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Key Points:
- The timing and intensity of gravel riverbed mobility vary between regions
- Sediment supply is the primary driver of the intensity of bed mobility
- Regional variation in bed mobility has implications for aquatic habitat and sediment transport "memory effects"

Supporting Information:
- Supporting Information S1

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Regional Variation in Gravel Riverbed Mobility, Controlled by Hydrologic Regime and Sediment Supply

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Abstract The frequency and intensity of riverbed mobility are of paramount importance to the inhabitants of river ecosystems as well as to the evolution of bed surface structure. Because sediment supply varies by orders of magnitude across North America, the intensity of bedload transport varies by over an order of magnitude. Climate also varies widely across the continent, yielding a range of flood timing, duration, and intermittency. Together, the differences in sediment supply and hydroclimate result in diverse regimes of bed surface stability. To quantitatively characterize this regional variation, we calculate multidecadal time series of estimated bed surface mobility for 29 rivers using sediment transport equations. We use these data to compare predicted bed mobility between rivers and regions. There are statistically significant regional differences in the (a) exceedance probability of bed-mobilizing flows ($W^* > 0.002$), (b) maximum bed mobility, and (c) number of discrete bed-mobilizing events in a year.

Plain Language Summary How often does the gravel on a riverbed move? Do the timing and intensity of gravel riverbed motion vary between regions? The answers (a) shape habitat for macroinvertebrates that live on the riverbed surface and (b) drive "history effects" that render river gravel more stable through time between storms. To answer these questions, we calculate gravel mobility using decade-long river gage records and channel measurements from 29 rivers across the United States. We show that there are strong regional trends in the timing and intensity of riverbed mobility between the West Coast, Rocky Mountains, and central Appalachians. These previously unrecognized regional differences are explained by trends in flood timing and trends in the amount of sediment that flows into the rivers. We show that the Appalachians, a region with few published river gravel transport studies, may be especially susceptible to history effects.

1. Introduction

When does a riverbed move? A reductionist view of gravel riverbed mobility based on the threshold channel concept would suggest that, on average, the riverbed just exceeds the threshold for motion during bankfull floods (Phillips & Jerolmack, 2016). Because bankfull floods tend to occur an average of once every 1 to 2 years (Leopold et al., 1964), we might infer that gravel beds mobilize with the same recurrence interval. However, natural rivers experience a wide diversity in both hydroclimatic regimes (Hirschboeck, 1991) and sediment supply conditions (Pfeiffer et al., 2017). This variability hints at a more complex array of bed mobility timing and intensity among gravel bedded rivers.

Riverbed mobility is a function of channel geometry, flow regime, and the grain size distribution (GSD) of the bed surface, which is shaped in part by sediment supply (Dietrich et al., 1989). Rivers with high sediment supply tend to have finer bed surface grain size (Pfeiffer et al., 2017), which increases mobility for a given discharge (Lisle et al., 2000). As an extreme example, the rivers draining Mt. Pinatubo responded to the dramatic increase in sediment supply after the 1991 volcanic eruption through fining of the bed surface grain size and reduction in surface roughness, enabling remarkable rates of sediment transport even at low flow (Montgomery et al., 1999). Lisle et al. (2000) explored variability in bed mobility among six rivers of different sediment supply. They used grain size mapping and 2-D flow models to characterize the heterogeneity of bed mobility within each reach and found that a larger portion of the bed was mobile during bankfull flow in sediment rich channels than in low-supply channels. However, they did not consider the effects of flow intermittency but instead compared bed mobility at bankfull flow.

The threshold for sediment motion is defined as the transition from an immobile bed, in which grains are not moving, to a partially mobile bed, in which a small number of grains are mobile. In practice, the threshold for motion (hereafter "threshold mobility") is commonly defined as the stress at which the sediment transport rate exceeds a reference value, often stated in terms of the dimensionless transport parameter (W^*):

$$W^* = Rgq_s/(ghS)^{3/2} \tag{1}$$

where R is submerged specific gravity of sediment, g is gravitational acceleration, q_s is the volumetric sediment transport rate per unit channel width, h is average flow depth, and S is channel slope. Threshold mobility is commonly defined as the bed surface shear stress at which $W^* = 0.002$ (Parker, 1990). As flow increases beyond threshold mobility, the proportion of the bed that is mobile increases until nearly all grains on the bed surface are in motion (Andrews, 1994; Wilcock & McArdell, 1997). This transition occurs at roughly twice the stress associated with the threshold for motion (Andrews, 1994). Here we use the term "immobile bed" to refer to the transport state below threshold mobility ($W^* = 0.002$), "full mobility" to describe the state in which most grains are in motion (defined here as twice the reference stress, see section 2 below), and "partial mobility" to describe the transport stage in between. These transport rates are calculated for the full GSD, as opposed to separating the mobility stages for each size fraction (e.g., Wilcock & McArdell, 1997).

