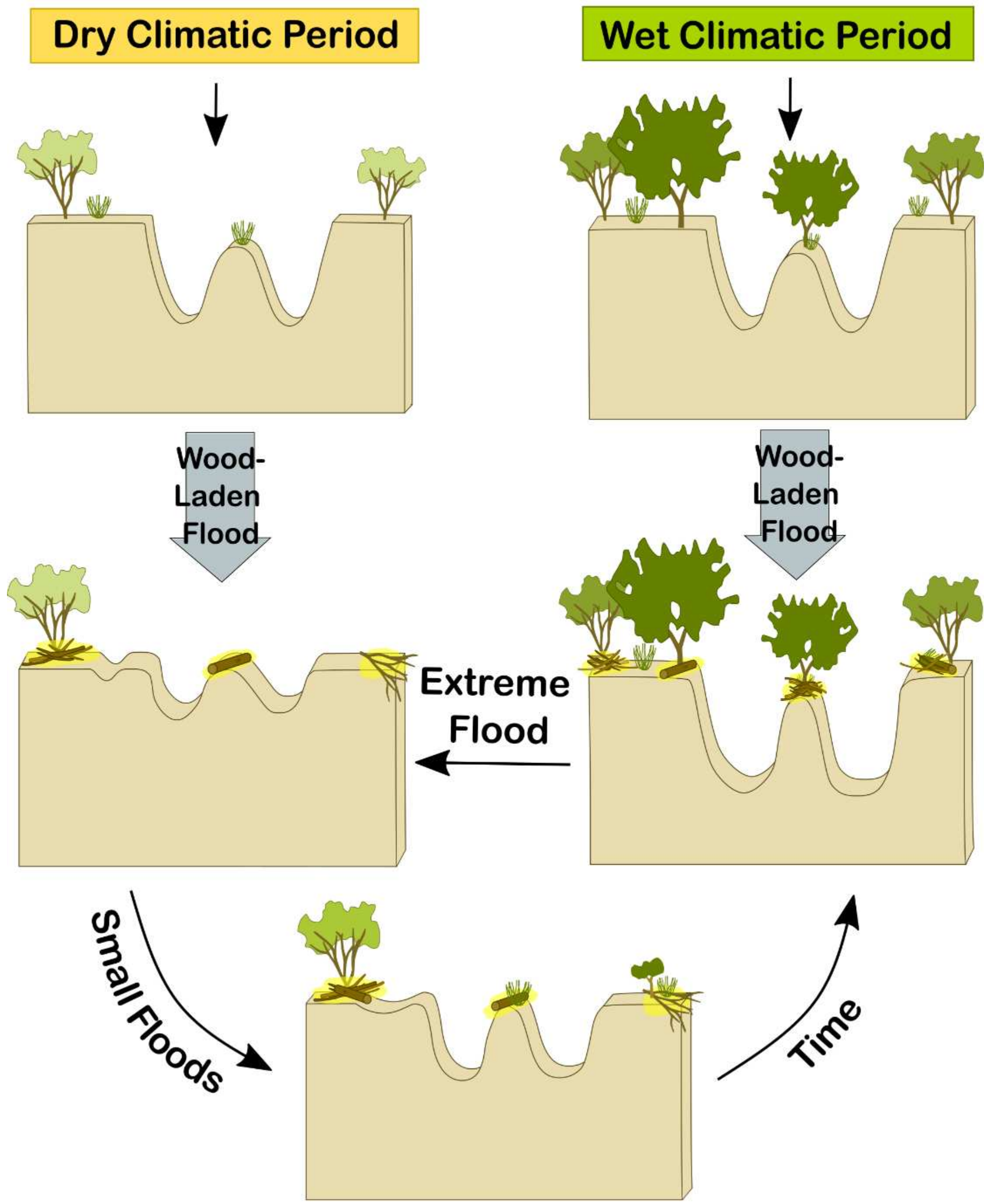

Figure 4.8. Conceptual diagram showing deposition potential and channel change following a moderate, wood-laden flood. Under wet climatic conditions with healthy vegetation, large wood would be trapped on vegetation trunks, leading to increased riparian roughness and deeper and wider channels. Under dry climatic conditions, where vegetation has begun to die back and riparian roughness is low, runoff would likely spread evenly across the reach, resulting in massive deposition. In this scenario, deposition of large wood and CPOM could provide sites of increased moisture and nutrients for seedling establishment, thus encouraging vegetation growth. Over time and subsequent small floods, this could provide positive feedback leading to denser and healthier vegetation. Extreme floods could uproot vegetation and reset the reach.

