TRANSPORT OF DETRITAL SEDIMENTS IN LOW-GRADIENT STREAM SECTIONS IN THE TETON MOUNTAIN RANGE AND THE GUADALUPE AND SACRAMENTO MOUNTAINS

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ABSTRACT

The Teton Mountain Range of Wyoming and the Guadalupe and Sacramento Mountains of New Mexico offer differing mountain stream environments, though all lie along the eastern margin of the Basin and Range Province. Due to the arid setting of the Guadalupes and Sacramentos, stream beds remain dry until activated by storm events, while streams actively flow year-round in the Tetons, thus transporting detrital sediment through varied processes. However, in mountain streams, obstacles such as talus accumulation, glacial incision, and vegetation may reduce local slope so that sand transport is limited. Such sediments may be useful in determining erosion rates and patterns, but results may not be faithful if the sediments are trapped in certain portions of the stream. In this study, we examine low-gradient sections of mountain streams in the Tetons, Guadalupes, and Sacramentos in order to determine whether sand sized sediments are accumulated or transported in these channels.

Cross-sections were measured and sediment samples were collected during 2011 and 2012 in the Tetons and during 2013 in the Guadalupes and Sacramentos in canyons with catchment areas ranging from 0.974 - 94.8 km^2 and 0.13 - 120.78 km^2 respectfully. Sediment samples were then sieved using sieve classifications from <0.063 – 45 mm and sorted to determine d_{50} and d_{95} values. We calculated total stream power based on cross-sectional information and determined its relation to catchment area, elevation, and annual precipitation. Despite a large decrease in total stream power in the Tetons from 2011-2012, we found that d_{50} particles would be transported through everyday flow based on measured average stream velocities. However, nearly all of the largest observed clast sizes require higher velocity storm flow in order to be transported. In the Guadalupes and Sacramentos, there was a negative correlation between catchment area, total stream power, and d_{50} grain size, with increasing areas resulting in decreasing stream powers and d_{50} values. Based on calculated velocities, sand sized sediment will be transported, but only when precipitation events occur. Despite the differences in climate and main mode of sediment transportation, detrital sediments are successfully transported in these streams and should offer accurate erosion information.

BACKGROUND

The youngest of the Rocky Mountains, the Teton Mountain Range lies in northwestern Wyoming and has been affected by the Yellowstone Hotspot, Laramide Orogeny, and Basin and Range Province. Composed of metamorphic, igneous, and sedimentary rocks, mountain streams act as effective agents of erosion, incising into the bedrock and transporting sediment. To the far south, the Guadalupe and Sacramento Mountains lie along the eastern margin of the Rio Grande rift in south-central New Mexico. Composed of only sedimentary rocks, the arid climate causes erosional processes to be relatively slower, as precipitation events are required to activate stream flow and transport sediment. In all three mountain ranges, previous studies using detrital sediments have investigated erosion rates and patterns based on apatite (U-Th)/He thermochronology. Work has also been done in the Tetons to study the effects of lithology and channel morphology on sediment transport in streams in relation to different impacts on erosion. Detrital minerals can be used to spatially reconstruct erosion patterns, but these results are dependent on sediment eroding from the top of the catchment and successfully being transported downstream. By comparing the date of detrital grains to bedrock derived age-elevation relationships, one can estimate spatial variation in erosion. However, if sediments become trapped in the stream channel, specifically in low-gradient sections, they might provide unfaithful erosion information. This study works to examine whether sand-sized sediments are successfully transported in streams in the Tetons, Guadalupes, and Sacramentos and to further understanding of sediment transport.

Figure 1. a.) Garnet Canyon in the Teton Mountains, with talus fans and low slopes that may trap sediment.
b.) Oliver Lee Campground Trail in the Sacramento Mountains, similar to other sampled smaller catchment areas in the Guadalupes (0.13-26.24 km^2).
c) Sitting Bull Canyon in the Guadalupe Mountains, the canyon with largest catchment area (120.78 km^2).

