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OVERVIEW

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An overview of the hydrology of non-perennial rivers and streams

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Abstract

Non-perennial rivers and streams are ubiquitous on our planet. Although several metrics have been used to statistically group or compare streamflow characteristics, there is currently no widely used definition of how many days or over what reach length surface flow must cease in order to classify a river as non-perennial. At the same time, the breadth of climate and geographic settings for non-perennial rivers leads to diversity in their flow regimes, such as how often or how quickly they go dry. These rivers have a rich and expanding body of literature addressing their ecologic and geomorphic features, but are often said to be ignored by hydrologists. Yet there is much we do know about their hydrology in terms of streamflow generation processes, water losses, and variability in flow. We also know that while they are prevalent in arid regions, they occur across all climate types and experience a diverse set of natural and anthropogenic controls on streamflow. Furthermore, measuring and modeling the hydrology of these rivers presents a distinct set of challenges, and there are many research directions, which still require further attention. Therefore, we present an overview of the current understanding, methodologic challenges, knowledge gaps, and research directions for hydrologic understanding of non-perennial rivers; critical topics in light of both growing global water scarcity and ever-changing laws and policies that dictate whether and how much environmental protection these rivers receive.

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arid zone hydrology, dryland hydrology, ephemeral stream, groundwater recharge, intermittent river

1 | INTRODUCTION

Approximately half of the world's flowing waterways (e.g., streams and rivers) are categorized as non-perennial, meaning they do not have continuous surface water flow throughout the year (Datry, Bonada, & Boulton, 2017; Datry, Larned, & Tockner, 2014). Rivers in semi-arid and arid landscapes (i.e., dryland rivers) are perhaps the most well-known members of this group (Costigan et al., 2017; Sheldon et al., 2010). However, non-perennial rivers are not unique to drylands but are found in a wide variety of environments from the headwaters of mountain or alpine watersheds (Jensen, McGuire, McLaughlin, & Scott, 2019) to the lowlands (Zimmer & McGlynn, 2017). They are also characteristic of seasonally frozen regions such as glaciated or permafrost areas (Watson, Kooi, & Bense, 2013; Welch et al., 2003), as well as karst environments, where flows originate or move into subsurface tubes (Bonacci, Terzić, Roje-Bonacci, & Frangen, 2019).

Given this diversity of landscapes that support non-perennial flow, it is unsurprising that these rivers are known by many names (Busch et al., 2020). Common terms for them are "intermittent," typically referring to seasonal flow, and "ephemeral" when flows are short and in direct response to precipitation (Costigan, Jaeger, Goss, Fritz, & Goebel, 2016). However, "arid" (Hay, Jenkins, & Kingsford, 2018), "temporary" (von Schiller et al., 2011), "dry" (Steward, von Schiller, Tockner, Marshall, & Bunn, 2012), and "seasonal" (Keller et al., 2019) are also common throughout the literature, as are a wide range of regional names. Moreover, flowing surface waters of all sizes, from small streams to wide, powerful rivers can be non-perennial (and therefore stream and river are used interchangeably herein). This spectrum of terminology can be confusing for nonscientists and scientists alike (Shanafield, Godsey, et al., 2020); however, the same basic hydrological concepts universally apply.

In both dryland and humid environments, non-perennial rivers host diverse aquatic and riparian ecosystems (Datry et al., 2014; Katz, Denslow, & Stromberg, 2012; Stubbington, England, Wood, & Sefton, 2017) and perform a variety of critical ecosystem services, including hydrologic connection between perennial river reaches or with the aquifer (e.g., groundwater recharge), transport of biota, materials, nutrients and water within the landscape, and habitat for humans and other animals (Acuña, Hunter, & Ruhí, 2017; Datry et al., 2018; Koundouri, Boulton, Datry, & Souliotis, 2017; Yeakley et al., 2016). For example, suspended sediment concentrations range from 35 to 1,700 times higher in non-perennial systems than in perennial systems (Reid & Frostick, 1987). Streambed infiltration during periodic flow serves as the primary source of recharge to aquifers in dryland catchments environments (Niswonger, Prudic, Pohll, & Constantz, 2005; Shentsis & Rosenthal, 2003; Sorman & Abdulrazzak, 1993; Subyani, 2004) and also contributes to the water balance in humid environments (Zimmer & McGlynn, 2017). Estimates of seasonal streamflow in glacially fed rivers and streams can provide information on how quickly glaciers are melting, contributing to our understanding of global climate change (Bring, Shiklomanov, & Lammers, 2017).

A rich history of research in related disciplines provides critical foundational information about non-perennial rivers from which hydrologists can build from. For example, the study of fluvial geomorphology is rooted in dryland rivers (Tooth, 2000) and there have been a wide variety of studies quantifying the endemic flora and fauna of dryland systems (Bogan, Leidy, Neuhaus, Hernandez, & Carlson, 2019; Katz et al., 2012; Pusey, Kennard, Douglas, & Allsop, 2018; Romaní et al., 2017; Stromberg, Setaro, Gallo, Lohse, & Meixner, 2017). Although the ecological understanding of non-perennial rivers is quite extensive, these rivers have been historically under-represented in the hydrologic literature, with the weight of our research placed on understanding how perennial rivers function (Bishop et al., 2008; Datry et al., 2018; Steward, Negus, Marshall, Clifford, & Dent, 2018; Williams, 1988). Indeed, many of the seminal papers on the hydrology of non-perennial rivers have been written by ecologists (e.g., Arthington & Pusey, 2003; Dodds, 1997; Kennard et al., 2010; Poff, 1996; Poff et al., 1997; Puckridge, Sheldon, Walker, & Boulton, 1998; Stanley & Boulton, 1993) as a framework in which to aid in the contextualization of the ecology. This lack of hydrologic focus is partly because many of the common methods used for monitoring and data collection in river systems are not appropriate in these often flashy, highly dynamic non-perennial systems, and data analysis must take into account physical processes that may not be dominant in perennial systems (Gutiérrez-Jurado, Partington, Batelaan, Cook, & Shanafield, 2019; Ye, Jakeman, & Young, 1998). In fact, many streamflow gaging stations are preferentially located on perennial rivers worldwide (De Girolamo, Lo Porto, Pappagallo, Tzoraki, & Gallart, 2015; Eng, Wolock, & Dettinger, 2016). For example, 3% of US Geological Survey gaging stations report periods of zero flow regularly and 20% of gaging stations in the Global Runoff Data Center network report zero flow regularly (Zimmer et al., 2020).

The hydrology of non-perennial rivers has been addressed in primary literature and reviews, although these resources do not present a full summary of hydrologic processes relevant to the breadth of global non-perennial rivers. Instead, they focus on particular aspects, such as the flow regime controls relevant to ecological systems (Costigan et al., 2017; Stubbington et al., 2017), or on specific climatic regions, such as drylands (Bull & Kirkby, 2002; Simmers, 2003; Steward et al., 2018; Wheater, Mathias, & Li, 2010). There is also a body of literature centered on the categorization and prediction of streamflow in rivers with seasonal low flows (Smakhtin, 2001); rivers which are not exclusively non-perennial. Other reviews summarize research conducted within a specific theme of an intergovernmental scientific cooperation program (Cudennec, Leduc, & Koutsoyiannis, 2007; Peters et al., 2012; Simmers, 2003) or within a regional context (Buttle et al., 2012; United States Environmental Protection Agency [EPA], 2015). A global overview of the hydrology of non-perennial rivers is therefore still lacking.

Therefore, we (1) briefly summarize the known hydrologic characteristics particular to non-perennial rivers, (2) highlight common approaches to, as well as challenges in, measuring and modeling the hydrology of non-perennial streams, (3) synthesize our hydrologic understanding of the global breadth of non-perennial rivers, and (4) conclude by highlighting a list of future research directions that we feel are critical for addressing major gaps in our understanding of non-perennial river hydrology.

