A morphologically-consistent expression for the transition from stream-power-law regime to a debris-flow regime

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Many long-term landscape evolution models are currently combining equations describing the evolution of the surface under fluvial incision (using the so-called stream-power incision model) and hillslope transport (often modeled as linear diffusion). Some models combine these two terms (e.g., Fastscape) and implicitly contain a transition from hillslope to fluvial processes dependent on the ratio of the diffusive and fluvial erosional parameters, D and K respectively (Perron et al., 2009). Other models require as input a hillslope-fluvial transition length (e.g., DAC) and apply hillslope erosion from the ridge-top to this lengthscale and fluvial incision only downstream of it. Still, in both cases the influence of non-linear processes such as landslide and debris-flow on this transition are not accounted.

We have analyzed the scaling between slope gradient and drainage areas in LIDAR-derived high-resolution DEM for >30 catchments, with apparent steady-state morphology, and where long-term denudation estimates, E, were estimated from cosmogenic nuclides. The catchments span different lithology, climate and denudation rates from ~0.05 to ~3 mm/yr but show a consistent pattern where substantial portion of upstream channels exhibit slope gradient roughly constant with drainage area, and transition towards a negative scaling between slope and area (characteristic of fluvial processes) after a critical drainage area, Ac. Previous work (Stock and Dietrich, 2003) suggested the portion with constant slope may be dominated by erosion due to debris-flow processes, maintaining the channel at a critical slope, Sdf.

Here we show that both Sdf and Ac are strongly correlated to the long-term denudation, E. Further, we find that Sdf seems to saturate at a critical slope angle, Sc, near 40° when denudation rates reach about 1 mm/yr consistent with predictions for the slope of a non-linear diffusive hillslopes (Roering et al., 2007). Combining this expression with the empirical model for the steady-state slope of Stock and Dietrich, 2003, and enforcing the consistency with a stream-power-law downstream we find that the steady state values for Sdf and Ac can be fully expressed as analytical functions of E, K, D and Sc. We assess the validity of these expressions with independent estimate of K and D extracted from local channel steepness and hilltop curvature.

As the impact of debris flow on landscape morphology seems ubiquitous on landscape with more than 0.1 mm/yr of erosion, the classical landscape evolution formulation may need to be upgraded to correctly represent steady-state morphology of the upstream part of catchment (i.e.,
<1km²). Even if it still lack physical basis, we propose a formulation that adequately represent the steady state morphology from ridge to large drainage area. We show that it yield a new definition of Chi that may be better match the morphology of channel approaching ridges and we also discuss how to implement this new-steady state formulation in landscape evolution models.