The Role of Geology in Sediment Supply and Bedload Transport Patterns in Coarse Grained Streams

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This paper compares gross differences in rates of bedload sediment moved at bankfull discharges in 19 channels on national forests in the Middle and Southern Rocky Mountains. Each stream has its own "bedload signal," in that the rate and size of materials transported at bankfull discharge largely reflect the nature of flow and sediment particular to that system. However, when rates of bedload transport were normalized by dividing by the watershed area, the results were similar for many sites. Typically, streams exhibited normalized rates of bedload transport between 0.001 and 0.003 kg s^{-1} km^{-2} at bankfull discharges. Given the inherent difficulty of obtaining a reliable estimate of mean rates of bedload transport, the relatively narrow range of values observed for these systems is notable. While many of these sites are underlain by different geologic terrane, they appear to have comparable patterns of mass wasting contributing to sediment supply under current climatic conditions. There were, however, some sites where there was considerable departure from the normalized range of values. These sites typically had different patterns and qualitative rates of mass wasting, either higher or lower, than observed for other watersheds. The gross differences in sediment supply to the stream network have been used to account for departures in the normalized rates of bedload transport observed for these sites. The next phase of this work is to better quantify the contributions from hillslopes to help explain variability in the normalized rate of bedload transport.

Keywords: *bedload transport, sediment supply, mass wasting*

Introduction

Differences in the underlying lithology of watersheds cause variation in the stability of the landscape and, hence, variation in the modes of sediment supply to a stream channel. While the rate and patterns of coarse sediment transported in gravel bed streams reflect many watershed factors (e.g., climate, land use, natural disturbances) the characteristics of materials supplied from hillslope and in-channel sources are of particular importance. Specifically, the size of material, the rate and volume of sediment delivered, the timing of delivery relative to high flows, and the periodicity of failures, all influence sediment supply and the stream's ability to transport sediment delivered from adjacent hillslope erosion. In areas where mass wasting processes and rates are largely comparable, one might expect similarity in the rate and patterns of sediment transport.

The primary purpose of this paper is to compare and contrast rates of bedload transport measured at bankfull discharges for a number of stream sites on national forest lands in Colorado and Wyoming. Bankfull discharge, or the flow that just fills the channel banks, was used as a reference point so that transport rates at a common discharge scaled to the size of the channel could be compared. Because comparisons are made between watersheds of varying size, the data are normalized by dividing the rate of bedload transport by the area of the drainage basin. Similarities and differences between these normalized values are discussed, using examples to compare and contrast the relationships and relate them to gross differences in geologic terrane and associated patterns of mass wasting. Specifically, the paper is divided into the following three areas:

- Commonalities in the normalized rate of bedload transport for several sites in central Colorado and southern Wyoming. These areas are underlain primarily by granite, gneiss, and schist, and have relatively low rates of mass wasting relative to those that have occurred in the past (Caine 1986).
- Substantial departure in normalized rates of transport observed in watersheds underlain by extrusive volcanic and granitic terrane on the San Juan National Forest in southwestern Colorado. Here, the normalized values are among the highest and lowest observed in this series of comparisons and are linked to gross differences in observed mass wasting patterns.
- Variations in transport rates observed at two sites in the Gros Ventre Range in western Wyoming. While

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both sites are underlain by deformed sedimentary formations common to this area, there are distinctive differences in patterns of mass wasting between these two watersheds that can be used to explain substantial variation in observed rates of sediment transport.