RESULTS

Control variable	Location	Max. Elevation	Mean elevation	CA	Precipitation	CA* Precipitation	T_0	T_c	ω	Q	Sieved d_{50}	Sieved d_{95}	Slope
Ω	Tetons 2011	0.0264~	0.0114~	0.1751~	0.0345	0.1742~	0.031	**0.4773**	0.01	**0.6345**	0.1112~	0.1235	0.1594
	Tetons 2012	0.0154~	0.0921~	0.208	0.1652	0.1681	0.0287	0.1025	0.1119	**0.7504**	0.0674~	0.0505	0.0299~
	Guadalupes	0.1695	0.0678	**0.4154***	—	—	**0.4199***	**0.9922***	**0.4047***	**0.79988***	**0.7345***	0.3147*	**0.8859**
CA	Tetons 2011	0.0834	0.0752	—	0.148	—	0.031	**0.4773~**	0.01	0.1209	**0.4773~**	0.2225	0.0027
	Tetons 2012	**0.4325**	0.1038	—	**0.4227**	—	0.0287	0.1025	0.1119	**0.5289**	0.1025	0.2149	0.121
	Guadalupes	0.0067	0.0522	—	—	—	**0.4199***	0.278	**0.4047***	0.1325	**0.99228***	**0.9638**	**0.5966***
S	Tetons 2011	0.0002	0.0036	0.0027	0.042	0.0041	**0.4198**	**0.6963**	0.2859	0.0007	**0.6963**	**0.5999**	—
	Tetons 2012	0.1921	0.0003	0.121	0.1562	0.1106	0.3903	0.3834	0.0418	0.0736	0.3834	0.0117	—
	Guadalupes	0.0205	0.0085	**0.5966***	—	—	**0.9234**	0.0215	**0.936**	0.3833	**0.5953**	**0.614***	—

Table 1. Coefficients of determination (r^2) for linear/exponential regressions between primary control variables (Ω, CA [catchment area], S) and reach scale response variables. The Guadalupes/Sacramentos showed the strongest correlations among catchment area, total stream power, and d_{50}, while there were very few strong correlations among variables in the Tetons samples.
*Denotes an exponential relationship, all others are linear. ~Denotes the exclusion of outliers from regression. Correlations >0.4 are bolded.

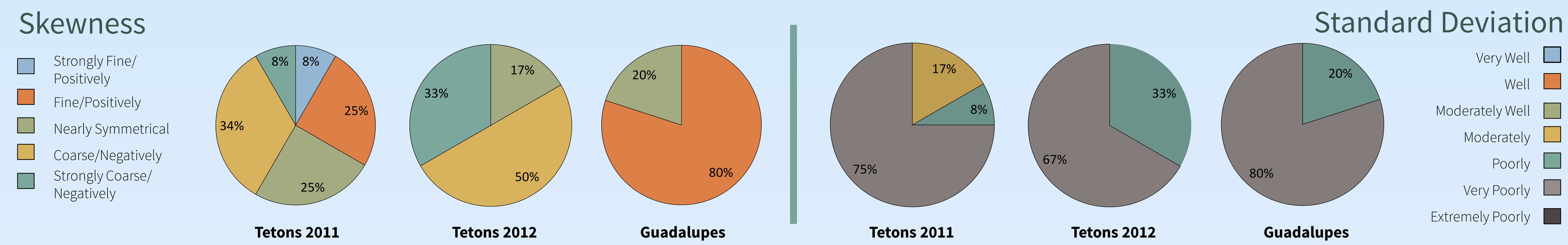

Figure 3. Pie charts showing skewness and standard deviation grain sorting information for all sieved samples, calculated from Equations12-14. Calculations were done using ϕ grain sizes, and positive skewness indicates a negative phi/coarse grain size mode. The 2011 Teton samples had the greatest variance in skewness and standard deviation, though no sample was better than moderately sorted, which would be expected in these mountain stream environments.

	Measured Avg. Vel. (m/s)	Sieved d_{50} Velocity (m/s)	Sieved d_{95} Velocity (m/s)	Sieved d_{50} Value (mm)	Sieved d_{95} Value (mm)	Graphic Mean (mm)	Q (m^3/s)
Tetons 2011	1.074956	0.217788*	0.760135	1.375*	18.15333	1.2899*	1.188695*
Tetons 2012	0.569539	0.121909	0.541215	0.332857	7.285714	0.40322	0.791407
Guadalupes	—	0.276368	0.569935	2.032	8.62	1.893365	14.98619

Table 2. Average measured velocities of streams compared to velocities necessary to transport sieved d_{50} and d_{95} particles. Though the 2011 Teton samples had the highest sieved d_{95} values, the Guadalupes/ Sacramentos had the highest sieved d_{50} values.
Measured avg. velocity > calculated d_{50}/d_{95} velocities indicates successful sediment transport.
* denotes exclusion of outliers

