Modeling the source: *A mechanistic approach for hillslope sediment fluxes*

Josh Roering, University of Oregon
Bill Dietrich, University of California, Berkeley

Modeling the source: Outline

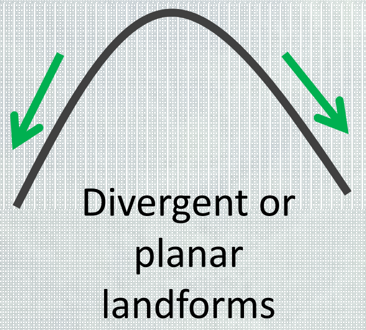
1) Hillslopes and channels: function and coupling

2) Tectonics, climate, lithology, topography,and sediment fluxes: Quantitative framework and first-order linkages

3) Process-based models
   - Soil (or sediment) production
   - Sediment transport
   - Catchment-averaged predictions

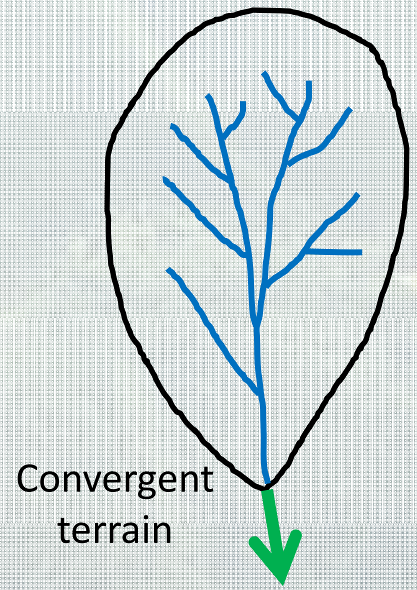
Hillslope processes:

1. Control the pace and character of sediment flux into channel networks
2. Determine landscape morphology (e.g., relief)



Channel networks:

1. Set the lower boundary condition to which hillslopes adjust
2. Transfer sediment produced by hillslope processes



Framework for process-based prediction of sediment fluxes

$$\frac{\partial z_s}{\partial t} = U - \frac{\rho_r}{\rho_s} P + \frac{\partial h}{\partial t}$$

$$\frac{\partial h}{\partial t} = \frac{\partial q_s}{\partial \mathrm{x}} + \frac{\rho_r}{\rho_s} P$$

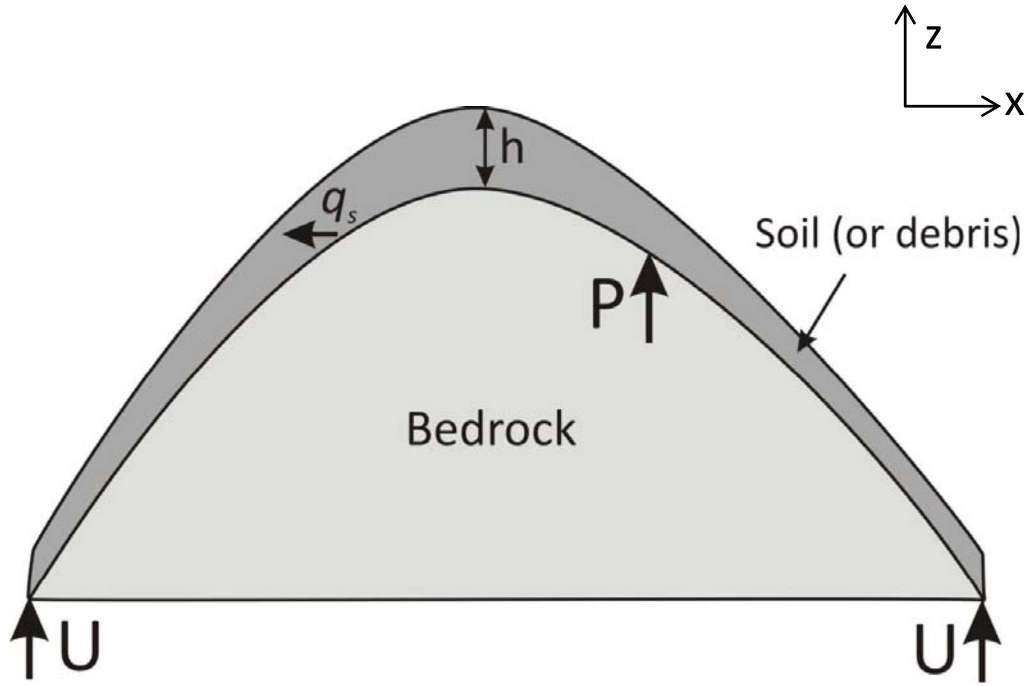
P = soil production

q_s = sediment flux

h = soil thickness

z_s = surface elevation

U = rock uplift (or baselevel lowering)



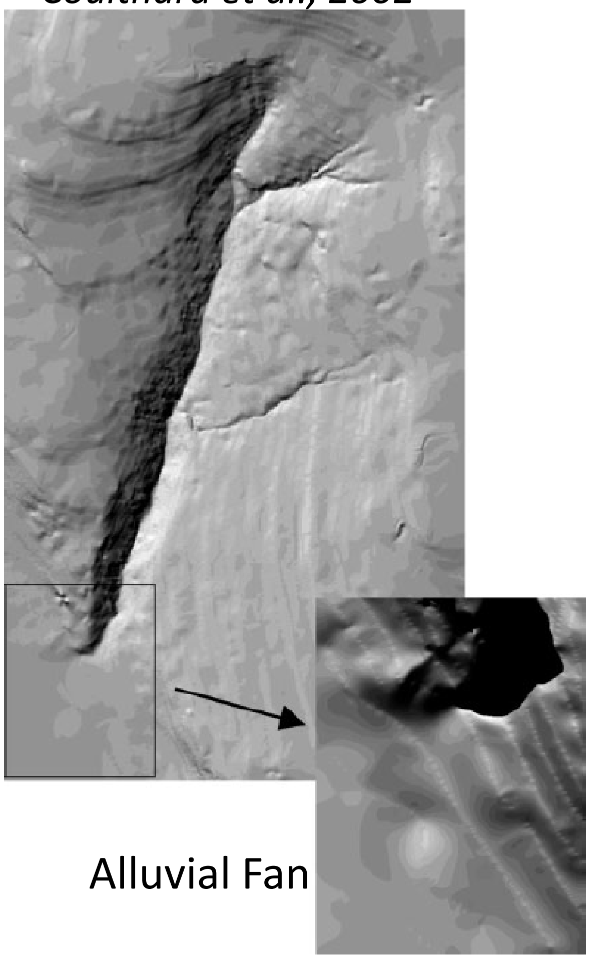
q_s **and** ***P*** **depend on:**

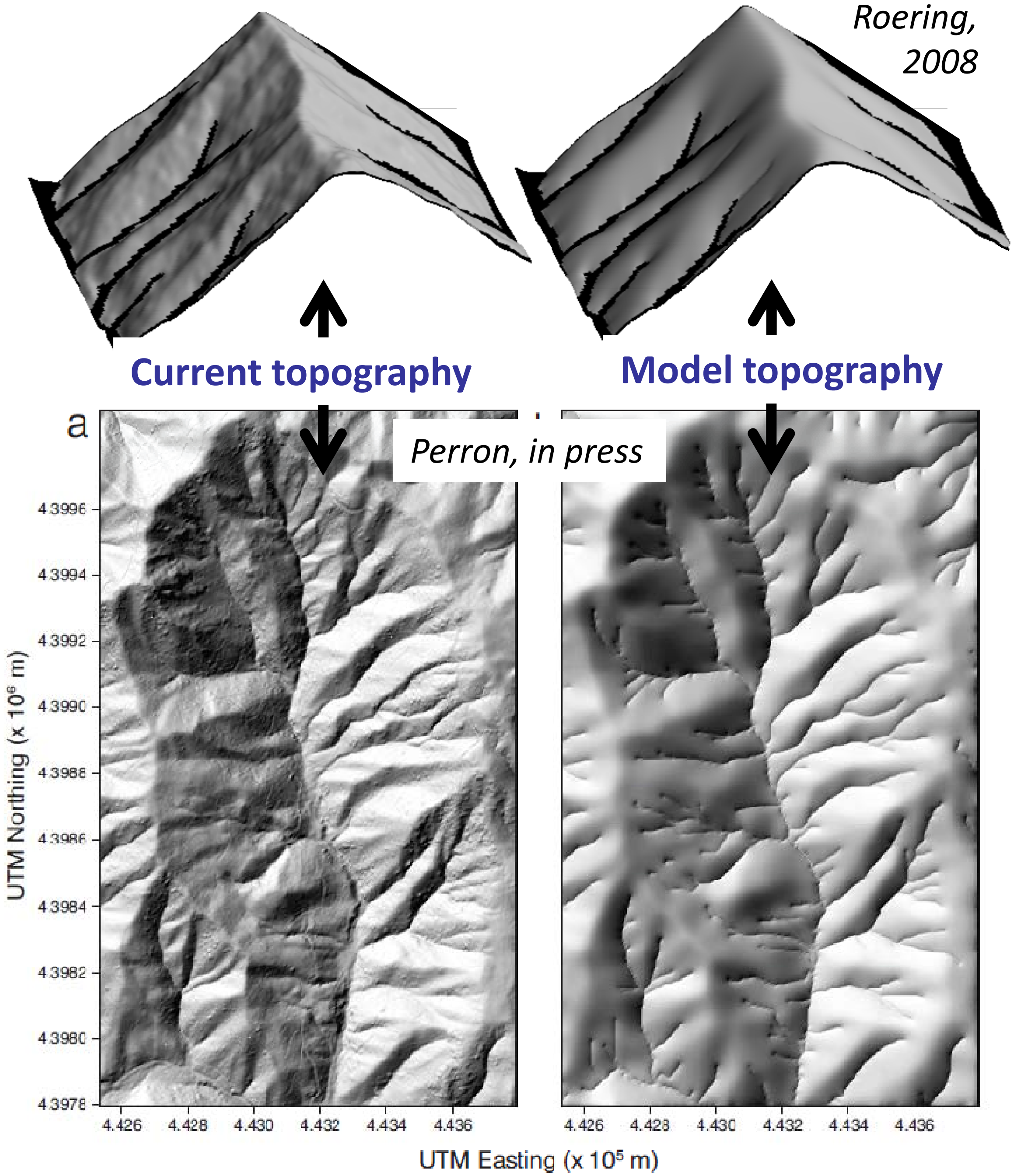
- Topography
- Climate & Biology
- Lithology
- Tectonic forcing
- Human activity

