Watershed Context Tools and Techniques

Sediment Transport in Stream Assessment and Design
Tuesday, August 2, 2022
Patrick Belmont
Roadmap

YESTERDAY

Basic Reconnaissance
With a tight budget, what do you really need to know?

Watershed Sediment Budget
Tools and techniques for robust constraints on sources and sinks.
Case studies in sediment supply, transport, and morphodynamics
Basin-average erosion rates: The cosmo method
Millennial-scale landscape rates of erosion.

TODAY

Push-button Geomorphology
The geek approach. What computer models can and can’t tell you.

A bit of hydrology
Targeted modeling and metrics. Stationarity Assumption?

Reservoir and pond sedimentation rates
Time- and space-integrated measurements that may be useful.
Sediment budget: An accounting tool

"Our books are balanced. 50% of our numbers are real and 50% are made up."

\[ I - O = \Delta S \]

Over a specified time period

Inputs from watershed to channel
Output measured at channel outlet
Change in channel storage
Sediment budget: Sources and sinks with uncertainty

Typically need several different tools to constrain each of these.

Redundancy in measurements is good practice.
Four keys to constraining a budget

(1) specificity regarding location, mechanism, and rates of sediment erosion

(2) accurate treatment of changes in sediment storage

(3) redundant measurements for all sediment fluxes

(4) appropriate methods for up-scaling local observations

Smith et al., 2011
## Common techniques for developing budgets

<table>
<thead>
<tr>
<th>Technique</th>
<th>Used to Measure Erosion or Deposition</th>
<th>Watershed Elements Quantified</th>
<th>Time Scales</th>
<th>Applicable Spatial Scales</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring suspended sediment loads</td>
<td>erosion and deposition</td>
<td>watersheds and tributaries, channel reaches</td>
<td>years, decades, individual storm events</td>
<td>km</td>
<td>Milliman and Meade [1983], Parker [1988], Fitzpatrick et al. [1999], Svyatski et al. [2003], Gellis et al. [2006]</td>
</tr>
<tr>
<td>Aerial photography and LIDAR&lt;sup&gt;a&lt;/sup&gt;</td>
<td>erosion and deposition</td>
<td>stream banks, roads, land use/land cover</td>
<td>years, decades, individual storm events</td>
<td>m, km</td>
<td>Bartley et al. [2008], Keen et al. [2008], Pizuto et al. [2007], Piégay et al. [2005], Thoma et al. [2005], Gellis [2002], Evans et al. [2006], Lawler [1993]</td>
</tr>
<tr>
<td>Aerial photography&lt;sup&gt;a&lt;/sup&gt;</td>
<td>erosion</td>
<td>mass movements</td>
<td>years, decades, individual storm events</td>
<td>km</td>
<td>Wallbrink et al. [2002], Larsen and Santiago-Roman [2001], Dietrich et al. [1982]</td>
</tr>
<tr>
<td>Historical maps</td>
<td>erosion and deposition</td>
<td>channels, channel bars</td>
<td>years, decades</td>
<td>m, km</td>
<td>Kesel et al. [1992]</td>
</tr>
<tr>
<td>Erosion pins</td>
<td>erosion and deposition</td>
<td>sheetwash</td>
<td>years, days, individual storm events</td>
<td>cm, m</td>
<td>Leopold et al. [1966], Visser et al. [2007]</td>
</tr>
<tr>
<td>Field surveying, historical surveys, and inventorying</td>
<td>erosion and deposition</td>
<td>channels, gullies, channel bars</td>
<td>years, decades, individual storm events</td>
<td>m, km</td>
<td>Leopold et al. [1966], Munro et al. [2008], Marzolf and Ries [2007], Gellis et al. [2001b], Wijdenes and Bryan [2001], Kesel et al. [1992], Trimble [1983]</td>
</tr>
<tr>
<td>Radionuclides as time horizon markers&lt;sup&gt;b&lt;/sup&gt; (137Cs, 210Pb)</td>
<td>erosion and deposition</td>
<td>upslope areas of varying land use and land cover</td>
<td>decades</td>
<td>km</td>
<td>Campbell et al. [1988], Ritchie and McHenry [1990], Walling and Bradley [1990], Walling and Quine [1991], Walling and He [1999b], Nagle et al. [2000], Wallbrink et al. [2002], Walling et al. [2003b], Zapata [2002]</td>
</tr>
<tr>
<td>Radionuclides inventories&lt;sup&gt;c&lt;/sup&gt; (137Cs, 210Pb)</td>
<td>deposition</td>
<td>floodplains, lake and pond sediment</td>
<td>decades</td>
<td>km</td>
<td>Amos et al. [2009], Ritchie et al. [2004], Terry et al. [2002], Walling and He [1997b], Walling et al. [2001]</td>
</tr>
<tr>
<td>Dendrochronology</td>
<td>erosion and deposition</td>
<td>floodplains</td>
<td>decades</td>
<td>m, km</td>
<td>Allmendinger et al. [2007], Hupp and Bazemore [1993], Dietrich et al. [1982]</td>
</tr>
<tr>
<td>Clay pads</td>
<td>deposition</td>
<td>stream banks</td>
<td>years, days, individual storm events</td>
<td>m</td>
<td>Gellis et al. [2009], Hupp and Bazemore [1993]</td>
</tr>
<tr>
<td>Bank pins</td>
<td>erosion and deposition</td>
<td>stream banks</td>
<td>years, days, individual storm events</td>
<td>cm, m</td>
<td>Thorne [1981], Bartley et al. [2006], Lawler [1993]</td>
</tr>
<tr>
<td>Sediment traps</td>
<td>erosion</td>
<td>upslope areas of varying land use and land cover</td>
<td>years, days, individual storm events</td>
<td>m, km</td>
<td>Gellis et al. [2006], Larsen et al. [1999]</td>
</tr>
<tr>
<td>Resuspension cylinder sediment fingerprinting</td>
<td>deposition</td>
<td>watershed areas under varying land cover or geologic type</td>
<td>years, individual storm events</td>
<td>M</td>
<td>Lambert and Walling [1988]</td>
</tr>
<tr>
<td>Sediment models&lt;sup&gt;d&lt;/sup&gt;</td>
<td>erosion and deposition</td>
<td>channel storage, watershed areas under varying land cover or geologic type</td>
<td>years, individual storm events</td>
<td>km</td>
<td>Walling and Woodward [1995], Collins et al. [1997], Moha et al. [2003], Walling [2005]</td>
</tr>
<tr>
<td>Ponds and lakes</td>
<td>deposition</td>
<td>lake bottoms and deltas</td>
<td>decades, years</td>
<td>km</td>
<td>Leopold et al. [1966]</td>
</tr>
<tr>
<td>Sediment models&lt;sup&gt;d&lt;/sup&gt;</td>
<td>erosion and deposition</td>
<td>hillslopes, channels</td>
<td>decades, years, individual storm events</td>
<td>m, km</td>
<td>Fu et al. [2010], Evans et al. [2006], Croke and Nethery [2006], Aksoy and Kavvas [2005], Chen and Lai [2005], Merritt et al. [2003], Bhuyan et al. [2002]</td>
</tr>
</tbody>
</table>
Basic questions you want to answer