The timing and predictability of riverbed mobility are important drivers of aquatic habitat in river ecosystems. The threshold mobility is often associated with a dramatic reduction in benthic macroinvertebrates density (Gibbins et al., 2007; Power et al., 2008; Robinson et al., 2004). In a New Zealand stream, benthic macroinvertebrates returned gradually (both biomass and number of species) over the 3 months following a large storm (Scrimgeour et al., 1988). Thus, a biologically relevant characterization of riverbed mobility should define both the intensity of bed mobility and wait times between bed-mobilizing storms.

In addition to implications for river ecosystem function, the timing of bed mobility and immobility likely influences history effects in rivers. The flow conditions preceding a storm can affect the stability of the bed. Physical experiments have shown that the threshold for riverbed mobility can increase with the duration of premobility low flows (Haynes & Pender, 2007; Masteller & Finnegan, 2017; Ockelford & Haynes, 2013). This phenomena is associated with subtle reorganization of the bed surface, rendering grains more stable. The threshold for sediment transport can also vary as a function of net imbalances between sediment supply and sediment transport (Johnson, 2016). In addition to these abiotic processes, biologically mediated stabilization of gravel during prolonged low-flow, high-productivity periods may represent another history effect controlled by bed mobility timing. For example, caddisfly larvae build silk nets that bind individual particles together, significantly increasing the threshold for sediment motion during subsequent storms (Albertson, Sklar, et al., 2014; Albertson, Cardinale, & Sklar, 2014; Cardinale et al., 2004; Johnson et al., 2009). Because it may take months for caddisfly populations to rebound after extreme bed-mobilizing flows (e.g., Power et al., 2008), the timing and intensity of these storms have the potential to determine the threshold for mobility during subsequent high-flow events. While existing sediment transport models do not take these effects into account, bed mobility frequency analysis can reveal how variable interstorm wait times actually are between rivers and regions.

Bed mobility provides a lens through which to consider how sediment supply and hydroclimatic patterns are reflected in gravel bedded river geometry. Sediment supply and hydrology vary enormously, but differences in river geometry are comparatively subtle. For example, Pfeiffer et al. (2017) showed that an ~2 orders of magnitude variation in sediment supply are associated with only an approximately twofold difference in the ratio of the bankfull shear stress to the critical shear stress associated with bed mobility. These findings suggest that channel geometry and grain size reflect sediment supply; however, it is impossible to fully capture/understand how channels reflect variation in sediment supply without recognizing the importance of flow intermittency (Hassan et al., 2006). A channel that experiences sediment mobilizing floods lasting 1 week a year likely transports substantially more sediment than one that transports sediment at the same rate for only a few hours. To the extent that river channels tend toward a dynamic, quasi-equilibrium between sediment supply inputs and sediment transport outputs, patterns in bed mobility should reflect the combined effects of magnitude and frequency.

Here we use multidecadal time series of modeled sediment transport for 29 rivers across the continental United States to show that predicted bed mobility varies enormously (in terms of intermittency, timing, and intensity) between gravel bedded rivers. We focus on the significant regional trends and suggest that these trends are a direct function of the continent-scale trends in hydroclimatic regime and sediment supply.

10.1002/2017GL076747

2. Methods

We calculate multidecadal time series of predicted bed surface mobility using fractional sediment transport equations (Parker, 1990). The method requires measurements of the bed surface GSD, channel slope, and long-term stream discharge records. We use the time series of predicted bed mobility to compare between rivers and regions.

2.1. Site Selection

We compiled a data set of 29 gravel bedded rivers across the continental United States (supporting information Table S1). We selected sites with gravel beds and long-term (mean = 24.2 years) U.S. Geological Survey (USGS) continuous discharge (15-min interval) records. The sites are situated in single-threaded reaches. Bed surface grain size and channel slope data came from the literature. The distributions of slope, drainage area, and median grain size (D_{50}) represented in each region are shown in Figure S1. In the absence of full GSDs (n = 16), we created synthetic GSDs using reported D_{50} and D_{84} for the reach, assuming a lognormal GSD (as in Pfeiffer & Finnegan, 2017). In five cases we lacked D_{84} data and estimated D_{84} as $2.1D_{50}$ (Rickenmann & Recking, 2011).

We focused our study on three regions: the West Coast, the Rocky Mountains, and the Mid-Atlantic Appalachians. These regions represent a gradient in sediment supply (Pfeiffer et al., 2017) and have varying flood hydrology. The West Coast is characterized by high erosion rates (average long-term erosion rate = 336 mm/kyr, Pfeiffer et al., 2017) and has a Mediterranean climate with dry, warm summers and mild, wet winters (Hirschboeck, 1991). The Mid-Atlantic is characterized by low erosion rates (22 mm/kyr mean long term) and weak seasonality in precipitation. Floods result from early autumn tropical cyclones, wintertime "nor'easters," and, occasionally, intense summer thunderstorms (Hirschboeck, 1991). The Rocky Mountain region has moderate erosion rates (114 mm/kyr mean long-term erosion rate, with notably lower short term erosion rates, Kirchner et al., 2001). Rivers in the Mid-Atlantic Appalachians and along the West Coast tend to experience a substantial number of "flashy" storms (Smith & Smith, 2015). This is not the case in the Rocky Mountains, where most floods predictably occur during peak snowmelt in the spring or early summer (Hirschboeck, 1991).

