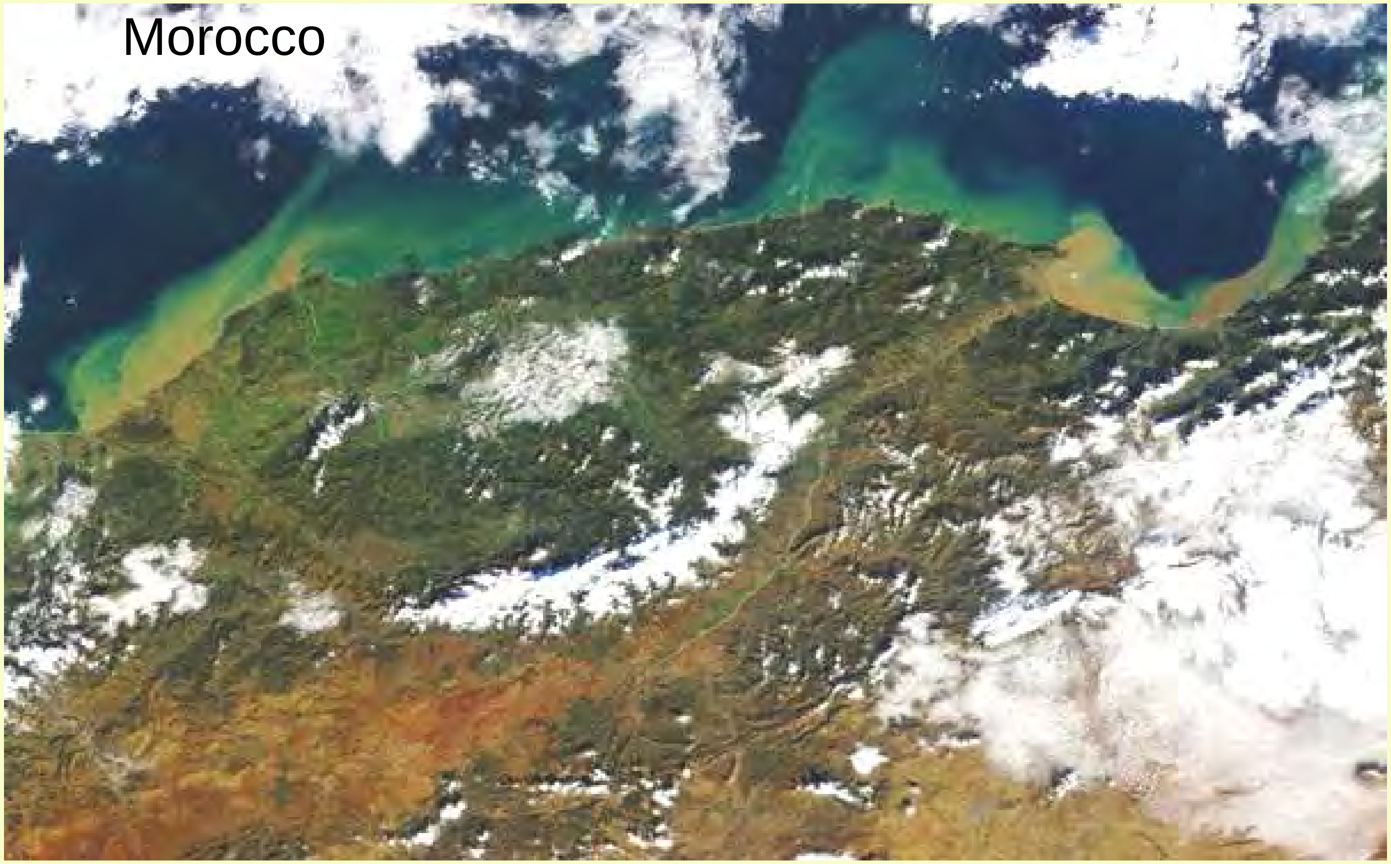
Rivers as Land to Sea Transport Arteries

James P.M. Syvitski
Community Surface Dynamic Modeling System
UC-Boulder, CO, USA



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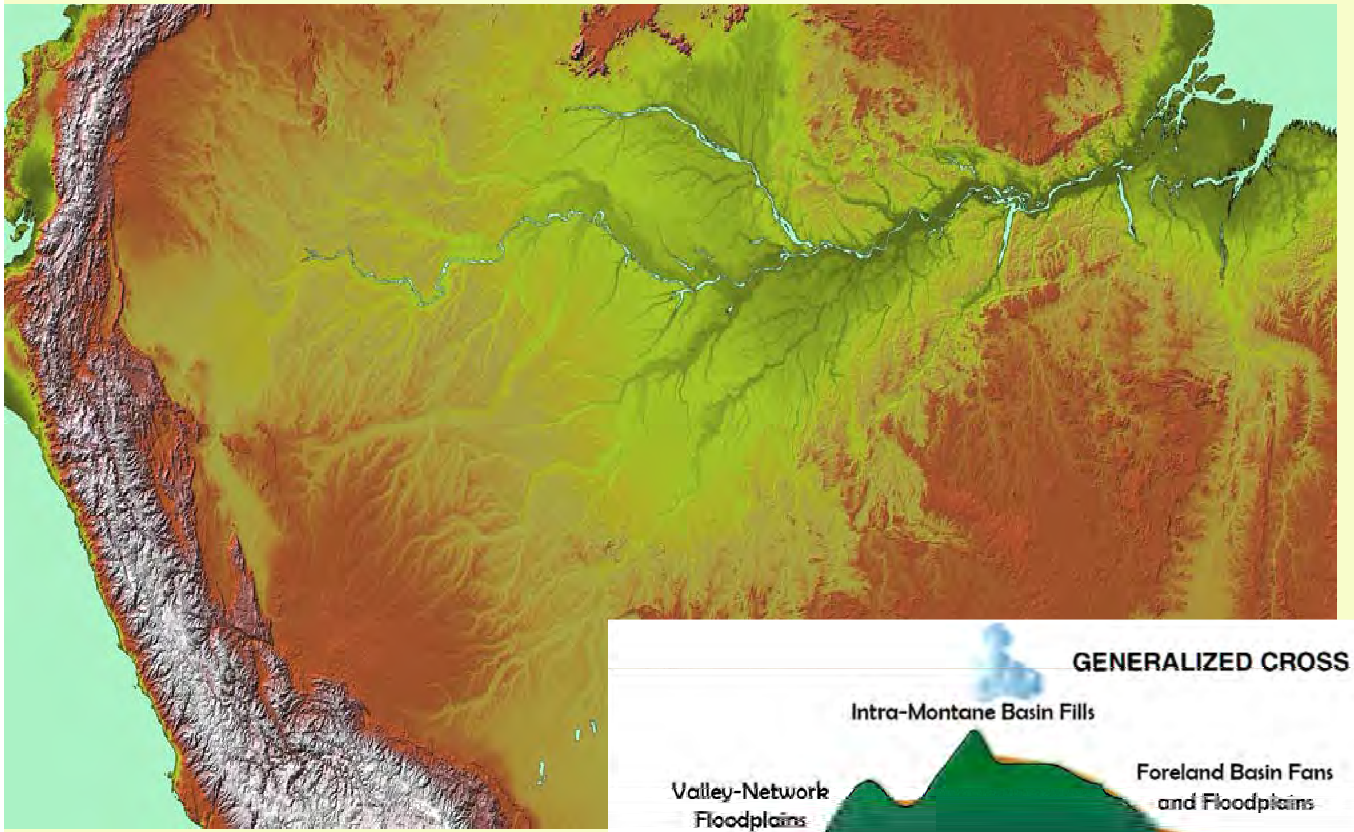
Outline

Sediment Production: nature vs. humans

Sediment Delivery: bed material load, suspended & wash load

Sediment Sequestration: floodplains

Sediment Sequestration: deltas



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Sediment Production: nature vs. humans

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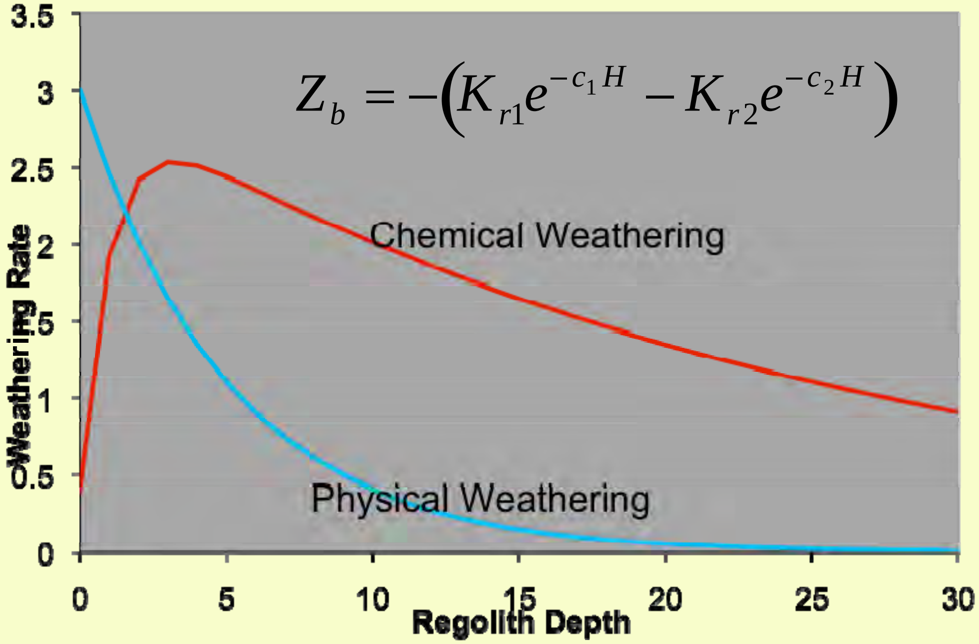
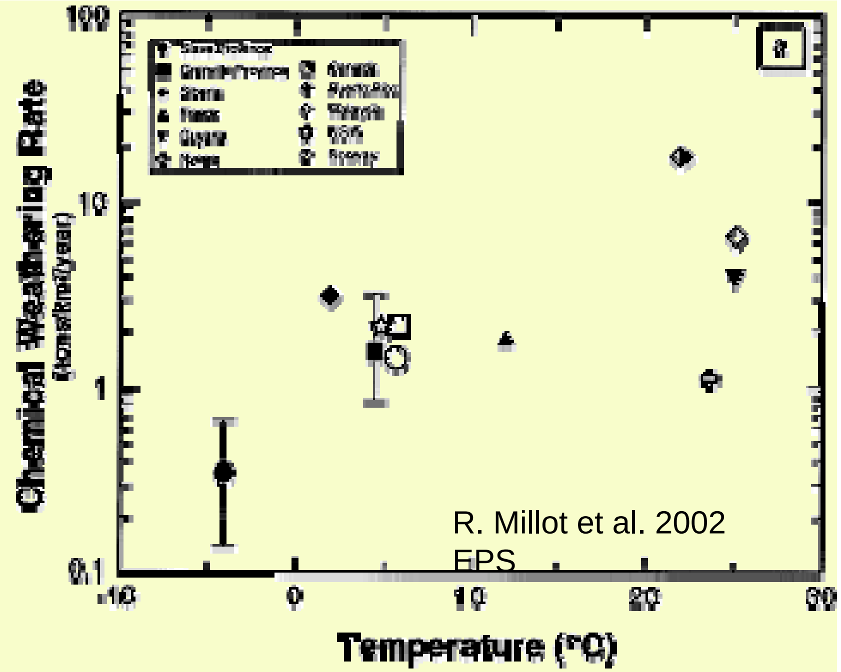
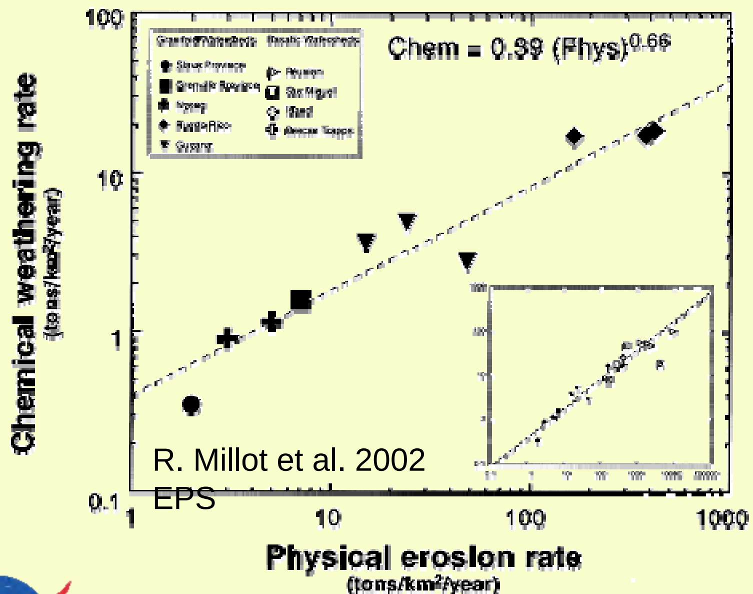
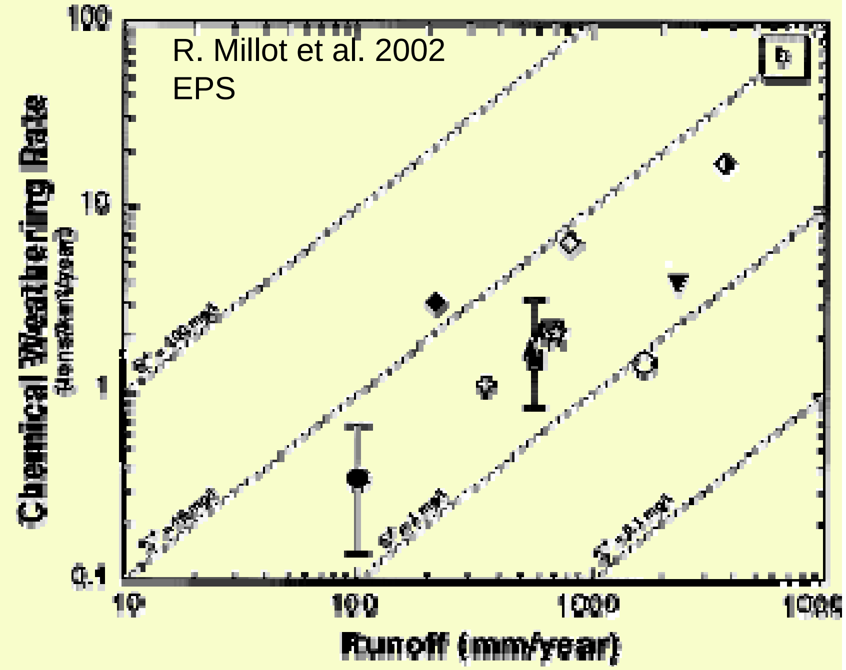
Sediment Production

$$Z_b = -\left(K_{r1}e^{-c_1 H} - K_{r2}e^{-c_2 H}\right)$$









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Sediment Production

mass failure

subglacial

freeze-thaw

cryogenesis

abrasion

biochemical

biological

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Sediment Production

SOIL CREEP

THRESHOLD LANDSLIDING

SATURATION-EXCESS RUNOFF

PORE-PRESSURE DRIVEN LANDSLIDING

CHILD simulations: G. Tucker, 2002

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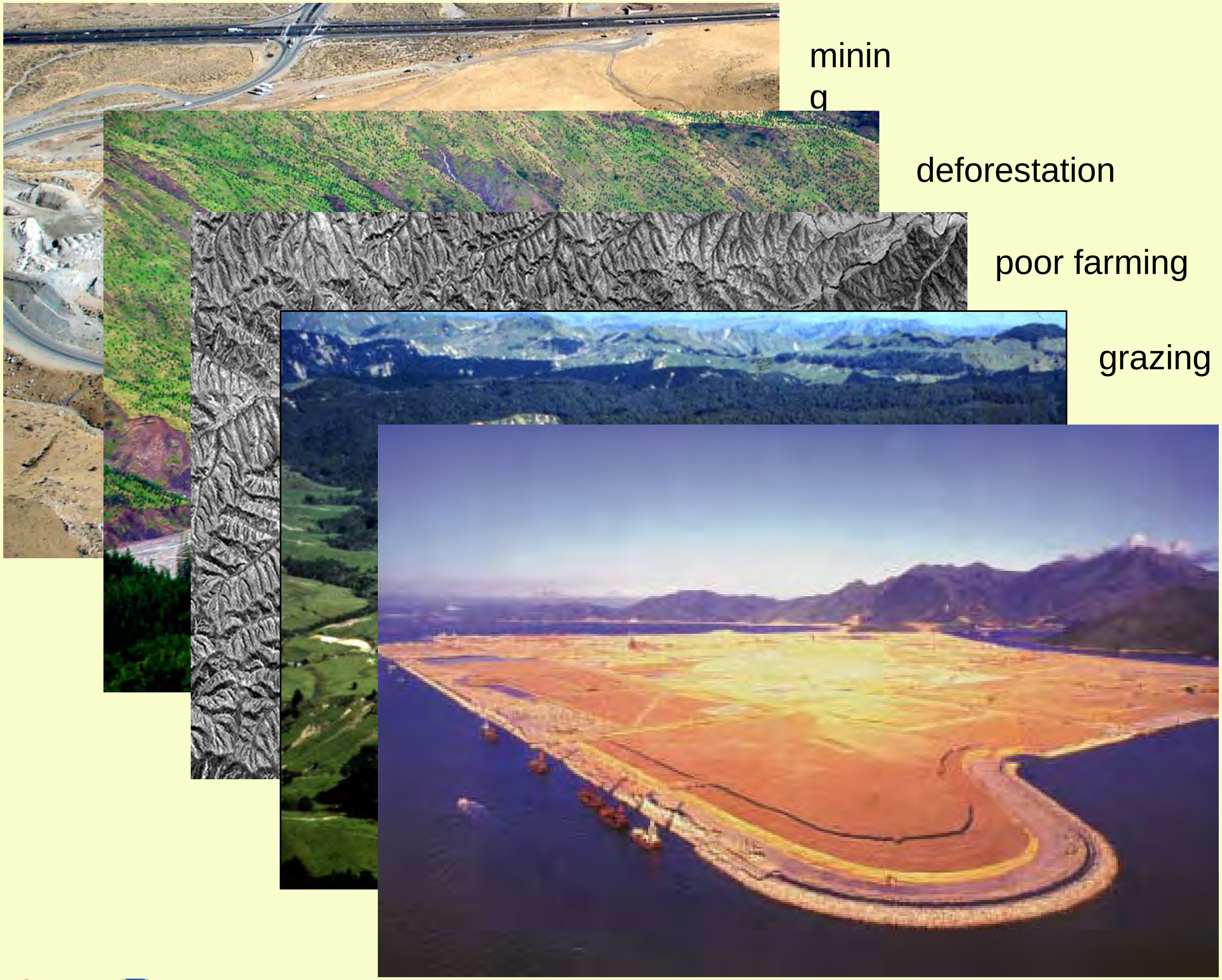
Sediment Production



minin
g

deforestation

poor farming

grazing

construction

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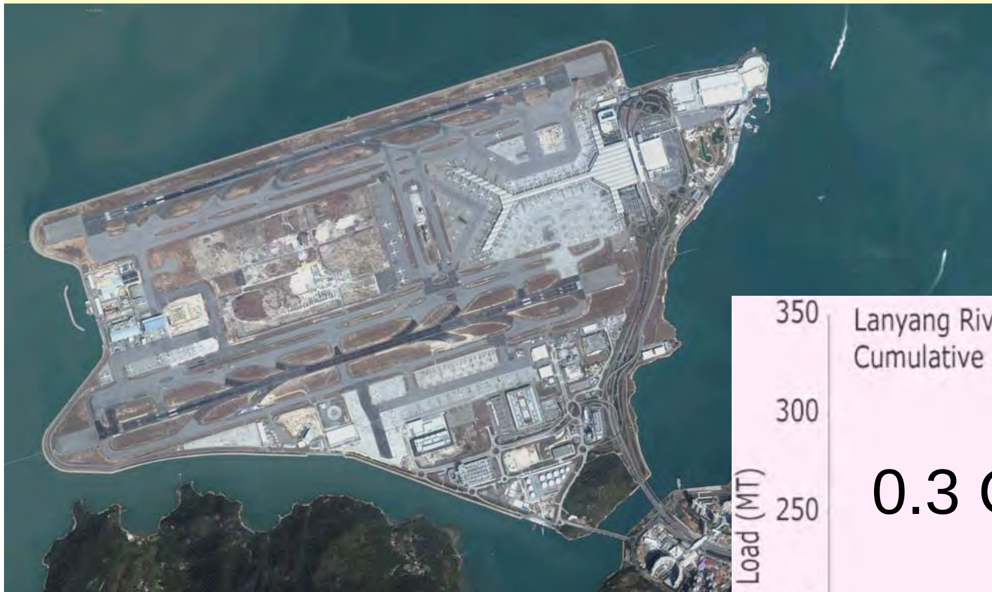
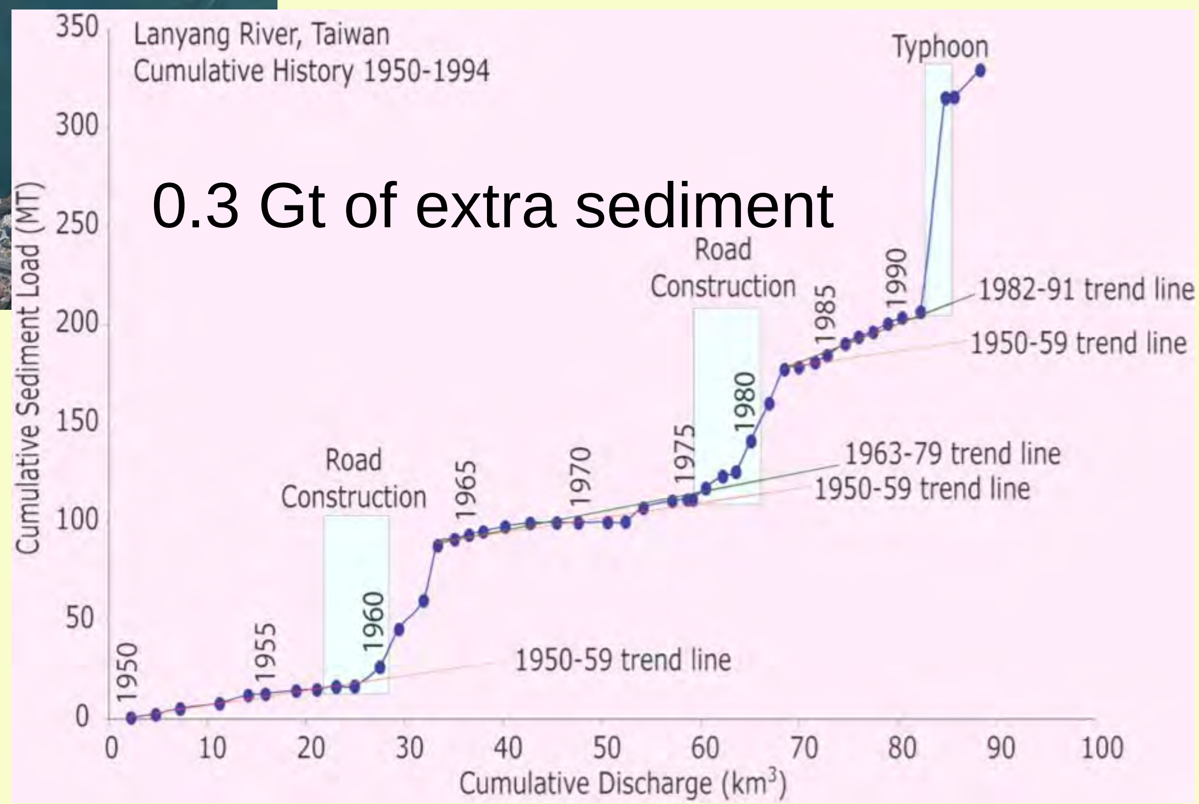
Anthropocene impacts

