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Landscapes on the edge: river intermittency in a warming world

Jonah S. McLeod*[1,2], Alexander C. Whittaker[1], Rebecca E. Bell[1], Gary J. Hampson[1], Stephen E. Watkins[3], Sam A.S. Brooke[4], Nahin Rezwan[1], Joel Hook[1], Jesse R. Zondervan[5], Vamsi Ganti[6,7], Sinéad J. Lyster[8]

[1]Department of Earth Science and Engineering, Imperial College London, London, UK;

[2]Science and Solutions for a Changing Planet DTP, Grantham Institute, London, UK;

[3]JBA Consulting, UK;

[4]Terrabotics, UK,;

[5]Department of Earth Sciences, University College London, UK;

[6]Department of Geography, University of California Santa Barbara, Santa Barbara, CA, USA;

[7]Department of Earth Science, University of California Santa Barbara, Santa Barbara, CA, USA;

[8]Department of Geosciences, The Pennsylvania State University, State College, PA, USA

*Corresponding author: Jonah McLeod (jonah.mcleod18@imperial.ac.uk)

ABSTRACT

Sediment transport in rivers is not uniform through time. Highly intermittent systems, which only transport bedload during the most significant flow events, are particularly sensitive to changes in climate and precipitation patterns. Quantifying river intermittency is critical for assessing how fluvial landscapes will respond to projected changes in precipitation extremes due to climate change, and due to the vulnerability of landscapes and people to fluvial processes. Here, we generate 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 Gulf of Corinth, Greece, and Holocene sediment accumulation rates. Results reveal some of the lowest documented intermittency factors to-date, showing Mediterranean rivers can transport their entire annual sediment budget in a rare storm event. Coupling intermittency calculations with historical flood and precipitation data indicates rivers in this environment are dominated by bedload transport during one storm every c. 4 years, associated with rainfall > 50 mm/d and subsequent floods; this hydroclimate is typical of the Mediterranean.

Furthermore, climate models predict precipitation extremes will increase across Europe, and the frequency of events that surpass thresholds of sediment transport will increase non-linearly, potentially causing sediment budgets to double by 2100. As the global area of arid land likely to host intermittent rivers also increases, intermittency-dominated landscapes are on the edge of significant geomorphic change, driven by global warming.

INTRODUCTION

Rivers are the primary driver of water and sediment transport across the continents (Milliman & Meade, 1983), and their dynamics have a powerful impact on landscapes over decadal to millennial timescales (Romans et al., 2016). A key aspect of river discharge regime, and one that is vital to understanding landscape response to climate change, is intermittency. River intermittency describes the distribution of water and sediment transport through time, and can be defined with an intermittency factor, I_f (Paola et al., 1992), which represents the ratio of bankfull water or sediment flux over a set timescale to the actual flux over the same period (Hayden et al., 2021; Lyster et al., 2023). With increasing intermittency, rivers concentrate activity in shorter, isolated periods of discharge, separated by longer periods of low or no discharge.

Ephemeral, or highly intermittent rivers, defined by I_f less than ~0.1 (Hedman & Osterkamp, 1982), are widespread but associated with characteristic climate and precipitation patterns (Hansford et al., 2020) including infrequent but extreme precipitation. Climate models (e.g. IPCC, 2022) show that precipitation extremes are increasing in many regions, and will continue to increase driven by anthropogenic climate change. In Europe and the Mediterranean, estimates suggest that by the year 2100, extreme precipitation and associated flooding could increase by 20% (e.g., IPCC, 2022; Supplemental Information).

Ephemeral rivers typically transport large volumes of sediment as a proportion of their annual budget during floods. Therefore, increasing the frequency of floods that surpass thresholds for sediment transport could drastically change sediment budgets in the coming decades, impacting landscape degradation, infrastructure integrity, nutrient fluxes and carbon burial. How sensitive are ephemeral rivers to changing precipitation patterns, and to what extent will increasing weather extremes impact geomorphic and sedimentary systems in the near future?