METHODS

In the Teton Mountain Range, 23 cross-sections were measured and 12 samples were collected in 2011 and 15 cross-sections were measured and 7 samples collected in 2012. During 2013, 4 cross-sections were measured and 4 samples were collected in the Guadalupes, and 1 cross-section was measured and 1 sample collected in the Sacramento Mountains. [Data and results from the Guadalupes and Sacramentos are grouped together here under "Guadalupes."] Cross-sections and samples were collected from stream sections with low gradients **(Fig. 2).** Samples were washed, dried, and sieved, sorted into grain size categories ranging from silt and clay to very coarse gravel (<0.063-45mm). We created particle size distributions, histograms, and cumulative curves in order to determine grain size distributions and to find the d50 and d95 values for each sample. Using the average measured velocity of the streams in the Tetons, we used the following equations from Haug et al. (2010) to calculate each largest grain size that the stream could carry, solving for d_1:

$$V_b = 0.20 d_1^{0.455} \quad \text{Eq. 1}$$

$$V_b = 0.18 d_1^{0.487} \quad \text{Eq. 2}$$

$$V_b = \left[\frac{2(\gamma_s - \gamma_f) d_1 g \mu}{\gamma_f (C_L + C_D)}\right]^{0.5} \quad \text{Eq. 3}$$

We solved for V_b to determine the velocity needed to transport the maximum grain size, sieved d_{50} grain size, and sieved d_{95} grain size from each stream in the Tetons, Guadalupes, and Sacramentos. We calculated the cross-section area, wetted perimeter, hydraulic radius, and slope of all the streams, using the following equations:

$$A = \left(\frac{D_1 + D_2}{2}\right) W_1 + \cdots + \left(\frac{D_m + D_n}{2}\right) W_n \quad \text{Eq.4}$$

$$P = \sqrt{(D_2 + D_1)^2 + W_2} + \cdots + \sqrt{(D_n + D_m)^2 + W_2} \quad \text{Eq. 5}$$

$$R = \frac{A}{P} \quad \text{Eq. 6}$$

$$S = \frac{VD_2 - VD_1}{HD_2 - HD_1} \quad \text{Eq. 7}$$

Based on the calculations in Wohl et al. (2004), we calculated bankfull boundary shear stress, critical shear stress, total stream power, and unit stream power for all the streams:

$$\tau_0 = \gamma RS \quad \text{Eq. 8}$$

$$\tau_c = \tau_c^* (\rho_s + \rho_w) g d_{50} \quad \text{Eq. 9}$$

$$\Omega = \gamma QS \quad \text{Eq. 10}$$

$$\omega = \tau_0 v \quad \text{Eq. 11}$$

To understand environmental controls on the sediments that were transported, we created scatter plots to determine relationships between total stream power, catchment area, maximum elevation, mean elevation, mean annual precipitation, discharge, and slope, among other calculated variables. With the cumulative curves we created for all the sieved sediment samples, we calculated graphic mean, standard deviation, and skewness based on the equations from Boggs (2011) to summarize the distribution of grain sizes:

$$M_z = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3} \quad \text{Eq. 12}$$

$$\sigma_i = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6} \quad \text{Eq. 13}$$

$$SK_t = \frac{(\phi_{84} + \phi_{16} - 2\phi_{50})}{2(\phi_{84} - \phi_{16})} + \frac{(\phi_{95} + \phi_5 - 2\phi_{50})}{2(\phi_{95} - \phi_5)} \quad \text{Eq. 14}$$

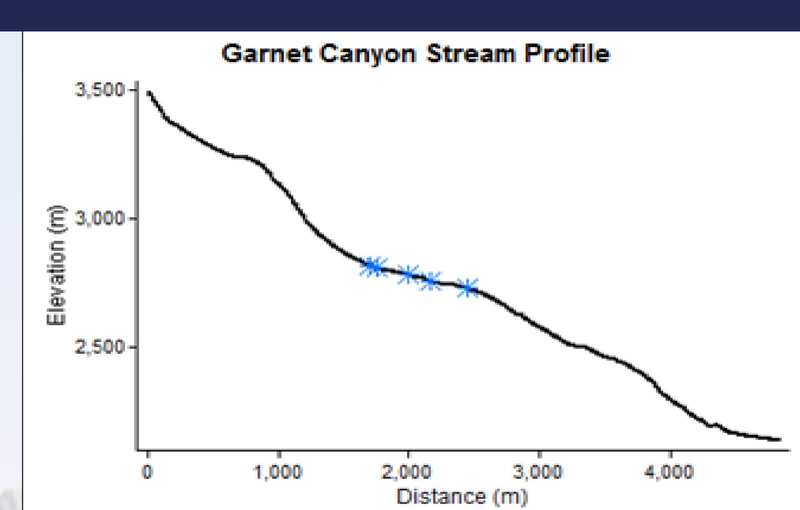

Figure 2. Stream profile of Garnet Canyon in the Teton Mountain Range. Blue crosses indicate sampling locations and are from low-gradient sections of the stream.