Transportation systems: gullying, soil erosion, river scouring



Hong Kong Airport at 12.5 km^2
displaced 0.6 Gt of 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

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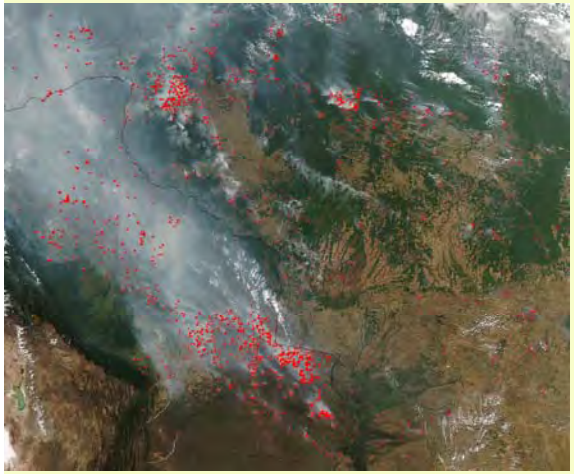
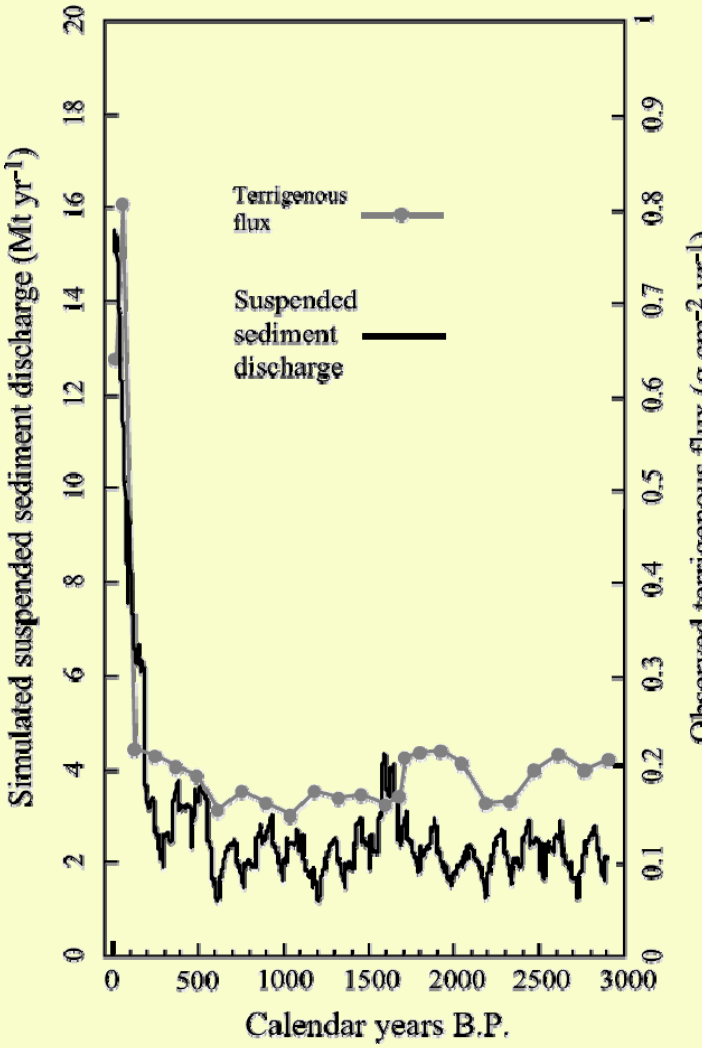
Anthropocene impacts

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



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Anthropocene impacts

Infrastructure and Urbanization: earth surface reshaping

Palm Deira island (not shown) when completed will use 2.0 Gt of sand.

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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

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.

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.

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Sedient Delivery: bed material load, suspended & wash load

Sediment Delivery

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

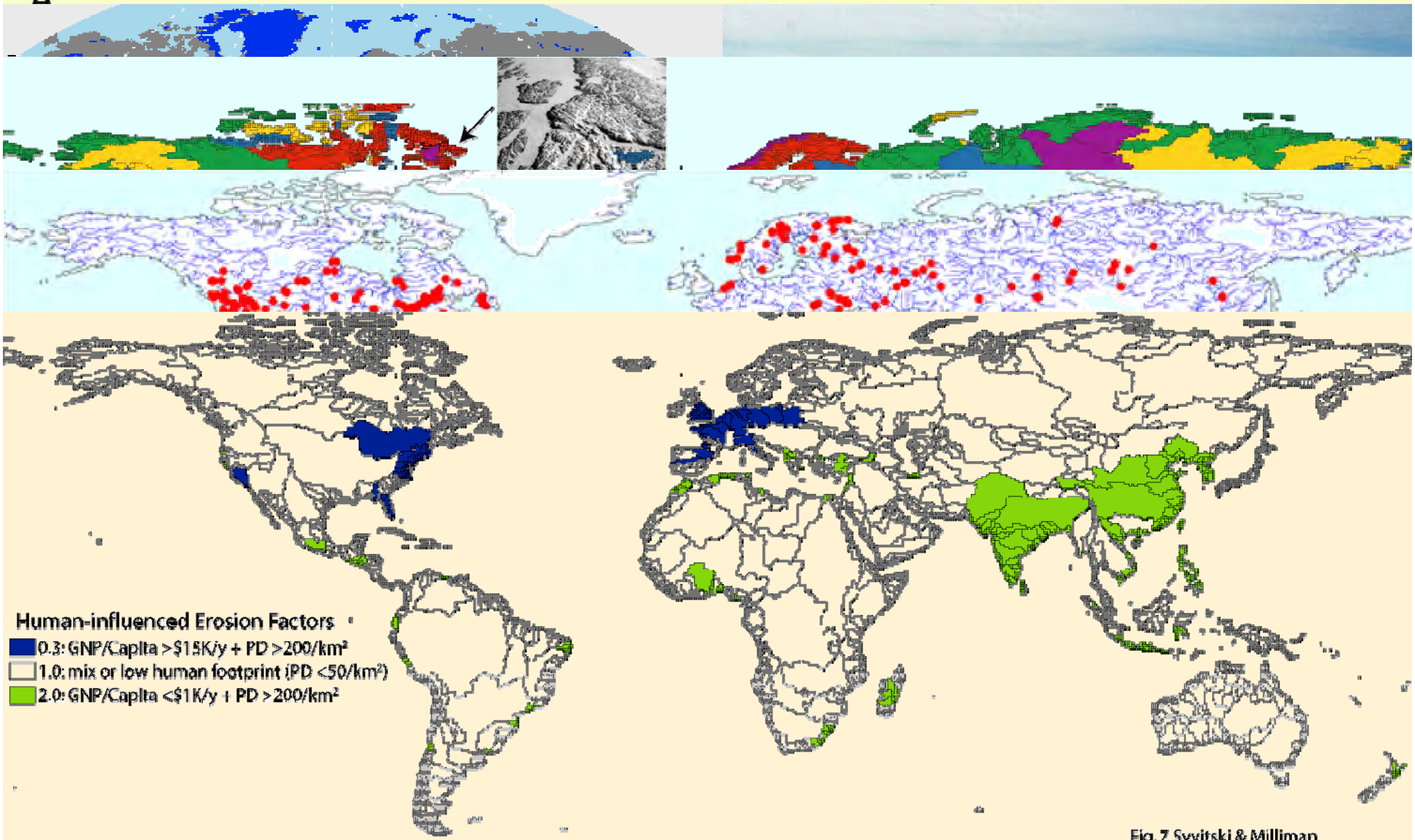

Fig. 7 Syvitski & Milliman

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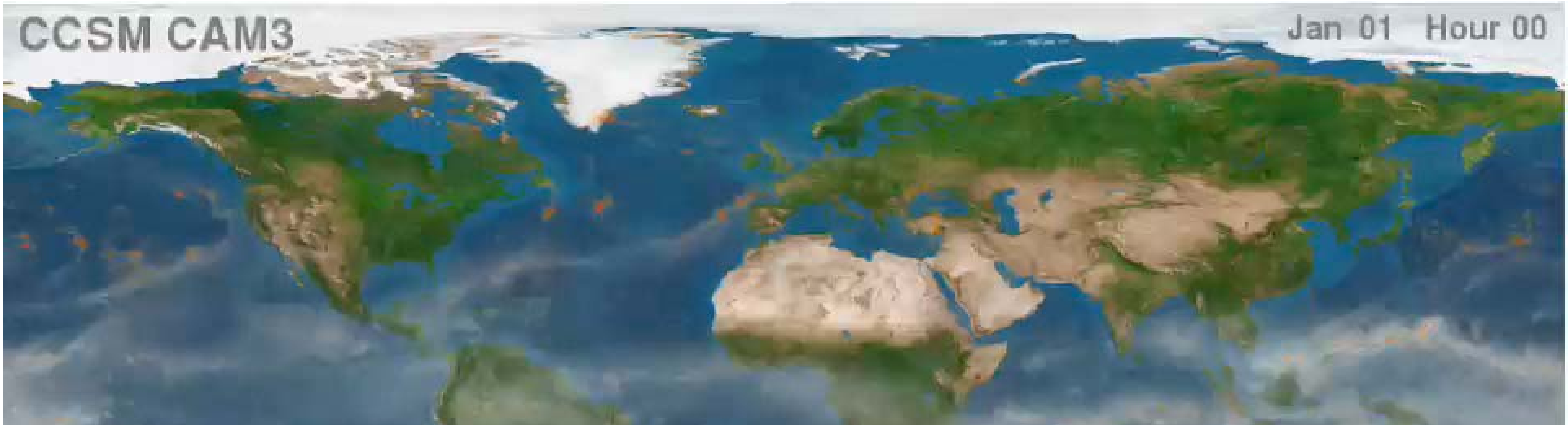

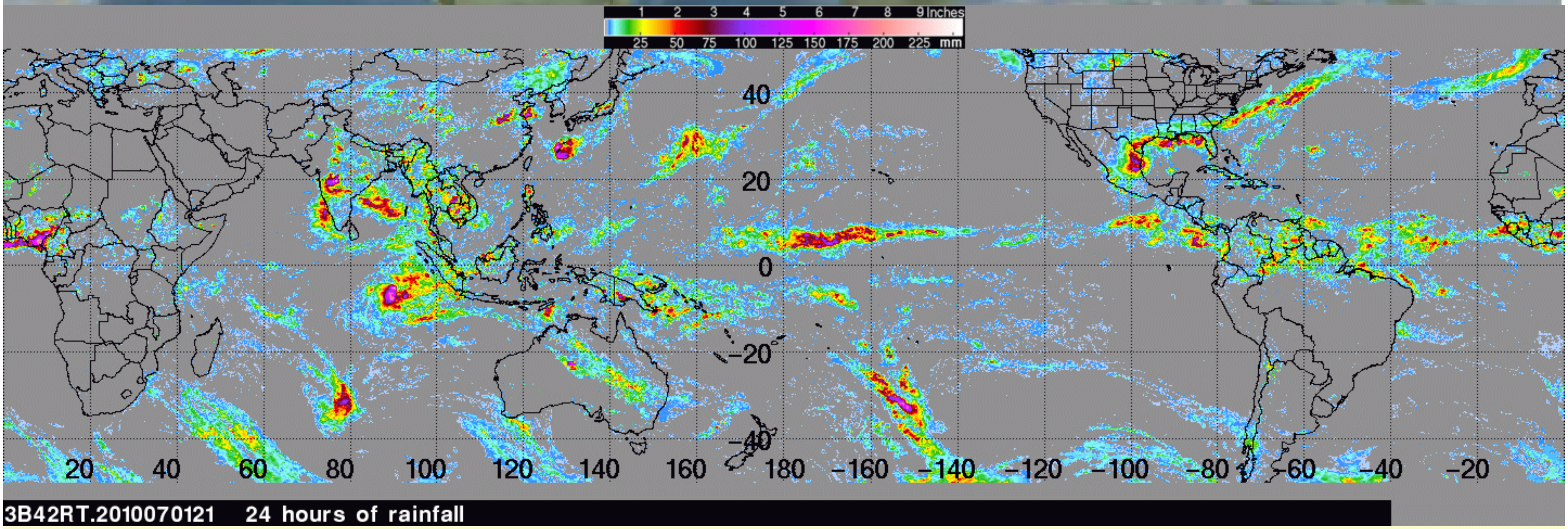

$$Q_s=[\omega\rho g^{0.5}]\ [1+0.09A_g]\ L\ (1-T_E)\ E_h\ Q^{0.31}\ A^{0.5}\ R\ T$$

Basin-averaged climate incorporates spatially variable rainfall and temperature

NSF NASA

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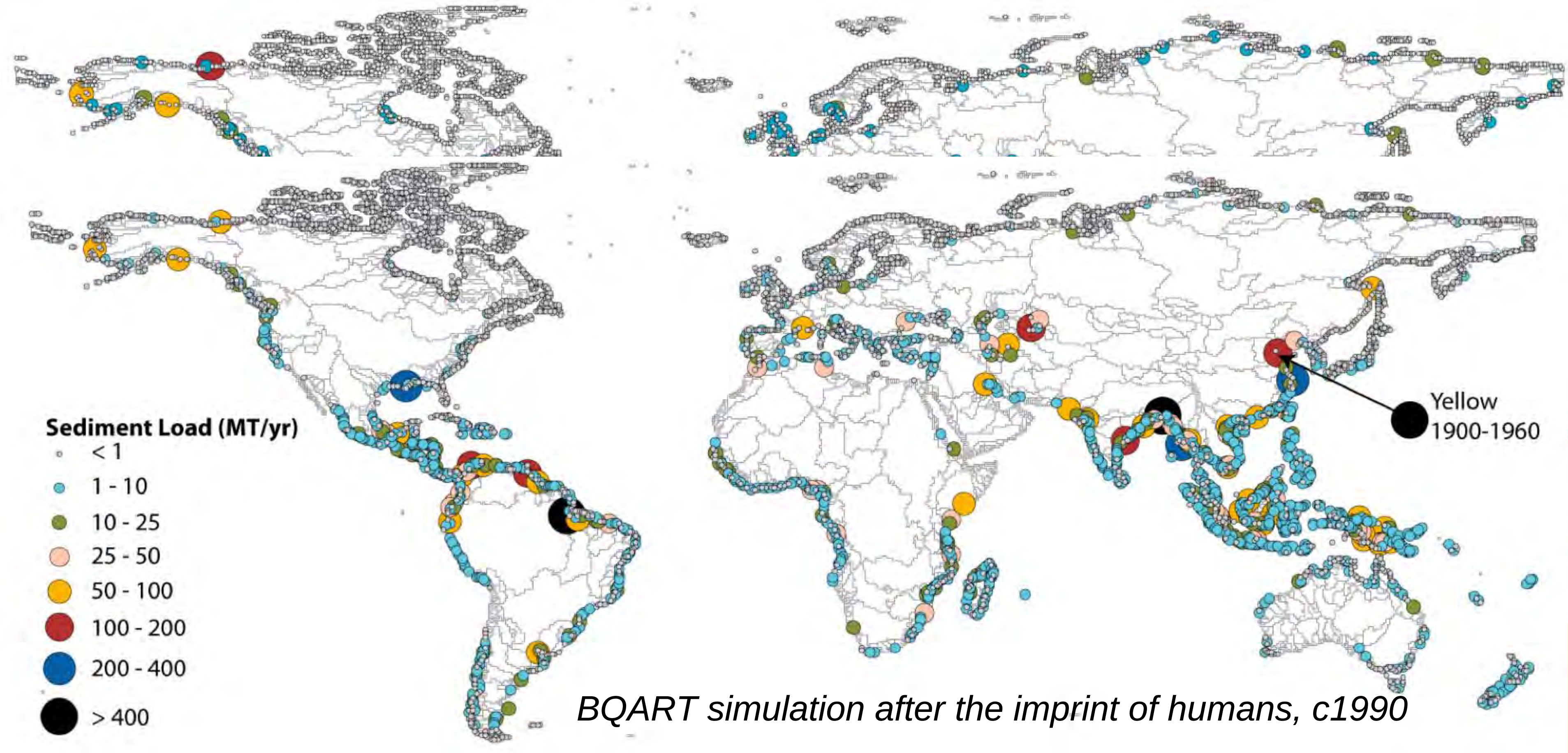
Sediment Delivery

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



BQART simulation after the imprint of humans, c1990

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.

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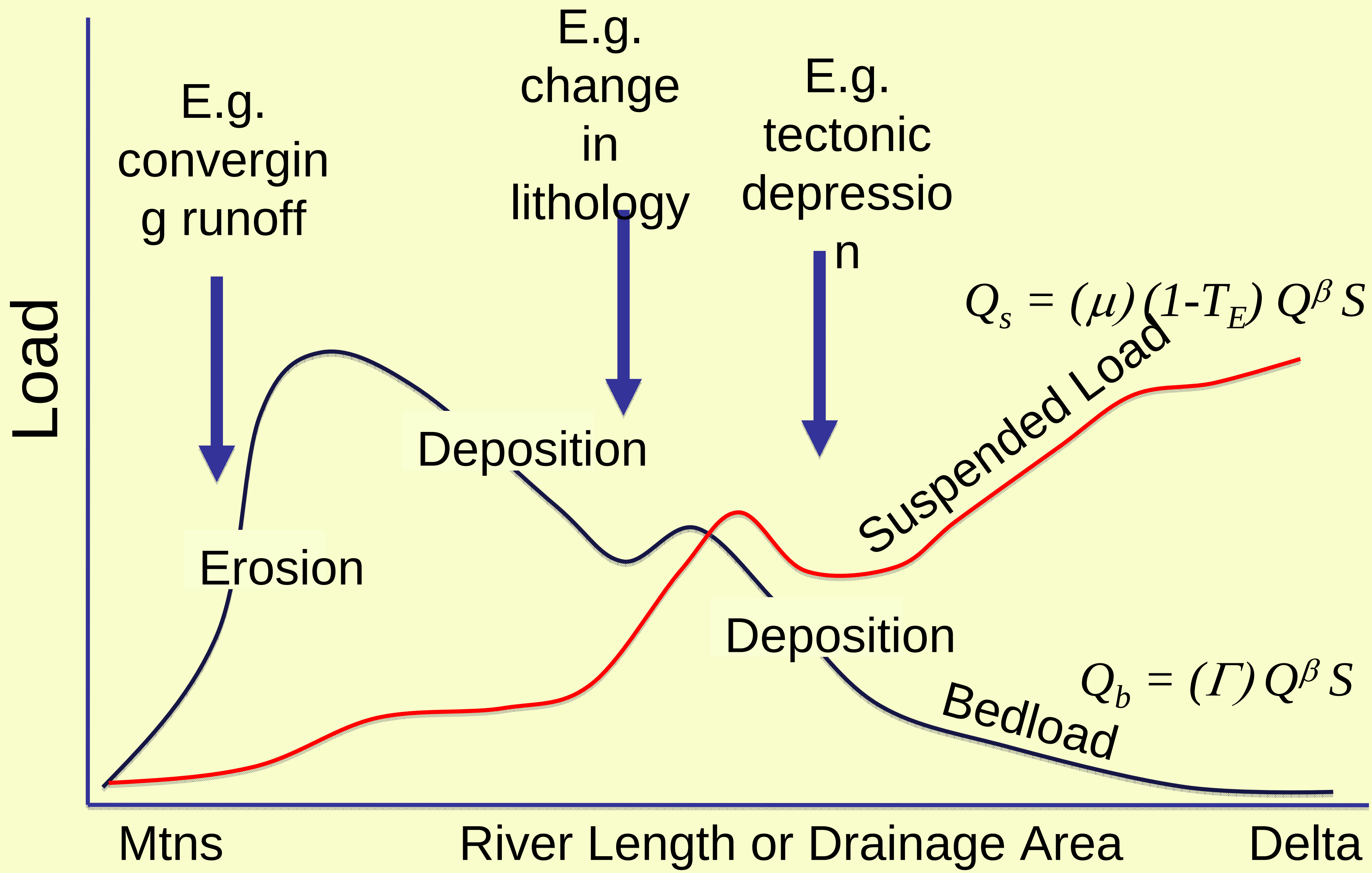
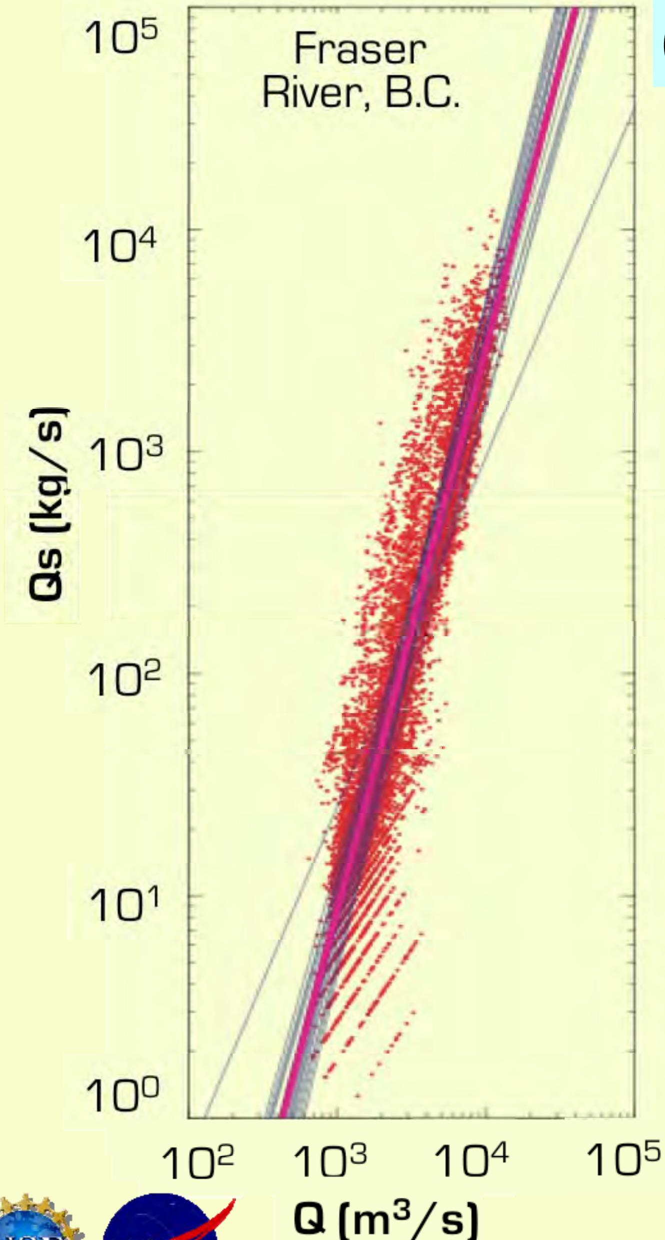


