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Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL092598

Key Points:

- Rivers transport sediment intermittently; intermittency factor relates river duration to deposit volume and bankfull river characteristics
- Intermittency factors we calculated have a 5–95 percentile range of 0.0064–0.73, independent of timescale, grainsize, and climate
- Application to Mars implies fluvial activity over thousands to millions of years

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Hayden, A. T., Lamb, M. P., & McElroy, B. J. (2021). Constraining the timespan of fluvial activity from the intermittency of sediment transport on Earth and Mars. *Geophysical Research Letters*, *48*, e2021GL092598. https://doi.org/10.1029/2021GL092598

Received 18 JAN 2021
Accepted 24 MAY 2021

Constraining the Timespan of Fluvial Activity From the Intermittency of Sediment Transport on Earth and Mars

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Abstract The timespan recorded in deposits from fluvial activity is a key gap in our understanding of ancient environments on Earth and Mars. Because riverine sediment transport occurs under time-variable water discharge, common models that represent sediment transport with a single bankfull discharge require an intermittency factor. For this reason, the ability to predict intermittency factor values based on environmental factors would improve estimates of time from fluvial deposits. To address this knowledge gap, we calculated intermittency factors from 201 modern rivers and six fans and deltas with depositional timespans of months to millions of years. Intermittency factors range from 0.0064–0.73; they are uncorrelated with averaging timescale, bed-material grainsize, or climate aridity, but are larger in river catchments with greater rates of denudation relative to precipitation. Application to ancient fluvial systems on Mars indicates long-lived depositional river systems for up to 10^4–10^6 years.

Plain Language Summary To estimate the lifespan of ancient river courses, geologists estimate the time it took to transport and deposit all of the sediment within a landform, such as an alluvial fan or delta. This method relies on sediment-transport calculations, which often assume a single reoccurring flood event that fills the river channel, even though river discharge varies in time from low flows to large floods. While the discharge of the channel-filling flood event can be constrained from channel geometry or deposit characteristics, flow variability is unknown, and an intermittency factor is needed to adjust the sediment transport calculation. In this work, we calculated intermittency factors for 201 rivers and six river deposits on Earth. We also examined correlations between intermittency factor and environmental variables, and found no correlation with averaging timescale, bed-material grainsize, or climate aridity. However, intermittency factors are larger in catchments that receive a large supply of sediment. Applying the new intermittency factor values to river deposits on Mars suggests that some of those rivers persisted for millions of years.

1. Introduction

Measuring timespans recorded in river deposits is a key goal in better understanding ancient environments on Earth and Mars (Paola et al., 2018). On Mars, using river deposits is particularly useful because most geochronological methods to constrain depositional timespans are unavailable. Moreover, it is unclear whether early Mars had a long-lived, stable hydrological cycle or multiple intermittent, short-lived, river-forming episodes (e.g., Pollack et al., 1987; Segura et al., 2002; Wordsworth et al., 2018). There is clear geologic evidence for rivers and lakes across Mars during Noachian/Early Hesperian time in the form of river valleys (Craddock & Howard, 2002; Hynek et al., 2010); river, fan, and deltaic deposits (Burr et al., 2009, 2010; Fassett & Head, 2005; Moore et al., 2003) lake deposits (Grotzinger et al., 2015); crater lakes with outflow channels (Goudge et al., 2012); and crater-erosion patterns (Forsberg-Taylor et al., 2004). However, there is less information about the timespan of fluvial activity.

One way to constrain the timespan of fluvial activity is to compare the volume of a fluvial deposit (e.g., in a fan or delta) to the fluvial sediment discharge (e.g., Kleinhans, 2005). This comparison is hampered, however, by a paucity of data on the intermittency of sediment-transporting flood events in different climates and across timescales (Sadler, 1981), and by high variability in sediment discharge (Figure S1), which can be zero for long durations (e.g., Lajeunesse et al., 2018; Phillips et al., 2013).

Despite the inherent variability in fluvial sediment discharge, over geomorphic timescales sediment transport is often well characterized by a reoccurring water discharge that transports the most sediment (Wolman

& Miller, 1960). This representative value is calculated as the flow that maximizes the product of the magnitude and frequency distributions of bed-material sediment load (Wolman & Miller, 1960), and it corresponds well to the bankfull water discharge, that is, when the channel fills with water to the brim (Leopold et al., 1964). The water discharge at bankfull has the largest influence on channel morphology, and is often also reflected in the geometry of fluvial strata (e.g., Mohrig et al., 2000). Consequently, geomorphic models often simplify the natural world by simulating only bankfull floods (e.g., Sinha & Parker, 1996; Tucker & Slingerland, 1997), though models including flow variability are increasingly used (e.g., Blom et al., 2017; Chadwick et al., 2019; Chatanantavet et al., 2012).

