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Landscapes on the edge: River intermittency in a warming world

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ABSTRACT

Sediment transport in rivers is not steady through time. Highly intermittent river systems, which only transport bedload during the most significant flow events, are particularly sensitive to changes in climate and precipitation patterns. People and landscapes can be vulnerable to fluvial processes, and quantifying river intermittency is critical for assessing landscape response to projected changes in precipitation extremes due to climate change. We generated new constraints on recent to modern fluvial intermittency factors—the frequency at which bedload is mobilized in a river—based on field measurements in the Corinth Rift, Greece, and Holocene sediment accumulation rates. Results reveal some of the lowest documented intermittency factors to date, showing Mediterranean rivers can transport an entire annual sediment load in a rare storm event. Coupling intermittency calculations with historical flood and precipitation data indicates these rivers transport bedload during one storm every ∼4 yr, associated with rainfall >50 mm/d, and subsequent floods; this hydroclimate is typical across the Mediterranean region. Furthermore, climate models predict precipitation extremes will increase across Europe, and the frequency of events that surpass thresholds of sediment transport will increase significantly, potentially causing sediment loads to double by 2100 CE. As the area of arid land likely to host intermittent rivers also increases, sensitive landscapes are on the edge of significant geomorphic change, driven by global warming.

INTRODUCTION

River dynamics have a powerful impact on landscapes over decadal to millennial time scales (Romans et al., 2016). A key aspect of a river's discharge regime, and one that is vital to understanding landscape response to climate change, is its intermittency. A river intermittency factor, I_f, can be defined as the fraction of time that a river requires to transport its yearly water or sediment budget if it acted at maximum transport capacity (Paola et al., 1992). In other words, I_f is a ratio of average flux over a set time scale to potential bankfull flux if it were sustained over the same period (Hayden et al., 2021; Lyster et al., 2024), or how much material a river is moving versus what it could be moving. With increasing intermittency (i.e., decreasing I_f), rivers concentrate activity in shorter, isolated periods of discharge, separated by longer periods of low or no discharge.

Ephemeral, or highly intermittent rivers (generally considered to have measurable flow <10% of the time; Hedman and Osterkamp, 1982), corresponding to $I_f < 0.1$, are associated with particular climate characteristics (Hansford et al., 2020), including high evaporation rates and infrequent but extreme precipitation. Climate models (e.g., IPCC, 2022) show that precipitation extremes are increasing in many regions as a result of anthropogenic climate change. In Europe and the Mediterranean region, estimates suggest that by the year 2100 CE extreme precipitation and flooding could increase by 20% (e.g., IPCC, 2022; see Supplemental Material[1]).

Ephemeral rivers transport large proportions of their annual sediment load during floods. Therefore, an increase in the frequency of floods that surpass thresholds for sediment transport could drastically change transport capacities and, potentially, sediment budgets in the coming decades, degrading landscapes, threatening infrastructure integrity, and impacting nutrient fluxes and carbon burial. But how sensitive are ephemeral rivers to changing precipitation patterns, and to what extent will changing weather patterns impact sedimentary systems in the near future?

To answer these questions, better constraints on intermittency factors are imperative, but these require study sites where long-term sediment fluxes can be constrained. We focus on rivers draining the Corinth Rift, Greece (Fig. 1A; Watkins et al., 2019, 2020), one of the fastest expanding rifts in the world (McClusky et al., 2000). The Gulf of Corinth basin is closed and sediment-starved, allowing accurate age models and sediment volumes to be reconstructed from seismic stratigraphy and International Ocean Discovery Program (IODP) cores (Nixon et al., 2016; McNeill et al., 2019; Watkins et al., 2019, 2020). Rivers are ephemeral, transport-limited, and gravel-bedded (Figs. 1C–1E). They have well-constrained Holocene and interglacial bedload fluxes (Watkins, 2019; Watkins et al., 2020), and hydroclimatic similarities to many

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[1]Supplemental Material. Additional background on climate, extended methodology, and extended intermittency results. Please visit https://doi.org/10.1130/GEOL.S.25395718 to access the supplemental material; contact editing@geosociety.org with any questions.

