Earth-surface Dynamics Modeling & Model Coupling

A short course

James P.M. Syvitski & Albert J Kettner
CSDMS, CU-Boulder
Module 2: Modeling discharge and Sediment Flux


DEM to flow paths (3)
Climate to discharge (7)
Paleo-discharge (5)
Hydrological Modeling (5)
Sediment Delivery (8)
U.S. East Coast Example
Waipaoa Model (2)
Summary (1)
Step 1): use an appropriate topographic DEM: LIDAR (1-5 m), SRTM (30-90m), GLOBE & GTOPO30 (1km), ETOPO2/5 (4-10km)

SRTM Data Resolution
○ A horizontal pixel is 1-arc or 3-arc seconds, depending on data availability

Mississippi floodplain detail

30 m horizontal resolution  90 m horizontal resolution
Step 2): Clean up the DEM for errors: e.g. 1) User developed (e.g. RiverTools), 2) SRTM Water Body Data Set – 30 m; 3) Hydro1K, 4) HydroSheds (6km), 5) STN30 (50km).

Replace Bad Values

3-arcsecond SRTM, Korea
Step 3): Develop flow routing: e.g. SRTM WBSD has lakes >600m flattened to a constant height, and rivers >183m in width delineated and monotonically stepped down in height.
1. Gridded 0.5° by 0.5°: CRU or U. Delaware rain gauge data, based on: NSDC Global Historical Climatology Network 1,870 to 16,360 stations between years 1950-1999; Legates and Willmott archive 26,858 precipitation stations
Global distribution of 3423 met stations providing monthly averages on precipitation and temperature, with most stations reporting between 50 and 100 years of observations.
Precipitation

2. TRMM (Passive Microwave Radiometer, Precipitation Radar, and Visible-Infrared Scanner), plus the Special Sensor/Microwave Imagery, plus rain gauge data, run through algorithm 3B-43 equals 0.5° x 0.5° grid every 3 hours.

3. SSM/I (0.5° x 0.5°) plus GOES IR (1°x1°, 3-hourly) plus TIROS Operational Vertical Sounder (TOVS; 1°x1°, daily) plus ground data, equals 1° x 1° grid daily, since 1997.

4. The Community Climate Model (CCM3) state of the art atmospheric general circulation model with a horizontal resolution 37 km, every hour, 1 year

5. NCAR/NCEP Reanalysis assimilates ground observations & satellite data in numerical weather/climate models to provide gridded 2°x2° data, 1948 and 2004, every 6 hrs
Precipitation to Discharge

1. Precipitation as rain or snow: Need DEM, gridded temperature, lapse rates
2. Snow to glacial ice: Need DEM, equilibrium line altitude of glaciers and ice sheets
3. Snowmelt, glacial melt: Need DEM, gridded temperature, lapse rates
Precipitation to Discharge

4. Rainfall to Runoff: Need DEM, canopy, evapotranspiration, soil properties
5. Meltwater to Runoff: Need DEM, routing, distribution of lakes/reservoirs

Runoff

Discharge Model Examples

1. WBTM: global 2D at 50x50km, monthly for 50 years
2. INSTAAR-HydroTrend: basin by basin, 1km resolution (1D), daily, for years to millennium
3. INSTAAR-TopoFlow: local to regional, 100m resolution, minutes, for weeks to year, functional routing.
**Polar zones:** low frontal rainfall; large contribution from snow & ice meltwater; short runoff season; low lapse rates; high inter annual variability; permafrost

**Temperate zones:** discharge from springtime snowmelt, summer convective rainfall, and fall time frontal rainfall; high alpine freeze-thaw cycles; highly industrialized hinterland

**Tropical zones:** little to no meltwater, intense convective rainfall, strong orographic influences, tropical storms (typhoons); monsoons; intense chemical weathering
Small rivers offer greater variability than large rivers.