To apply the bankfull concept to modeling long-term evolution of alluvial rivers and fans, Paola et al. (1992) introduced the intermittency factor, I_f, defined as the fraction of total time in which bankfull flow would accomplish the same amount of sediment transport as the real hydrograph. That is,

$$I_f = \sum Q_s\left(t\right) / \left(Q_{s,\mathrm{bf}} \sum t\right) \tag{1}$$

in which $\sum Q_s\left(t\right)$ is the sum of the time-dependent sediment discharge, $Q_{s,\mathrm{bf}}$ is the sediment discharge during bankfull conditions, and $\sum t$ is the timespan. The intermittency factor is a powerful tool for calculating the depositional timespan of sedimentary deposits because Equation 1 can be rearranged as,

$$\sum t = V / I_f Q_{s,\mathrm{bf}} \tag{2}$$

in which the volume of a deposit is $\sum Q_s\left(t\right) = V$, so long as V represents the accumulated bed-material load and the deposit captures all sediment. Because ancient fans and deltas might have had multiple channels active simultaneously, the intermittency factor value includes uncertainty due to the unknown number of channels.

Only a few measurements of intermittency factors have been reported for modern terrestrial river systems. For instance, Sklar and Dietrich (2004) estimated $I_f = 0.06$ for the gravel-bedded Eel River using sediment volume estimated from catchment erosion rates and bankfull bed-material load estimated from magnitude-frequency analysis. Wright and Parker (2005) combined USGS streamgage data, sediment-rating curves for suspended bed-material sediment discharge, and bankfull survey data and found $I_f = 0.26$–0.35 for the sand-bedded Atchafalaya, Mississippi, and Red Rivers. Czuba and Foufoula-Georgiou (2014) used similar methods to calculate sediment discharge, and found $I_f = 0.175$ for the sand-bedded Minnesota River. Intermittency factor has been used in landscape evolution models, often using $I_f = 1$ for simplicity or $I_f \approx 0.01 - 0.1$ to approximate formative events occurring a few days to several weeks annually (e.g., Dong et al., 2016; Sinha & Parker, 1996; Tucker & Bras, 2000; Wickert & Schildgen, 2019). However, the controls and ranges of I_f values are largely unknown. It also is unclear whether I_f values measured for modern rivers apply to longer timescales represented in depositional basins, in which changes in tectonics, climate, and autogenic dynamics may control sediment-discharge variability (e.g., Paola, 2013; Sadler, 1981; Straub et al., 2009). It is further untested how I_f varies with climate or sediment supply.

Equation 2 is of particular interest in Mars science, where it has been used to estimate the timespan of ancient martian rivers from observations of sedimentary deposits. Intermittency factors commonly used for Mars are $I_f \approx 0.001 - 0.05$ by analogy to terrestrial bankfull recurrence intervals for water discharge, or $I_f = 1$ in the endmember case of constant bankfull flow (e.g., Fassett & Head, 2005; Hauber et al., 2009; Kleinhans, 2005; Orofino et al., 2018). Buhler et al. (2014) estimated I_f for a deposit on Mars, finding values between 0.00008 – 0.004 by dividing the timescale to fill a crater with sediment at the bankfull sediment discharge by an estimated formation timescale of a nearby bedrock valley. Lapôtre and Ielpi (2020) compared the estimated sediment-generation timescale (deposit volume divided by denudation rate) to deposition timescale for a fan in Jezero crater and calculated values between $I_f = 0.00005$–0.0001. These values are orders of magnitude smaller than those measured on Earth, which could be evidence of the rarity of climates supporting liquid water on Mars, but could also be due to high uncertainty in the estimated depositional timespans.

To help address these knowledge gaps, we compiled published data from six depositional systems and used daily river data from 200 gaging stations in the U.S. and one in Antarctica (Section 2) to calculate intermittency factors that average over timescales of 10^{-2}–10^{6} years for both sand- and gravel-bedded rivers (Section 3). We compared these values to aridity index, bed-material grainsize, depositional timespan, and catchment-averaged denudation and precipitation rates (Section 4). We applied the new intermittency factors to previously studied alluvial deposits on Mars to estimate the timespan of river activity there (Section 4.4).