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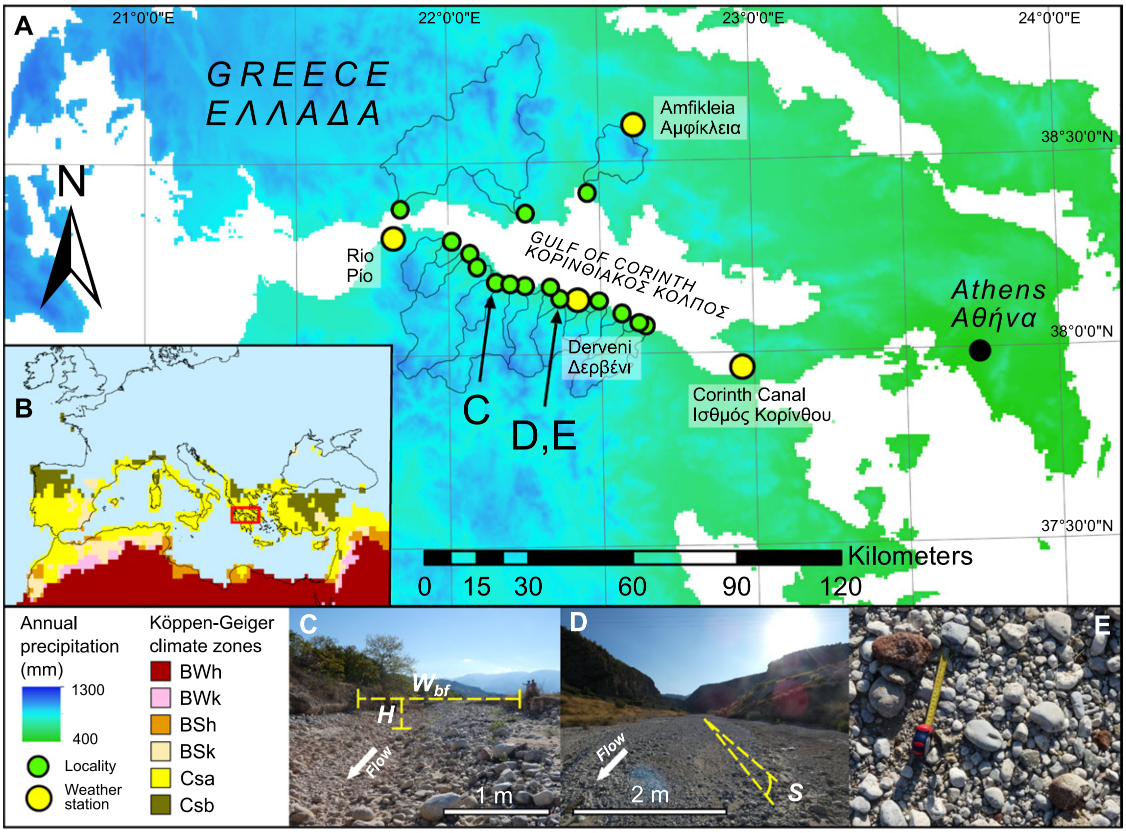

Figure 1. (A) Map of the Gulf of Corinth rift region showing mean annual precipitation (WorldClim, https://worldclim.org; Hijmans et al., 2005), field localities, weather stations used in analysis, and river catchments (black outlines). (B) The Mediterranean region, with the dry and arid Köppen-Geiger climate zones (Rohli et al., 2015; see Supplemental Material [see footnote 1]) highlighted. (C) Field data collection methodology for bankfull channel width (W_{bf}) and depth (H) at Kerinitis (location shown in A). (D) Same as C but for slope (S) at Krios (location shown in A). (E) Example of bedload sediment.

ephemeral rivers documented across Europe (see Supplemental Material), such as temperature, precipitation, and discharge regime. We use multiple approaches to estimate sediment flux I_f and we link results to known precipitation hydrographs, revealing the sensitivity of such landscapes to storm-driven precipitation in the present and future.

METHODS

Data Collection

We collected field data in the Corinth Rift from 16 rivers (Figs. 1A and 1B). Sites were located along channels where fluvial processes dominate, upstream of the backwater zone. To reconstruct potential bankfull bedload flux, measurements of bankfull depth (H_{bf}) (see Supplemental Material), width (W_{bf}), and slope (S) were collected using a Haglöf Laser Geo range finder to a precision of ±5 cm (Figs. 1C and 1D). We used field measurements of slope in our analysis, verified using 30 m (NASA JPL, 2020) and 5 m (Hellenic National Cadastre and Mapping Agency S.A, 2016) digital elevation models. Median bedload grain size (D_{50}) was determined using the Wolman point count method (Fig. 1E; Wolman, 1954), providing a minimum bound on the maximum transport capacity of the river.