Eel River Discharge ($m^3/s$)

Amazon River $10^3$ $m^3/s$

5 orders of magnitude

1 order of magnitude
Paleo-discharge

Climate model (CCM, GFDL, CCC, GEN, BMRC, CCSR, GISS, CSIRO) runs are typically 10 yr runs for particular time slices (21K, 18K, 16K, 15K, 14K, 12K, 9K, 6K, 3KBP) at 2.5° to 7° grids, at hourly to daily steps.

---

Earth-surface Dynamic Modeling & Model Coupling, 2009
Parameterization of lapse rate

A) The NCEP/NCAR Reanalysis of global lapse rates [°C/km] on a 2.5° grid. Note the strong latitudinal banding.

B) Lapse rate [°C/km] and latitude for every pixel in a global grid (A) along with the predicted fit.

Syvitski et al, Sedimentary Geology, 2003

\[ L(x) = \left( a_0 x^2 + a_1 \right) \left( 1 - a_2 \exp\left(-\frac{x}{a_3}\right) \right) \]

Earth-surface Dynamic Modeling & Model Coupling, 2009
Parameterization of basin-averaged temperature

A) 2.5° grid of surface temperatures

B) Global station temperature versus latitude and the best-fit model.

C) Lapse-adjusted temperature versus latitude shows the general tightening of the fit

\[ T(x, \theta, H) = T_0(x, \theta) - \left[ L(x) H \right] \]

\[ T_0 = T + \left[ L(x) H \right] \]

Syvitski et al, Sedimentary Geology, 2003
Parameterization of basin-averaged temperature

Observed versus predicted station temperatures. Half of the data falls within 1°C of prediction, and 82% falls within 2.5°C. Basin averaging of station temperatures reduces local variability and provides for basin-averaged values of ±1.5°C.

Climate-Hydrologic Modeling brainstorming

Components of water discharge
- snow melt
- ice melt
- rainfall runoff
- groundwater efflux

Snow or rain: hypsometry, lapse rate, freezing line, temperature
Snow and ice: ELA, hypsometry, freezing line, temperature
Nival freshet model: dry melt: \( f_T \); wet melt: \( f_T \); rain
Solid vs. wet evaporation
Rainfall vs. groundwater: rainfall intensity, canopy interception,
- hydraulic conductivity, saturation excess, pool size
Kinematic wave effect vs. lake modulation
Variability vs. coherency
Drainage basin area vs. storm size and direction
Interannual vs. intra-annual variability
Climate change effects and water storage changes
HydroTrend

Set basin attributes

Precipitation Model or Input File

Set climate attributes

Snow Fall/Melt Model

Rain Fall Model

Evaporation-Evapotranspiration Model

Glacier Storage/Melt Model

Glacier Advance/Retreat Model

Groundwater Infiltration-Efflux Model

Reservoirs

Runoff/Discharge Model

Lakes

Channel - Distributary Channel Hydraulics Model

Sediment Load (Qs & Qb) Models
KLINIKLINI SIMULATION

TOTAL DISCHARGE (m³/s)

ICE DISCHARGE (m³/s)

RAIN DISCHARGE (m³/s)

HAIL DISCHARGE (m³/s)

DAY

Earth-surface Dynamic Modeling & Model Coupling, 2009
Data Assimilation

- NCDC historical & NCEP Reanalysis Climate Data
- SRTM to DEM
- DODS
- GeoML
- RiverTools
- file
- Equilibrium Line Altitude Data
- GIS
- Ocean Climatology: waves, currents, winds, pressure, tides
- GIS
- Basin Properties: relief, lakes, river hypsometry, flow network
- DODS
- Coastal Basin Model: SedFlux
- file
- Sediment Discharge Model: HydroTrend

Syvitski et al, Terra Nostra, 2002
Hydrological Functionality

- Runoff (daily timestep)
- Routing
- Irrigation
- Reservoir Operation
- Data Assimilation

Mississippi time series

Gulf of Maine Daily Runoff

Wisser et al. In Preparation

Earth-surface Dynamic Modeling & Model Coupling, 2009
Sediment Delivery

\[ Q_b = \frac{\rho_s}{\rho_s - \rho} \frac{\rho g Q^\beta S e_b}{\tan \phi} \]

when \( u \geq u_{cr} \) \[ Q_b = (\Gamma) Q^\beta S \]

\[ \frac{Q_s}{\rho g^{1/2} A^{5/4}} = \alpha \left( \frac{R}{A^{1/2}} \right)^n \]

