Rivers as Land to Sea Transport Arteries

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Outline
Sediment Production: nature vs. humans
Sediment Delivery: bed material load, suspended & wash load
Sediment Sequestration: floodplains
Sediment Sequestration: deltas
Sediment Production: nature vs. humans
\[ Z_b = -(K_{r1}e^{-c_1H} - K_{r2}e^{-c_2H}) \]

**Sediment Production**

![Graph showing sediment production with depth](image1)

**Chemical Weathering**

**Physical Weathering**

![Graph showing chemical weathering rate vs. temperature](image2)

![Graph showing chemical weathering rate vs. physical erosion rate](image3)

**R. Millot et al. 2002 EPS**

![Graph showing chemical weathering rate vs. runoff](image4)

**R. Millot et al. 2002 EPS**
Sediment Production

mass failure

subglacial

freeze-thaw

cryogenesis

abrasion

biochemical

biological
Sediment Production

SOIL CREEP

THRESHOLD LANDSLIDING

SATURATION-EXCESS RUNOFF

PORE-PRESSURE DRIVEN LANDSLIDING

CHILD simulations: G. Tucker, 2002
Sediment Production

- mining
- deforestation
- poor farming
- grazing
- construction
Anthropocene impacts

Transportation systems: gullying, soil erosion, river scouring

Hong Kong Airport at 12.5 km² displaced 0.6 Gt of sediment

0.3 Gt of extra sediment

How large is 0.6 Gt? The Great Wall of China is ~6,250,000m x 7m x 5m or ~0.4 Gt of sediment
Anthropocene impacts

Deforestation: soil erosion, slope failure, and sedimentation;

Even the little Waipaoa R in NZ has discharged an extra 1 GT of sediment above background pre-Anthropocene levels.
Anthropocene impacts

Infrastructure and Urbanization: earth surface reshaping

Palm Jebel Ali Island 0.4 Gt

‘The World’ 0.55 Gt

Palm Jumeirah Island 0.2 Gt

Palm Deira island (not shown) when completed will use 2.0 Gt of sand.
Anthropocene impacts
Tillage, terracing: soil erosion, creep, siltation

• proliferation of small farms
• poor tilling practice
• prolonged drought caused 23.5 million acres to lose 12.5 Gt of topsoil – Great Plains
Anthropocene impacts

Mining; material displacement, sedimentation, subsidence

Hull-Rust-Mahoning Fe Mine, Hibbing, Mn: >1.2 Gt of material removed since 1895.
Kiruna Fe Mine, Finland: >1 Gt of material removed since 1900.

Athabaska oil sands, Canada, has 14,000 km$^2$ suitable for surface mining. Syncrude mine, one of many, is the largest at 191 km$^2$ & processed >30 Gt of sediment.
Sediment Delivery: bed material load, suspended & wash load
Sediment Delivery

\[ Q_s = [\omega p g^{0.5}] [1 + 0.09A_g] L (1-T_E) E_h Q^{0.31} A^{0.5} R T \]
Basin-averaged climate incorporates spatially variable rainfall and temperature.

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

Basin-averaged climate incorporates spatially variable rainfall and temperature.
Sediment Delivery

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

BQART estimates fall on average within 38% of the measured loads on 488 global rivers that drain 63 per cent of the global land surface.
E.g. converging runoff

E.g. change in lithology

E.g. tectonic depression

\[ Q_s = (\mu) (1 - T_E) Q^\beta S \]

\[ Q_b = (\Gamma) Q^\beta S \]
$$\left( \frac{Q_s}{\bar{Q}_s} \right) = \psi \left( \frac{Q}{\bar{Q}} \right)^C$$

$$E(C) = f(T, R, \bar{Q_s})$$

$$\sigma(C) = f(\bar{Q})$$

$$\sigma(\psi) = f(\bar{Q})$$

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

\[ Y_s = \alpha B Q^{0.31} A^{-0.5} R T \]
Anthropocene impacts on geomorphology & sediment flux
Tillage, terracing: soil erosion, creep, siltation

The Yellow transported ≈ 0.5 Gt/y extra for ≈1000 years to the coastline from the Loess Plateau during the Anthropocene or ≈500 Gt.

