Geology, Geography, and Humans Battle for Dominance over the Delivery of Fluvial Sediment to the Coastal Ocean

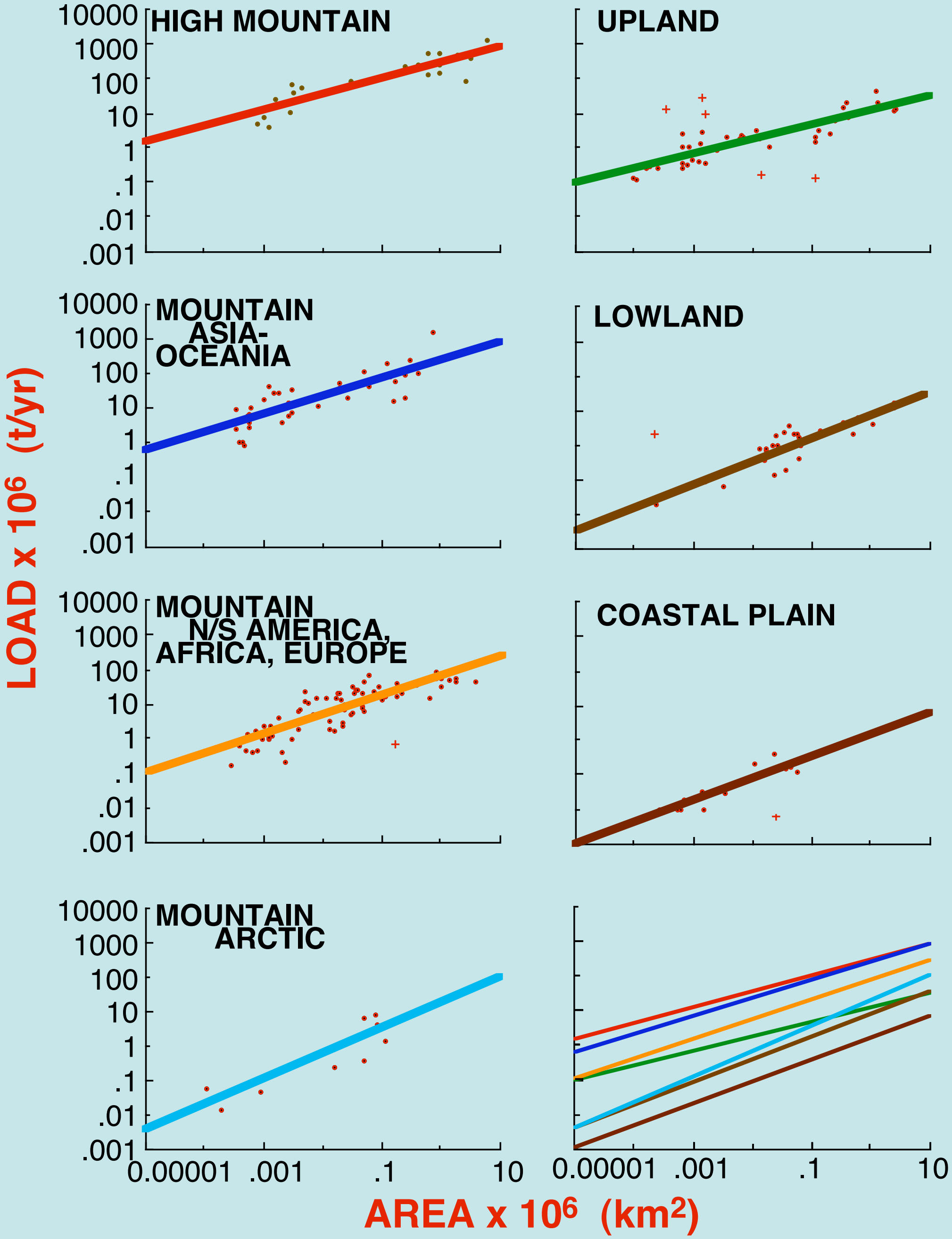
James P.M. Syvitski
Environmental Computation and Imaging Facility, INSTAAR, CU-Boulder
John D. Milliman
Virginia Institute of Marine Sciences, William & Mary, VA