2. Methods

Calculating intermittency factor for modern rivers with Equation 1 requires long timeseries of sediment discharge, $Q_s(t)$, which are rare, so instead we calculated $Q_s(t)$ from the timeseries of water discharge, $Q_w(t)$ using sediment transport relations, as done in the prior work (Czuba and Foufoula-Georgiou, 2014; Wright and Parker, 2005). To calculate $Q_s(t)$, we combined surveyed values of bankfull depth, bankfull width, bankfull cross-sectional area, slope, and median bed grainsize (H_{bf}, W_{bf}, A_{bf}, S, and D_{50}, respectively); measured rating curves (Q_w vs. stage height, G) and mean daily $Q_w(t)$ from USGS streamgages; models of sediment discharge based on shear stress (Engelund and Hansen, 1967; Fernandez Luque and van Beek, 1976); and a model of channel geometry (Allen et al., 2018). We used input data ($Q_{w,\mathrm{bf}}$, H_{bf}, W_{bf}, A_{bf}, S, D_{50}, and Q_w vs. G) to create synthetic rating curves (Q_w vs. depth, H) and applied them to $Q_w(t)$ to calculate the timeseries of depth and Shields stress, which we then used to calculate sediment discharge for the bed-material load using distinct models for sand-bedded rivers (Engelund and Hansen, 1967) and gravel-bedded rivers (Fernandez Luque and van Beek, 1976). Because the cross-sectional geometry of the channels are mostly unknown, we used the model of Allen et al. (2018) to find a best-fit channel geometry that reproduced the surveyed values at bankfull water discharge. Finally, we calculated $Q_s(t)$ and $Q_{s,\mathrm{bf}}$ and combined them with the total duration, $\sum t$ in Equation 1 to calculate I_f. See Supporting Information Text S2 for details.

We studied 200 rivers that had at least 10 years of mean daily Q_w, a rating curve, and also had surveyed H_{bf}, W_{bf}, S, and D_{50} (see Data Availability Statement). See Figure S2 for a map of streamgage locations in the continental United States and Alaska. We separately obtained data for the Onyx River, Antarctica, using published channel cross section, slope, and grainsize (Shaw and Healey, 1980) and water-discharge timeseries (LTER et al., 2019).

We also studied six basins that can be reasonably approximated as complete traps of bed-material load, some with measurements at different times, yielding a total of 64 different pairs of deposit volumes and depositional timespans: Devils Gate Dam (LADPW & LACFCD, 2013), Wax Lake Delta (Roberts, 1997), Gulf of Mexico fans/deltas (Galloway et al., 2011), Mississippi River Delta (Roberts et al., 1997), and the Triassic Boreal Delta (Klausen et al., 2019) (Supporting Information Text S1; Table S1). They represent sand-bedded-river deposits formed over months to tens of millions of years, with bankfull depths of 0.5–26 m and deposit volumes of 5.2×10^{-6} to 1.1×10^{5} km^3. To calculate intermittency factor for these deposits, we calculated bankfull sediment discharge (Engelund and Hansen, 1967), using D_{50} from prior studies (Supporting Information Text S1) and H_{bf} taken from field surveys or reconstructed from channel-belt dimensions (Hayden et al., 2019) for ancient deposits (Supporting Information Text S1). We obtained total sediment volume, V, as the total deposit volume multiplied by $f(1-\lambda)$, where $f = 0.4$ is the sand fraction (to exclude mud that is not calculated in the sediment-transport equations but is present in fluvial deposits; Heller et al. (2015) reported 20%–80% sand-mud ratios for fluvial deposits, in which 40% ($f = 0.4$) is the geometric mean of that range) and $\lambda = 0.35$ is the porosity (Supporting Information Text S1.3).

To quantify uncertainty in our calculation of intermittency factor, we combined contributing uncertainties with Gaussian error propagation, assuming they are independent and distributed log-normally (Supplemental Information Text S3). We estimated uncertainty in sediment discharge to be a factor of ∼9, which we validated by comparing measured sediment discharges from Brownlie (1981) (a compilation of 1764 sand- and gravel-bedded rivers at different flow stages) to our predictions. We also incorporated uncertainty on channel geometry and sediment volume; most total uncertainties did not exceed a factor of 10.

We also compiled catchment variables hypothesized to affect intermittency. We estimated sediment supply by taking the nearest (within 100 km) cosmogenic catchment-averaged denudation rate rate, E, from the Harel et al. (2016) compilation. We used published values of the catchment-averaged mean annual precipitation rate, P, for each streamgage (Falcone, 2011) and took aridity index at each streamgage location from a map of aridity index (Trabucco and Zomer, 2019). We arbitrarily defined ephemeral rivers as those rivers having zero flow at least 5% of the time in the streamgage data.

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3. Results

We found intermittency factors for modern rivers spanning a 5–95 percentile range of 0.0064–0.73 with a median of 0.10 (Figure 1). Intermittency factors for the sedimentary deposits were similar, with a 5–95 percentile range of 0.0025–0.26 and a median of 0.037 (Figures 1c and 1d). The values we calculated are similar to those typically applied and calculated on Earth ($I_f \approx 0.01 - 1$; e.g., Czuba and Foufoula-Georgiou, 2014; Sklar & Dietrich, 2004; Wickert & Schildgen, 2019) and Mars ($I_f \approx 0.001 - 1$; e.g., Hauber et al., 2009; Hoke et al., 2011; Orofino et al., 2018).