What are the grain sizes of interest?

Where do those exist in the watershed?

What geomorphic processes convey them to the channel?

Contributions from near-channel sources or hillslope/watershed sources?

Near channel:
river migration, incision, widening processes

Hillslope/watershed:
creep, rill erosion, debris flows, landslide processes

Where are erosion/deposition hotspots? Natural or human influenced?

Erosion relatively steady or pulsed?

Where are the disconnects in the sediment routing system?
Basic questions you want to answer

What are the grain sizes of interest?

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Washload

Hillslope soils

Floodplain/Terraces

Trails/Roads
Basic questions you want to answer

What are the grain sizes of interest?

Where do those exist in the watershed?

What geomorphic processes convey them to the channel?

- Bed material
  - Hillslopes
  - Trails/Roads
Sediment, nutrient problems in the upper Mississippi River

Minnesota River Basin: 336 impairments for sediment, nutrients, aquatic life

MRB is primary source of sediment and nutrients for the upper Mississippi
Corn and soybeans
The cause of the problem is obvious, right?
Artificial drainage

Minnesota River Basin (4 Mainstem, 8 Tributary Gages)

- Mean Annual Flow
- Peak Daily Flow Spring (Mar - May)
- Peak Daily Flow Summer & Fall (Jun - Nov)
- 7 Day Low Flow Summer (May - Oct)
- 7 Day Low Flow Winter (Jan - Apr & Nov - Dec)
- High Flow Days
- Extreme Flow Days

Normalized Flow

Landscape Evolution Context
Identify the landscape units...

- Uplands: flat land, passive rivers
- Knick zone: steep, highly dynamic, incising rivers
- Minnesota River Valley: rapidly aggrading channel and floodplain
13.4 ka: 60 m baselevel fall

Rapid Holocene incision in lower 40 km
Big bluffs and ravines within knickzone

Widespread agriculture began ~ 1830

Extensive artificial drainage began ~ 1950

Sediment loads increase ~ 3x in knickzone
On average, 50,000 Mg/yr
From excavation of the valley

For details on incision history, see Gran et al., 2013, GSA Bulletin
Sediment Sources and Sinks

Different measurements needed for mud vs. gravel
Many tools available...

Sediment fingerprinting

Aerial Lidar analysis

Gages galore!

Modeled Soil erosion rates

50+Field surveys

70 years of bluff erosion rates

70 years of river migration & widening

14C & OSL-Dates for incision history

4 years of terrestrial lidar
Le Sueur Sediment (mud) Budget

Sources

U: Uplands
Fp: Floodplain
Bl: Bluffs
Ba: Banks
C: Channel incision
R: Ravines

Constraints

1. Gaging data
2. Geochemical tracers
3. Aerial lidar analysis
4. Terrestrial lidar scans
5. Air photo analysis
6. Numerical modeling
7. Field surveys
8. Optically Stimulated Luminescence and $^{14}$C dating
Large shift in sediment sources

Engstrom et al., 2009; Kelley & Nater. 2000
Shift between upland and near-channel sediment sources in the Upper Mississippi Basin

Sediment Fingerprinting Results

- Mid 20th Century: Conservation reduces upland erosion, but hydrology amplifies erosion of near-channel sources...sediment loading remains high
- Mid 20th Century: Poor land management causes pulse of upland soil erosion
- Pre-settlement: primarily near-channel sources

Belmont et al., 2011
Uplands:  
Gravel contributions == negligible
Bluffs: Gravel contributions

Mostly fine-grained, but grapes, oranges, and watermelons distributed randomly
Less than 1% of till fabric
Bluffs: Gravel contributions

Bluffs capped with terraces are gravel-rich and eroding quickly.
Bluffs: Historic Air Photo Analysis

67 year bluff retreat: segregate bluffs with terraces...

70 – 90% gravel load?
Ravines: Gravel contributions

10 - 30% gravel load

2009 Gaging Stations

- ditch
- ravine
- river
Closing the budget, considering uncertainty

<table>
<thead>
<tr>
<th>Component</th>
<th>Est. Rate (Mg/yr)</th>
<th>Uncertainty (±Mg/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil creep</td>
<td>65</td>
<td>20</td>
</tr>
<tr>
<td>Debris flows</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Landslides</td>
<td>35</td>
<td>10</td>
</tr>
<tr>
<td>Channel widening</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Net floodplain deposition</td>
<td>(20)</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
<td></td>
</tr>
</tbody>
</table>

Observed load (2005-2015) = 80 Mg/yr

Budget components over-estimate by 20 Mg/yr
Basic questions you want to answer

What are the grain sizes of interest?

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What geomorphic processes convey them to the channel?

How to map the relevant landforms and measure/constrain rates?
Geomorphologic change detection from lidar

Change detection from 1m DEMs over 2000 km²

Spatially variable uncertainty

New methods to:
- Account for veg uncertainty
- Eliminate errors in legacy data

Schaffrath et al., 2015, see also Wheaton et al., 2010 and Passalacqua et al., 2015
TerEx Tool: maps terraces, measures heights
See Stout and Belmont, 2013, ESPL
Terrestrial lidar scans

Sub-cm precision annual erosion rates
Terrestrial lidar scans
Terrestrial lidar scans

See Day et al., 2013 ESPL; Wheaton et al., 2010 ESPL
Structure from Motion Photogrammetry

I. Acquire Photos

II. Build Model

III. Model Validation

2 sites monitored for 3 years

Kelly et al., 2018
SfM Photogrammetry and GCD

Use ordinary photographs and SfM software (Agisoft), to generate point clouds and derive elevation models.

