



Persistently high bedload flux in ephemeral channels

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Abstract We present the most comprehensive dataset of bedload transport in ephemeral channels compiled to date. These nine ephemeral channels cover a range of dryland climates and channel types. First, we evaluate these channels and how they compare with each other. Next, we contrast this database with a previously compiled bedload dataset encompassing 92 perennial rivers. While previous studies have identified differences between measured bedload flux in perennial and ephemeral systems, we quantify those differences across a wide range of channel types and shear stress conditions. We find that the ephemeral dataset is statistically distinct, showing greater average transport across flow conditions in normalized shear vs. bedload flux space. Prior researchers have variously attributed these high transport rates to a combination of factors that commonly define ephemeral channels: lack of armoring, mixed sand and gravel, flashy hydrographs, erodible banks, and lack of vegetation. We tested the influence of armoring by comparing transport differences at different transport stages, finding that bed armor contributes to the observed differences, but is not the sole reason. In addition to these previously proposed mechanisms, we add that the abundance of very coarse sand and fine gravels in ephemeral channels provides easily-mobilized but difficult-to-suspend particles.

Non-technical summary Bedload transport, the rate at which sediment rolls and bounces downstream in a channel, has been observed to be high in rivers that rarely flow. However, it is unclear why the duration of flow should affect sediment transport rates, since the physics of water flowing over sand and gravel is the same in all channels. Rarely flowing channels do have several sediment properties that previous scientific studies have suggested may enhance their ability to transport this sediment, such as a high rates of sediment delivery from sparse desert landscapes. By comparing high-flow conditions to low-flow conditions, we demonstrate that part of the difference is explained by the coarse covering that forms via removal of fine grains in consistently flowing channels. This so-called bed armor helps explain how rarely-flowing rivers may have an advantage in transporting sediment. When flow gets strong enough to break the armor, the relative advantage declines. But, importantly, the rarely-flowing rivers retain a large portion of their transport advantage even at these high flow conditions, meaning an additional explanatory factor is still required. We propose that interactions among the wide range of grain sizes present in rarely-flowing channels further explains this transport advantage.

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1 Introduction

1.1 Motivation and approach

Multiple published reports based on field studies of bedload transport in ephemeral channels note that the bedload flux is high compared to values typically observed in perennial systems (e.g., Cohen and Laronne, 2005; Liébault et al., 2016; Stark et al., 2021). In this paper we focus on two questions which this observation inspires. First, is this observation generally true, or is it due merely to site specific conditions in each study, or perhaps due to a bias in the size or frequency of flow events being measured at these sites? And second, if it is true for ephemeral channels in general, why should such a difference be observed, given that the physics of fluid flow and particle entrainment are the same whether the flow is continuous or episodic?

We investigate these questions first by compiling a dataset of instantaneous bedload flux measurements from nine diverse ephemeral channels (Fig. 1), which encompass most published data on the topic, and by comparing this database to one of bedload flux measurements from perennial channels (Recking, 2010; Hinton et al., 2017). In an effort to control for wide ranges in both channel and grain size, we focus on the normalized bedload flux (Einstein bedload parameter; Einstein, 1950) as a function of normalized shear stress (Shields number; Shields, 1936). Based on these comparisons, we then explore potential reasons for differences between bedload transport in ephemeral and perennial channels. In this search for explanations we consider both measured characteristics in our databases such as dimensionless shear and median grain size, as well as unmeasured (or partially measured) ones such as grain size distribution, hydrograph shape, bank erodibility, and sediment supply.

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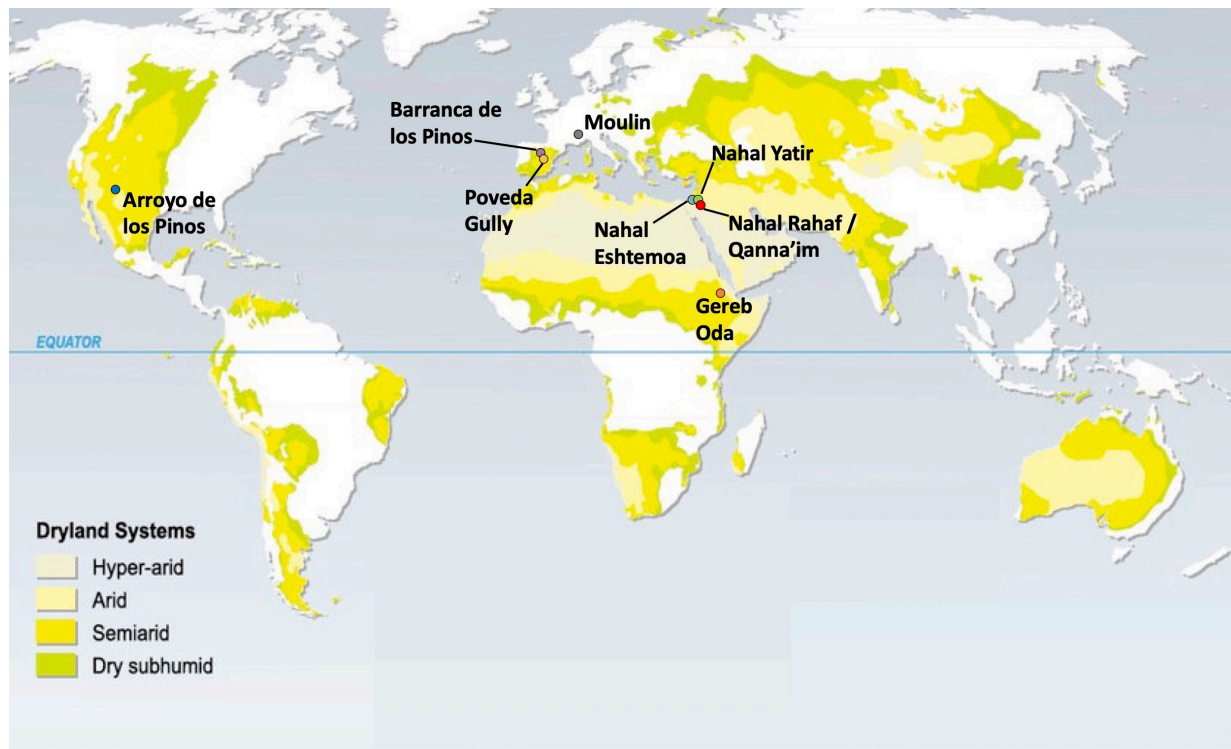


Figure 1 World map depicting the extent of dryland systems and the location of the nine channels analyzed in this study. Base map and classification source: Adeel and World Resources Institute, 2005.

1.2 Background

Non-perennial streams and rivers reside on a continuum, ranging from nearly perennial (water flowing almost year-round) to intermittent to fully dry (a channel completely abandoned). The abundance of these non-perennial channels worldwide is difficult to assess, though one recent study of global river datasets suggests that 40-50% of rivers cease flowing for at least one month per year (Messager et al., 2021). Recognizing this continuum and full range of non-perennial channels, we focus on ephemeral channels: streams or portions of streams that flow briefly in direct response to rainfall in the immediate vicinity, and which are at all times above the groundwater table (U.S. EPA, 2015; Goodrich et al., 2018). Ephemeral channels exist in landscapes worldwide, often as first order channels that directly drain hillslopes. Larger, high-order ephemeral channels occur in drier climates, where rainfall is less frequent and where storms are usually smaller in aerial extent (Fig. 1). They are known regionally by many names: arroyos, washes, wadis, gullies, ditches, ravines, etc. Direct measurements of sediment transport dynamics in these systems are limited to a few channels, despite their widespread existence in landscapes worldwide and their ubiquity in semi-arid and arid lands. While ephemeral channels are commonly thought of being similar to one another in their ability to transport sediment (Laronne and Reid, 1993; Powell et al., 1996), more recent studies have observed differences in sediment transport between ephemeral channels across climates and landscapes (Stark et al., 2021). However, these investigations were limited in scope and did not encompass the full range of available data.