To answer these questions, better constraints on intermittency are imperative, but these require study sites where sediment budgets are independently constrained. Here we focus on ephemeral rivers in Europe where the Gulf of Corinth, Greece, offers an ideal natural laboratory to address this problem (Fig. 1a; (Watkins et al., 2019, 2020). Today, the Gulf is one of the fastest expanding rifts in the world (McClusky et al., 2000) and the basin is closed and sediment starved, allowing accurate age models and sediment volumes to be reconstructed from seismic stratigraphy and IODP cores (Nixon et al., 2016; Watkins et al., 2019, 2020; Perissoratis et al., 2000). Rivers are ephemeral and characterized by gravel beds (Fig. 1c-e), with well-constrained Holocene and interglacial bedload fluxes (Watkins, 2019; Watkins et al., 2020). They share characteristics with many ephemeral channels documented across Europe (Supplemental Information). We use multiple approaches to estimate sediment flux intermittency and we link the results to known precipitation distributions, revealing the sensitivity of such landscapes to storm-driven precipitation in the present and future.

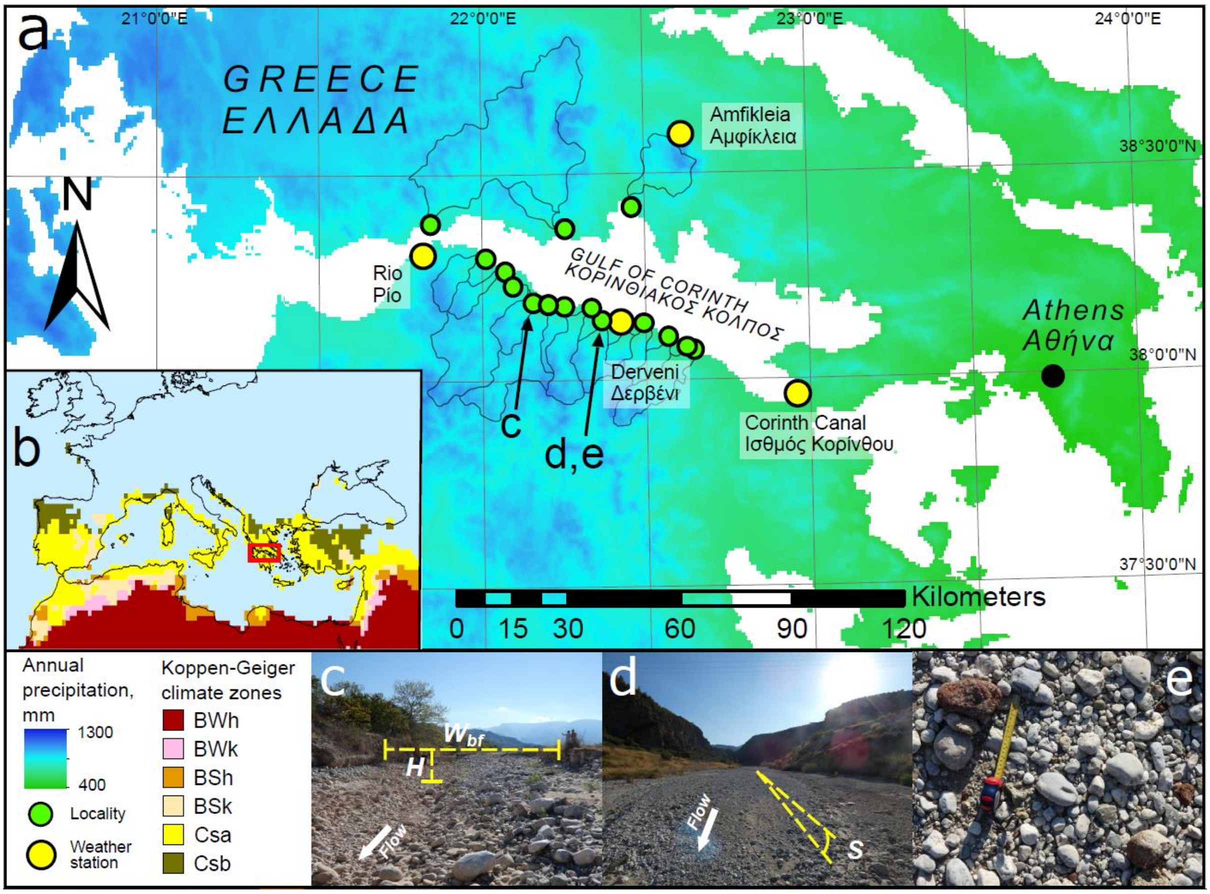

Fig 1. a) Map of the Gulf of Corinth showing mean annual precipitation, MAP (WorldClim; Hijmans et al., 2005), field localities, weather stations used in analysis, and river catchments (black outlines); b) The Mediterranean, with the dry and arid Köppen-Geiger climate zones (Rohli et al., 2015; Supplemental Material) highlighted; c) field data collection methodology for bankfull channel width (W_{bf}) and depth (H) at Rio Kerinitis; d) same as (c) but for slope (S) at Rio Krios; e) example of bedload sediment.

METHODS

Data collection

Field data were collected in the Gulf of Corinth from 16 rivers (Fig. 1a, b). Sites were located upstream of the backwater zone where fluvial processes dominate. To reconstruct potential bankfull bedload flux, measurements of bankfull depth, H_{bf} (Supplemental Information), width, W_{bf}, and slope, S, were collected using a Haglof Geo Laser range finder to a precision of ± 5 cm (Fig. 1c, d). Slope was also determined from 30 m (NASA JPL, 2020) and 5 m (Hellenic National Cadastre & Mapping Agency

S.A, 2016) digital elevation models (DEMs). Median bedload grain-size, D_{50}, was determined using the Wolman point count method (Fig. 1e; Wolman, 1954).