COMMUNITY SURFACE DYNAMICS MODELING SYSTEM

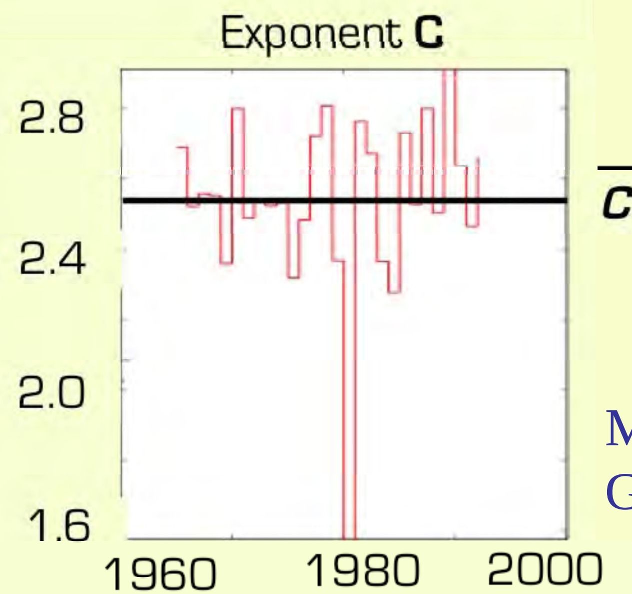
$$\left(Q_s / \overline{Q_s}\right) = \psi \left(Q / \overline{Q}\right)^C$$



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

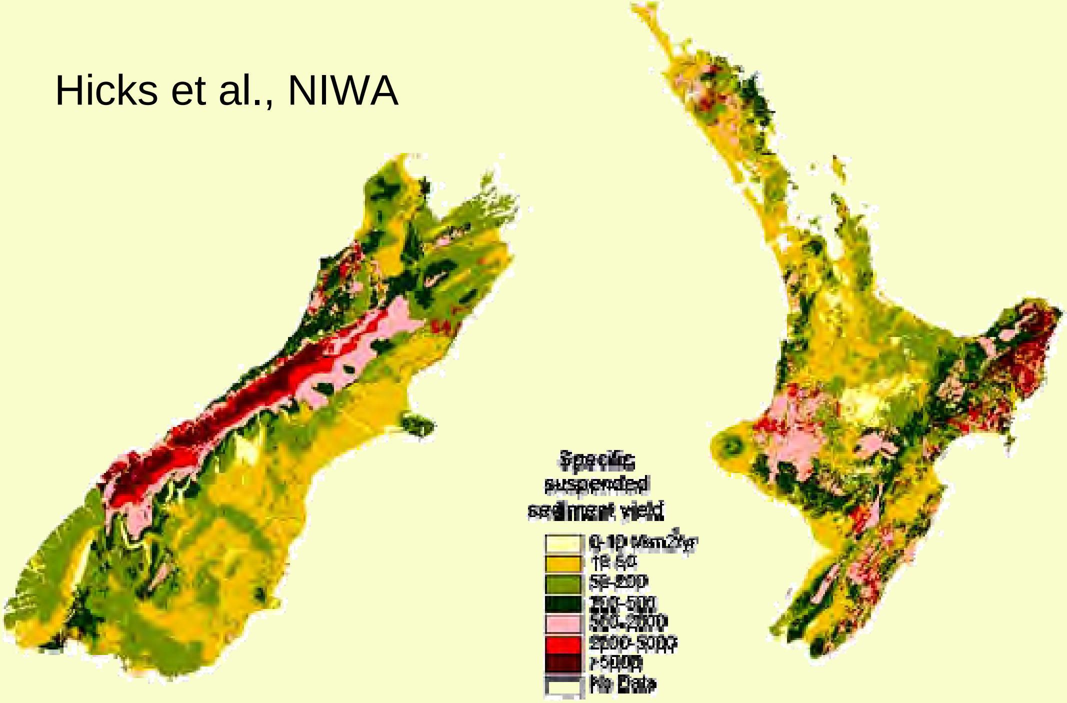
$$\sigma(C) = f(\overline{Q})$$

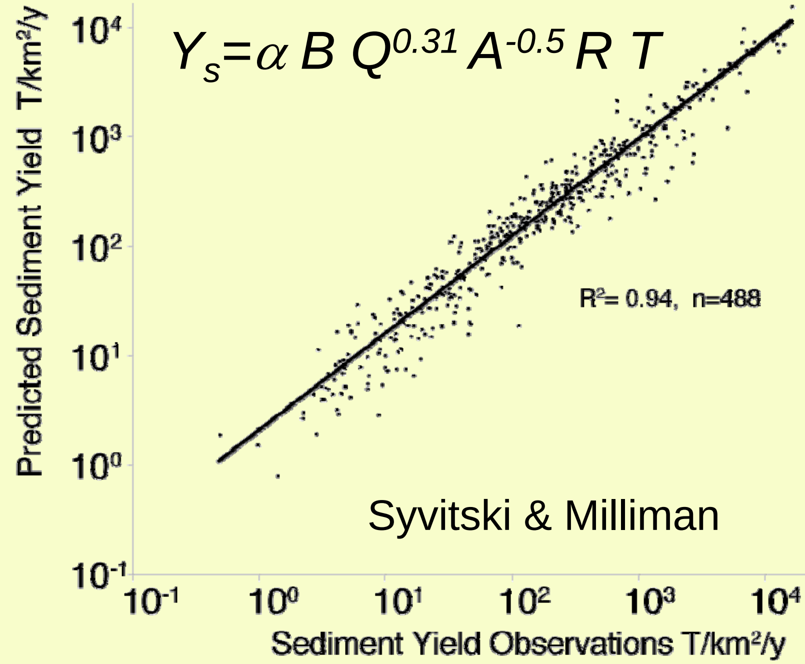
$$\sigma(\psi) = f(\overline{Q})$$

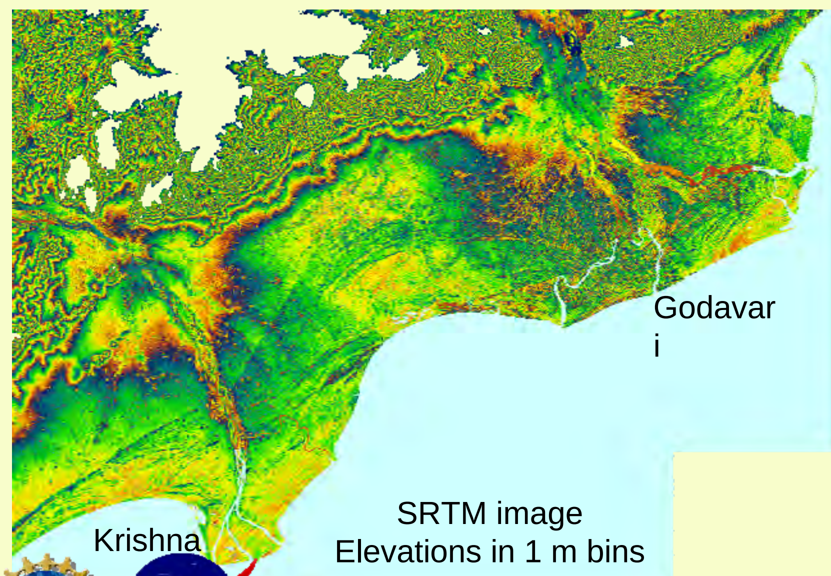


Morehead et al,
GPC, 2003

Hicks et al., NIWA







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

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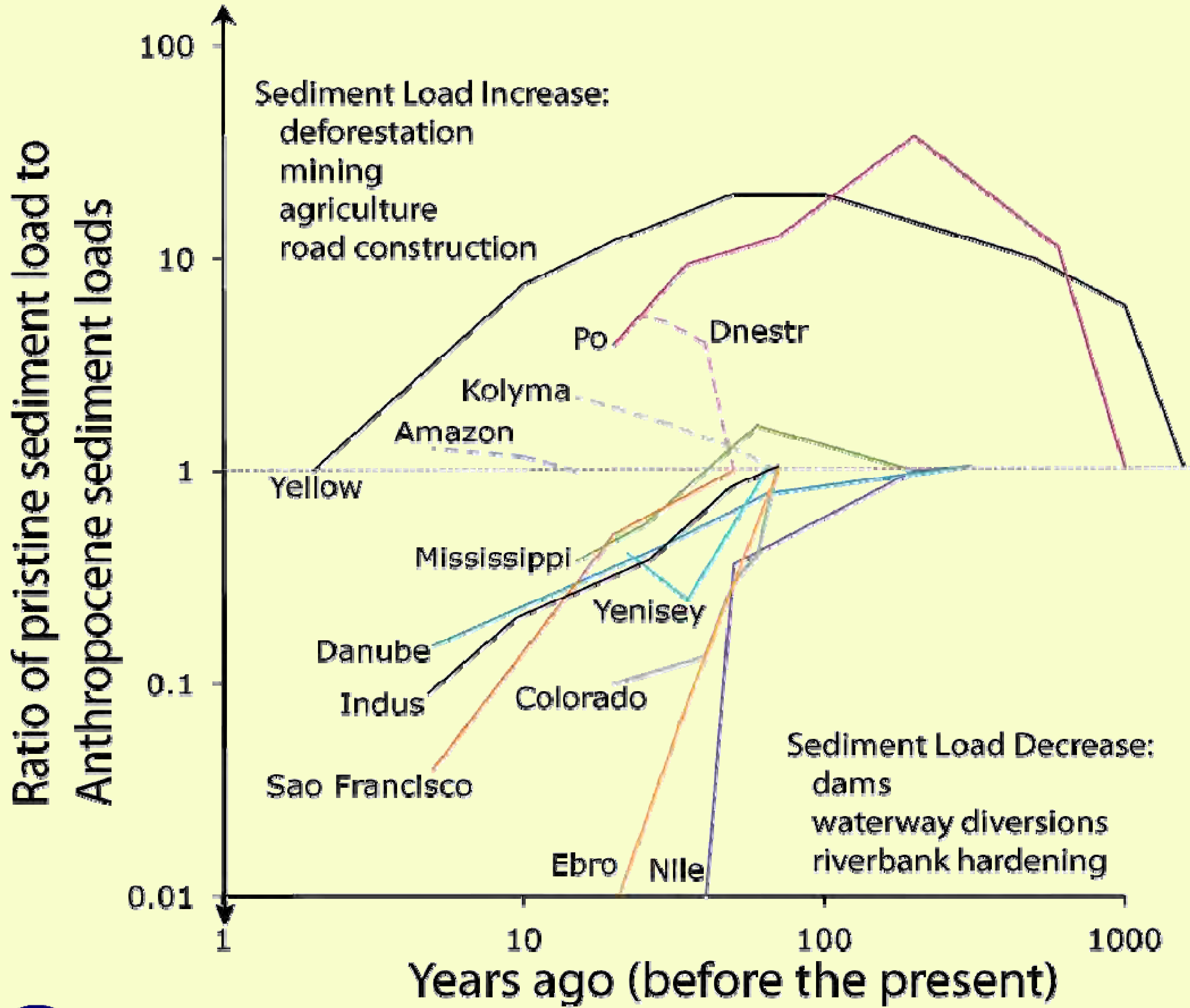

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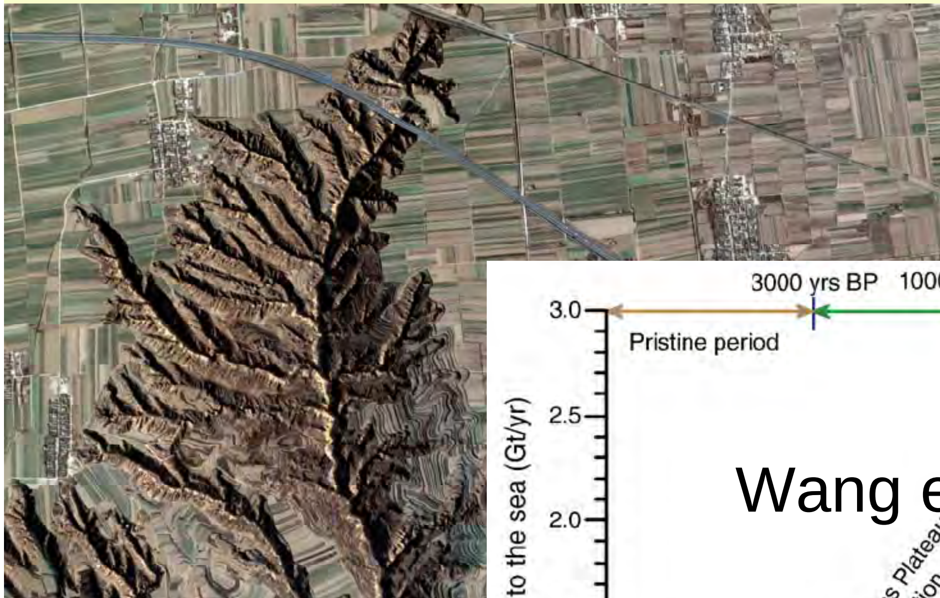
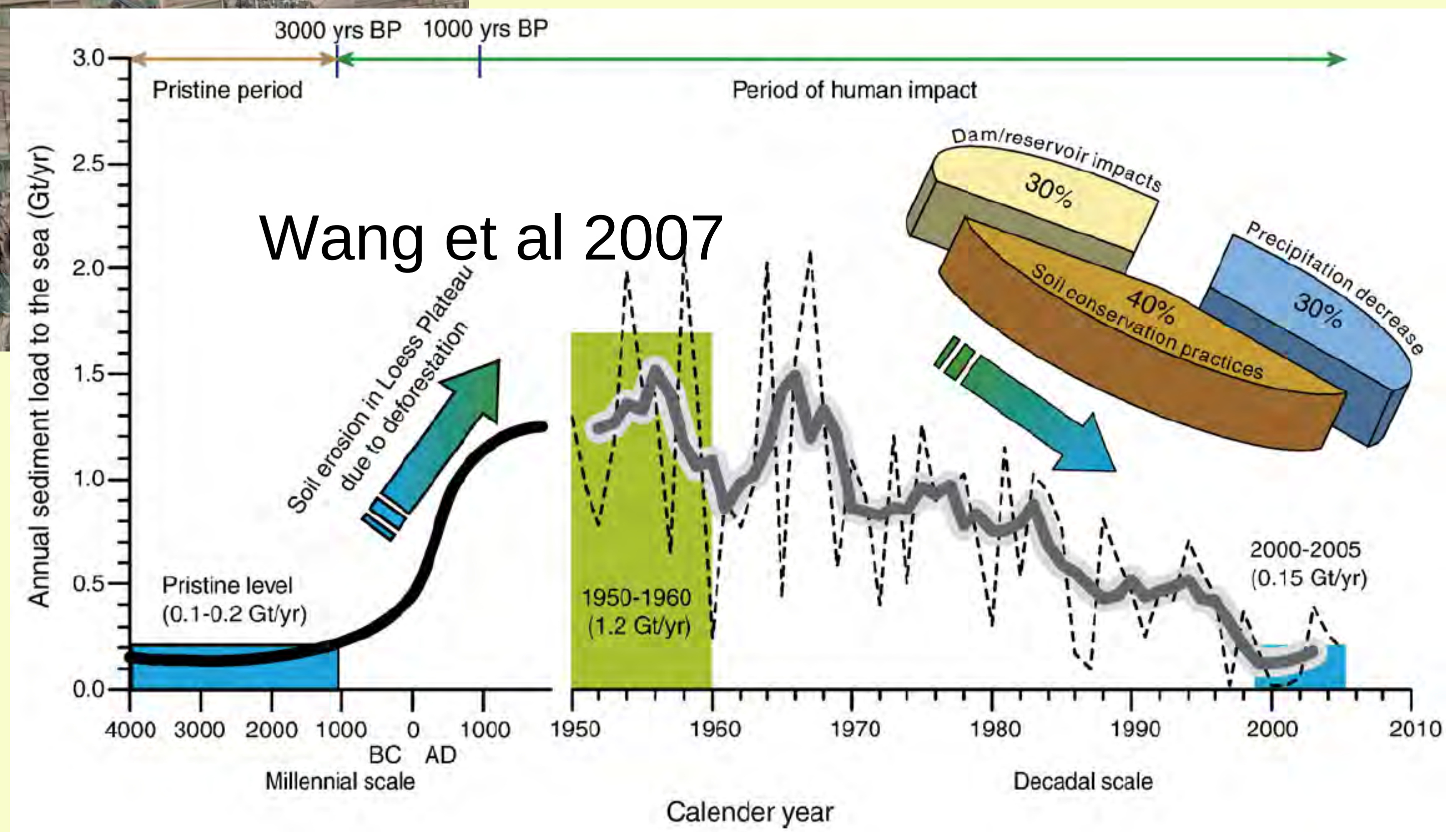
Anthropocene impacts on geomorphology & sediment flux

Tillage, terracing: soil erosion, creep, siltation



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



Wang et al 2007

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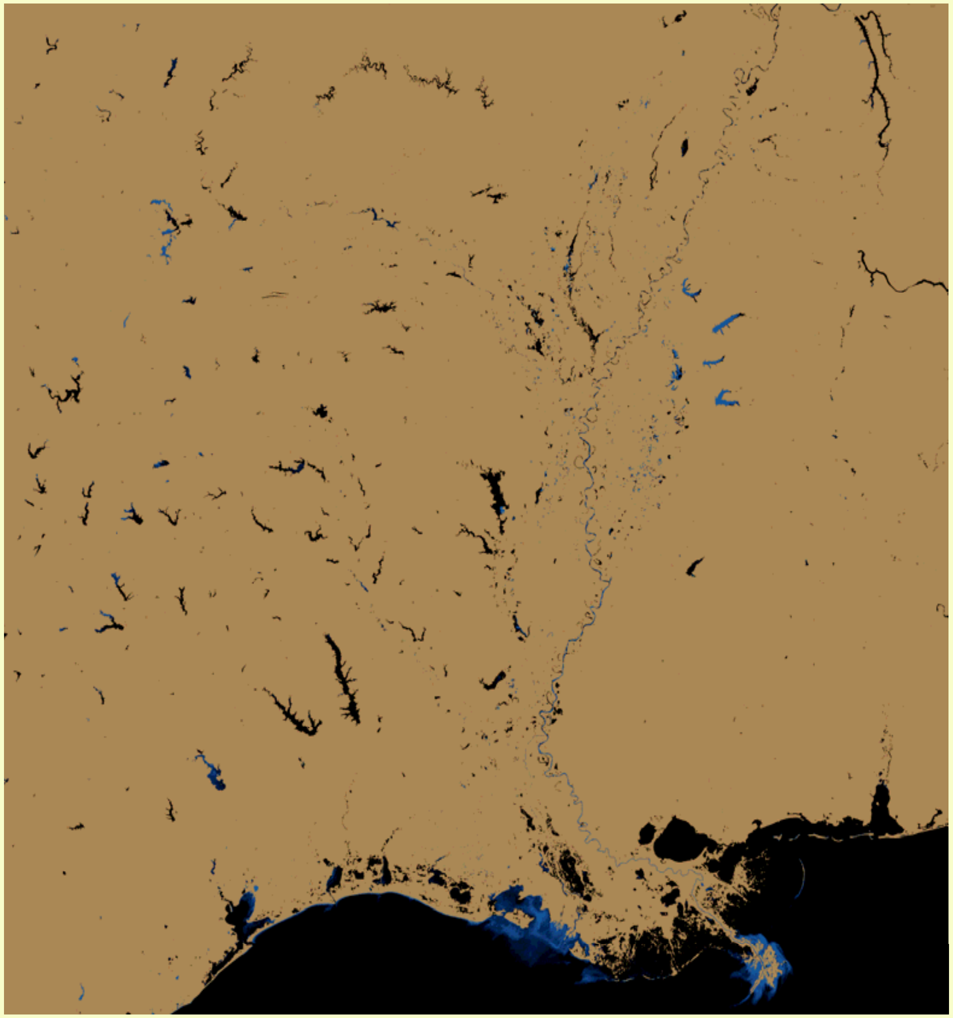
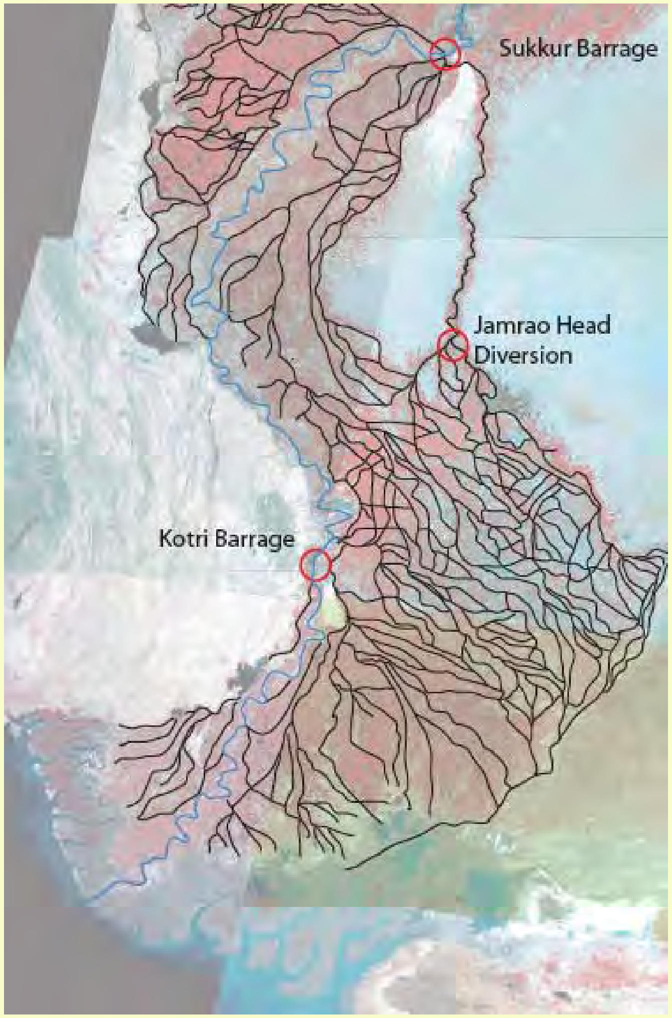
Anthropocene impacts