STUDY AREAS

All of the study sites are located on streams where the USDA Forest Service or the U.S. Geological Survey have initiated studies on sediment transport over the past 10-20 years. The streams are located within either the Middle or Southern Rocky Mountain provinces (Hunt 1974) and are tributaries to the Snake, Platte, Colorado, Arkansas, and San Juan Rivers (Figure 1). Most sites are located near presently- or historically-operating gaging stations and represent a range of channel sizes and types (Ryan et al. 2005). Drainage areas range from 2.9 to 230 km^2 and the sites are between 2000 to 3000 m in elevation. Channels are characterized by moderate to steep gradients (0.01 to 0.05 m/m). The median grain size of the bed surfaces range from very coarse gravel to coarse cobble sizes that are poorly to very poorly sorted (Ryan et al. 2005). Channel types include step-pool, plane-bed, pool-riffle, and one moderately braided site (Table 1).

The lithology of the studied areas is quite diverse (Tweto 1979; Love and Christiansen 1985) (Table 1). Most of the sites are underlain by granite, gneiss, and schist bedrock while other streams flow through areas with sedimentary formations including sandstone, conglomerate, and limestone. The East Fork San Juan and Silver Creek, in southwestern Colorado, are underlain by complex volcanic formations consisting of layered lavas flows. Nearly all of the sites have been glaciated and are