2 | DISTINCTIVE HYDROLOGIC ASPECTS OF NON-PERENNIAL RIVERS

Non-perennial rivers are often identified by their flow regimes (Busch et al., 2020; Svec, Kolka, & Stringer, 2005). This fundamental aspect of these systems is often used to categorize non-perennial rivers from perennial rivers. However, variability in flow regimes reflect distinct differences in the internal processes or external forcings across these systems. Here, we introduce and describe our understanding of the complicated streamflow generation processes and variability in in-stream hydrologic partitioning that are distinctive to non-perennial river systems. We also discuss the spatiotemporal variability in flow regimes, which is a defining characteristic of these systems.

2.1 | Variability in streamflow generation processes

The volume and mechanisms of streamflow generation within a specific river system dictate its overarching flow regime, which is commonly defined as the magnitude, frequency, duration, and timing of streamflow, as well as how quickly those characteristics change in time (Poff et al., 1997). The flow regime, in turn, determines a wide range of other riverine functions, such as material and solute transport and in-stream and streambed habitat conditions (Bunn & Arthington, 2002; Larned, Gooseff, Packman, Rugel, & Wondzell, 2015).

To date, many studies have focused on characterizing when and where non-perennial systems flow (Durighetto, Vingiani, Bertassello, Camporese, & Botter, 2020; Goulsbra, Evans, & Lindsay, 2014; Jaeger et al., 2019; Jensen et al., 2019; Whiting & Godsey, 2016; Wigington, Moser, & Lindeman, 2005). Precipitation (either rainfall or snowmelt) is the driving force for flow activation in most non-perennial rivers; when it rains, some percentage of this precipitation makes its way via various physical hydrologic processes into river channels (Figure 1). These processes include overland flow caused either the rate of rainfall exceeds the potential rate of infiltration into the soil (i.e., the subsurface remains

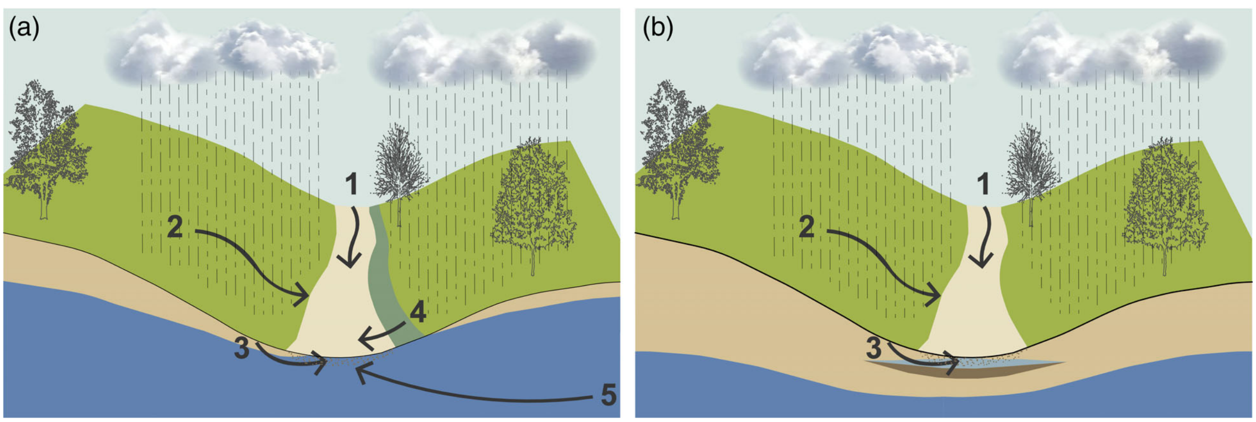


FIGURE 1 Streamflow generation processes in (a) a stream that is hydraulically connected to the groundwater system (common in humid climates and perennial rivers) and (b) a stream underlain by the unsaturated zone (common in dryland river systems). Streamflow can be generated by [1] water falling directly on the stream channel or flowing down the stream channel from further up in the watershed [2] infiltration excess overland flow (due to the rainfall rate exceeding the infiltration rate of the soil) or saturation excess overland flow (once soil becomes fully saturated; panel a only), [3] interflow through unsaturated or partially-saturated soils that may be perched above a low-permeability layer (as in panel b), [4] interflow through saturated soils, and [5] groundwater outflow into the stream. See also Gutierrez et al. (2019)

unsaturated; infiltration excess overland flow), or the soil becomes saturated (saturation excess overland flow; Schreiner-McGraw & Vivoni, 2017, 2018). Streamflow can also be generated by gradient-driven flow through the shallow subsurface, through either saturated or unsaturated soils, if there are macropores and other preferential pathways (Lange & Leibundgut, 2003).

As infiltration within the catchment riparian area proceeds, groundwater levels may rise, leading to outflow of regional groundwater into the river, or lateral contributions from groundwater that has been pushed out of saturated soil within the hillslope (i.e., piston flow). Contributions of groundwater to a river are termed baseflow (de Vries, 1995). Groundwater generally discharges where topographic low points intersect the water table (these low points can be caused by incision of stream networks into the landscape) or at the edges of aquifers, where they intersect the surface (Bourke, Shanafield, Hedley, & Dogramaci, 2020). This groundwater outflow can manifest as discrete springs or generate stream flow across distances of kilometers or more (Bryan, 1919; Harrington, Gardner, & Munday, 2013; Springer & Stevens, 2009). By definition, this groundwater discharge must cease for some portion of the year (in at least some reaches) for streamflow to cease.

Although there is an increasing body of knowledge on the physical mechanisms and factors linked to non-perennial flows (Gutiérrez-Jurado et al., 2019; Prancevic & Kirchner, 2019; Sutfin, Shaw, Wohl, & Cooper, 2014; Ward, Schmadel, & Wondzell, 2018; Yu, Bond, Bunn, & Kennard, 2019; Zimmer & McGlynn, 2017), our general understanding of the physical mechanisms of streamflow generation stems largely from perennial catchments, in which hillslope processes are important and both infiltration excess and saturation excess overland flow can play significant roles (Beven, 2012; Dunne & Black, 1970; Freeze, 1974). Streamflow response to a rainfall event is largely driven by catchment topography (Penna, Tromp-van Meerveld, Gobbi, Borga, & Dalla Fontana, 2011) and changes in soil moisture content; that is, streamflow increases after the soil becomes saturated (Berthet, Andréassian, Perrin, & Javelle, 2009; Tramblay et al., 2010). For some non-perennial rivers, where antecedent moisture levels are high, conditions (and therefore dominant streamflow generation mechanisms) may be similar to perennial rivers (Figure 1a). For example, the onset of flow in polar streams is often dominated by saturation excess overland flow, as typically only a thin layer of soil thaws initially, and this layer is quickly saturated by the large volumes of melt water (Zhang, Kane & Hinzman, 2000; Woo & Guan, 2006).

The onset of streamflow in many non-perennial streams is a complex and dynamic balance between geology (soil type), antecedent soil moisture, depth to groundwater, and the intensity and duration of rainfall (Gutiérrez-Jurado et al., 2019). Rainfall magnitudes and intensity can be spatially variable, especially across large river basins (Graef & Haigis, 2001; Pilgrim, Chapman, & Doran, 1988; Shannon, Richardson, & Thornes, 2002), and it can be difficult to predict whether a rainfall event will lead to streamflow. In particular, watershed response to rainfall events in dryland non-perennial systems that are underlain by a substantial unsaturated zone (Figure 1b) can behave distinctly from perennial systems (Gutiérrez-Jurado et al., 2019; Wheater et al., 2010). With thick unsaturated zones saturation excess overland flow is unlikely to be widespread; even though the shallowest soil horizons may be temporarily saturated, there is still an unsaturated zone below (Zimmer & McGlynn, 2017), and runoff generation is dominated by infiltration excess overland flow. Furthermore, water storage and movement within the unsaturated zone itself can play a critical role in streamflow generation (Pilgrim et al., 1988). High evaporation rates and soil infiltration capacity can mean that rainfall that falls directly on the stream channel or riparian zone is especially important (e.g., Gutiérrez-Jurado et al., 2019; Partington et al., 2013).