Dryland streams in general go through wet and dry phases, with morphology based on climate (Burkham, 1972; Graf, 1988). Wet phases are defined by years to decades of above average precipitation, while dry phases are characterized by below average precipitation. (Nanson and Croke, 1992; Manners et al., 2014). During wet phases, vegetation thrives, and more frequent moderate to low magnitude floods do not readily remove vegetation or rework the floodplain. Dry phases result in vegetation dieback, and intermittent large floods are able to significantly erode the channel and floodplain, effectively widening the unvegetated channel. In either phase, a sufficiently large flood may reset the river corridor by removing vegetation and widening the channel (Friedman et al., 1996; Friedman and Lee, 2002). Increased vegetation density upstream of Flume 1 in WGEW since the 1930s – concurrent with increased precipitation in the watershed –has led to effective channel narrowing, with the development of more expansive vegetated floodplains (Nichols et al., 2005). Although our models suggest that the 2017 flood was large enough to widen the channel, stability provided by vegetation and enhanced by jams prevented topographic reset in the form of significant erosion or deposition. Our study reach therefore provides an example of the stability provided by vegetation and LW in ephemeral streams during relatively wet climatic periods (Figure 4.8).

4.5.2. Modeling Limitations

Modeling results can be explained and supported by prior field studies in both perennial and ephemeral dryland watersheds, suggesting that the model outputs are reasonable and interpretable. Given the traditional difficulty in collecting data during flash floods (Borga et al., 2014), a modeling approach can provide the benefit of a first-order approximation of the morphodynamic influence of LW in an ephemeral stream, compared to the more well-known influence of vegetation. Still, limited field data prevent the models presented in this study from being fully validated with other flow events, meaning that model parameters could not be applied to a different discharge event or watershed without further calibration. Additionally, the scale at which modeling can be conducted is dependent on the scale of topographic inputs and computational power. To reduce complexity in the model, jams were estimated by generally increasing roughness in large areas of concentrated jam deposition, which is consistent with hydrological models developed for LW in perennial rivers (Addy and Wilkinson, 2019). However, the surface area covered by jams is minimal in Walnut Gulch, and the influence of individual LW jams (particularly local sedimentation and scour) occurs on too fine a scale to be captured by this model. Instead, our model represents potential reach-scale changes which can have implications for macro-scale sediment transport and river corridor morphology. Future studies monitoring the persistence of LW jams and high-resolution sedimentation and erosion around LW in ephemeral streams could provide more insight into micro-scale geomorphic changes and habitat associated with jams and LW.

4.5.3. Impact of Sediment Dynamics on Dryland Ecosystems

The majority of rivers globally are non-perennial (Messager et al., 2021), and in the American Southwest, up to 80% of the river network is estimated to be ephemeral or intermittent (Levick et al., 2008). Ephemeral streams are important sources of water, nutrients, and sediment to downstream perennial rivers and waterbodies (Goodrich et al., 2018). Excess sediment delivery from ephemeral streams can have a negative impact on water quality, waterway health, and reservoir sedimentation (Sandercock and Hooke, 2011). However, sediment is also a necessary resource for the creation of key fluvial features (i.e., bars, which are useful for both recreation and habitat) and for the creation of fresh alluvial surfaces necessary for the establishment of many riparian trees (Hupp and Osterkamp, 1996; Kemper et al., 2021).

Ultimately, the balance between storage and erosion of sediment from ephemeral streams such as Walnut Gulch can have important implications for downstream ecosystems and watershed-scale management.

In addition, local erosion and deposition can affect vegetation health and habitat within a reach. Sediment deposition is necessary for the establishment of many riparian pioneer species, but excess sedimentation can cause tree mortality and limit seedling survival (Levine and Stromberg, 2001; Kui and Stella, 2016). Erosion can prevent vegetation burial, but excess scour can uproot and remove vegetation (Rominger et al., 2010). Therefore, the balance between erosion and deposition matters for local, reach-scale ecosystems as well.

The calibrated jam model was more stable (resulted in lower volumes of erosion and sedimentation) than the no-vegetation experiment, yet more active (greater net sediment accumulation) than the no-jam experiment (Table 4.3), suggesting that jams could help maintain the balance between scour and deposition that supports local and downstream ecosystems in ephemeral watersheds. Sediment stability around LW and CPOM jams can additionally support biota. LW and CPOM accumulations are relatively stable compared to mobile, sandy beds and can retain moisture for longer post-flow, thus providing valuable habitat for aquatic invertebrates (Ward et al., 1982; Chester and Robson, 2011). On floodplains and surfaces inundated less frequently, LW and CPOM piles can also be colonized by lizards, rodents, and desert turtles (Bulhmann et al., 2009). Therefore, LW and CPOM jams in Walnut Gulch could provide multiple ecosystem benefits beyond impacts to channel morphology.