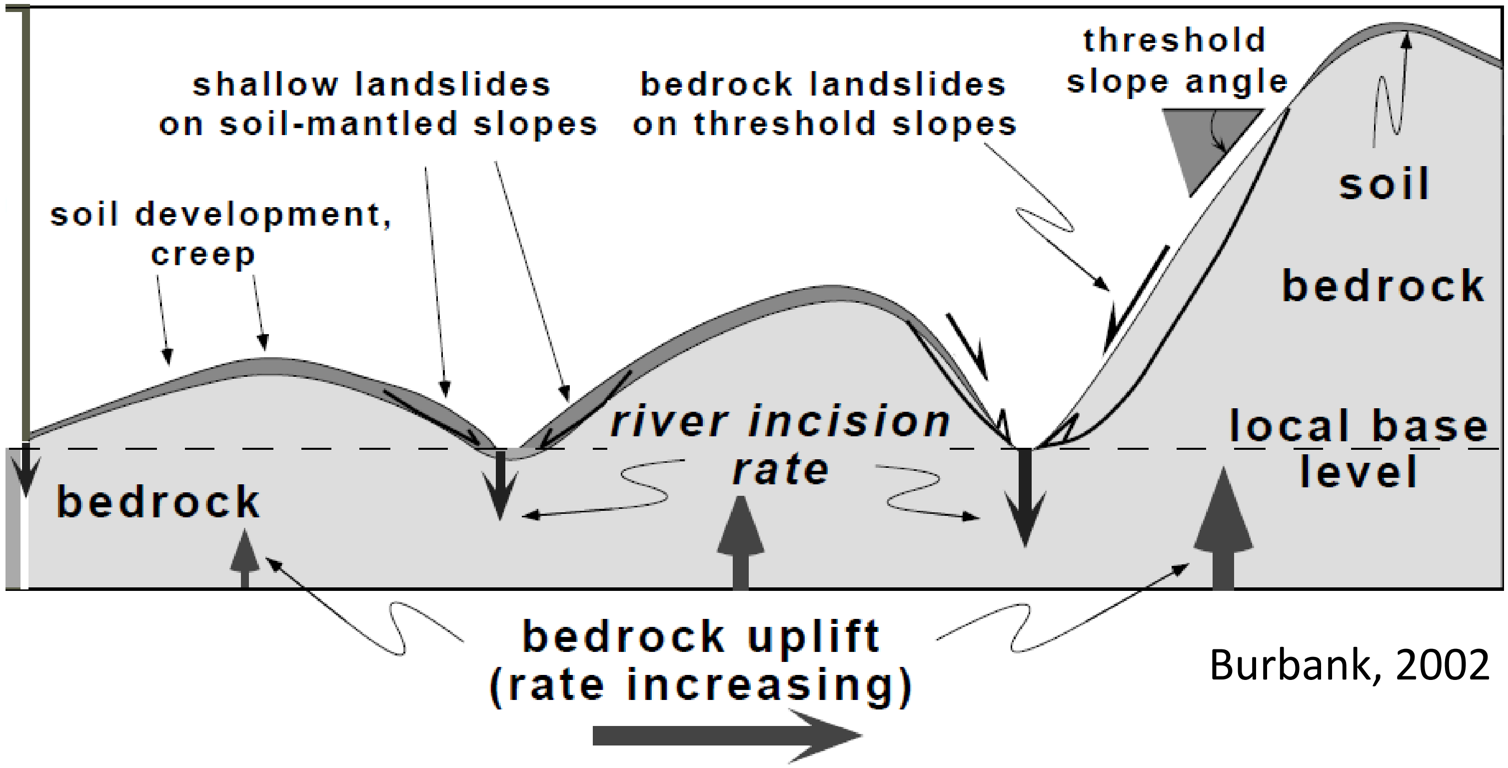
Sediment delivery predictions:

1) **Spatially explicit**
2) Catchment-averaged

Coulthard et al., 2002







Burbank, 2002

- *For constant climate, biology, and lithology,* **relief increases with rock uplift**
- Landsliding limits topographic development
- Sediment delivered to channels will be fresher and coarser along this continuum

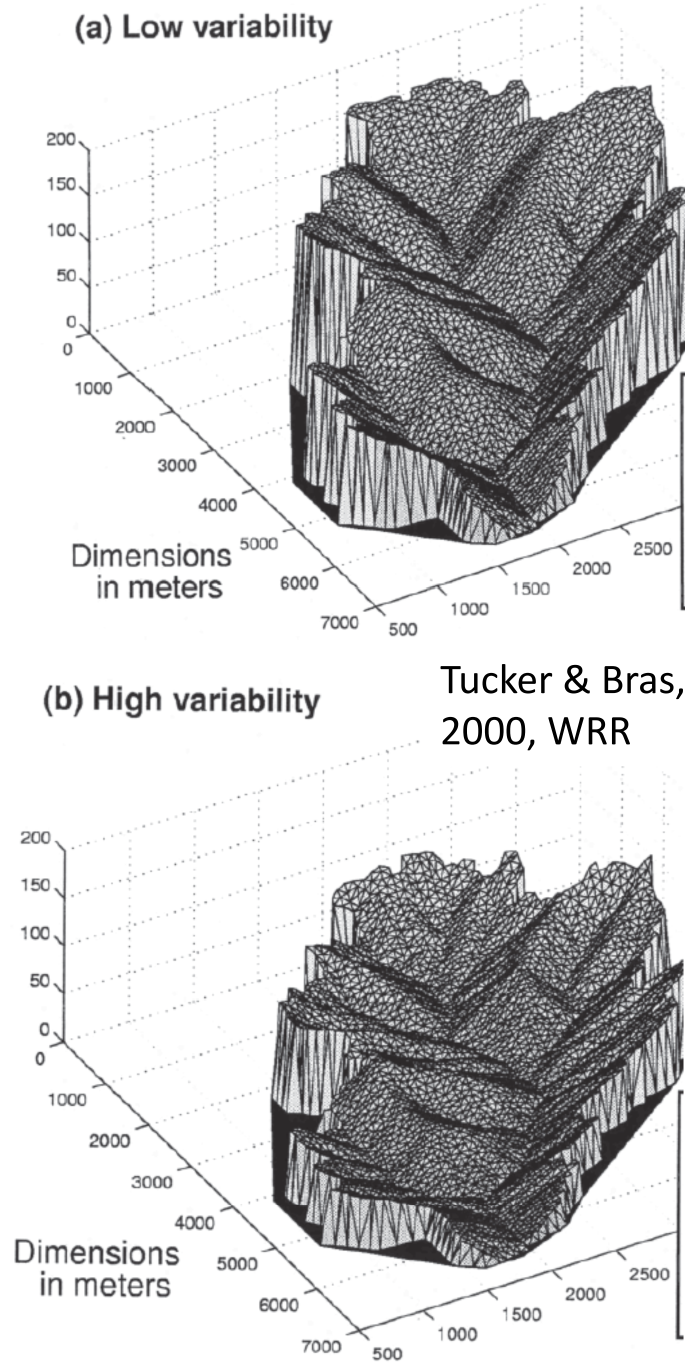
First-order linkages

- Ultimately, hillslope erosion rate is set by baselevel lowering

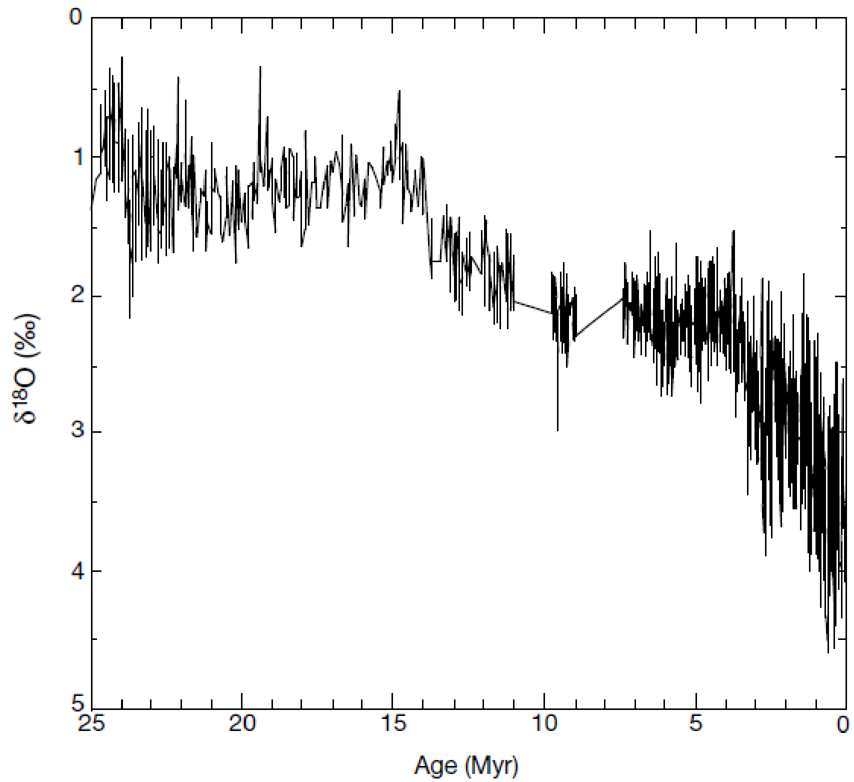
- **Climate/biology/lithology set the hillslope form** required to supply sediment and keep pace with baselevel lowering