Bedload, as distinct from suspended load, has fre-

quent contact with the channel bed during transport. Techniques to measure bedload transport in ephemeral channels have often resorted to integrated measurements of bedload flux. Because these channels experience regular periods of no flow, tools such as scour chains, tagged particles, or sedimentation ponds are commonly deployed (Leopold et al., 1966; Laronne et al., 1992a; Hassan et al., 1999; Martín-Vide et al., 1999; Nichols, 2004; Nearing et al., 2007). These studies revealed systems that are very active, with mobile and fluctuating beds, where a scour-and-fill process is commonly observed (Hassan, 1993; Schick and Lekach, 1993). However, these proxy methods have limitations: scour chains only provide an integrated estimate of scour and fill through multiple events, tagged particles are limited to discrete grain sizes (typically larger gravels), and sedimentation ponds provide event estimates of the total sediment load, with a potential bias toward suspended load, as it may be partially trapped in the pond (Martín-Vide et al., 1999). To better evaluate the range of bedload transport rates possible in these settings, researchers have deployed direct-measurement equipment and methodologies, including instantaneous bedload samplers (e.g., pressure differential samplers) and sampler pits or traps, both of which are described at length in the methods sections.

Studies of erosion and transport in ephemeral systems are still somewhat uncommon, but a growing body of work exists in characterizing the frequency, magnitude, and distribution of channel-forming processes (Tooth, 2000). Hortonian overland flow is common on the hillslopes draining to these channels due to the sparse vegetation and the commonly high, though localized, intensity of rainfall (Tongway et al., 2001; Marra

and Morin, 2018). Drainage densities of ephemeral channel networks tend to be high, but these networks are poorly connected because of the rapid infiltration and evaporation of water (Reid and Frostick, 1987). As a consequence of this rapid infiltration, high transmission losses are common, with large decreases in downstream flood volume (Sharma and Murthy, 1994; Goodrich et al., 1997; Dahan et al., 2008; Mujere et al., 2022). Compared to perennial systems, ephemeral channel networks have high width-depth ratios, relatively low sinuosity, slightly greater increases in downstream velocity, and relatively simple geometries, all of which may contribute to higher bedload fluxes due to generally higher shear stresses (Leopold and Miller, 1956; Graf, 1983; Merritt and Wohl, 2003; Singer and Michaelides, 2014). Historically, these systems are thought to be in a state of disequilibrium, whereby infrequent events may cause varying rates of erosion and deposition along the channel (Schumm and Lichty, 1965; Graf, 1983; Bull, 1997). Recent studies challenge these assumptions, as several cases have demonstrated that ephemeral channels approximate equilibrium conditions, where bed and banks are stable (Tooth and Nanson, 2000).

Ephemeral channels are more likely to retain significant amounts of fine-grained bedload sediment in their beds due to a lack of winnowing by base flow (Stark et al., 2021). Flume and field studies have shown that when mixtures of sand and fine-grained gravel are added to gravel-bed channels, coarse particles are transported at higher rates (Laronne et al., 1994; Wilcock and Crowe, 2003; Miwa and Parker, 2017; An et al., 2019). Despite this issue, relatively simple relationships between bedload flux and bed shear stress were obtained by a long-running field study (Cohen et al., 2010). In addition, this lack of winnowing combined with steeper slopes, a general lack of armoring (Graf, 1988; Laronne and Wilhelm, 2002), and rapid flood recessions (Hasan et al., 2006), interact to promote a greater fraction of sediment transported as bedload (Alexandrov et al., 2009). The lack of baseflow also creates a system of channel bars and patches that are usually coarser than the channel thalweg, which is the opposite of the coarser thalweg typically observed in perennial rivers (Yuill et al., 2010; Storz-Peretz and Laronne, 2013).

1.3 Scientific questions and objectives

In this study we present the largest compilation of bedload flux measurements from ephemeral channels assembled to date. Using this database, we address two driving questions:

- I. How different are bedload fluxes in ephemeral rivers from those in perennial rivers? If differences exist, are there differences in empirical scaling equations relating bedload flux to driving shear for the two populations, or do they exist along a similar continuum when accounting for flow and sediment conditions?
- II. If there are differences, is there adequate data to evaluate potential mechanisms? In the liter-

ature, various mechanisms have been suggested to explain the observed high transport rates in ephemeral channels, such as lack of armoring (Stark et al., 2021), inclusion of fine-grained material (Wilcock and Crowe, 2003), differences in sediment supply (Reid et al., 1995; Liébault et al., 2016), and hydrograph shape (Meirovich et al., 1998).

2 Methods and Database Descriptions

2.1 Ephemeral river database

For the purposes of this analysis, we have gathered ephemeral channel datasets that contain direct, instantaneous measurements of bedload transport. Combined with measurements of flow magnitude, these measurements are comparable to similar direct measurements made in perennial systems. Other bedload flux estimates made using proxy methods provide important context for what might be expected in a wider range of channel settings, but were not used in this study of direct bedload flux measurements. We compiled nine bedload transport datasets obtained from channels ranging in texture (grain size), watershed area, slope, and climate (Figs. 1 and 2, Table 1). These nine channels are the result of a comprehensive search for available bedload data via online literature search engines and review of publicly available databases of sediment transport. Specific data requirements — bed grain size of 16th, 50th, and 84th percentiles (D_{16} , D_{50} , and D_{84} , respectively), contemporaneous flow strength measurements, and bed slope — prevented the use of some datasets (e.g., Malmon et al., 2004; Cantalice et al., 2013). While the database does not include these datasets due to specific data requirements, we are confident that it spans the range of ephemeral channel climates and grain sizes, capturing the relevant available bedload flux data. The data are preserved in a separate data repository (Stark et al., 2021).

A narrative description for each of the channels is presented here to frame the discussion of these channels; more thorough descriptions of the methods and characteristics are found in the principal citations provided in the appendix (Table S1). The **Arroyo de los Pinos** is a direct tributary to the Rio Grande, a main stem perennial channel. The Pinos is a gravel bed river with a significant sand component (34%) (Stark et al., 2021). The **Gereb Oda** is a sand-bed channel with some larger boulder-sized grains in northern Ethiopia. The climate is temperate but with significant dry periods, promoting the ephemeral nature of the channel (Billi, 2011). The **Nahal Rahaf** has an unstable gravel bed located in the Judean Desert. Annual rainfall is typically less than 100 mm; it is hyper-arid at the outlet. The **Nahal Qanna'im** is a small, direct tributary to the Nahal Rahaf in the hyper-arid canyon lowlands, with a slightly finer bed ($D_{50} = 9$ mm) (Cohen and Laronne, 2005). The **Nahal Yatir** is an ephemeral channel in semiarid southern Israel. It is a small gravel bed river with a moderate component of sand and fines (16%) (Laronne et al., 1992b; Reid et al., 1995). The **Nahal Eshtemoa** is another ephemeral channel in semiarid southern Israel. It

