Landscape evolution using a sediment flux-dependent bedrock incision model incorporating bedrock macro-roughness

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Jeffrey Kwang[1] and Gary Parker[1,2] [1]Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, [2]Department of Geology, University of Illinois at Urbana-Champaign

Introduction and Motivation

Capacity-based Saltation Abrasion (CSA) Model

Sklar and Dietrich [e.g. 2004] introduced a mechanistic bedrock incision formulation that relates incision to the local sediment transport rate. Unlike the stream power incision model (a commonly-used bedrock incision model), the bedrock incision rate is based on natural processes of bedrock incision. In this model, we assume that the bedrock incision is caused by sediment tools corrading the bed.

$$\varepsilon = \beta(1 - p_c)q$$

p_c is the aerial fraction of bed covered by alluvium (0, bare bed to 1, covered bed) and β is an abrasion coefficient. In their work, they related the cover factor to a ratio corresponding to the sediment transport rate, q, divided by the sediment transport capacity, q_c.

$$p_c = \begin{cases} q/q_c & q < q_c \\ 1 & q \geq q_c \end{cases}$$

Macro-Roughness-based Saltation Abrasion Alluviation (MRSAA) Model

Zhang et al. [2015] introduced a new model that includes alluvial morphodynamics. In this model, the cover factor is related to the ratio of the local alluvial thickness, η_a, divided by the bedrock macro-roughness, L_{mr}.

$$p_c = \begin{cases} \eta_a/L_{mr} & \eta_a < L_{mr} \\ 1 & \eta_a \geq L_{mr} \end{cases}$$

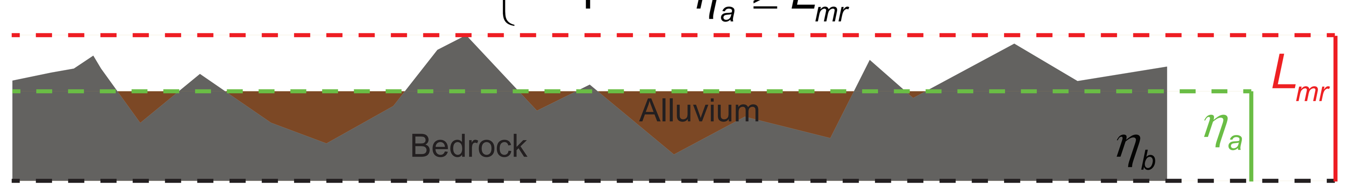

Figure 1: Schematic of bedrock macro-roughness and alluvial thickness.

Reach Scale vs. Landscape Scale

Reach Scale

- The single source of sediment comes from the upstream boundary.
- At equilibrium, the sediment transport rate is uniform and equals the prescribed sediment input rate in the entire channel.

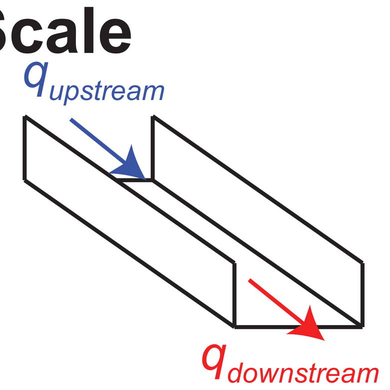

Figure 2: Conceptual drawing of the reach scale of a river.

Landscape Scale

- Sediment is fed from both the upstream boundary and the hillslopes.
- At equilibrium, the sediment transport rate increases in the downstream direction.

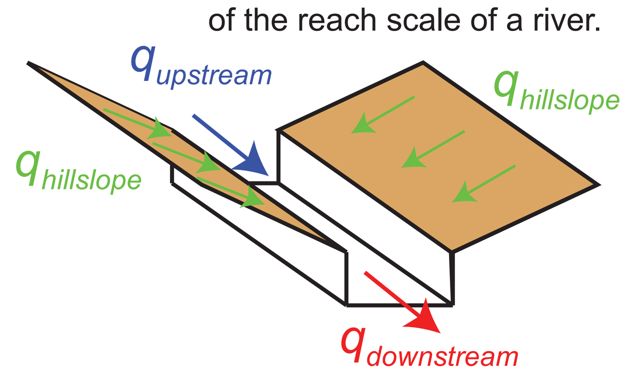

Figure 3: Conceptual drawing of the landscape scale of a river.

The Model

Where does this work fit in the literature?

	Reach Scale	Landscape Scale
CSA	e.g. *Sklar and Dietrich*, 2004	e.g. *Gasparini et al.*, 2007 and *Chatanantavet and Parker*, 2009
MRSAA	*Zhang et al.*, 2015	This Work


Figure 4: Pillsbury rubs her scenting glands on her newly acquired territory.

Governing Equations

Bedrock conservation equation:

The bedrock elevation rises due to a vertical rock uplift rate and lowers due to corrasion of the bed from sediment particles striking the bed.

$$\frac{\partial \eta_b}{\partial t} = \upsilon - \alpha I \beta (1 - p_c) q$$

bedrock elevation (η_b); time (t); rock uplift rate (υ); proportion of sediment load that is bedload (α); intermittency factor (I); abrasion coefficient (β); cover factor (p_c); total sediment load transport rate (q). Uplift term: υ. Incision term: $\alpha I \beta (1 - p_c) q$.