Using the globally-averaged value \( n=1 \), and the global relationship between \( Q \), in m\(^3\)/s, and \( A \), in km\(^2\) \( (Q = 0.075 A^{0.8}) \)

\[ Q_s = w B \cdot Q^{0.31} A^{0.5} R \cdot T \quad \text{for } T \geq 2^\circ C \]

\[ Q_s = 2 w B \cdot Q^{0.31} A^{0.5} R \quad \text{for } T < 2^\circ C \]

\[ Q_s = \left[ \omega \rho g^{0.5} \right] \left[ 1 + 0.09 A_g \right] L \left( 1 - T_E \right) E_h Q^{0.31} A^{0.5} R T \]
Sediment Delivery

\[ Q_s = \left[ \omega p g^{0.5} \right] \left[ 1 + 0.09A_g \right] L \left( 1 - T_E \right) E_h Q^{0.31} A^{0.5} R T \]
\[ T_E = 1 - \left( \frac{0.05}{\sqrt[3]{Q_{m}}^2} \right) \]

\[ T_E = 1 - \frac{A_R}{1.00021V_R} \]

\[ Q_m = \frac{Q_{up}\left( \frac{A_R}{A_{up}} \right)}{} \]

\[ Q_s = \omega g^{0.5} [1 + 0.09A_g] L (1-T_E) E_h Q^{0.31} A^{0.5} R T \]
Sediment Delivery

\[ Q_s = [\omega p g^{0.5} \left[ 1 + 0.09 A g \right] L \left( 1 - T_E \right) E_h Q^{0.31} A^{0.5} R T ] \]

**BQART simulation after the imprint of humans, c1990**

Sediment Load (MT/yr)
- < 1
- 1 - 10
- 10 - 25
- 25 - 50
- 50 - 100
- 100 - 200
- 200 - 400
- > 400

Earth-surface Dynamic Modeling & Model Coupling, 2009
\[
\left( \frac{Q_s}{\bar{Q}_s} \right) = \psi \left( \frac{Q}{\bar{Q}} \right)^C
\]

\[
E(C) = 1.4 - 0.025T + 0.00013R + 0.145\ln(\bar{Q}_s)
\]

\[
\sigma(C) = 0.17 + 0.0000183\bar{Q}
\]

\[
\sigma(\psi) = 0.763(0.99995)\bar{Q}
\]

Morehead et al, GPC, 2003
Sediment yield decreases away from highlands because:
1) Highland-produced sediment is trapped on floodplains & delta-plains
2) Lowland sediment production is low, e.g., low locale relief, rain shadows, vegetation cover
Sediment Delivery

\[ Q_b = \frac{\rho_s \rho g Q^\beta S e_b}{\rho_s - \rho \tan \phi} \quad \text{when } u \geq u_{cr} \quad \Rightarrow \quad Q_b = (\Gamma) Q S \]
### Sediment Delivery

\[
Q_b = \frac{\rho_s}{\rho_s - \rho} \frac{\rho g Q^\beta S e_b}{\tan \phi}
\]

when \( u \geq u_{cr} \)

\[
Q_b = (\Gamma) Q S
\]