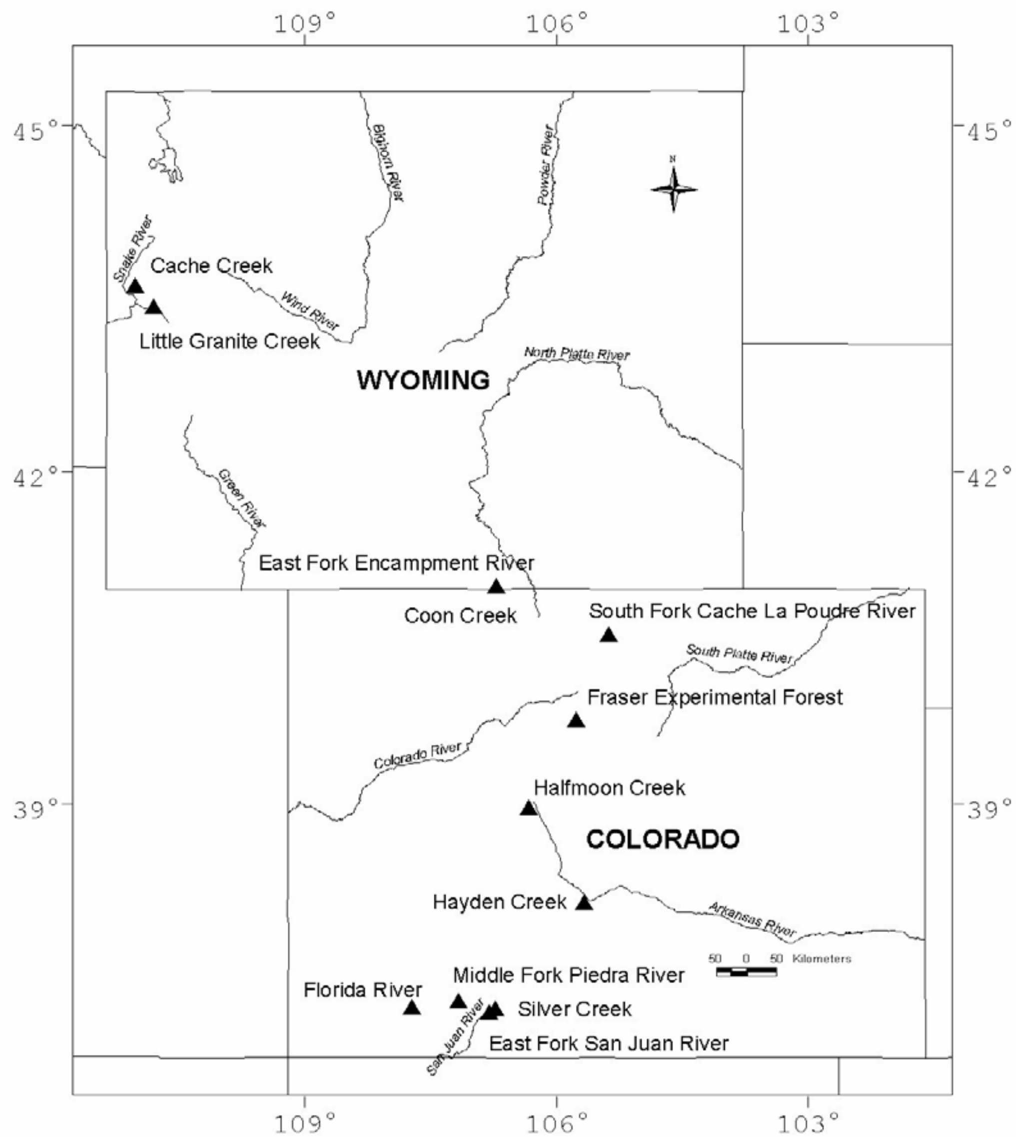


Figure 1. Map of study sites located in Colorado and Wyoming. Eight of the sites are located within the Fraser Experimental Forest, including St. Louis Creek sites 1-4, 4a, and 5, East St. Louis Creek, and Fool Creek.

Table 1. Watershed and channel characteristics.

Site	Channel Type	Management History	Drainage Area (km^2)	Bankfull Discharge $Q_{1.5}$ (m^3/s)	Transport Rate at Bankfull (kg/s)	Primary Lithology	National Forest	State
St. Louis 1	step-pool	diversion	55.6	4.41	0.115	gneiss/granite	Arapaho-Roosevelt	CO
St. Louis 2	plane	diversion	54.2	4.75	0.077	gneiss/granite	Arapaho-Roosevelt	CO
St. Louis 3	riffle	diversion	54.0	4.59	0.104	gneiss/granite	Arapaho-Roosevelt	CO
St. Louis 4	plane	free-flowing, pristine	33.8	3.61	0.048	gneiss/granite	Arapaho-Roosevelt	CO
St. Louis 4a	riffle	free-flowing, pristine	33.5	3.37	0.053	gneiss/granite	Arapaho-Roosevelt	CO
St. Louis 5	step-pool	free-flowing, pristine	21.3	2.63	0.021	gneiss/granite	Arapaho-Roosevelt	CO
E. St. Louis Cr.	step-pool	free-flowing, pristine	8.0	0.86	0.013	gneiss/schist	Arapaho-Roosevelt	CO
Fool Cr.	plane	free-flowing, harvested	2.9	0.30	0.010	gneiss/schist	Arapaho-Roosevelt	CO
Little Granite Cr.	plane	free-flowing, pristine	54.8	5.95	0.137	sedimentary	Bridger-Teton	WY
S.Fk. Poudre R.	riffle	free-flowing, some private ownership	231.0	11.44	0.283	gneiss/granite	Arapaho-Roosevelt	CO
Coon Cr.	plane	free-flowing, harvest, tie-driven	16.7	2.77	0.031	gneiss/granite	Medicine Bow-Routt	WY
E.Fk. Encampment R.	plane	free-flowing, historical harvest, tie-driven	9.1	1.45	0.007	gneiss/granite	Medicine Bow-Routt	WY
Halfmoon Cr.	riffle	free-flowing, historical harvest	61.1	6.23	0.240	gneiss/granite	Pike-San Isabel	CO
Hayden Cr.	plane	free-flowing, harvested	46.5	1.92	0.044	sedimentary	Pike-San Isabel	CO
Cache Cr.	plane	free-flowing, pristine	27.5	1.84	0.004	sedimentary	Bridger-Teton	WY
E.F. San Juan R	riffle-braided	free-flowing, some private ownership	166.0	15.66	4.742	volcanic	San Juan	CO
Silver Cr.	plane	free-flowing, pristine	15.7	1.30	0.305	volcanic	San Juan	CO
Upper Florida R.	step-pool	free-flowing, pristine	115.0	14.50	0.023	granite	San Juan	CO
M. Fk. Piedra R.	riffle	free-flowing, pristine	86	10.05	0.308	volcanic/sed.	San Juan	CO