Alluvial Morphodynamics:

In the channel, the bed receives alluvium from both upstream sources and hillslopes, increasing the alluvial thickness. The local sediment transport rate removes alluvium, decreasing the thickness.

$$\frac{\partial \eta_a}{\partial t} = \frac{\alpha}{(1 - \lambda_p) p_c W} \frac{\partial}{\partial x}(\varepsilon A - IqW)$$

alluvial thickness (η_a); time (t); proportion of sediment load that is bedload (α); bed porosity (λ_p); cover factor (p_c); channel width (W); longitudinal coordinate (x); bedrock incision rate (ε); drainage area (A); intermittency factor (I); total sediment load transport rate (q); channel width (W). Sediment feed from hillslopes: εA. Channel sediment transport: IqW.

The Results

Alluvial Morphodynamics (0-5 yrs)

Alluvial Cover Stripping

Figure 5: Starting with a completely but barely alluviated bed (p_c = 1.0), the sediment feed is reduced to zero.

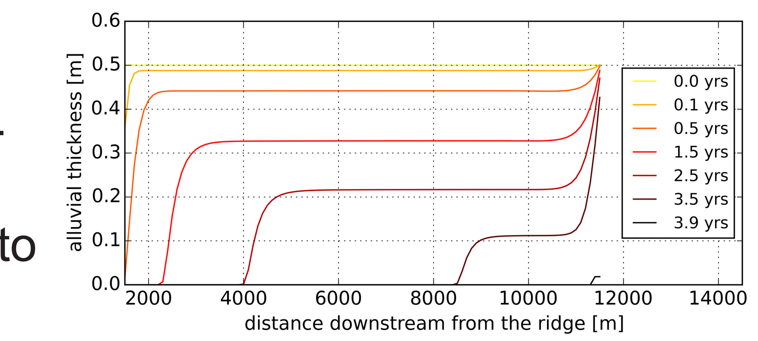

Figure 5: Stripping of the alluvial cover.

Alluvial Cover Deposition

Figure 6: The bed is initially bare, and a sediment feed is introduced, causing emplacement of an alluvial layer.

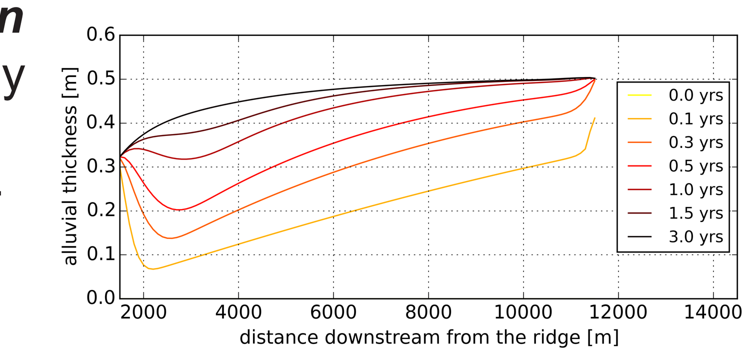

Figure 6: Depositing of the alluvial cover.

Halving the Sediment Supply

Figure 7: The bed is initially at equilibrium with a prescribed sediment feed; then the feed is halved, decreasing the alluvial thickness.

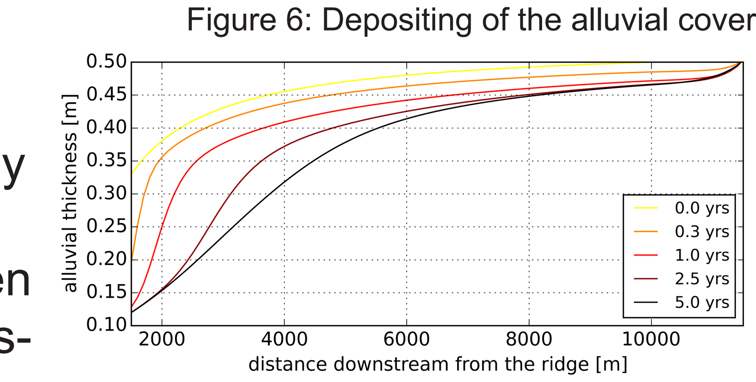

Figure 7: Alluvial cover response to halving the sediment supply.

Doubling the Sediment Supply

Figure 8: The bed is initially at equilibrium with a prescribed sediment feed; then the sediment feed is doubled,increasing the alluvial thickness.