Use GCD to quantify erosion and deposition from Day et al. 2013

Using daily photos, we can identify the processes that triggered each failure:

Shallow landslide triggered by heavy rains

Kelly and Belmont, 2018
I. Data Acquisition  
June (2013) 2015 – May 2017

- > 12,000 Daily Photographs
  - 20 Sites

- 7 Repeat Photograph Surveys
  - 2 Sites

- Repeat TLS Surveys
  - 17 Sites – Day et al. 2013

- USGS and MNDNR Daily Streamflow

II. Data Analysis

Failures:
- 2705 total
- 347 large (> 1 m²)
- 169 large, bluff face

1. Counted and Classified Failure Events

2. Measured Erosion:
   - SfM-MVS Workflow and GCD
   (Westoby et al. 2012; Smith et al. 2016; Wheaton et al. 2010)

3. Estimated Erosion:
   - Volume ~ Area Relation
   (Hovious et al. 1997)

4. Normalized Discharge and Computed Flow Duration Curves
SfM Geomorphic Change Detection: LS10 – 20-year flood

Net Change: 1100 m³ erosion

Flow Direction

June 17, 2014

June 18, 2014

FACE

TOE

Depth of Change (m)

Volume of Change (m³)

Erosion

Deposition

>2.5 m
Erosion

0 m
Deposition
2.5 m

Discharge (cfs)

June 2014

Sept 2016
SfM Geomorphic Change Detection: LS9 – 40-year flood

Depth of Change (m)
-9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4

Volume of Change (m³)
-160 -120 -80 -40 0 40 80 120 160

Erosion
Deposition

Net Change: 3500 m³ erosion

Flow Direction

September 20, 2016

October 4, 2016

Flow Direction

Depth of Change (m)

>2.5 m Erosion

0 m Deposition

2.5 m
Q: When and why do bluffs erode?

A: Two events accounted for:

- **LS9:**
  - June 2014: 23%
  - September 2016: 74%
  - Total: 97% of total site erosion over 3 years!

- **LS10:**
  - June 2014: 26%
  - September 2016: 53%
  - Total: 79%
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Channel and Floodplains

When are they net sources?
A) When the stream is entrenched
B) When cut bank is higher than depositing bank
C) Transient periods of channel widening

Is this stream entrenched?

Why do streams become entrenched?
Channel and Floodplains

When are they net sources?

A) When the stream is entrenched
B) When cut bank is higher than depositing bank
C) Transient periods of channel widening

Under what conditions would this happen?

Conservation of channel geometry
Measuring **difference in bank heights** and **meander migration rate**

Download NCED Planform Statistics Tool: [http://www.nced.umn.edu/content/tools-and-data](http://www.nced.umn.edu/content/tools-and-data)
Channel and Floodplains

When are they net sources?

A) When the stream is entrenched
B) When cut bank is higher than depositing bank
C) Transient periods of channel widening

\[ L_0 = L_i + \sum B_i - \sum B_o \]
Channel and Floodplains

When are they net sources?
A) When the stream is entrenched
B) When cut bank is higher than depositing bank
C) Transient periods of channel widening

![Graph showing the average width of the Le Sueur and Maple Rivers over time.](chart.png)
How to measure channel width/widening?

1. Delineate channel polygon (10+ bends).
2. Divide by channel center length.

Why would a channel widen?

Schottler et al., 2013
Historic air photo analyses: sources of error

<table>
<thead>
<tr>
<th>Factors affecting uncertainty in remotely sensed images and measurements of planform changes</th>
<th>Expected influential factors</th>
<th>Considerations</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Georeferencing uncertainty</strong></td>
<td>Image warping (camera optics)</td>
<td>Periphery of images affected relatively more than centers</td>
<td>Fryer &amp; Brown (1986)</td>
</tr>
<tr>
<td></td>
<td>Georeferenced control points</td>
<td>Hard points reduce error compared to soft points</td>
<td>Mount et al. (2003); Hughes et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>Image resolution/quality</td>
<td>Coarser resolution decreases ability to find GCPs</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Anthropogenic changes</td>
<td>Urban development changes availability of GCPs</td>
<td>Hughes et al. (2006); Donovan et al. (2015)</td>
</tr>
<tr>
<td></td>
<td>Georectification transformation</td>
<td>2nd-order polynomial is consistently the best choice</td>
<td>-</td>
</tr>
<tr>
<td><strong>Digitization (i.e., delineation) uncertainty</strong></td>
<td>Vegetation density</td>
<td>Vegetation cover reduces visibility of channel edge</td>
<td>Güneralp et al. (2013, 2014); Winterbottom (2000)</td>
</tr>
<tr>
<td></td>
<td>Shadows along river boundary</td>
<td>Shadows reduce visibility of channel edge</td>
<td>Güneralp et al. (2013, 2014)</td>
</tr>
<tr>
<td></td>
<td>Scale of image during delineation</td>
<td>Increased scale (zooming in) reduces delineation error</td>
<td>Liro et al. (2015)</td>
</tr>
<tr>
<td></td>
<td>Water level</td>
<td>Will impact which vegetated-edge boundaries are visible</td>
<td>Lauer et al. (2017)</td>
</tr>
<tr>
<td></td>
<td>Arbitrary user inconsistency</td>
<td>Users are prone to inconsistency in boundary interpretations</td>
<td>Gurnell et al. (1994); This study</td>
</tr>
<tr>
<td></td>
<td>Topographic data availability</td>
<td>High-resolution DEMs increase delineation accuracy</td>
<td>Mount et al. (2013); Donovan et al. (2015)</td>
</tr>
<tr>
<td><strong>Automated delineation/classification uncertainty</strong></td>
<td>Manual vs. [semi]automated</td>
<td>Automated approaches are generally less accurate and vary by which algorithm or software tool is used</td>
<td>Pavlesky &amp; Smith (2008); Rowland et al. (2016); Schwenk et al. (2017)</td>
</tr>
<tr>
<td></td>
<td>Channel width &amp; complexity</td>
<td>Narrow channels and highly complex bar arrangements can reduce automated classification accuracy</td>
<td>Rowland et al., (2016)</td>
</tr>
<tr>
<td><strong>Detecting changes in delineated boundaries</strong></td>
<td>Magnitude of changes</td>
<td>Larger changes more likely to exceed level of detection</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>Duration between images</td>
<td>Broader timescales span periods of greater change</td>
<td>Anders &amp; Byrnes (1991)</td>
</tr>
<tr>
<td></td>
<td>Reference datum changes</td>
<td>After adjusting images to a common datum, differences may arise due to distinct datum offsets</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>LoD threshold calculation</td>
<td>Uniform LoD thresholds erroneously reduce number (and quality)* of significant measurements</td>
<td>Lea &amp; Legleiter (2016); *This study</td>
</tr>
</tbody>
</table>
Historic air photo analyses
Spatially variable error