2.2 | Stream water loss

The majority of non-perennial rivers are losing rivers for much or all of the year. This water loss is commonly referred to as "transmission loss" and is largely driven by hydraulic gradients between the regional water table and the streambed (Wheater et al., 2010; Winter, Harvey, Franke, & Alley, 1998). The rate of transmission loss is controlled by both the streambed characteristics (e.g., hydraulic conductivity and moisture content) and the underlying geology (Quichimbo, Singer, & Cuthbert, 2020). Although often equated to groundwater recharge, transmission losses also include streamflow "lost" to unsaturated zone storage and evapotranspiration (ET; plant water use; Shanafield & Cook, 2014). These longitudinal streamflow losses can produce declines in channel width and capacity over relatively short distances (Dunkerley, 1992).

In dryland regions, transmission losses through non-perennial river channels are thought to be the primary source of groundwater recharge (Shanafield & Cook, 2014; Wang, Pozdniakov, & Vasilevskiy, 2017). This is because lack of vegetation, hydrophobic soils, and high evaporation rates severely limit diffuse infiltration throughout the terrestrial watershed, while stream channels receive the runoff from heavy storm events and transmit water to the subsurface via relatively permeable alluvial sediments, often to perched aquifers (Wheater et al., 2010). As excessive groundwater withdrawals have been identified as a cause of concern in dryland regions for several decades now (Kundzewicz & Döll, 2009; Llamas & Martinez-Santos, 2005; Shannon et al., 2002), the primary goal of many hydrologic studies has been to quantify these transmission losses and associated groundwater recharge.

The likely implications of reduced precipitation and increased ET predicted under climate change scenarios in many dryland regions (Dai, 2013; Huang, Chen, Zhang, & Wu, 2018) also reinforce the need to consider ET within water balances in non-perennial systems. ET plays a leading role in the water balance of some rivers (Dean et al., 2016; Wilcox & Thurow, 2006). In fact, plant water use has been shown to comprise up to 100% of the perched aquifer water balance after ephemeral river flood events (Bauer, Held, Zimmermann, Linn, & Kinzelbach, 2006; Villeneuve, Cook, Shanafield, Wood, & White, 2015). Even in sub-tropical and tropical areas, a water deficit can exist for much of the year when ET is high (Prosser, 2011; Zimmer & McGlynn, 2017). Unfortunately, ET can be one of the most difficult components of the water balance to estimate (Martinet et al., 2009; Shanafield et al., 2017), and connections between streamflow and ET are often complex and difficult to parse out (Dresel et al., 2018; Hughes, 2005).

2.3 | Spatio-temporal variability in flow

Non-perennial rivers have high spatial and temporal variability in where flow both begins and ends across their geomorphic networks (Figure 2). For example, there is a wealth of emerging research investigating the expansion and contraction of seasonal headwater streams that flow in response to snowmelt or other seasonal processes (Buttle, Dillon, & Eerkes, 2004; Godsey & Kirchner, 2014; Van Meerveld, Kirchner, Vis, Assendelft, & Seibert, 2019; Ward et al., 2018). The classical conceptual model for headwater streams is where flow seasonally propagates upstream from perennial, higher order reaches below due to the seasonal rise of groundwater, which intersects the streambed and produces flow (described simply in Biswal & Marani, 2010 and Day, 1978). In comparison, in many dryland regions, precipitation due to orographic uplift (or other processes) causes flow to start in the upstream reaches of a river, wetting up the channel in a downward direction as it progresses (e.g., Niswonger et al., 2005). Finally, the wetted channel may expand as pools get linked, or may propogate downstream from channel heads that begin at springs or seeps (Deemy & Rasmussen, 2017; Godsey & Kirchner, 2014). Therefore, streamflow in downstream reaches of a catchment may have been generated locally or may originate due to rainfall occurring in wetter areas such as mountain headwaters (Bull & Kirkby, 2002).

Both perennial and non-perennial rivers can terminate at the sea, in lakes, or as tributaries into larger rivers. In non-perennial rivers, the terminus may also vary through time, especially in flashy rivers where flow only occurs directly following a particular precipitation event (Morin et al., 2009), and where there is little topographic relief

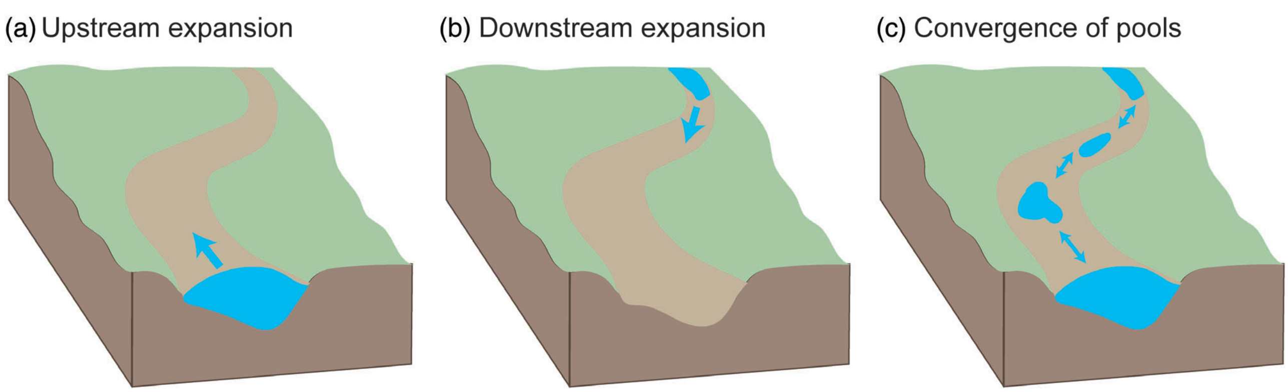


FIGURE 2 Non-perennial stream networks are dynamic in space and time. They can (a) expand upstream from perennial reaches (e.g., alpine headwaters), (b) wet from upstream to downstream (e.g., ephemeral desert rivers), or (c) flow as a convergence of pools (e.g., in karst regions or where persistent pools line the river). At the catchment scale, a combination of these possibilities may exist in time and space, due to variability in geology, topography, and groundwater levels. See also Bhamjee and Lindsay (2011)

(Costelloe, Grayson, Argent, & McMahon, 2003). The "floodout," where the channel becomes indistinct and remaining flow simply spreads out over a playa to evaporate and infiltrate, is a terminus unique to dryland rivers (Jaeger, Sutfin, Tooth, Michaelides, & Singer, 2017; Villeneuve et al., 2015). However, rivers in humid regions may terminate suddenly due to a variety of reasons including diversion of water for human use (Deitch, Kondolf, & Merenlender, 2009), the presence of subsurface flow through karst geology (Costigan, Daniels, & Dodds, 2015), and drawdown from ET (Graham, Barnard, Kavanagh, & McNamara, 2013). Although we typically denote rivers as "dry" once surface flows cease, lack of surface flows may not mean the streambed is dry. Pools or springs may persist as surface water features within or adjacent to the channel for most or all of the year (Bogan et al., 2014; Bourke et al., 2020), and may also be connected by subsurface flows (Anna, Yorgos, Konstantinos, & Maria, 2009; Boulton, Valett, & Fisher, 1992). These isolated pools or moist streambeds provide critical habitat and refuge in otherwise dry environments (Bogan & Lytle, 2011; Goodrich, Kepner, Levick, & Wigington, 2018; Sheldon et al., 2010).