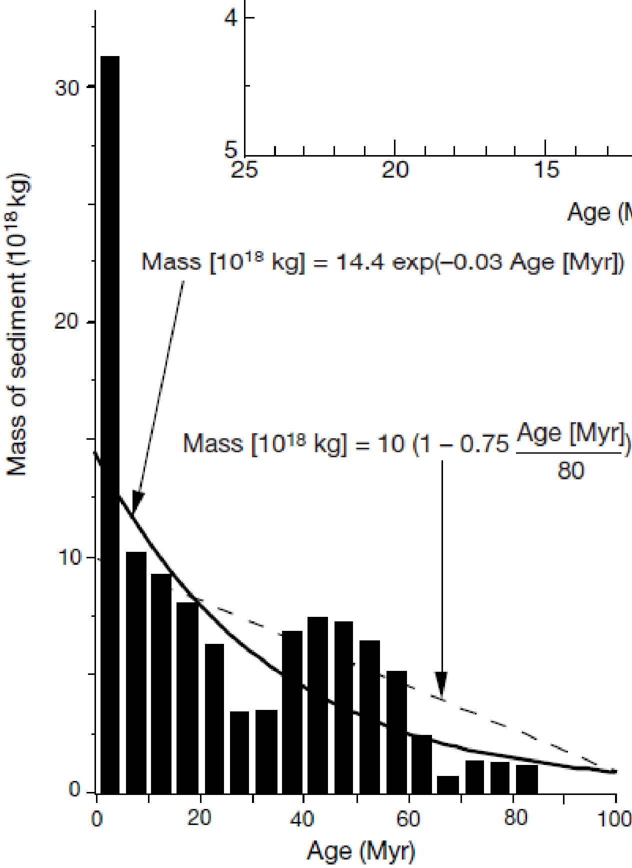
→ Process-form connection
→ Mechanistic understanding
→ Predictive capability for interpreting sedimentary record (especially variations)

- Thus, the direct influence of climate, biology, and lithology on sediment yield is elusive: **These factors should be incorporated through process models (*q_s* and *P*)**



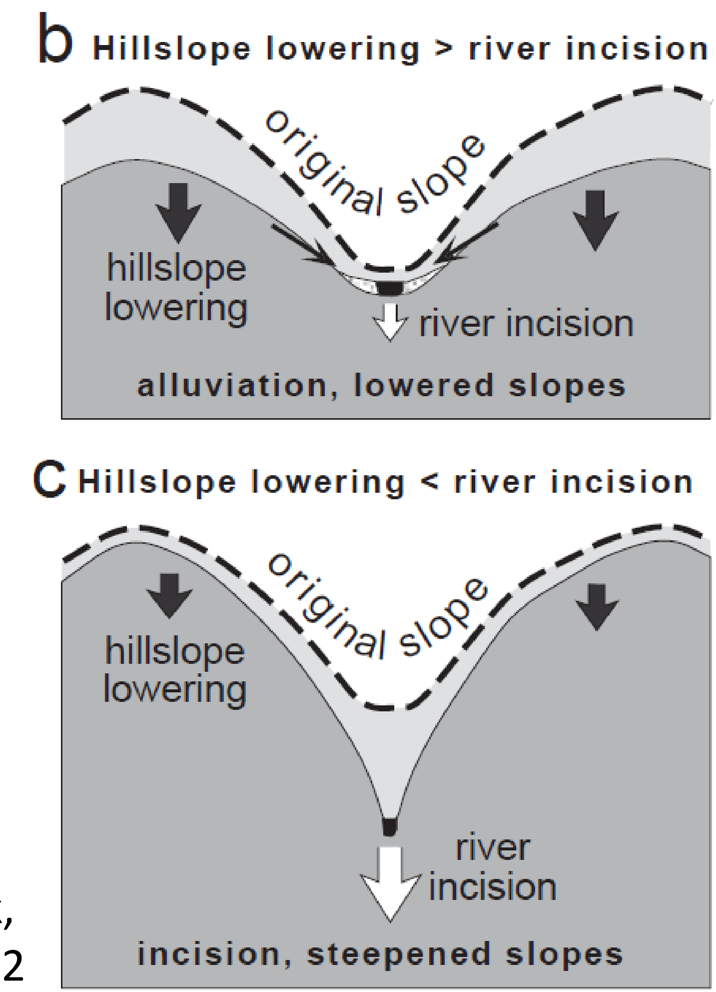
Tucker & Bras, 2000, WRR





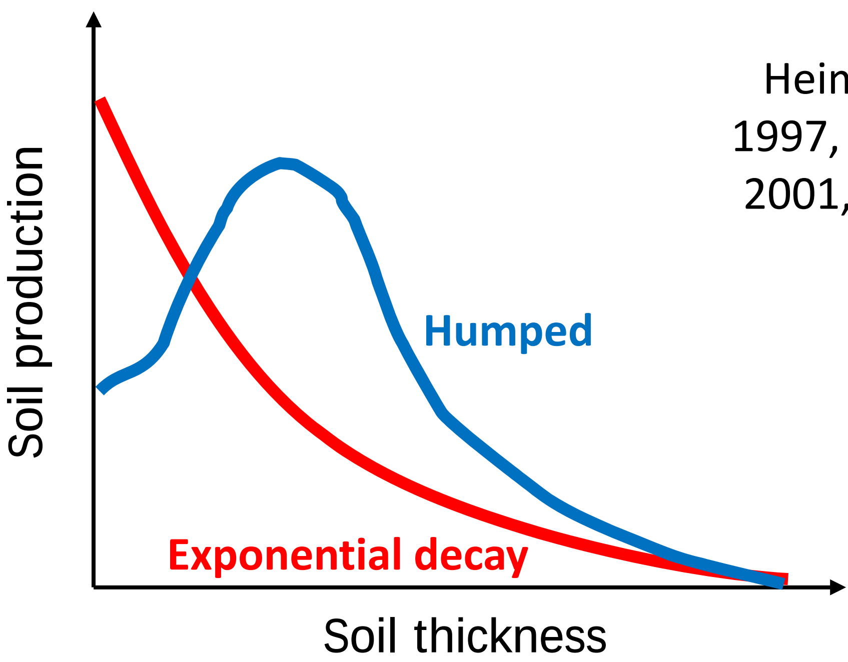
Peizhen, 2001, Nature

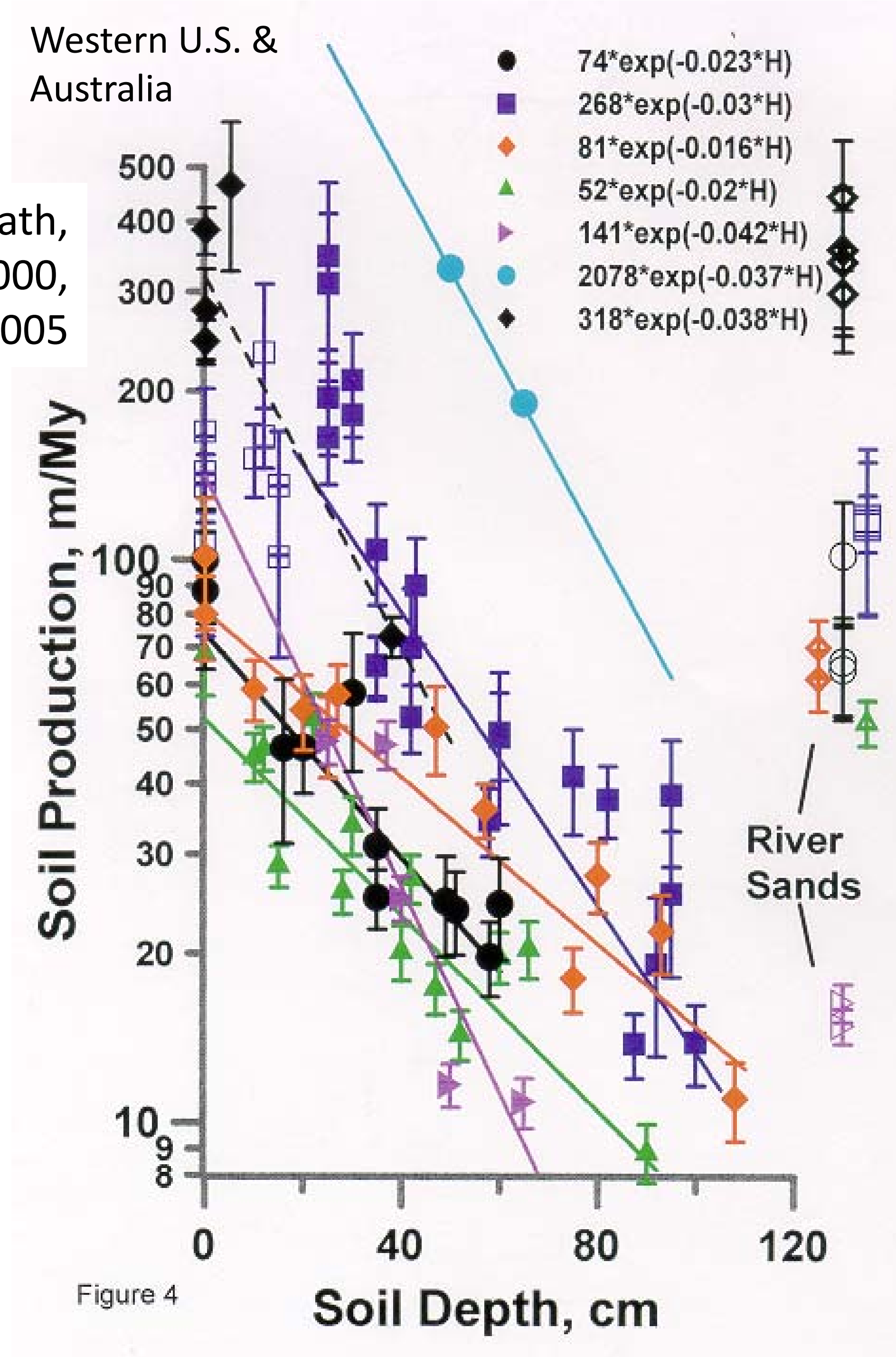
- Do fluctuating climate states generate greater sediment yield than the mean of those states?
- Are hillslopes in a perpetual state of adjustment?