If you assume spatially uniform error, you probably:
- discard many reliable measurements of small magnitude
- keep some erroneous measurements of large magnitude
Sediment fingerprinting

Two types that may provide different information

Geographic: Where in the landscape?

Geomorphologic: Which landforms contributing

Gellis and Walling, 2011
Koiter et al., 2013
Belmont et al., 2014
Fingerprinting case study in Root River, SE MN

Trimble, 1999
Mostly ag, mostly unglaciated big increases in flow, big fill terraces.
Much variation in source tracer concentrations

\(^{10}\)Be: Most samples exclusively overlap with ag fields

\(^{210}\)Pb: Majority of samples are 20-50% field
Roadmap

Yesterday

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Tools and techniques for robust constraints on sources and sinks.

Case studies in sediment supply, transport, and morphodynamics

Basin-average erosion rates: The cosmo method
Millennial-scale landscape rates of erosion.

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Push-button Geomorphology
The geek approach. What computer models can and can’t tell you.

A bit of hydrology
Targeted modeling and metrics. Stationarity Assumption?

Reservoir and pond sedimentation rates
Time- and space-integrated measurements that may be useful.
Rivers change. When, where, and how?

• How do alluvial channels **adjust to changes** in flow and/or sediment supply?

• What determines the **mode & magnitude** of the response to perturbations?

• What are the implications for **floodplain inundation & evolution**?
Minnesota River Basin:
Flows have gone waayyy up
Striking differences in form and behavior along the lower 175 km of the Minnesota River
Transition in slope,

\[ S = 0.0002 \quad S = 0.0001 \]
Transition in slope, grain size,
Transition in slope, grain size, bedload transport

Bedload: 19% → 0.5% → 0.00%

Mixed bedload and suspended load

Suspended load dominated

Kelly, 2019
Transition in slope, grain size, bedload transport causes distinct differences in bar morphology...
...and big differences in process rates

Kelly, 2019
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Sixth Water ~ Diamond Fork watershed
Downstream changes in slope, valley bottom width
Sixth Water ~ Diamond Fork watershed
Big, deliberate changes in Q, Qs

Jones et al., (in prep)
A reasonably well-constrained disturbance and recovery series


1952 flood 1980s floods

Reduced augmented flows 2011 flood

Changed tunnel outlet


Jones et al., (in prep)
Oodles of info from air photos

For every photo set, for all 32 km, mapped:

- Active channel and measured width
- In-channel and bank attached bars
- Floodplain vegetation

Jones et al., (in prep)
Distinct reaches

Valley setting

Sediment regime

- Big source
- Transport
- Accumulation

Confined
Partially confined
Unconfined

Jones et al., (in prep)
Distinct response of reaches

Minimal change

Confined + source
Confined + transport
Partially confined + transport
Partially confined + accumulation
Unconfined + accumulation

Jones et al., (in prep)
Partly confined, transport reach

- Widen in response to disturbance flows when $Q_s$ is high
- Narrow in the absence of $Q_s$ pulse
- Stable width of 12 m since 2004

Jones et al., (in prep)
Unconfined, accumulation reach

Widen in response to disturbance flows

Narrowing to ~20 m during recovery time

Continued narrowing since 2004

Median width ~12 m

Jones et al., (in prep)
Valley setting and sediment regime (supply/transport capacity) exert strong control over channel response.

Across watershed, tendency towards a uniform width of ~12 m, appears to be maintained by base flows.
Rivers change. When, where, and how?

- How do alluvial channels adjust to changes in flow and/or sediment supply?

- What determines the mode & magnitude of the response to perturbations?

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Case Study:
Post-wildfire debris flows influence, and are influenced by, connectivity

Twitchell Canyon Fire
September 20th, 2010
NASA Picture of the day
Started by lightning strike

Burned 45,000 acres

1/3 burned at high severity
~ 2 m deposition!
What do we need to model this system?

- **Burn Severity**
- **Post-fire Rainfall**
- **Debris Flow Generation**
- **Sediment Inputs**
- **Sediment Routing**

Murphy et al., 2019
Predicting debris flow susceptibility

D. Bone and K. Schaffrath applied model of Cannon et al. 2010
Predicted debris flow impacts align with observations of channel change
Most debris flow sediment is NOT delivered to the main channel

Murphy et al., 2019
Normalized steepness throughout the channel network.
Normalized steepness throughout the channel network.
Where are the sediment transport ‘bottlenecks’?

Murphy et al., 2019
Minnesota River: Dynamically adjusting to increased flow and sediment supply through channel migration and widening

Spatial difference in channel form can be explained by sediment supply and transport

Sixth Water – Diamond Fork: Valley setting and sediment supply control channel response to flow/sediment disturbance events

Twitchell: Connectivity and valley bottom morphology strongly influence channel response
Roadmap

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- With a tight budget, what do you really need to know?

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- Tools and techniques for robust constraints on sources and sinks.
- Case studies in sediment supply, transport, and morphodynamics
- Basin-average erosion rates: The cosmo method
  - Millennial-scale landscape rates of erosion.

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- The geek approach. What computer models can and can’t tell you.

A bit of hydrology
- Targeted modeling and metrics. Stationarity Assumption?