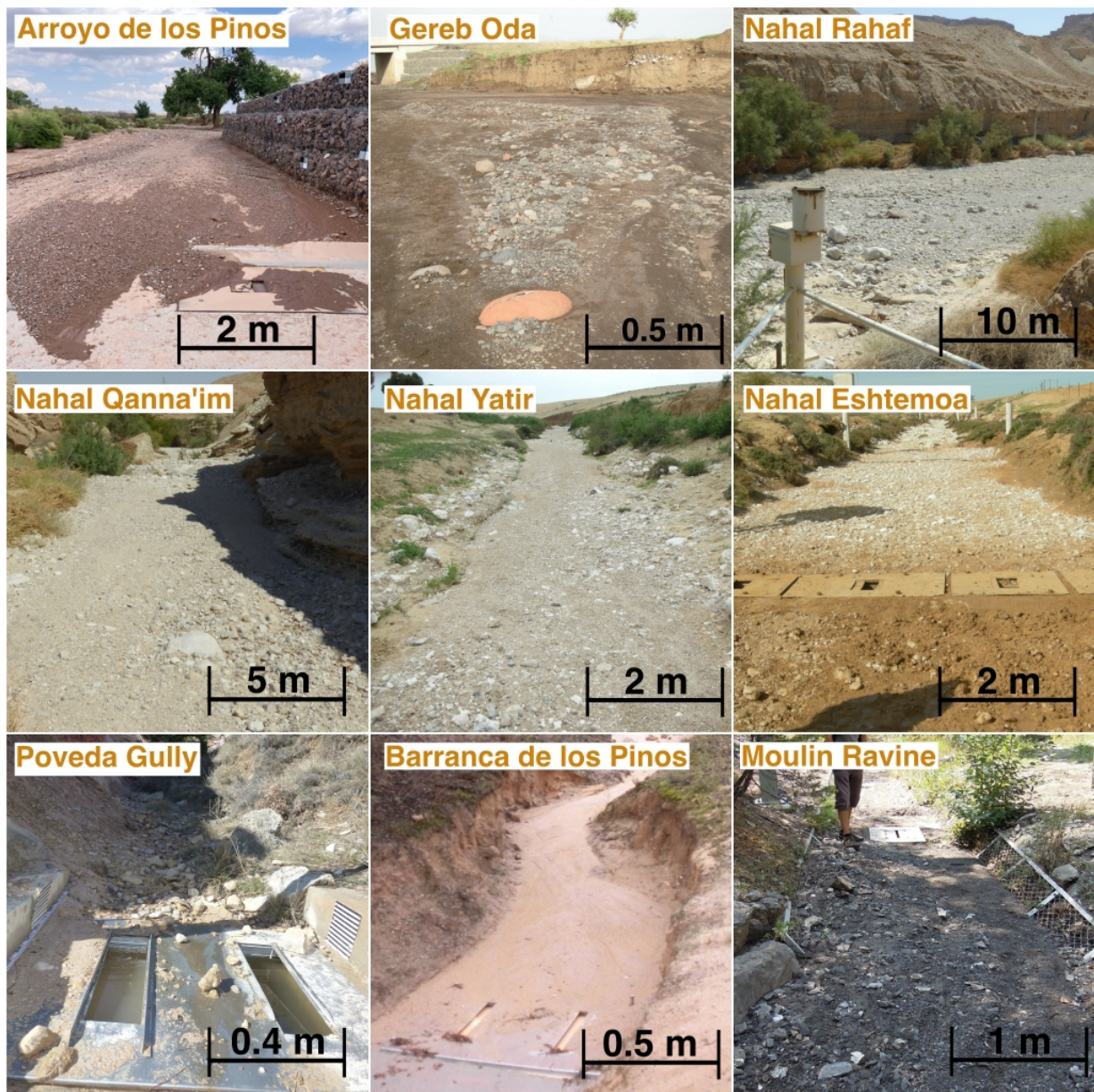


Figure 2 Photographs of each of the nine ephemeral channels evaluated. From top left, across: Arroyo de los Pinos (USA), Gereb Oda (Ethiopia), Nahal Rahaf (Israel), Nahal Qanna'im (Israel), Nahal Yatir (Israel), Nahal Eshtemoa (Israel), Poveda Gully (Spain), Barranca de los Pinos (Spain), and Moulin Ravine (France).

is slightly coarser-grained than the Yatir ($D_{50} = 16$ mm) (Larone and Reid, 1993; Cohen et al., 2010). **Poveda Gully** is located in east-central Spain. It is a small, first-order channel with steep, vertical cliff banks. The gullied portion of the watershed has a steep slope (15%) with a variable sand component (10-50%) and significant gravel (50-90%) in the bed. Poveda Gully is the only ephemeral channel analyzed here with a seasonal armor layer and broad changes to the bed material occurring between flow events, suggesting a highly active channel despite the seasonal armoring (Zapico et al., 2018). The **Barranca de los Pinos** has a Mediterranean climate with cool summers in north-central Spain. It is a second-order gullied channel with steep cliff banks. Bed material in the Barranca de los Pinos consists mostly of sand ($D_{84} = 0.8$ mm) and the majority of the transported sediment is sand sized or smaller (Lucía et al., 2013). The **Moulin Ravine** is a hillslope-confined

alluvial channel in the Mediterranean climate of south-eastern France. The bed material of the Moulin includes gravel, but is primarily sand with a large fraction of silts and clays (Liébault et al., 2016, 2022). Of the nine channels, the Moulin is the channel located in the wettest environment (Table S1).

Monitoring the flow and sediment regime of these channels is non-trivial. Due to their short, unpredictable flows, automated systems are usually required to capture flow events. For water depth and discharge, pressure transducers were used in all studies except the Gereb Oda where a wading rod was used. To monitor bedload flux, all of the channels use Reid-type (Birkbeck) slot samplers (Poreh et al., 1970; Reid et al., 1980) except for the Gereb Oda, which utilized a BLH-84. With a Reid-type slot sampler, bedload flux is measured continuously; grains are deposited in the sampler and their mass is recorded using a pressure system. The

Table 1 Summary characteristics of the nine ephemeral channels. Grain size can vary widely within a channel reach and between events. We choose to report the values used in our calculations, which represent a composite of all samples (when multiple samples were reported) in the original manuscript.

Channel	Data points	Number of events	Surface D_{16} (mm)	Surface D_{50} (mm)	Surface D_{84} (mm)	Bed slope (%)	Bed shear stress (N m^{-2})	Measured bedload fluxes ($\text{kg s}^{-1} \text{m}^{-1}$)
Arroyo de los Pinos	558	15	0.5	3.84	16	1.2	4.8 – 54	0.08 – 13.1
Nahal Eshtemoa	682	23	6	16	54	0.75	7.1 – 56	0.01 – 7.1
Nahal Yatir	71	4	2	6	13	0.87	8.8 – 37	0.2 – 7.1
Nahal Qanna'im	80	7	3	9	49	1.7	23 – 135	0.06 – 20.6
Nahal Rahaf	46	7	9.5	17.5	32	2.7	8.9 – 125	0.01 – 36.8
Barranca de los Pinos	1,920	21	0.19	0.39	0.8	6.6	0.31 – 103	0.01 – 11.6
Poveda Gully	1,268	7	18	40	61	15	0.13 – 153	0.006 – 4.8
Gereb Oda River	7	1	0.15	0.57	9.4	1.47	16.1 – 56	0.1 – 1.0
Moulin Ravine	843	41	0.06	2	6.5	4.5	3.0 – 134	0.06 – 23.4

slots are equipped with lateral wings to prevent bedload flux from moving in a cross-stream direction and depositing in the sampler. While active, these samplers are 100% efficient at sampling bedload (Haber-sack et al., 2001), but their capacity limits their ability to collect data for an entire flow event. Portable bedload samplers, such as the one used in the Gereb Oda and most perennial rivers are pressure differential samplers (e.g., BLH-84, Elwah, or Helley-Smith samplers). These samplers direct bedload into a mesh bag by creating a pressure differential, increasing flow velocities, and enabling efficient sampling of bedload particles (Helley and Smith, 1971). These samplers may inappropriately capture coarse gravel-sized particles under some conditions (Bunte et al., 2004), miss sediment particles moving under the sampler (Vericat et al., 2006), and are sensitive to the choice of mesh size.