Calculating Intermittency Factors

Bankfull bedload sediment fluxes ($Q_{s,bf}$, m^3/s) were calculated using the Meyer-Peter and Müller formula (Meyer-Peter and Müller, 1948; Wong and Parker, 2006):

$$Q_{s,bf} = W_{bf}(gD_{50}{}^3\Delta\rho)^{0.5}C(\tau_b^* - \tau_c^*)^{\alpha}, \quad (1)$$

where $g = 9.81$ ms^{-2}, $\Delta\rho$ is the dimensionless submerged specific gravity of sediment (1.6), dimensionless basal shear stress $\tau_b^* = H_{bf}S/\Delta\rho D_{50}$, and dimensionless critical shear stress τ_c^* and constants C and α are taken as 0.047, 4.93, and 1.6, respectively (after Wong and Parker, 2006). The sediment transport intermittency factor, I_f (Hayden et al., 2021; Lyster et al., 2024), is given by:

$$I_f = \frac{\Sigma Q_s(t)}{Q_{s,bf}\Sigma t}, \quad (2)$$

where $\Sigma Q_s(t)$ is the sum of the time-dependent sediment discharge, and t is the timespan. We use two methods to reconstruct Holocene sediment fluxes: ΣQ_s, a delta volume (DV) approach, and a catchment-basin volume (CBV) approach.

The DV approach exploits the prominent Gilbert-type deltas that prograde into the Gulf of Corinth. Uplifted delta successions, published grain-size analyses, and hydrodynamic reconstructions (Watkins et al., 2020) confirm that modern deltas represent the vast majority of the bedload fraction supplied to the basin, with the suspended fraction transported to the distal basin floor. A reasonable (but minimum) estimate of $\Sigma Q_s(t)$ was acquired using a simplified model of delta volume (see Supplemental Material) and a Holocene age (t) for active modern deltas (Watkins et al., 2020).

The CBV approach uses published sediment fluxes matched to a Holocene basin isopach previously verified for the studied catchments by Watkins et al. (2019, 2020). Their data set primarily documents suspended sediment flux, so to scale down to bedload flux, the ratio of bedload to total sediment flux (R_{bt}) must be estimated. Watkins et al. (2019, 2020) assumed $R_{bt} = 0.35$ (Pratt-Sitaula et al., 2007), and we have conducted an alternative analysis of the volumetric ratio of coarse (rift-margin) and fine (basin-floor), yielding $R_{bt} = 0.25$. To represent uncertainty, we present CBV I_f for $R_{bt} = 0.25$ and 0.35 (see Supplemental Material, section 4.3). All uncertainty has been propagated through calculations using Monte Carlo simulations (Fig. 2C; see Supplemental Material).

We used daily precipitation data (from the National Observatory of Athens, https://www.noa.gr; Lagouvardos et al., 2017) from the study area (Fig. 1A) over the full available record (11 yr) to establish precipitation frequency-magnitude distributions that are representative of the studied catchments through time, since modern sediment fluxes are similar to those from across the Holocene (Watkins et al., 2019). We compared these distributions with I_f estimates and a literature data set documenting storms and floods between 2007 and 2021 CE within 50 km of the study area (see Supplemental Material).