Reservoir and pond sedimentation rates
- Time- and space-integrated measurements that may be useful.
Long-term, basin-average erosion rates from cosmogenic nuclides

Establish ‘background’ erosion rate for a watershed

Quantify sediment supply
($10^2$ - $10^5$ year time scale)

Quantify human-induced changes in erosion (decadal time scale)

Recent reviews:
Granger et al., 2013
von Blanckenburg and Willenbring, 2014
Dunai and Lifton, 2014
Measuring basin-average erosion rates

In a steady-state erosional environment...

TCN concentration in eroding material records the rate at which the sediment moved through the exposure window.

By ‘erosion rate’, we really mean DENUDATION RATE:

\[ D = E + W \]
Using $^{10}$Be to estimate basin-average erosion rates


Let nature do the averaging...

\[ \varepsilon(t) = \frac{PN}{\Lambda} \]

\[ t \approx \frac{\Lambda}{\varepsilon} \]

$P$ – altitude, latitude

$\Lambda$ – rock/soil density

von Blanckenburg 2005
Some profound observations about watershed-average erosion rates

Form does not translate easily to rates... tectonic uplift is the primary driver...
Some profound observations about watershed-average erosion rates

Climate does not translate easily to rates... vegetation feedbacks matter.
Long term and short term rates not always equal

Many sites where short-term rates faster than long-term.

Either or both timescales might be relevant depending on your needs.

Cosmo erosion rate database https://earth.uow.edu.au/
Roadmap

YESTERDAY

Basic Reconnaissance

With a tight budget, what do you really need to know?

Watershed Sediment Budget

Tools and techniques for robust constraints on sources and sinks.

Case studies in sediment supply, transport, and morphodynamics

Basin-average erosion rates: The cosmo method

Millennial-scale landscape rates of erosion.

TODAY

Push-button Geomorphology

The geek approach. What computer models can and can’t tell you.

A bit of hydrology

Targeted modeling and metrics. Stationarity Assumption?

Reservoir and pond sedimentation rates

Time- and space-integrated measurements that may be useful.
Oodles of watershed hydro-erosion models

For a relatively comprehensive review: Merritt et al., 2003 Env. Mod. & Soft.

See also Aksoy and Kavvas, 2005
For a useful, if uncritical, review
# Semi-quantitative models

Pacific Southwest Inter-Agency Committee (PSIAC)
See review by: De Vente and Poesen, 2005

<table>
<thead>
<tr>
<th>Factor</th>
<th>Score</th>
<th>Main characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface geology</td>
<td>0</td>
<td>(a) massive hard formations</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>(a) rock, (b) medium hardness, (c) moderately weathered</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>(a) marine shales and related mudstones and siltstone</td>
</tr>
<tr>
<td>Soils</td>
<td>0</td>
<td>(a) high percentage rock fragments, (b) aggregated clays, (c) high in organic matter</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>(a) medium texture, (b) occasional rock fragments, (c) caliche layers</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>(a) fine texture, easily dispersed, saline-alkaline, high shrink–swell characteristics, (b) single grain silts and fine sands</td>
</tr>
<tr>
<td>Climate</td>
<td>0</td>
<td>(a) humid climate with low intensity of snow, (b) precipitation in form of snow,</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>(c) arid climate with low-intensity storms, (d) arid climate with rare convective storms</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>(a) storms of moderate duration and intensity, (b) infrequent convective storms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(a) storms of several days duration with short periods of intense rainfall, (b) frequent intense convective storms, (c) freeze–thaw occurrence</td>
</tr>
<tr>
<td>Runoff</td>
<td>0</td>
<td>(a) low peak flows, (b) low volume of runoff per unit area, (c) rare runoff events</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>(a) moderate peak flows, (b) moderate volume of flow per unit area</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>(a) high peak flows, (b) large volume of flow per unit area</td>
</tr>
<tr>
<td>Topography</td>
<td>0</td>
<td>(a) gentle upland slopes (&lt;5%), (b) extensive alluvial planes</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>(a) moderate upland slopes (&lt;20%) (b) moderate floodplain development</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>(a) steep upland slopes (&gt;30%), high relief, little or no floodplain development</td>
</tr>
<tr>
<td>Ground cover</td>
<td>-10</td>
<td>(a) completely protected by vegetation, rock fragments, litter; little opportunity for rainfall to reach erodible material</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>(a) cover &lt;40%; noticeable litter, (b) if trees present understory not well developed</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>(a) ground cover &lt;20%, vegetation sparse, little or no litter, (b) no rock in surface soil</td>
</tr>
<tr>
<td>Land use</td>
<td>-10</td>
<td>(a) no cultivation, (b) no recent logging, (c) low-intensity grazing</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>(a) &lt;25% cultivated, (b) 50% or less recently logged, (c) &lt;50% intensively grazed, (d) ordinary road and other construction</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>(a) &gt;50% cultivated, (b) almost all of the area intensively grazed, (c) all of area recently burned</td>
</tr>
<tr>
<td>Upland erosion</td>
<td>0</td>
<td>(a) no apparent signs of erosion</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>(a) about 25% of the area characterised by rill and gully or landslide erosion, (b) wind erosion with deposition in stream channels</td>
</tr>
<tr>
<td>Channel erosion and sediment transport</td>
<td>0</td>
<td>(a) &gt;50% of the area characterised by rill and gully or landslide erosion</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>(a) wide shallow channels with flat gradients, short flow duration (b) channels in massive rock, large boulders or well vegetated, (c) artificially controlled channels</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>(a) moderate flow depths medium flow duration with occasionally eroding banks or bed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(a) eroding banks continuously or at frequent intervals with large depths and long flow duration, (b) active headcuts and degradation in tributary channels</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>After summation of the individual scores, the total index class can be determined and translated into an estimated sediment yield</th>
<th>Index class</th>
<th>Estimated sediment yield ranges (t/km²/year) (For the Pacific Southwest USA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;100</td>
<td>&gt;1830</td>
<td></td>
</tr>
<tr>
<td>75–100</td>
<td>610–1830</td>
<td></td>
</tr>
<tr>
<td>50–75</td>
<td>300–610</td>
<td></td>
</tr>
<tr>
<td>25–50</td>
<td>120–300</td>
<td></td>
</tr>
<tr>
<td>0–25</td>
<td>&lt;120</td>
<td></td>
</tr>
</tbody>
</table>
Semi-quantitative models
Factorial Scoring Model (FSM)
Verstraeten et al., 2003

