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Kevin Pogue (Whitman College) and Chris Oze (Bryn Mawr College)
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Students: Evan Anderson, Anna Lavarreda, Ken O'Donnell, Walter Persons, Jessica Williams

Development and Analysis of Millennial-Scale Tree Ring Records from Glacier Bay National Park and Preserve, Alaska (Glacier Bay)
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Keck Geology Consortium: Projects 2007-2008
Short Contributions – Alps

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CAN THE STREAM POWER LAW BE USED TO QUANTIFY DIFFERENTIAL LANDSCAPE EVOLUTION FROM BEDROCK INCISION IN THE CENTRAL ALPS, SWITZERLAND?

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INTRODUCTION

Bedrock rivers dictate rates and patterns of denudation and determine much of the topographic relief of mountainous landscapes (Snyder et al., 2000). In previous studies on bedrock incision the stream power erosion law has served as a foundation for modeling bedrock channel evolution because of its simplicity and derivation from known hydraulic relations (Stock and Montgomery, 1999; Snyder et al., 2000). The basic stream power law is

$$E = kA^m S^n, \qquad (1)$$

where E is the incision rate, k is a poorly defined rock erodibility constant, A is upstream drainage area, S is channel gradient, and m and n are positive empirical constants used for weighting the importance of drainage area and gradient.

The aim of this study is to explore controls on the high altitude (above approximately 2 km in elevation) landscape of the Swiss Central Alps by focusing on small areas of the Lepontine Dome and Graubünden canton (Fig. 1). Much of the high altitude landscape of the Central Alps is littered with debris from repeated Quaternary glaciations, as observed in the Graubünden study area. In contrast, the high altitude landscape of the Lepontine Dome exhibits more exposed bedrock and less debris.

The Lepontine Dome receives high rates of precipitation, while the adjacent Graubünden receives lower amounts (Frei and Schär, 1998). To analyze possible influences, including precipitation variation, on erosion rates in the Central Alps, an adaptation of the stream power law is applied to data from bedrock-incising river reaches in both study areas. The stream power law used in this study replaces drainage area, A, in equation 1 with discharge rate normalized over upstream drainage area, Q, in order to include precipitation variability and still account for the size of the drainage area for a specific field site:

$$E = kQ^m S^n. \qquad (2)$$

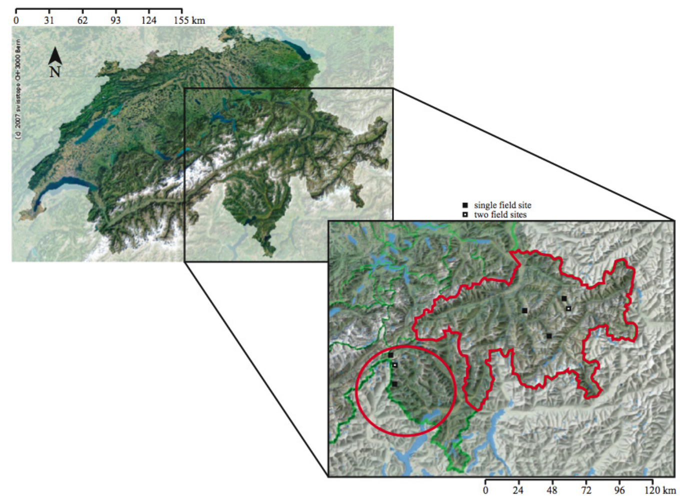

Figure 1. Location map of Switzerland. Enlarged map shows canton boundaries in green and locations of field sites, denoted by black squares. In red are the Lepontine Dome and Graubunden study areas. Maps from online database Swistopo (http://prod.swisstopogeodata.ch/kogis_apps/ga/ga.php?lang=de).

EROSIONAL PROCESSES IN THE STUDY AREA

Throughout the Quaternary, the Central Alps experienced widespread glaciation which repeatedly reshaped the landscape (Brocard and van der Beek, 2006). In the Lepontine Dome and Graubünden regions, sediment accumulation in valley bottoms is a consequence of post-glacial erosion (Dadson and Church, 2005). Following the Last Glacial Maximum (LGM), rivers have locally incised v-shaped channels into the glacially polished bedrock of the valley floor. Bedrock channels are characterized by a lack of continuous alluvial sediment cover, although episodes of rapid sediment delivery from hillslopes may result in temporary sediment coverage of the ordinarily bare bed and banks (Howard et al., 1994; Whipple, 2004).