Calculating intermittency

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

$$Q_{s,bf} = W_{bf}\left(g\, {D_{50}}^{3}\, \Delta\rho\right)^{0.5} C(\tau_b^* - \tau_c^*)^{\alpha}$$

Eq. 1

where g = 9.81 ms^{-2}; $\Delta\rho$ is the non-dimensional submerged specific gravity of sediment (1.6); dimensionless basal shear stress $\tau_b^* = H_{bf}S\,/\Delta\rho D_{50}$; critical shear stress $\tau_c^* = 0.047$; and C and α are constants, taken as 4.93 and 1.6, respectively, after Wong & Parker (2006). The sediment transport intermittency factor, I_f (Hayden et al., 2021; Lyster et al., 2023) is given by:

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

Eq. 2

where $\Sigma Q_s(t)$ is the sum of the time-dependent sediment discharge, and t is the timespan. Two methods are used to reconstruct Holocene sediment fluxes per year, $\Sigma Q_s(t)$: a delta-volume (DV) approach; and a catchment-basin volume (CBV) approach. The DV approach exploits the prominent Gilbert-type deltas which prograde into the Gulf. Uplifted delta successions, published grain-size analysis, and hydrodynamic reconstructions (Watkins et al., 2020) confirm that modern deltas represent the bedload fraction supplied to the basin, with the suspended fraction transported to the distal basin floor. ΣQ_s is estimated using a simplified model of delta volume (Supplemental Information) 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 dataset primarily documents suspended sediment flux, so, to obtain 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 an alternative analysis of the volumetric ratio of coarse (rift-margin) and fine (basin-floor), yielding R_{bt} = 0.26 (Supplemental Information). To display this uncertainty simply, we therefore present CBV intermittency results for R_{bt} = 0.35 and 0.25. All uncertainty has been propagated through calculations using Monte Carlo simulations (Fig. 2c; Supplemental Information).

Daily precipitation data (National Observatory of Athens; Lagouvardos et al., 2017) from an 11-year period (Fig. 1a) were used to establish precipitation frequency-magnitude distributions that are representative of the studied catchments. We compare these distributions with estimates of I_f and a dataset compiled from literature documenting storms and floods between 2000 and 2021 within 50 km of the study area (Supplemental Information).

