Modelling Feedback Loops in Soil Erosion

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A. Introduction

There are feedback loops in soil erosion (Fig. 1) that should be taken into account when simulating major erosion events or when modelling over long time scales.

Surface soil may become coarser due to the preferential transport of fine particles off site, or become finer if it is a net deposition area for sediment eroded from an upper region. This change in the particle size distribution (PSD) feeds back into the erosion processes.

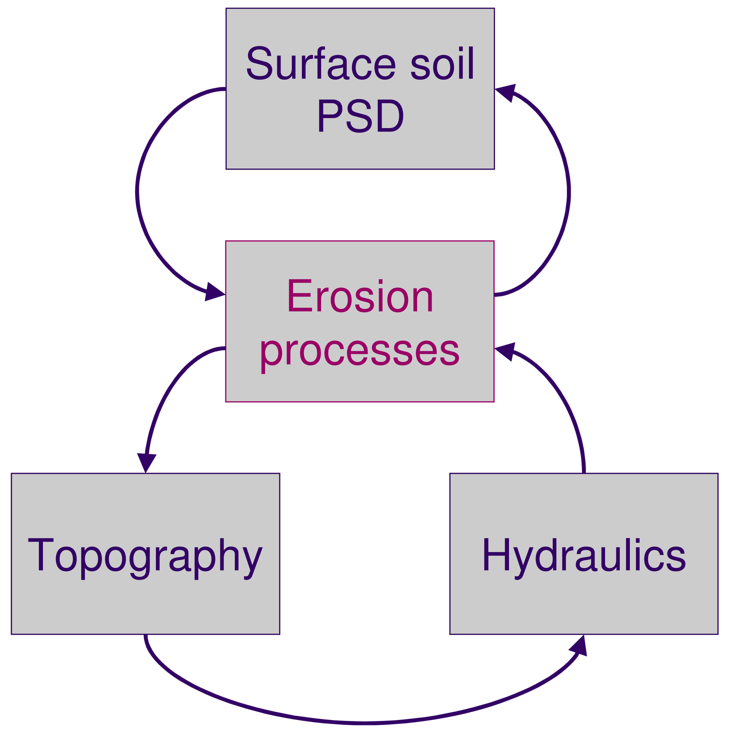

Figure 1. Feedback loops in soil erosion.

Topographical changes resulting from the erosion and deposition of sediment affect surface runoff, which in turn has a bearing on soil erosion and sediment transport.

The Hairsine-Rose (H-R) soil erosion model [Hairsine and Rose 1991, 1992a, b] is a multiple-size-class model that takes into account the evolution of the surface soil. By coupling this model with the St. Venant equations—allowing for topographical changes—in a finite volume scheme, we are able to model these two feedback loops in soil erosion.

B. Governing Equations

H-R equations (for sediment class i):

$$\frac{\partial(hc_i)}{\partial t}+\frac{\partial(qc_i)}{\partial x}=e_i+e_{ri}+r_i+r_{ri}-d_i,$$

$$\frac{\partial m_i}{\partial t}=d_i-e_{ri}-r_{ri},$$

h is flow depth,

q is unit discharge,

c_i is sediment concentration,

m_i is the deposited sediment mass per unit area,

e_i and e_{ri} are the rates of detachment and re-detachment due to rainfall,

r_i and r_{ri}, are the rates of entrainment and re-entrainment due to runoff,

d_i is the deposition rate.

St. Venant equations:

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=R-\frac{\partial z}{\partial t},$$

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{q^2}{h}+\frac{1}{2}gh^2\right)=-gh\left(\frac{\partial z}{\partial x}+S_f\right),$$

R is excess rainfall,

z is bed elevation,

S_f is friction slope.

Bed evolution:

$$\frac{\partial z}{\partial t}=\frac{\sum(d_i-e_i-e_{ri}-r_i-r_{ri})}{(1-p)\rho_s},$$

p is bed porosity,

ρ_s is sediment density.

The full system of equations is solved numerically using a finite volume scheme [Heng *et al.* 2009].

C. Application

Polyakov and Nearing [2003] subjected a rill to alternating net erosion and net deposition conditions to investigate consequent effects on sediment transport. We apply the H-R model to study the feedback mechanisms in such scenarios.

The output for one scenario is shown in Fig. 2, with the method-of-lines (MOL) solution as an independent check. The model performs well under net erosion as well as net deposition conditions with a single set of model parameters, the SSC being a consequence of the dynamic interplay between erosion and deposition rates. There is clearly a significant difference between the fixed and variable bed models in the transition from net deposition to net erosion.

