Sediment Budget and Hydrology

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Provo, Utah

http://i.infopls.com/images/states_imgmap.gif
Units in this Section

1. Introduction
2. Overview of soil loss and erosion
3. Components of the sediment budget
4. Estimating or measuring each component
5. Land use impacts on sediment budget
6. River transport of sediments
7. Measuring transported sediments
8. Making the sediment budget
9. Measuring streamflow discharge rates
Objective

• Help you learn specific steps you can take to calculate a sediment budget for watersheds in your country, or for a river at a national boundary
1. Introduction

• What is a sediment budget?
• Budgets have
  – Inflows (income)
  – Outflows (payments)
  – Storage (savings or unpaid bills)
• We will apply this to sediment
  – Consider sediment mass
  – Mass has units of
    • Metric tons (tonnes)
    • kg
Conservation of Mass Equation

\[ 0 = \frac{\partial}{\partial t} \iiint \rho \, d\mathbb{V} + \iint \vec{V} \cdot \vec{n} \, dA \]

Where

- \( t \) = time
- \( \rho \) = density
- \( \mathbb{V} \) = volume
- \( \vec{V} \) = velocity vector
- \( \vec{n} \) = unit normal vector
- \( A \) = area
Meaning of Equation

• \( 0 = \frac{\partial}{\partial t} \iiint \rho \, d\mathcal{V} + \iint \mathbf{V} \cdot \mathbf{n} \, dA \)

• \( 0 = \text{change of sediment in C.V} + \text{Outflow} - \text{Inflow} \)

1. Introduction
Applied to a Watershed

\[ 0 = \text{change of sediment in C.V} + \text{Outflow} - \text{Inflow} \]

Negative: loss

http://www.raritanbasin.org/Pictures/watershed.jpg

1. Introduction
No Sediment Added?

- Considers watershed from divide to mouth
- **POSSIBLE** sources outside the ‘control volume’
  - Dust deposition
    [Image](http://www.crh.noaa.gov/ddc/swaw/glddust.JPG)
  - Ash deposition
    [Image](http://www.thorvaldseyri.is/skrar/image/Frettir/oskubylur.JPG)
  - Tectonic uplift
    [Image](http://www.conjugatemargins.com/images/Source_to_Sink.jpg)

1. Introduction
Applied to Subwatersheds

- Each colored area is its own watershed
- Now “0 = change of sediment in C.V + Outflow – Inflow” has changed
  - Outflow from upstream is equal to inflow to downstream
- What if each colored area were a country?

http://www.munuscongwatershed.org/media/pages/subwatersheds_1.jpg

1. Introduction
2. Overview of Soil Loss and Erosion

• It all begins with soil in the watershed
• Processes (budget later)
  1. rainfall splash
  2. freeze/thaw
  3. overland flow
  4. landslides
  5. mechanical movement

These 3 combined for soil erosion budget
Rainfall Splash

• Rainfall detaches soil
• Function of
  – Soil strength
  – Rainfall intensity
    • Location on planet
    • Time of year
    • What other factors?

2. Overview of Soil Loss and Erosion
Freeze/Thaw

• Expansion upon freezing
• Can “cryoturbate” soil
• Makes more susceptible to erosion
• Can be a significant factor

2. Overview of Soil Loss and Erosion
Overland Flow

- “Rill” can be plowed over
- “Gully” cannot be plowed over
- Not restricted to agricultural lands

http://soilerosion.net/image/hillslope_rills.jpg

http://www.teara.govt.nz/files/p19790pc.jpg

2. Overview of Soil Loss and Erosion
Landslide Input

- Can be massive
- Function of
  - Geology
  - Land use history
  - Precipitation


2. Overview of Soil Loss and Erosion
Mechanical Movement

- Mechanical push into stream
- Often done during
  - Mining
  - Logging
  - Other watershed disturbance

2. Overview of Soil Loss and Erosion

http://upload.wikimedia.org/wikipedia/commons/d/dc/Mining_Debris_in_Cwm_Nant_lago_-_geograph.org.uk_-_300633.jpg
3. Components of the Sediment Budget

1. Dust deposition/scour
2. Soil erosion: combine
   1. Rainfall detachment
   2. Freeze/thaw
   3. Overland flow
3. Landslides
4. Mechanical Movement
5. Streambank erosion
6. Reservoirs associated with dams
7. Tributary input
Dust Deposition/Scour

- Deposition is input to watershed
- Scour and transport by air is loss from watershed
- Usually very long term process