Timescale, bed-material grainsize, aridity, and ephemerality all appear independent of intermittency factor (Figure 1). Median intermittency factors are indistinguishable within uncertainty for sand-bedded (0.16) and gravel-bedded (0.092) rivers. Although rivers and sedimentary deposits that represent ≤100 years of sediment discharge have a wider range of values than sedimentary deposits formed over more than 10^6 yrs, the ranges overlap and a two-factor Kolmogorov-Smirnov test fails to reject the null hypothesis ($p = 0.095$) of similar intermittency factors between short timescales ($\sum t < 10^2$ years; $n = 244$) and long timescales ($\sum t > 10^6$ years; $n = 16$). Additional data beyond centennial timescales is needed for more nuanced time analyses. The ranges overlap for all climates, though rivers in semi-arid climates have higher intermittency factors (median: 0.19, 5–95 percentile range: 0.022–0.51) than humid (median: 0.041, 5–95 percentile range: 0.0037–0.75) or arid (median: 0.077, 5–95 percentile range: 0.0066–0.72) climates. Surprisingly, even the ephemeral, glacier-melt-fed Onyx River in Antarctica has a comparable intermittency factor to rivers across the United States (Figure 1c), though similarity to other melt-fed systems is untested. Furthermore, ephemeral rivers (circled points in Figure 1c) are similar across climates, and have values in the same range as non-ephemeral rivers. Ephemerality thresholds other than >5% time with nonzero flow yielded similar results (Supplemental Information Text S4; Figure S3).

The intermittency factor does follow an approximate linear scaling relation with the ratio of denudation to precipitation (E/P) (Figure 1e) despite the thousand-year averaging timescales for denudation rates and centennial timescales for the streamgages. The ratio of denudation to precipitation (E/P) can be considered a proxy for the sediment supply normalized by the water supply, which are both major controls on other aspects of alluvial river morphodynamics (e.g., Mackin, 1948; Lane, 1955; Parker et al., 2007; Pfeiffer et al., 2017). Regions in our database with generally high E/P include Idaho, Wyoming, and coastal California, while the lowest intermittency factors came from the Appalachian region (Figure S2).

4. Discussion

4.1. Intermittency Factor and Bed Grainsize

Intermittency factor is similar across grainsize classes, despite significant differences in the transport regimes of gravel- and sand-bedded rivers (e.g., Parker, 1978; Dunne & Jerolmack, 2018). To investigate the roles of grainsize and sediment-transport frequency in setting intermittency factor, we plotted I_f against the fraction of time where shear stress exceeds the critical value for sediment transport, and found correlation for most gravel-bedded rivers (Figure 2a). This is expected because gravel-bedded rivers tend to have bankfull shear stress near the threshold for sediment transport (Parker, 1978); gravel is not transported during low flows, and floods that exceed bankfull conditions may not produce bed stresses that far exceed the critical stress due to overbank flow onto the floodplain or channel widening (Phillips & Jerolmack, 2016).

However, the sand-bedded rivers do not plot on the one-to-one line and instead, for almost all times, they have shear stress above critical, independent of intermittency factor. To help explain the sand-bedded river data, it is useful to reformulate Equation 1, as

$$I_f = \left(\frac{\sum t\left(\tau_* > \tau_{*,c}\right)}{\sum t}\right)\left(\frac{\overline{Q_s\left(\tau_* > \tau_{*,c}\right)}}{Q_{s,\mathrm{bf}}}\right) \tag{3}$$

where $\overline{Q_s\left(\tau_* > \tau_{*,c}\right)} = \sum Q_s\left(\tau_* > \tau_{*,c}\right) / \sum t\left(\tau_* > \tau_{*,c}\right)$ is the mean nonzero sediment discharge, which is the mean sediment discharge only when shear stress exceeds critical so sediment is in motion, that is, $\sum t\left(\tau_* > \tau_{*,c}\right)$. Equation 3 reduces to Equation 1 because $\sum Q_s = \sum Q_s\left(\tau_* > \tau_{*,c}\right)$. Equation 3 reveals that the