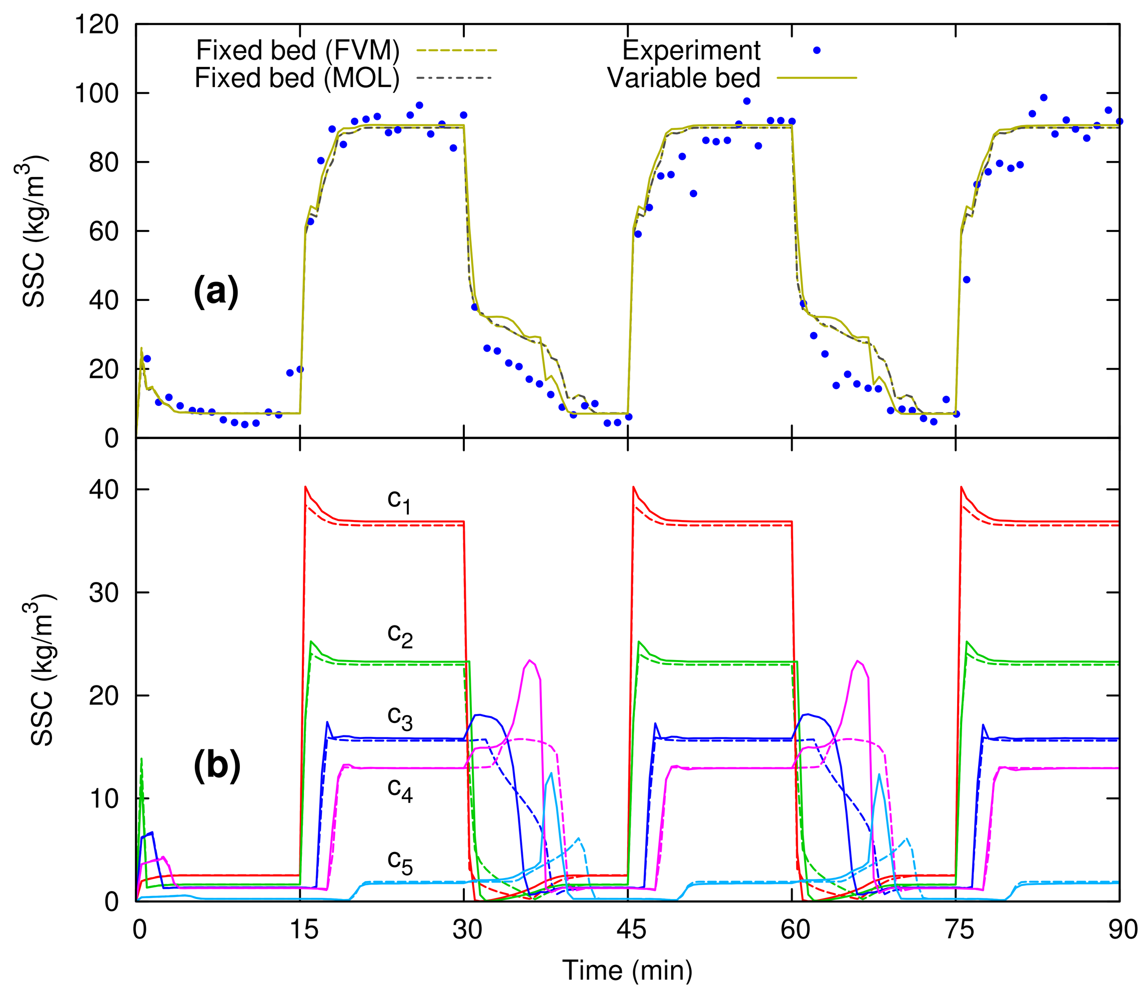

Figure 2. Suspended sediment concentration (SSC) in 6 l/min runoff under alternating net erosion and net deposition conditions in 15 min periods. Rill length L = 2 m. (a) Fixed and variable bed model output with experimental data for total SSC. (b) Fixed bed (dashed lines) and variable bed (solid lines) model output for individual size classes.

Another consequence of ignoring topographical feedback is the non-physical build-up of deposited sediment near the inlet under net deposition conditions (Fig. 3). In reality, the deposition of sediment near the inlet results in a steeper slope, leading to increased stream power and erosion rates. This feedback mechanism is captured in the variable bed model (Fig. 4a).

In period 3, the deposited sediment is eroded away by the clear inflow, exposing the cohesive (and less erodible) parent soil (Fig. 4b), leading to a decline in sediment delivery.

The surface soil coarsens significantly from an initial parent soil PSD under net deposition as well as net erosion conditions (Fig. 5), but is finer under the former regime. The feedback mechanism between surface soil and eroded sediment explains why the eroded soil is finer under net deposition conditions. The model under-predicts the difference because we have assumed that the sediment fed into the flume has the same PSD as the parent soil, whereas aggregate breakdown could have occurred in the process [Polyakov and Nearing 2003].

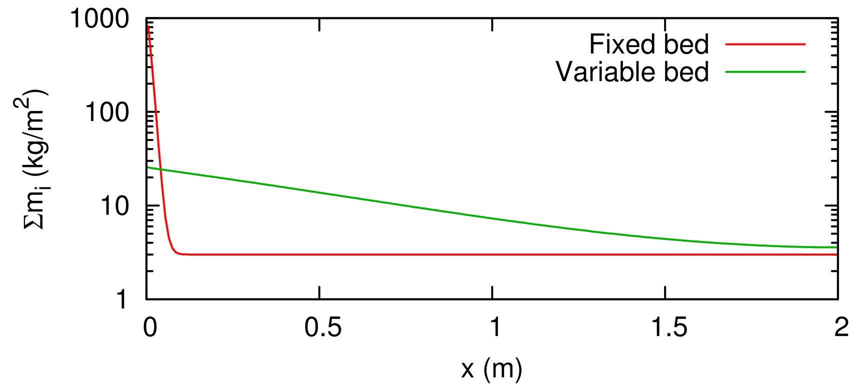

Figure 3. Spatial variation of total deposited mass.