2.2 Perennial river database

Instantaneous bedload flux measurements in perennial streams are far more common than for ephemerals. Recking (2010) and Hinton et al. (2017) compiled databases derived from perennial rivers varying in size, climate, and grain size. We combined these databases (after excluding ephemeral rivers, the data of which are reproduced in the ephemeral dataset) to compare bedload fluxes from ephemeral channels to those from a wide range of perennial systems. Not all channels from these databases could be included because several lacked one or more parameters required for our analysis. We used the same minimum data requirements as we did for inclusion in the ephemeral database: D_{16} , D_{50} , D_{84} , contemporaneous flow strength measurements, and bed slope. Additionally, we converted bedform transport rates provided in (Nitttrouer et al., 2008) from the lower Mississippi River to bedload transport estimates to compare our ephemeral data to the largest regional river system in North America. This dataset was included because it represents an extreme case where we can test how the data from a wide variety of channels compare. In principle, the nondimensionalization process should allow direct comparisons of channels across a range of sizes and shapes – includ-

ing data from the Mississippi River, part of our effort to find an explanation for any differences in the two databases. Narrowing the range of perennial streams included in the comparison could limit our ability to make general comparisons. Data from the lower Mississippi River are converted to transport rates based on the channel widths and relative water depths reported at a nearby stage gauge. Channel bed grain size information was estimated from (Nitttrouer et al., 2008, 2011). The list of references for these datasets is summarized in supplementary material (Table S2), while a detailed description of the rivers can be found in Recking (2010), Hinton et al. (2017), and (Nitttrouer et al., 2008), respectively. Briefly, the subset of the perennial river database presented in this manuscript contains:

- 92 individual rivers;
- 6,349 individual bedload flux measurements (on average 69 measurements per channel);
- Median grain size (D_{50}) of surface channel bed material in the range 0.25–220 mm;
- Drainage areas ranging from 1.28 to 2,900,000 km^2 ;
- Longitudinal channel bed slopes between 0.025% and 8.56%.

2.3 Data analysis

Data from each channel in each of the databases have generally been preserved as-is from the principal citations. Some of the data from ephemeral channels based on Reid-type slot samplers were originally reported at small sampling intervals (< 10 s). To compare these data to those from the other ephemeral channels, the sampling intervals of which were 30 s or longer, datasets with shorter sampling intervals were resampled by averaging the data within each 30 s window and all parameters were recalculated at that sampling interval.

Contemporaneous cross-sectional average bed shear stress was estimated assuming uniform, steady flow by the depth-slope product:

$$\tau = \rho_w g R S \quad (1)$$

where ρ_w (kg m^{-3}) is water density, g (9.8 m s^{-2}) is the acceleration due to gravity, R (m) is hydraulic radius, and S is bed slope. Water density values varied depending on the source publication. We used the original values when available, and used a default of 1000 kg m^{-3} when no value was provided (51% of all data used the generic value). In some instances, water depth (m) was used in lieu of R and water surface slope was used in place of S (68% of all data used the generic values). We elected to follow the procedure originally described by the authors to preserve consistency between publications, noting that using depth instead of hydraulic radius caused less than a 3% difference in shear stress values and using bed slope in lieu of water surface slope causes up to an 8% difference (Meirovich et al., 1998) unless flood bores are considered (Halfi et al., 2018).

We considered several alternative parameters to represent flow strength (e.g., water discharge, stream power) but decided to focus on bed shear stress for several reasons. First, most of the ephemeral database lacks measurements of water velocity; this then would require estimates of roughness to calculate discharge, potentially introducing additional error. Second, the vast majority of bedload transport equations use bed shear stress to calculate bedload flux (Meyer-Peter and Müller, 1948; Van Rijn, 1984; Wilcock and Crowe, 2003); this allows our analysis to build upon other efforts in evaluating total flux. Finally, recent research (Ancey and Recking, 2023) suggests that shear stress, and by extension non-dimensional shear stress, is as good or better at predicting bedload flux when compared to predictions that use water discharge.

We nondimensionalized bed shear stress using the Shields number (Shields, 1936):

$$\tau^* = \frac{\tau}{(g(\rho_s - \rho_w)D_{50})} \quad (2)$$

where ρ_s is sediment density ($2,650 \text{ kg m}^{-3}$), and D_{50} (m) represents the bed grain size of which 50% of the sediment is finer. Bedload fluxes were nondimensionalized using the Einstein transport parameter (Einstein, 1950):

$$q_b^* = \frac{q_b}{\rho_s \sqrt{(gD_{50}^3 (\frac{\rho_s - \rho_w}{\rho_w}))}} \quad (3)$$

where q_b is the measured unit bedload flux ($\text{kg s}^{-1} \text{ m}^{-1}$). The choice of characteristic length was also considered. Some recent research (e.g., Recking, 2010) suggests using D_{84} or some other characteristic length instead of the traditional D_{50} . We considered this and chose to adopt D_{50} as our characteristic length for two reasons. First, the results and discussion below did not change when using another characteristic length and second, D_{50} is a more widely available grain size, which can facilitate future efforts to build on our work. Figures that were nondimensionalized using D_{84} as a characteristic length is provided in supplementary material.

Lastly, we adopt a common language of different flow regimes that follows the original descriptions by Parker (1978): Phase 1, when rare transport occurs, Phase 2, where partial transport of sediment occurs, and Phase 3 when grains are equally mobile relative to their bed proportions. These phases of transport are important when

comparing gravel-bed rivers. Bed armoring typically begins to break up when shear stresses approach Phase 3 transport. Defining these transitions and evaluating the two databases around these transitions is a principal goal of this study. Others, such as Ancey and Recking (2023), used a separate set of terms, adopted from Baginold (1966): (i) no (or very rare) transport, (ii) the transitional regime, where only part of the bed grains are mobile, and (iii) the sheet flow regime, where all grains are mobile in equal proportion. The transitional regime is roughly equivalent to Phase 1 and Phase 2 transport and the sheet flow regime is equivalent to Parker's Phase 3 transport. Transitions between these groups are often difficult to define, but we follow Ancey and Recking (2023) and define them using the critical Shields parameter as the transition into Phase 1 (or early transitional) transport, and $\tau_1^* = 0.4$ to represent the beginning Phase 3 (or sheet flow) transport.

2.4 Statistical analysis

To quantitatively investigate the differences between the ephemeral and perennial datasets, we employed several statistical tests, including a Mann-Whitney U test, multiple linear regression tests (with an evaluation of the relative importance of each independent variable), and evaluations of the cumulative distribution functions (CDFs). The Mann-Whitney U test is a non-parametric test that compares two independent groups. It assesses whether there is a significant difference in the distribution of ranks between two groups. The test ranks each data point and tests whether one group tends to have higher or lower ranks than the other. Crucially, this test does not require normally distributed datasets. We utilize the Mann-Whitney U test to establish whether there is a statistically significant difference between the two populations (ephemeral and perennial). Three Mann-Whitney tests were performed on three different subsets of the ephemeral and perennial datasets: the full dataset, perennial channels filtered to channels that have less than 40 mm median grain size (to match the ephemeral channels), and isolating data from Phase 3 transport only.

Multiple linear regression was used to evaluate the relationship between bedload flux and several independent variables, including shear stress, watershed size, and database (perennial and ephemeral), and D_{84}/D_{16} ratio (to evaluate the effect of grain sorting). Independent variables D_{50} and slope were also considered, but excluded in this test because of their use in the calculation of shear stress and in the nondimensionalization process (Section 2.3). Other predictors, such as the percentage of sand, mean annual rainfall, or armor ratio may be relevant but are not widely available in the assembled databases. After establishing the linear regression, we evaluated the relative importance of each variable using an R^2 contribution averaging and ordering approach described in Chevan and Sutherland (1991). This method decomposes the total R^2 into contributions from each predictor. Four data subsets were established from the ephemeral and perennial datasets: the full dataset, perennial channels filtered to channels that

