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Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs

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Abstract. The longitudinal profiles of bedrock channels are a major component of the relief structure of mountainous drainage basins and therefore limit the elevation of peaks and ridges. Further, bedrock channels communicate tectonic and climatic signals across the landscape, thus dictating, to first order, the dynamic response of mountainous landscapes to external forcings. We review and explore the stream-power erosion model in an effort to (1) elucidate its consequences in terms of large-scale topographic (fluvial) relief and its sensitivity to tectonic and climatic forcing, (2) derive a relationship for system response time to tectonic perturbations, (3) determine the sensitivity of model behavior to various model parameters, and (4) integrate the above to suggest useful guidelines for further study of bedrock channel systems and for future refinement of the stream-power erosion law. Dimensional analysis reveals that the dynamic behavior of the stream-power erosion model is governed by a single nondimensional group that we term the uplift-erosion number, greatly reducing the number of variables that need to be considered in the sensitivity analysis. The degree of nonlinearity in the relationship between stream incision rate and channel gradient (slope exponent n) emerges as a fundamental unknown. The physics of the active erosion processes directly influence this nonlinearity, which is shown to dictate the relationship between the uplift-erosion number, the equilibrium stream channel gradient, and the total fluvial relief of mountain ranges. Similarly, the predicted response time to changes in rock uplift rate is shown to depend on climate, rock strength, and the magnitude of tectonic perturbation, with the slope exponent n controlling the degree of dependence on these various factors. For typical drainage basin geometries the response time is relatively insensitive to the size of the system. Work on the physics of bedrock erosion processes, their sensitivity to extreme floods, their transient responses to sudden changes in climate or uplift rate, and the scaling of local rock erosion studies to reach-scale modeling studies are most sorely needed.

1. Introduction

1.1. Motivation

Recent recognition of potential global-scale interactions between climate, surface processes, and tectonics [e.g., *Adams*, 1985; *Molnar and England*, 1990; *Isacks*, 1992; *Raymo and Ruddiman*, 1992] has sparked the field of tectonic geomorphology and brought the problem of the dynamics of bedrock channel fluvial systems to the forefront of theoretical geomorphology [e.g., *Seidl and Dietrich*, 1992; *Wohl*, 1993; *Howard et al.*, 1994; *Seidl et al.*, 1994; *Wohl et al.*, 1994; *Zen and Prestegaard*, 1994; *Montgomery et al.*, 1996; *Tucker and Slingerland*, 1996]. Knowledge of the dynamics of bedrock channels is of profound importance for understanding the interaction of tectonics and surficial processes because (1) the channel network defines the texture (planview) of the landscape, (2) channel longitudinal profiles determine much of the relief structure of the landscape, (3) rivers transmit tectonic and/or climatic signals throughout the landscape, and (4) bedrock channels set the boundary conditions for hillslope processes (e.g., soil creep and landslides) responsible for denudation of the land surface. Thus bedrock channels significantly influence both the rates and patterns of erosional unloading in fluvial landscapes and, consequently, long-term sediment fluxes to basins.

Significant progress has been made in developing physically based formalisms for modeling the dynamics of bedrock channel systems [*Howard and Kerby*, 1983; *Seidl and Dietrich*, 1992; *Anderson*, 1994; *Howard*, 1994; *Howard et al.*, 1994; *Kooi and Beaumont*, 1994; *Rosenbloom and Anderson*, 1994; *Seidl et al.*, 1994; *Goldrick and Bishop*, 1996; *Stock*, 1996; *Tucker and Slingerland*, 1996; *Stock and Montgomery*, 1999]. Of the models that have been proposed, the stream-power (or shear-stress) model is most satisfying as it is cast directly in terms of the physics of erosion [*Howard and Kerby*, 1983]. The stream-power model is quite general and has been profitably used in a diversity of modeling studies [*Anderson*, 1994; *Howard*, 1994; *Rosenbloom and Anderson*, 1994; *Humphrey and Heller*, 1995; *Moglen and*

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