Erosion in steady state drainage basins: an experimental approach

Les Hasbargen
Department of Earth Sciences
SUNY College at Oneonta

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Overview

- Experimental models of eroding drainage basins
- Scale issues

**Key results from experiments**

- We can develop coupled stream and hillslope systems in the lab
- We can measure process interactions and monitor dynamic behavior
- *Drainage basins exhibit intrinsic instabilities* (knickpoints, landslides, divide migration)
Drainage basins are erosional structures: an interacting system of hillslopes and channels.

Streams initially erode faster than hillslopes, which then start eroding faster to keep up with channel incision.

**Key prediction:**
at steady state, erosion is everywhere constant and $= \text{uplift}$
San Gabriel Mts., California
(DEM, view north)

5 km (appx)
San Gabriel Mts., California

1 km (aprx)
Cuyama Badlands, California

Photo by J. Shelton

1 km (appx)
Badlands, Columbia, S. America

Note bushes for scale
## Exhumation depths for rocks currently exposed at Earth’s surface

<table>
<thead>
<tr>
<th>Location</th>
<th>Lithostatic load (km)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Alps (Dora Maira)</td>
<td>10-75</td>
<td>Rubatto and Hermann (2001)</td>
</tr>
<tr>
<td>European Alps (Zermatt-Saas)</td>
<td>6-65</td>
<td>Amato et al. (1999)</td>
</tr>
<tr>
<td>Irian Jaya Indonesia</td>
<td>&gt;4</td>
<td>Weiland and Cloos (1996)</td>
</tr>
<tr>
<td>Crete Greece</td>
<td>25</td>
<td>Thomson et al. (1999)</td>
</tr>
<tr>
<td>Nepalese Himalaya</td>
<td>25</td>
<td>Harrison et al. (1997)</td>
</tr>
<tr>
<td>K2 Karakoram</td>
<td>&gt;3</td>
<td>Foster et al. (1994)</td>
</tr>
<tr>
<td>Kokchetav Kazakhstan</td>
<td>160</td>
<td>Hacker et al. (in review)</td>
</tr>
<tr>
<td>Nanga Parbat Pakistan</td>
<td>15-20</td>
<td>Zeitler et al. (2001)</td>
</tr>
<tr>
<td>Basin and Range USA</td>
<td>10-15</td>
<td>Foster and John (1999)</td>
</tr>
<tr>
<td>Denali Alaska</td>
<td>6</td>
<td>Fitzgerald et al. (1995)</td>
</tr>
<tr>
<td>Olympic Range Washington</td>
<td>9</td>
<td>Brandon et al. (1998)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Erosion rate (m/Myr)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Great Smoky Mountains, USA</td>
<td>19-37</td>
<td>Matmon et al. (2001)</td>
</tr>
<tr>
<td>Santa Monica Mountains, USA</td>
<td>500</td>
<td>Meigs et al. (1999)</td>
</tr>
</tbody>
</table>

Modeling drainage basin scale erosion

- Simplified physics approach
  - Erosion rate $\varepsilon$ depends on erosion processes (stream power, soil creep, landslides, etc) and rock resistance

- Couple erosion processes with uplift in a time evolving grid: $z_{(i,j,t+1)} = z_{(i,j,t)} + \Delta t(U_{(i,j)} - \varepsilon_{(i,j)})$

- Models successfully capture planform statistics, and area-slope relations

- Key result: At steady forcing, models evolve to a uniformly eroding (static) surface
  - Requires 1 to 3 ‘reliefs’ of erosion
Numerical model landscapes

Howard’s 1994 model

Stark and Stark, 2001; time series erosion rate following uplift rate increase.
Landscape evolution in numerical models...