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





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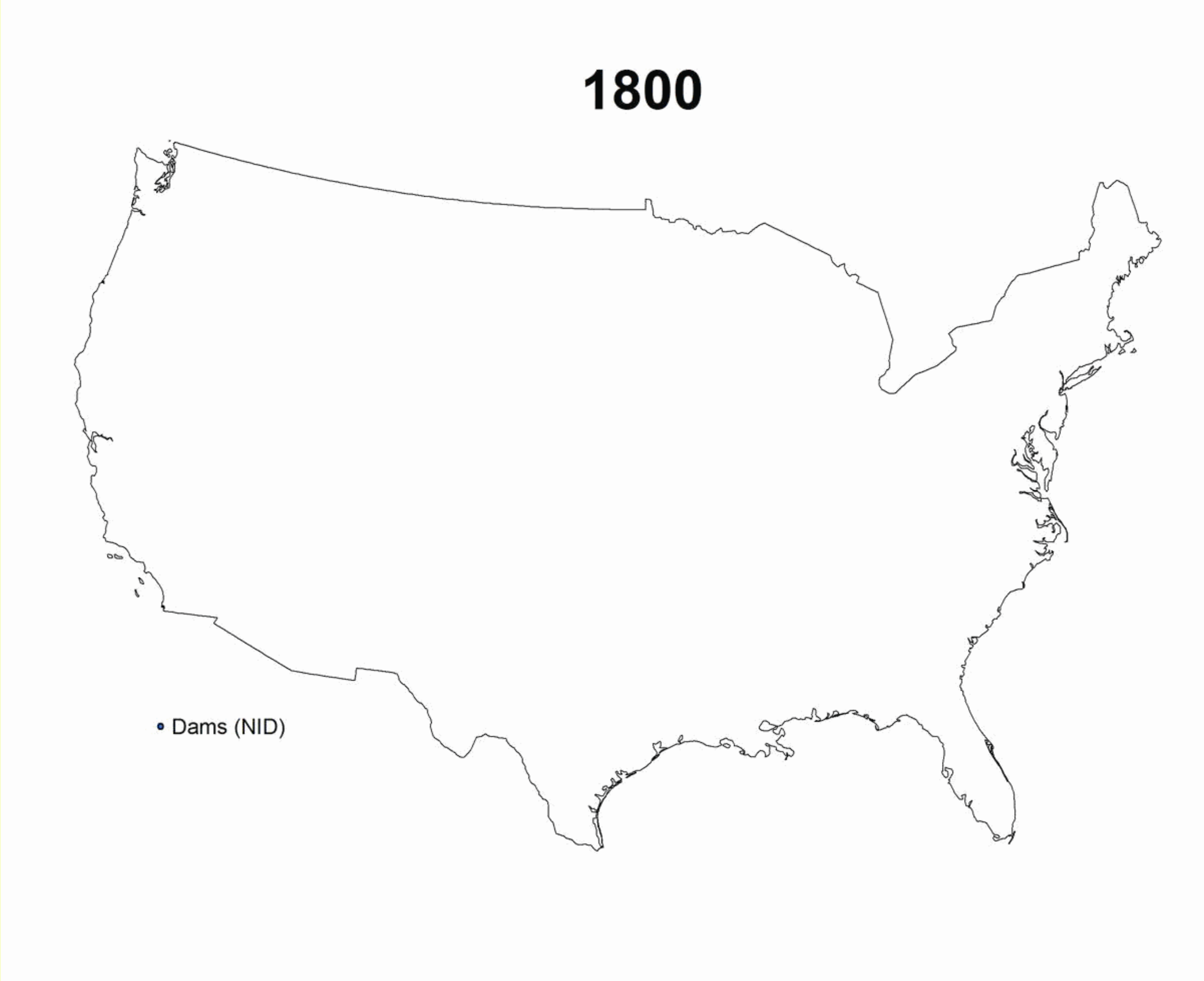

Reservoirs

❖2.3 Gt/y LESS sediment reaches the coast worldwide

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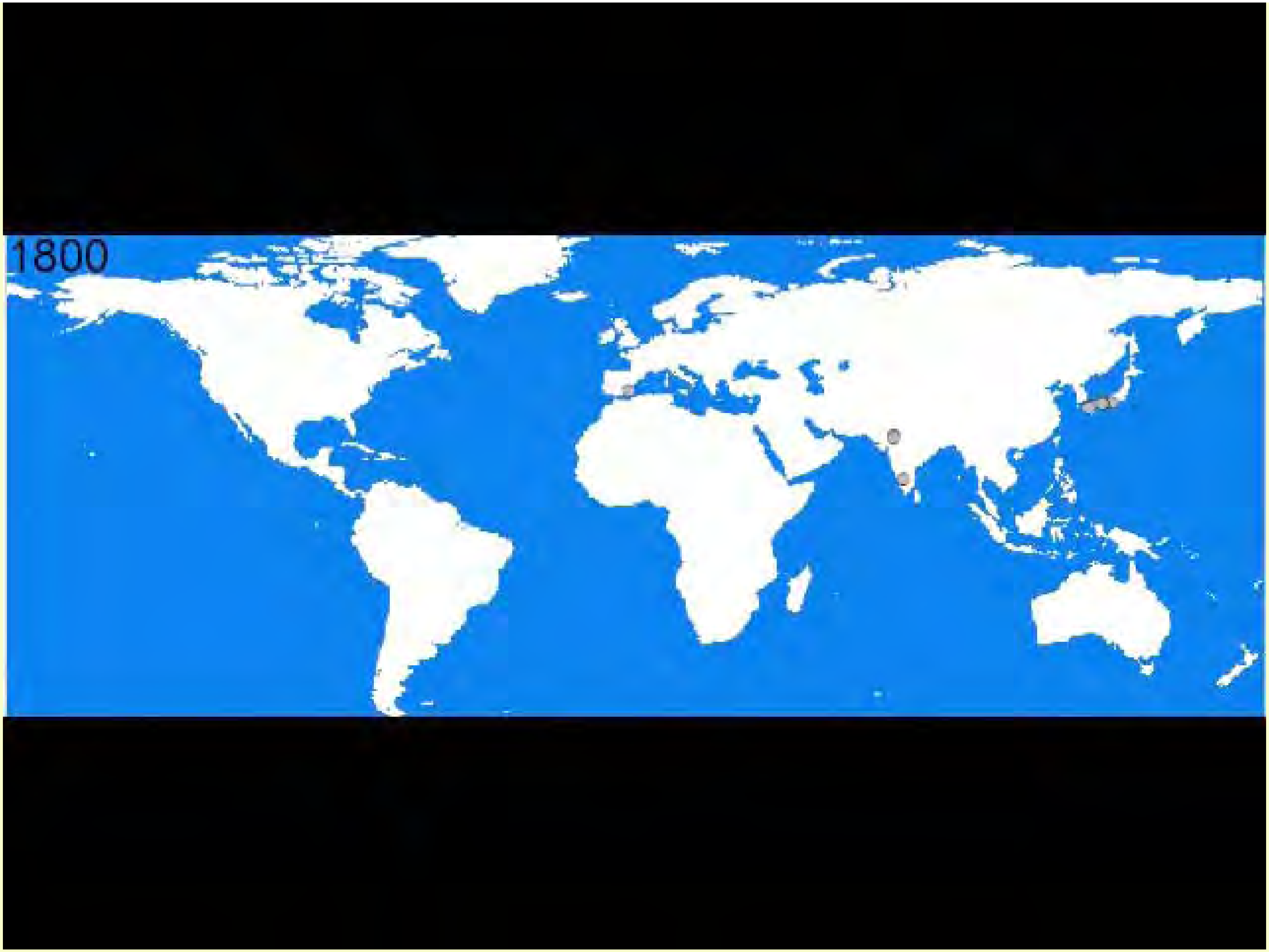

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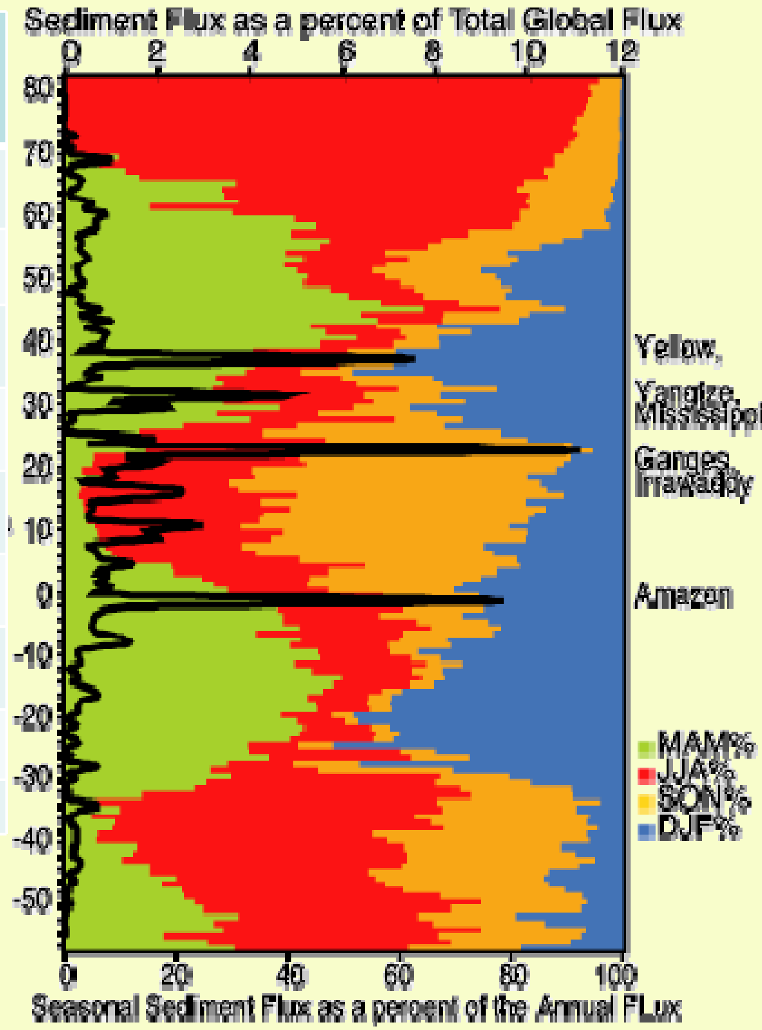
Continent	*Q* (km^3/y)	*Qs* with Humans (Gt/y)	*Qs* Pre-Humans (Gt/y)
Africa	3797	1.1	1.6
Asia	9806	4.8	5.3
Australasia	608	0.28	0.24
Europe	2680	0.4	0.6
Indonesia	4251	2.4	2.4
North America	5819	1.5	1.7
Oceans	20	0.004	0.003
South America	11529	2.4	3.3
Global	38510	12.8	15.1



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.

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Sediment Transfer & Storage: Floodplains

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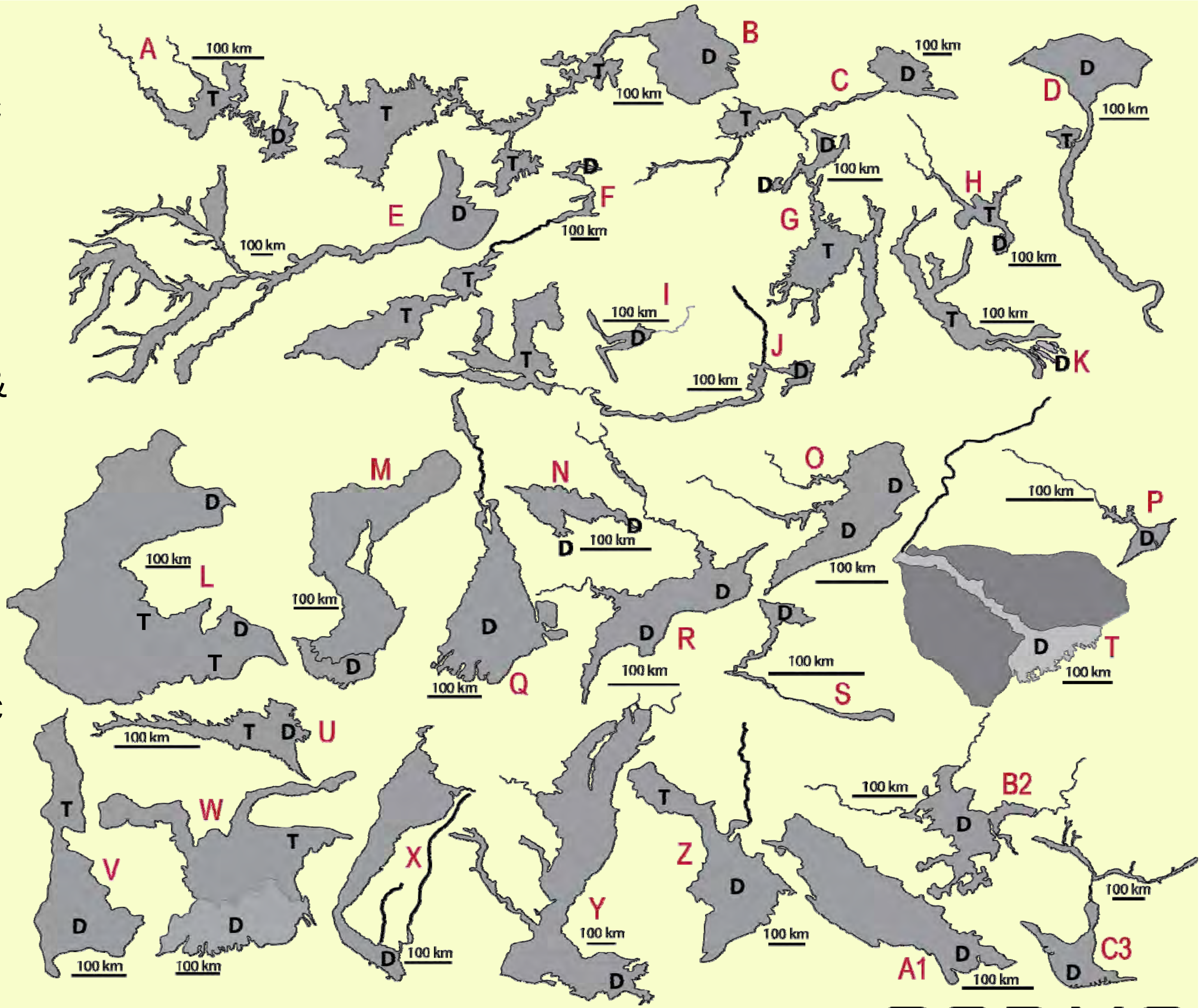
Rorschach Art

- •33 Late Quaternary floodplains & deltas
- •boundaries are ≤100 m asl
- •**D** = delta;
- •**T** = tectonic depression



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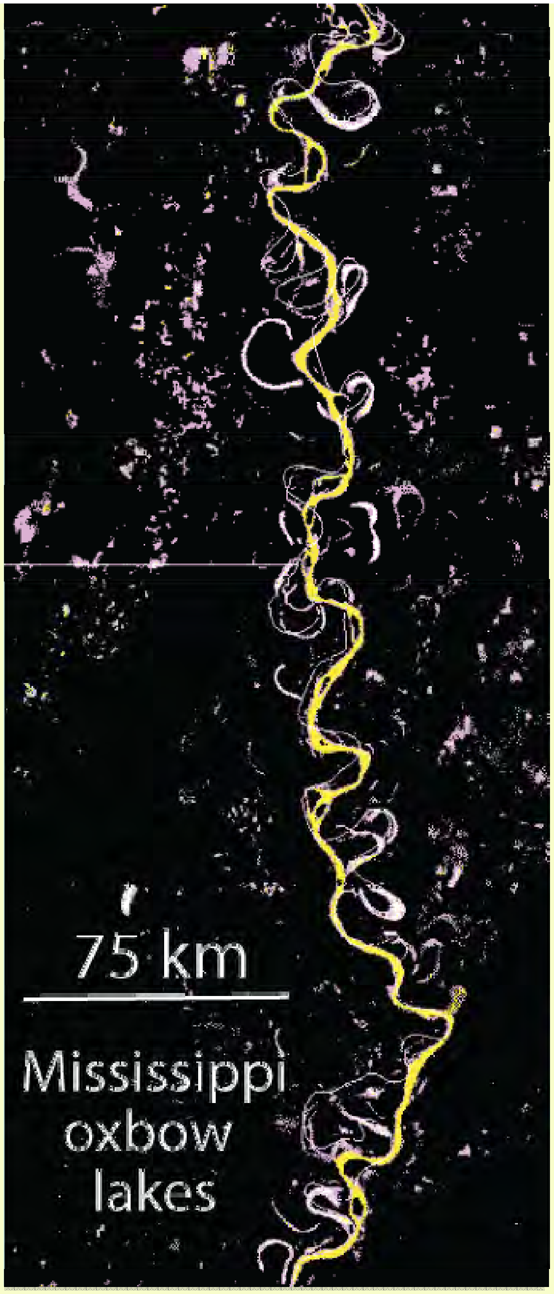

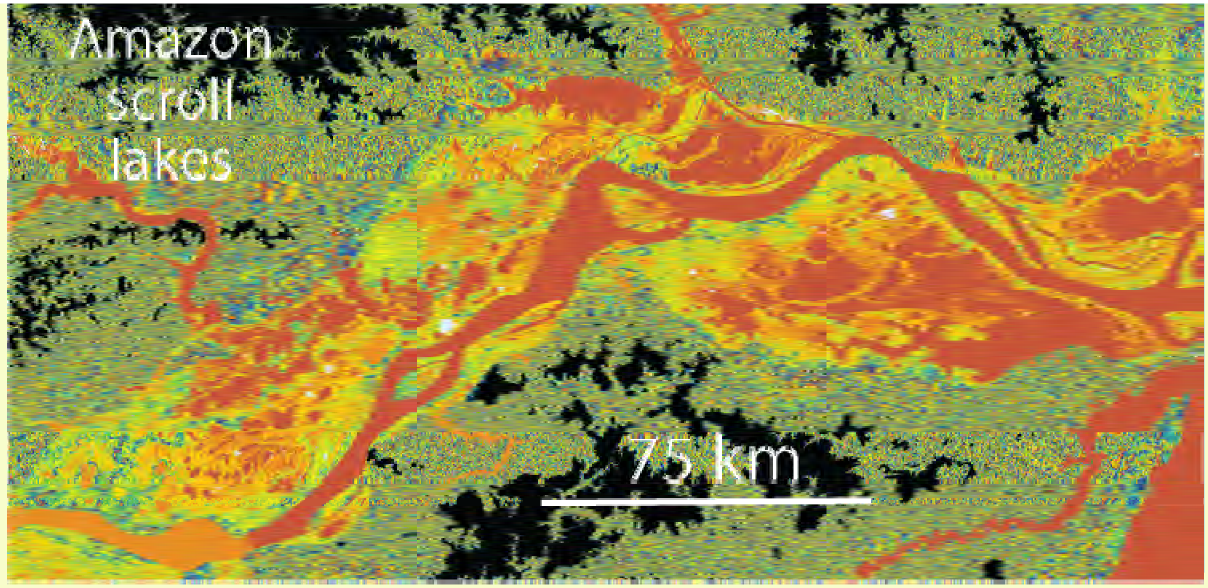

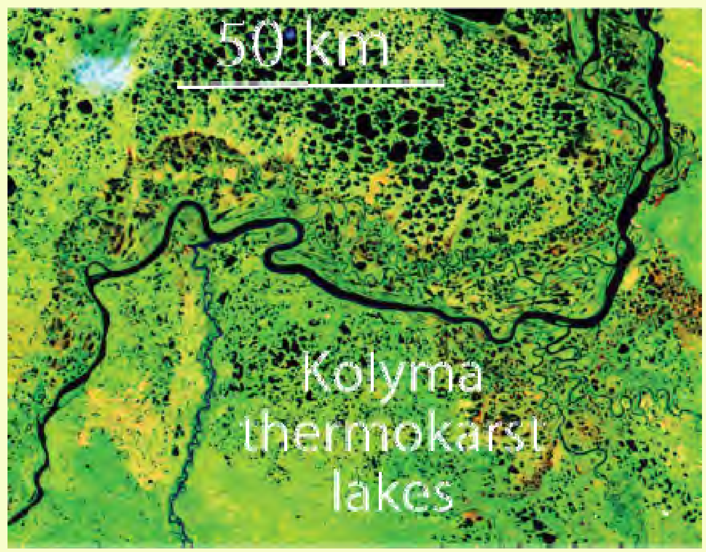

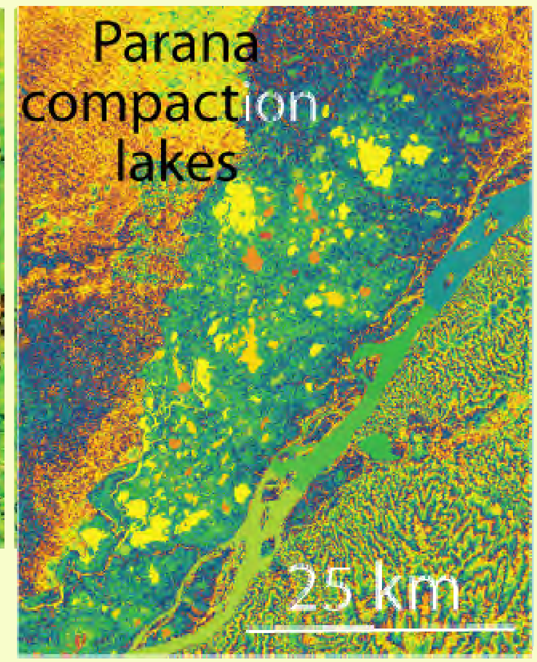

Lakes are a common element of floodplains where flood waters can sequester sediment