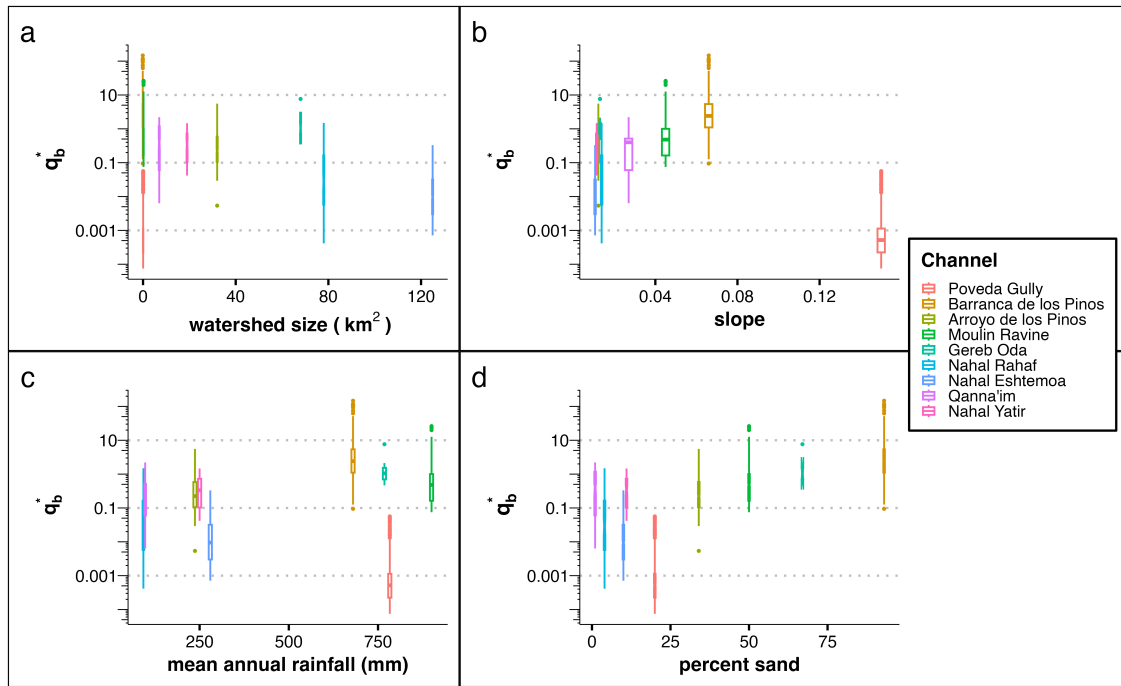


Figure 3 Average nondimensional bedload flux vs. parameters of interest: (a) watershed size, (b) mean annual rainfall, (c) channel bed slope; (d) percent of channel bed material sand-sized.

have less than 40 mm median grain size (to match the ephemeral channels), isolating data from Phase 3 transport only, and isolating the data to phase 1+2 transport only.

Finally, we evaluated the CDF of non-dimensional bedload flux and shear stress, specifically for gravel-bed rivers ($D_{50} > 2$ mm). CDF plots scale and rank every data point in a population, so that their distributions can be directly compared. We prepared CDFs for non-dimensional bedload flux and shear stress, splitting the data between phase 1+2 and phase 3 transport. This test is intended to interrogate the effect of armoring on the distributions of non-dimensional bedload flux values.

3 Results

3.1 Ephemeral database

s

We first present an evaluation of the ephemeral database to consider how bedload flux varies with different independent variables. This is a critical step to establish obvious trends in the ephemeral data. The perennial database was assembled by others and evaluated in detail by Recking (2010) and Hinton et al. (2017), whereas the ephemeral database has yet to be interrogated. Although evaluating data in dimensional space can be useful, specifically to understand the distribution of the datasets, nondimensionalization allows for direct comparison across the different channel settings and sizes. We compared the non-dimensional bedload fluxes from the ephemeral database to each site's watershed size, mean annual rainfall, channel slope, and the percent of bed material comprising sand (Fig. 3). As with the statistical tests, other variables, such as D_{50} , were considered but excluded due to their use in the nondimensionalization process. No clear trend

emerged when evaluating watershed size ($R^2 = 0.06$), or annual rainfall ($R^2 = 0.01$), but a moderate correlation was found between median non-dimensional bedload flux and channel sand fraction ($R^2 = 0.60$) and channel

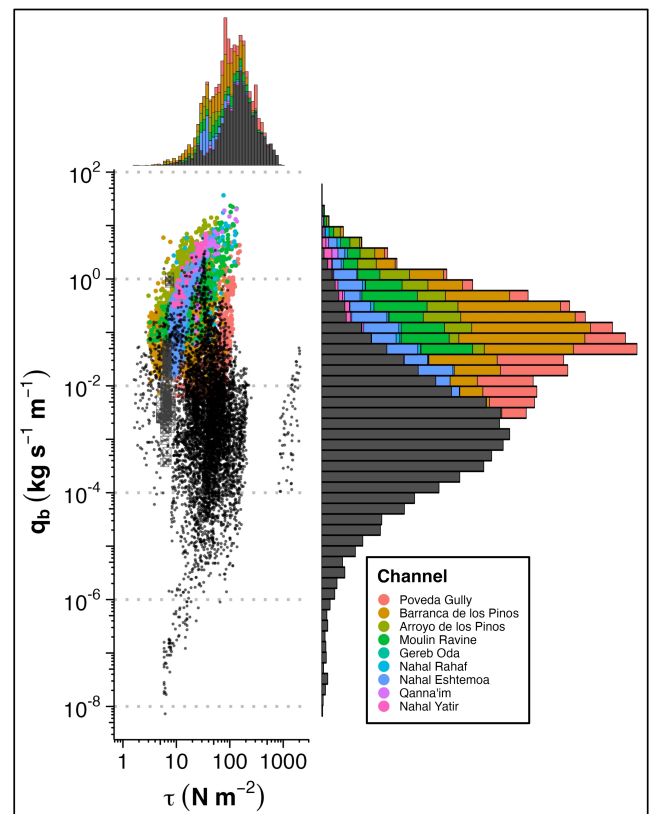


Figure 4 Bedload flux vs. shear stress. Colored points are data from the ephemeral database - black data points are from the perennial database. The large black squares are the Mississippi River dataset. The histograms show the distribution of the data (scaled to the corresponding axis).

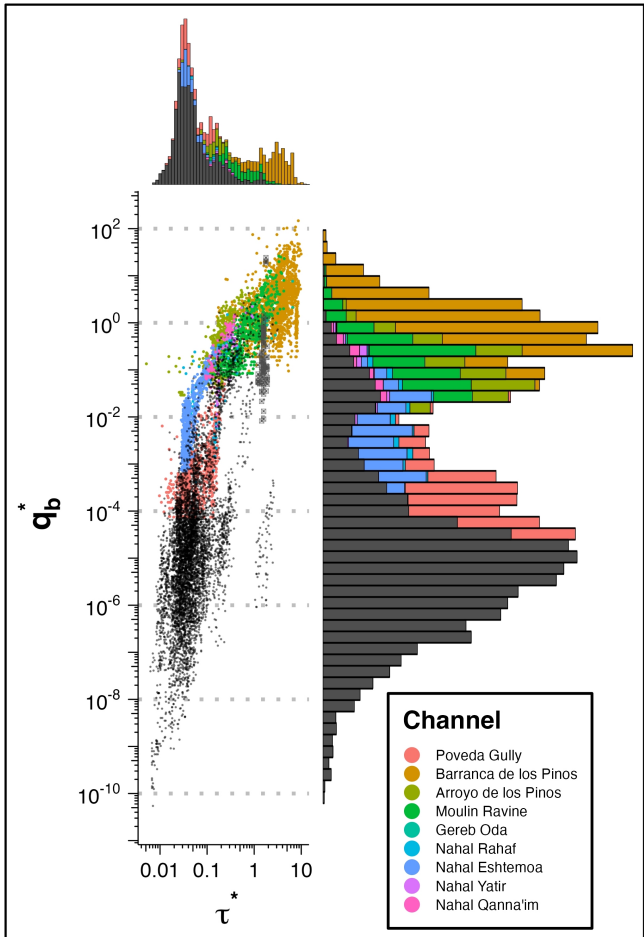


Figure 5 Nondimensional bedload flux vs. shear stress The black boxes are the Mississippi River dataset. Data are nondimensionalized using D_{50} as a characteristic length. The histograms show the distribution of the data (scaled to the corresponding axis).

slope ($R^2 = 0.23$).