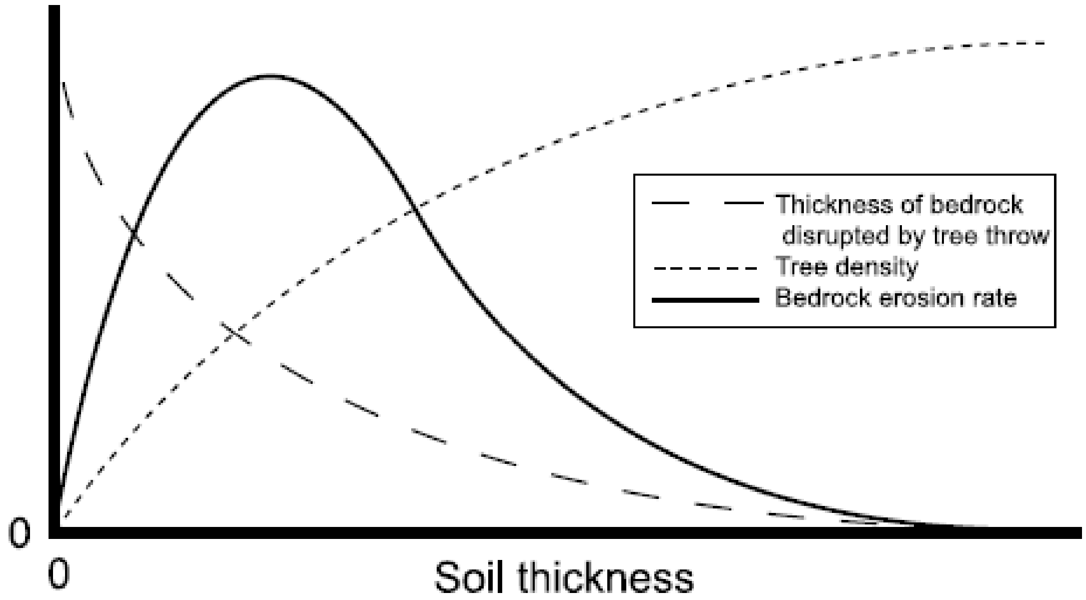
Burbank, 2002

Models: Soil production





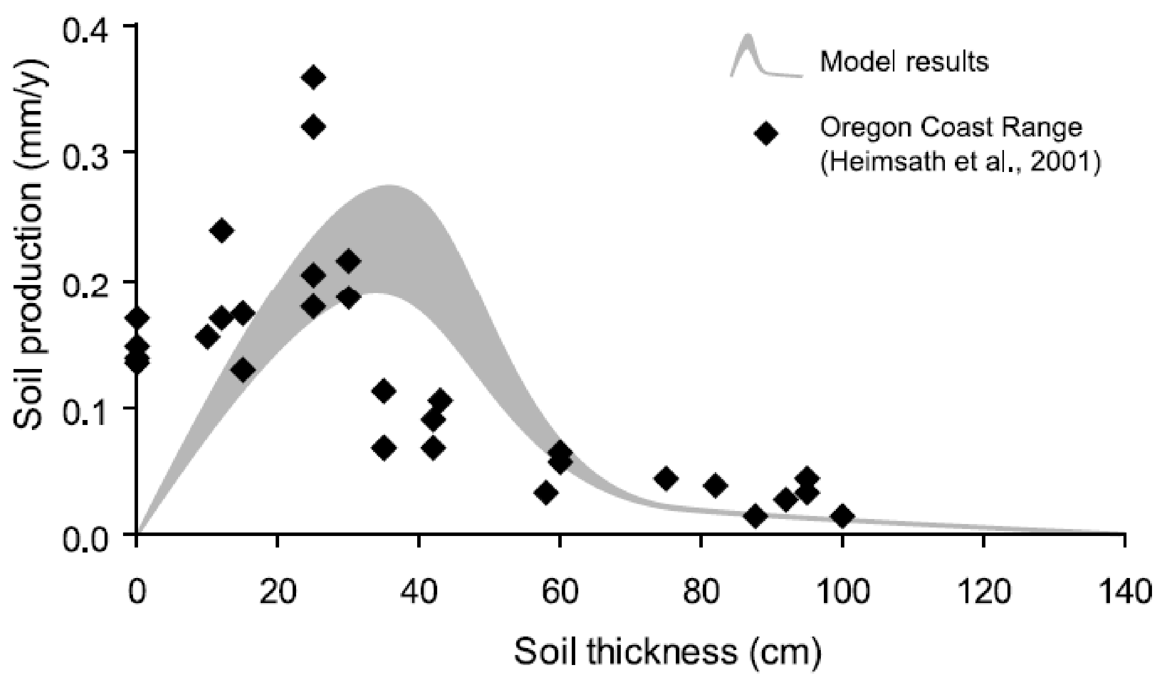
- What controls peak production rates and the functional form?
- What controls the production of landslide-prone material (i.e., strength reduction via weathering)?



Humped soil production emerges from forest dynamics:

- tree-driven bedrock disturbance decreases as soils thicken
- tree density increases as soils thicken

Mudd and Gabet, 2010, JGR



Models: Sediment transport into channels

- Disturbance-driven (e.g., bioturbation, frost processes)
- Landsliding (e.g., rockfalls, debris flows, deep-seated slides)
- Overland flow erosion (e.g., wash, rills, gullies)

$$q_s = f(slope, upslope\ area, soil\ thickness)$$

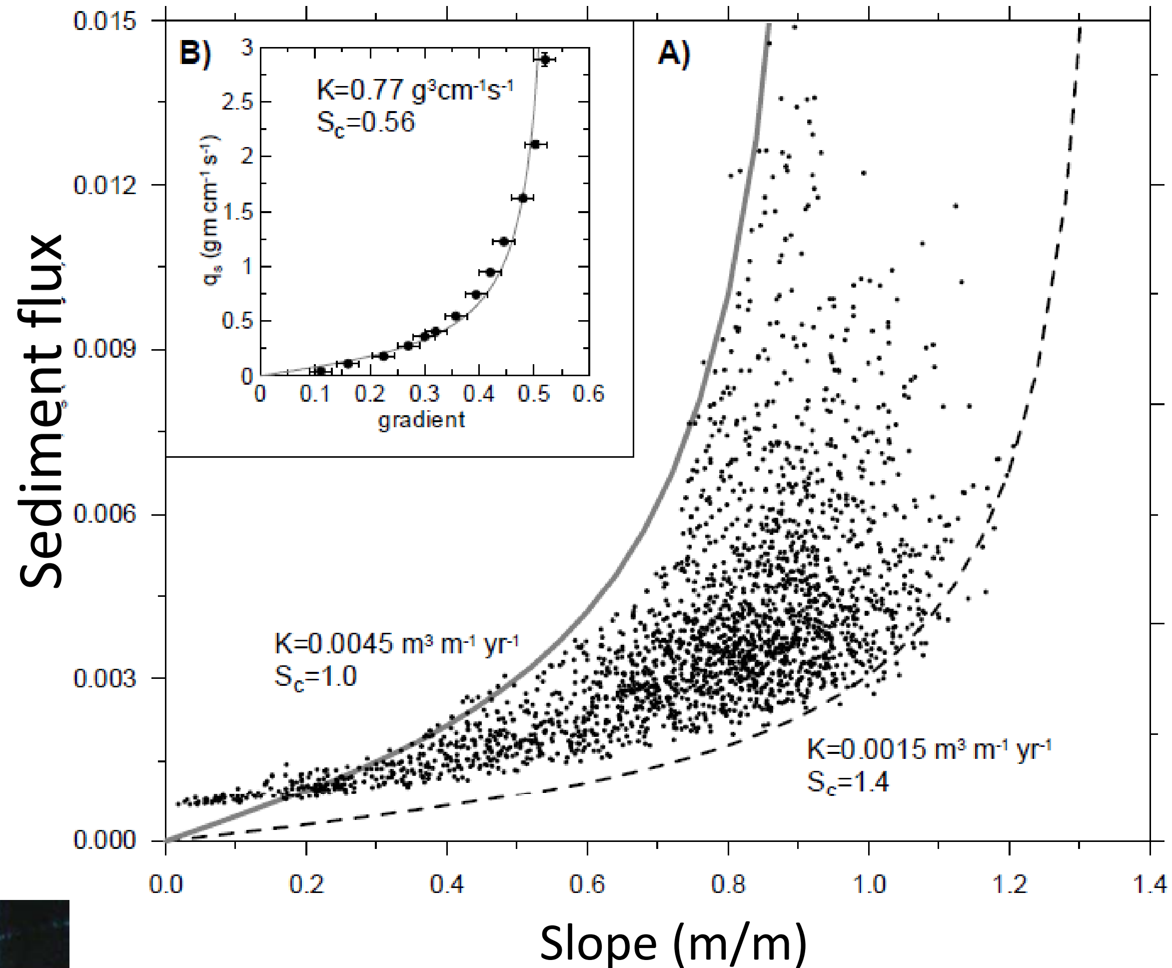
Note: Functional relationships for climate, biology, and lithology are unknown

Disturbance-driven transport varies nonlinear with slope

$$q_s = \frac{KS}{1-(S/S_c)^2}$$

K = *f* (power from disturbance agents & soil thickness)

S_c = Critical slope



Experimental, field, and morphologic evidence (Gabet, 2000, 2003; Pelletier, 2007, 2009; Roering, 1999, 2001, 2005, 2008)

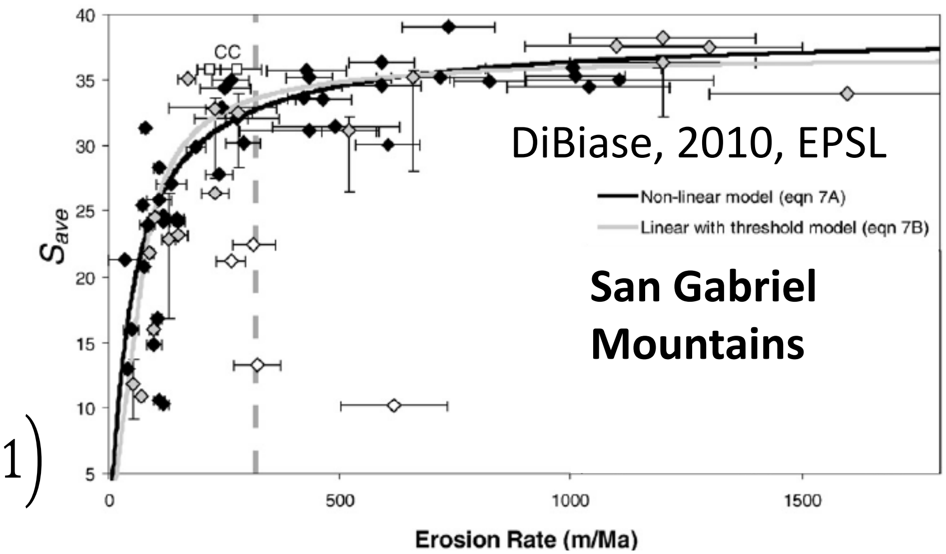
How does K vary with climate, lithology, and biology?