mantled by till and glacial outwash correlative of Bull Lake and Pinedale aged deposits (e.g., Nelson and Shroba 1998). At many sites, hillslopes are relatively stable under the current climatic regime and vegetative cover, though there is evidence of active mass wasting in the past (Caine 1986). Exceptions include Little Granite Creek, in western Wyoming, where there are active, deep-seated earthflows, and the sites underlain by volcanic formations, where debris chutes and ravel from unstable terrain deliver materials directly to the stream system (Ryan 2001).

Runoff at all of the studied sites is strongly influenced by the melting of snow in spring (Jarrett 1990), though the timing of the annual peak varies between sites. Peak discharge occurs typically from early May to late June and low flow occurs in January or February. A second peak discharge can occur in late summer at the sites in the San Juan Mountains in southwestern Colorado, due to the influence of the Arizona monsoon. Most of the study sites are free-flowing, though three of the Fraser Experimental Forest sites are located in channels from which an average of 40% of the total annual flow is diverted (Ryan 1994). However, water is rarely diverted from these sites at high flow when bedload is usually sampled. Small portions of flow at East Fork San Juan and South Fork Cache la Poudre sites are diverted for household or agricultural purposes upstream of the study sites. Some of the watersheds have been deforested to different degrees (e.g., Troendle and King 1985; Troendle et al. 2001) and a few of the channels were tie-driven in the historical past (Young et al. 1994) (Table 1). Other watershed areas have been selectively cut, the extent to which is either relatively minor or unknown.

METHODS

Discharges used in flow frequency analyses were gaged either by the U.S. Geological Survey or the Forest Service. For the purposes of this analysis, the bankfull discharge is approximated using the 1.5-year return interval flow from Log Pearson type-III analysis (U.S. Interagency Advisory Committee on Water Data 1982). Previous work from these sites indicates that this value is a suitable approximation for the discharge that just fills the channel to its active floodplain (Ryan et al. 2005). Watershed area was obtained either from the metadata included with U.S. Geological Survey gaging data or was digitized from 1:24,000-scale topographic maps.

Bedload was measured using hand-held pressure difference samplers, such as a Helley-Smith bedload sampler (Helley and Smith 1971) or an Elwha sampler (Childers et al. 2000). Bedload was sampled once or twice daily over several weeks during snowmelt runoff using the Single Equal Width Increment (SEWI) method (Edwards and Glysson 1998). Bedload samples were dried and sieved using standard sedimentological methods (Folk 1968). Rate of transport was calculated using the total weight of the sample (in kg) divided by the total sampling time (number of verticals and time in seconds) and width of the sampler (in m) to obtain the unit bedload transport rate (kg m^{-1} s^{-1}). This value is multiplied by the width of the channel (m) to obtain the mean transport rate through the channel cross-section (in kg/s). The datasets used for developing bedload rating curves for individual sites contain between 40 and 200 pairs of flow and bedload observations. Bedload rating curves were developed from these data, and were then used to estimate the mean rate of bedload transport for the bankfull discharge. Additional information on these rating curves is available in Ryan et al. (2005).

Geologic type and patterns of mass wasting were evaluated at a relatively coarse scale. Geologic type was determined from published data and geologic maps available for individual areas. Patterns of mass wasting were determined from field reconnaissance or aerial photography and published maps, as available.