4.6. Conclusion

The presence of LW and CPOM jams in dryland ephemeral streams has been documented globally, but a quantitative assessment of the morphodynamic impact of LW has been lacking. Morphodynamic modeling provides a useful framework by which hydro- and morphodynamics can be estimated in flash flood-dominated systems, such as Walnut Gulch. Modeling revealed that LW creates similar channel changes as vegetation. Primarily, LW jams and vegetation help confine high velocity flows, leading to deeper and wider channels. The additional roughness of LW increased channel scour and floodplain deposition by +/- 0.1-0.3 m. Results suggest that LW jams could enhance sediment mobility in the channel and sediment stability in the floodplain along ephemeral channels, which can have implications for local and downstream ecosystems.

4.7. References

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CHAPTER 5: CONCLUSIONS

5.1. Key Findings and Implications

Ephemeral river corridors – particularly floodplains – are sinks and sources of sediment, water, and nutrients in drylands. Ephemeral stream floodplains share these characteristics in common with perennial rivers, but the extent and duration of storage and change are markedly different. Flashy streamflow and high sediment load in ephemeral streams and their surrounding floodplains have cascading impacts on the chemistry and ecology of ephemeral river corridors and drylands in general. Prior work has largely not identified the importance of floodplains separate from ephemeral stream channels, and many prior studies have lumped the two aspects of the river corridor together given that both are variably inundated systems. However, research presented here emphasizes the importance of ephemeral stream floodplains separate from that of the channel. Particularly, the ubiquity of ephemeral streams – commonly the vast majority of rivers by length in drylands – emphasizes the potential importance of the functions provided by their floodplains.

Functions are thought to be related to physical and ecological complexity, including geomorphic heterogeneity, which is indicative of variations in topography and grain size that can drive differences in inundation, saturation, and biota. Geomorphic heterogeneity – including the density, diversity, and evenness of geomorphic units – varies across watersheds, driven by patterns in floodplain width, planform, grain size, and channel change. In contrast to the hypothesis that inputs via floods would drive heterogeneity, floodplain width exerted the greatest importance for predicting both density and diversity of units, thus suggesting that flow regime has a lesser impact on heterogeneity. Metrics of heterogeneity in the selected ephemeral sites were comparable in magnitude to prior studies in perennial river corridors. However, influxes of sediment, water, and organic matter were estimated via proxies in this study, and direct measurements may help elucidate the relationship between floods and heterogeneity in non-perennial river corridors.

In the absence of direct flood observations, morphodynamic modeling was used to investigate the relationships between floods, large wood, vegetation, and reach-scale morphology. Experimental models showed that interactions between vegetation and streamflow, in particular, are driving hydraulics in the channel and on the floodplain, which in turn influences erosion, deposition, and general channel stability. Hydraulic roughness associated with vegetation confined high velocity flows to the main channel, causing greater in-channel scour and allowing low velocity flows to spread across the floodplain. In the absence of vegetation, the main channel widened, causing erosion of stable bars and sedimentation in secondary channels. Large wood adds to the template set by vegetation by creating additional stability on the floodplain via deposition.

Results have implications for the management and protection of floodplains along ephemeral streams in drylands globally. Wider floodplains could be hotspots of habitat, storage, and productivity in non-perennial watersheds. Floodplain vegetation in these reaches could particularly influence sediment dynamics and heterogeneity. Management and restoration efforts could therefore be targeted in wide, forested reaches to protect desirable functions; for example, grazing exclosures to protect riparian vegetation. Future work could help additionally explore some of the relationships found here to further constrain best practices for protecting ephemeral stream floodplains and their associated functions.

5.2. Opportunities for future work

Future work is needed to further elucidate the relationship between geomorphic heterogeneity, floodplain function, and potential drivers not measured here. Fundamentally, questions remain as to what aspect of heterogeneity (e.g., stratigraphic, topographic, vegetative, etc.) or metrics (e.g., evenness, diversity, or patch density) sustain core ecosystem functions (e.g., infiltration, uptake of nitrogen, etc.) in ephemeral stream floodplains. Studies that explicitly connect heterogeneity aspects and metrics to floodplain functions could inform what types of heterogeneity should be monitored in the future to assess river corridor health.

Additionally, more work is needed to fully understand the impact of disturbances (i.e., flash floods) on geomorphic heterogeneity. Although channel change over time suggests that disturbance could be an important factor, direct measurements of geomorphic context were more important for determining heterogeneity. Modeling provides one outlet for better understanding the impact of streamflow on floodplain morphology and geomorphic heterogeneity, but limited data collected prior to, during, and following flash floods prevent the modeling of a greater range of flood frequencies and magnitudes. Future studies are therefore needed to better constrain the importance of the natural flow regime in ephemeral streams for determining reach-scale heterogeneity and subsequent floodplain function. Given that high energy, stochastic events like flash floods are difficult to measure and monitor, understanding the linkages between flow regime and floodplain morphology could further the application of geomorphic heterogeneity as a metric for monitoring long and short-term disturbance in dryland watersheds.