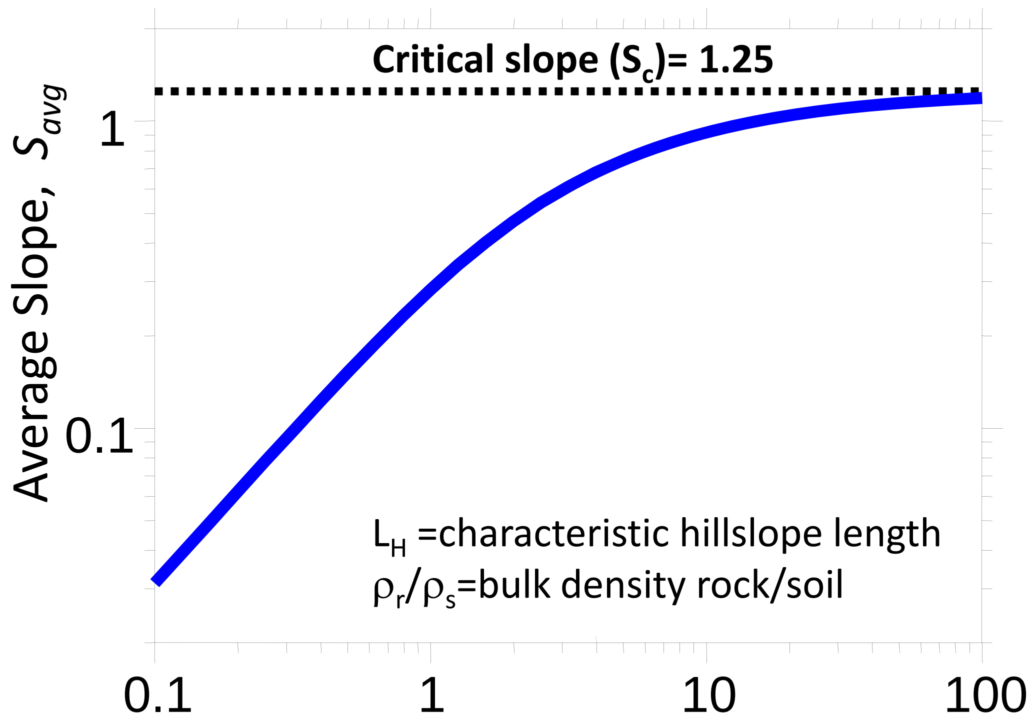
Catchment-averaged nonlinear model

$$q_s = \frac{KS}{1-(S/S_c)^2}$$

1) steady-state
2) integrate

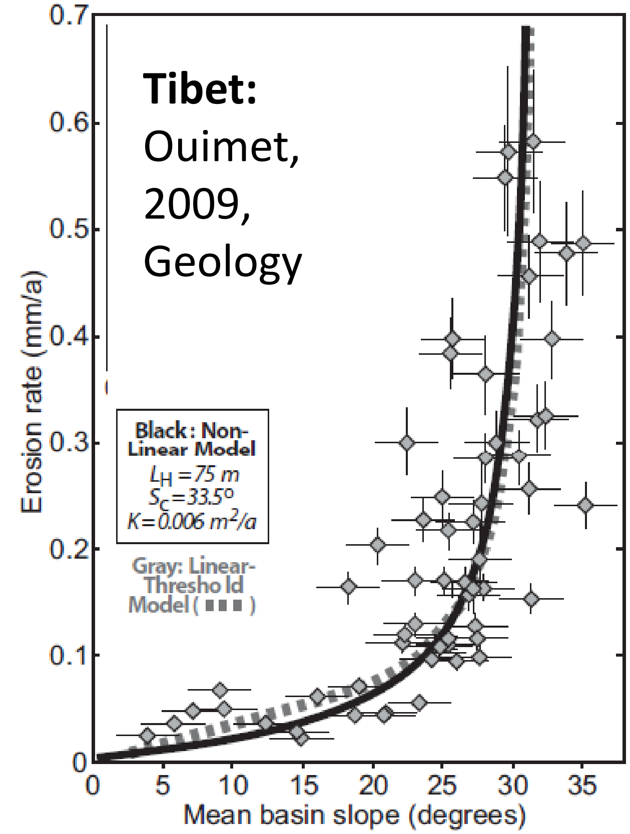
$$S_{avg} = \frac{S_c}{E^*}\left(\sqrt{1+(E^*)^2} - \ln\left(\frac{1}{2}\left(1+\sqrt{1+(E^*)^2}\right)\right) - 1\right)$$





Roering,
2007

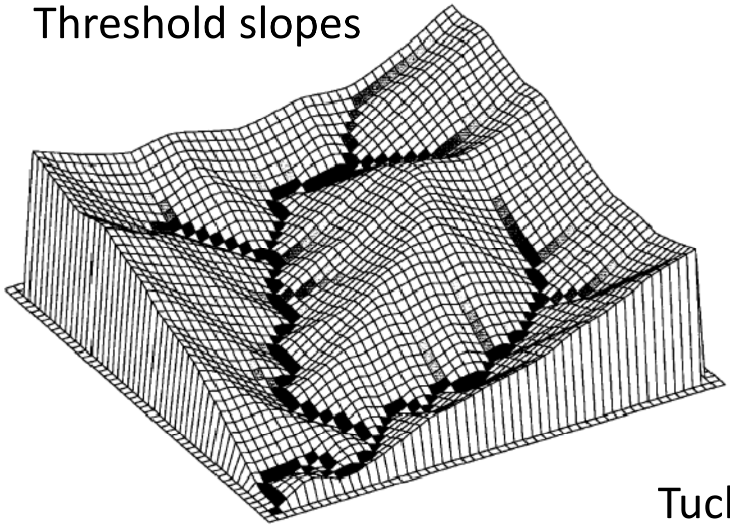
$$E^* = \frac{2E(\rho_r/\rho_s)L_H}{KS_c}$$



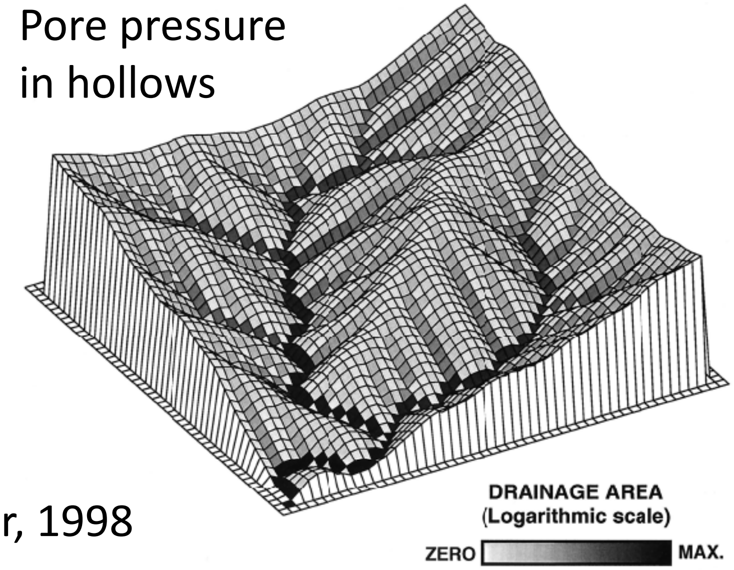
Models: Landslide transport requirements (Stark, 2009)

1. Trigger event spatial and temporal distribution (e.g., rainfall, EQ)
2. Number and volume distribution of landslides generated per event
3. Delivery of landslide debris into channels