Variables for Equations 1-14

- V_b Flow velocity (m/s)
- d_1 Sampled max grain size (m)
- γ_s Sediment density (kg/m3)
- γ_f Fluid density [water] (kg/m^3)
- g Acceleration due to gravity (m/s^2)
- μ Coefficient of static friction
- C_L Lift Coefficient
- C_D Drag Coefficient
- A Area (m^2)
- D Depth (m)
- W Width (m)
- P Wetted Perimeter (m)
- R Hydraulic radius (m)
- S Slope
- VD Vertical distance (m)
- HD Horizontal distance (m)
- τ_0 Bankfull boundary shear stress (N/m^2)
- γ Specific weight of water (N/m^3)
- τ_c Critical shear stress (N/m^2)
- τ_c^* Critical shear stress parameter
- ρ_s Sediment density (kg/m^3)
- ρ_w Water density (kg/m^3)
- d_{50} Median grain size (m) / (mm)
- d_{95} 95th percentile grain size (m) / (mm)
- Ω Total stream power (kgm/s^3)
- Q Discharge (m^3/s)
- ω Unit stream power (W/m^2)
- v Bankfull velocity (m/s)
- M_z Graphic mean
- σ_i Standard deviation
- SK_t Skewness
- Φ_x X percentile Phi grain size

CONCLUSIONS

As the calculated velocities necessary to transport d_{50} and d_{95} particles in the Tetons were less than the average measured stream velocities, sand-sized sediments should successfully be transported in these surveyed stream sections. Grain sorting was relatively similar across sampled years, with the greatest variance among the 2011 Teton samples. Skewness ranged from strongly fine/positively to strongly coarse/negatively in these samples, and along with the Guadalupe and Sacramento samples, they showed a weak correlation to stream velocity. As stream velocity increased, skewness became more positive, with increasingly negative phi grain sizes (coarser sediment). Throughout all samples, there did not appear to be any correlation between skewness and standard deviation, but each sampling year showed a correlation between standard deviation and a different variable (v, Ω, CA). The majority of samples had a standard deviation between 2.00-4.00 ϕ (very poorly sorted), so there does not appear to be just one factor in control of sorting.

In the Guadalupe and Sacramento Mountains, catchment area had the strongest relationship with the size of the sediment that can be transported, with smaller catchment areas having higher stream powers and larger sediments transported. In larger catchment areas, where there were lower slopes, smaller sediment sizes were transported.

There was no single variable in the Tetons that stood out as being closely related to the size of sediment transported, though stream slope had the strongest correlation. Even among the 8 locations surveyed and 3 sediment samples collected in 2011 from Garnet Canyon in the Tetons, there was a 1.20 m/s difference between high and low average measured velocities and a 13.2 mm difference between high and low d_{95} values. D_{50} values were relatively similar, only varying 0.38 mm, but there did not appear to be a correlation with upstream/downstream locations. Therefore, it is probable that erosion or talus deposits in Garnet Canyon interfered with the stream channel randomly throughout the catchment to create this lack of a clear pattern.

FUTURE WORK

In order to better understand detrital sediment transport, precipitation and storm event models for different canyons in the Tetons, Guadalupes, and Sacramentos can be created. For the Tetons, it would be useful to model storm events that would create water velocities that can entrain the largest observed clast sizes. Year-round monitoring of precipitation and stream velocity would also be beneficial in testing seasonal control on effective transport. As streams in the Guadalupes and Sacramentos are only activated by precipitation and storm events, models can be created based on the stream velocities necessary to transport d_{50}, d_{95}, and maximum clast sizes.

Additionally, more work can be done to illuminate the relationship between elevation, total stream power, and sediment transport. There were no clear correlations between maximum or mean elevation and stream power, so it would be interesting to further look into the role, or lack thereof, of elevation in transport.

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