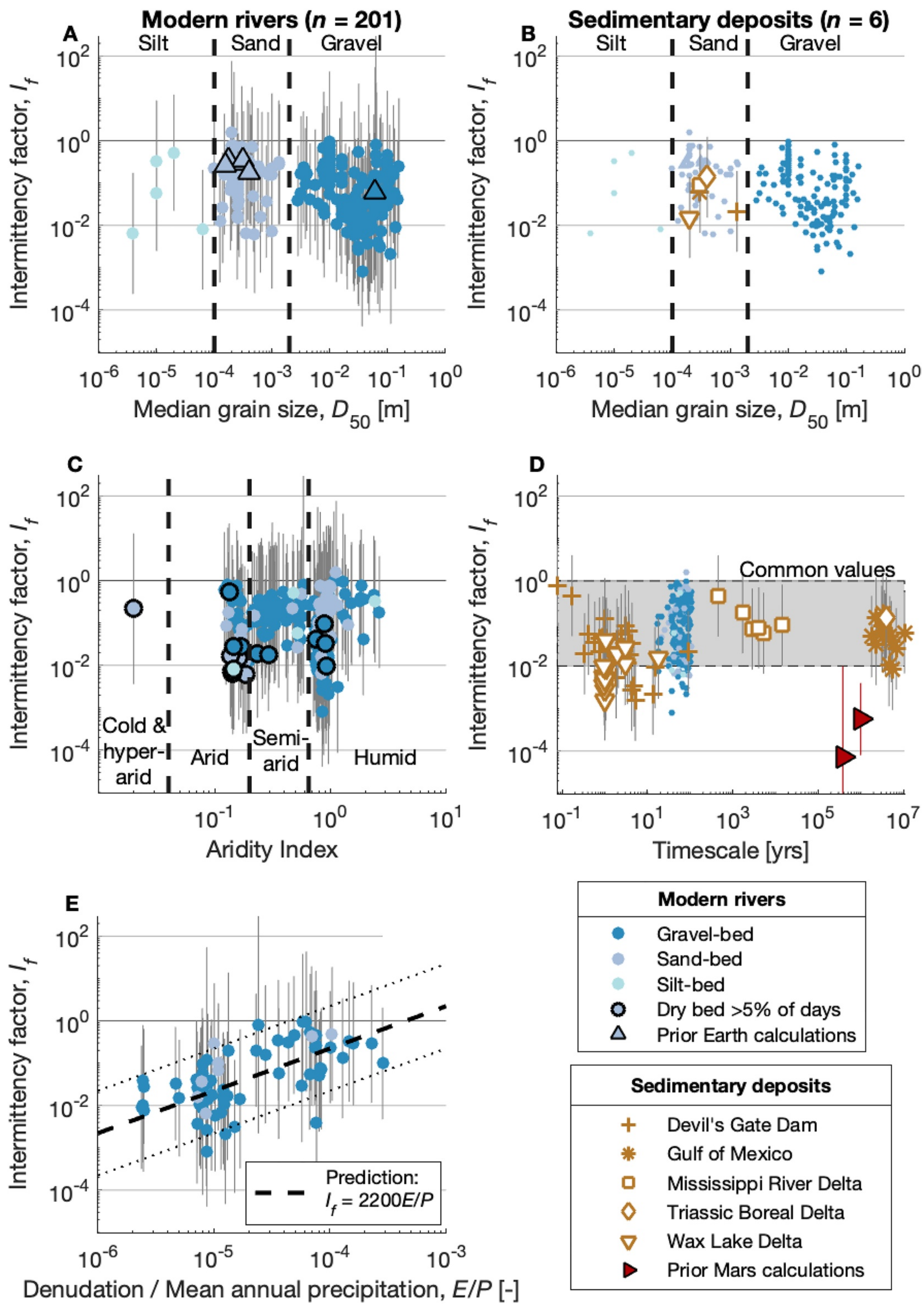

Figure 1.

intermittency factor can be thought of as the product of two terms: the fraction of time that the river exceeds the critical shear stress (time-fraction term), and the ratio of mean nonzero sediment discharge to the bankfull sediment discharge (flux-ratio term). Gravel-bedded rivers tend to have a flux-ratio term near one, and therefore their intermittency factors are approximated by the fraction of time above the critical stress

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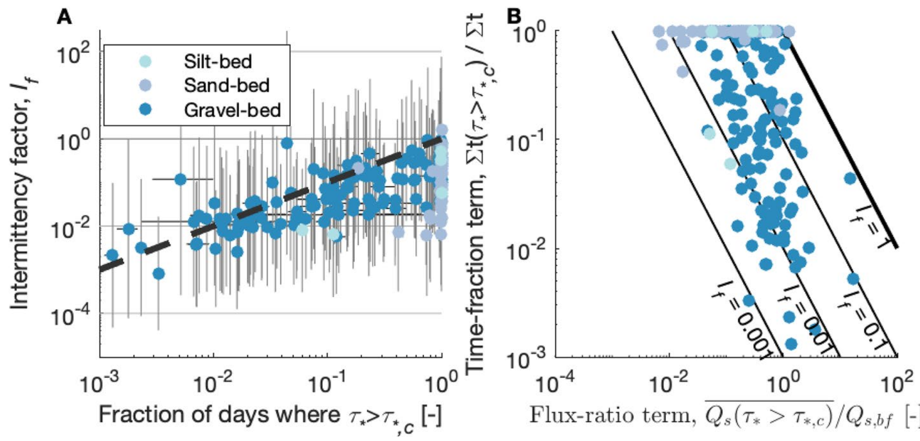