These phases of flow, ponding, and drying often have dramatic impacts on water quality. For example, irrigation return flows and other waters passing through agricultural lands that result in streamflow generation in non-perennial rivers can mobilize naturally occurring toxic elements in soils as well as pesticides, nutrients, and other pollutants (Jackson & Pringle, 2010), and flows can be quite toxic to the ecosystems in persistent pools along the river corridor. The rate and frequency of re-wetting (i.e., flash floods induced by a storm versus seasonal groundwater level rising) can influence transport and processing of leached nutrients and organic matter (Harjung, Sabater, & Butturini, 2018; Shumilova et al., 2019). Similarly, where dams and impoundments are located within the stream network, flows may flush water of high temperature and low oxygen downstream of the impoundment, stressing aquatic communities in the river (Chandesris, Van Looy, Diamond, & Souchon, 2019; Four et al., 2019). River ecosystems are typically very sensitive to water quality, including physical parameters such as temperature and turbidity, and nutrient and solute concentrations including salinity and alkalinity (Horton, 1965; Perrin et al., 2018). As ecological models begin to move beyond correlative relationships and develop mechanistic relationships between the hydrology and ecology of these systems (Lytle, Merritt, Tonkin, Olden, & Reynolds, 2017; Rogosch et al., 2019), linking the flow and resultant water quality will be imperative.

3 | GLOBAL PERSPECTIVES: INTERACTING DRIVERS OF FLOW INTERMITTENCY

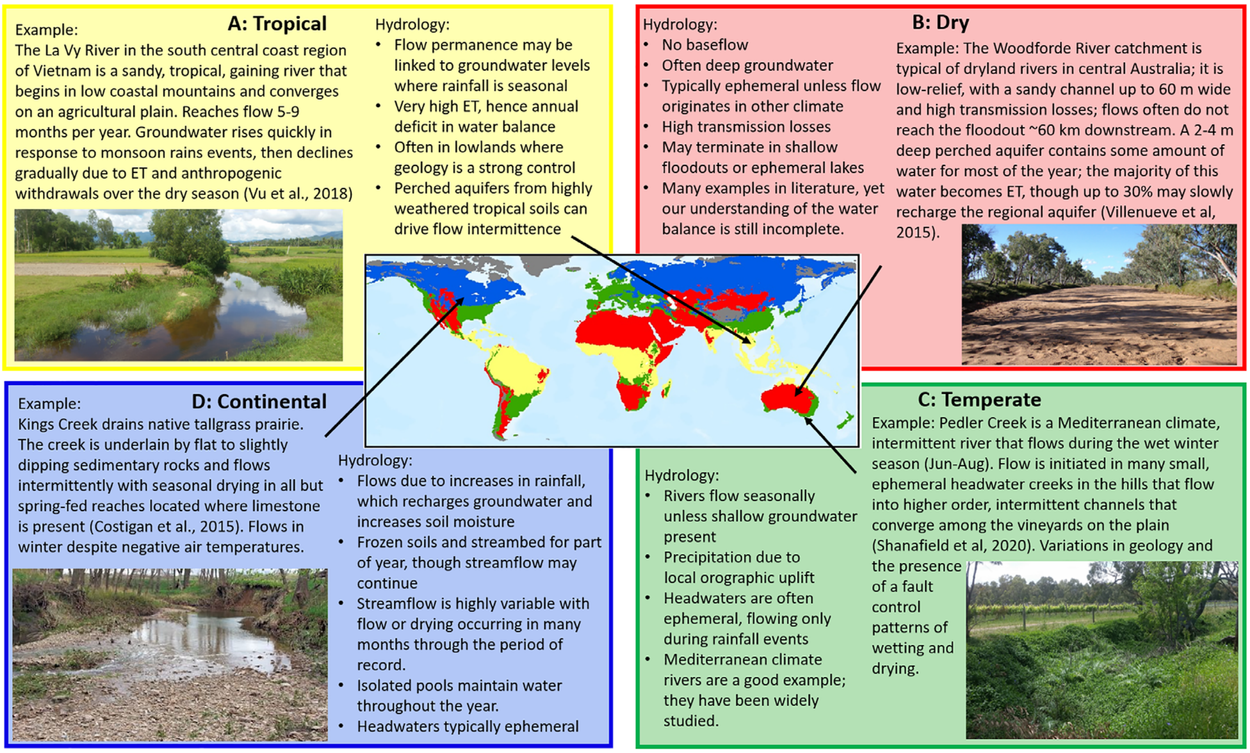
As summarized above, there are key hydrologic processes that are ubiquitous across most non-perennial river systems. However, the global diversity of these river systems has not yet been fully captured in the literature, which has, to date, focused primarily on dryland settings. Climate, geology, vegetation, and human interference determine the flow regimes of rivers (Bunn & Arthington, 2002; Poff et al., 1997; Tooth, 2000). The relative importance of each of these controls depends on each catchment, and the flow regime itself also has feedback on these controls (Wolman & Gerson, 1978). River systems can be classified by each of these controls separately (Dodds, 1997; Knoben, Woods, & Freer, 2018; Koppen, 1923; Sutfin et al., 2014) and each of these controls is briefly discussed below; however, in reality none of these controls act in isolation, but instead sum to shape the river networks we see globally.

3.1 | Climate

Non-perennial rivers are found in all major climate types around the world, from tropical to dry and temperate to continental (see Box 1). Climate determines the timing and volume of precipitation, and the lag time until that precipitation can reach stream channels (i.e., through snowmelt and antecedent soil moisture). Although humid regions may have high annual precipitation, they also typically have high rates of ET, which can result in reduced or depleted runoff. For example, in much of the tropical north of Australia, ET exceeds runoff for 10 months of the year, leading to a wealth of non-perennial streams (Prosser, 2011). Alternatively, air temperature can limit the availability of water for streamflow in humid regions. For example, the flow regimes of many alpine streams are dictated by seasonal warming, which results in discharge from snowmelt and glacial runoff (Fritz, Johnson, & Walters, 2008; Fureder, Schutz, Wallinger, & Burger, 2001; Hale & Godsey, 2019; Roy & Hayashi, 2009).

Even in polar climates, there are many examples of non-perennial rivers, as liquid water is frozen and unavailable for streamflow during much of the year (Walker, 1975). In fact, non-perennial rivers in polar regions may be among the world's most sensitive rivers to climate drivers; their streamflow is controlled by summer rainfall as well as air

BOX NON-PERENNIAL RIVER EXAMPLES OCCUR ACROSS DIVERSE CLIMATES AROUND THE WORLD



The Koeppen–Geiger climate classification (Koeppen, 1923; Geiger, 1961, center map) includes five primary branches; A. tropical, B. dry, C. temperate, D. continental, and E. polar (not shown); the typical hydrologic conditions and an example of a non-perennial river are given for each. Data for the Koeppen classification sourced from WorldBank (2017; World map of the Köppen–Geiger climate classification observed using CRU TS 2.1 temperature and GPCC Full v4 precipitation data, period 1976–2000; accessed April 19, 2020). Kings Creek photo credit: Kirk Hargadine; all other photos taken by M. Shanafield.

temperatures, which dictate how much ice melts and for how long. Changes in the size of ice dams or melting of permafrost has already been shown to cause both the total collapse of some drainage basins and the formation of new ones, as well as drastic changes in flow regimes (Vincent & Laybourn-Parry, 2008).

Yet the majority of non-perennial rivers are in dryland areas. We typically think of dryland rivers as ephemeral desert arroyos and wadis, and it is easy to understand why rivers in these regions are dry for much of the year. However, drylands represent a wide variety of landscapes, which belong not only to the dry climate categories, but also the temperate and continental climates, and are found on almost every continent (Tooth, 2000). For example, Mediterranean climates (which are temperate climate, dryland systems) host many dryland rivers. Rainfall is typically seasonal in this climate, and streams flow intermittently through the wet season, with flow continuing into the dry season only if there are baseflow contributions from groundwater (Lovill, Hahm, & Dietrich, 2018).