Results

Commonalities in Normalized Values

Measured (or dimensional) rates of bedload transport typically vary between sites, indicating that individual stream systems exhibit their own "bedload signal" where the rate and size of materials transported largely reflect the nature of flow and sediment particular to that system. Moreover, it was observed that for sites within the same watershed, increases in sediment loads moving from small tributaries to larger channels were fairly predictable. In the St. Louis Creek watershed, there was about an order of magnitude increase in the rate of transport moving from a small watershed (East St. Louis Creek, drainage area about 5 km^2) to lower St. Louis Creek (St. Louis 1; about 50 km^2) (Figure 2). The normalized rate of bedload transport at bankfull for these eight stream sites was on average 0.0018 kg s^{-1} km^{-2} (standard deviation + 0.0008) (Figure 3). By comparison, when transport rates measured at additional sites (Figure 3) were normalized by watershed area, many exhibited about the same level of bedload transport per unit area at the bankfull discharge as observed for the St. Louis Creek sites. These normalized values ranged from about 0.001 to 0.003 kg s^{-1} km^{-2} (Figure 3). Given the inherent uncertainty in the estimate of bedload transport associated with gravel bed streams, similarity among a number of sites is noteworthy. This suggests that the transport rate is fairly predictable within and between watersheds with similar flow, sediment, and supply relationships, and that drainage area can be used to help predict rates of sediment transport for an individual site. There were, however, several notable exceptions from this range of values, including the relatively high rates of transport from the East Fork San Juan River and Silver Creek (about 0.025 kg s^{-1} km^{-2}) and the relatively low rates from Cache Creek and the Florida River (about 0.0002 kg s^{-1} km^{-2}). While these exceptions may be attributed to a number of factors, it was noted that there were distinct differences in patterns of mass wasting in these watersheds that would cause variation in sediment supply to the stream system and associated differences in rates of bedload transport. This is explored in greater detail below.

San Juan Sites, Southwestern Colorado

It is worth noting that data for all of the sites in the San Juan area (East Fork San Juan, Silver Creek, Middle Fork Piedra, and Florida River) were collected using a pressure-

Figure 2. Relationship between estimated transport rate at bankfull discharge and drainage area for main stem and tributaries to St. Louis Creek, Fraser Experimental Forest.