Figure 2. (a) Intermittency factor vs. the fraction of time in which Shields stress exceeds critical Shields stress. Dashed line is a 1:1 correlation. (b) The time-fraction term versus the flux-ratio term (Equation 3). Lines of constant I_f have slope of −1. Legend is the same as panel (a).

(Figure 2b). In contrast, sand-bedded rivers generally have a time-fraction term near one, such that their intermittency factors are determined by the flux-ratio term. Because sand-bed rivers move sediment almost constantly, including at low flows, the mean sediment discharge is dominated by low values. Therefore, intermittency factors are similar for sand-bedded and gravel-bedded rivers, despite their different mechanisms of transport variability.

Equation 3 also suggests a reason that the values we calculated are similar to prior estimates of intermittency factor using the fraction of time when floods occur (Sinha & Parker, 1996; Tucker & Slingerland, 1997; Wickert & Schildgen, 2019). The time-fraction term approximates the fraction of time above bankfull for gravel-bedded rivers because they are typically threshold channels (Parker, 1978). Since sand-bedded and gravel-bedded rivers have similar intermittency factors within uncertainty, the estimates based on bankfull floods may work even though the term that appears to control intermittency (flux-ratio term) is different for sand-bedded rivers.

4.2. Intermittency Factor and Timescale

We found that intermittency factors are similar between modern rivers and sedimentary deposits across timespans from months to millions of years (Figure 1d), though we lack data for depositional timespans between 10^4 and 10^6 years. The result is surprising because additional influences on intermittency factor measured in the depositional record—for example, channel meandering and avulsion, sediment trapping in floodplains, and long-term climate and tectonic variations—might accumulate over long timescales. In fact, an inverse correlation between sediment deposition rate and measurement timescale is so ubiquitous that it is named the Sadler Effect (Sadler, 1981). However, the Sadler Effect applies most strongly to measurements at individual locations (e.g., individual stratigraphic section), and is less pronounced if entire deposits are included in the analysis because mass balance requires that non-deposition at one location is accompanied by active deposition at another (e.g., Sadler & Jerolmack, 2015; Paola et al., 2018). For example, the Mississippi River Delta has multiple lobes active at distinct times (e.g., Frazier, 1967); routing of the river

Figure 1. Values for intermittency factor for modern rivers and ancient sedimentary deposits vs. (a) bed-material grainsize for modern rivers, (b) grainsize for sedimentary deposits, (c) aridity index, (d) averaging timescale, and (e) ratio of catchment-averaged denudation rate to mean annual precipitation. Error bars represent uncertainty in channel geometry and in calculating sediment discharge (Supplementary Information Text S3), and bars for Mars represent the reported range. Shades of blue indicate grainsize and are consistent across panels. Triangles are values from prior work (Czuba and Foufoula-Georgiou, 2014; Sklar & Dietrich, 2004; Wright and Parker, 2005). Circled points in panel C are ephemeral rivers. In panel D, 64 points for six depositional systems represent individual measurements on each system. For modern terrestrial deposits (Wax Lake, Devil's Gate Dam), timescale is the measurement duration. For the other deposits, timescale is the reported depositional duration. The shaded region represents common values for rivers on Earth (I_f = 0.01–1). Martian values are from (Buhler et al., 2014; Lapôtre & Ielpi, 2020).

through any lobe necessitates it be absent at the others, but analyzing all the lobes together shows relatively continuous river activity.

4.3. Intermittency Factor, Climate, and Sediment Supply

Intermittency is often thought to correlate with climate; arid climates have more intermittent precipitation and more ephemeral rivers (e.g., Farquharson et al., 1992; Osterkamp & Friedman, 2000). Though climate influences the variability in stream flow, our data suggest that climate is not a strong control on the intermittency factor as calculated for sediment transport. Instead of aridity, we found that intermittency factor has an approximately linear relationship with the ratio of catchment-averaged denudation to precipitation (E/P; Figure 1e). In our compilation, denudation rate effectively sets E/P; mean annual precipitation spans a factor of 8 (410–3,340 mm/yr) while denudation rates span a factor of 190 (2.5–490 mm/kyr). We selected precipitation as the denominator for dimensional consistency, and because the sediment supply normalized by the water supply is a strong control on other aspects of alluvial river morphodyamics (e.g., Lane, 1955). Intermittency factor trends only weakly with catchment area (Figure S3) suggesting that the ratio of sediment to water supply exerts stronger control than the total mass discharge of either.