SSY = 4139*A^{-0.44} + 7.77*FSMIndex − 310.99

Must be calibrated to a particular landscape

Common critique: these evaluations may be more likely to reinforce pre-conceptions than provide new, objective insight
Push-button Geomorphology
USLE: Universal Soil Loss Equation

Predicts long-term average erosion (of fine sediment) from sheet or rill erosion
NOTE: does not account for gully, wind, or tillage erosion

Developed in 1940s – 60s for Corn Belt using empirical data

Typically applied to agricultural and construction sites

Calibrated with 10,000 plot-years of runoff and erosion measurements from 49 locations
USLE: Universal Soil Loss Equation

\[ A = R \times K \times LS \times C \times P \]

- **A** = long-term soil loss (t/ac)
- **R** = rainfall and runoff factor (geographic location)
  - curve number, greater intensity, duration \( \rightarrow \) higher \( R \)
- **K** = standardized soil erodibility factor (t/ac)
  - \( = f \) (texture, structure, permeability, OM)
- **LS** = slope length factor
  - steeper, longer slopes more prone to erosion
- **C** = crop/vegetation and management factor
  - compares field to standard, fallow, untilled field
- **P** = support management practices
  - attempts to quantify effect of BMPs
RUSLE: Revised USLE

\[ A = R \times K \times LS \times C \times P \]

\( A = \) long-term soil loss (t/ac)

\( R = \) rainfall and runoff factor (geographic location)

\( K = \) standardized soil erodibility factor (t/ac)
  - new maps, time varying-erodibility

\( LS = \) slope length factor
  - new approach to computing sensitivity to gradient and length

\( C = \) crop/vegetation and management factor
  - new approach for evaluating sensitivity

\( P = \) support management practices
  - new conservation practices incorporated
RUSLE2: Revised USLE (again)

\[ A = R \times K \times LS \times C \times P \]

new Graphical User Interface (GUI)
several updates to equations and maps
attempts to account for deposition and sediment delivery ratio implicitly using concavity/convexity of landscape
doesn’t allow for dynamic vegetation, but differentiates between canopy and ground cover
distribution of live and dead roots
soil moisture
MUSLE: Modified USLE

\[ A = 11.8 (Q_{\text{surf}} \times q_{\text{peak}} \times \text{area}_{\text{hru}})^{0.56} \times K \times LS \times C \times P \times \text{CFRG} \]

An empirical attempt to account for detachment and transport

\[ Q_{\text{surf}} = \text{runoff volume (mm/d)} \]
\[ q_{\text{peak}} = \text{peak runoff rate (m}^3/\text{s)} \]
\[ \text{area}_{\text{hru}} = \text{area of hydro response unit} \]

Coarse fragment factor
\[ = e^{-0.053r} \]
\[ r \text{ is } \% \text{ rock in first soil layer} \]
Push-button Geomorphology

**SWAT**

* Common Limitations:
  - No basis to distinguish terrestrial vs channel sources: problem for calibration
  - Flow and sediment routing mechanisms are primitive
  - Hydrology run with curve number or Green-Ampt Infiltration Equation

**WEPP**

Useful at small scale to obtain relative sensitivity of terrestrial sediment sources

Common Limitations:

No basis to distinguish terrestrial vs channel sources: problem for calibration
Flow and sediment routing mechanisms are primitive
Hydrology run with curve number or Green-Ampt Infiltration Equation

Lots of knobs to turn, users limited in ability to identify problematic variables
The Sediment Delivery Problem

Walling, 1983

de Vente et al., 2007
TopoFilter: Where does sediment come from?
Se Jong Cho, Peter Wilcock

Goal: use USLE to predict local soil erosion rates and a DEM to account for the topographic effect on sediment storage, to map the primary sources of eroded sediment that reaches the watershed outlet.
TopoFilter: Where does sediment come from?
Se Jong Cho, Peter Wilcock

1. A simple topographic relation

\[
\frac{\partial x}{\partial y} = f \left( x, \frac{\partial x}{\partial y} \right) = \exp \left( \frac{\partial x}{\partial y} \right) \times y
\]

\[
\frac{\partial y}{\partial x} = f \left( x, \frac{\partial y}{\partial x} \right) = \exp \left( \frac{\partial y}{\partial x} \right) \times x
\]

2. Run 10,000 simulations using values of \( a_1, a_2, b_1, b_2 \) drawn randomly from a uniform distribution.

3. Narrow the range for each parameter \( a_1, a_2, b_1, b_2 \) by eliminating portions that never produce an adequate fit to the observed total sediment delivery. This is called ‘conditioning’.

4. Sediment Delivery \( SD \) from 10,000 simulations. The median (3,445 Mg) is close to the observed (3,252 Mg).

5. Do we believe that any of these 10,000 simulations (combinations of \( a_1, a_2, b_1, b_2 \)) are correct? No way!

But we note that some locations just about always contribute the most sediment.

Map shows locations that contribute to 90% of the sediment delivery in 95% (red), 75% (red + green) and 50% (red + green + blue) of the simulations.

area = 335 sq.km
Push-button Geomorphology

SedMAP: Effects of hydrologic connectivity on delivery of coarse material

Reid et al., 2007

See also: sednet.org
Roadmap

**YESTERDAY**

- Forget rates. What can we learn from basic form-process relationships?
- Basic Reconnaissance
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- Push-button Geomorphology
  - The geek approach. What computer models can and can’t tell you.
- A bit of hydrology
  - Targeted modeling and metrics. Stationarity Assumption?
- Reservoir and pond sedimentation rates
  - Time- and space-integrated measurements that may be useful.
Have key hydrologic fluxes changed systematically?
What are the implications?

Hydrology matters...
Excellent perspective on the frontier of hydrologic modeling


Hydro-erosion models: if you’re going to use them, make sure they are calibrated for the relevant flows.
Have flows changed?

Lytle and Poff, 2004
A basic lexicon of flow regime characteristics

- **Magnitude:** the amount of water moving past a fixed location per unit time. The larger (or smaller) the magnitude of a flood (or drought), the greater the expected physical impact.

- **Frequency:** the number of events of a given magnitude per time interval (e.g. per year). For a given river or stream, frequency is typically related inversely to magnitude.