3. Sediment Budget Components
Soil Erosion

- We’ve already reviewed *processes*
- Soil erosion budget includes
  - Rainfall detachment
  - Freeze/thaw
  - Overland flow
- Important: Erosion vs. Delivery
  - *Erosion*: loss of soil from its *Delivery*: that portion of soil loss that is delivered to a stream or river
- Sediment delivery ratio (SDR): delivered/eroded
- SDR primarily a function of watershed size

3. Sediment Budget Components
Soil Erosion and SDR

- A LOT of soil is stored in the watershed!
- Where?
  - Floodplains
  - Flatter areas
- Careful when calculating budget

3. Sediment Budget Components

<table>
<thead>
<tr>
<th>Drainage Area (Square Miles)</th>
<th>Sediment Delivery Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.33</td>
</tr>
<tr>
<td>1.0</td>
<td>0.30</td>
</tr>
<tr>
<td>5.0</td>
<td>0.22</td>
</tr>
<tr>
<td>10.0</td>
<td>0.18</td>
</tr>
<tr>
<td>50.0</td>
<td>0.12</td>
</tr>
<tr>
<td>100.0</td>
<td>0.10</td>
</tr>
<tr>
<td>200.0</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Landslides and Mechanical Movement

- Part of erosion and soil loss, but
- Separate budget items because processes are fundamentally different
Streambank Erosion

http://www.cws.bse.vt.edu/images/sized/images/upload/s/Pic_2__streambank_erosion-440x230.jpg

http://www.crwr.utexas.edu/gis/gishydro03/Classroom/trmproj/Lancaster/AustinErosion_files/image002.jpg

3. Sediment Budget Components
Streambank Erosion

- 37% of the total load in River Ouse, Yorkshire, UK
- 50% in Midwestern streams, USA
- 78% in the Gowrie Creek, Australia
- 80% in the loess area of Midwest USA
- Up to 92% in Gelbaek stream, Denmark
- From Yong Lai, U.S. Bureau of Reclamation who has sources for each example

3. Sediment Budget Components
Reservoirs Associated with Dams

- Reservoirs are sinks within a watershed
- Sediment stored in reservoir
- May or may not be released
- Matilija Dam, CA
  - Being removed
  - Sink becomes a source

3. Sediment Budget Components

http://www.usbr.gov/pmts/sediment/projects/Matilija/images/ReservoirDelta.png
Tributary Input

• Confluence of Ohio River and Mississippi Rivers, USA
• One carries more sediment than the other


3. Sediment Budget Components
## 4. Estimating or Measuring Each Component: Summary

<table>
<thead>
<tr>
<th>Component</th>
<th>How Estimated/Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust deposition/scour</td>
<td>Floodplain excavation; anecdotal evidence</td>
</tr>
<tr>
<td>Soil erosion</td>
<td>Several components: section 2 for components</td>
</tr>
<tr>
<td>Streambank erosion</td>
<td>Field surveys and aerial mapping</td>
</tr>
<tr>
<td>Landslides</td>
<td>Aerial photography and survey</td>
</tr>
<tr>
<td>Mechanical movement</td>
<td>Field survey</td>
</tr>
<tr>
<td>Reservoir sedimentation</td>
<td>Reservoir sediment surveys</td>
</tr>
<tr>
<td>Tributary input</td>
<td>Riverine measures of sediment transport</td>
</tr>
</tbody>
</table>
Estimating/Measuring Dust

• Time scale: centuries or more
• Floodplain excavation
• Stratigraphic analysis
• Example: London, England
Observed at a Global Scale: from Des Walling

Sediment yield

50 100 250 500 750 1000

Deserts and permanent ice
Predicted at a Global Scale

• Pixel-by-pixel computer modeling using GIS tools at a very large scale
• Predicts the kind of charts that Walling produced from observed data
Modeled Sediment Yield
1/(sediment delivery ratio)
Estimating/Measuring Soil Erosion – Local Scale

- Does not include landslides or mechanical movement
- Simplest: nails in a board
- Harder: measure from plots

Estimating Soil Erosion

• Based upon many plot experiments
• **Universal Soil Loss Equation (USLE)**

\[ A = RKLSCP \]

where
- \( A \) = soil loss, tons/acre
- \( R \) = rainfall erosivity index
- \( K \) = soil erodibility index
- \( LS \) = hillslope length-slope factor
- \( C \) = cropping management factor
- \( P \) = erosion-control factor
USLE

• Published 1965
• Much information available
• Figures, charts, tables for each parameter
• Most common method for estimating soil loss
• Does NOT predict delivery
• US Department of Agriculture now advocates the use of RUSLE2
RUSLE2