In the future, ephemeral river corridors will increasingly be impacted by stressors such as climate and land use change. However, there is limited research that shows the effect of such stressors, such as drought and urbanization, on the functioning and form of ephemeral stream floodplains, including the impact on heterogeneity metrics. Without knowing expected directions and magnitudes of potential future changes due to anthropogenic pressures, management is limited to responding to changes rather than anticipating. Further research on expected changes could encourage proactive adaptation and restoration, although studies investigating the impact of stream restoration on ephemeral floodplains (and particularly, the impact on heterogeneity) are likewise limited. Long-term monitoring studies are needed to understand the lasting physical impact of impairment, management, and restoration on ephemeral stream floodplains.

The function and form of ephemeral stream floodplains has only just begun to be understood as it has for perennial rivers. Future research and watershed management need to consider the importance of floodplains separate from variably inundated channels and rarely saturated uplands in non-perennial watersheds in order to protect their vital resources in a changing world.

APPENDIX A: GEOMORPHIC UNIT CLASSIFICATIONS

Group	Description	Class	Region(s) Present
Floodplain Surface	Floodplain surfaces are relatively planar areas adjacent to the channel(s) that are separated by a bank. Multiple floodplain surfaces existed varying in character based on grain size and vegetation cover class. Additionally, channelized floodplains are hummocky features characterized by multiple cross-cutting channels <1-m in width, therefore not classified separately.	Fine, Unvegetated Floodplain Coarse, Unvegetated Floodplain Herbaceous Floodplain Shrub Floodplain Forested Floodplain Channelized Floodplain	CANY, GSENM GSENM CANY, GSENM, WGEW CANY, GSENM, WGEW CANY, GSENM CANY
Channel	Channels are low-lying and largely unvegetated areas with evidence of flow conveyance, typically separated from other features by a bank.	Main Channel Secondary Channel Swale Headcut	CANY, GSENM, WGEW CANY, GSENM, WGEW CANY, GSENM GSENM
Bar	Bars are crescent or oblong shaped features elevated from yet sloping towards channels. Two main types of bars are identified: point bars which are attached to banks or floodplain surfaces, and longitudinal bars which are surrounded by channel surfaces.	Fine Point Bar Coarse Point Bar Herbaceous Point Bar Shrub Point Bar Herbaceous Longitudinal Bar Forested Longitudinal Bar Shrub-dominated Longitudinal Bar	CANY, GSENM CANY, GSENM CANY, GSENM, WGEW CANY, GSENM GSENM, WGEW GSENM, WGEW CANY, GSENM, WGEW
Levee	Levees are elevated, convex features adjacent to channels.	Levee	CANY, GSENM, WGEW

Group	Description	Class	Region(s) Present
Floodplain Bench	Benches are planar, inset features typically crescent shaped and lower than a floodplain surface yet distinct from channels and bars.	Unvegetated Bench Herbaceous Bench Shrub Bench Forested Bench	GSENM CANY, GSENM CANY, GSENM, WGEW CANY
Riparian	Riparian areas are as vegetated longitudinal features adjacent to a channel or bar and typically lower than floodplain surfaces.	Riparian Forest	CANY, GSENM, WGEW
Backswamp	Backswamps are concave features, typically with increased moisture, separated from channels by a levee or floodplain	Backswamp	CANY, GSENM, WGEW
Relict	Relict floodplains are features there are no longer active (i.e., elevated from the current river corridor) but surrounded by floodplain features.	Shrub-Dominated Terrace Inselberg	CANY, GSENM GSENM

APPENDIX B: OPTICALLY STIMULATED LUMINESCENCE DATING PROTOCOLS AND EQUIVALENT DOSE DISTRIBUTIONS

B.1. Supplementary Methods and Results for Optically Stimulated Luminescence Dating

All samples were opened and processed under dim amber safelight conditions within the lab. Sample processing for quartz optically stimulated luminescence (OSL) dating followed standard procedures involving sieving, HCl and bleach treatments, heavy mineral separation at 2.72 g/cm^3, and acid treatments with HCl and HF to isolate the quartz component of a narrow grain-size range, 150-250 µm. The purity of the quartz samples was checked by measurement with infra-red stimulation to detect the presence of feldspar.