3.2 Comparison of the ephemeral and perennial databases

The ephemeral streams exhibit higher bedload fluxes ($\text{kg s}^{-1} \text{m}^{-1}$) than perennial streams across the full range of reach average bed shear stress (N m^{-2}) (Fig. 4). Visual inspection shows two datasets that appear in two distinct ranges across a similar range of shear stresses (Fig. 4 histograms). Median shear stress of the ephemeral and perennial databases were 19.63 N m^{-2} and 40.1 N m^{-2} , respectively. Bedload fluxes showed a similar disparity, with median values of $0.19 \text{ kg s}^{-1} \text{m}^{-1}$ (ephemeral) and $0.0023 \text{ kg s}^{-1} \text{m}^{-1}$ (perennial). When evaluating these systems against each other in non-dimensional parameter space, significant differences are even more apparent. In q_b^* vs τ^* space (Fig. 5), ephemeral channels have high transport rates at relatively low Shields numbers, forming an upper envelope of the data even among the ephemeral channels. Instantaneous bedload flux in the perennial database approaches and occasionally exceeds transport rates observed in some ephemeral systems, but such instances are rare. In total, only 6.9% of perennial data points exceed the median non-dimensional bedload flux of the ephemeral database. This remains true when

subsetting the data into gravel-bed channels (4.2% of the perennial data exceeds the median value of the ephemeral database) and sand-bed channels (3.3%).

Investigating these features more quantitatively, we find that all nine of the ephemeral channels ranked among the top 15 in median instantaneous nondimensional bedload flux. This is confirmed with the Mann-Whitney U Tests. Because the data are best represented in log space (e.g., Fig. 5), the statistical tests were performed on log-transformed data. We also evaluated the non-transformed data – those produced similar results and are presented in supplementary material S2. The tests produced statistically significant results for all three data subsets. On average, the population medians were shifted towards the ephemeral dataset by 4 log-units (10,000 times) for the entire dataset, 2 log-units (100 times) when limiting the perennial data to channels with a $D_{50} < 40 \text{ mm}$, and 1 log-unit (10 times) when limiting both databases to channels with a $D_{50} < 40 \text{ mm}$ and phase 3 transport. All three tests produced significant results with p-values $< 2 \times 10^{-16}$.

Results of the multiple linear regressions (Table 2), designed to evaluate the relative importance of selected parameters in contributing to the overall best-fit, showed a strong dependence on non-dimensional shear stress in predicting bedload flux. After shear stress, the database each data point belonged to (ephemeral or perennial) was the second-most important predictor tested. Watershed size and D_{84}/D_{16} ratio was not an important predictor in any of the data subsets.

Table 2 Results of multiple linear regression analysis and the relative contribution of different independent variables.

Data Subset	Parameter	relative contribution to total R^2
Full	total fit	0.82
	shear stress	0.45
	ephemeral vs. perennial	0.34
	D_{84}/D_{16} ratio	0.02
	watershed size	0.01
$D_{50} < 40 \text{ mm}$	total fit	0.73
	shear stress	0.53
	ephemeral vs. perennial	0.19
	watershed size	0.01
	D_{84}/D_{16} ratio	0.01
Phase 3 and $D_{50} < 40 \text{ mm}$	total fit	0.44
	shear stress	0.21
	ephemeral vs. perennial	0.15
	D_{84}/D_{16} ratio	0.04
	watershed size	0.03
Phase 1+2 and $D_{50} < 40 \text{ mm}$	total fit	0.54
	shear stress	0.23
	ephemeral vs. perennial	0.25
	D_{84}/D_{16} ratio	0.03
	watershed size	0.02

Non-dimensional bedload flux also increases with an increase in sand content. Through the nondimensionalization process, the sand-bed rivers concentrate at the upper end of the distribution. They cover a bedload flux range of approximately 4 orders of magnitude over

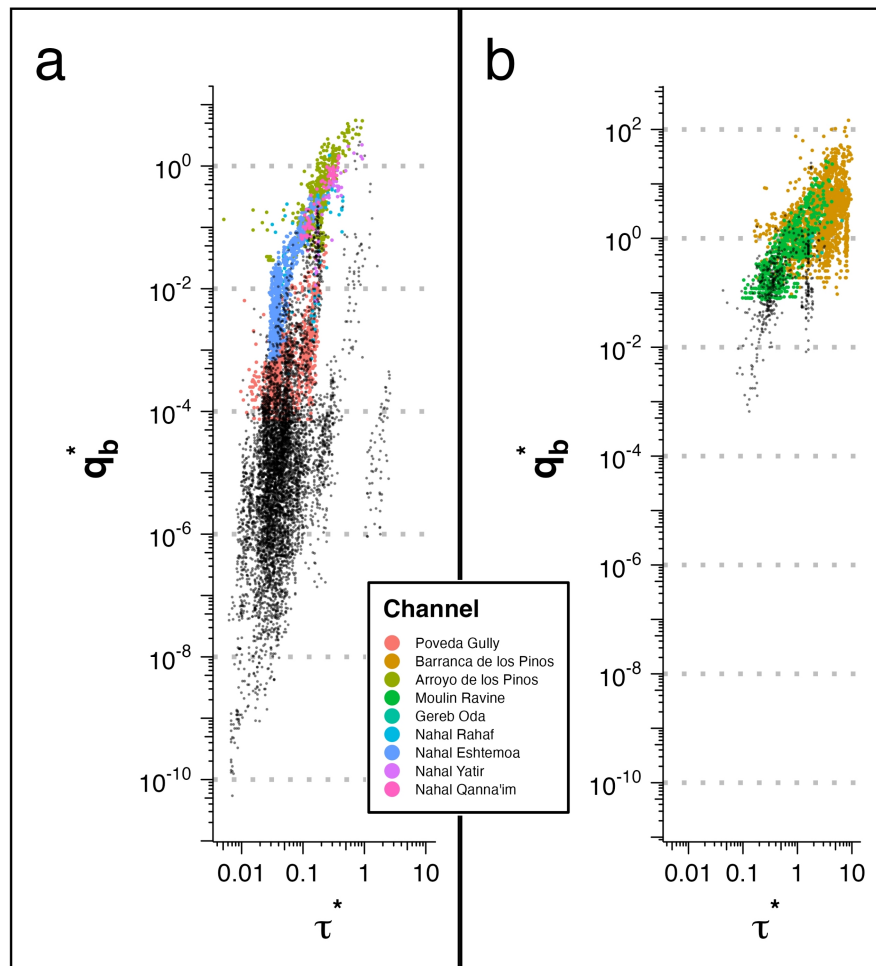


Figure 6 Distribution of gravel- (a) and sand-bed (b) rivers. Black dots represent data from the perennial river database. Data are nondimensionalized using D_{50} as a characteristic length.

2 orders of magnitude of shear stress measurements (Fig. 6b). Conversely, gravel-bed channels have a much wider range of reported bedload flux, covering nearly 10 orders of magnitude merely over 3 orders of magnitude of shear stress (Fig. 6a).

This wide range of non-dimensional bedload flux values among the gravel-bed river data is why our final statistical test focused on the gravel-bed river data subset. For this, we ranked all non-dimensional bedload flux and shear stress data for phase 1+2 and separately phase 3 transport (Fig. 7), conducting Mann-Whitney tests to compare the two populations. Significant differences between the two datasets persist, particularly for periods of low shear stress (Fig. 7a). Ephemeral channels tend to have many factors that have been proposed to contribute to these multiple-order-of-magnitude greater rates of instantaneous bedload transport (lack of an armor, sand-and-gravel mixtures, high bank erodibility, etc.). As flow strength increases, the gap between perennial and ephemeral channels decreases, although it persists in the data gathered for this analysis (Fig. 7b). The persistence of these differences in flux cannot be explained by armoring, since these values represent periods after armor breakup. It also is not due to differences in flow strength, as the population of shear stresses of the perennial channels database is greater than that of the

ephemeral channels during high transport conditions (Fig. 7d).

4 Discussion

4.1 Analysis of the ephemeral database

Our investigation into ephemeral channels broadly match other meta analyses into bedload flux (Recking, 2010; Hinton et al., 2017; Ancy and Recking, 2023). Bedload flux is principally controlled by flow strength (in our case shear stress), with other basin-wide characteristics, such as watershed size or annual rainfall, having little predictive power. Grain size is an important characteristic, and we found the percentage of sand to be a relatively strong predictor of bedload flux ($R^2 = 0.60$).