APPLICATION OF THE STREAM POWER MODEL

Stream power models are based on the premise that bedrock channel incision rate can be approximated by a basic power law function of mean bed shear stress or stream power (Howard and Kerby, 1983; Kobor and Roering, 2004; Whipple, 2004). Numerous studies have applied adaptations of the stream power model to field and topographic data (Howard and Kerby, 1983; Stock and Montgomery, 1999; Snyder et al., 2000), and values of *k*, *m* and *n* generally fall between 0 and 1.

Data

In July and August of 2007, measurements of nine sections of bedrock incising rivers (mostly first-order) from high alpine glacialted valleys were taken from seven rivers (Table 1). All field sites in this study are above 1,700 m and incise into glacially polished bedrock. These channels are assumed to have triangular cross-sections and straight reaches. Distance measurements were collected using an Impulse 200 laser by Laser Technology Inc.

From the measurements of these high alpine bedrock incising rivers, the incision rate, *E*, and channel gradient, *S*, for each of the nine sites are calculated using field measurements, triangle trigonometry, and Microsoft Excel. The depths that these channels have incised into the bedrock are assumed to directly correlate to the amount of fluvial erosion since the most recent deglaciation of the Central Alps. For simplicity, it is assumed that this occurred at the LGM approximately 20 ka (Kelly et al., 2006).

The normalized discharge parameter, *Q*, which incorporates both the discharge rate and upstream drainage area for each field site, could not be measured in the field. To find these data and the upstream drainage areas, we used modern precipitation data (Frei and Schär, 1998) and a 90 m DEM. The stream power model focuses on discharge rates, upstream drainage area, and channel gradient to describe incision rates. However, bedrock incision rates are also largely controlled by climate, tectonics, lithology, and topography (Whipple, 2004). Between the Lepontine Dome and Graubünden study areas, many of these factors are similar and will be assumed to have little consequence to the application of the stream power model in this study.

Mathematical Methodology

The data collected from these nine reaches of bedrock incising rivers are used to describe three of the six parameters of the stream power model (equation 2). Therefore, this stream power model can be written for each of the river reaches. The parameters *k*, *m*, and *n* have theoretical values, but are calculated with a least squares analysis in order to find a stream power law describing the Central Alps study area.

	Graubünden					Lepontine Dome			
	Piz Sausura 1	Piz Sausura 2	Fluela	Crap Alo Laiets	Lenzerheide	Val Bavona 1	Val Bavona 2	Bosco Gurin	Lago delle Pigne
Latitude	46.736	46.736	46.787	46.572	46.726	46.436	46.436	46.311	46.490
Longitude	9.958	9.958	9.919	9.803	9.578	8.481	8.481	8.462	8.449
Discharge (m^3/s)	0.00753	0.00925	0.00031	0.00162	0.00005	0.00406	0.00406	0.00265	0.00347
Upstream Drainage Area, A, (km^2)	2.454	3.054	17.269	0.559	6.456	0.802	0.802	0.510	0.693
Normalized Discharge, Q, (m/s)	3.067×10^{-9}	3.030×10^{-9}	1.766×10^{-11}	2.890×10^{-9}	8.365×10^{-12}	5.059×10^{-9}	5.059×10^{-9}	5.187×10^{-9}	$5.008E\times10^{-9}$
Total Volume Incised (m^3)	14212.950	7184.536	16133.697	4637.642	19628.044	226047.910	263768.392	29122.208	14391.683
Average Depth of Incision (m)	4.388	11.891	9.024	2.989	11.501	14.712	14.549	7.137	5.371
Channel Gradient, S	0.121	0.448	0.364	0.244	0.460	0.190	0.096	0.362	0.311
Time (since last glacial retreat)	20000.0	20000.0	20000.0	20000.0	20000.0	20000.0	20000.0	20000.0	20000.0
Incision Rate, E, (m/yr)	2.194×10^{-4}	5.946×10^{-4}	4.512×10^{-4}	1.495×10^{-4}	5.751×10^{-4}	7.356×10^{-4}	7.274×10^{-4}	3.569×10^{-4}	2.686×10^{-4}