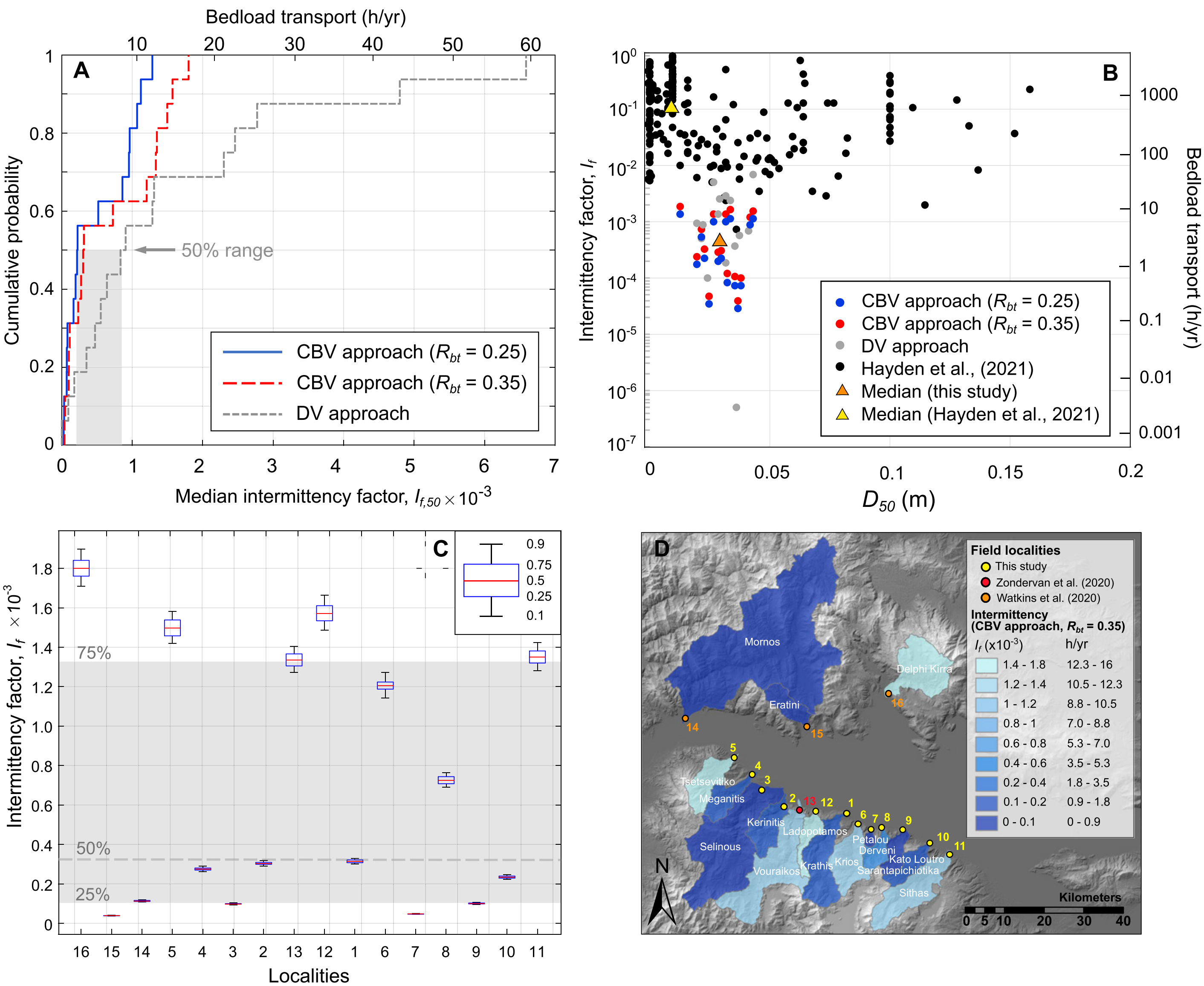

Figure 2. Fluvial intermittency. (A) Cumulative distribution function of the median intermittency factor ($I_{f,50}$; Paola et al., 1992) for Gulf of Corinth (Greece) catchments (primary *x*-axis) and equivalent hours of bedload transport per year (secondary *x*-axis) for our two approaches to reconstructing Holocene sediment fluxes (see the text): CBV—catchment-basin volume approach; DV—delta volume approach; R_{bt}—ratio of bedload to total sediment flux. (B) Scatter plot showing ranges in I_f and median bedload grain-size (D_{50}) in the Gulf of Corinth compared to the compilation of Hayden et al. (2021). On the secondary *y*-axis, I_f is presented as hours of bedload transport per year. (C) Boxplot showing I_f calculated using the CBV [R_{bt} = 0.35] approach, where localities in panel D are ordered anti-clockwise around the Gulf of Corinth. (D) Map of studied catchments, colored according to I_f.

RESULTS AND DISCUSSION

Intermittency Factors

The DV and CBV approaches produce consistent results (Fig. 2A and 2B) and show that rivers draining into the Gulf of Corinth are highly intermittent—the median bedload transport I_f across our three estimates is 4.67 × 10⁻⁴ (Fig. 2A) with lower and upper quartiles of 2.10 × 10⁻⁴ and 1.56 × 10⁻³, respectively. This result implies that, on average, rivers transport bedload sediment less than 0.05% of the time, and at bankfull conditions, they would need 4 h of bedload transport to complete their annual sediment load (0.05% of 1 yr). Our estimated I_f values are among the lowest documented to date, showing sediment transport in ephemeral Mediterranean catchments is 100–400× more intermittent than that of previous compilations of modern rivers focused on the United States (Fig. 2B; Hayden et al., 2021) and of recent palaeohydrological reconstructions (McLeod et al., 2023; Lyster et al., 2024; Sharma et al., 2024). There is no spatial trend in I_f around the Gulf of Corinth (Figs. 2C and 2D), and no correlation is found with channel or catchment parameters (see Supplemental Material), implying that the key driver of intermittency is likely to be climate, rather than other thresholds to sediment transport.