RESULTS AND DISCUSSION

Intermittency factors

DV and CBV approaches produce consistent results (Fig 2a, b) 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 hours of bedload transport to complete their annual sediment load (0.05% of a year). 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 USA-focused compilations of modern rivers (Fig. 2b; Hayden et al., 2021) and of recent palaeohydrological reconstructions (Lyster et al., 2023; McLeod et al., 2023; Sharma et al., 2023). There is no spatial trend in I_f around the Gulf of Corinth (Fig. 2c,d) and no correlation is found with channel or catchment parameters (Supplemental Material), implying that the key driver of intermittency is likely to be climate, rather than other thresholds to sediment transport.

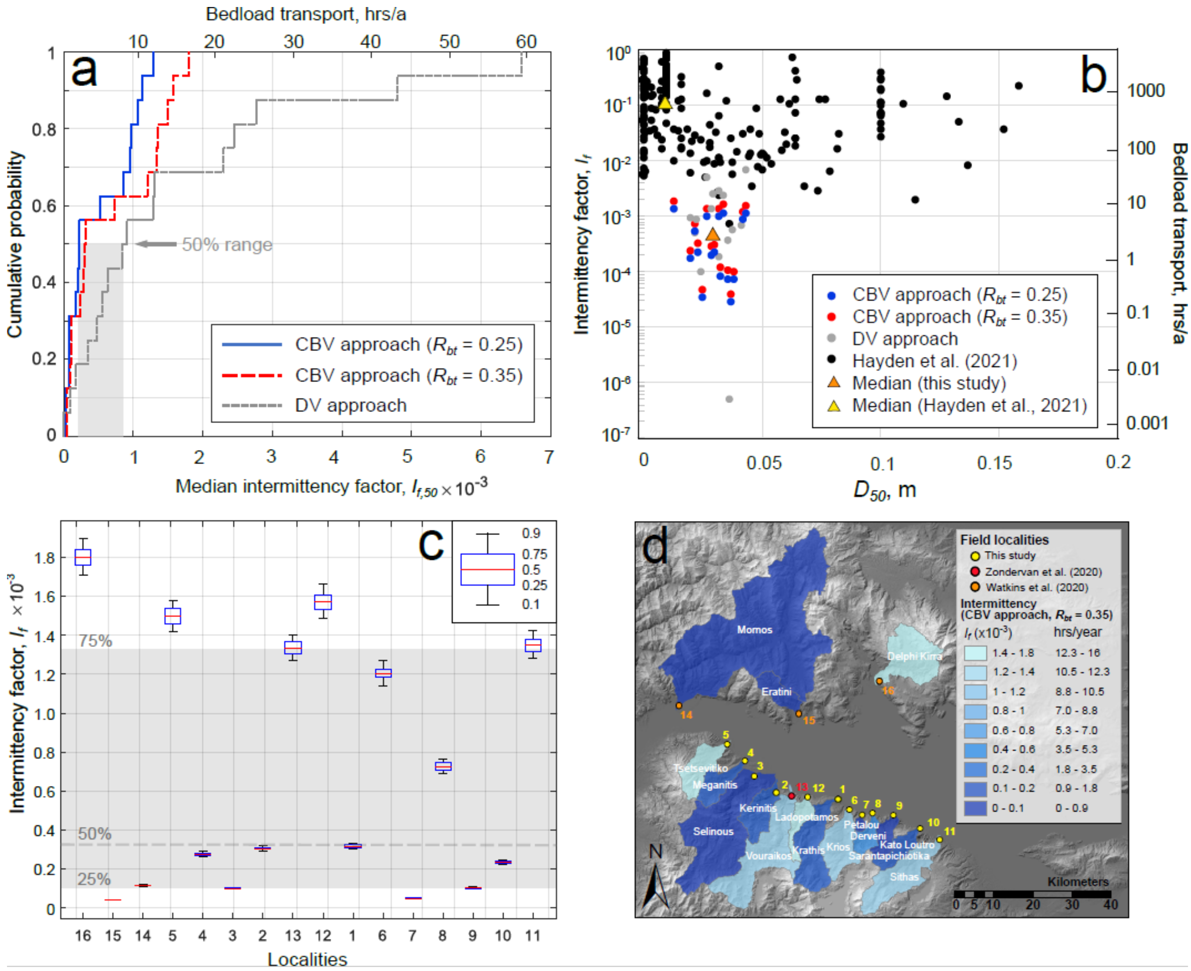

Fig 2. Intermittency results: a) Cumulative distribution function (CDF) of I_f for each catchment (primary x-axis) and equivalent hours of bedload transport per year (secondary x-axis), for the three approaches; b) scatter plot showing ranges in I_f and bedload grain-size in the Gulf of Corinth compared to the compilation of Hayden et al. (2021); c) boxplot showing I_f calculated using the CBV [0.35] approach, where localities are ordered anti-clockwise around the Gulf; d) map of studied catchments, coloured according to I_f .