While USGS instantaneous discharge data exist for hundreds of sites across the continental United States, many well-studied sites proved unsuitable for our analysis. In particular, small Rocky Mountain streams tend to be frozen for a large portion of the year, with ice breaking up during the spring high flows. Those missing data impede exceedance probability analysis. We excluded sites that have large, seasonally consistent data gaps. In cases with more moderate winter data gaps (e.g., East River), where the full duration of the missing data occurred during subthreshold transport conditions, we filled in the missing data using a linear interpolation between flows of known magnitude.

2.2. Streamgage Data Processing and Bed Mobility Calculations

To transform USGS discharge records into time series of average flow depth, we utilize stage-discharge rating curves and field measurements available through the USGS Water Science Centers. Building on the method described by Phillips and Jerolmack (2016; detailed in Text S1), we create a modified rating curve for each site that relates average flow depth (instead of stage) to discharge. The average depth rating curve maintains the shape of the stage-discharge rating curve but is shifted to obtain a best fit between discharge and field measurements of average flow depth. This transformation is necessary because (a) average flow depth has significance for sediment transport, whereas stage is simply water height measured above an arbitrary datum, and (b) complex channel geometry often results in kinked or stepped rating curves, which are not captured in a simplistic power law scaling relationship between depth and discharge. We use the average depth rating curves to transform USGS multidecadal time series of discharge to time series of average flow depth for bed mobility calculations.

We used the same discharge and channel geometry data to create a rating curve to relate average channel width (w [m]) to discharge (Q [m^3/s]). These relationships were well modeled using a standard hydraulic geometry scaling relationship ($w = aQ^b$, where a and b are empirical parameters determined through least squares best fit analysis).

Here we use the Parker (1990) fractional sediment transport equations, modified to account for slope dependence of the threshold for motion. The model and modifications are described in detail in Text S2. See Pfeiffer (2017) for bed mobility results calculated using different sediment transport formulae. We do not account for history effects that may alter the threshold for motion, though we discuss the potential implications of these effects below. In this analysis, we characterize bed mobility using the dimensionless transport parameter, W^*, because it has a specific, frequently used value associated with threshold mobility: by definition (e.g., Parker, 1990), the reference transport rate associated with the threshold mobility occurs at $W^* = 0.002$. This is in contrast to τ^*, which has a range of values associated with the threshold for motion and is less directly related to sediment transport. Full mobility, a transport stage associated with the mobility of nearly all grains on the bed surface, tends to occur at roughly twice the critical stress in mountain streams (Andrews, 1994). We can plug this ratio ($\tau^*/\tau_r^* = 2$) into the Parker (1990) sediment transport formulae to find the value of W^* associated with the transition to full mobility (0.9776). Thus, we define an immobile bed as one in which $W^* < 0.002$, a partially mobile one as $0.002 \geq W^* > 0.9776$, and fully mobile as $W^* \geq 0.9776$.

2.3. Analysis of Bed Mobility Results

To characterize bed mobility intermittency, we calculated wait times between bed-mobilizing flood events. We counted a mobility event ($W^* > 0.002$) as distinct if it was preceded by at least 24 h of $W^* < 0.002$.

We tested the statistical significance of differences between regions using a Welch's analysis of variance, a test that is robust to analyze data sets of unequal size with unequal variance. We log transformed the data before running the analysis of variance to account for lognormal (rather than normal) distributions within regions. When statistically significant differences were found ($\alpha < 0.05$), we employed a Games-Howell post hoc test to make pairwise comparisons.

As an order-of-magnitude test of our sediment transport results, we compare predicted average annual bedload transport to estimates of average annual bedload supply (Q_{supply} [m^3/year]) based on data in the literature. If a riverbed is neither aggrading nor incising, the sediment transport through the reach should be in equilibrium with the sediment supply to the reach. Our methods for estimating bedload supply varied by river, depending on the available information. Site specific details are given in supporting information Table S2.

3. Results and Discussion

Predicted gravel riverbed mobility varies enormously among the rivers in our compilation. Given the importance of bed mobility to lotic ecosystems, it is an important dimension by which we can (and perhaps should) compare rivers. On one end of the spectrum captured in our data compilation, we predict that some rivers fail to reach reference mobility ($W^* = 0.002$) more than a few times over the course of decades (e.g., Mahoning). On the other end, our calculations suggest that the Nisqually River, which drains the glaciers of Mt. Rainier, has a mobile bed the majority of the time.