- Original surface is flat with random roughness
- System is energized by lowering base level (flow leaves basin at a single point)
- Erosion Rules: water flows down the steepest slope, and erodes according to stream power
- Repeatedly rain/route water over surface (a bizzillion times!)
- Feedback between erosion and flow capture creates a dendritic pattern
- The rules above lead to a stable (i.e., static) network
Testing numerical models

- The stability achieved by models is very difficult to test in field settings
  - Requires 1-3 relief units of erosion ($H_r$) to achieve stability in numerical simulations
  - e.g., to erode 1 km relief at 1 mm/yr requires 1 Myr
  - Over this time scale, climate and tectonic forcing vary

- The Test: Will a physical model with similar simplifying assumptions achieve a stable (static) arrangement of ridges and valleys?
Erosion facility

view from digital camera

video camera
digital cameras

rainfall ($r$)
to water supply

Experimental drainage basin

relief ($H_r$)
ground surface
sliding gate ($U$)
overflow

gearbox and motor
cable to sliding gate

‘flux-o-meter’

0                       50 cm
Steady Forcing Conditions

![Graph showing water and sediment flux over runtime (s) with base level and runoff lines. The graph plots water and sediment flux (g/s) on the y-axis against runtime (s) on the x-axis.}]
Experimental drainage basins...

- Rain on the surface
- Rower the outlet at a constant rate
- Substrate erodes via surface runoff and hillslope failures!

90 cm ~ 60 hours of erosion

100 cm ~ 90 hours of erosion
Experimental erosional processes

• Surface runoff (very hard to see, but the dominant process)
• Hillslope failures
• Knickpoint development and migration
• Temporary sediment storage (deposition)
• Note: it’s difficult to prescribe *a priori* process activity…
The water-to-rock ratio \((r/u)\)

- Uplift \((u)\) and rainfall \((r)\) rates were varied between several experiments.
- Water-to-rock ratio, \(r/u\), is a convenient way to measure forcing.

\[
r = R \rho_w \quad \text{where } R \text{ is rainfall rate [L/T], } \rho_w \text{ is water density [M/L}^3\text{]}
\]

\[
u = U \rho_r \quad \text{where } U \text{ is uplift rate [L/T], } \rho_r \text{ is substrate density [M/L}^3\text{]}
\]

\[
\frac{r}{u} = \frac{R \rho_w}{U \rho_r} \quad \text{where } r/u \text{ is a dimensionless forcing parameter}
\]

- As \(r/u\) increases, surface runoff dominates erosion.
- At low \(r/u\), mass movements play a larger role.
Uplift and rainfall rates control overall topographic expression

Topographic measures vs forcing

- Average local slope
- Area-slope intercept
- Regional slope
- Valley area (a/A)
- Maximum relief (cm)
$r/u = 1$ (slope failure and runoff dominated)

- Initial surface remnant
- Slope failure
- Smooth hillslopes
- Smooth valley floor (deposition/transport/erosion)
$r/u = 6$ (runoff dominated)

deposition

crenulated ridge crests

failure and dam

terrace
\( r/u = 8 \) (runoff dominated)

- Smooth valleys
- ‘Peaky’, irregular ridge crests
- Concave hillslopes
- Knickpoint
Decaying landform, fixed base level
Low angle photo of knickpoint
Vertical photo of knickpoint incision
Sediment Storage and Excavation

Time between photos: 10 minutes (base level fall of 3 mm);
Width of view is ~30 cm; Local relief ~ 6 cm
Hillslope profile before and after a significant slump occurred. Approximately 5 minutes elapsed between the photographs. Topographic profiles were extracted from DEMs derived from stereophotogrammetry.
What’s the scale!!??

• There isn’t one…
• At least not for fluid forces
  – Re and Fr are typically used for scaling flows
  – Specifying Re and Fr uniquely sets flow velocity and depth—no scaling is possible without changing viscosity or gravity
  – However, relative strength of fluid forces are approximately satisfied by thin film flows (gravity and inertial forces dominate; viscosity less important)
What's the scale!!?? (cont.)

\[ Re = \frac{UD}{\nu} \]
Where \( U \) is velocity, \( D \) is depth
\( \nu \) is kinematic viscosity, \( g \) is gravity

\[ Fr = \frac{U}{\sqrt{gD}} \]

Reynolds number gives the ratio of inertial forces to viscous forces; large numbers imply viscous forces are not important;

*Rivers are always turbulent; thin flows can be…*

Froude number gives the ratio of inertial forces to gravity; most river flows are dominated by gravity, but can roughly balance inertial and gravitational forces

**Drainage basins have large spatial changes in fluid forces**
(flow accumulates downstream; flows vary in time)
### How do experiments scale?