Precipitation and floods

Fluvial landscapes with low I_f are likely to be particularly sensitive to changes in the magnitude and distribution of extreme events (Sharma et al., 2023; Tucker & Slingerland, 1997). To investigate the characteristics of precipitation events that drive major transport events in the Gulf of Corinth, we use an 11-year time-series of daily precipitation data from four weather stations (e.g. Fig. 3a; Lagouvardos et al., 2017), establishing frequency-magnitude distributions representative of the catchments studied (Fig. 3b, c). The median I_f of 4.67×10^{-4} for bedload transport, if averaged over one year, suggests the probability threshold for a precipitation event associated with bedload transport is 99.95% ($=1–4.67\times10^{-4}$, 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 (Fig 3, blue dashed lines; e.g., Karl et al., 1995). Recent floods in the region are caused by rainfall with mean duration of 14 hours, and mean rate of 99 mm/d (Supplemental Material), and floods can be considered to have a similar duration to their formative precipitation in this region (e.g., Giannaros et al., 2020; Papagiannaki et al., 2017). If bedload were in motion for a 14-hour flood period, the I_f of 4.67×10^{-4} (corresponding to 4 hrs/a) indicates sediment is more likely moved during one flood every 3.5 years. The average recurrence of floods caused by precipitation magnitudes > 50 mm/d and > 99.95% are 4 and 4.6 years, respectively (Fig. 3b). This is consistent with recurrence periods reconstructed from I_f, and flood frequency recorded by the four analysed precipitation time series (stars on Fig. 3a, 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 every c. 4 years.

Future projections

These fluvial 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 (IPCC, 2022; Jongman et al., 2014; 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; Supplemental Material) for Mediterranean regions with similar climate characteristics strongly suggest the region could see a c. 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 MAP by 2%, MAP in this region may in detail decrease while the extremes increase in magnitude and frequency (e.g., IPCC, 2022; Tramblay & Somot, 2018) but this illustrative model highlights the significant impact of *extreme* climate-driven precipitation on dryland rivers. We also note the increase of extreme sediment transport with precipitation is not 1:1. This 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.