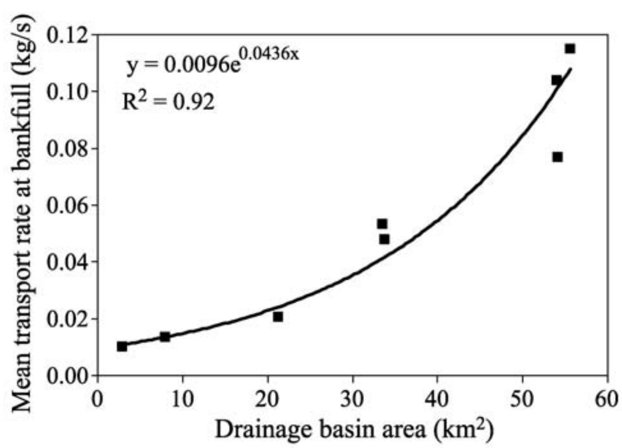
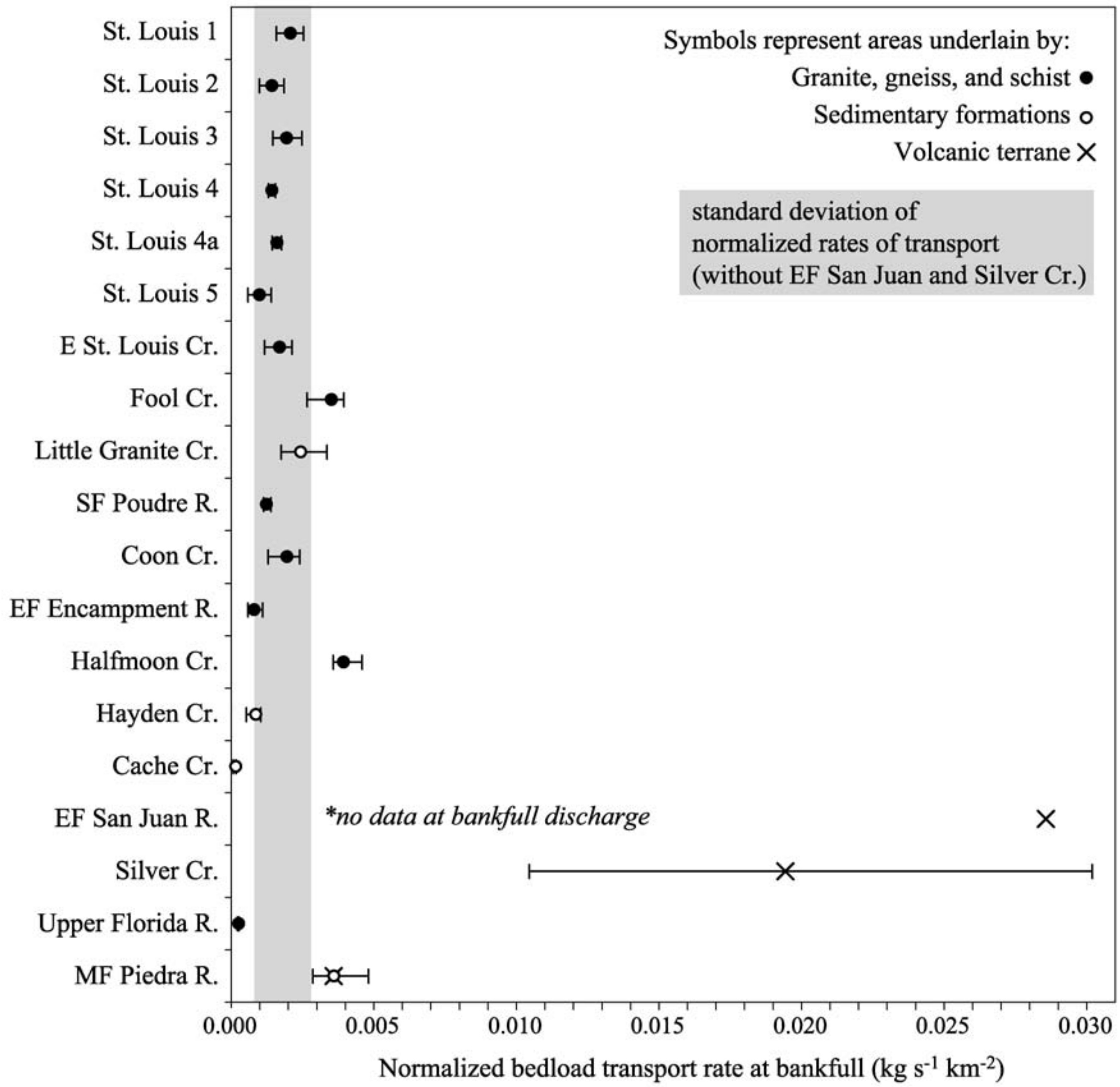


Figure 3. Normalized rates of bedload transport for 19 sites in Colorado and Wyoming measured between 1992 and 2001. Data were normalized by dividing the estimated rate of bedload transport at the bankfull discharge (and calculated 95% confidence limits) against the drainage area upstream of the sampling site. The black circles represent areas underlain by granite, gneiss, and schist, open circles represent areas underlain by sedimentary formations, and crosses represent areas draining volcanic terrane. The Middle Fork Piedra lies on a transition between volcanic and sedimentary bedrock and so two symbols are used. The area in gray represents the standard deviation of the normalized rates of transport, exclusive of the East Fork San Juan and Silver Creek sites. No confidence limits could be estimated for the East Fork San Juan site because there was no data at bankfull discharge. The wide error bars observed for the Silver Creek data are attributed to probable hysteresis effects observed in the dataset (Ryan 2001; Ryan et al. 2005).