In addition, coefficients of variation (CV - the ratio of mean to standard deviation) of the bedload flux data were high relative to values for perennial streams, suggesting fewer damping factors such as bed armoring and particle hiding. The lowest CV of any of the ephemeral channels is reported at the Poveda Gully (0.36). The value is still higher than all but five of the channels in the perennial database and is notable because the Poveda Gully is the only ephemeral channel in our database that contains an occasional armor. Za-

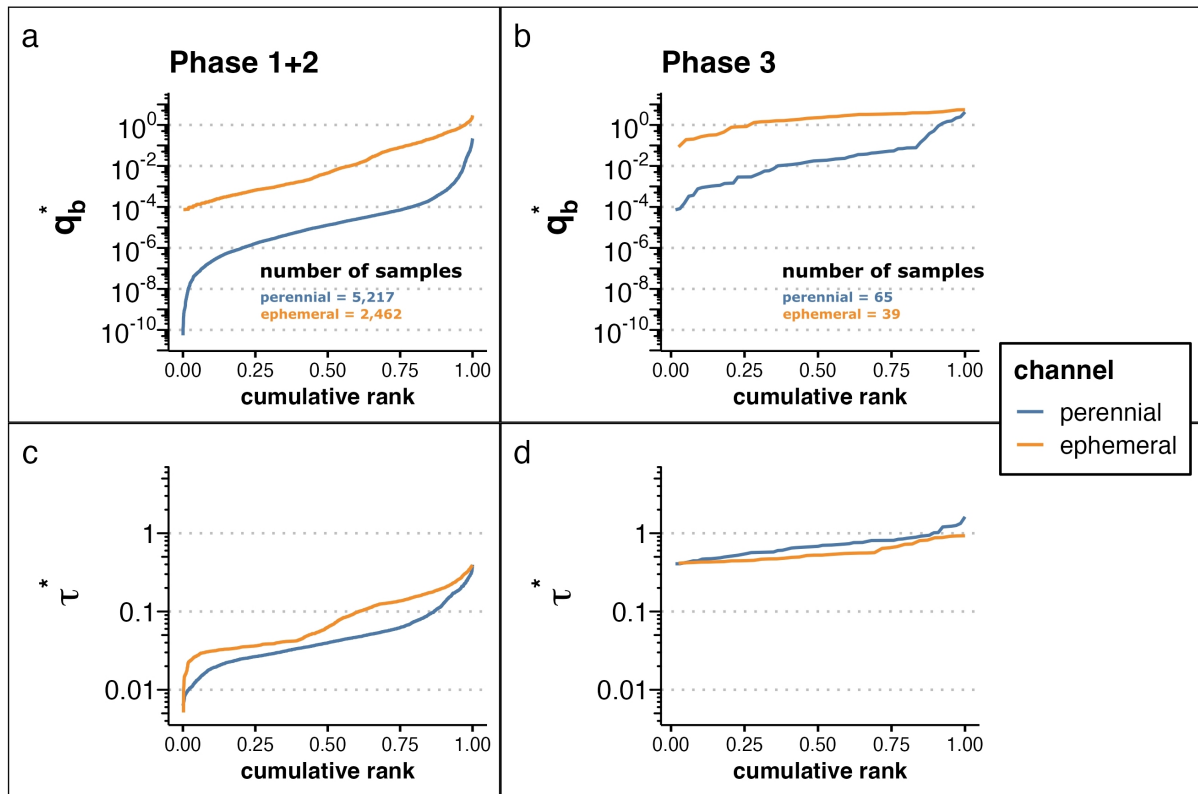


Figure 7 Empirical CDF plots of nondimensional bedload flux and shear stress for gravel-bed rivers ($D_{50} > 2$ mm) during Phases 1 and 2 transport (**a** and **c**) and Phase 3 transport (**b** and **d**). Each dataset is ordered such that 0 represents the smallest q_b^* and τ^* values and 1 represents the largest. Phase 3 transport is defined using a threshold value τ^* of 0.4, after Ancey and Recking (2023).

pico et al. (2018) note that this armor caused variability in the sediment availability and led to lower-than-expected rates of bedload transport. In general though, none of the ephemeral channels departed significantly from the established q_b^* vs. τ^* trend, the most important predictor of bedload flux remains flows strength.

4.2 Analysis of the Ephemeral Database

We have established a quantified and persistent discrepancy in non-dimensional bedload flux between the perennial and ephemeral databases. We hypothesize that these observed differences are the result of several possible differences between the two populations. Below we explore the most likely possibilities and comment on their relative importance based on a wider body of bedload research. This discussion largely focuses on gravel-bed rivers, where bedload flux varies more with flow strength (Fig. 6).

4.3 Bed armoring

The existence of coarse armor lags in perennial rivers, produced by winnowing during baseflow, is a clear candidate mechanism to reduce instantaneous perennial river bedload flux relative to ephemeral rivers. Yet, as this armor breaks up and the underlying unsorted sediment is exposed, as in phase 3 transport, this mechanism is reduced and largely eliminated. The observed differences in relative transport between ephemeral and perennial rivers at phases 1 and 2 transport should include the influence of armoring, whereas the ob-

served differences at phase 3 transport should not. In our analysis of gravel-bed rivers, where armor development is possible, both databases have similar driving force distributions (Fig. 7c and 7d), meaning differences in shear should not be dominating differences in bedload flux. As expected, during phases 1 and 2, the ephemeral channels have higher normalized bedload flux (Fig. 7a), by over two orders of magnitude (Mann-Whitney test 95% confidence interval for difference in location of 2.6-2.8 in log space). This is consistent with a strong influence due to bed armoring.

However, much of the difference persists in the data collected during phase 3 transport (Fig. 7b), after armor breakup. In spite of the perennial database having slightly higher Shields parameter values, the ephemeral database still has a statistically higher bedload flux population (Mann-Whitney test 95% confidence interval for difference in location of 1.8-2.3 in log space). An additional mechanism appears to be playing a significant role in promoting sediment transport in ephemeral channels.

If winnowing and armoring drive this difference, then a surface coarsening would be anticipated in the perennial database relative to the ephemeral database for channels with equivalent subsurface (i.e., pre-armor) grain size distributions. Because both shear and bedload flux values were normalized according to surface D_{50} , this may play a role in separating the two populations. However, armor ratios (surface D_{50} over subsurface D_{50}) are not available for all rivers in the databases, leaving such an analysis as a target for fu-

ture research. Normalizing Phase 3 transport data using subsurface D_{50} would be a novel approach to the issue.

4.4 Grain size distribution and sand/gravel mixtures

The breadth of the grain size distribution, especially when there is a mix of sand and gravel, has been shown to influence bedload flux (Wilcock and Crowe, 2003; Miwa and Parker, 2017), by altering the shielding and exposure of particles. Perhaps this is the additional mechanism implied by our data analysis. Unfortunately, only limited sorting data is available in the two databases we analyzed. Some channels had D_{84} and D_{16} data, but for those with data, the ephemeral channels had a similar range of D_{84}/D_{16} ratios as the perennial channels (4-64), although for a given ratio the ephemeral channels were consistently finer-grained. More extreme ends of the distribution may be required to quantify this effect, for example a D_{95}/D_{05} ratio, but those data are not currently available for the databases. Hence, we cannot fully evaluate the role of this mechanism in driving the differences in observed bedload flux.

An additional explanation may lie in the lack of specific size classes. Perennial channels are reported to have a paucity of coarse sand and fine gravels in the 1-5 mm range, producing an observed 'sediment gap' in bed material (An et al., 2024). Ephemeral processes do not have as much time to develop such a gap, according to the proposed mechanisms (An et al., 2024). Indeed, small gravels (1-5 mm) can be quite abundant in ephemeral channels, for example accounting for over 26.5% of bed material in the Arroyo de los Pinos, one of the gravel bed ephemeral channels included in our new database. It is possible that by having a paucity of material in this easily transported bedload size class, both sand-bed and gravel-bed perennial rivers will experience a reduction in total bedload flux compared to ephemeral channels under the same hydraulic conditions.