### Table: River Sediment Delivery

<table>
<thead>
<tr>
<th>River</th>
<th>( A ) ( \text{km}^2 )</th>
<th>( R ) ( \text{m} )</th>
<th>( Q ) ( \text{m}^3/\text{s} )</th>
<th>( Q_s ) ( \text{kg/s} )</th>
<th>( Q_b ) ( \text{kg/s} ) ( @100\text{m} )</th>
<th>( Q_b ) ( \text{kg/s} ) ( @10\text{m} )</th>
<th>( Q_b ) loss per km</th>
<th>( Q_b ) lost %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chao Phrya (Thai)</td>
<td>160000</td>
<td>1920</td>
<td>963</td>
<td>349</td>
<td>1200</td>
<td>730</td>
<td>218</td>
<td>29</td>
</tr>
<tr>
<td>Fly (PNG)</td>
<td>64400</td>
<td>3990</td>
<td>2510</td>
<td>2219</td>
<td>1130</td>
<td>901</td>
<td>577</td>
<td>70</td>
</tr>
<tr>
<td>Godavari (India)</td>
<td>287000</td>
<td>1650</td>
<td>2650</td>
<td>5387</td>
<td>1450</td>
<td>513</td>
<td>95</td>
<td>137</td>
</tr>
<tr>
<td>Indus (Pak)</td>
<td>964000</td>
<td>7830</td>
<td>3171</td>
<td>12683</td>
<td>3180</td>
<td>1188</td>
<td>220</td>
<td>70</td>
</tr>
<tr>
<td>Irrawaddy (Burm)</td>
<td>430000</td>
<td>5881</td>
<td>13558</td>
<td>8239</td>
<td>2150</td>
<td>1078</td>
<td>337</td>
<td>338</td>
</tr>
<tr>
<td>Mekong (Viet)</td>
<td>811000</td>
<td>6100</td>
<td>14770</td>
<td>5070</td>
<td>4425</td>
<td>1008</td>
<td>566</td>
<td>783</td>
</tr>
<tr>
<td>Niger (Nig)</td>
<td>1240019</td>
<td>2130</td>
<td>6130</td>
<td>1268</td>
<td>4170</td>
<td>1023</td>
<td>242</td>
<td>182</td>
</tr>
<tr>
<td>Po (Ita)</td>
<td>70000</td>
<td>4800</td>
<td>1904</td>
<td>545</td>
<td>652</td>
<td>467</td>
<td>141</td>
<td>70</td>
</tr>
<tr>
<td>Rhone (Fr)</td>
<td>90000</td>
<td>4810</td>
<td>1700</td>
<td>1982</td>
<td>820</td>
<td>215</td>
<td>67</td>
<td>264</td>
</tr>
<tr>
<td>Euphrates (Iraq)</td>
<td>1050000</td>
<td>2960</td>
<td>1500</td>
<td>1680</td>
<td>2815</td>
<td>1157</td>
<td>511</td>
<td>48</td>
</tr>
<tr>
<td>Vistula (Pol)</td>
<td>200000</td>
<td>2500</td>
<td>1050</td>
<td>79</td>
<td>1091</td>
<td>547</td>
<td>86</td>
<td>42</td>
</tr>
<tr>
<td>Yangtze (PRC)</td>
<td>1958000</td>
<td>6800</td>
<td>28278</td>
<td>15210</td>
<td>4670</td>
<td>1771</td>
<td>840</td>
<td>642</td>
</tr>
</tbody>
</table>

Earth-surface Dynamic Modeling & Model Coupling, 2009
\[
\overline{Q_s} = \alpha R^{3/2} A^{1/2} e^{kT}
\]

Regression formula of Syvitski et al. (2002) for long-term average sediment discharge
Figure 6. Comparison of 39 years of daily simulated and observed suspended sediment concentrations in the Waipaoa River at Matawhero.

Figure 10. Comparison of the late Holocene suspended sediment discharge (99-yr running mean) from the Waipaoa River system computed using HydroTrend and the observed rate of terrigenous mass accumulation on the middle shelf at core site MD972122 [after Gomez et al., 2007] (see Figure 1 for location).
Modeling discharge and Sediment Flux Summary

- **DEM to flow paths**: DEM data quality, resolution, flow paths
- **Climate to discharge**: gridded data, satellite systems, precip to runoff to discharge, climate zones, discharge variability
- **Paleo-discharge**: time slices, resolution, boundary conditions, T°C,
- **Hydrological Modeling**: processes to model coupling, simulations, data assimilation, humans
- **Sediment Delivery**: bedload, suspended load, wash load, factors, reservoirs, lithology, climate, predictions, variability, yield, deposition
- **U.S. East Coast Example**: gridding
- **Waipaoa Model**: Human disturbance