*For basins of 3rd to 5th stream order...*

<table>
<thead>
<tr>
<th>Feature</th>
<th>Natural</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>length scale, $L \sim A^{1/2}$</td>
<td>$10^3 - 10^4$ m</td>
<td>$10^0$ m</td>
</tr>
<tr>
<td>relief, $H_r$</td>
<td>$10^2 - 10^3$ m</td>
<td>$10^{-1}$ m</td>
</tr>
<tr>
<td>regional slope, $H/L$</td>
<td>$10^{-1}$</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>hill slopes, $h/l$</td>
<td>$10^{-1} - 10^0$</td>
<td>$10^{-1} - 10^0$</td>
</tr>
<tr>
<td>knickpoint height, $h/H_r$</td>
<td>$10^{-5} - 10^{-1}$</td>
<td>$10^{-2} - 10^{-1}$</td>
</tr>
<tr>
<td>landslide size, $a/A$</td>
<td>$10^{-5} - 10^{-1}$</td>
<td>$10^{-3} - 10^{-1}$</td>
</tr>
<tr>
<td>ridge area, $a/A$</td>
<td>$10^{-2} - 10^{-1}$</td>
<td>$10^{-2} - 10^{-1}$</td>
</tr>
<tr>
<td>valley area, $a/A$</td>
<td>$10^{-2} - 10^{-1}$</td>
<td>$10^{-2} - 10^{-1}$</td>
</tr>
</tbody>
</table>

Note: key difference is slope, which is typically 2-3 x steeper in experimental basins
Hack’s law: Sub-basin length increases with drainage area

Niemann and Hasbargen, in prep. 2004
Area-Slope comparison

```
Slope vs Drainage area

y = -0.22x + 0.30

log (slope)

CuyamaPeak_subbasin
ReyesPkBadlands
experiment (r/u = 6)

y = -0.24x - 0.36
y = -0.25x + 0.02

log (area) (m² for USGS dems, cm² for r/u=6)
```
Experimental landscape activity: Hillslope failure distribution

Bigi et al., 2006
Experimental landscape activity: Knickpoint propagation and hillslope failures

Bigi et al., 2006
Experimental landscape activity: Sediment yield and knickpoint propagation
Measuring landscape dynamics: erosion rate variability

• Compute local erosion rates by differencing elevation grids
• Determine the variability in erosion rates as distance between surfaces increases
• **Remember: Numerical landform erosional variability is nil**
Sequential elevations, spatial erosion rates, and flow changes

Elevation, $T_i$

Large variation in erosion rates
$\pm 1.5 \, U$

Elevation $T_{i+1}$

($h/H_r = 0.3$)

Organized

Flow path change
black = flow reversal
white = same flow path
Numerical vs experimental erosion rate variability

![Graph showing coefficient of variation vs eroded relief (h/H_r)](image-url)
Divide Migration: Spatial Organization of Erosion

Relative height time series for a landscape at complete dissection

Erodes through ~3 units of relief (this took several days at continuous forcing!)
Divide Migration:

an inevitable result of erosion rate variability

\[
\frac{\Delta x}{\Delta t} = \frac{W_\alpha - W_\beta}{\tan \alpha + \tan \beta}
\]

Divide migration is a function of erosion rates on either side of the divide \((W_\alpha \text{ and } W_\beta)\), and hillslope angles \(\alpha\) and \(\beta\).

When erosion rates on either side of divide are equal, regardless of asymmetry of hillslopes, there is no migration…
Divide Migration in natural settings: Is it recognizable?