The USU Luminescence Lab follows the latest single-aliquot regenerative-dose (SAR) procedures for single-grain (SG) OSL dating of quartz sand (Duller et al., 1999; Murray and Wintle, 2000, 2003; Wintle and Murray, 2006; Duller, 2008). The SAR protocol includes tests for sensitivity correction and brackets the equivalent dose (D_E) the sample received during burial by irradiating the sample at three different doses (above the D_E, a zero dose and a repeated dose to check for recuperation of the signal and sensitivity correction). The resultant data are fit with a linear regression for young sediments. Cumulative D_E is calculated on the Minimum Age Model (MAM) of Galbraith and Roberts (2012). The SG-OSL age is reported at 2σ standard error and is calculated by dividing the D_E (in grays, gy) by the environmental dose rate (gy/ka) that the sample has been exposed to during burial.

Dose-rate calculations were determined by chemical analysis of the U, Th, K and Rb content using ICP-MS and ICP-AES techniques and conversion factors from Guérin et al. (2011). The contribution of cosmic radiation to the dose rate was calculated using sample depth, elevation, and latitude/longitude following Prescott and Hutton (1994). Dose rates are calculated based on water content, sediment chemistry, and cosmic contribution (Aitken and Xie, 1990; Aitken, 1998).

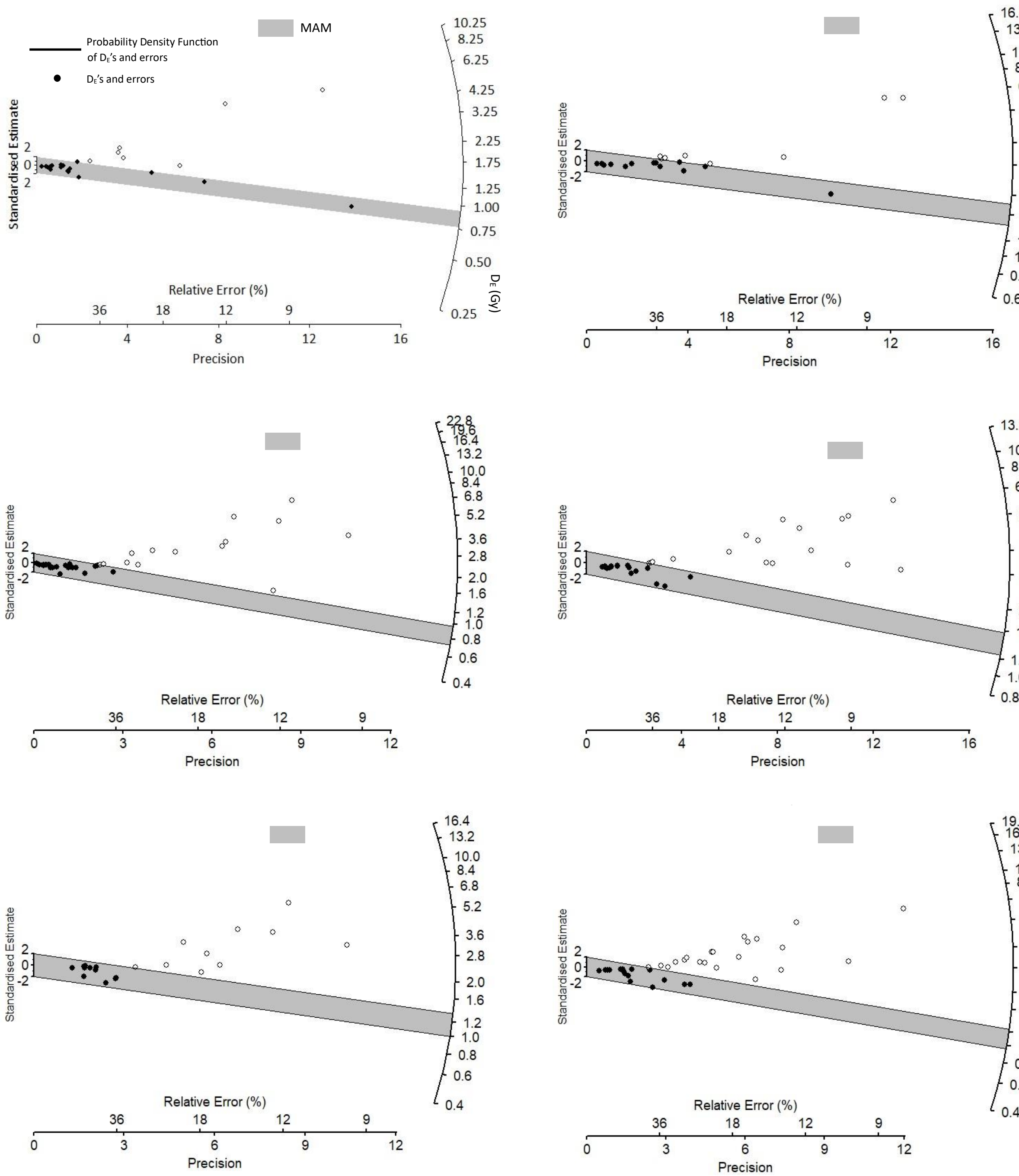

Figure B1. Equivalent dose (DE) distributions, including the probability function, radial plots, and -overdispersion (OD), for (A) TB-OSL 1, (B)HD-OSL 1, (C) DB-OSL 1, (D) I3-OSL, (E)DB-OSL 2, (F) I4-OSL.