Table 1. River channel data

RESULTS

For the entire study area, the value of the exponents m and n returned by the linear least squares analysis are surprisingly negative: -0.054 and -0.086 respectively. The calculated value of *k*, 1.17×10^{-4}, falls in the appropriate range as discussed in previous studies on this subject (Stock and Montgomery, 1999; Whipple et al., 2000). Thus, the stream power model for the entire study area takes the form

$$E = 1.17\times10^{-4}\, Q^{-0.054}\, S^{-0.086}$$

The incision rates estimated with the model are not linearly proportional to the observed incision rates, as would be expected (Fig. 2). Instead, estimated incision rates stay at approximately 0.4 mm/yr while the incision rates observed in the field vary over a larger range.

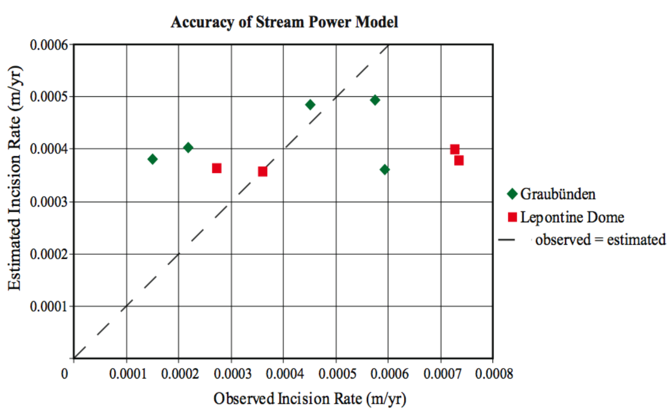

Figure 2. Estimated incision rates calculated using the stream power model found from the least squares analysis performed on all data sites. Note that the estimated incision rates have a smaller range of values than the observed incision rates. If this model was perfectly accurate, all points would be on the 1:1 line.

For comparison, the linear least squares analysis is performed on each of the small field areas separately. The stream power model of the Lepontine Dome is

$$E = 3.43\times10^{70}\, Q^{8.97}\, S^{-0.78},$$

while the stream power model for the Graubünden area is

$$E = 1.45\times10^{-6}\, Q^{-0.042}\, S^{0.74}.$$

As in the initial analysis, these models have values of m or n that are negative, and the erodibility coefficient for the Lepontine Dome model is extremely large. Despite the few incongruous parameters, the graphs of estimated incision rates against observed rates show that these models estimate incision rates more accurately than the stream power model for the entire study area (Fig. 3).

In order to extract more meaningful relationships from the parameters of a stream power model, the value of *k* is held at 0.1, because it produces estimated incision rates similar to the observed incision

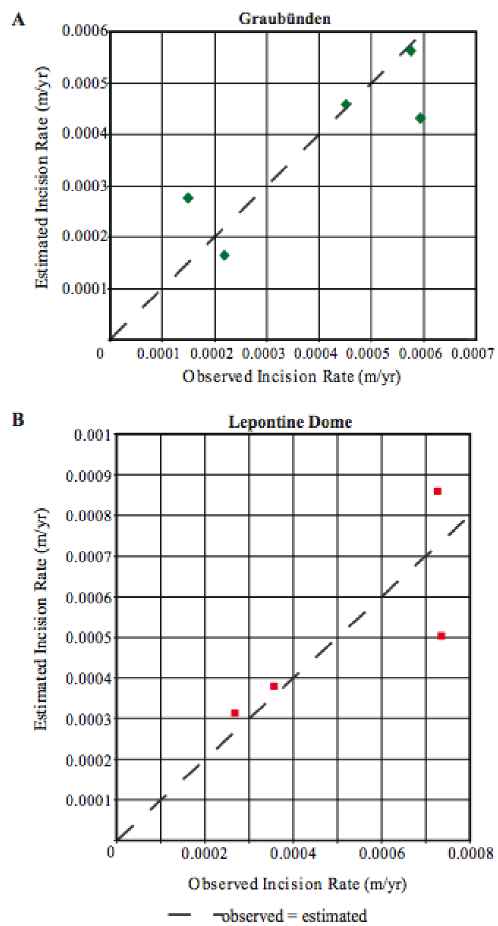

Figure 3. Estimated incision rates calculated using the stream power model found for each study area. If this model was perfectly accurate, all points would be on the 1:1 line. Both (A) Graubunden and (B) the Leopontine Dome models are more accurate than the analysis using all field sites.