3.2 | Geology

Geology also has a critical role in determining whether many rivers will flow perennially (Mayer & Naman, 2011). For example, the prevailing geology of a region determines the slope and topography, which are strongly linked to

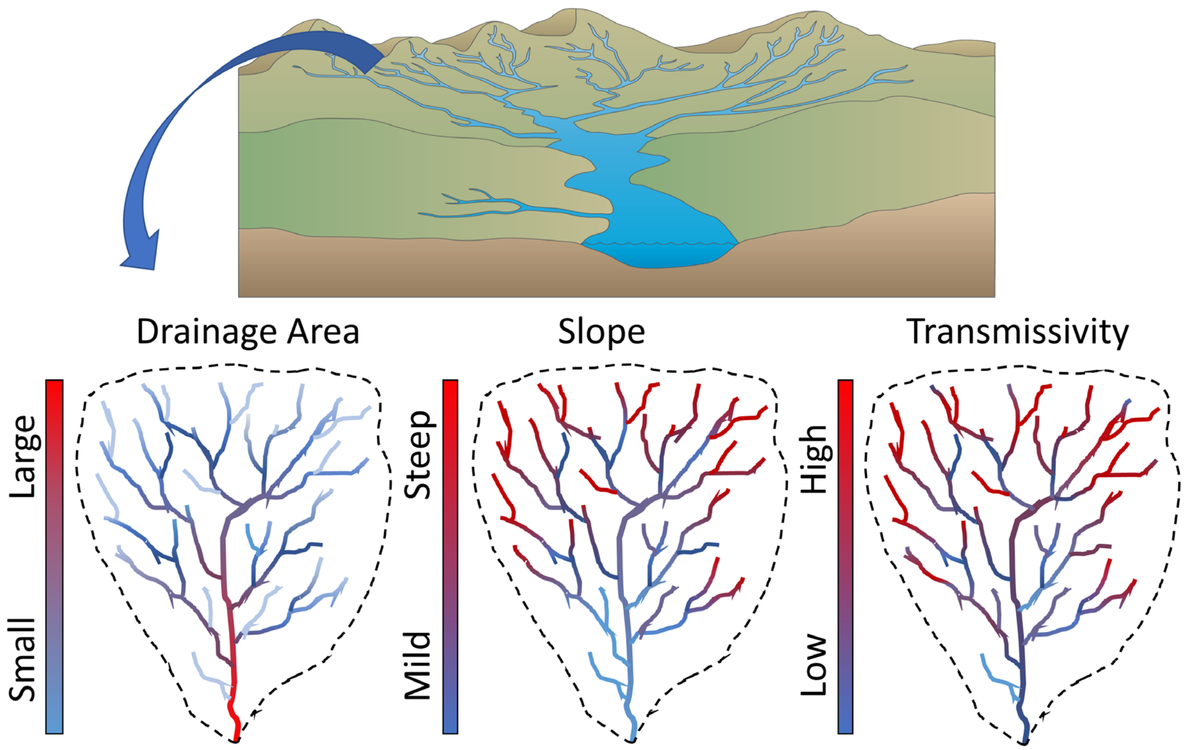


FIGURE 3 Topography, which is determined by a combination of geology and climate, plays a controlling role in the presence of streamflow within a catchment, especially in the persistence of seasonal flow within a catchment. Prancevic and Kirchner (2019) propose that a combination of drainage area, slope, and changes in transmissivity (i.e., the capacity to transmit flow through the subsurface) within the drainage area can be used to predict the expansion and contraction of the stream network seasonally. Figure generalized from the authors' original; 3D catchment base image courtesy of Jason C. Fisher, Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/)

flow regimes (Figure 3). Geology also controls the permeability of sediments and therefore the interactions between surface runoff and groundwater, as well as the extent of riparian areas (Newman, Vivoni, & Groffman, 2006). In both humid and temperate dry climates, groundwater levels typically fluctuate over the course of the year.

In dryland non-perennial river systems, both climatic and geological controls typically result in groundwater levels well below the ground surface, and much of the precipitation that falls on dryland basins becomes unsaturated subsurface storage without contributing to streamflow generation or groundwater recharge (Lange & Leibundgut, 2003; Scanlon et al., 2006). Spatial distributions of porosity and permeability, which are controlled by geological processes (Berger, 2000), determine which streamflow generation processes occur in space and time (Figure 1).

Geological controls on flow can also occur in humid climates. For example, rivers in karst areas of humid climates have been shown to only have surface flow connectivity during very wet periods, as large volumes of water can infiltrate through areas of permeable bedrock or sinkholes and flow underground (Bonacci et al., 2019; Deemy & Rasmussen, 2017; Hoetzl, 1996). Geologic controls are also present in polar regions, despite the acute sensitivity to climate. For example, in the McMurdo Valley of Antarctica, comparison of flow regimes in streams within one basin showed that streams that received contributions from storage in the hyporheic zone had longer durations of flow than those without (Welch et al., 2003).

3.3 | Vegetation

Vegetation affects both how much water gets into the stream from the landscape (e.g., xerophytic vegetation retains water; Pilgrim et al., 1988) and how much water is available through a stream reach (Schreiner-McGraw et al., 2020). The high environmental variability of non-perennial streams results in them having higher riparian vegetation species richness and cover than ephemeral or perennial streams (Katz et al., 2012). Rivers experience diurnal fluctuations in water levels due to evaporation and transpiration by riparian and catchment vegetation (Ward, Schmadel, Blaen, &

Zarnetske, 2019), especially in summer months (Bond, 2002). This phenomenon is observed even where riparian vegetation comprise a very small portion of total catchment area (Gannon, Kinner, Styers, & Lord, 2020); where catchment-scale changes in vegetation occur, long-term shifts in streamflow pattern can be observed (Garcia, Amengual, Homar, & Zamora, 2017).

3.4 | Human impacts on streamflow

Human alteration of river flow is widespread and can take many forms, including but not limited to direct abstraction or impoundment of streamflow itself, reduction of groundwater levels, and long-term changes in climate (Smakhtin, 2001; Zimmer et al., 2020). Dam management has resulted in periods with no flow downstream of large reservoirs (Cooney & Kwak, 2013; Steward et al., 2012). Groundwater abstraction has altered regional water balances and resulted in lowered water tables and therefore large reductions in streamflow (Mayer & Naman, 2011; McCallum, Andersen, Giambastiani, Kelly, & Ian Acworth, 2013; Petrone, Hughes, Van Niel, & Silberstein, 2010) and transitions from perennial to non-perennial flow regimes (Kustu, Fan, & Robock, 2010; Smettem, Waring, Callow, Wilson, & Mu, 2013). Periodic drought conditions or shifts in precipitation regimes from climate change have been linked to widespread river drying (Allen et al., 2019; Datry et al., 2018; Silberstein et al., 2012). In fact, widespread desertification, or land surface drying, has been observed and is anticipated to extend across many portions of the globe as a direct result of climate change (Döll & Schmied, 2012).

4 | KEY CHALLENGES IN MEASURING AND MODELING THE HYDROLOGIC PROCESSES OF NON-PERENNIAL RIVERS

Understanding non-perennial river hydrology relies on information regarding the drivers of flow regime, how water both enters and exits the river channel and therefore how flow varies in space and time. Capturing this information across the diversity of non-perennial flow characteristics and function is complicated by the difficulty of refining measurement and modeling toolkits in areas that are often remote or harsh environments, with unpredictable flow, and where there is often only minimal long-term data and permanent infrastructure. Here, we introduce several common approaches and challenges to measuring and modeling these systems.

4.1 | Measuring streamflow

Given the spatial and temporal variability in flow described above, a wide variety of methods have evolved to upscale our understanding of basin-scale non-perennial river hydrology. This is imperative for linking the hydrology with critical environmental conditions and processes, such as the aquatic and riparian ecosystem health, groundwater recharge, and biogeochemical cycling. Such mapping of wet and dry reaches at the basin scale can be done by manual, automated, or remotely sensed observation of flow, through citizen science, using long-term datasets statistically, or using model simulations. Here we present some of the advantages and limitations of each.