- Computer-assisted software and documentation

4. Estimating/Measuring
RUSLE2, continued

4. Estimating/Measuring
Landslide

- Aerial photography
- Somewhat random
- Estimate volume by
  - Map measurements
  - Ground survey

http://ars.els-cdn.com/content/image/1-s2.0-S0169555X06000067-gr6.jpg

4. Estimating/Measuring
Estimating/Measuring Mechanical Movement

• Field-based survey
• Usually required as part of a restoration or reclamation plan
• Meet required performance criteria

http://www.eoearth.org/files/123401_123500/123460/250px-Surface_mine_reclamation.jpg
Estimating/Measuring Streambank Erosion

- Historical maps for meander belts
- Mississippi River

http://www.jenbervin.com/images/mississippi/meanderbeltmap.jpg
Estimating/Measuring Streambank Erosion

• Aerial photography for more recent bank failure
  – Good for reconnaissance

• Can field survey for more accurate data

http://water.epa.gov/scitech/datait/tools/warsss/images/fig30.jpg
Estimating/Measuring Streambank

- Erosion Pins
- Easily used
- Monitor
  - Floods
  - Annually
  - Seasonally

[Images showing erosion pins at different times: June 24, 2004, and September 17, 2004]

http://pubs.usgs.gov/fs/2005/3134/images/fig07_left.jpg
Estimating/Measuring Reservoir Sedimentation

• Need initial survey
  – Topo map before construction
  – Bathymetric soon after closure

• Subsequent surveys
  – Best: multibeam echosounder - $80,000
  – Good: single beam echosounder: $25,000

http://t0.gstatic.com/images?q=tbn:ANd9GcRUS3Q8Fi9iX11K8VZibZ9Sdyu8QrpJ8ByLffWy2vn8cUKxeEege8UolJga6
Elements of Modern Surveys

4. Estimating/Measuring

http://sofia.usgs.gov/publications/ofr/00-347/images/survey.gif
Estimating/Measuring Tributary Input

• Milk River, Montana
• You may want to trace where sediment is coming from
• Go upstream looking at tributaries
• Measure tributary input
• See item 7

http://www.airphotona.com/stockimg/images/00066.jpg
5. Land Use Impacts on Sediment Budget

- Deforestation
- Well-known impacts
- Exposure to rainfall splash
- Loss of soil strength

Urbanization

- Often clear land for entire subdivisions
- Increase in
  - Runoff
  - Erosion
- Can impact an entire region/country or countries

http://passel.unl.edu/Image/siteImages/UrbanRillErosion-NRCS-LG.jpg

5. Land Use Impacts
Agriculture

- Centuries-old problem
- Cultivating perpendicular to contours
- Add water
- And...increase erosion!

http://static.howstuffworks.com/gif/irrigation-soil-erosion.jpg

5. Land Use Impacts
Other Land Use Impacts

• You name them!
...And NO land use impact?

- Low Precip = Low Erosion
  - http://farm2.static.flickr.com/1299/556137713_6ef65e479e.jpg

- Moderate Precip = High Erosion
  - http://2.bp.blogspot.com/-F0reiSazSEs/Tvt41ItJ6rl/AAAAAAAAA-
    w/1UU8KGzdOC/s1600/Lesotho+Landscape.JPG

- High Precip = Low Erosion

Mean Annual Precipitation

5. Land Use Impacts
6. River Transport of Sediments

- **Bedload**
  - Along streambed

- **Suspended Load**
  - In water column
  - Can deposit

- **Washload**
  - Very fine
  - Does not deposit
Bedload

• Requires high Q
• VERY nonlinear
• Einstein’s challenge
• Can be between 5 and 80% of total sediment load
• Low end = gravel
• High end = sand

6. River Transport of Sediments

Suspended Load

- New Zealand
- Glacial outwash
- Grey is suspended load
- Can see previous bedload

http://www.swisseduc.ch/glaciers/new_zealand/fox_glacier/icons/17_river_turbulent.jpg

6. River Transport of Sediments
Wash Load

• Very fine material
• Colors water
• Deposits only
  – In reservoirs
  – On floodplains
• *Colorado* River

http://therockyriver.com/wp-content/uploads/2012/08/ColoradoRiverSedimentLoadMonsoonHugeFishKill.png

6. River Transport of Sediments
7. Measuring Transported Sediments

- Suspended Load
  - DH-48
  - Hand-held
  - Only small rivers
- Manual procedure
  - Very expensive

Larger Rivers

• Deployed from bridges
• Still expensive


7. Measuring Transported Sediments
Emerging Suspended Load Methods

• Continuous recording turbidity meter
  – Mounted on bottom of stream
  – Light shines upward
  – Records turbidity