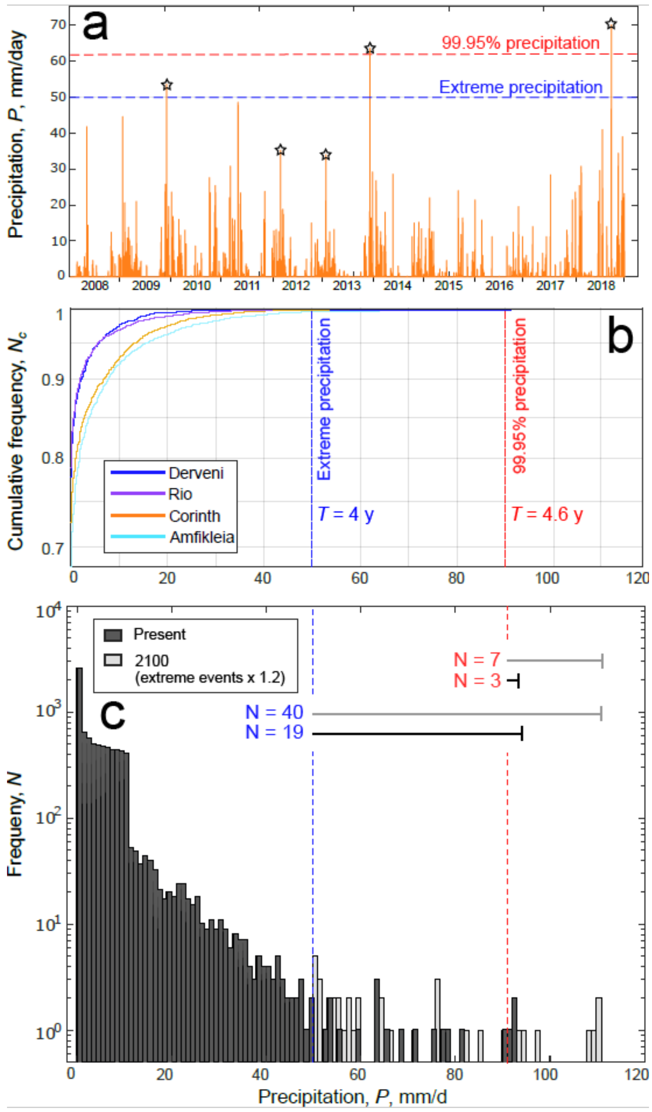

Fig 3. Precipitation analysis: a) daily precipitation time series (median 0.4 mm/d) measured at the Corinth weather station from 2008-2018 (Lagouvardos et al., 2017), where stars represent observed floods near the study area, the blue dashed line shows the threshold for extreme precipitation (50 mm/d), and the red dashed line represents the 99.95% rainfall value across the observed period (91 mm/d across all weather stations, 62 mm/d at the Corinth weather station); b) CDF of precipitation from four weather stations (Fig. 1a), including return interval for threshold-surpassing events; c) precipitation frequency histogram, with measured precipitation data (dark grey) and potential precipitation in 2100 (light grey), including the number of threshold surpassing events in each scenario.

Changing landscapes

This disproportionate geomorphic climate response is emphasised 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) project a 1.6×10^6 km^2 increase in the global area of dry and arid land from 2000 – 2100, 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 timescales 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., IPCC, 2022; Jongman et al., 2014; 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 x10^{-4} (0.05% of a year; Fig. 2). Combined with flood and precipitation records, we calculate that such rivers are characterised 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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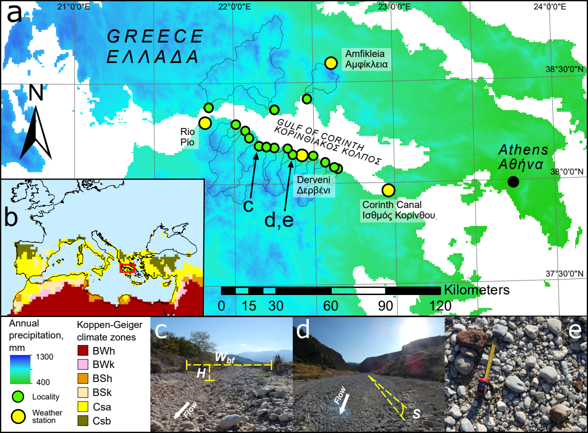