- **Duration:** the period of time associated with a particular flow event. Expressed in terms of number of days a flood or drought lasts.

- **Timing:** the date during the year that flood or drought occurs, often derived from long-term flow records.

- **Predictability:** the degree to which flood or drought events are autocorrelated temporally, typically on an annual cycle. Predictable events might also be correlated with other environmental signals (e.g. rainfall events, seasonal thermal extremes, sudden increases or decreases in flow).

Lytle and Poff, 2004
Flow Duration Curves?
Organizing ‘chaos’... Flow Duration Curves

Minnesota River: daily averaged flows
Illustrating shifts in FDCs

Lauer et al., 2017
Changes (or not) in Flow Duration Curves

1. Sort big to small
2. Rank \((m)\) from 1 to \(n\)
3. Compute \(EP = \frac{m}{(n+1)}\)

Most geomorphic work is done by these flows.
FDCs: Choose your axes carefully
R package for automated download of USGS flow data
basic streamflow metric analysis & plots

Using R in hydrology: a review of recent developments and future directions
Louise J. Slater¹, Guillaume Thirel², Shaun Harrigan³, Olivier Delaigue², Alexander Hurley⁴, Abdou Khouakhi⁵, Ilaria Prosdocimi⁶, Claudia Vitolo³, and Katie Smith⁷

Precompiled binary distributions of the base system and contributed packages. Windows and Mac users most likely want one of these versions of R:

- Download R for Linux
- Download R for (Mac) OS X
- Download R for Windows

R is part of many Linux distributions, you should check with your Linux package management system in addition to the link above.

Source Code for all Platforms

Windows and Mac users most likely want to download the precompiled binaries listed in the upper box, not the source code. The sources have to be compiled before you can use them. If you do not know what this means, you probably do not want to do it!

- The latest release (Thursday 2016-03-10, Very Secure Dishes) R-3.2.4.tar.gz: read what's new in the latest version.
- Sources of R alpha and beta releases (daily snapshots, created only in time periods before a planned release).
Flood frequency analysis?
Flood frequency analysis

\[ P = \frac{1}{T} \]

\( T \) = Return Period or Recurrence Interval

\( P \) = Probability of Exceedance

\[ \log Q_T = \mu_{\log Q} + K_T \sigma_{\log Q} \]

\( Q_T \) = Discharge you are computing

\( \mu_{\log Q} \) = Mean of the log transformed annual peak flow series

\( \sigma_{\log Q} \) = Standard deviation of the log transformed annual peak flow series

\( K_T \) = Frequency factor (from table, = f (skew and return period)

\[ Q_T = 10^{\log Q_T} \]

See flood frequency document distributed with electronic course materials for a detailed explanation of probability and statistics that go into flood frequency analysis.
FDC and FF spreadsheet

Alternative flood frequency tools

USGS Peak FQ Program
http://water.usgs.gov/software/PeakFQ/

USDA Flood Frequency Calculation
http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/?&cid=stelprdb1042910
Frequencies of hydrologic phenomena (e.g., precipitation, streamflow) can be represented by a time-invariant PDF that can be estimated from historic record.

These PDFs provide the basis for evaluation of risks to water supplies, floodplain development, infrastructure.

Hornberger, 1998
The **stationarity assumption** in hydrology

In some places, these PDFs are **systematically changing**

Non-stationary conditions

---

Hornberger, 1998
Atmospheric Moisture

Interception Storage

Surface Storage

Unsaturated Zone Storage

Saturated Zone Groundwater Storage

Channel Storage

Plant Storage

transpiration

evaporation

stemflow, canopy drip

infiltration

percolation

plant uptake

climate non-stationarity

land use non-stationarity

outlet

rain, snow, condensation

evaporation

surface runoff

sub-surface runoff

seepage

seepage

plant uptake

water flow directions and processes in a hydrological cycle.
Stuck on stationarity?

Standard practice for predicting flood frequency/magnitude assumes stationarity (Interagency, 1982)

Review of techniques to adjust for non-stationarity provided by Gilroy & McCuen (2012)
Finding Hydrologic Data

Precipitation:
PRISM
http://www.prism.oregonstate.edu/

NOAA: Frequency Duration Data
http://hdsc.nws.noaa.gov/hdsc/pfds/

NOAA: NNDC data
http://www7.ncdc.noaa.gov/CDO/dataproduct

NRCS: Snotel
http://www.wcc.nrcs.usda.gov/snow/

NRCS: SCAN
http://www.wcc.nrcs.usda.gov/scan/

Streamflow:
USGS: Water Watch
http://waterwatch.usgs.gov/

USGS: NWIS
http://waterdata.usgs.gov/nwis

Many state agencies, consortiums

Groundwater:
USGS: NWIS
http://waterdata.usgs.gov/nwis/gw

Soil Moisture:
NWS: CPC
http://www.cpc.ncep.noaa.gov/soilmst/w.shtml
Roadmap

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  - The geek approach. What computer models can and can’t tell you.
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- Reservoir and pond sedimentation rates
  - Time- and space-integrated measurements that may be useful.
Small water bodies distributed throughout US
2-9 million ponds < $10^4$ m$^2$

Relevant because reservoirs/ponds may:
1. serve as sediment traps
2. be useful for estimating space- and time-integrated sediment yields

Humans have simultaneously:
*Increased* sediment transport by global rivers by $2.3 \pm 0.6$ B Mg/yr via soil erosion, and
*Decreased* delivery to global oceans by $1.4 \pm 0.3$ B Mg/yr via retention within reservoirs
-Syvitski et al., 2007
Global Reservoir and Dam (GRanD) Database