Early studies of flow in non-perennial rivers involved direct observations of flow permanence (Blyth & Rodda, 1973; Day, 1978; Gregory & Walling, 1968). Although manual observations still present advantages in the amount of stream channel detail that can be captured (Yu et al., 2019), there is a strong limitation on the spatial and temporal watershed coverage that is possible. This limitation can be overcome with the use of remotely sensed data (Spence & Mengistu, 2016). As opposed to the relatively coarse pixel size available from most satellite data, LiDAR (Light Detection and Ranging) and other imagery data captured at low aerial elevations allow the fine spatial resolution data needed to capture the flow status of relatively small rivers and stream networks (Hooshyar, Kim, Wang, & Medeiros, 2015; Liu, Wang, Xin, & Li, 2018). When coupled with hydraulic modeling, such imagery can even be used to quantify stream discharge (King, Neilson, & Rasmussen, 2018). The burgeoning use of unmanned aerial vehicles (drones) to capture imagery is therefore quite promising (Langhammer & Vacková, 2018; Spence & Mengistu, 2016), though challenges related to regulation, sensors, canopy cover, and data processing still remain (Whitehead & Hugenholtz, 2014). In addition, aerial imagery or high-resolution satellite data often only represent coarse snapshots in time, which makes it difficult to capture the dynamic nature of many flashy non-perennial river systems. Alternatively, citizen science projects allow the manual collection of data points to be shared by the public, and therefore have the potential to gather more data over large areas and through time. There are now many examples of successful citizen science projects gathering streamflow data in non-perennial catchments (Allen et al., 2019; Datry, Pella, Leigh, Bonada, & Hugueny, 2016; Turner & Richter, 2011); this is an expanding area of research with great potential (Buytaert et al., 2014). Challenges regarding consistency in participation of citizen scientists and training programs to ensure accurate data collection make this approach limited and time intensive.

A growing number of studies are also advancing our ability to collect automated data on flow permanence and spatiotemporal variability in flow events through the deployment of simple, relatively inexpensive sensors. This includes temperature sensors (Blasch et al., 2004; Constantz, Stonestorm, Stewart, Niswonger, & Smith, 2001; Gungle, 2006), electrical resistivity sensors (Adams, Monroe, Springer, Blasch, & Bills, 2006; Blasch, Ferre, Christensen, & Hoffmann, 2002; Goulsbra, Lindsay, & Evans, 2009; Jaeger & Olden, 2011; Peirce & Lindsay, 2015), a combination of these two sensors (Bhamjee & Lindsay, 2010; Chapin, Todd, & Zeigler, 2014), and more sophisticated setups that include float switches and/or flow sensors (Assendelft & van Meerveld, 2019; Epting et al., 2018). Water level sensors provide a more expensive method of monitoring but give valuable information on water depth over time that can be used for modeling wetting front progression and infiltration rates (Niswonger, Prudic, Fogg, Stonestrom, & Buckland, 2008; Noorduijn et al., 2014; Rodríguez-Burgueño, Shanafield, & Ramírez-Hernández, 2017). Each of these automated sensor options has its advantages and limitations. For example, while one setup might work well in headwater streams in alpine settings, high sediment loads or scouring may make it inappropriate for dryland rivers. Especially in ephemeral rivers, drastic changes in energy due to the often flashy nature of flows leads to distinct zones of scour and deposition, with upstream reaches often scoured, and downstream areas experiencing varying degrees of sediment transfer and deposition, depending on the magnitude of the flow event (Frostick, Reid, & Layman, 2009; Jaeger et al., 2017; Reid & Frostick, 2011). Indeed, there may be so much streambed mobilization during flow events in large ephemeral dryland rivers that securing anything to the bed of the river is nearly impossible. For example, Graf (1983) observed that during a large flood in the Salt River, Arizona, sediment 7 m below the streambed was in motion.

While our understanding of streamflow in perennial rivers can be derived from continuous, preferably long-term (e.g., typically 15–30 years) flow data, frequent periods of no flow in non-perennial rivers mean that we rely heavily on the information we can gather from seasonal flows or sometimes only from rare events (e.g., Lange et al., 2000). However, where large datasets of flow and watershed parameters exist, these can be used to better understand not just the spatial and temporal variability of flow patterns, but the biophysical drivers as well. For instance, a suite of flow metrics represent the co-dependent, highly related characteristics of flow regimes; namely the magnitude, frequency, duration, and timing of streamflow (Poff et al., 1997; Richter, 1996; Richter, Baumgartner, Wigington, & Braun, 1997). Researchers have related these flow metrics to watershed parameters to identify commonalities and differences in drivers within and across regions (e.g., Eng et al., 2016; Kennard et al., 2010). Such efforts are critically important for management efforts related to flow augmentation and habitat conservation.

4.2 | Measuring water loss

Transmission losses are generally estimated at a point or reach scale (Shanafield & Cook, 2014). At the point scale, infiltration measurements are often made during no-flow periods using a constant or falling head experiment, usually with an infiltrometer or permeameter (Dahan, Shani, Enzel, Yechieli, & Yakirevich, 2007; Dunkerley, 2008; Stewart-Deaker, Stonestorm, & Moore, 2007). These measurements are typically used to estimate the hydraulic properties (e.g., field saturated hydraulic conductivity) of the very shallow streambed. The properties estimated during these no-flow conditions are assumed to be valid also during natural flow events. However, in reality, the infiltration during natural flow events can be both higher or lower than under controlled conditions, due to a combination of factors including deposition of fine material effectively clogging the streambed surface (Crerar, Fry, Slater, Langenhove, & Wheeler, 1988; Dunkerley, 2008) and infiltration through preferential pathways and macropores (Dahan et al., 2007). Additionally, potentially large reaches of the streambed may remain unsaturated, even during periods of streamflow (Crosbie, Taylor, Davis, Lamontagne, & Munday, 2014; Lamontagne et al., 2014; Schilling, Irvine, Hendricks Franssen, & Brunner, 2017); therefore, saturated hydraulic conductivity values may overestimate actual infiltration (Dahan et al., 2008). Moreover, infiltration rates can both increase or decrease in response to groundwater levels rising during a flow event and causing hydrologic reconnection of the surface water with the underlying aquifer (Quichimbo et al., 2020; Shanafield, Cook, Brunner, McCallum, & Simmons, 2012).

Differential temperature measurements collected at the streambed surface and within the streambed are a common approach used to estimate time-varying vertical (or, less often, two-, or three-dimensional) fluxes during periods of flow, even in non-perennial rivers (Halloran, Rau, & Andersen, 2016; Hoffmann, Blasch, Pool, Bailey, & Callegary, 2007; McCallum et al., 2013; Prudic, Niswonger, Harrill, & Wood, 2007; Rodríguez-Burgueño et al., 2017). The most widely used of these methods assume the streambed is saturated (i.e., saturated hydraulic conductivity), although variably-saturated approaches have also been developed, which are more appropriate to understanding the hydrology of many non-perennial river systems (Blasch, Constantz, & Stonestrom, 2007; Rau et al., 2017). Although the use of temperature measurements as a tracer of streambed infiltration avoids certain issues associated with infiltration measurements in dry streambeds (i.e., it can capture temporal variations in infiltration during an actual flow event), severe scouring and changes in the physical composition of sediment during periods of flow can impact the quality of flux estimates.

At the reach scale, water losses are commonly measured through comparison of streamflows at several locations or gages along the length of a river (Abdulrazzak, 1995; Harte & Kiah, 2009; Pool, 2005; Schmadel, Neilson, & Stevens, 2010). This method of quantifying transmission losses is often used as a proxy for measuring groundwater recharge (i.e., unsaturated storage and ET are considered negligible), because recharge is difficult to measure directly, and because this loss can be measured at a reach scale (Abdulrazzak & Sorman, 1994; Dogramaci, Firmani, Hedley, Skrzypek, & Grierson, 2015; Osterkamp, Lane, & Menges, 1995; Walters, 1990). However, in non-perennial rivers this method has several limitations. From a practical point of view, most non-perennial rivers are either ungauged or have a single gauging station located along the mainstem of the river, and flow data has long been identified as a limitation for hydrologic monitoring in non-perennial river systems (Buttle et al., 2012; Shannon et al., 2002; Zimmer et al., 2020). Flood events in dryland rivers, in particular, can involve a great deal of scour and deposition (Dunkerley, 1992), making it difficult to establish accurate rating curves even for permanent gauging stations (Constantz & Thomas, 1997); therefore, there is often a great deal of error involved in estimating discharge at multiple points along a non-perennial river.