difference sampler with a larger opening (4 x 8 inches; 10 x 20 cm) than deployed at the other sites (3 x 3 inches; 7.6 x 7.6 cm). This could explain, in part, lower rates of transport observed elsewhere (Figure 3) if the smaller sampler has a low capacity relative to the rate of bedload transport. However, not all sites where the larger sampler was used exhibit elevated rates of normalized bedload transport. Data from the Florida River indicate low normalized rates of transport, while data from the Middle Fork Piedra site suggest slightly elevated values, though not to the levels observed at East Fork San Juan River and Silver Creek (Figure 3). Hence, the differences in normalized rates of transport from these sites cannot be attributed simply to sampler type, but more likely reflect differences in sedimentation processes in the watersheds (Ryan et al. 2005).

As a causative explanation for the differences in normalized rates of bedload transport, it was observed that the San Juan sites have distinctive modes of sediment supply linked to the instability of the extrusive volcanic bedrock (Tertiary) and to the relative stability of the granite formations. In Silver Creek, precipitous, unstable hillslopes impinge on the steep tributary, and materials from active debris/avalanche chutes are delivered directly into the channel. The channel becomes an effective conduit for transporting the delivered sediment, particularly on the rising limb of the seasonal hydrograph after the overwinter sediment supply has accumulated in the channel. Transport rates are at times high, though irregular, in this system (0.002 - 0.031 kg s^{-1} km^{-2} at bankfull), reflecting the episodic nature of the sediment supply (Ryan 2001). Sediment moved by Silver Creek and other tributaries is deposited downstream in a wide valley bottom with a braided to plane-bed channel (East Fork San Juan) that also has high rates of transport (about 0.029 kg s^{-1} km^{-2} at bankfull). This value is on the same order as the mean normalized rate observed for Silver Creek (Figure 3). The similarity in rates of transport between these two sites is likely a systematic effect, determined by sediment supplied by the upper sites (such as Silver Creek) to the mainstem.

By contrast, observed rates of sediment transport are quite low (0.0002 kg s^{-1} km^{-2}) at the Upper Florida River site. This watershed is underlain by stable granitic terrane and the channel upstream of the site flows over bedrock, signifying a relatively low supply of sediment. The primary source of material in this system is from the channel beds and banks, as there were few observed external sources of sediment, such as active landslides, upstream. Sand and fine gravel, originating from sand and gravel patches interspersed between very large particles, are transported over a largely stable, interlocking boulder and cobble bed. Because of the relative stability of the channel bed, widespread entrainment is unlikely to occur over a majority of the channel surface (Ryan 2001). Hence, the low normalized rate of sediment transport is likely due to low supplies of sediment that characterize the Florida River watershed.