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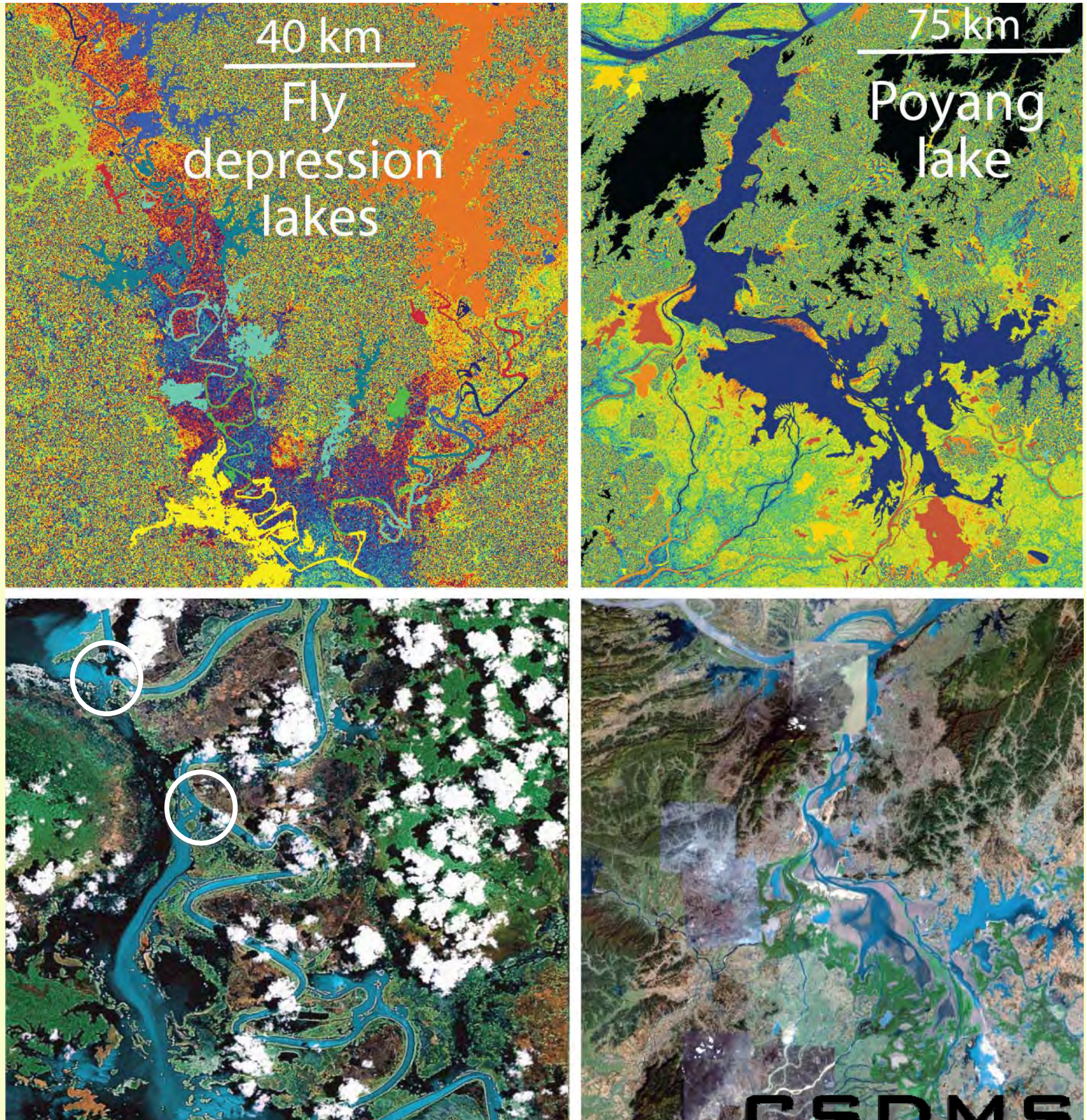
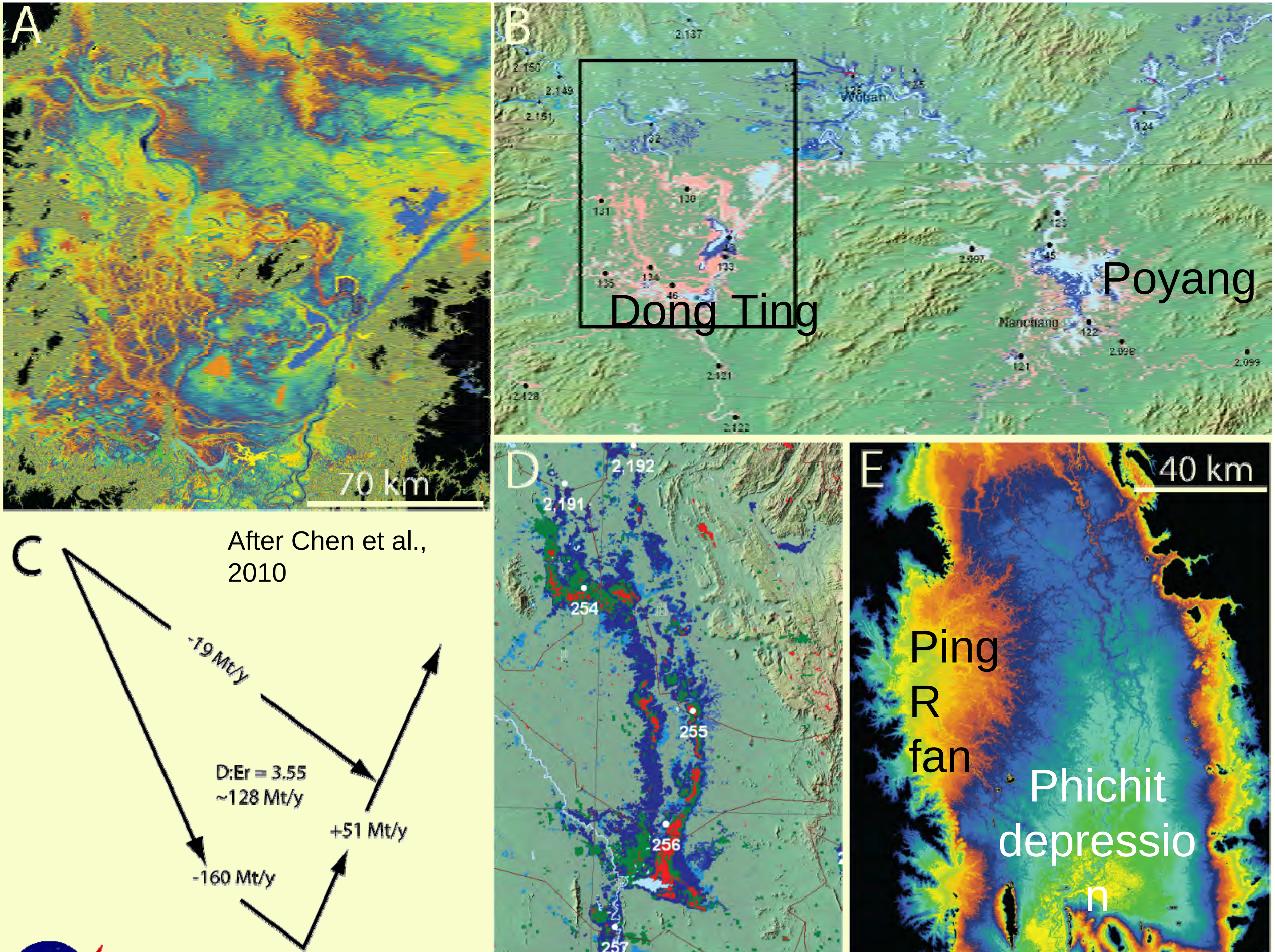
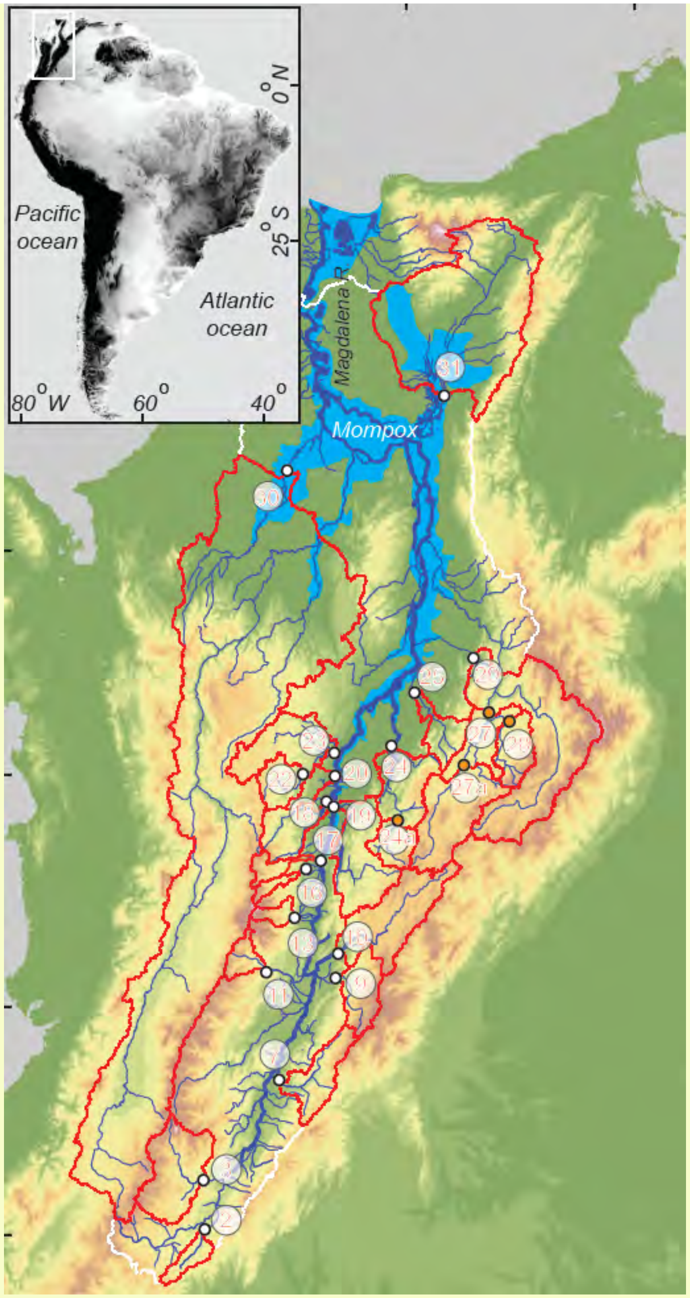
Tectonic Depressions: have a few common characteristics — no one is diagnostic:

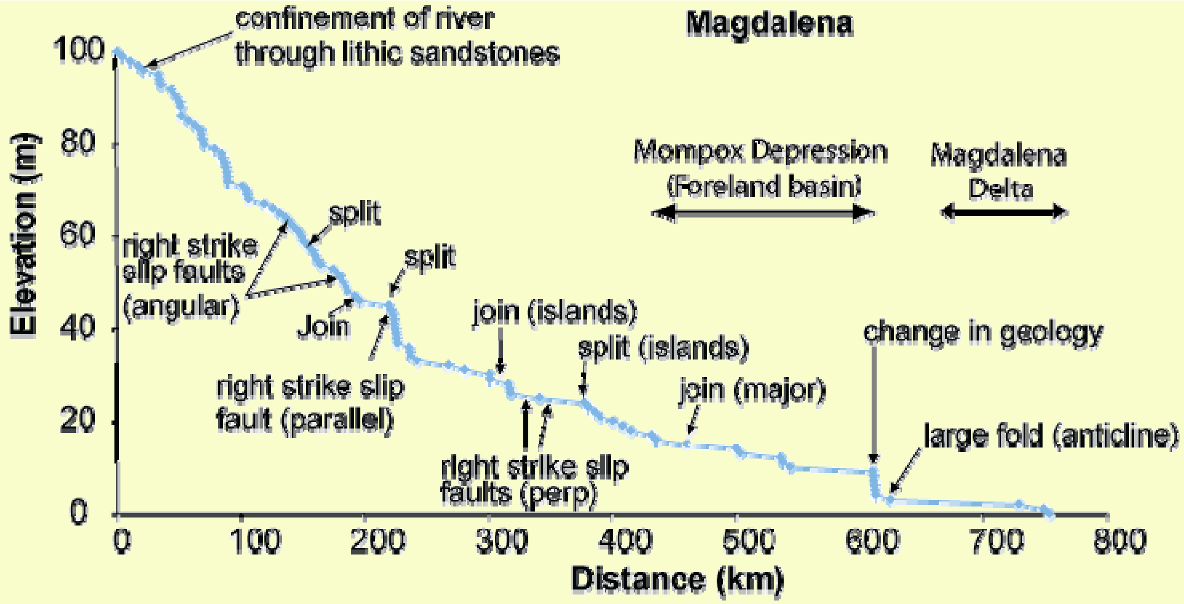
- ➢ statistically flatter down-valley slopes;
- ➢ expanded valley widths;
- ➢ multiple overflow channels similar to deltaic distributary channels;
- ➢ lakes connected to the main river channel;
- ➢ highly prone to flooding, often annually;
- ➢ [illegible]ed lakes

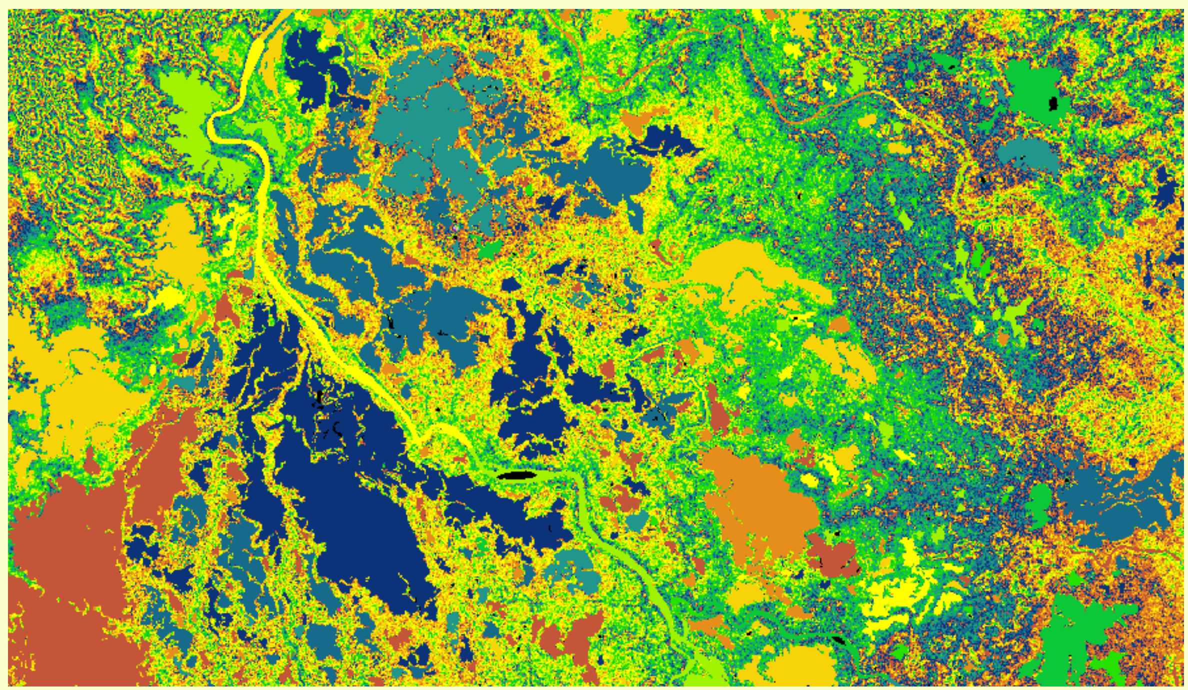




After Chen et al., 2010







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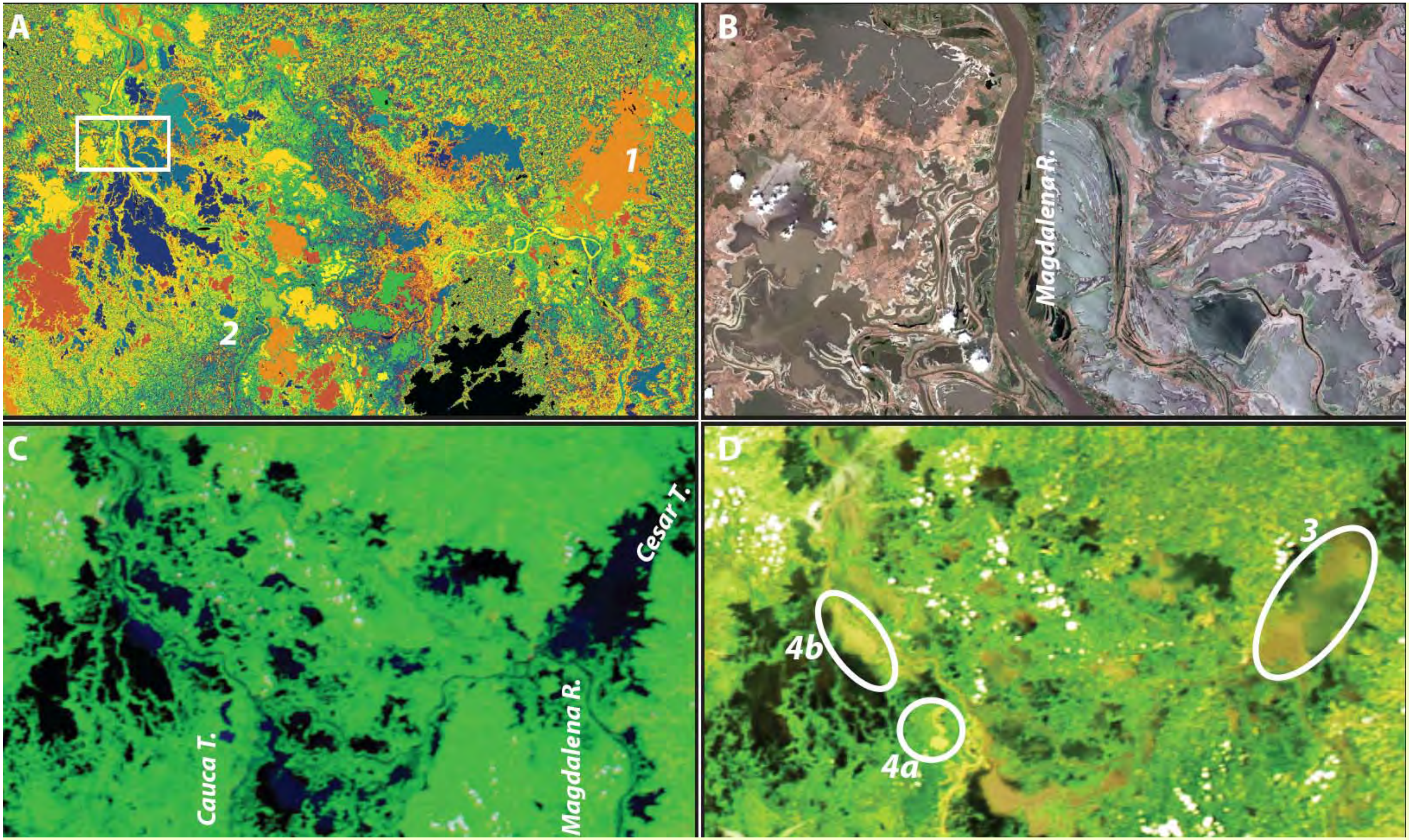

Mompox depression: overflow & levee failures cause extensive flooding (April – Nov)
Over last 7500 y, aggradation rate is 3–4 mm/y with deposits 10m to 130m thick
With 27 yr of observation, 14% of Magdalena sediment load is trapped *Kettner et al., 2010*

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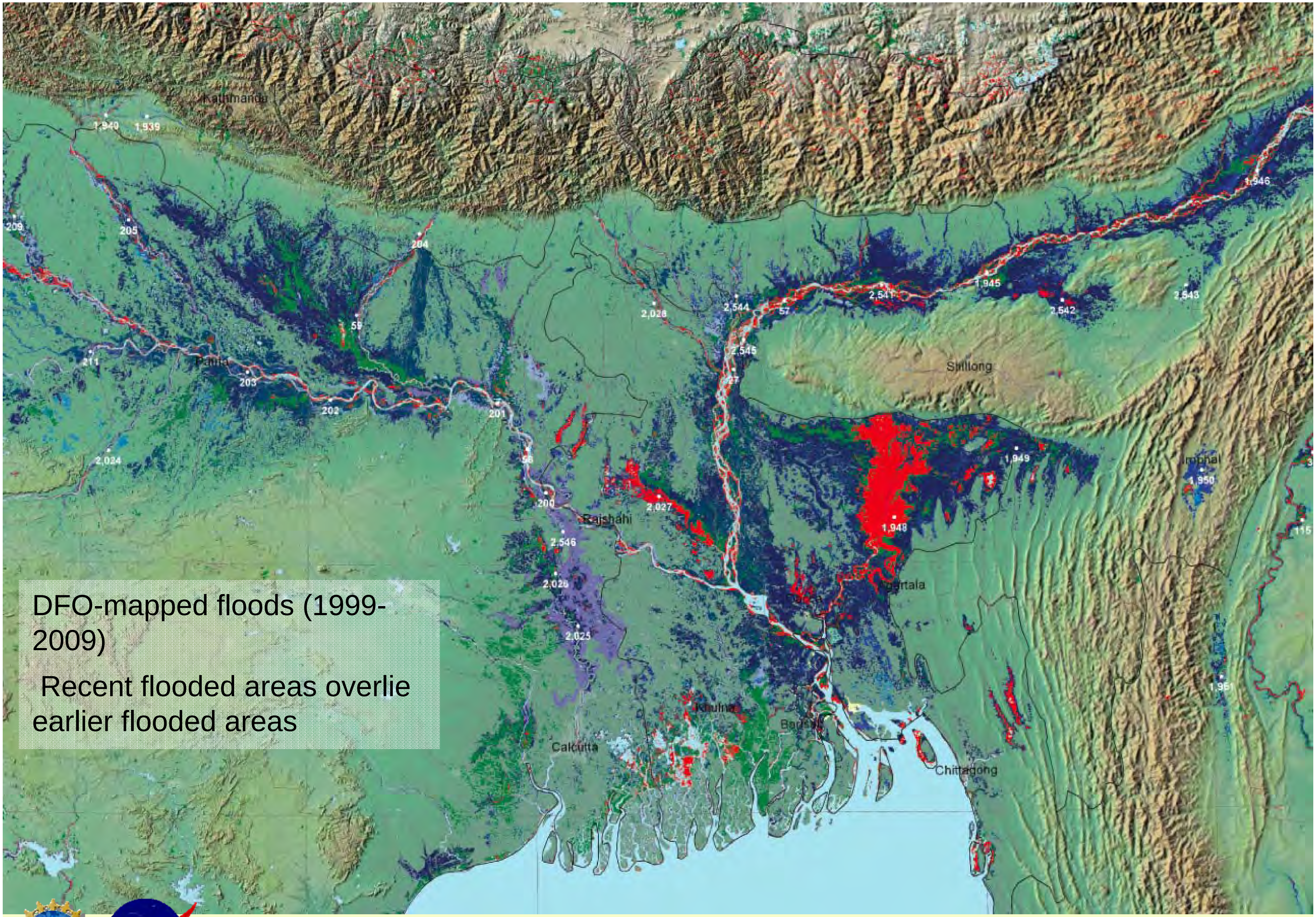