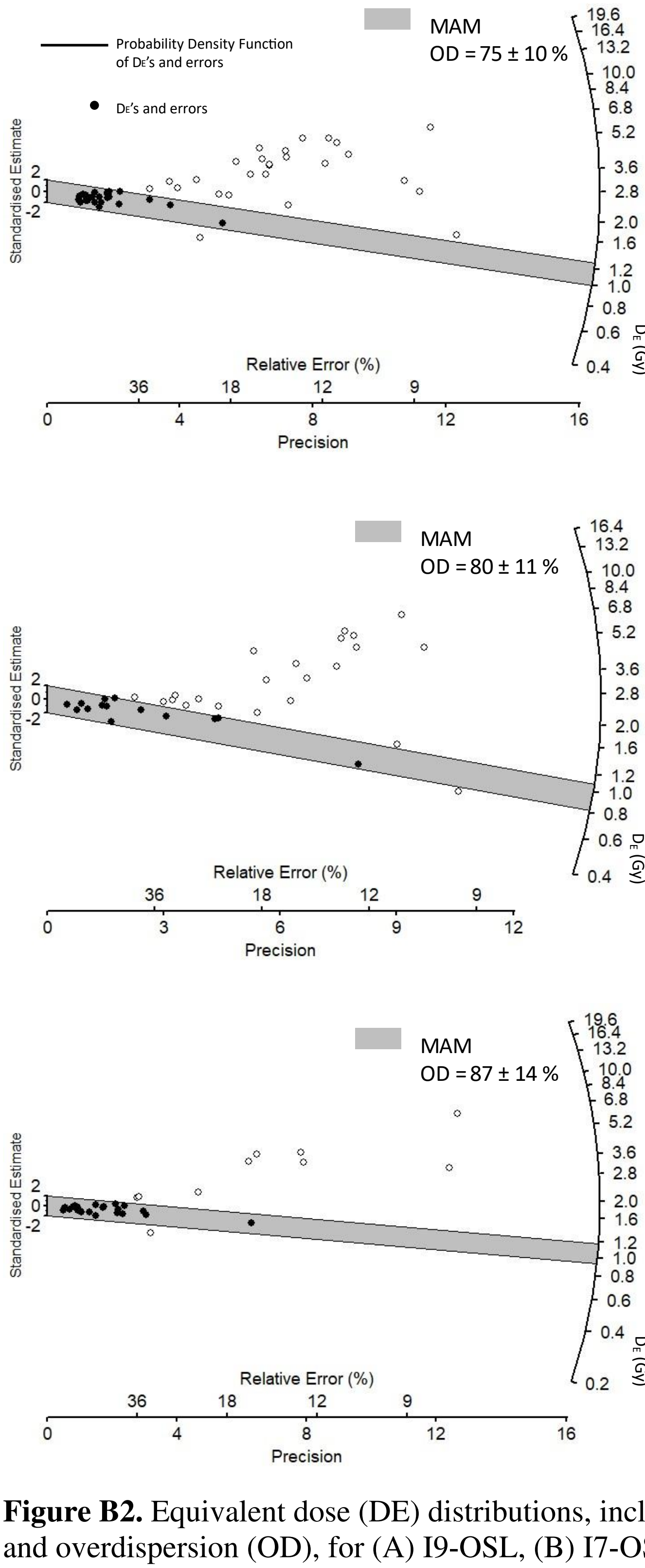

Figure B2. Equivalent dose (DE) distributions, including the probability function, radial plots, and overdispersion (OD), for (A) I9-OSL, (B) I7-OSL1, (C) and I7-OSL2.