Wang et al 2007
Anthropocene impacts

Waterway re-plumbing: reservoirs and dams, diversions, channel levees, channel deepening, discharge focusing, and ultimately coastline erosion;
Reservoirs

- 2.3 Gt/y LESS sediment reaches the coast worldwide
Modern seasonal sediment load for global rivers: **Green** - March-May; **Red** - June-August; **Orange** - September-November; **Blue** - December-October. Superimposed is the annual sediment flux averaged across 1° of latitude. Major rivers are hot spots of sediment discharge.

<table>
<thead>
<tr>
<th>Continent</th>
<th>$Q$ (km$^3$/y)</th>
<th>$Q_{s}$ with Humans (Gt/y)</th>
<th>$Q_{s}$ Pre-Humans (Gt/y)</th>
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<td>Global</td>
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</table>
Sediment Transfer & Storage: Floodplains
Rorschach Art

- 33 Late Quaternary floodplains & deltas
- Boundaries are ≤100 m asl
- D = delta;
- T = tectonic depression
Lakes are a common element of floodplains where flood waters can sequester sediment.
Tectonic Depressions: have a few common characteristics — no one is diagnostic:

- statistically flatter down-valley slopes;
- expanded valley widths;
- multiple overflow channels similar to deltaic distributary channels;
- lakes connected to the main river channel;
- highly prone to flooding, often annually;
After Chen et al., 2010

\[
\begin{align*}
&D: Er = 3.55 \\
&\sim 128 \text{ Mt/y} \\
&+51 \text{ Mt/y} \\
&-160 \text{ Mt/y} \\
&-19 \text{ Mt/y}
\end{align*}
\]
Mompox depression: overflow & levee failures cause extensive flooding (April – Nov)
Over last 7500 y, aggradation rate is 3–4 mm/y with deposits 10m to 130m thick
With 27 yr of observation, 14% of Magdalena sediment load is trapped  Kettner et al.,
DFO-mapped floods (1999-2009)
Recent flooded areas overlie earlier flooded areas
Mekong River (Vietnam) flooding (backfilling) of the tectonic depression Tonle Sap (Cambodia) with both water and sediment
Images are GeoTiffs from either MODIS-Terra or MODIS-Aqua

100 km
The elevated deposit is 50 Gt or 10% of the 500 Gt extra sediment transported by the Yellow to the coastline.

The Yellow once freely migrated across its 700 km wide floodplain and is now fixed as a narrow elevated floodplain.
Sediment Transfer & Storage: Deltas
Controls on Delta Elevation

\[ \Delta_{RSL} = A - \Delta E - C_n - C_A \pm M \]

\[ \Delta_{RSL} \] = Vertical change in delta surface elevation (m/yr)

A = Sediment Aggradation Rate (m/yr)
\( \Delta E \) = Eustatic Sea Level Rise (m/yr)
Cn = Natural Compaction (m/yr)
Ca = Accelerated Compaction (m/yr)
M = Crustal Vertical Movement (m/yr)
Flooding on deltas can occur from
1. Channel overbanking,
2. Ocean surges (cyclones, tsunamis)

Aggradation will depend on the sediment flux being carried by the flood waters, and the retention rate on the delta

\[ \Delta_{RSL} = \pm A - \Delta E - C_n - C_A \pm M \]
In the pre-dam period when sediment erosion was rampant (1600 – 1950) deltas rapidly expanded, and in some cases formed prograding from coastal plain systems.
Sedimentation occurred between distributary channels from overbank flooding.

Mahanadi R.  
Brahmani R.  
Svitski et al.; 2009  
Syvitski et al.; 2009
Stop-banks super-elevate the riverbed above the floodplain.

Channel Retention: — Deposition within distributary channels.

Aggradation from migration of channels.
Natural Compaction Rates changes in the void space within sedimentary layers (dewatering, grain-packing realignment, organic matter oxidation)

Present compaction rates for deposits with thickness of \( \approx 100 \text{m} \) and accumulation time of \( \approx 10 \text{Ky} \).

\[ \Delta_{\text{RSL}} = \pm A - \Delta E - C_n - C_A \pm M \]

Present compaction rates for deposits with thickness of \( \approx 100 \text{m} \) and accumulation time of \( \approx 10 \text{Ky} \).