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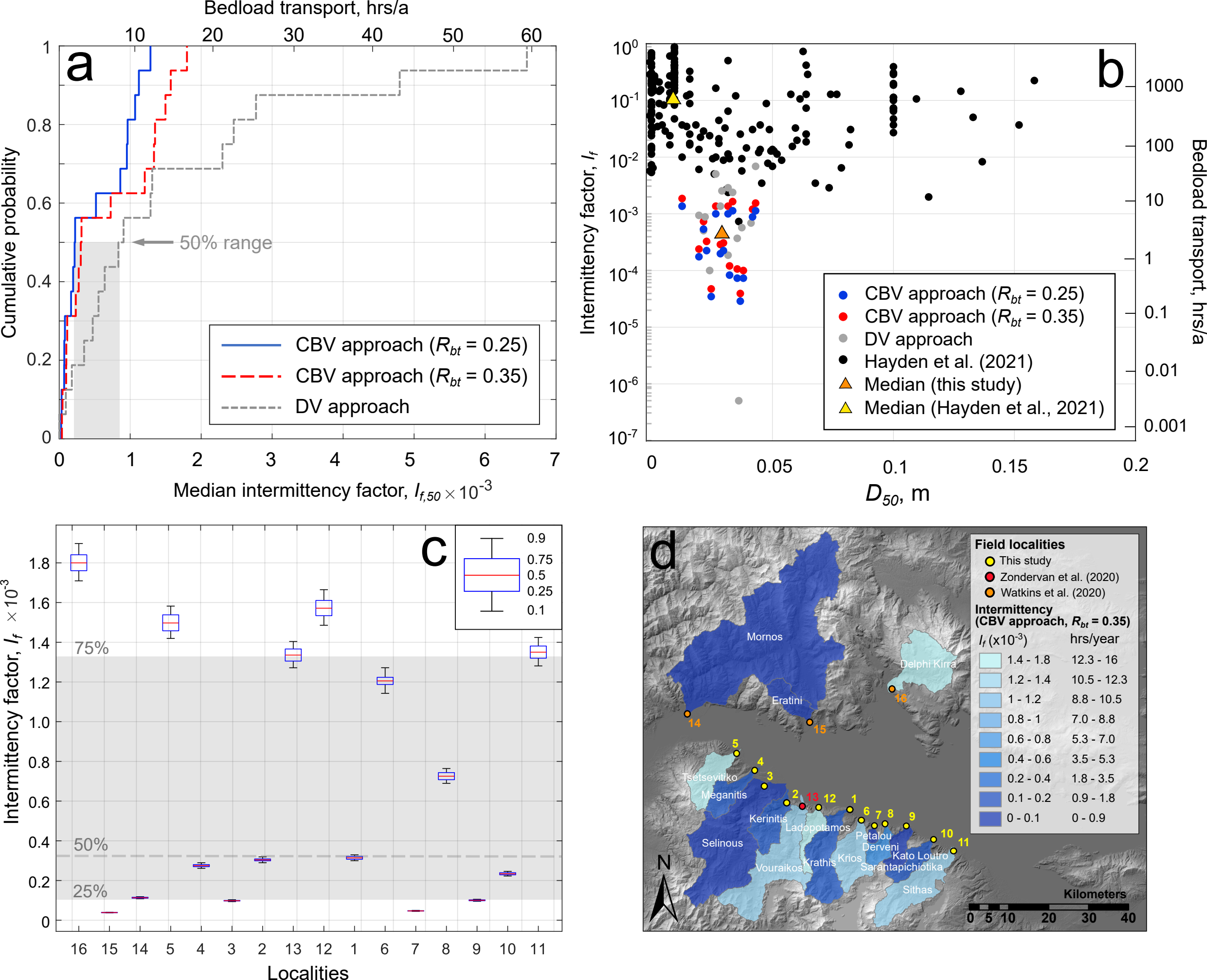
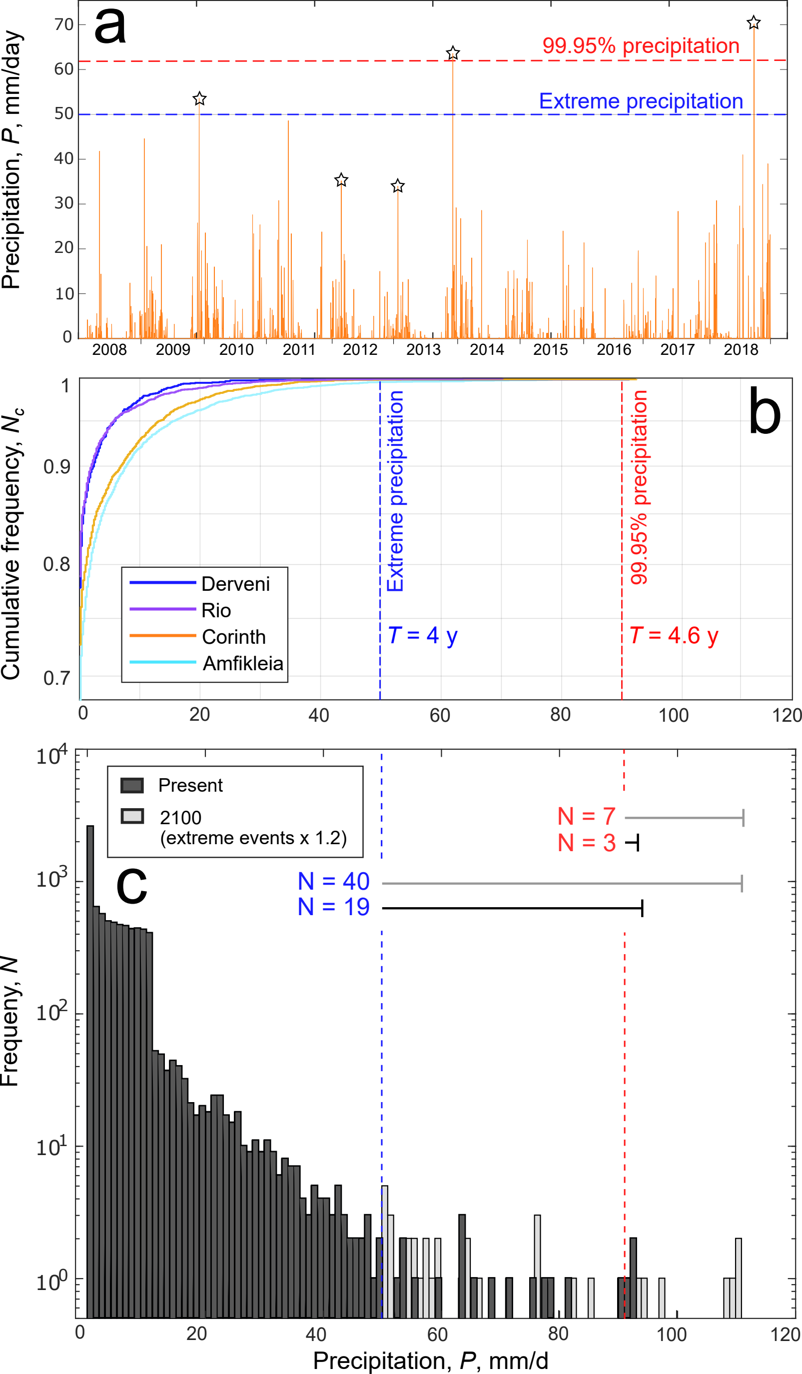