The first-order relationships between hydrology and bed mobility are clear in the time series of bed mobility (Figures 1 and 2). The Rocky Mountain rivers (Figures 1b, 1c, and 2d–2f) have floods that are generally consistent in timing and magnitude between years. Peak floods tend to occur during the late spring, which coincides with snowmelt. In most of the Rocky Mountain streams in our data set, the threshold mobility (a term we use to refer to $W^* = 0.002$) occurs at approximately bankfull flow. West Coast rivers experience many short-duration, high bed mobility events throughout the winter and spring (Figures 1d, 1e, and 2a–2c). This is the case even for streams in our data set that drain Mt. Rainier (Carbon, Nisqually, and Puyallup), even though the upper reaches of those basins contain glaciers and receive substantial winter snowfall. In many West Coast streams in our data set, the annual peak value of bed mobility varies substantially between years. We lack bankfull depth measurements for most of the West Coast rivers in our compilation. However, we predict partial bed mobility at low recurrence-interval flows. The Appalachian rivers experience short-duration high-flow events throughout the year (Figures 1f, 1g, and 2g–2i). The maximum intensity of bed mobility varies substantially between the Appalachian rivers in our compilation. The peak bed mobility events do not have a strong seasonal control, unlike the West Coast and Rocky Mountain rivers. The relationship between bankfull flow and the predicted initiation of bed mobility is inconsistent across Appalachian rivers. In several of the rivers (e.g., Spring and Mahoning), bed mobilization occurs well above bankfull flow.