Based on our data set, it is not straightforward to determine what controls the intermittency factor. Although previous work has implied that intermittency is an externally imposed parameter on channelized flow (e.g., by precipitation variability), the lack of correlation with aridity in our data does not support this hypothesis. We speculate, instead, that intermittency factor could be internally controlled, or at least modulated, through morphodynamic feedbacks, similar to other attributes of alluvial rivers like river width and bed slope (Lane, 1955; Mackin, 1948; Parker et al., 2007). The intermittency factor depends on sediment discharge at both bankfull and non-bankfull conditions (Equation 1). Morphodynamic feedbacks can regulate channel bed slope, cross-sectional shape, and levee and floodplain elevations, thereby controlling the boundary shear stresses and relative amount of sediment transport that occurs by low flows and high flows. For example, increasing sediment supply relative to water supply (E/P) over long time periods is known to steepen the channel bed (Lane, 1955; Mackin, 1948). A steepened bed slope increases bed shear stress approximately linearly for all flows, but sediment discharge is nonlinear with shear stress due to a threshold for motion, such that larger E/P could increase the intermittency factor (i.e., if mean sediment discharge increases more than bankfull sediment discharge). Thus, intermittency might be one of many internally determined parameters that adjust to produce stable conditions in channelized flow.

The complexity in river response to external changes, which is thought to affect the preservability of climate and tectonic signals in sedimentary records (e.g., Ganti, Lamb, & McElroy, 2014; Jerolmack & Paola, 2010; Phillips & Jerolmack, 2016), is compounded by the intermittency factor. Because the intermittency factor appears to scale with E/P, changes in the intermittency factor could play a role in filtering the effects of changes in climate and tectonics on river morphology and deposits. For example, if sediment supply doubles, some of the increase should be accommodated by increased sub-bankfull sediment discharge so the bankfull sediment discharge might only increase a small amount. There is a clear need for future work to probe the mechanics of how alluvial rivers respond to intermittent forcing, through morphodynamic feedbacks, to determine the intermittency factor.

4.4. Application to Mars

We found that across diverse climates and depositional settings on Earth, including Antarctica, I_f does not vary systematically with aridity, bed-material grain size, or averaging timescale, supporting the application of terrestrial I_f values to martian fluvial systems. The only parameter we found strongly correlating to intermittency factor is the ratio of catchment-averaged denudation rate to mean annual precipitation (Figure 1). Estimated regional erosion rates on Mars during the Noachian range between 10^{-5} to 10^{-6} m/yr (Golombek et al., 2006), which are among the lower denudation rates in our study; however, far larger rates have been estimated for coupled bedrock valley and alluvial fan systems, potentially as high or higher than terrestrial erosion rates (e.g., Stucky de Quay et al., 2019).

To examine potential impacts of the range of intermittency factor values on calculated duration of fluvial activity on Mars, we compiled some examples in which intermittency factor was used to constrain

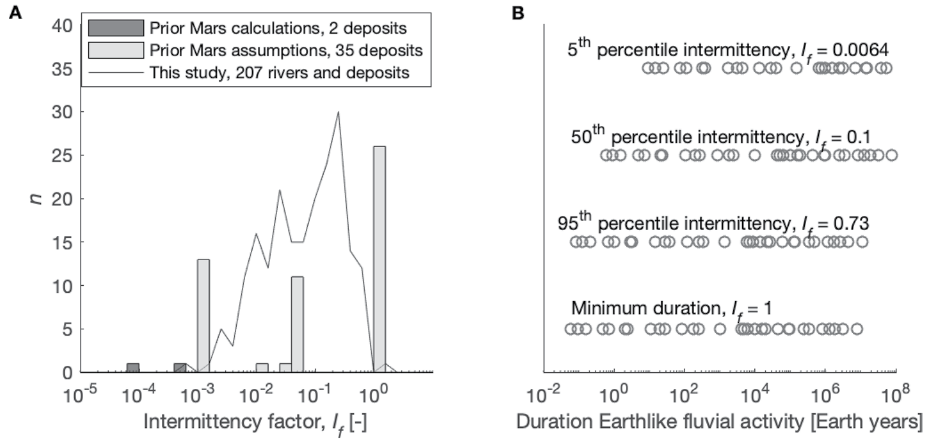

Figure 3. (a) Histogram of the number of study locations versus the intermittency factor for our study of terrestrial rivers and deposits, and for deposits on Mars showing the values assumed in previous work and the values calculated for Mars (Buhler et al., 2014; Lapôtre & Ielpi, 2020). (b) Calculated depositional timespan for previously studied Mars deposits using the 5th, 50th, and 95th percentile values of intermittency factors from this study.