Where water level sensors can be installed along a river, flood routing models can be used to estimate spatial and temporal variability in water loss during flood events (Gianni, Richon, Perrochet, Vogel, & Brunner, 2016; Morin et al., 2009; Mudd, 2006; Noorduijn et al., 2014; Walter, Necsoiu, & McGinnis, 2012). This approach offers the potential to understand both transmission loss and recharge over a relatively large portion of a catchment (Lange, 2005; Shanafield et al., 2014). Combining flow gaging with tracers, or multiple tracers, can also be used to understand both ET and recharge over longer time scales of one or more years (Dogramaci et al., 2015; Stonestrom, Constantz, Ferré, & Leake, 2007; Villeneuve et al., 2015).

Challenges associated with each of these methods, as well as the fact that many of these rivers are in remote areas that are difficult to access during flow events, have limited our large scale understanding of water losses in non-perennial rivers (Shanafield & Cook, 2014; Shannon et al., 2002). Recent advances in telemetered sensors can help with the latter (Cooper et al., 2018; Ellison et al., 2019). Geophysical surveys of potential recharge during no-flow periods also offer the opportunity to gain a better understanding of streambed dynamics over a larger scale (Callegary, Leenhouts, Paretti, & Jones, 2007; Ferré et al., 2007; Shanafield, Gutiérrez-Jurado, et al., 2020), although more work is needed to tie this method to streambed hydraulic properties and verify water losses during flow events. There is also growing use of remote sensing data to estimate flow along rivers in remote areas. When paired with sensors on the ground, remotely sensed data can be used to establish rating curves of streamflow and examine changes in streambed morphology after flood events (Gleason, Smith, & Lee, 2014; Huang et al., 2018; Nathanson et al., 2012). Dryland areas still pose the greatest challenge for remotely sensed discharge measurements due to the infrequent and flashy nature of flows (Van Dijk et al., 2016). If timed with flow activation, remotely sensed data can be used in the prediction of inundation extent over time, especially where travel distances along a wetting front are large (Costa, Bronstert, & de Araújo, 2012; Foody, Ghoneim, & Arnell, 2004).

4.3 | Modeling streamflow generation

To understand and predict how flow develops in response to precipitation at the watershed-scale, computational modeling is typically used. The conceptual models that underpin this process vary widely, depending on the availability of data, the physical processes thought most likely to occur, and the desired output information (Beven, 2012). These models typically simulate the hydrograph at the outlet of the watershed, given a precipitation event of known volume and duration (i.e., rainfall-runoff models). That is, these models simulate how much of the precipitation will become streamflow (runoff generation), and how that streamflow moves through the watershed (runoff routing). This information is necessary not only for understanding catchments from a scientific point of view, but also for management purposes (Bennett et al., 2017; Forsee & Ahmad, 2011; Yu, Bond, Bunn, Xu, & Kennard, 2018).

There is a plethora of watershed rainfall-runoff models, each representing the components of the water balance with varying levels of spatial and physical complexity. Rainfall-runoff models of both perennial and non-perennial rivers suffer from difficulties in establishing accurate parameters for groundwater contributions, lack of knowledge of antecedent conditions, and lack of understanding of subsurface processes. Additional challenges associated with non-perennial rivers include flashy hydrographs and low information content in long-term data, especially for ephemeral rivers where the flow is zero over most of the year (Beven, 2002, 2012; Ye, Bates, Viney, Sivapalan, & Jakeman, 1997). Notable improvements have been made in overcoming these challenges (Costelloe, Grayson, & McMahon, 2005; Ivkovic, Croke, & Kelly, 2014; Ye et al., 1998). The use of artificial neural networks (ANNs) has become an increasingly adopted alternative to conventional approaches (ASCE, 2000) because ANN performance for rainfall-runoff modeling has been equivalent or superior to conventional models, as demonstrated in several non-perennial river applications (Daliakopoulos & Tsanis, 2016; Kisi & Kerem Cigizoglu, 2007; Sajikumar & Thandaveswara, 1999).

Rainfall-runoff models can be calibrated against field data and, given an expert understanding of the watershed by the model user, used to simulate downstream hydrograph response to flood events even for non-perennial rivers. But, they tell us little of the physical processes and dominant hydrologic flowpaths by which water migrates from its landing place within the catchment to become streamflow. For this, physically based models are needed. These have rarely been used to simulate non-perennial rivers, due to a lack of data necessary to adequately parameterize the model and determine a unique solution, the numerical challenges associated with sudden, widespread transitions from dry to wet (and often even ponded) conditions, and the impacts of soil heterogeneity across catchments (Gutiérrez-Jurado et al., 2019; Heppner, Loague, & VanderKwaak, 2007; Maxwell, 2010).

5 | FUTURE RESEARCH DIRECTIONS

Much of our historic understanding of the hydrology of non-perennial comes from research done in drylands. As the geographic extent of our research on these systems continues to spread into other climates, it is critical to provide the rapidly expanding research community with a synthesis of needed research directions. Here, we outline 10 core hydrologic research directions that we believe require attention to continue advancing our understanding of non-perennial systems. This list of knowledge gaps both embraces the findings of related hydrologic syntheses (e.g., Buttle et al., 2012; Costigan et al., 2017) and reflects the authors' collective frame of reference; that is to say, it is not exclusive, but instead food for thought.

5.1 | Physical mechanisms of flow generation

To not just understand but predict flow characteristics and their relation to water quality, ecologic health, surface water-groundwater interactions, and other river functions, streamflow generation mechanisms in non-perennial systems must be quantified. Limited work has been done using the physically-based, integrated surface-subsurface models needed to accurately characterize the processes that determine: (a) temporal shifts between different flow regimes (e.g., ephemeral to intermittent flow), (b) the subsequent attenuation of hydrological processes that lead to the cessation of streamflow, (c) what portion of the watershed contributes to the generation of flow at a given time, and (d) how the physical processes of streamflow generation will shift under a changing climate. Understanding the physical mechanism of streamflow generation and cessation will also be imperative for managing and restoring the growing number of formerly perennial rivers that now have (non-perennial) altered flow regimes due to climate changes and water withdrawals.

5.2 | Cross-disciplinary datasets

The relative paucity of flow data is described above; but while flow is the most fundamental data type needed to understand these systems, there is also a systemic lack of comprehensive, cross-disciplinary datasets co-located within hydrologic measurements in non-perennial systems. That is, there is a lack of hydrologic, ecologic, geomorphic, and biogeochemical datasets developed in tangent to comprehensively understand non-perennial systems.

Without such co-developed datasets, it is difficult to relate observed ecologic or biogeochemical function to flow conditions, or to make predictions of how a system may function in the future in response to changes in climate (e.g., fluctuating precipitation regimes and prolonged drought conditions). Communication is needed across disciplines when designing experiments and sensor networks to ensure critical hydrologic information (e.g., directionality of surface water-groundwater interaction, flow duration, and hydrograph recession rates) is being monitored alongside other disciplinary observations.

5.3 | Links between flow and water quality

Although it is well understood that river ecosystems are sensitive to water quality conditions, links between the often dynamic and rapidly changing flow patterns in non-perennial rivers and resultant water quality are not well known. Specifically, more research is needed to understand: (a) the role of flow regimes in moderating stream temperature and salinity in many non-perennial rivers, where periods of ponding and drying alter streambed biogeochemical reactions, and rewetting events can compromise water quality (Sabater, Timoner, Borrego, & Acuña, 2016), (b), the impacts of multiple stressors, such as the combined effects of altered water quality and reduced flow on the ecosystem (Kalogianni et al., 2017), and (c) carbon cycling in non-perennial rivers, which is potentially a significant contribution to the global carbon budget (Gómez-Gener et al., 2015; Hale & Godsey, 2019; Looman, Maher, Pendall, Bass, & Santos, 2017; Daniel von Schiller et al., 2014). This information is imperative for developing a holistic understanding of how hydrology, biogeochemistry, and ecology interact and are impacted by human alterations.