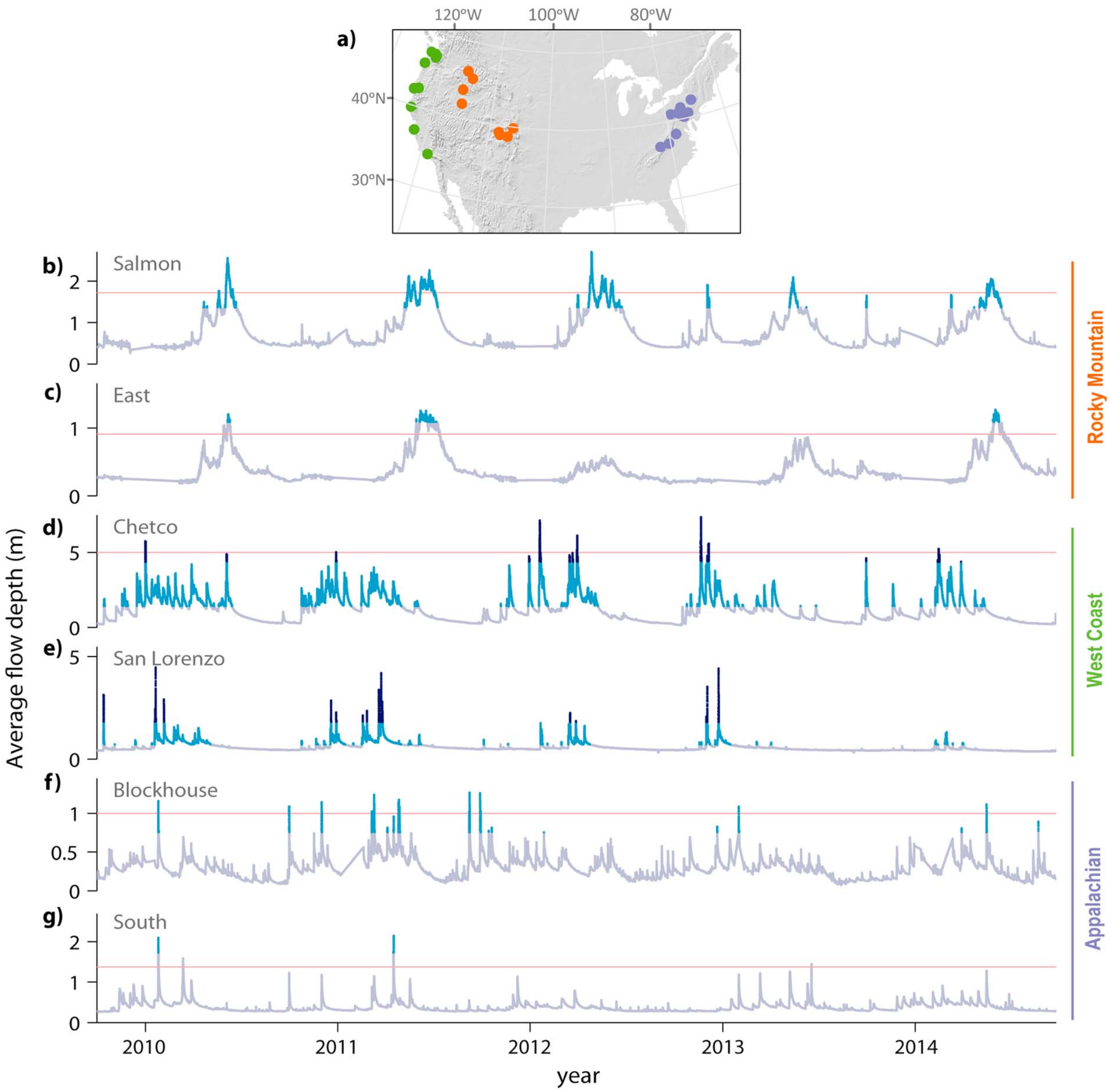

Figure 1. (a) Site map (Appalachian sites are shown in purple, Rocky Mountain sites in orange, and West Coast sites in green) and (b–g) example average flow depth hydrographs for water years 2010–2014, colored by bed mobility. Transport below W^* = 0.002 is shown in gray, "marginal mobility" in light blue, and full mobility in dark blue. Where available, bankfull depths are shown, for reference, in red.

Clear regional trends are captured in the calculated relationship between the exceedance probability of reference flows and the maximum bed mobility (Figure 3a). We see that the data cluster by region. West Coast and Rocky Mountain rivers have statistically significantly higher exceedance probability of threshold mobility (the beds are mobile a large portion of the time) when compared to Appalachian rivers ($p < 0.0001$ and $p = 0.02$, respectively). In terms of maximum bed mobility, West Coast rivers have statistically significantly higher maximum mobility than both Rocky Mountain (p = 0.002) and Appalachian rivers (p = 0.005), which are not statistically different from one another.

There are significant regional trends in the number of bed-mobilizing events per year and the wait time between the events. West Coast rivers have significantly more mobility events per year than both Rocky Mountain (p = 0.0002) and Appalachian rivers (p = 0.006). West Coast and Rocky Mountain rivers experience a mean of 9.7 (±3.2 standard deviation, S.D.; duration = 9.5 days) and 2.0 (±1.1 S.D.; duration = 10 days) discrete bed-mobilizing events per year, respectively. Appalachian rivers experience a mean 2.6 discrete