Precipitation and Floods

Fluvial landscapes with low I_f are likely to be particularly sensitive to changes in the magnitude and distribution of extreme climate events (Tucker and Slingerland, 1997; Sharma et al., 2024). To investigate the characteristics of precipitation events that drive major transport events in the Gulf of Corinth, we used an 11 yr time series of daily precipitation data from four weather stations (Derveni, Rio, Corinth, and Amfikleia in Fig. 1A; e.g., Fig. 3A for the Corinth station; Lagouvardos et al., 2017), establishing frequency-magnitude distributions representative of the catchments studied (Figs. 3B and 3C). The median I_f of 4.67 × 10⁻⁴

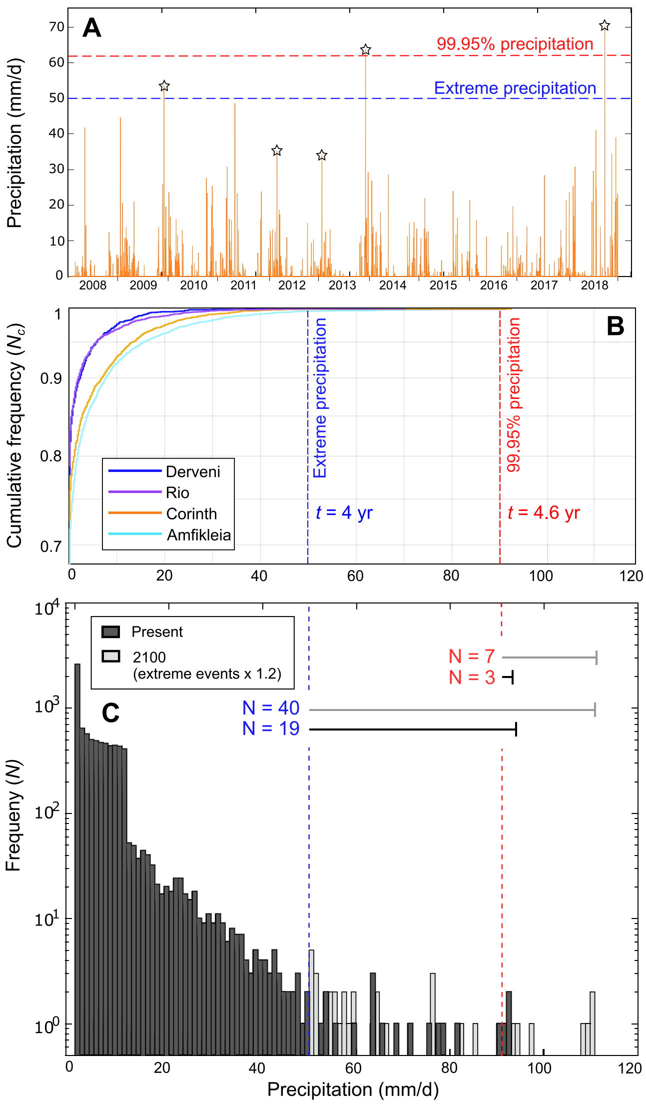

Figure 3. Precipitation analysis for the Gulf of Corinth, Greece. (A) Daily precipitation time series (median 0.4 mm/d) measured at the Corinth weather station (orange curve in B) from 2008 to 2018 CE (Lagouvardos et al., 2017), where stars represent observed floods near the study area, the blue dashed line shows the global threshold for extreme precipitation (50 mm/d; Karl et al., 1995), and the red dashed line represents the 99.95% rainfall value across the observed period (91 mm/d across all four weather stations shown in B [locations shown in Fig. 1A]; 62 mm/d at the Corinth weather station). (B) Cumulative distribution function of precipitation from the four weather stations, including return interval (*t*) for threshold-surpassing events. (C) Precipitation frequency histogram, with measured precipitation data (dark gray) and potential precipitation in 2100 CE (light gray), including the number of threshold-surpassing events in each scenario.