• Related to suspended load concentration
  – Occasional water samples collected for calibration

http://ga.water.usgs.gov/edu/pictures/TurbiditySond.jpg

7. Measuring Transported Sediments
Emerging Suspended Load Methods

- Satellite imagery
- Coloration indicates suspended load
- Need some calibration
- Very useful and emerging technology

Coastal Singapore: infrared (left) and turbidity (right)


7. Measuring Transported Sediments
Bedload Sediment Measurements

- Hand-held method
  - Small streams
  - Labor intensive
  - Dangerous

- Helley-Smith

http://www.halltechaquatic.com/wp-content/themes/halltechaquatic/images/cat1/bedloadsampler621.jpg

7. Measuring Transported Sediments
Larger Rivers

- Heavier Helley-Smith!
- Deployed from bridge
- Still expensive

http://www.rickly.com/ss/images/HELLEY.JPG

7. Measuring Transported Sediments
Emerging Bedload Methods

• Sandy streams: ADCP
  – Measures water velocity
  – Tracks bottom sediments

• Can estimate velocity of bedforms


7. Measuring Transported Sediments
Other Bedload Methods

- Impact
  - Strikes plate
  - Sound ~ transport


- Painted rocks, magnetic rocks

7. Measuring Transported Sediments
8. Making the Sediment Budget

- Two approaches
  - Add up components
  - Simulate components with computer models
- First approach
  - $\textit{Sediment Yield} = \sum \textit{All of the components}$
  - Usually simply measured as riverine transport
  - Individual budget items allow you to focus on those particular items
2nd Approach: Computer Modeling

- Use measure data to calibrate a computer model
- Use the model to predict impacts of changes
# Computer Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Reference</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGNPS: Agricultural Non-Point Source Pollution Model</td>
<td>Google “AGNPS”</td>
<td>Upland watersheds</td>
</tr>
<tr>
<td>MIKE SHE</td>
<td><a href="http://www.crwr.utexas.edu/gis/gishyd98/dhi/mikeshe/Mshemain.htm">http://www.crwr.utexas.edu/gis/gishyd98/dhi/mikeshe/Mshemain.htm</a></td>
<td>Comprehensive rainfall/runoff model</td>
</tr>
</tbody>
</table>
Hydrology

- We’ll not talk about each component
- Focus: discharge rates
- MIKE SHE and GSSHA simulate all components

http://geofreekz.wordpress.com/the-hydrosphere/

9. Measuring Streamflow Discharge Rates
9. Measuring Streamflow Discharge Rates

- Why focus on measuring streamflow discharge rates?
- Sediment yield = sediment concentration x water discharge
  - Example: (3,000 mg/l) x (1 million l/s) = 1 billion mg/s = 1 million kg/s = 1,000 metric tons/s
Smaller Streams

• USA: Price meter
• Used since 1880s
• Deploy by
  – Wading
  – From bridge
• Most common method for 100 years


9. Measuring Streamflow Discharge Rates
Smaller Streams

- Online video training

9. Measuring Streamflow Discharge Rates
Medium to Large Rivers: Modern Method

- **Acoustic Doppler Current Profiler (ADCP)**
- 0.8 m-long ‘boat’
- Dragged across river or drone
- Acoustic signals use Doppler effect to measure velocity

9. Measuring Streamflow Discharge Rates
ADCP Methods

• 4 sensors: 1 for depth, 1 each for velocity in x, y, and z directions
• Integrates measurements instantly
• Gives detail about discharge distribution

http://www.eoearth.org/files/110701_110800/110736/310px-Adcp_600.jpg

9. Measuring Streamflow Discharge Rates
Accessing Records: U.S. Geological Survey (USGS)

http://waterwatch.usgs.gov/

9. Measuring Streamflow Discharge Rates
State-Scale View

- Shows all current streamgages
  - Continuous
  - Crest stage only
  - Water quality including suspended sediment!
- Each location icon is clickable
Provo River, Provo, Utah

- Plots for one week
- All axes can be changed
- Updated frequency each day
- State of art

9. Measuring Streamflow Discharge Rates
Summary

• Sediment Budgets
  – Consider each component
  – What is dominant in your watershed/country?
  – Invest in data collection!!

• Riverine sediment concentration measurement
  – Collaborate across countries
  – Use consistent methods and training
  – All data put online in real time

• Stream discharge measurement is foundation
  – Add sediment measurements to the discharge net
  – Many other topics to discuss!
Thank you!