10.1002/2017GL076747

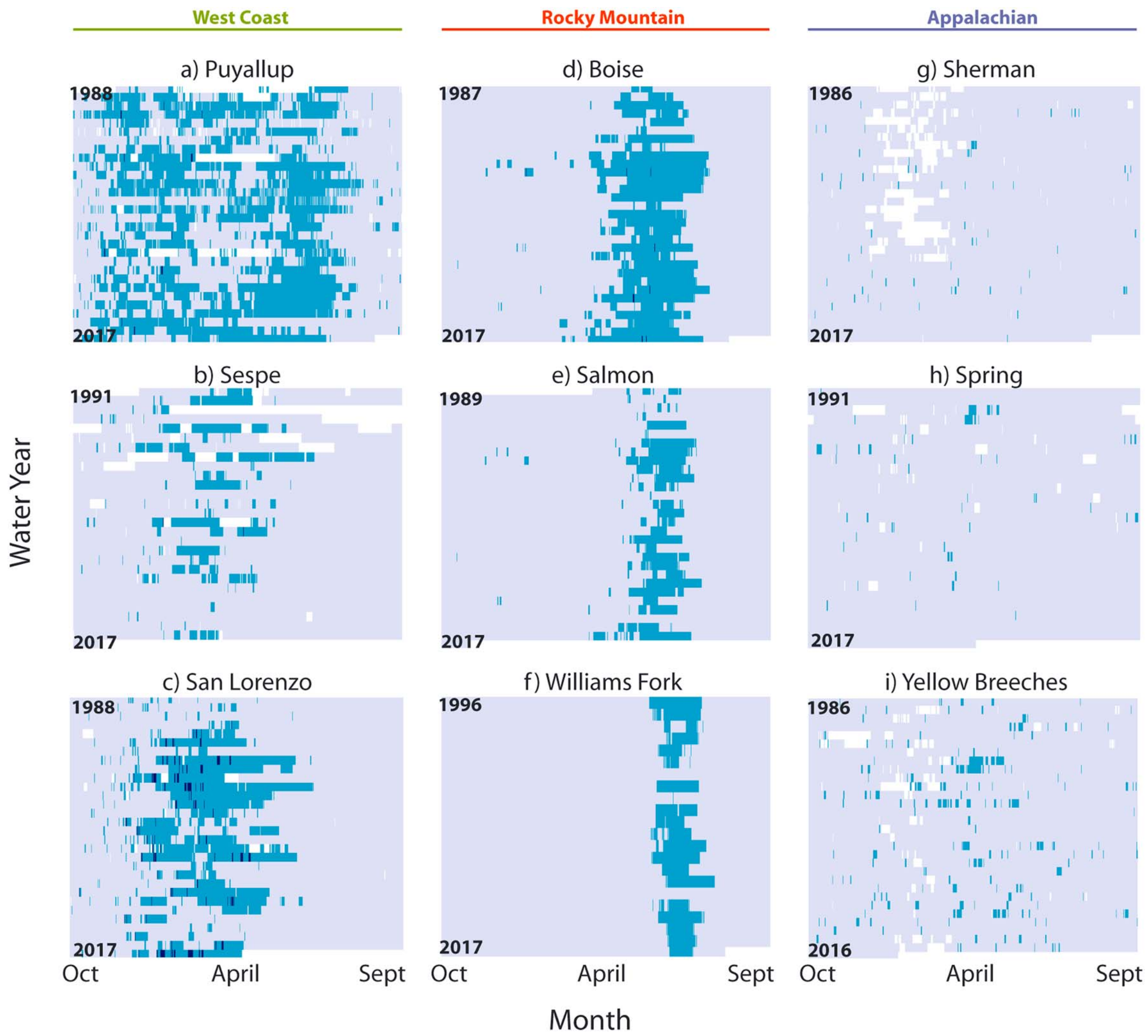

Figure 2. (a–i) Bed mobility intensity through time for nine example sites, three from each geographic region. Data are separated by water year. Water year is on the vertical axis, month within the water year is on the horizontal axis. Immobile bed is shown in gray, partial mobility in light blue, and full mobility in dark blue. Data gaps are shown in white.

bed-mobilizing event per year (duration = 0.7 days), though the variation between rivers is substantial, with a S.D. of 2.2 events. Bed mobilizing events in Rocky Mountain rivers tend to occur after a ~3–10- or ~300-day wait time (Figure 3b). This strong annual frequency is apparent in Figures 2d–2f. West Coast channels have similarly bimodal wait times, though the majority of events happen after a 3–30-day period of subreference mobility. There is not a strong mode to the wait time between bed-mobilizing storms in the Appalachian rivers. Wait times vary from 2 to 2,000 days, with two weak modes around 60 and 400 days.

These findings define broad regional trends in calculated bed mobility, which we can use to categorize bed mobility regimes. Hassan et al. (2014) categorized streams according to the exceedance probability of effective discharge. Though this analysis is focused on mobility thresholds rather than effective discharge, we can apply a similar scheme. In general, the West Coast rivers, with a median of 83 days above reference mobility annually (including a median of 0.1 annual days of full mobility), are “frequently mobile, occasionally fully mobile” gravel rivers. While 9 of 10 West Coast sites reached predicted full mobility at some point, only 1 Appalachian (Yellow Breeches, Figure 2i) and 1 Rocky Mountain (Boise, Figure 2d) river reached full mobility. The Rocky Mountain rivers, which tend to have a long period of marginal mobility during the spring snowmelt (average of 28 days of partial mobility), tend to be “frequently partially mobile.” We term the Appalachian rivers “infrequently, briefly mobile,” with a region-wide median of 1.7 days of partial mobility.

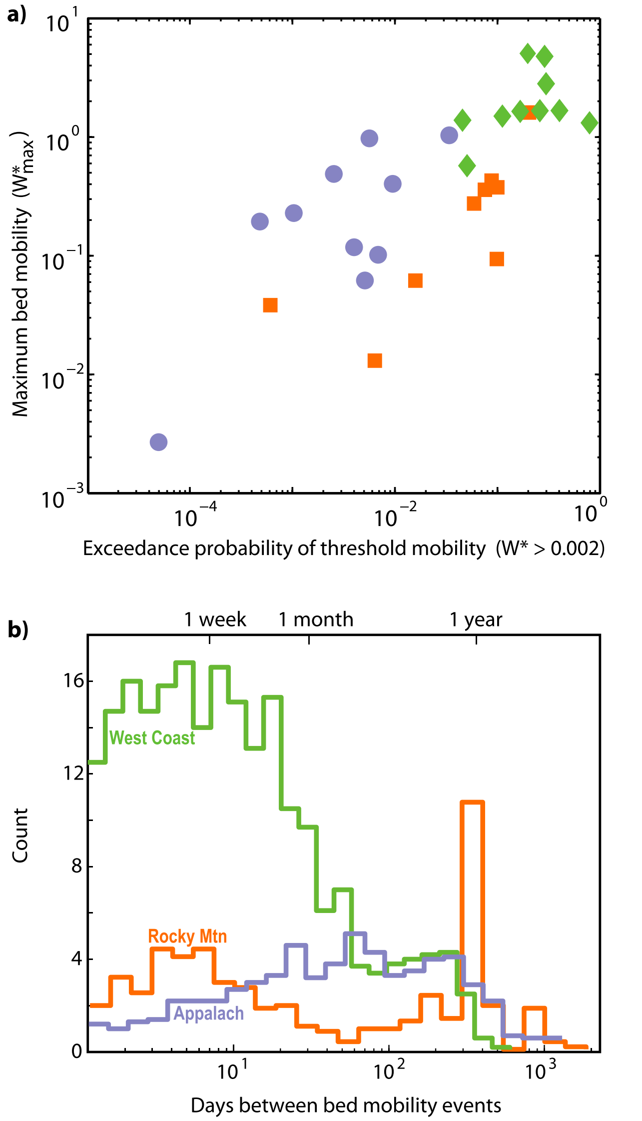

Figure 3. Regional trends in bed mobility. (a) Comparison of the exceedance probability of mobility ($W^* > 0.002$) and the maximum bed mobility. Data are colored by region: West Coast = green diamonds; Rocky Mountains = orange squares; Appalachian = purple circles. Note the strong regional clustering. (b) Histogram showing the number of days in between bed mobility events ($W^* > 0.002$), separated by region. Counts are normalized by the number of sites in that region. Colors match previous figures.