\( P_{90} = 2.2 \text{ mm/yr} \)

\( P_{10} = 0.69 \text{ mm/yr} \)

Meckel et al., 2007
Accelerated Compaction Rates

$$\Delta_{RSL} = \pm A - \Delta E - C_n - C_A \pm M$$

Examples

- **Yangtze**: 28 mm/y before controls
- **Niger**: 25 to 125 mm/y
- **Chao Phraya**: 50 to 150 mm/y
- **Po**: 60 mm/y before controls

Bangkok’s population went from 1M to 12M in 35 years

Saito et al., 2008
Subsidence of the Po Delta, Italy

Accelerated Compaction Rates

A. Subsidence through gas mining
B. Recovered subsidence
C. Natural subsidence

Recovery from accelerated compaction occurs within years

Simeoni et al., 2007

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Crustal Subsidence

Each location on a large delta sinks at different rates, depending on their load history.

Mississippi delta lobes weigh between 200 to 900 billion tonnes. Today the various Mississippi lobes are sinking at between:

1) 0.3 to 3.6 mm/y (Hutton & Syvitski, 2008)
2) 2.0 to 6 mm/y (Ivins et al., 2007)
Net Changes in a Delta’s Relative Sea Level

**Aggradation** (≤50 mm/y)
(new layers of sediment added to a delta's surface)

**Eustasy** (1.8 – 3 mm/y)
(increase in ocean volume & warming ocean)

**Load Isostasy** (0 – 6 mm/y)

**Natural Compaction** (0.7 – 2.2 mm/y)

**Accelerated Compaction** (0 – 150 mm/y)
(petroleum & water mining)

Controls on Delta Surface Elevation

\[ \Delta_{RSL} = A - \Delta E - C_n - C_A - M \]

e.g. natural conditions (mm/y) 
+ 5.5 = 10 - 0.5 - 2 - 0 - 2

e.g. anthropogenic forcing (mm/y) 
−15 = 5 - 3 - 2 - 13 - 2

NSF | NASA

COMMUNITY SURFACE DYNAMICS MODELING SYSTEM
Relative sea level has risen 4 times faster along deltas than the global average.
Pink areas are below sea level

Modern Deltas below sea level

Nile

Mississippi

Vistula

Ganges

Indus

Mekong

Euphrates

Yellow

Mahakam
Hyperpycnal discharge is limited to small & medium-sized rivers that drain mountains capable of generating hyper-elevated sediments during infrequent high-energy floods.

Critical Concentrations, $Cs^*$, for marine hyperpycnal flow conditions:
- Equatorial: $Cs^* > 36 - 36.4 \text{ kg/m}^3$
- Sub-tropical: $Cs^* > 38.7 - 39 \text{ kg/m}^3$
- Temperate: $Cs^* > 42 - 43.3 \text{ kg/m}^3$
- Sub-polar: $Cs^* > 43 - 43.5 \text{ kg/m}^3$

Jhuoshuei, Taiwan

Skeidarasundar, Iceland, 1996
Anthropocene impacts on coastal sediment flux

1) Reduced sediment concentration decreases or eliminates hyperpycnal currents.

Wang et al. 2010

1) Elevated sediment concentrations generate more hyperpycnal currents.

Hutton et al., 2007
Summary

➤ We have predictive but basic understanding of sediment production, delivery and storage at global, regional and local scales.

➤ The human footprint is ubiquitous and significant: by 1600 AD soil disturbance rampant; by 1900 AD mechanization, mining, terracing, deforestation lead to global land-sea signals; by 1930 AD subsidence began for many deltas; by 1950 AD sediment sequestration behind dams is a dominant signal in most rivers.

➤ Tectonic depressions located on many (55%) floodplains within ≤100 m asl are natural traps of the delivery of sediment to the coastal zone — sequestration mechanisms are highly varied.
- Global deltas have large areas (>>100,000 km²) <2m a.s.l.; most (75%) experienced flooding in the last decade, submerging >260,000 km² of land. Vulnerable low-lying lands are expanding rapidly, due to sinking.

- Deltas are sinking 4 times more rapidly than ocean level is rising due to human interference in river basins and their deltas due to:
  1. Reduced sediment delivery to the deltas (>2.3 Gt less sediment reaches these deltas per year)
  2. Sediment delivery bypassing the delta plains (fixed distributaries with stop banks).
  3. Accelerated compaction due to subterranean mining: 70% of deltas

- Infrastructures for growing mega-cities is a dominant factor.

- Sediment dispersal into the coastal ocean is strongly influenced by humans.