Threshold slopes

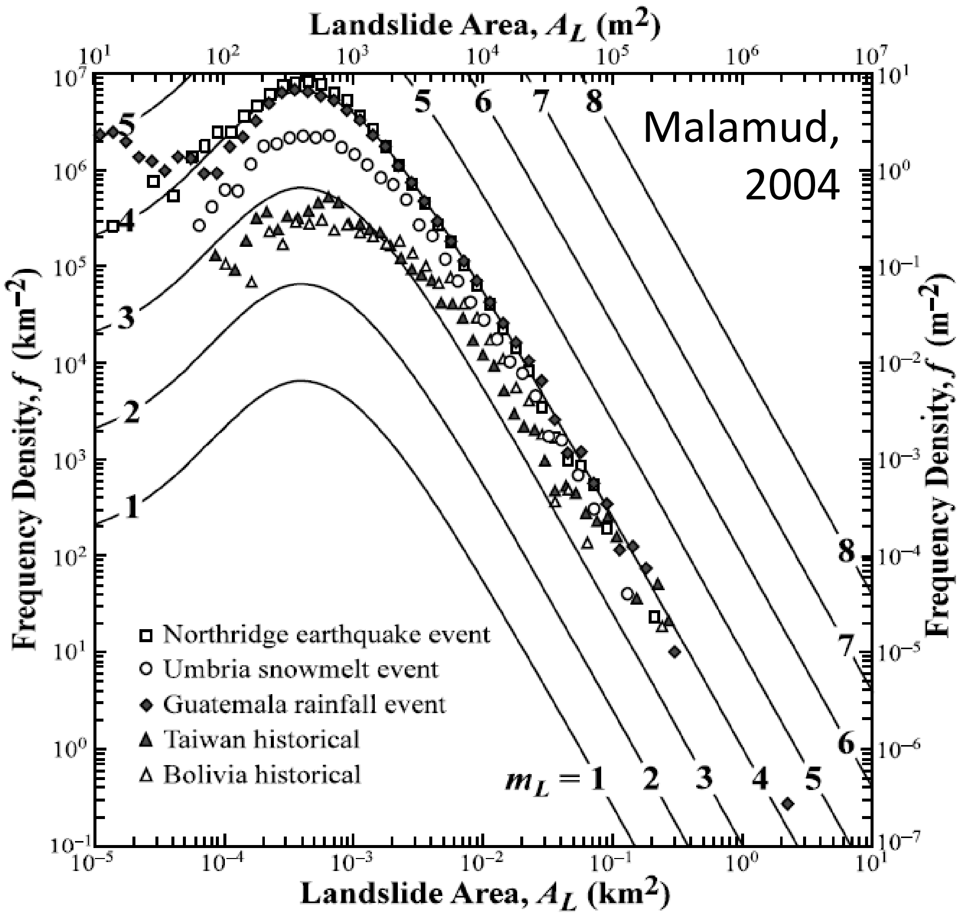


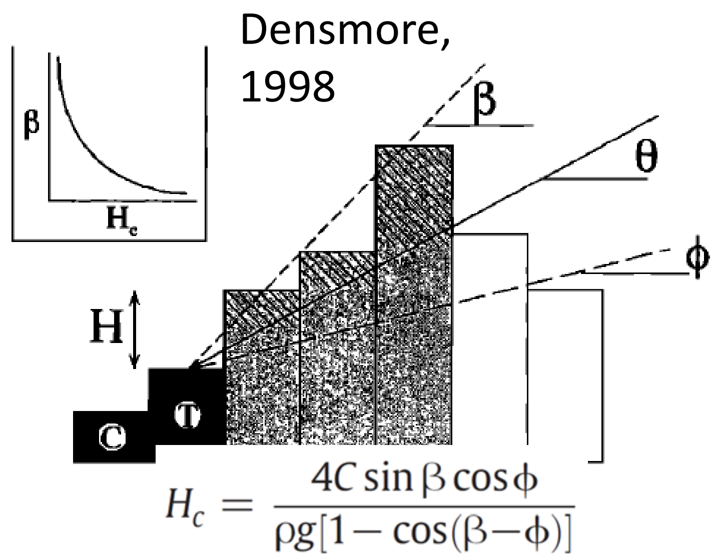
Pore pressure in hollows

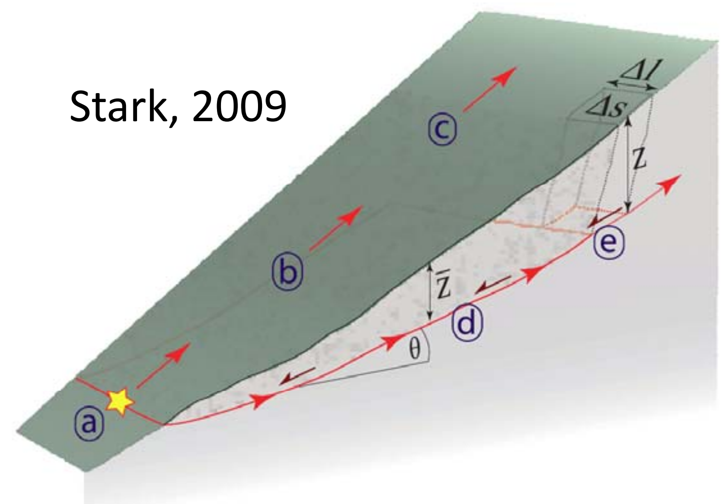


Tucker, 1998

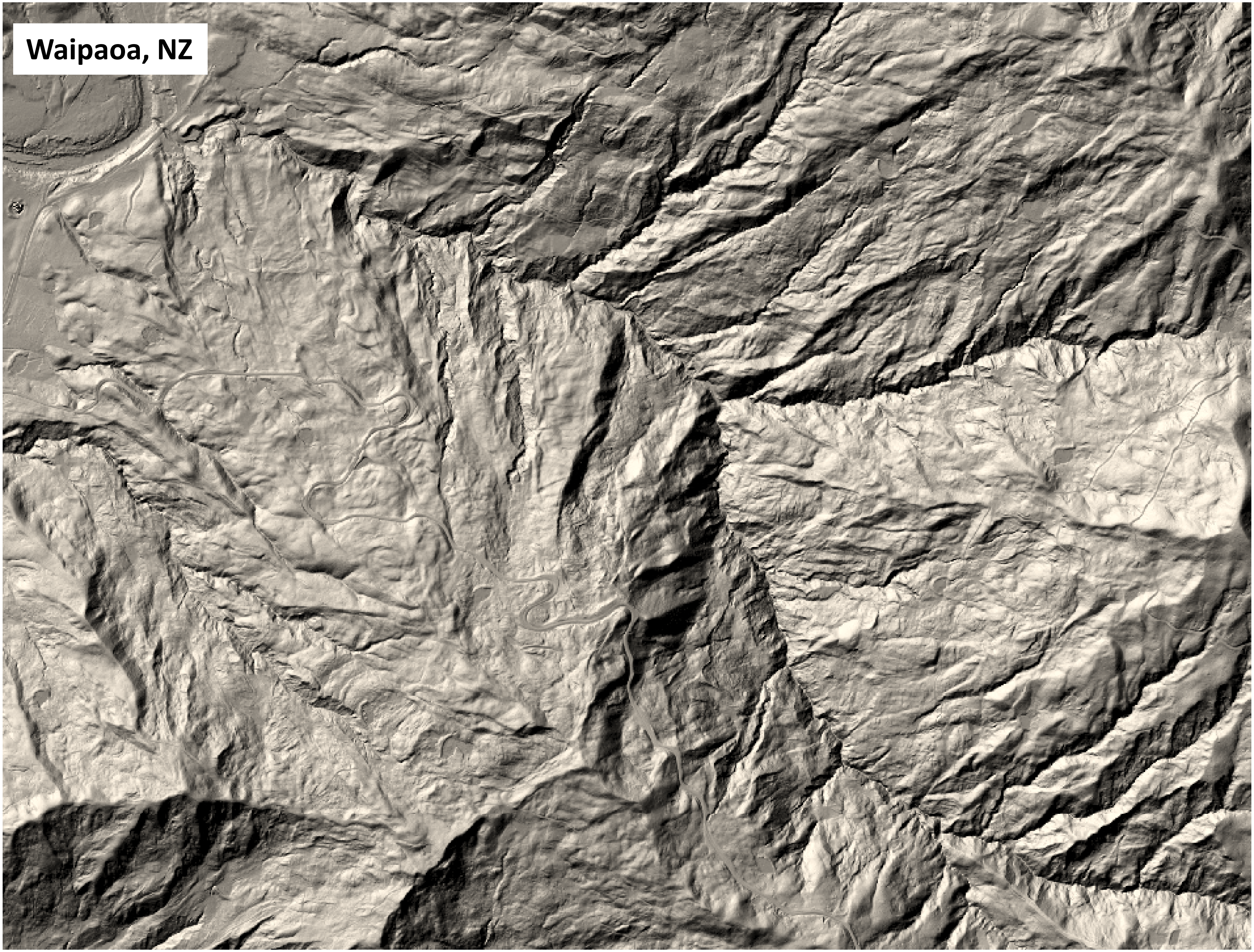
A statistical approach for landslides



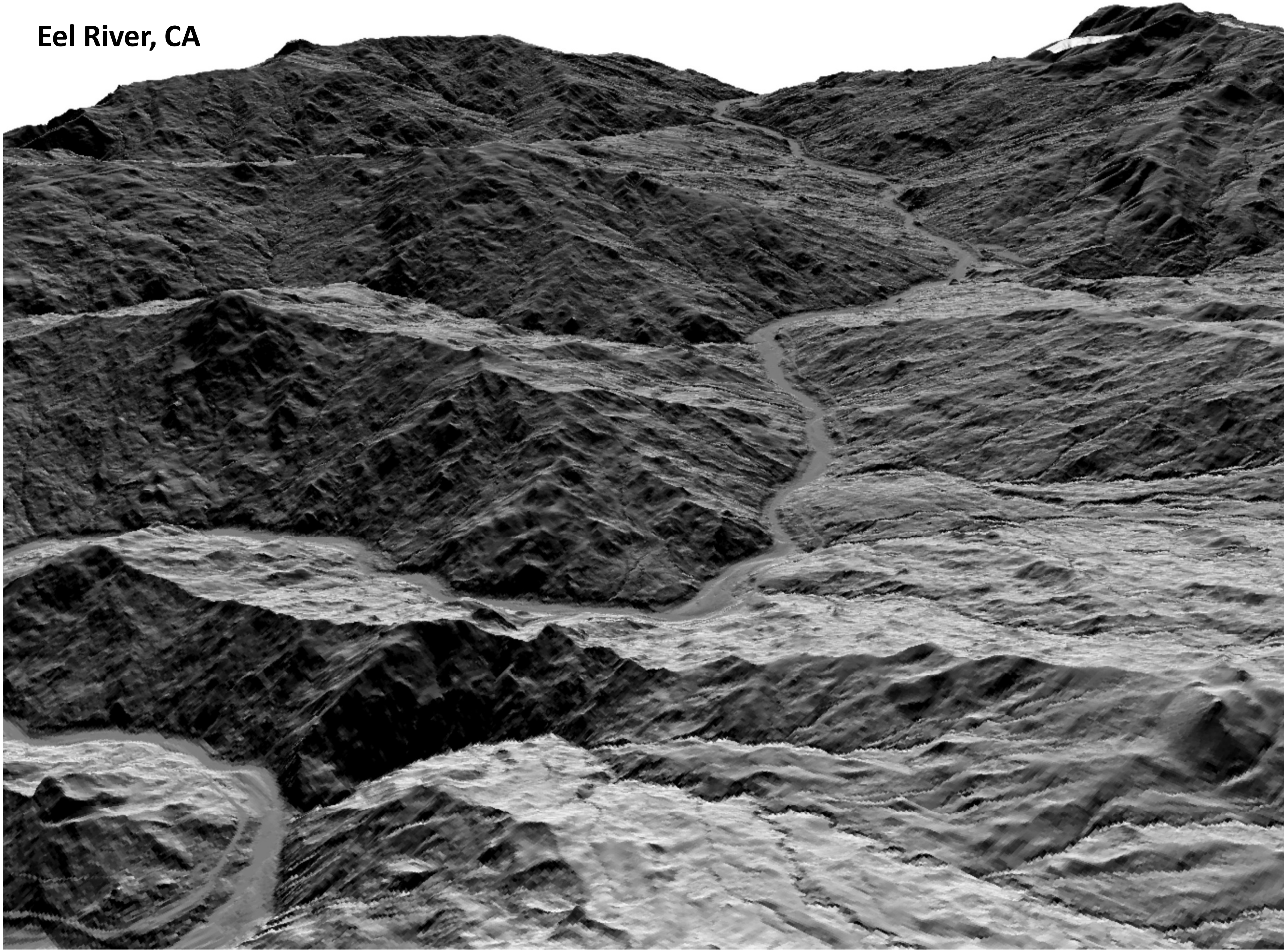




- Landslide volumes are limited by topography (relief and drainage density)
- Can statistical properties be used to estimate sediment yields?