DFO-mapped floods (1999-2009)

Recent flooded areas overlie earlier flooded areas

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NSF NASA

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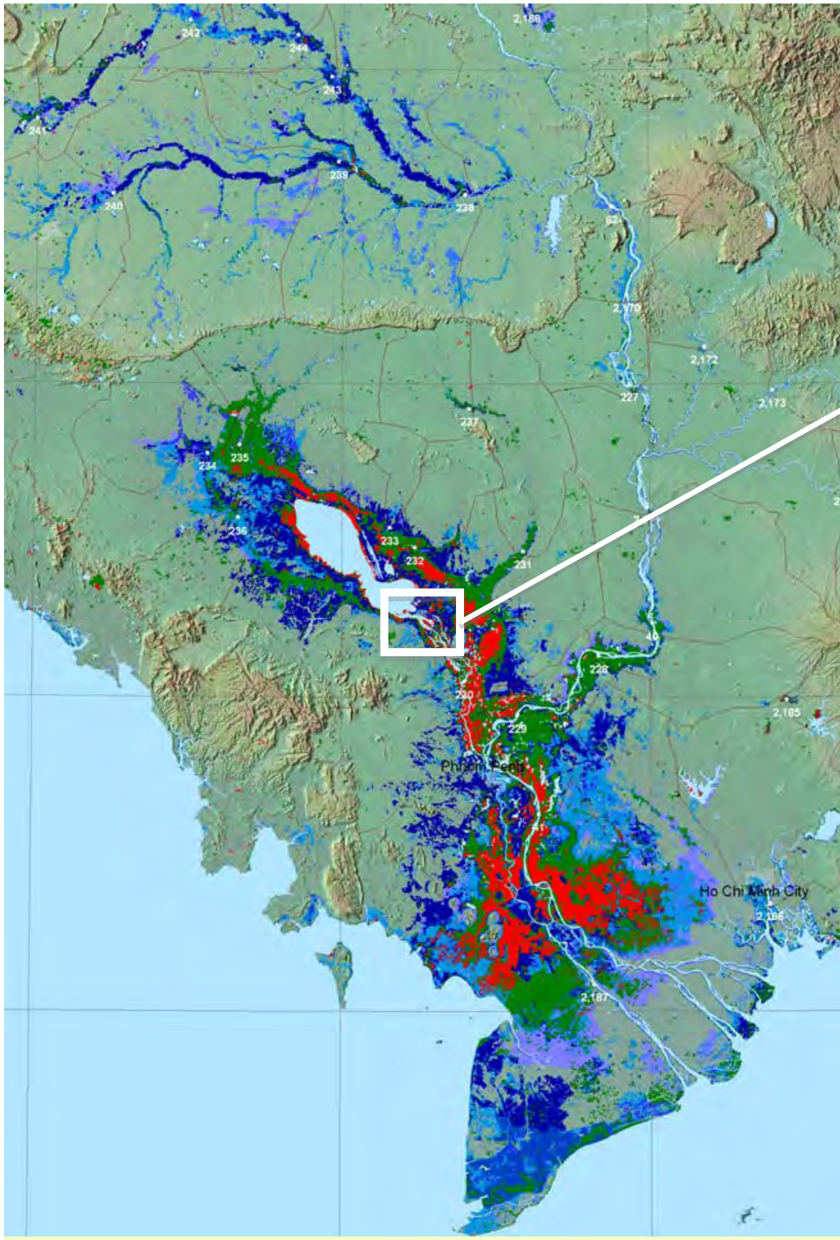

Mekong River (Vietnam) flooding (backfilling) of the tectonic depression Tonle Sap (Cambodia) with both water and sediment

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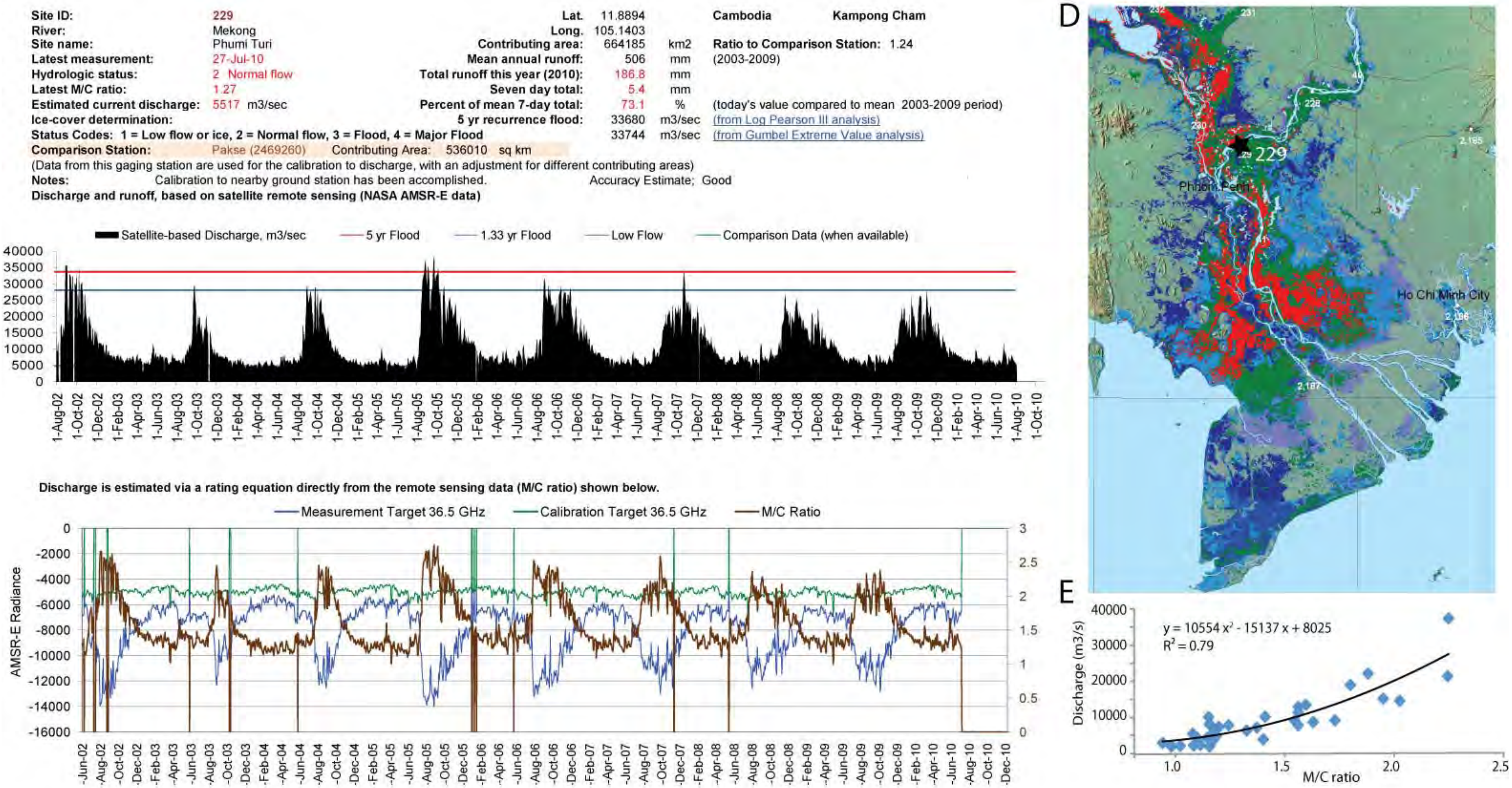

Microwave-sensed river discharge: A) DFO-River Watch station 229 July 27, 2010, Mekong River. B) Daily discharge-AMSRE (2002-2010). C) Daily radiance river reach target, calibration target & M/C ratio. D) Station location. E) International station calibration employs monthly means where station data are available. U.S. and European River calibration uses daily in situ discharge data.

Images are GeoTiffs from either MODIS-Terra or MODIS-Aqua

210 215 220 225 230 235 240 245 250 255 260

DAYS, 2010

100 km

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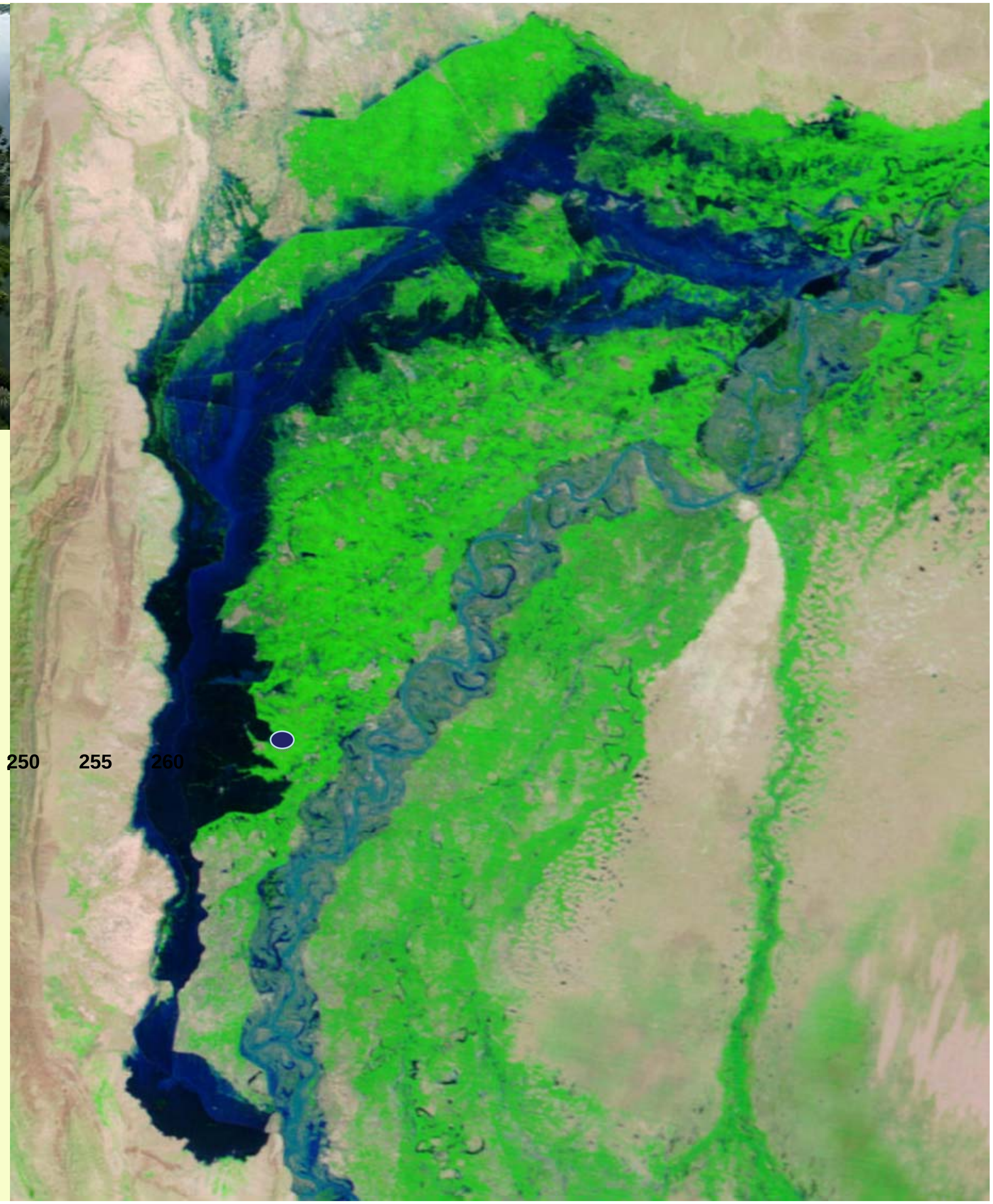

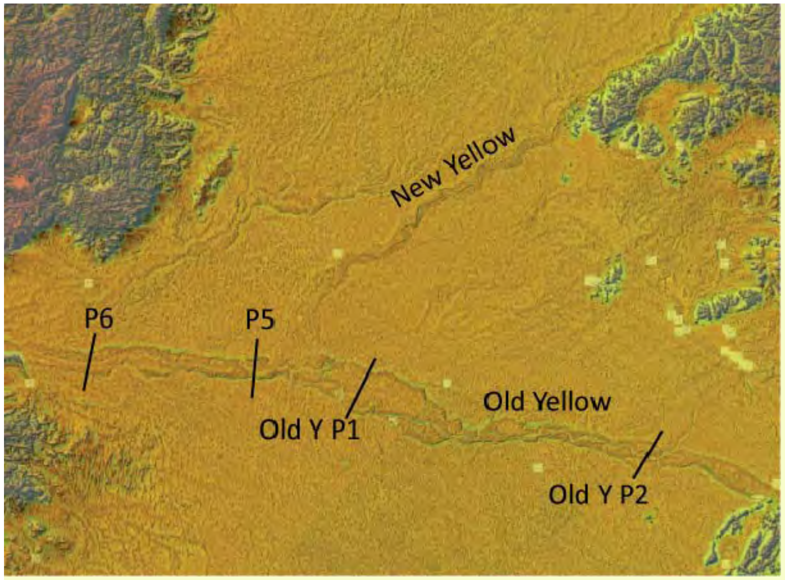

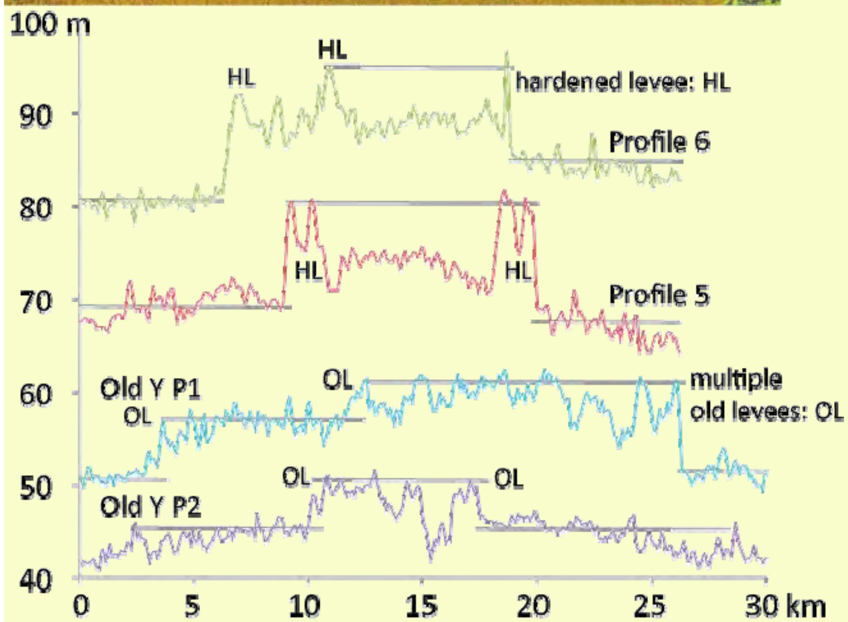

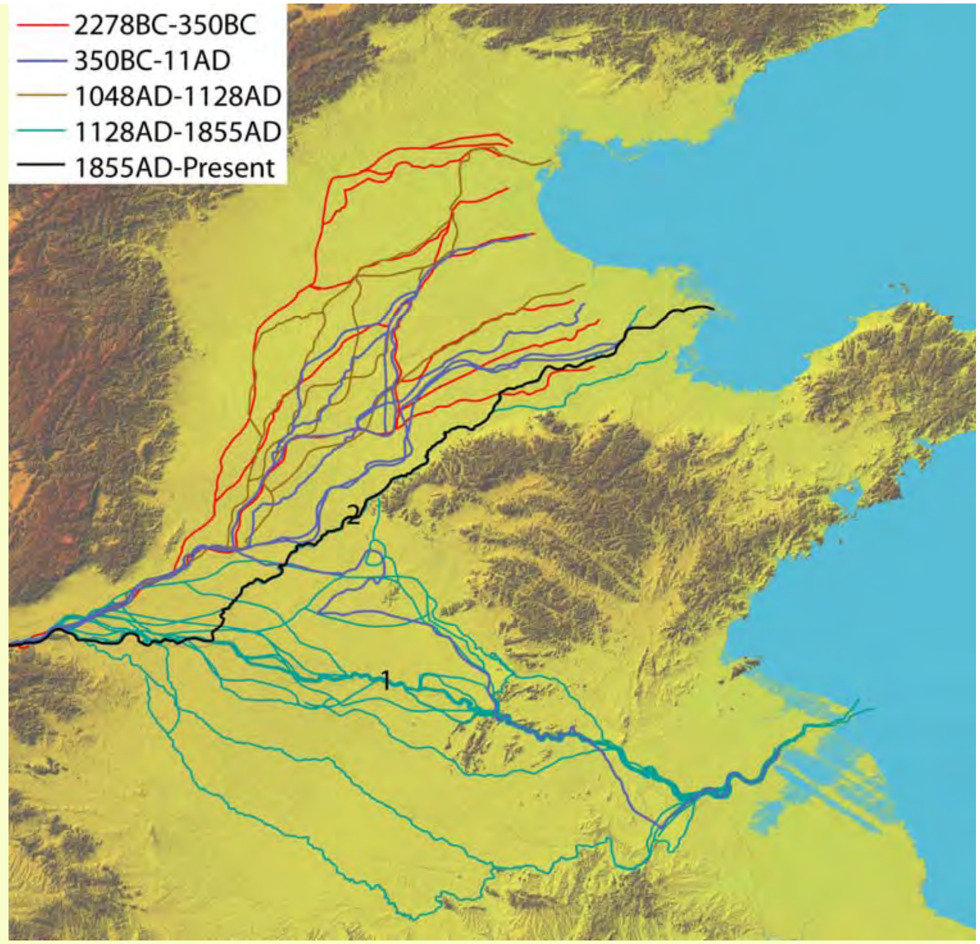

The Yellow once freely migrated across its 700 km wide floodplain and is now fixed as a narrow elevated floodplain.