These regional trends in calculated gravel riverbed mobility can be explained by the combined effects of coarse sediment supply and basin hydrology. The intensity of bed surface mobility is primarily driven by sediment supply. The gradient in sediment supply represented by these three regions (336, 114, 22 mm/kyr average erosion rate for West Coast, Rocky Mountains, Appalachian, respectively, Pfeiffer et al., 2017) is reflected in the patterns of bed mobility (Figure 2). The West Coast rivers have significantly higher peak transport intensity (W^*_{max}) than both Appalachian and Rocky Mountain rivers and significantly higher exceedance probability of mobility when compared to Appalachian rivers. These findings build on the work by Lisle et al. (2000), who showed that bankfull bed mobility varied systematically with sediment supply. In addition, this supports the observation of Pfeiffer et al. (2017) that the ratio of bankfull to critical Shields stress varies with sediment supply and that the ratio is substantially higher in West Coast rivers. In general, rivers that are supplied more sediment are mobile more often.

Basin hydrology is the other obvious driver of bed mobility differences between regions. The effects of hydrology are apparent in the relationship between peak mobility and exceedance probability of reference mobility (Figure 3a). Appalachian and Rocky Mountain rivers have similar peak mobility intensity (difference in W^*_{max} is not statistically significant); however, moderate sediment transporting flows occur a greater portion of the time in Rocky Mountain streams than in Appalachian ones (significant difference in exceedance probability). This pattern results from the differences in hydrology between the two regions. Rocky Mountain rivers experience long periods of high flow during the spring snowmelt, whereas Appalachian rivers experience abrupt, brief floods (Figure 2).

Our approach to bed surface mobility analysis could be used to test ecological disturbance theories, enabling first-order quantitative characterization of bed surface disturbance regimes without requiring extensive field surveys or 2-D flow models. Segura et al. (2011) suggested that periphyton accumulation is controlled by both bed mobility and growth stimulation (e.g., temperature and nutrient availability). Viewed along these axes, we might expect the Rocky Mountain rivers (low temperatures limiting growth and moderate bed mobility) and West Coast rivers (higher temperatures but intense bed mobility) to have low periphyton growth compared to Appalachian rivers (higher temperatures, low bed mobility).

The regional differences in predicted bed mobility timing have potential implications for history effects (e.g., changes in sediment transport that depend on interstorm wait times); in turn, these history effects have unaccounted for implications for the reality of sediment transport. Biologically mediated history effects almost certainly operate differently in Appalachian streams than in West Coast and/or Rocky Mountain ones. In most Rocky Mountain and West Coast streams, the high-flow season predictably brings (either marginal or full) bed-mobilizing flows. In most years, the late summer and early fall months are characterized by relative immobility. In these regions, the first bed-mobilizing flow following the dry season may result in less intense bed mobility than we have predicted due to bed stabilization, both abiotic (e.g., Haynes & Pender, 2007) and biotic (e.g., Johnson et al., 2009). We suggest that history effects may have an even greater influence in Appalachian rivers. While floods in the West Coast and Rocky Mountain Rivers tend to occur in quick succession (median wait time between mobility events is 7 and 14 days, respectively), Appalachian rivers have long periods of immobility between most storms (median = 45 days; mean = 115; Figure 3b). This allows more time for macroinvertebrates to build bed-stabilizing silk nets (Albertson, Sklar, et al., 2014) and low flows to stabilize the bed through subtle grain reorganization (e.g., Ockelford & Haynes, 2013) before the next storm. Interestingly, these potential effects would further increase the discrepancy in bed mobility between regions, making the Appalachian streams even less mobile. These feedbacks are not accounted for in the transport predictions made herein. Further work is needed to understand, document, and model history effects in sediment transport and the degree to which they vary between regions.

This approach to characterizing bed mobility does not require bankfull flow depth; this represents a notable benefit. While convenient in many situations, bankfull depth can be an imprecise metric of river dimensions. "Bankfull" flow has several different definitions and does not have a characteristic recurrence interval across (or even within) regions (Williams, 1978). Some channels have poorly defined floodplains or multiple topographic breaks, complicating the characterization of a single bankfull channel. By characterizing the mobility of a riverbed in terms of exceedance probabilities and interstorm wait times, we use metrics that have uniform meaning and biological relevance between regions. Furthermore, in the myriad rivers where upstream dams regulate flow, the bankfull channel may represent predam conditions, rather than the flow and sediment supply that determine postdam bed mobility. Bed mobility has biological relevance in regulated rivers as well as unregulated ones. Our method for characterizing bed mobility can be applied to regulated rivers.