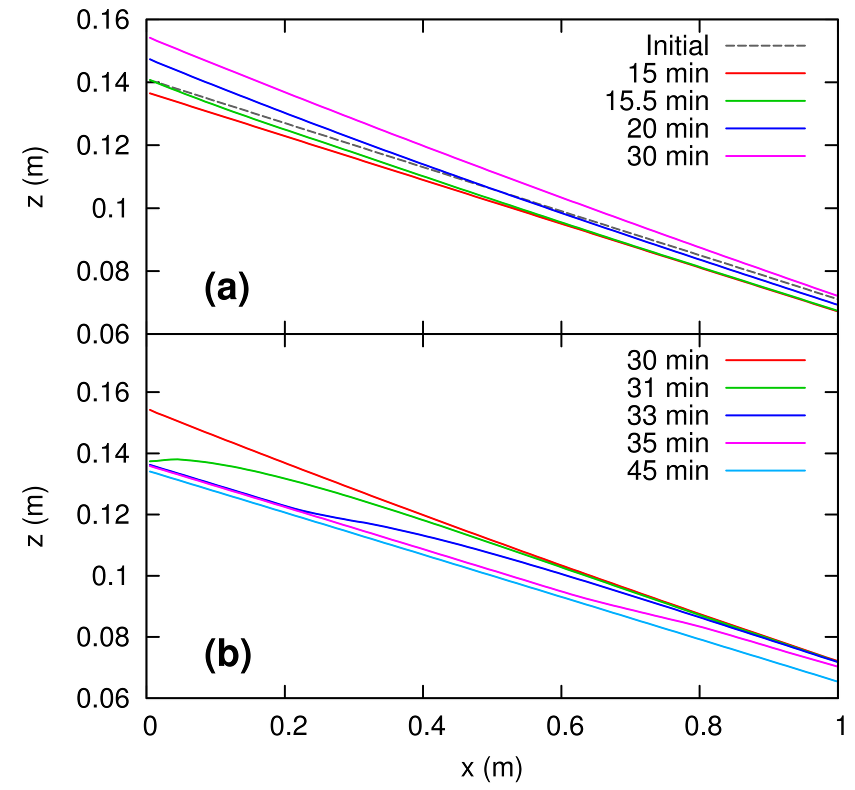

Figure 4. Bed evolution. (a) Net deposition. (b) Net erosion.

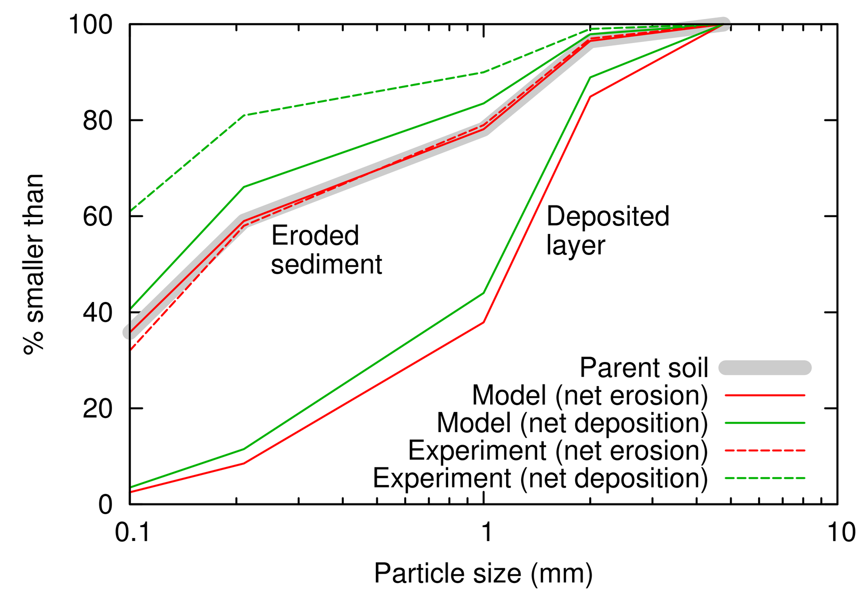

Figure 5. PSD curves under net deposition conditions differ from those under net erosion, for the deposited layer as well as for the eroded sediment.

D. Conclusion

Feedback mechanisms can significantly impact soil erosion processes. The H-R model coupled with the St. Venant equations encapsulates two such mechanisms: surface soil PSD and topography-hydraulics. The above application shows that the model is capable of simulating complex experimental scenarios.

Future work includes extending the model to two dimensions and incorporating chemical transport equations to model nutrient transport dynamics.

E. References

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