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

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Sediment Transfer & Storage: Deltas

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Controls on Delta Elevation

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

Δ_{RSL} = Vertical change in delta surface elevation (m/yr)

A	=	Sediment Aggradation Rate (m/yr)
ΔE	=	Eustatic Sea Level Rise (m/yr)
Cn	=	Natural Compaction (m/yr)
Ca	=	Accelerated Compaction (m/yr)
M	=	Crustal Vertical Movement (m/yr)

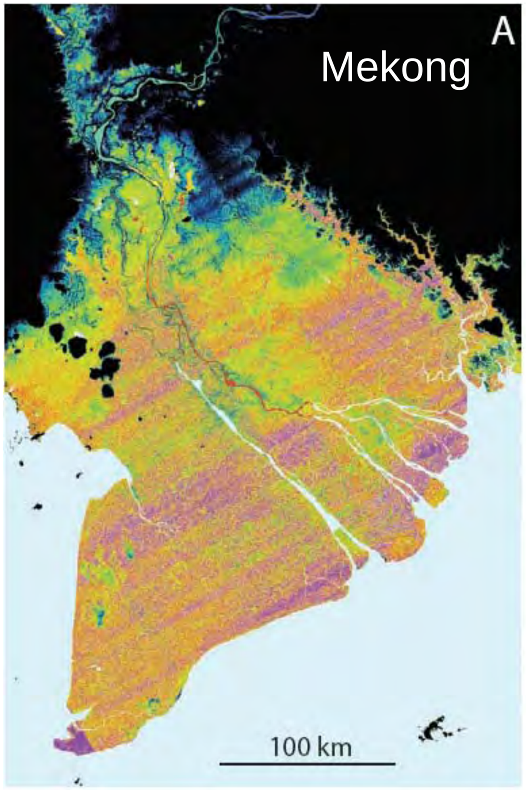
$$\Delta_{RSL} = \pm A - \Delta E - C_n - C_A \pm M$$

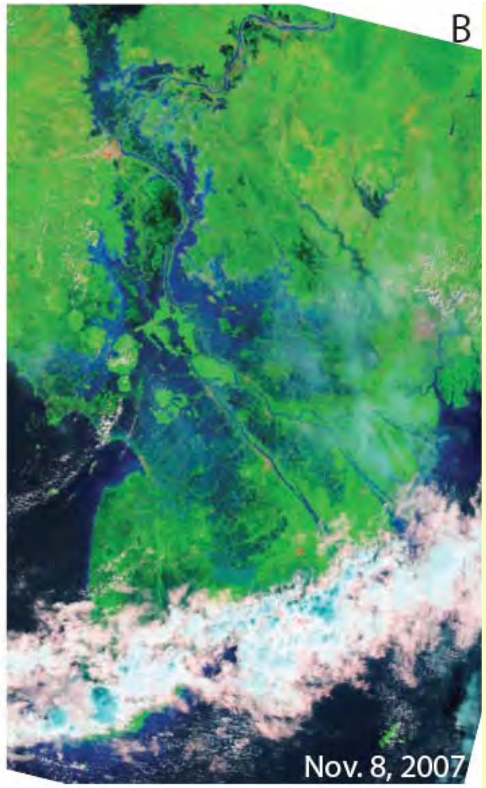
Flooding on deltas can occur from

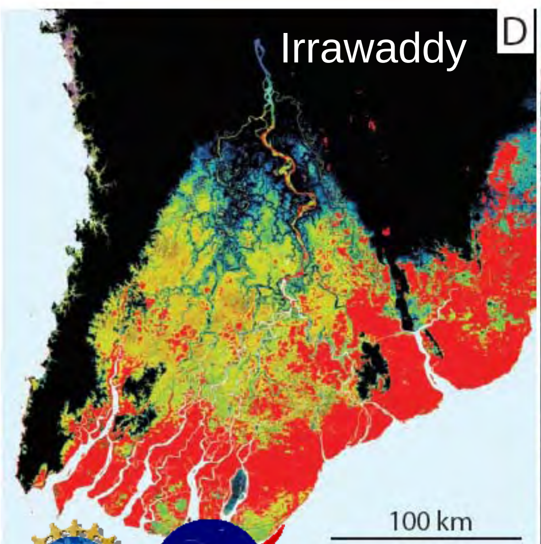
1. Channel overbanking,

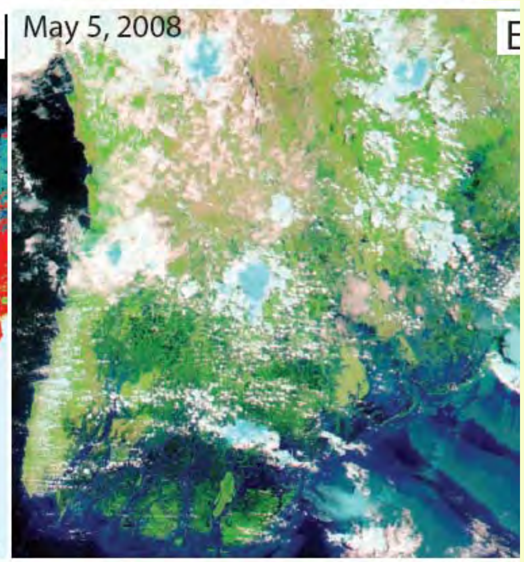
2. Ocean surges (cyclones, tsunamis)

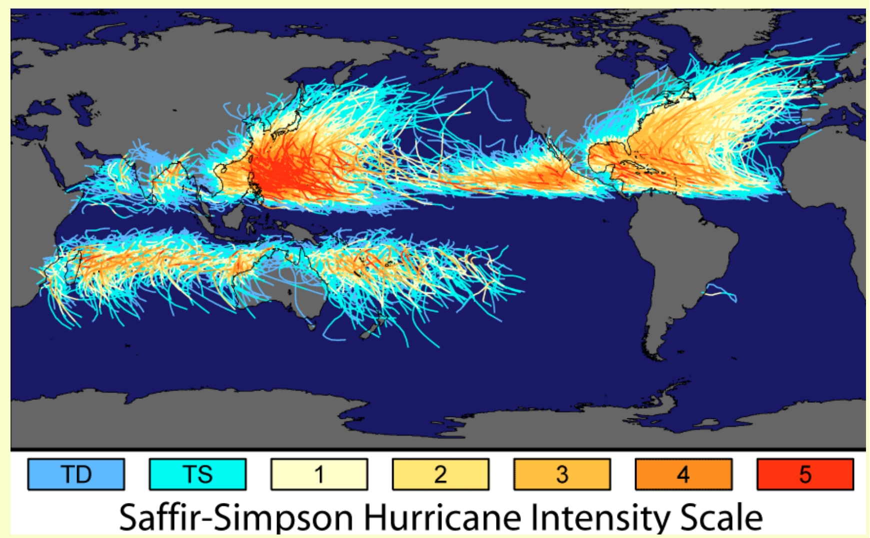
Aggradation will depend on the sediment flux being carried by the flood waters, and the retention rate on the delta











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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.

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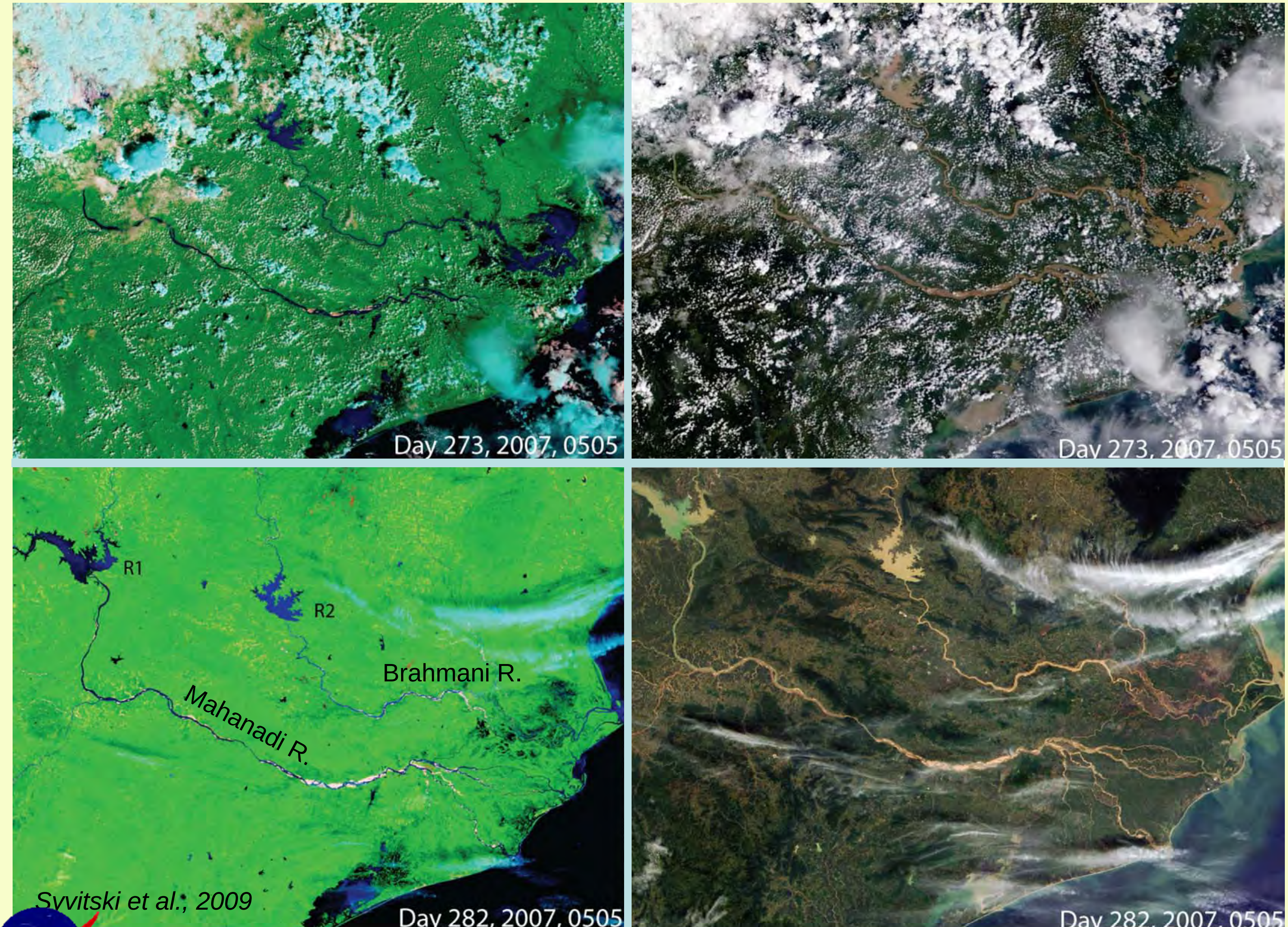
Sedimentation occurred between distributary channels from overbank flooding.



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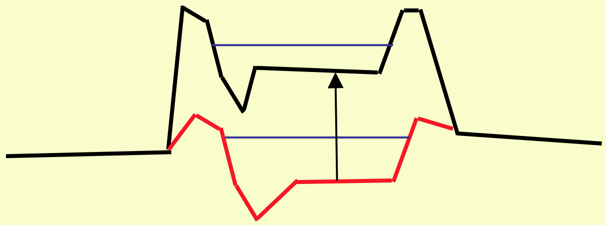
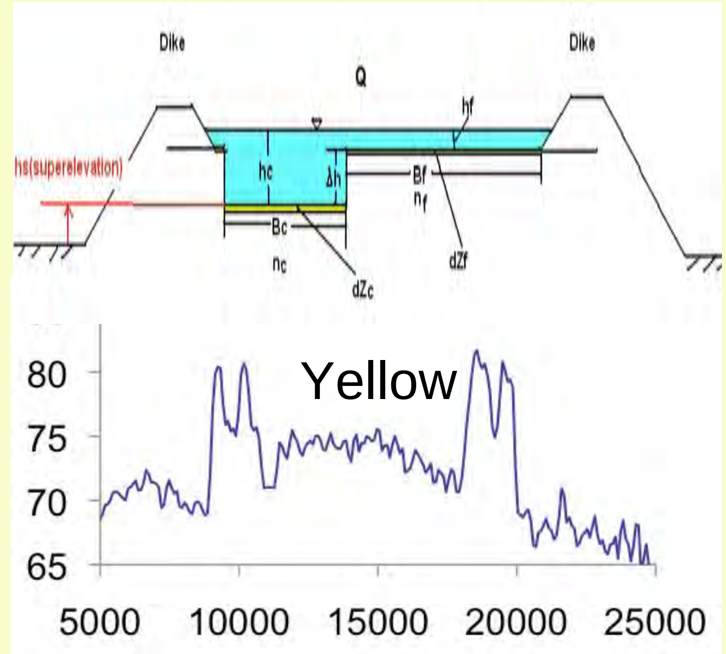
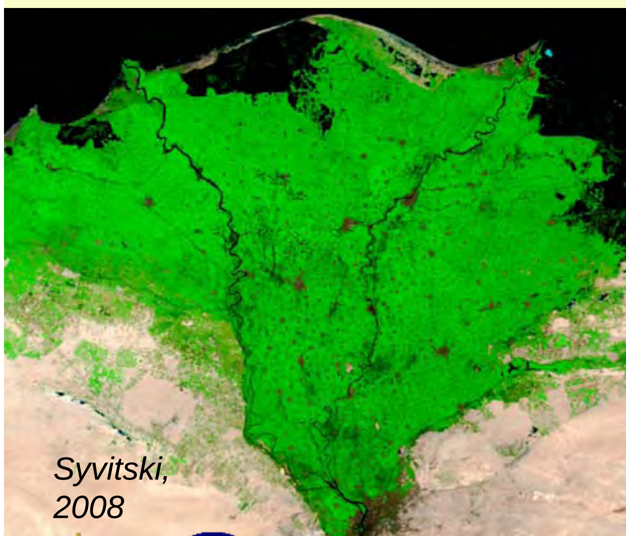
Channel Retention: — Deposition within distributary channels

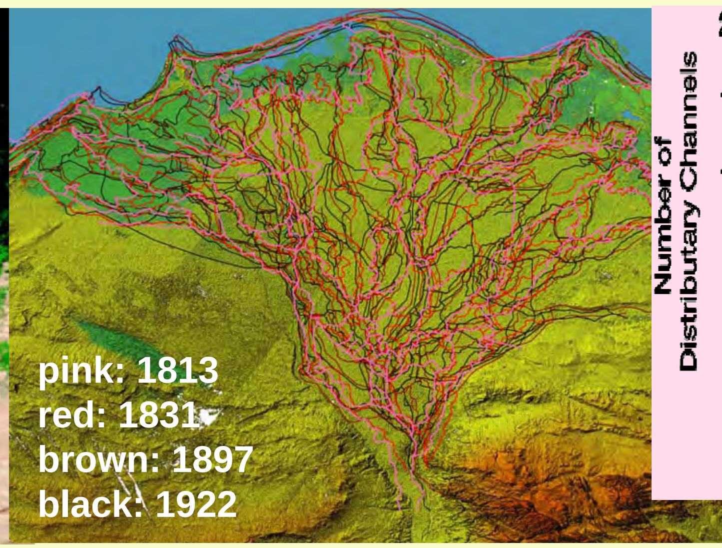


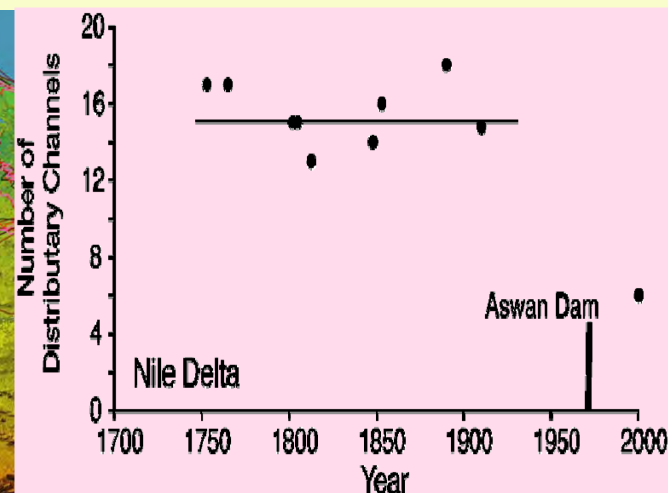
Stop-banks super-elevate the riverbed above the floodplain.



Aggradation from migration of channels.







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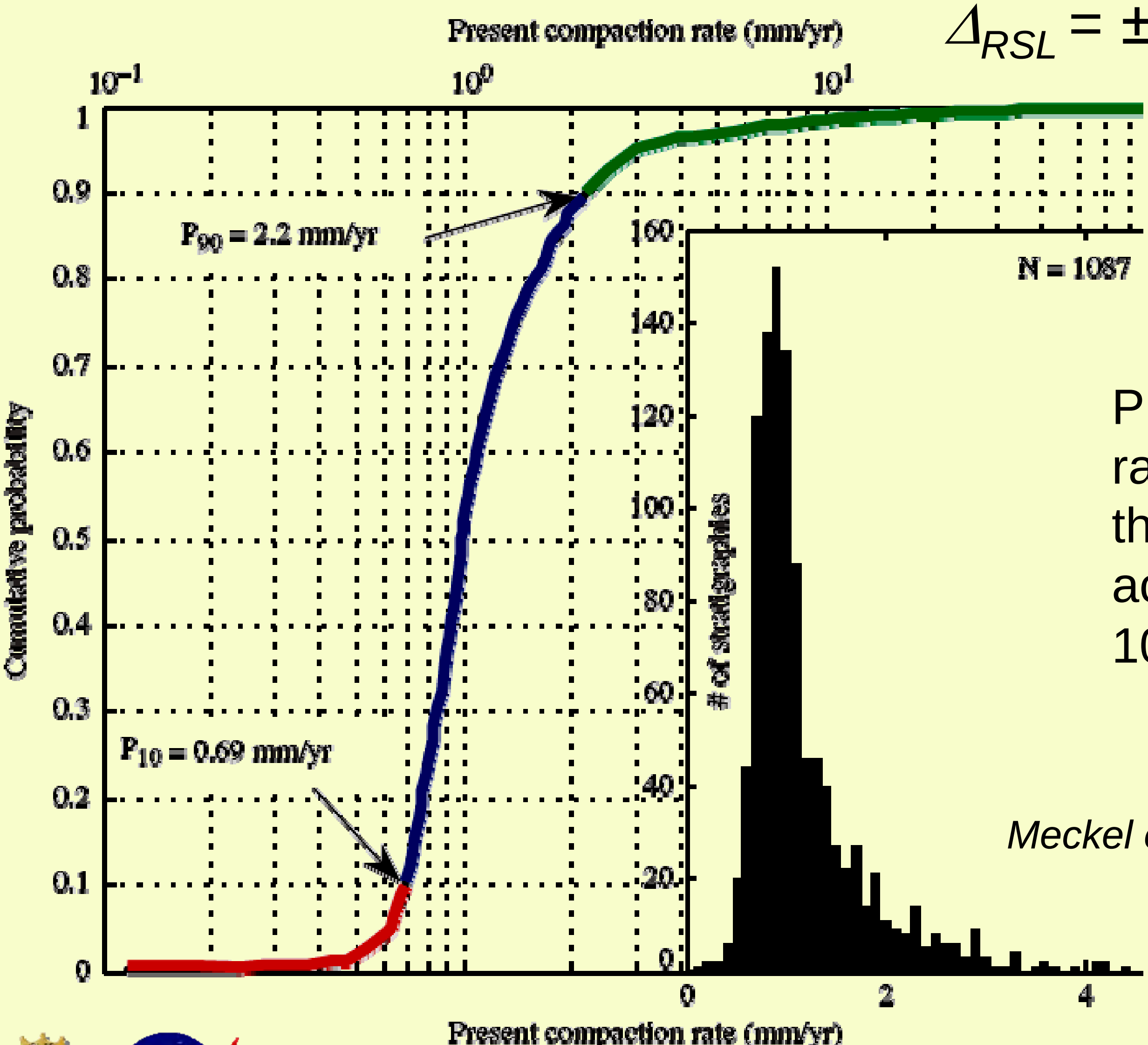
Natural Compaction Rates changes in the void space within sedimentary layers (dewatering, grain-packing realignment, organic matter oxidation)

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



Present compaction rates for deposits with thickness of ≈100m and accumulation time of ≈ 10Ky.

Meckel et al., 2007

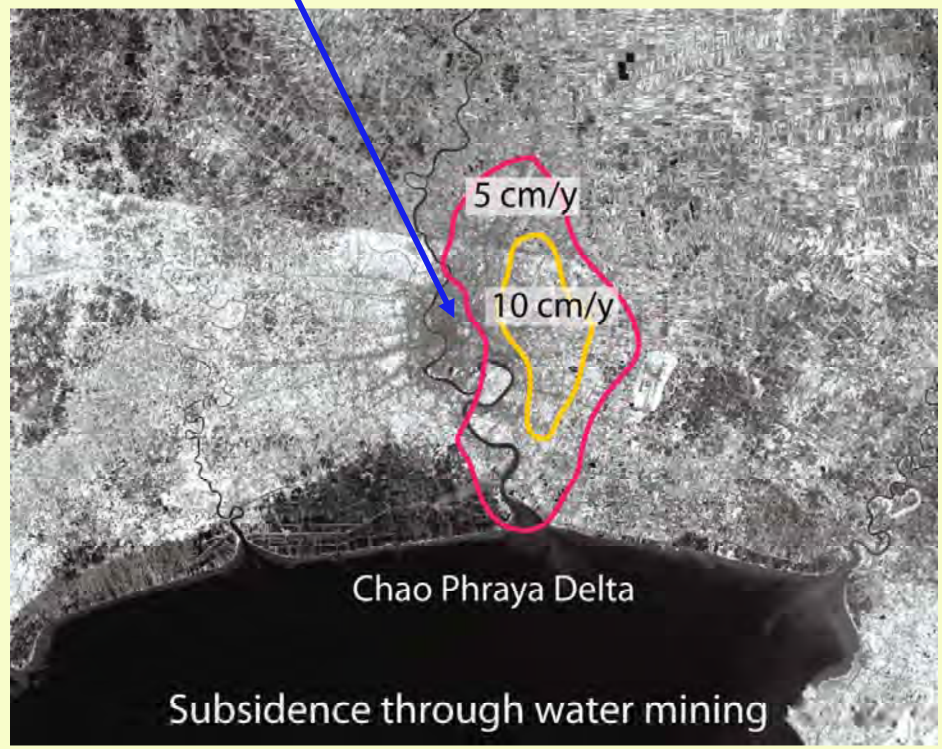
Accelerated Compaction Rates

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

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

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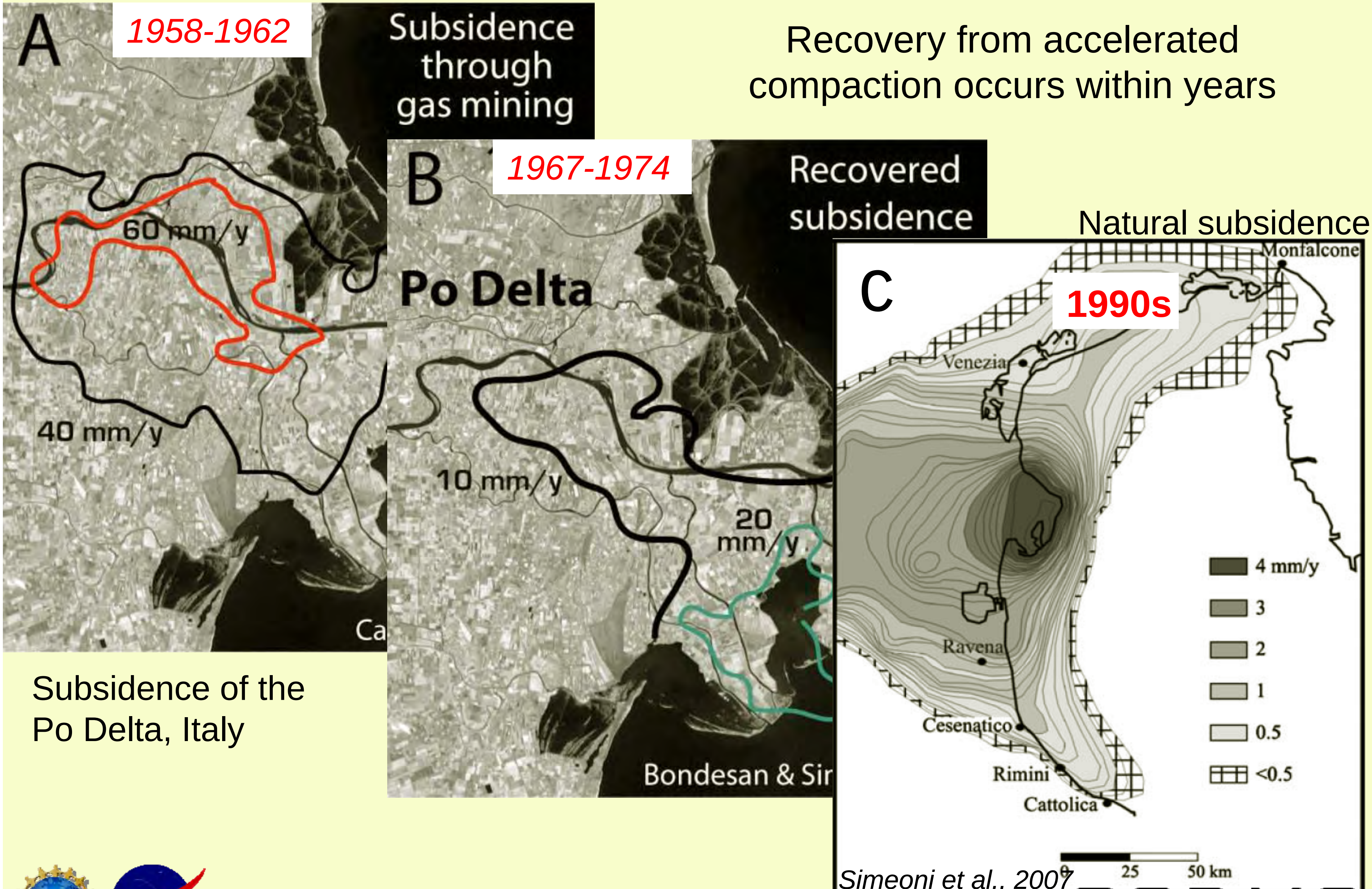
Accelerated Compaction Rates