duration of a martian fluvial system with an approach like Equation 2 (Fassett & Head, 2005; Hauber et al., 2009; Hoke et al., 2011; Kleinhans et al., 2010; Morgan et al., 2014; Orofino et al., 2018). Intermittency factors used in these prior studies are most commonly $I_f \approx 0.001 - 0.05$ based on analogy to some bankfull recurrence intervals on Earth, or $I_f \approx 1$ representing the endmember case of constant bankfull flow (Figure 3a). We applied the 5th, 50th, and 95th percentile (0.0064, 0.10, 0.73) from our database in place of the previous intermittency factors, and kept the other values the same (Figure 3b). The median value and lowest values in our data set are similar to the commonly used values of 0.05 and 0.001, and applying the lowest values resulted in the longest calculated depositional timespans—some timespans for deposits from the Hoke et al. (2011) and Orofino et al. (2018) compilations exceed 10^6 years with $I_f = 0.0064$. Million-year depositional timespans on Mars are consistent with embedded crater counts from one site in Aeolis Dorsa (Kite et al., 2013).

The lower 5% bound on our data of $I_f = 0.0064$ is significantly larger than the values of $I_f \cong 0.0001$ estimated for two local studies on Mars (Buhler et al., 2014; Lapôtre & Ielpi, 2020). These relatively low I_f values on Mars could indicate major differences in ancient martian fluvial systems from their terrestrial counterparts—they could represent very low sediment-generation rates and/or high precipitation rates, or they could represent additional sources of intermittency beyond those present on Earth, such as a cold and icy climate with episodic clement climates induced by rare volcanic or impact events (e.g., Segura et al., 2002; Halevy & Head, 2014). Alternatively, I_f estimates for martian systems (Buhler et al., 2014; Lapôtre & Ielpi, 2020) have high uncertainty, so resolving the discrepancy between calculated terrestrial and martian I_f values requires further study of the mechanisms that set I_f, and additional local studies on Mars to better constrain input measurements.

5. Conclusions

Intermittency factors from 201 modern rivers range from 0.0064–0.73 (median 0.10) and are similar to 64 values from 6 depositional systems. We did not find significant differences between intermittency factor values for sand-bedded and gravel-bedded rivers (medians: 0.16 and 0.092). Intermittency factors for gravel-bedded rivers correlate strongly with the fraction of time when shear stresses exceed the critical stress to enable sediment transport, which is similar to the common approximation of intermittency as the fraction of time exceeding bankfull flow. In contrast, sand-bedded rivers transport sediment practically all of the time, but their average sediment discharges are less than the bankfull value, resulting in similar intermittency factors to gravel-bedded rivers. We also did not find major differences in intermittency factor between arid and humid climates (medians: 0.077 and 0.041), or between ephemeral and non-ephemeral rivers (medians: 0.019 and 0.10). Furthermore, intermittency factor did not differ systematically across depositional timespans ranging 10^{-1} to 10^{6} years. Instead, intermittency factor is systematically larger for rivers with greater ratios of catchment-averaged erosion rate to mean annual precipitation, and we hypothesized that changes in intermittency factor might result from channel self-adjustment. The range of intermittency factor values we found are similar to values used for Earth and Mars. Small intermittency factors applied to Mars suggest timespans of fluvial activity for individual systems lasting millions of years or longer.

Conflict of Interest

The authors have no financial conflicts of interest.

Data Availability Statement

Data from sedimentary deposits and modern rivers are at http://dx.doi.org/10.22002/D1.2023 and the supplement describes methods in additional detail. All survey data are available in the original publications: Emmett, 1972; Williams, 1978; Andrews, 1984; Elliott and Cartier, 1986; Castro and Jackson, 2001; McCandless and Everett, 2002; McCandless, 2003a, 2003b; Cinotto, 2003; Moody et al., 2003; Lawlor, 2004; Metcalf et al., 2009; Chaplin, 2005; Keaton et al., 2005; Sherwood & Huitger, 2005; Mistak and Stille, 2008; Agouridis et al., 2011; Wilkerson & Parker, 2011; Brockman et al., 2012; Foster, 2012. Original USGS streamgage data can be downloaded from https://waterservices.usgs.gov and McMurdo LTER streamgage data from https://mcm.lternet.edu/content/daily-summarized-seasonal-measurements-discharge-water-temperature-and-specific-conductiv-14.

Acknowledgments
This work was supported by NASA (grant NNX16AQ81G1960 to MPL and graduate fellowship support 80NSSC17K0492 to A. T. Hayden).

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