http://globaldamwatch.org/grand/

Lehner et al., 2011

7320 reservoirs
# Reservoir Sedimentation Survey Information

**System (RESIS, now RESSED)**

- **Approximately 7,000 surveys for 2,194 reservoirs**

---

**Table: REServoir SEDimentation DATA SUMMARY**

<table>
<thead>
<tr>
<th>1. OWNER</th>
<th>Weber River Water Users/</th>
<th>2. RIVER</th>
<th>Weber</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. SEC. TWP.</td>
<td>30</td>
<td>RANGE</td>
<td>3N</td>
</tr>
<tr>
<td>5. NEAREST TOWN</td>
<td>Echo &amp; Coalville</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. COUNTY</td>
<td>Summit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. STREAM BED ELEV.</td>
<td>5450</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. TOP OF DAM ELEV.</td>
<td>5770</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. SPILLWAY CREST ELEV.</td>
<td>5560</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. STORAGE ALLOCATION</td>
<td>11. ELEVATION TOP OF POOL.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. SURFACE AREA ACRES</td>
<td>13. STORAGE ACRE- FEET</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14. ACCUMULATED ACRE- FEET</td>
<td>15. DATE STORAGE TOOK PLACE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16. DATE NORMAL OPER. TOOK PLACE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17. LENGTH OF RESERVOIR</td>
<td>18. TOTAL DRAINAGE AREA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19. NET SEDIMENT CONTRIBUTING AREA</td>
<td>20. LENGTH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21. MAX. ELEV.</td>
<td>22. MEAN ANNUAL PRECIPITATION</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23. MEAN ANNUAL RUNOFF</td>
<td>24. MEAN ANNUAL RUNOFF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25. CLIMATIC CLASSIFICATION</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DATE OF SURVEY</th>
<th>PERIOD ACCL. YEARS</th>
<th>TYPE OF SURVEY</th>
<th>NO. OF RANGES OR CONTOUR INT.</th>
<th>SURFACE AREA ACRES</th>
<th>CAPACITY ACRE- FEET</th>
<th>% RATIO AC-F. PER SQ. MI.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 1930</td>
<td>24.0</td>
<td>24.0</td>
<td>R</td>
<td>1,470</td>
<td>75,718</td>
<td>103</td>
</tr>
<tr>
<td>Oct. 1954</td>
<td>24.0</td>
<td>24.0</td>
<td>R</td>
<td>1,470</td>
<td>75,718</td>
<td>101</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DATE OF SURVEY</th>
<th>PERIOD ANNUAL PRECIPITATION</th>
<th>PERIOD WATER INFLOW ACRE- FEET</th>
<th>WATER INF. TO DATE ACRE- FEET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 1954</td>
<td>14.5 - 35</td>
<td>203,125</td>
<td>203,125</td>
</tr>
<tr>
<td></td>
<td>415,700</td>
<td>4,875,000</td>
<td>4,875,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DATE OF SURVEY</th>
<th>PERIOD SEDIMENT DEPOSITS ACRE- FEET</th>
<th>TOTAL SED. DEPOSITS TO DATE ACRE- FEET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 1954</td>
<td>1818</td>
<td>1818</td>
</tr>
</tbody>
</table>

**Diagram:**

- 1950
- 2000

- Graph showing reservoir data.
Estimating trapping efficiency of reservoirs

\[ TE = \frac{S_{in} - S_{out}}{S_{in}} = \frac{S_{set}}{S_{in}} \]

- \( S_{in} \) = sediment mass entering a reservoir
- \( S_{out} \) = sediment mass leaving a reservoir
- \( S_{set} \) = sediment mass deposited within the reservoir

Controls on TE:
Particle size distribution of \( S_{in} \) relative to water retention time

Retention time depends on:
1) characteristics of inflow hydrograph and
2) geometric characteristics, including storage capacity, shape and outlet type

See review by Verstraeten and Poesen, 2000
Spreadsheet model: Minear and Kondolf, 2009
Controls on reservoir trapping efficiency

**Trap Efficiency**
fraction of incoming sediment particles trapped in the pond

**Settling Velocity**
of sediment particles

**Incoming Sediment Characteristics**
- particle size distribution
  - controls the settling velocity
  - flocculation
    - controls the particle size distribution

**Retention Time**
of runoff and sediment particles

**Inflow Characteristics**
- runoff volume
- peak discharge
- base flow

**Pond Characteristics**
- pond typology:
  - dry pond
  - semi-dry
  - permanently ponded
- surface area
- stage-area relation
- shape
- outlet dimension
- outlet type
- location of the outlet
- initial storage volume
- property of the bottom surface:
  - vegetated; not vegetated
  - stiffness and height of vegetation

Verstraeten and Poesen 2000
Empirical techniques for estimating TE

\[ TE = 100 \left( 1 - \frac{1}{1 + 0.0021D \frac{C}{W}} \right) \]

- **C**: reservoir storage capacity in \( m^3 \)
- **W**: watershed area in \( km^2 \)
- **D**: empirical form factor (range 0.046 – 1)

Brown (1943)
Cumulative effects of many dams?

Full buildout (133 dams)

Full buildout minus mainstem dams

Kondolf et al., 2013, using 3W adaptation of Brune, 1953
Quasi-physical techniques for estimating TE

Ward et al., 1980: for ephemeral flow-through ponds

\[
TE = 91.5 + 13.2 \frac{S}{Q} + 1.9(P_{20} - P_5) \left(\frac{T_D}{T_S}\right) - 1.4 \left(\frac{q_e}{q_i}\right)^{0.3} P_{20}
\]  

where:

- $S$ is the pond capacity up to the riser crest (m$^3$);
- $Q$ is the inflow volume (m$^3$);
- $P_{20}$ and $P_5$ are the percentage finer than 20 $\mu$m and 5 $\mu$m, respectively, at peak inflow rate;
- $T_D$ is detention time (h);
- $T_S$ is storm duration (h);
- $q_e$ is peak outflow rate (m$^3$/s); and
- $q_i$ is peak inflow rate (m$^3$/s).

Ward et al., 1980: for perennial ponds with baseflow

\[
TE = 93.1 + 27.6 \frac{S}{Q} + 0.046(P_{20} - P_5) \left(\frac{T_D}{T_S}\right) - 1.4 \left(\frac{q_e}{q_i}\right)^{0.3}
\]

Lewis et al., 2013 adapted Brune (1953) and Churchill (1948) for tropical rivers with high flow CV
Some take-away points:


2. Be a geek, it’s okay. Appropriate models, thoughtfully applied, can provide useful info. But be aware of (and transparent about) the simplifications and uncertainties in your model.

3. Cosmogenic nuclides measure long-term erosion rates and can be used to quantify erosion integrated over millennial timescales. Lots of existing data, use it!

4. Reservoirs may contain useful sedimentation records. Much data available, but may require additional analysis.