APPENDIX C: MORPHODYNAMIC MODEL CALIBRATION

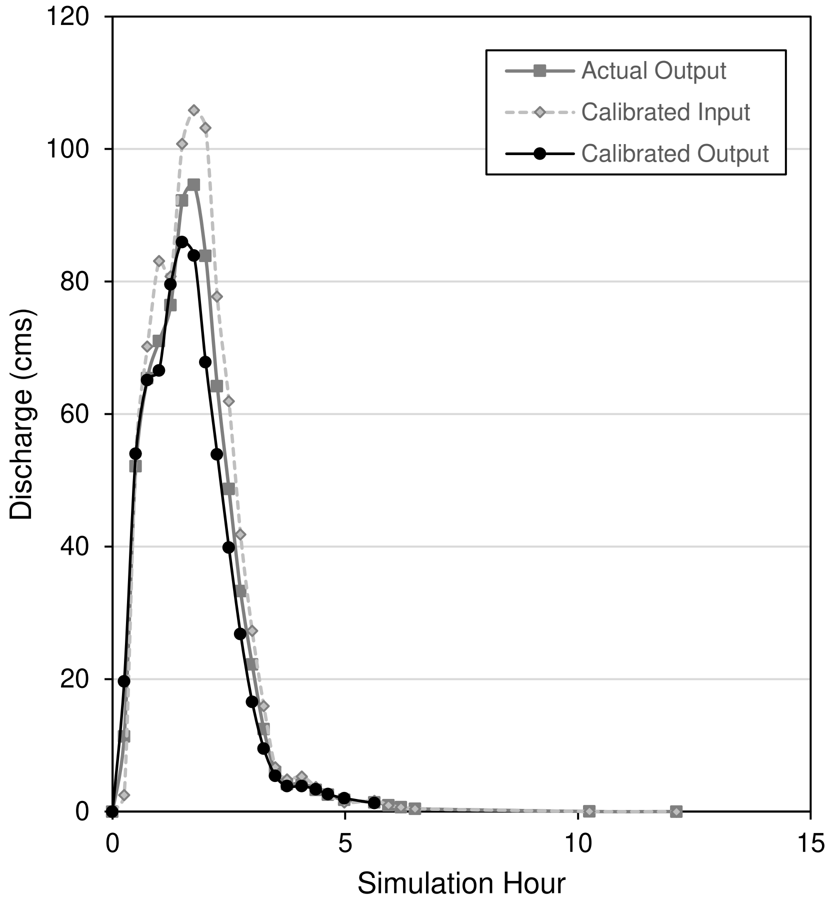

Figure C1. Calibrated input and output hydrograph used in the model compared to the actual output measured at Flume 1.

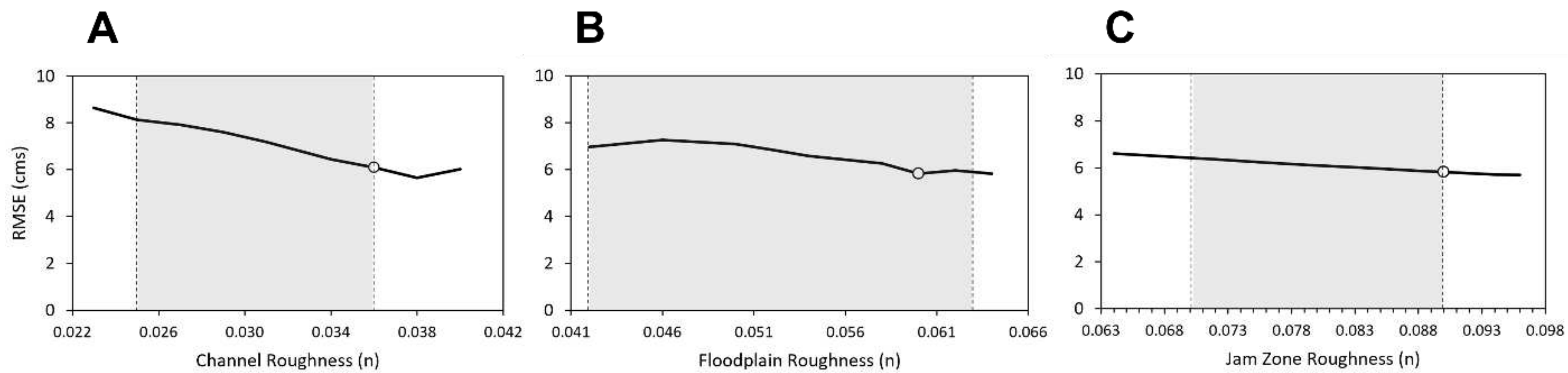

Figure C2. Root mean square error for the resulting hydrograph based on manning n values of (A) the channel, (B) the floodplain, and (C) the jam zones. The n values used for each region in the calibrated model are indicated by the marker. Acceptable ranges are shaded.

Table C1. Sediment equations and active layer thickness combinations that were used to calibrate modeled sediment transport.