Recovery from accelerated compaction occurs within years



Subsidence of the Po Delta, Italy

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

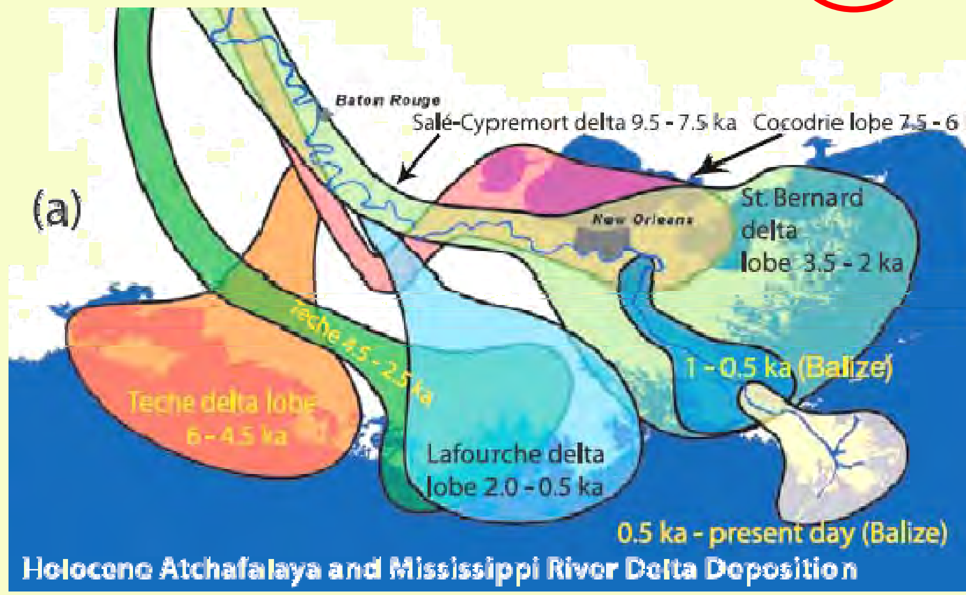
Crustal Subsidence

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

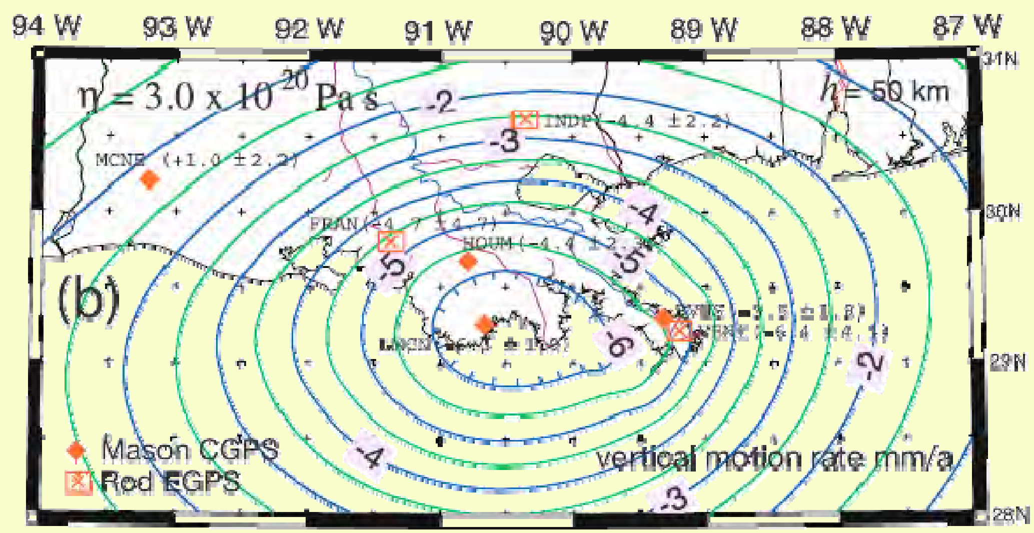
Mississippi delta lobes weigh between 200 to 900 billion tonnes. Today the various Mississippi lobes are sinking at between:

1)0.3 to 3.6 mm/y (Hutton & Syvitski, 2008)

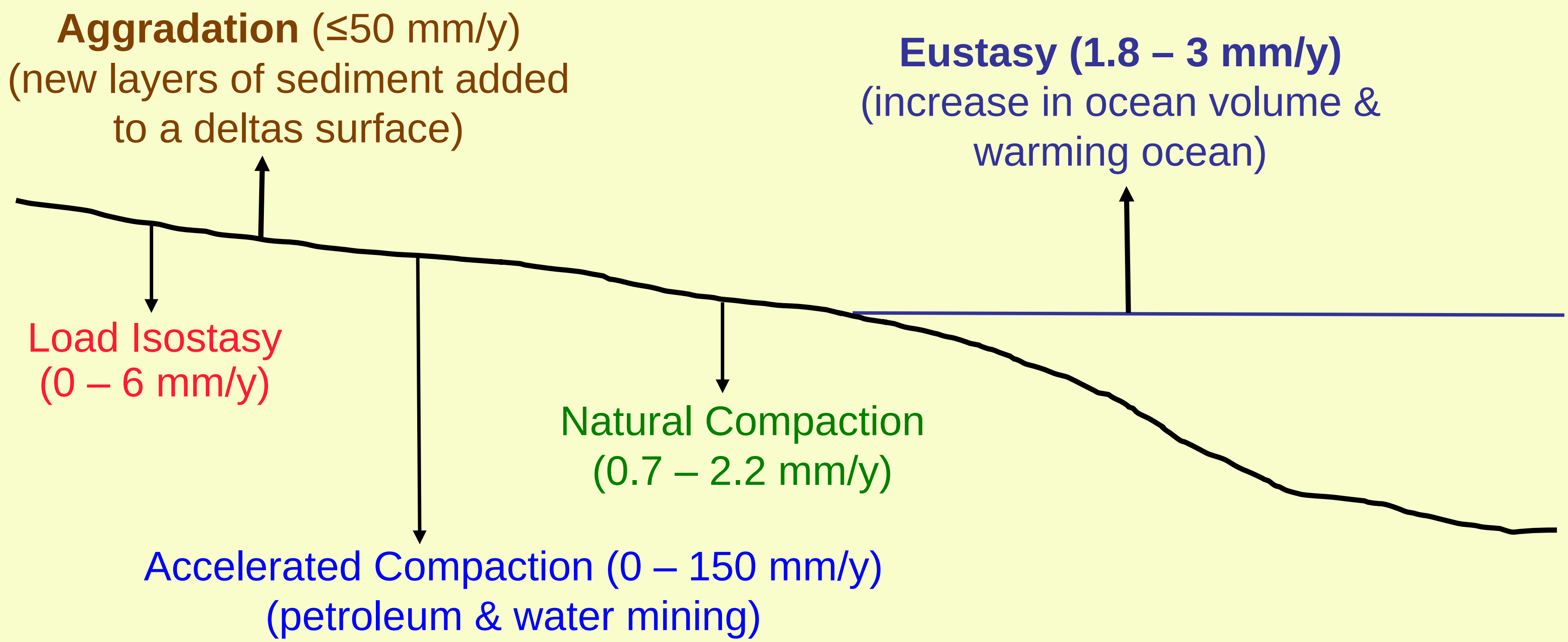
2) 2.0 to 6 mm/y (Ivins et al., 2007)



Ivins et al., 2007



Net Changes in a Delta's Relative Sea Level



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) $-15 = 5 - 3 - 2 - 13 - 2$

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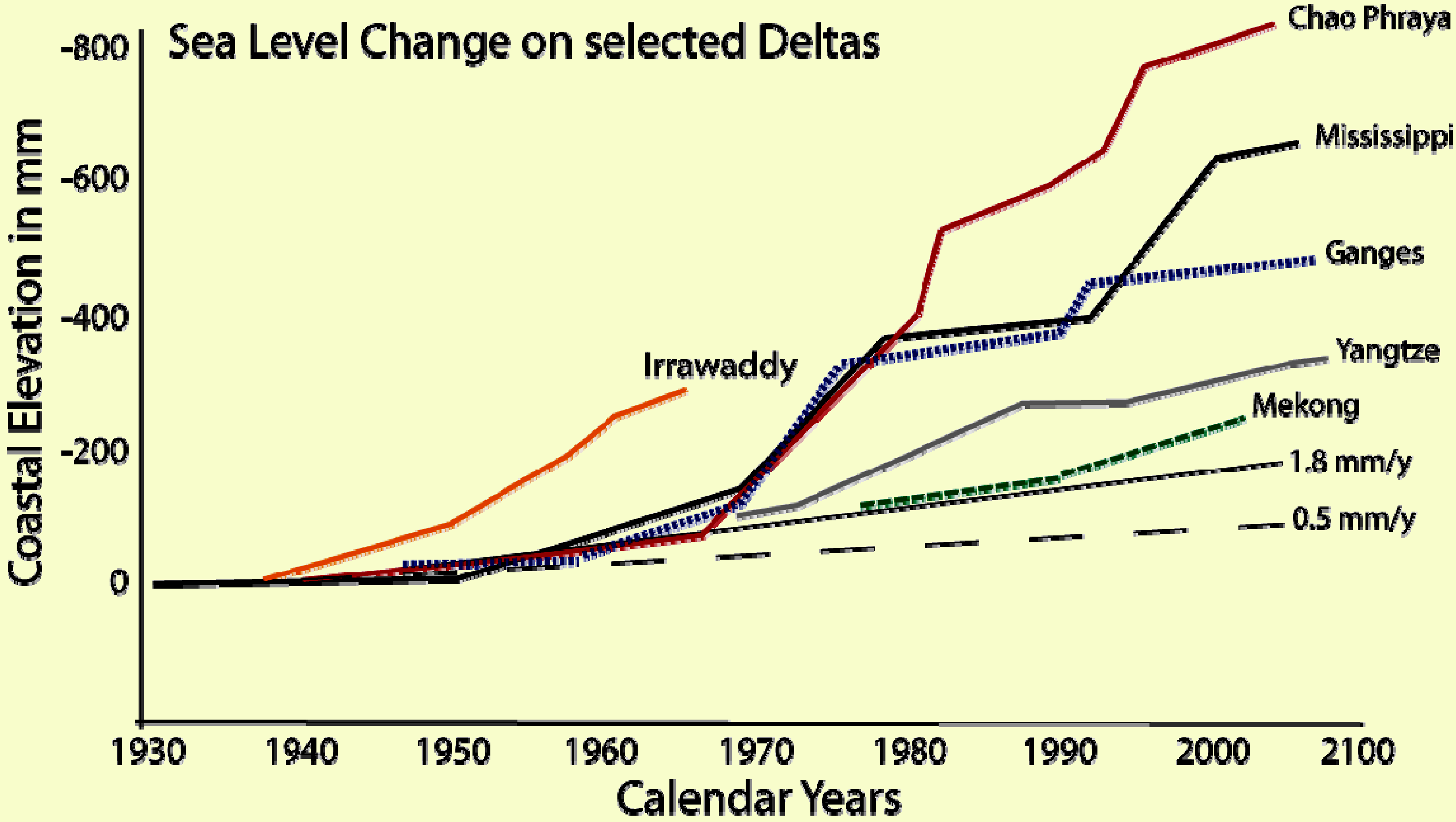
Relative sea level has risen 4 times faster along deltas than the global average.



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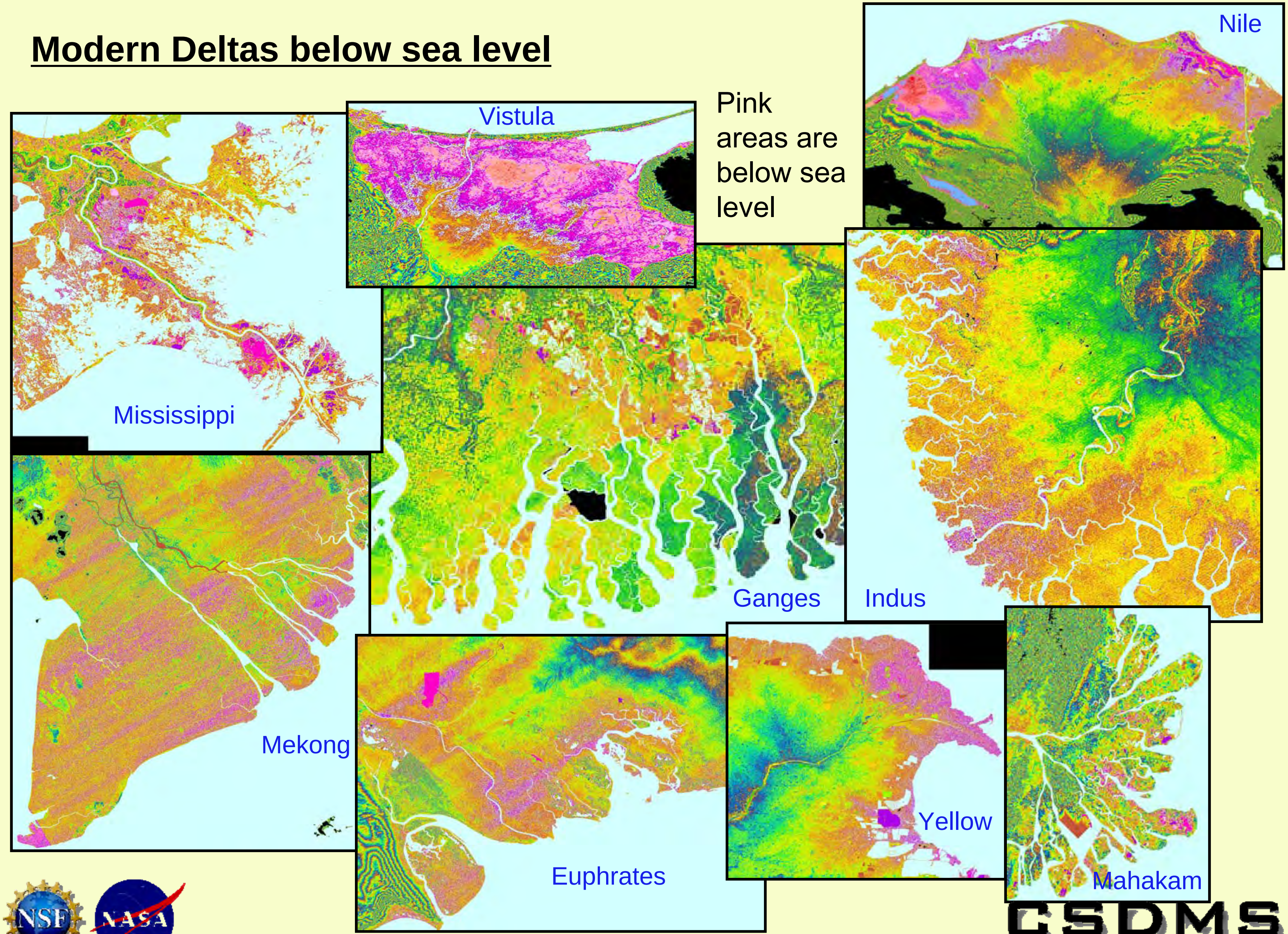
Modern Deltas below sea level



Pink areas are below sea level

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Hyperpycnal discharge is limited to small & medium-sized rivers that drain mountains capable of generating hyper-elevated sed ng infr .

Critical Concentrations, Cs*, for marine hyperpycnal flow conditions

Equatorial: Cs* > 36 - 36.4 kg/m^3
Sub-tropical: Cs* > 38.7 - 39 kg/m^3
Temperate: Cs* > 42 - 43.3 kg/m^3
Sub-polar: Cs* > 43 - 43.5 kg/m^3


Jhuoshuei, Taiwan


Skeidarasundar, Iceland, 1996


Skeidarasundar, Iceland, 1996

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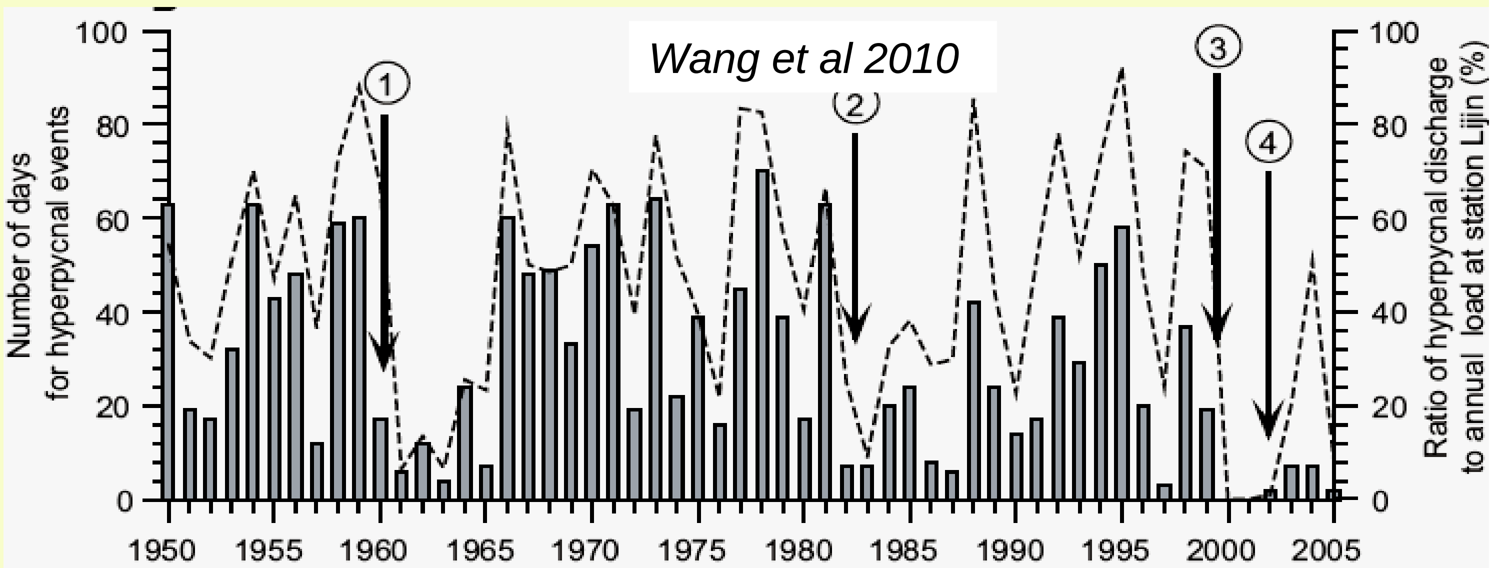
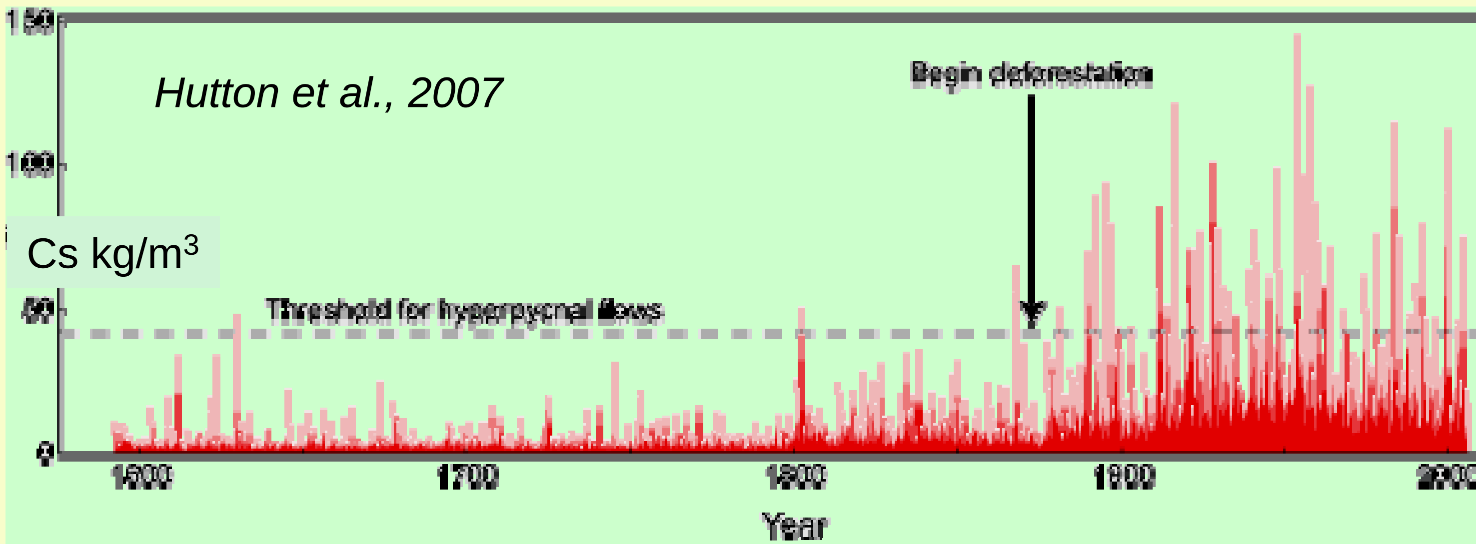
Anthropocene impacts on coastal sediment flux

1) Reduced sediment concentration decreases or eliminates hyperpycnal currents.



1) Elevated sediment concentrations generate more hyperpycnal currents.



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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.

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➢ global deltas have large areas (>>100,000 km^2) <2m a.s.l; most (75%) experienced flooding in the last decade, submerging >260,000 km^2 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 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

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