rates. Using all the field sites, this analysis produces the following stream power model:

$$E = 0.1\ Q^{0.22}\ S^{0.76}.$$

Although the model has values of k, m, and n that are acceptable, there is no correlation between the estimated incision rates and the observed incision rates (Fig. 4).

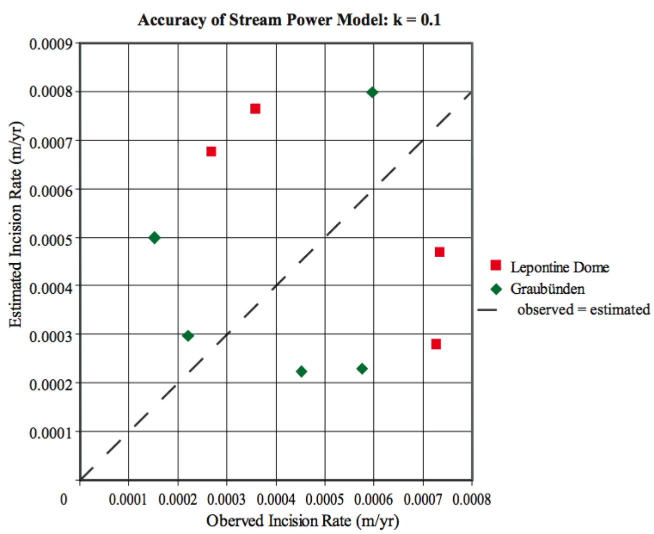

Figure 4. Estimated incision rates calculated using the stream power model found from all field sites, assuming the value of k is 0.1. If this model was perfectly accurate, all points would be on the 1:1 line, shown in gray. The estimated and observed incision rates from the Lepontine Dome show the opposite of what is expected; as the observed incision rates increase, the predicted values decrease.

DISCUSSION

Negative values for the *m* and *n* exponents are not supported by the theoretical foundations of the stream power equation since they suggest that incision rates are inversely related to normalized discharge and channel gradient, contradicting the principles that the stream power models are based on. A rudimentary test of the applicability of the stream power model to this data is to compare the observed incision rates with the product of normalized discharge and channel gradient of each of the field sites. A positive linear relationship is expected; however, the data show an inverse relationship.

Even with the generalizations of the stream power model, or perhaps due to them, the data used in this study produced models that generated irrational parameters and do not accurately estimate incision rates from field data. It is possible that the various assumptions constraining this study may have misrepresented the physical processes in the Central Alps. In particular, if the time of deglaciation differs significantly between sites, our estimated erosion rates may not represent the true variability in erosion across the region.

Additionally, the field sites may not be representative of the Central Alps because some characteristics of most sites, such as small drainage areas or stream order, may exceed boundary conditions for the models. More field sites covering a larger area of the Lepontine Dome and surrounding regions would greatly aid this study, and may produce more reasonable stream power models.

CONCLUSION

Using a least squares analysis, this study finds that the stream power models have values of *k*, *m*, and *n* that did not reveal meaningful relationships between the parameters *Q* and *S*, and may not be applicable to the field sites included in this study. When evaluated against previous studies, the coefficient *k* is at times too large, and the values of m and n are most often negative.

Although this study cannot identify the most influential controls on landscape evolution in the Central Alps, variation in precipitation over the two study areas may be influencing the landscape, as climate is a primary control on the nature and intensity of surface processes. The addition of more field sites of bedrock incising rivers from the Lepontine Dome and Graubünden canton may allow the stream power model to provide more concrete relationships between bedrock incision rates, precipitation variation and channel gradient.

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