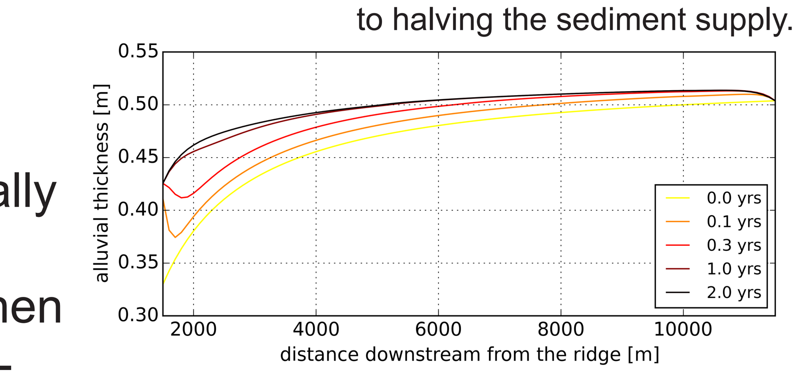

Figure 8: Alluvial cover response to doubling the sediment feed.

Bedrock Evolution (0-20,000 yrs)

Halving the Sediment Supply

Figure 9: In response to the decrease in sediment supply, the channel's slope becomes gentler.

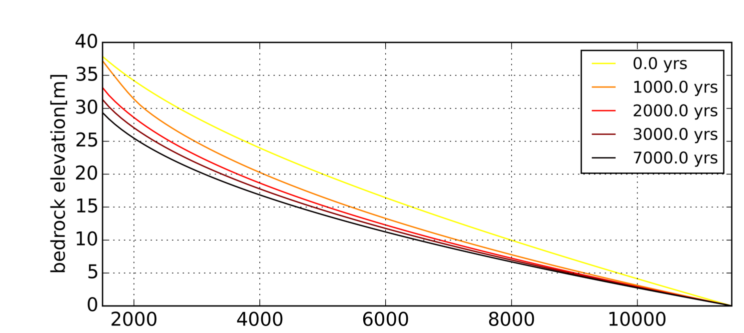

Figure 9: Bedrock response to decreased sediment feed.

Doubling the Sediment Supply

Figure 10: The bedrock channel steepens in response to the increased sediment supply.

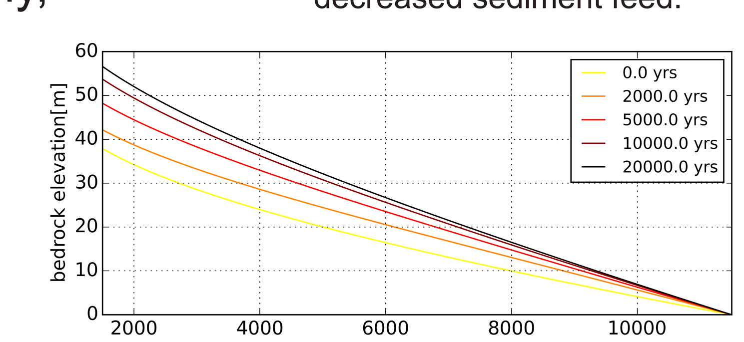

Figure 10: Bedrock response to increased sediment feed.

Discussion and Conclusions

Quasi-steady Approximation

The quasi-steady approximation is commonly used in the field of river morphodynamics and sediment transport. For example, flow hydraulics are commonly assumed to be steady (quasi-steady) while the bed evolves slowly. CSA assumes that the alluvial morphodynamics are quasi-steady while MRSAA does not. This approximation simplifies the computation of the model but does not always apply. In the case of flow hydraulics and sediment transport, the approximation is invalid when there are rapidly varying hydrographs.

CSA

- Assumes that the alluvial layer is quasi-steady.
- The alluvial layer adjusts instantaneously to changes in the bedrock channel
- The bedrock channel slowly evolves after changes in the alluvial layer.

MRSAA

- Unsteady alluvial morphodynamics are modeled.
- When the quasi-steady approximation is valid, MRSAA's solutions will converge to results similar to CSA's results.
- When there are rapid changes in sediment supply, CSA's assumption of quasi-steady alluvial morphodynamics is inappropriate, and the two models diverge.

Examples of Rapid Changes in Sediment Supply

- Sediment feed from the surrounding landscape is unsteady.
- Landslides and mass failures can add large amounts of sediment to the channel at intermittent intervals.

A landscape-scaled MRSAA model is a much needed forward step in better understanding the connections and feedbacks between hillslopes and bedrock channels.

Acknowledgments

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References

Chatanantavet, P., and G. Parker (2009), Physically based modeling of bedrock incision by abrasion, plucking, and macroabrasion, Journal of Geophysical Research, 114(F4), doi:10.1029/2008JF001044.

Gasparini, N. M., K. X. Whipple, and R. L. Bras (2007), Predictions of steady state and transient landscape morphology using sediment-flux-dependent river incision models, Journal of Geophysical Research, 112(F3), doi:10.1029/2006JF000567.

Sklar, L. S., and W. E. Dietrich (2004), A mechanistic model for river incision into bedrock by saltating bed load, Water Resources Research, 40(6), n/a-n/a doi:10.1029/2003WR002496.

Zhang, L., G. Parker, C. P. Stark, T. Inoue, E. Viparelli, X. Fu, and N. Izumi (2015), Macro roughness model of bedrock–alluvial river morpho-dynamics, Earth Surface Dynamics, 3(1), 113–138, doi:10.5194/esurf-3-113-2015.