a
Bedload transport, hrs/a
Cumulative probability
Median intermittency factor, $I_{f,50} \times 10^{-3}$
50% range
CBV approach (R_{bt} = 0.25)
CBV approach (R_{bt} = 0.35)
DV approach
b
Intermittency factor, I_f
Bedload transport, hrs/a
D_{50}, m
CBV approach (R_{bt} = 0.25)
CBV approach (R_{bt} = 0.35)
DV approach
Hayden et al. (2021)
Median (this study)
Median (Hayden et al., 2021)
c
Intermittency factor, $I_f \times 10^{-3}$
Localities
75%
50%
25%
0.9
0.75
0.5
0.25
0.1
d
Field localities
This study
Zondervan et al. (2020)
Watkins et al. (2020)
Intermittency
(CBV approach, R_{bt} = 0.35)
I_f (x10^{-3}) hrs/year
1.4 - 1.8 12.3 - 16
1.2 - 1.4 10.5 - 12.3
1 - 1.2 8.8 - 10.5
0.8 - 1 7.0 - 8.8
0.6 - 0.8 5.3 - 7.0
0.4 - 0.6 3.5 - 5.3
0.2 - 0.4 1.8 - 3.5
0.1 - 0.2 0.9 - 1.8
0 - 0.1 0 - 0.9
Mornos
Delphi Kirra
Eratini
Tsetsevitiko
Meganitis
Kerinitis
Ladopotamos
Selinous
Vouraikos
Krathis
Krios
Petalou
Derveni
Sarantapichiotika
Kato Loutro
Sithas
N
Kilometers
0 5 10 20 30 40



a
99.95% precipitation
Extreme precipitation
Precipitation, P, mm/day
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
b
Cumulative frequency, N_c
Derveni
Rio
Corinth
Amfikleia
Extreme precipitation
99.95% precipitation
T = 4 y
T = 4.6 y
c
Present
2100
(extreme events x 1.2)
N = 7
N = 3
N = 40
N = 19
Frequeny, N
Precipitation, P, mm/d