Waipaoa, NZ

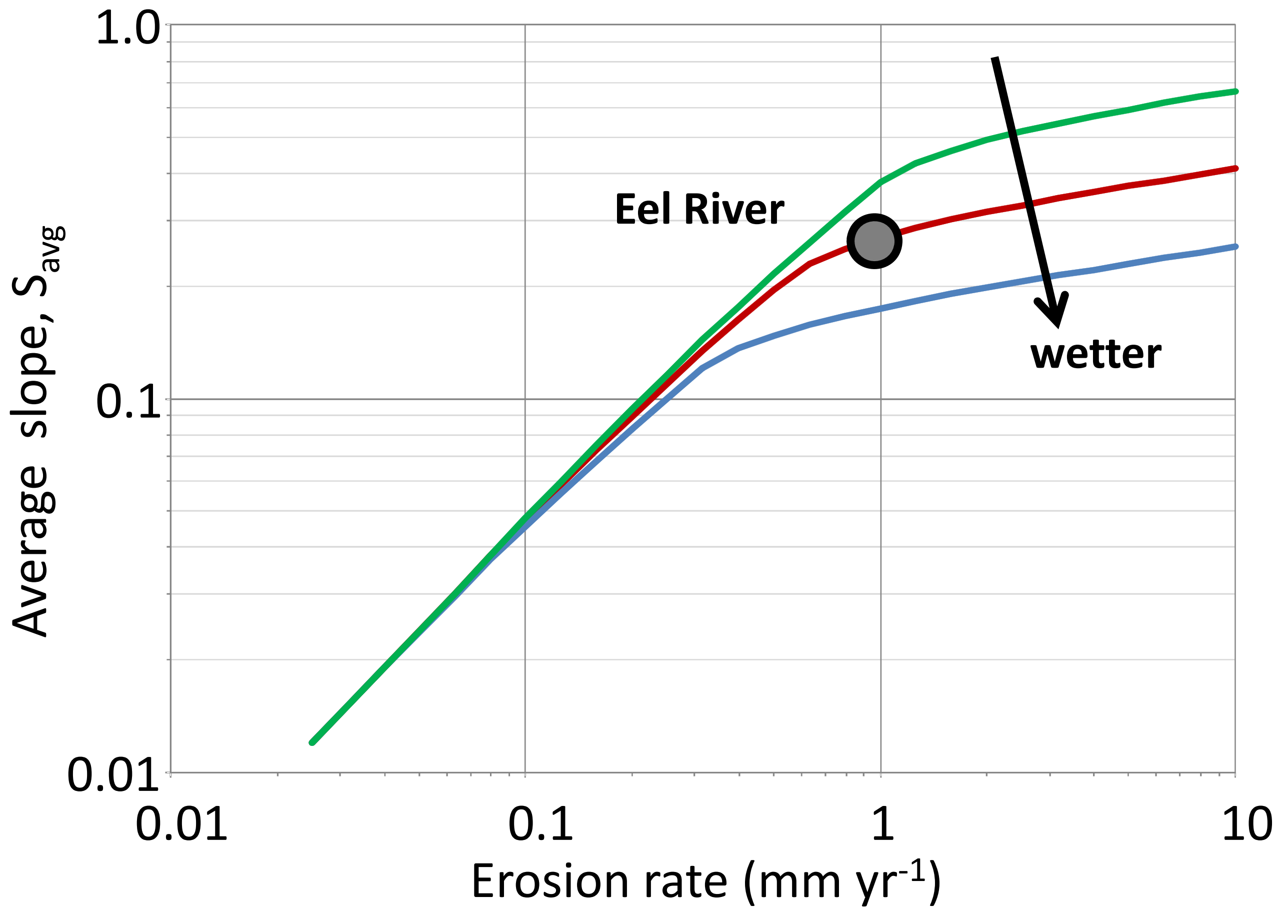
Eel River, CA



Erosion-topography relationship for earthflow-prone terrain

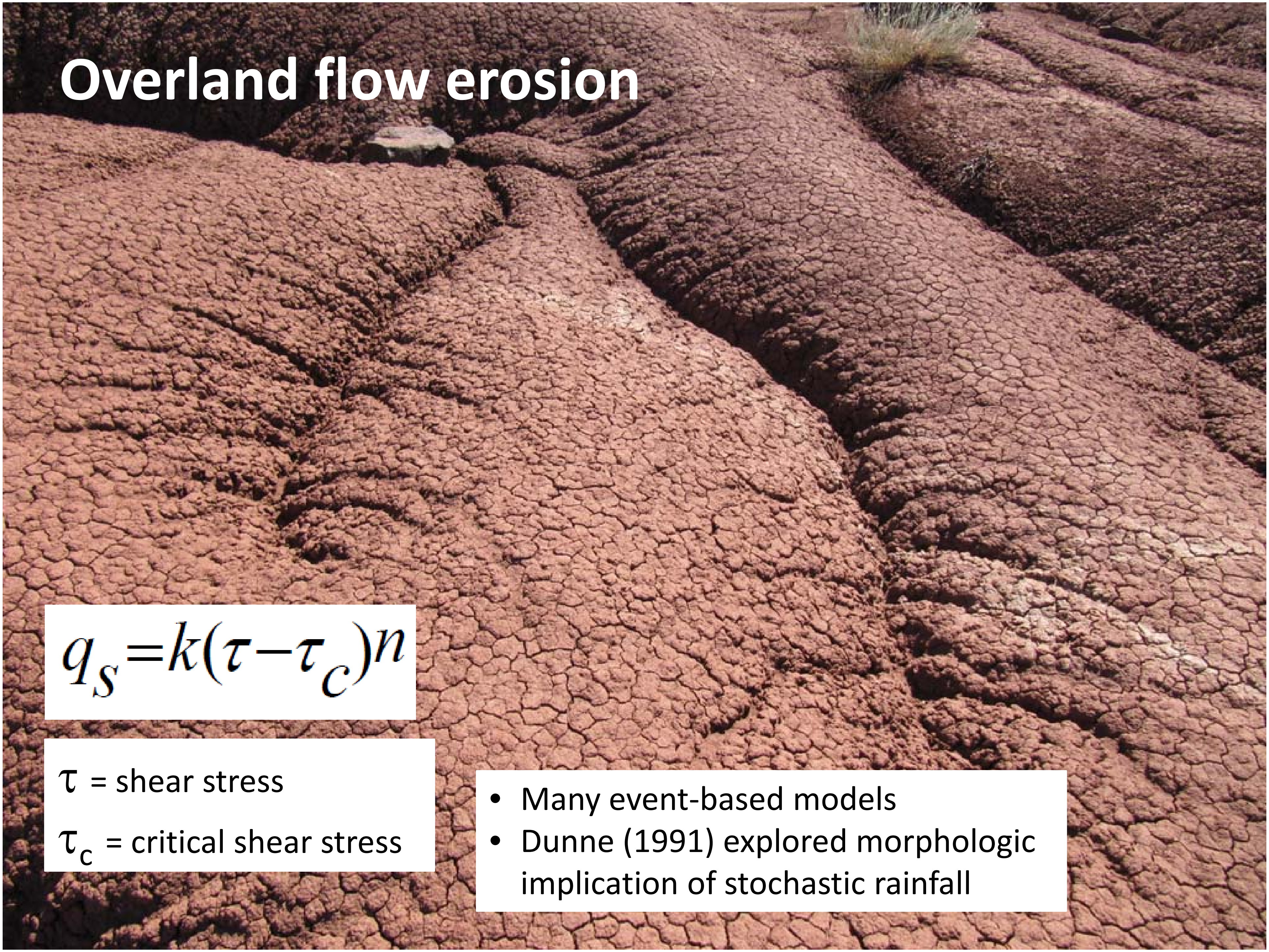
Soil creep — Earthflow transport — Gully incision

$$\frac{\partial z}{\partial t} = \frac{\rho_r}{\rho_w}U + D\frac{\partial^2 z}{\partial x^2} - \frac{a(\rho_w g)^p H^{p+2}}{p+2}\frac{\partial}{\partial x}\left(\left|\frac{\partial z}{\partial x}\right|^p\right) - K(x\Delta y)^m\left|\frac{\partial z}{\partial x}\right|^n$$



A. Booth, PhD thesis

Overland flow erosion



$$q_s = k(\tau - \tau_c)^n$$

τ = shear stress

τ_c = critical shear stress

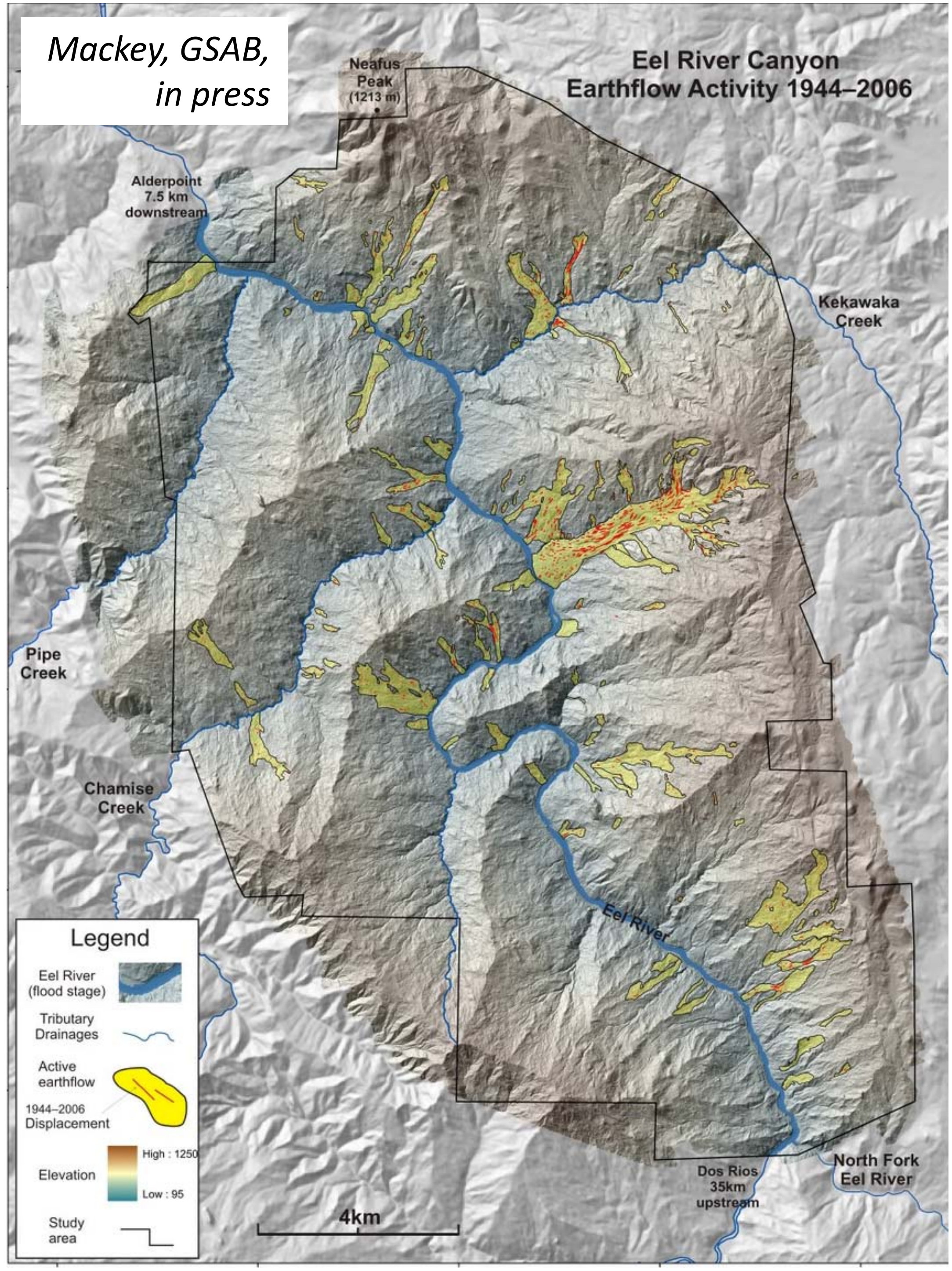
- Many event-based models
- Dunne (1991) explored morphologic implication of stochastic rainfall