A drawback of this method for characterizing bed mobility is that it requires long-term stream gage data, which is not available for many rivers. It would be convenient if commonly used metrics, such as the ratio of bankfull Shields stress to critical Shields stress, were sufficient to distinguish between bed mobility regimes. To test this, we looked at the relationship between τ^*_{bf}/τ^*_c and both $W^*_{\max}$ and the exceedance probability of partial mobility (supporting information Figure S2). In both cases, we find positive relationships between τ^*_{bf}/τ^*_c and bed mobility with substantial scatter. The relationship between hydrology, grain size, and sediment transport is complex, to say nothing of the complex drivers of bankfull geometry. As a result, it is not surprising to find that τ^*_{bf}/τ^*_c is not cleanly explained by bed mobility alone. That said, remarkably high or low τ^*_{bf} is likely a good indication of a highly mobile or immobile bed.

We used published sediment supply data for a subset of sites in our compilation to check our sediment transport calculations. This check is valuable because sediment transport is notoriously difficult to predict and the sediment supply estimates have substantial uncertainty as well. In eight out of nine sites, average annual sediment supply and average annual sediment transport (supporting information Figure S3) were within 1 order of magnitude. This is reassuring: it suggests that our bed mobility calculations are reasonable.

The remarkably low predicted bedload transport rates in the Appalachian sites, as well as the likely importance of history effects there, are intriguing. Unfortunately, we were unable to find published bedload sediment supply (or, for that matter, any individual bedload sample) data in the literature for rivers in the central Appalachians. All of the sediment supply data used in supporting information Figure S3 are from West Coast and Rocky Mountain sites. The lack of independent constraint for the Appalachian rivers is unfortunate and points to a gap in the literature. That said, the good agreement between sediment supply and sediment transport in the West Coast and Rocky Mountain rivers suggests that our approach yields reasonable bed mobility estimates.

In addition to assuming a constant reference stress for sediment transport (likely complicated by history effects), our method for calculating bed mobility assumes fixed channel geometry and bed surface grain size through time. This simplification is common in calculations of sediment transport, though somewhat unsatisfying, as channel geometry (e.g., Pizzuto, 1994) and bed surface grain size (e.g., Rubin & Topping, 2001) often change during major flood events. This suggests that in the years following an extreme event, our bed mobility estimates may be inaccurate. However, Rubin and Topping (2001) found that in alluvial rivers, discharge is the dominant driver of sediment transport, with changes in bed surface grain size playing a secondary role. While the exact values of bed mobility for a given site may vary depending on the antecedent high-magnitude flood history, the effects of variable grain size and channel geometry are unlikely to change the regional trends in bed mobility intensity and intermittency.

Here we have treated bed mobility as a reach-averaged problem. This is a substantial simplification, borne from the limited channel geometry and grain size patch information available in the literature. Both Lisle et al. (2000) and Segura et al. (2011) deal with the mobility of individual bed surface grain size patches within a reach. Both studies found that, even when the reach-averaged shear stresses were low, small fine-grained bed surface patches remained mobile. The patch-scale variations in bed surface mobility are certainly important for the benthic inhabitants living in those places. That said, Lisle et al. (2000) found that, while the details differed, reach-averaged bed mobility predictions were generally in agreement with the trends seen in patch-scale mobility. The simplified approach we propose here is, therefore, a good option for comparative studies between regions but not suitable for studies focused on subreach-scale processes.

The method we used to process USGS channel geometry and gage data was inspired by Phillips and Jerolmack (2016), but the results lead us to quite different conclusions. Phillips and Jerolmack (2016) argue that gravel bedded rivers adjust themselves to "filter" climatic variation, such that a wide variety of hydroclimatic conditions all result in rivers that are, roughly, threshold channels. Their analysis focused on the central tendency of gravel bedded rivers. Here we have focused on the variation between regions, viewing the problem through the lens of bed mobility. While the average river may indeed be a threshold channel, the wide variety of sediment supply and hydroclimatic conditions imposed on gravel bedded rivers yield statistically significant regional trends. Here we show that gravel bedded rivers reach threshold mobility at a wide variety of stages relative to bankfull flow.

4. Conclusions

Viewing sediment transport through the lens of calculated bed mobility, we show that there are substantial differences between regions across North America. Sediment supply appears to be the primary driver of the intensity of bed mobility, while the intermittency of bed mobility is largely determined by hydrologic regime. The regional differences represent diverse physical habitat regimes for the benthic inhabitants of river ecosystems and likely shape biotic and abiotic history effects in sediment transport. In turn, the history effects likely complicate the time series of bed mobility (not accounted for in our calculations here), with greater impacts in the Appalachian and West Coast rivers than those in the Rocky Mountains. Common approaches to sediment transport prediction do not account for these effects.

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