4.5 Sediment supply and hydrograph shape

Ephemeral channels are generally thought to be transport-limited rather than supply-limited (Reid et al., 1995; Halfi et al., 2020). Data from ephemeral channels compiled here support this; all principal citations comment that their channels are transport-limited. Conversely, perennial gravel-bedded rivers are often characterized by their supply limitations, particularly in steep, gravel-bedded mountain channels. Supply-limited channels report lower rates of transport, which may lead to an overprediction of bedload transport using transport equations (Yager et al., 2012). Differences in sediment supply may explain some of the dissimilarities we observe in the two datasets, especially between mountain gravel-bed channels and ephemeral channels. However, some instances of high sediment supply in perennial channels have been associated with high rates of bedload transport (Hayes et al., 2002; Nittrouer et al., 2011), although these examples are usually associated with

rare environmental events (e.g., mass wasting events, volcanic eruptions, see Hayes et al., 2002), and dam removals (Winter, 1990).

Hydrograph shape is another potential source of difference between ephemeral and perennial systems. Ephemeral channels are typically characterized by their flashy or bore-style flow, implying that they reach peak discharge faster than perennial systems of similar size and slope (Merritt et al., 2021). Most publications describe rainfall in these areas as high-intensity, which leads to high runoff ratios and steep hydrograph rises (Hassan, 1990; Dick et al., 1997). These characteristics, combined with the general lack of vegetation in many ephemeral systems (which leads to more Hortonian overland flow) could indeed cause higher rates of bedload transport (Thappeta et al., 2023).

4.6 Data quality and completeness

While the database of ephemeral channel bedload transport is the most comprehensive assembled to date, it is far from complete. Specific issues include: (i) a general lack of data from large magnitude floods; (ii) lack of data from cobble and boulder-bed ephemeral channels; and (iii) few data for flash flood rising stages of flow.

Ephemeral channels are typically in areas of low development and require automated systems to monitor. This, combined with the infrequency of flows, creates circumstances whereby bedload flux at high discharges were not evaluated. Even in systems with long records (i.e., the Nahal Eshtemoa's 29-year monitoring history), the system in place to measure bedload flux often reaches capacity before peak discharge (Halfi et al., 2020). For the entire record, less than 10% of flood periods on the Eshtemoa had direct measurements of bedload (E. Halfi, pers. comm.). A similar phenomenon has been observed on the Arroyo de los Pinos, where only 29% of flood periods have measured bedload transport rates. These data are further biased toward smaller flow magnitudes: only the lowest one-third of the observed flow magnitudes have associated bedload flux data at the Arroyo de los Pinos. Because of a lack of data from larger floods, the vast majority of bedload flux data presented in this manuscript are from small, commonly occurring (one to three-year recurrence) flow events in ephemerals. This issue of data incompleteness also exists for the perennial streams, especially gravel-bed rivers where the majority of data was collected during intra-flood periods. A notable exception to this is the Mississippi River dataset, where the highest measured bedload fluxes occurred during water discharges that had not been observed for over 10 years (Nittrouer et al., 2008). Both databases are biased towards commonly occurring flow events, or periods between floods. But it remains likely that the ephemeral database has a higher proportion of data from smaller flow events, simply because there are fewer individual streams in the database.

Another consideration is the lack of data from cobble and boulder-bed ephemeral channels. The channels with the largest median grain sizes (Poveda Gully and Nahal Eshtemoa) also include considerable compo-

nents of fine gravel or sand (Powell et al., 2001; Zapico et al., 2018). We speculate two reasons for this: first, the general lack of consistent data from diverse ephemeral channels, and second, the physical processes required to form channels with large boulders and few fines. The first is self-explanatory: with only nine channels in the database, the bedload data available from ephemeral channels is not as diverse or comprehensive as it is for perennial systems. Still, there may also be physical constraints on how coarse-grained an ephemeral channel may become. Without baseflow to cause winnowing, ephemeral channels are less likely to become exceptionally coarse-grained. Indeed, the formation of large, fine-grained bed areas (sometimes referred to as flats) between coarser bars is typical of short recessions in ephemerals. When an ephemeral channel is exceptionally coarse, such as typical channel reaches of dryland bedrock rivers (Finnegan et al., 2007), the finer fraction of sand or gravels is to a large extent transported downstream, such as is commonly found in alluvial fans at the outlets of desert bedrock rivers (Storz-Peretz and Laronne, 2013). Even when an ephemeral channel becomes partially armored, such as in the case of Poveda Gully, higher rates of bedload transport than in other armored channels suggest that large sections of the bed are mobile, even when the largest grains are not. This is true for cases where large boulder fractions exist in ephemeral channels: finer fractions still persist, and this fine material (sand-sized in this instance) contributes to the morphological features of the channel (Billi, 2016). All of these factors contribute to their high efficiency and their globally high rates of bedload transport.

An additional issue with the assembled ephemeral database relates to the assumptions associated with the estimation of near-bed shear stress. There are acknowledged drawbacks to using the depth-slope product to evaluate bedload transport (Biron et al., 2004; Yager et al., 2018). Unsteady and nonuniform flows are common in ephemeral channel settings because of their flashy nature. The implications of simplifying the estimates of tractive forces on the systems are not precisely quantified, but some studies suggest that estimates of shear stress will be underestimated, particularly during fast-rising bores (Meirowich et al., 1998; Halfi et al., 2018). These issues have broader implications for initiation of transport, but the unarmored beds and poorly sorted sediments of ephemeral channels may bring consistency in initiation of motion, at least when compared to perennial systems.

5 Conclusions

Based on a comparison of the assembled databases, ephemeral channels are shown to be highly effective at delivering bedload downstream, consistently delivering one to four orders of magnitude more bedload downstream than perennial channels, despite similar flow strengths (Fig. 7). These findings are remarkable not simply because these ephemeral channels are effective at transporting bedload; indeed, others have long suggested this (Langbein and Schumm, 1958; Laronne and

Reid, 1993; Reid et al., 1995). Rather, these results are noteworthy because of their consistency across grain size, watershed size, slope, climate, and flow strength. It is evident that ephemeral systems are the drivers of significant amounts of bedload transport worldwide, specifically because of the predominant lack of bed armoring, the absence of winnowing of fine-grained material, the general lack of vegetation, and the availability of transportable sediment. At low Shields stress (prior to armor breakup in perennial channels), the high bedload flux in ephemeral channels and the negligible flux in perennial channels indicate that fine grain winnowing and bed armoring is an important control on relative bedload transport. Yet the higher flux in ephemeral channels persists into later phases of transport, when armor in perennial channels is broken, indicating that armor is not the only cause of the differences between these systems. The differences at high flow must be attributed to a combination of other causes, such as the abundance of coarse sand and fine gravel (gap sediments), the ready availability of sediment from poorly vegetated banks, and the sudden rise of the hydrograph and the very fast recessions. Further data collection should focus on these characteristics, to enable evaluation of their relative roles. Collecting bedload flux data from major transporting events remains a fundamental challenge, from a logistics and safety perspective, but is the key to understanding these systems. Ephemeral channels and their hydraulic-geomorphic dynamics are crucially important to all river networks. Even in humid regions, headwater channels are often ephemeral. Yet these properties attain specific importance in areas where non-perennial rivers are most common: dryland climates worldwide.

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Land Recognition

We recognize that our work was completed from institutions located on the traditional and unceded lands of the Jumanos, Mescalero Apache, Pueblos, and Piro nations, as determined from the website (<https://native-land.ca>).

Data and Codes Availability

The perennial database used in the study is available via the original authors, Recking (2010), and Hinton et al. (2017) (who originally compiled the datasets). The ephemeral database, which includes the nine rivers detailed in Table 1, have been uploaded to the Harvard Dataverse Repository via <https://doi.org/10.7910/DVN/TAYWWJ> with license CC0 1.0. It is referenced in this manuscript as Stark et al. (2022).

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Conflict of Interest Disclosure

The authors have no competing interests.

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