for bedload transport, if averaged over one year, suggests the probability threshold for a precipitation event associated with bedload transport is 99.95% [=1 – (4.67 × 10^{-4}); Fig. 3]. The 99.95% value across the four weather stations is 91 mm/d. For comparison, the median across the four stations is 0.4 mm/d, and a commonly accepted value for rare and extreme precipitation globally is 50 mm/d (blue dashed line in Figure 3; e.g., Karl et al., 1995). Recent floods in the region are caused by rainfall with a mean duration of 14 h and mean rate of 99 mm/d (see Supplemental Material), and floods can be considered to have a similar duration to their formative precipitation in this region (e.g., Papagiannaki et al., 2017; Giannaros et al., 2020). If bedload were in motion for a 14 h flood period, the I_f of 4.67 × 10^{-4} (corresponding to 4 h/yr) indicates sediment is more likely moved during one flood every 3.5 yr. The average recurrence of floods caused by precipitation magnitudes >50 mm/d and >99.95% are 4 yr and 4.6 yr, respectively (Fig. 3B). This is consistent with recurrence periods reconstructed from I_f and flood frequency (stars in Fig. 3A) recorded by the four analyzed precipitation time series (see Supplemental Material). Further, all threshold-surpassing events from these stations were associated with large documented floods.

Combining geomorphic investigation of modern rivers with flood and precipitation records confirms that Mediterranean rivers can be extremely intermittent, and the average I_f of 4.67 × 10^{-4} suggests a regime where geomorphic change due to bedload transport is dominated by one storm approximately every 4 years.

Future Projections

These fluvial Mediterranean landscapes are dominated by extreme rainfall events. Where yearly sediment fluxes can be equalled in a few hours, one additional threshold-surpassing storm or flood can change sediment budgets significantly, with potential impacts for landscape degradation and infrastructure integrity (Jongman et al., 2014; IPCC, 2022; Yin et al., 2023). Our analysis directly implies that ephemeral rivers are likely to be disproportionately sensitive to future changes in the distribution of extreme rainfall events.

But how will this change in the future? A compilation of climate models (e.g., IPCC, 2022; see Supplemental Material) for Mediterranean regions with similar climate characteristics strongly suggests the region could see an approximately 20% increase in extreme precipitation by 2100. This means that the magnitude and/or frequency of the largest precipitation events are likely to increase markedly in the near future, driven by climate change.

Consequently, the frequency of events surpassing local thresholds for bedload transport will also increase. As an illustration, Figure 3C shows a transformation applied to historical precipitation data for the region, to reflect the projected 20% increase in precipitation extremes. By scaling the distribution of extreme precipitation by a factor of 1.2, the number of events expected to surpass current thresholds for extreme rainfall, generating significant bedload transport, increases by over 100%. This implies that by 2100, ephemeral rivers like those studied could see sediment fluxes more than double compared to today's benchmark. While this model increases mean annual precipitation (MAP) by 2%, MAP in this region may, in detail, decrease while the extremes increase in magnitude and frequency (e.g., Tramblay and Somot, 2018; IPCC, 2022), but this illustrative model highlights the significant impact of extreme climate-driven precipitation on dryland rivers. We also note that the increase of extreme sediment transport with precipitation is not 1:1. Our study adds to a growing body of work estimating landscape response to climate (e.g., Molnar et al., 2006) and establishes that arid regions can experience more sediment transport with increasing weather extremes.

Changing Landscapes

This disproportionate geomorphic climate response is emphasized by evolving global climate zones. Dry and arid climates are most likely to host ephemeral rivers (Sauquet et al., 2021), and Rohli et al. (2015) projected a 1.6 × 10^6 km^2 increase in the global area of dry and arid land from 2000 to 2100 CE, an area the size of France, Spain, Italy, and the UK combined. Therefore, by 2100, sediment fluxes may increase across a growing area of sensitive landscapes worldwide. While catchments may adjust to the changing intensity and distribution of rainfall over longer periods (Watkins et al., 2019), on decadal to centennial time scales, changing sediment budgets will increase erosion and aggradation rates in similar transport-limited systems, with implications for agriculture, infrastructure, and populations from source to sink (e.g., Jongman et al., 2014; IPCC, 2022; Yin et al., 2023).

Flood risk and associated societal damage will increase with every increment of global warming (IPCC, 2022). Our work demonstrates that many river systems in southern Europe, typified by the Gulf of Corinth, already have extremely intermittent sediment transport, with a median bedload I_f of 4.67×10^{-4} (0.05% of 1 yr; Fig. 2). Combined with historical flood and precipitation records, we calculate that such rivers are characterized by significant bedload transport, on average, during one extreme storm event every 4 years. We show these sensitive landscapes are now on the edge of very significant geomorphic change driven by anthropogenic global warming, which could more than double river sediment budgets by 2100.

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