5.4 | Shallow streambed processes and the hyporheic zone

The hyporheic zone is typically defined by hydrologists according to the flow paths or fluxes that occur within it, with hyporheic flux originating and ending at the surface, mixing with groundwater on relatively short time scales (Boano et al., 2014; Ward, 2016). However, in non-perennial rivers, these definitions do not fit well; as flow ceases, surface water and groundwater levels drop and no water in the subsurface may return to the surface. Yet, this shallow subsurface area below the streambed is still an important zone of ecological refugia and undergoes biogeochemical reactions during the wetting and drying cycles (Sabater et al., 2016. The hydrology of this zone, and even the terminology for it, are still largely undefined. More hyporheic zone research in non-perennial rivers is needed to understand (a) how the geometry of the hyporheic zone changes during drying and wetting phases and what this means for nutrient transport or attenuation of pollutants, (b) how we apply what we know about reaction kinetics and hydrologic residence times to systems that are not in hydrologic steady state, (c) how streambed sediment properties (e.g., clast size, sediment mobility) effect hydrochemical processes, and (d) how hydrochemical patterns (e.g., redox zonation, dissolved oxygen distribution with depth) evolve in response to wetting and drying phases.

5.5 | Sediment transport effects on flow regime

Sediment transport and deposition has an important influence on both stream geometry (and therefore flow regime) and potential streambed infiltration (and therefore surface water-groundwater interactions, aquatic habitat, and groundwater recharge). Despite a range of studies on sediment transport in non-perennial rivers in various climates (e.g., see Buttle et al., 2012), predicting the spatial patterns of sediment transport is challenging because of the limited amount of experimental data (Gamvroudis et al., 2015). Additional studies are needed to (a) link patterns in flow regime to spatial and temporal variation in scour and deposition within the streambed, (b) investigate the stability of infiltration and habitat with regard to this variability, and (c) identify a metric for predicting sediment transport across the spectrum of geologic, climatic, vegetation, and land use conditions globally.

5.6 | Hydrology of persistent surface water features

Pools and springs along non-perennial rivers are recognized as important ecologically; however, the hydrology of these features has not been well characterized or documented in the literature. In some areas, these pools provide pockets of surface water that are crucial seasonal refugia (Hamilton, Bunn, Thoms, & Marshall, 2005), while the spatial variability of flow persistence in other non-perennial rivers may actually be controlled by the dynamics of groundwater inflow. Additional research is needed to: (a) quantify the role of persistent surface water features within the water balance of non-perennial rivers and adjacent aquifers, (b) identify geologic or geomorphologic controls on groundwater inflows that support persistent surface water, and (c) improve our understanding of the susceptibility of persistent surface water features to climate shifts and groundwater pumping (Bourke et al., 2020).

5.7 | Geologic influences on non-perennial river hydrology

Due to the ecological focus of a large portion of the literature on non-perennial rivers, past research has only focused on the shallow streambed (i.e., within 1 m of the surface) while there is a need to understand links throughout the critical zone. Underlying geology controls depth, length, and flow rates of hydrologic flow paths, and the depth of channel sediments (Dahlin & Owen, 2005) as well as the locations of groundwater outflow to streams (Harrington et al., 2013). However, geologic controls (e.g., location of faults and geological boundaries, preferential erosion) on streamflow generation or persistence are not well understood along non-perennial rivers. Additional research is therefore needed to understand: (a) whether the increased storage capacity in areas of erosive geology leads to increased transmission losses or persistent surface water, (b) the prevalence of streamflow permanence in areas where aquifers intersect the surface, leading to groundwater discharge in otherwise dry riverbeds, (c) the geometry of source aquifers for predicting and managing impacts of groundwater withdrawals on stream-aquifer interactions (McCallum et al., 2013), and (d) how geology affects the distribution of macro and micro-nutrients (Jacobson, Jacobson, Angermeier, & Cherry, 2000) in non-perennial rivers.

5.8 | Groundwater recharge through non-perennial streambeds

Despite recognition of the primary importance of streambed recharge in dryland regions (e.g., Lange & Leibundgut, 2003), especially as our use of groundwater in dryland regions continues to surge (Cuthbert et al., 2019), estimating the volume of recharge, both spatially and temporally, remains a challenge that requires significant further attention. While there are comprehensive studies of transmission losses in certain regions in extensive (e.g., Stonestrom & Harrill, 2007), our ability to fundamentally characterize the mechanisms and drivers of recharge in non-perennial river systems at a broader scale is still limited, and lessons learned from individual studies often cannot be transferred to other river systems. Moreover, additional research is needed to quantify recharge rates in systems experiencing changing climates or human alteration of recharge regimes (e.g., Bourke et al., 2014), where long-term steady state conditions cannot be assumed.

5.9 | The role of plant-water interactions on streamflow

Although studies of in-stream losses often focus on downward transmission losses into streambeds, seasonal and diurnal loss of streamflow can also be due to hillslope and near-stream ET losses (Graham et al., 2013; McDonough, Lang, Hosen, & Palmer, 2015; Zimmer et al., 2020). This phenomenon is particularly apparent in regions where flows are low during the period when ET demand is high. Therefore, more research is needed to (a) account for "upward" ET losses in some systems with extensive near-stream vegetation or climatic conditions with high evaporative demand and (b) identify whether streamflow loss by ET is driven by drawdown of water by near-stream vegetation or decrease in streamflow contribution magnitudes due to uptake of water by hillslope vegetation.

5.10 | Recognizing non-perennial rivers in global studies

There is a growing body of literature that examines the flow, spatial distribution, and geometry of rivers on a global scale (e.g., Andreadis, Schumann, & Pavelsky, 2013; Lin et al., 2019; Van Vliet et al., 2013; Yamazaki et al., 2014). This is partly driven by the expanding availability of remote sensing data. Although improvements in the resolution and temporal coverage of these data are allowing rapid upgrades in the mapping and analysis of rivers globally, non-perennial river systems remain a weak point in the success of these efforts (Lehner, Verdin, & Jarvis, 2008; Wu et al., 2012; Yamazaki et al., 2019). To more adequately capture the full diversity and contribution (e.g., in terms of water availability, total length, carbon cycling, etc) of non-perennial rivers, additional work is needed to overcome challenges in correctly mapping rivers in arid regions and small catchments (e.g., headwater streams).

6 | CONCLUSION

Adequately representing the breadth and diversity in the hydrology of non-perennial rivers presents an exciting and critical challenge for our hydrologic community. Here, our goal has been to identify the primary flow regime drivers, explain distinctive hydrologic processes, and explain key research gaps within the expanding literature on non-perennial rivers. Thus, we have sought to bring together a general understanding that bridges both the primary and textbook literature across several subfields and climatic foci. Although our scientific understanding of non-perennial river hydrology has improved, our knowledge is not equal across different river types and ecoregions, and it is far from complete. There are still many unanswered hydrological questions begging for field studies, advanced modeling, and conceptualization, some of which we have highlighted above. Collaboration between scientific disciplines is needed to provide a more holistic understanding of the interplay of fluvial geomorphology, biogeochemistry, ecology, and hydrology within these systems. These efforts can help critical protection and management efforts of these systems.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Margaret Shanafield: Conceptualization; investigation; writing-original draft; writing-review and editing. **Sarah Bourke:** Formal analysis; writing-original draft; writing-review and editing. **Margaret Zimmer:** Conceptualization; investigation; writing-original draft; writing-review and editing. **Katie Costigan:** Conceptualization; investigation; writing-original draft; writing-review and editing.

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