Gros Ventre Range Sites, Northwestern Wyoming

The series of comparisons from St. Louis Creek and other sites in Colorado and Wyoming suggest the existence of common normalized bedload transport rates for areas underlain by similar geologic terrane. However, there can be substantial differences in sediment supply in areas where the geologic terrane is spatially variable over short distances. As an example, transport rates and patterns of mass wasting from two sites in the Gros Ventre Range in northwestern Wyoming are compared. The geology of the Gros Ventre Range consists primarily of Paleozoic and Mesozoic sedimentary rock formations, many of marine origin (Love and Christiansen 1985). These formations in many areas are highly deformed and relatively unstable. As a result, parts of the Gros Ventre Range are characterized by some of the highest densities of landslides in the United States (Wyoming State Geological Survey 2001). The area is also influenced by active faulting and a relatively high likelihood of earthquakes (Case and Green 2000). Hence, one might expect that channels draining watersheds in the Gros Ventre will exhibit high rates of sediment transport due to potentially large supplies of sediment from active mass wasting. Yet, measured rates of bedload transport from two sites in this range suggest otherwise. Normalized rates of transport from Little Granite Creek (0.0025 kg s^{-1} km^{-2}) are on the high end of the range while the rates from Cache Creek (0.0001 kg s^{-1} km^{-2}) are the lowest measured in this study. An evaluation of mass wasting patterns from the two watersheds (Wyoming State Geological Survey 2001) shows about five times the number of landslides in Little Granite Creek (118) compared to Cache Creek (23). Inspections of aerial photographs and field reconnaissance show that many of the slides in both watersheds are of the large, slow-moving, earth flow-type that often involves entire an entire hillslope (Varnes 1978). Several of the large slides identified in Little Granite Creek were observed to impinge directly on stream channels. Where these slides impinge, the toeslopes are actively raveling and the channel is pushed to the far side of the valley bottom, creating a second set of slides where the hillslope is undercut. These slides are a chronic source of sediment in this watershed, as materials deposited from the erosional faces are reactivated during high runoff. Moreover, the upper portion of the Little Granite watershed was glaciated and there are several currently active sources of sediment from glacial debris. While the upper watershed is a potential source of bedload in this system, much of the glaciated material comes off in suspension, as Little Granite Creek has an exceptionally high suspended load relative to bedload (Ryan and Emmett 2002). By contrast, there appear to be fewer chronic sources of sediment in Cache Creek, which flows through a largely stable inner gorge over most of its length above the sampling site near a U.S. Geological Survey gaging station. Hence, differences in the normalized rates of transport observed for these two sites are likely linked to variation in geologic controls, gross differences in the patterns of mass wasting, and inherent differences in sediment supply from the two watersheds. Therefore, one should be cautious in applying the sediment transport relationships even in watersheds draining similar geologic terranes without considering localized differences in sediment supply that potentially influence rates of sediment transport.

DISCUSSION

Results from this comparison of normalized rates of bedload transport suggest that streams in many of our watersheds exhibit comparable rates of sediment transport per unit watershed area at bankfull discharges (ranging between 0.001 and 0.003 kg s^{-1} km^{-2}). Variability in the range of these normalized values may be attributable to land use effects or recent disturbances, though this was not directly assessed in this work. However, given the inherent difficulty in obtaining reliable estimates of mean rates of bedload transport, the relatively narrow range of values observed for these systems is noteworthy. One might expect such similarity in watersheds with comparable rates of sediment supply (e.g., landslides, bank collapse, and stream bed entrainment). Other recent work on bedload transport supports the idea of similarity in processes for channels in inland western mountainous terrain, such as correspondence in dimensionless sediment transport relationships (Troendle et al. 2001) or comparable ranges of flow at which the onset of coarse sediment transport occurs (phase II) (Ryan et al. 2002; Ryan et al. 2005).

While the relatively narrow range of values suggests that many of these gravel bed systems behave in a in a similar way, the analysis also identified sites where there was substantial departure. Generally, when sediment supplies were abundant, the normalized rates of bedload transport were substantially greater than when sediment was restricted. Areas with active mass wasting from unstable landscapes, such as a volcanic terrane in the San Juan Range, had rates of normalized bedload transport that were about an order of magnitude greater than the average range. By contrast, areas in relatively stable landscapes exhibited rates of normalized bedload transport that were about an order of magnitude lower. As a caveat, while this series of comparisons suggests that scaled rates of bedload transport may be transferable across watersheds in similar geologic settings, one does need to consider localized influences that contribute to differences in sediment supply before applying the sediment transport relationships broadly.

The relationships between sediment supply and normalized transport described in this paper were qualitative, relying on broad classes to describe mass wasting patterns (high, medium, or low). The next phase of this work will focus on better quantification of sediment supplied from different sources, to help in explaining variability in the normalized rate of bedload transport. Natural levels of materials transfer and the relative importance of different modes of sediment production in a watershed can be assessed through a sediment source analysis (Reid and Dunne 1996). Such an analysis can be complex, requiring field identification of a range of sources, including large landslides, instream sedimentation, and sediment contributed by different land management practices. However, such assessments are necessary in order to better define the relationships between sediment supply and transport, and to improve our capability to predict rates of bedload transport.

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