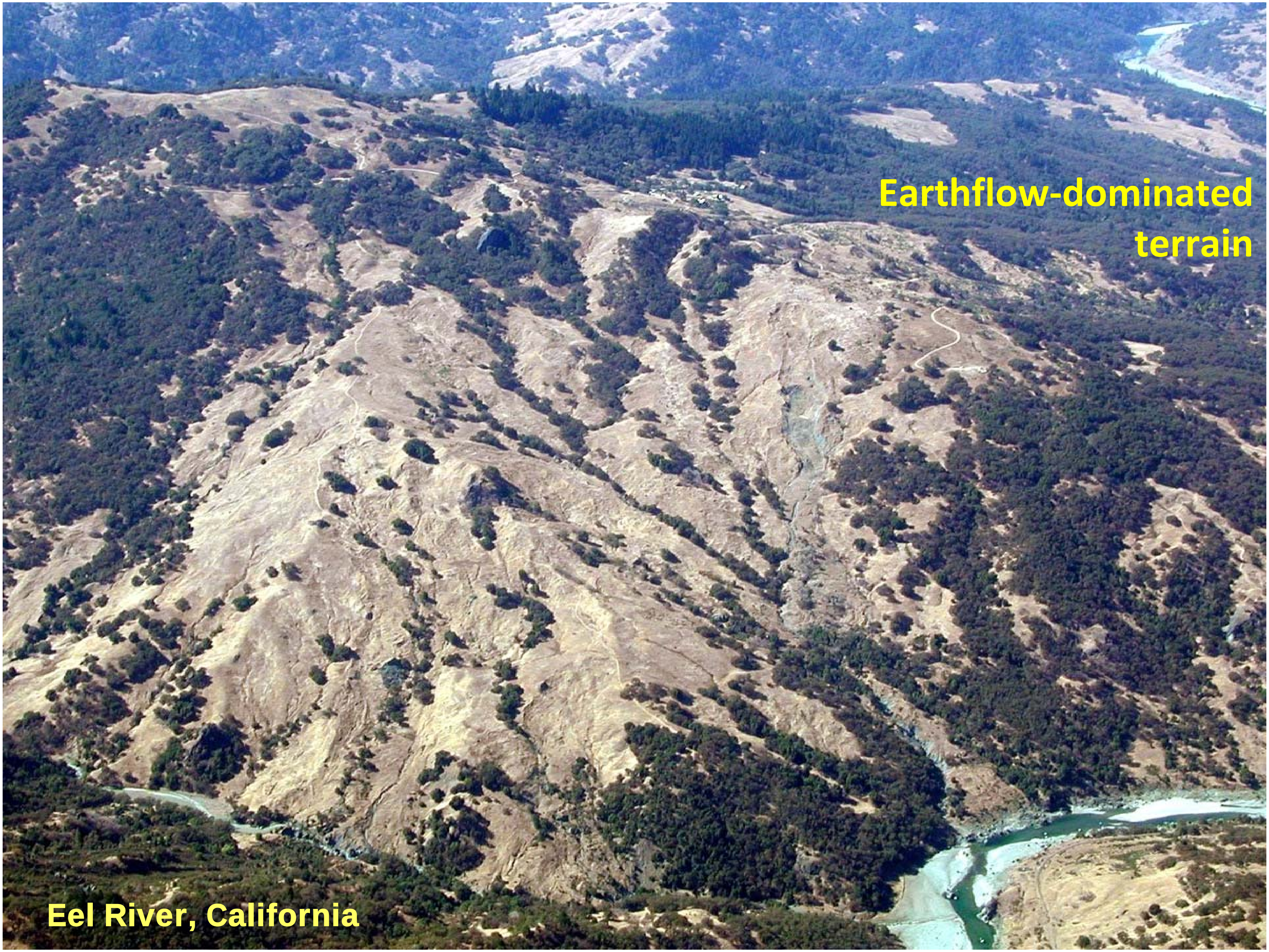
Conclusions

- When hillslopes and channels are coupled:
  - Baselevel lowering sets hillslope erosion rates
  - Climate, biology, and lithology set hillslope form, but the relationships are unknown (i.e., we can't yet use form to predict sediment yield)
- Depth-dependent soil production functions need mechanistic basis
- Models for production of landslide-prone material are unknown, but should depend on physical and chemical weathering processes (e.g., fracturing, hydrolysis, hydration)
- Nonlinear sediment transport models predict that average slope and relief become insensitive to erosion rate and have some field and morphologic evidence
- Functional relationships for how climate, biology, and lithology influence sediment flux are unknown

Real transport is stochastic
(e.g., landslides, tree throw)

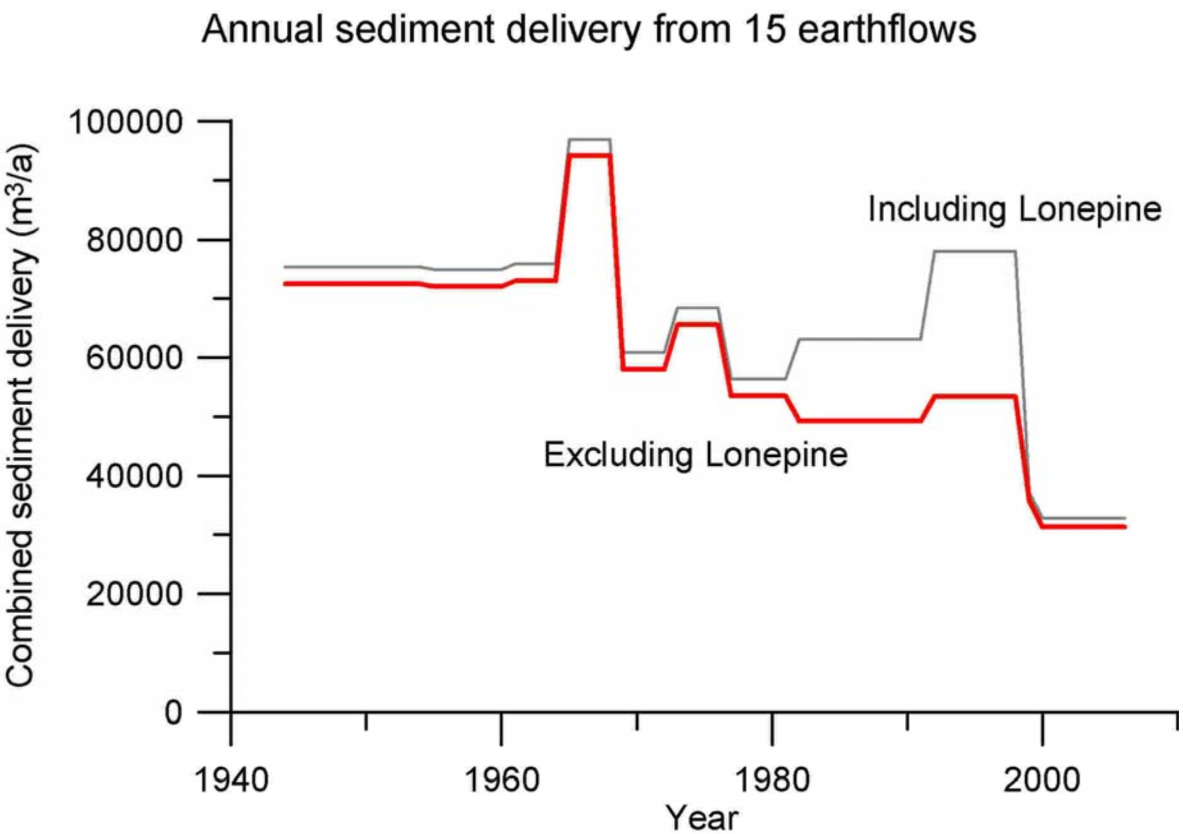
- Statistical approach
- Continuum models



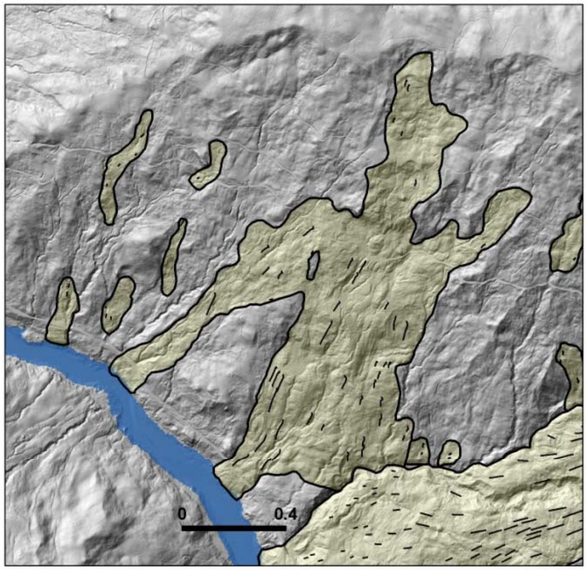

Earthflow-dominated terrain
Eel River, California

Temporal variations in sediment delivery

- Steadily decreases since 1960’s
- Lonepine slide dominates in early 1990’s



Lonepine earthflow: Active 1981-1998 b/c of railroad operations



Debris flow valley networks

In slope-area space, **debris flow networks steepen and curve** with increasing erosion rate

Theoretical and empirical evidence

Stock & Dietrich (2003, 2006)