Run	Sediment Equation	Active Layer Thickness (L_a)
1	Meyer-Peter & Muller	1.0
2	Meyer-Peter & Muller	2.0
3	Meyer-Peter & Muller	3.0
4	Engelund & Hansen	1.0
5	Engelund & Hansen	2.0
6	Engelund & Hansen	3.0

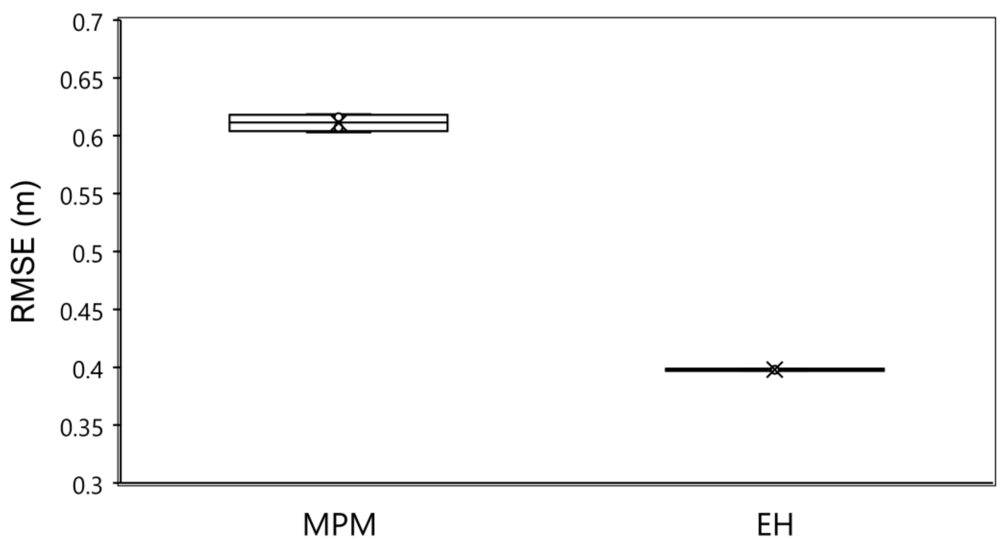

Figure C3. Error values for model runs of varying active layer thicknesses using the Meyer-Peter-Muller (MPM) and Englund-Hansen (EH) sediment transport equations.

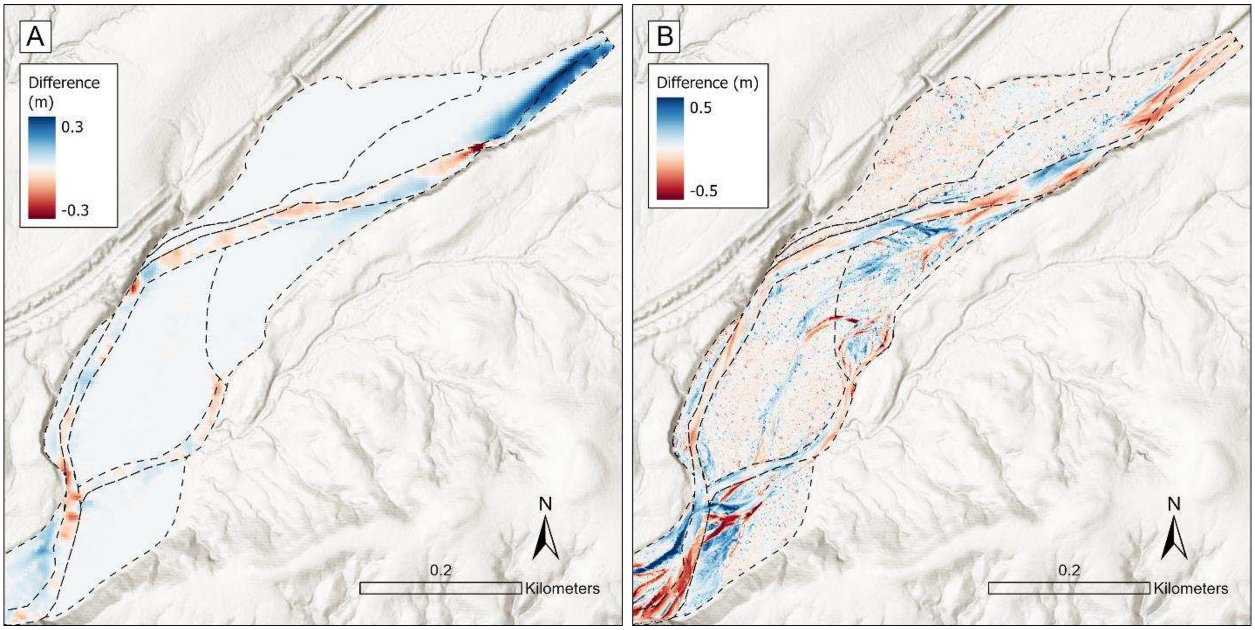

Figure C4. Comparison between modeled elevation change over the course of the calibrated model (A) and actual elevation differences between 2015 and 2018 in the study area (B).