Here’s some possible characteristics

– Asymmetric ridges
  • Migratory scarps
– Long narrow perched valleys
– Organized spatial erosion rate patterns
– Sediment flux variations between adjacent sub-basins
Ridge asymmetry

Deposition

Slope failure and dam

Terrace
Imminent capture and divide migration?
Mountains near Ojai, CA
Perched drainage and headward-migrating scarp?!
Hypothesis for divide migration: positive feedback

• Migrating divide captures runoff from adjacent basin
• Increases runoff and erosion on advancing side
• Decreases runoff and erosion on the scavenged side, which
• Drives more migration

• Migrating scarps
Mechanisms for instability

– Hillslope failures: streams near capacity are locally ‘overloaded’ with sediment
  • Triggers deposition, stream slope increases, and incision ensues (knickpoint development?)

– Out of phase erosion in adjacent drainages due to knickpoint propagation

– Drainage area capture (positive feedback)
  • Occurs in numerical models as well
  • Migrating divide increases runoff to the rapidly eroding side; decreased runoff on the scavenged side
  • Increased runoff increases erosion, which drives further migration
Future Work

- Expand work with natural settings
  - Characterize form/drainage structure around actively migrating ridges
  - Surface exposure dating to determine erosion rates
- Explore physical experiments further
  - Test effects of substrate resistance on stream geometry, landscape form, and dynamics
  - Incorporate control over groundwater
  - Investigate influences of rainfall/runoff variability
  - Focus on form in various tectonic styles (tilting, folding)
- Incorporate additional processes into numerical models
  - Better treatment of deposition
  - Concentration limits in stream erosion law
The next generation of experimental basins

Liam Reinhardt and Mike Ellis recent work at U. of Memphis (ongoing at St. Anthony Falls, U of MN)
Uniform uplift at all boundaries

Figure 3. Oblique views of experiment TC18 (cf. Fig. 2). A: \(t = 240\) min. B: \(t = 480\) min. Topographies are at steady state with uplift rate of 1.5 cm/h and under high rainfall rate conditions (top: mean rainfall rate 166 ± 5 mm/h) and low rainfall rate conditions (bottom: mean rainfall rate 98 ± 7 mm/h).

Stephan Bonnet and Alain Crave, Landscape response to climate change: Insights from experimental modeling and implications for tectonic versus climatic uplift of topography, Geology; February 2003; v. 31; no. 2; p. 123–126; 4 figures.
Lateral shortening and erosion

Fig. 3. Experiment of piedmont formation in frontal convergence compared to the Tian-Shan mountain. (a) Oblique and (b) map views with structural sketch. White frame corresponds to Fig. 5. Cross-section A–B corresponds to Fig. 6. (c) Oblique and (d) map views with structural sketch of the Tekesi River flowing down to the intramontaneous Yili basin (SRTM data, NASA). Note that north is oriented downward.
Fig. 4. Pictures of morphological features in experiment and equivalents in nature from Tian Shan northern piedmont (Landsat 7 satellite images). (a,a') Alluvial fans. Note active channels and old alluvial surfaces; (b,b') channel network with sub-parallel channel patterns in piedmont drainage basins. Note alluvial surfaces and knickpoints in experiments; (c,c') stair-step fluvial terraces. Several successive levels are preserved on both sides of active channels. Topographic profiles show the vertical height of each terrace. Note downward orientation of north for satellite pictures.
Summary of behavior in experimental landscapes...

- Very noisy erosion rates at short time scales!!
  - Short term variability in erosion rate due to
    - propagating knickpoints, slope failures, temporary sediment storage

- Divide migration can impose spatially correlated erosion rate patterns on landscape

- If a small basin looks like a duck (channels and hillslopes) and walks like a duck (surface runoff erosion, landslides, knickpoints), **Is it a duck? Dynamic questions...**
Implications...

- Small drainage basins exhibit striking similarity to natural settings, suggesting a cost effective tool for process exploration and model testing.
- Terrace development, often blamed on climate change, may be intrinsic behavior.
- Knickpoint development (often attributed to changes in tectonic uplift/climate change) may be intrinsic behavior.
- Drainage realignment may persist indefinitely, so long as erosion is occurring.
- Are natural landscapes as dynamic?!!
Thanks for your attention!
Questions?