With the great help of A. Kettner, S. Peckham, C. Vörösmarty, Y. Saito

International Council for Science
Scientific Committee on Oceanic Research

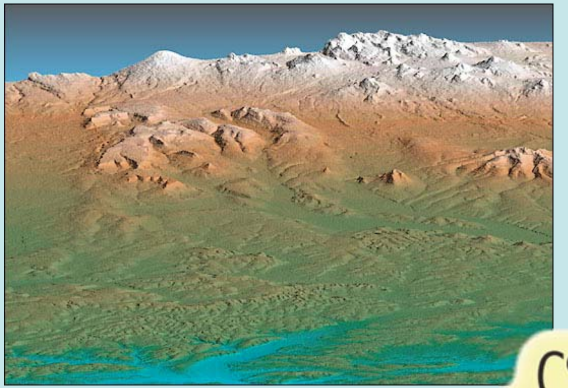
Dynamics of Sediment Retention in Estuaries, Boulder CO, 2007

Primary Influences on Sediment Load



Milliman & Syvitski, *J. Geology*, 1992, & Mulder & Syvitski, *J. Geology*, 1995 demonstrated the influence of Area and Relief on Qs. Syvitski & Morehead, *Mar. Geology*, 1999, used Buckingham π theory to formalize the empirical data as a dimensionless form of the relationship between the gravity-driven sediment yield & available potential energy.

$$\frac{\overline{Qs}}{\rho g^{1/2} A^{5/4}} = \beta\left(\frac{R}{A^{1/2}}\right)^n$$



CSDMS
Community Surface Dynamics Modeling System

$Qs/\rho g^{1/2}A^{5/4} = \beta[R/A^{1/2}]^n$

or $Qs = \beta\rho g^{1/2}A^{5/4-n(1/2)}R^n$

Syvitski, *Polar Research*, 2002, added basin temperature to the formulation with $\alpha e^{kT} = \rho g^{1/2}\beta$

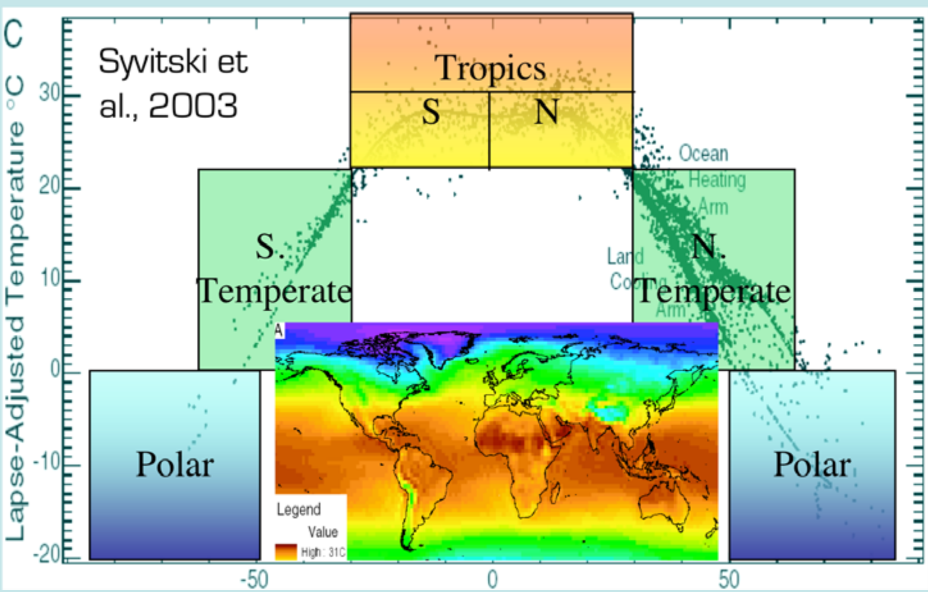
Syvitski et al., *Sed. Geology*, 2003, noted $n \approx 0.4$ to 1.5 from regional data if $n = 1$ then $Qs = \alpha \mathbf{A}^{3/4}\mathbf{R}e^{kT}$

Syvitski & Milliman, *Geology*, 2007, noticed runoff "Q/A" was not independent of drainage basin size. With $Q_{m3/s} = 0.075(A_{km2})^{0.8}$ then $A^{3/4}=2.25A^{1/2}Q^{0.31}$ *and thus*

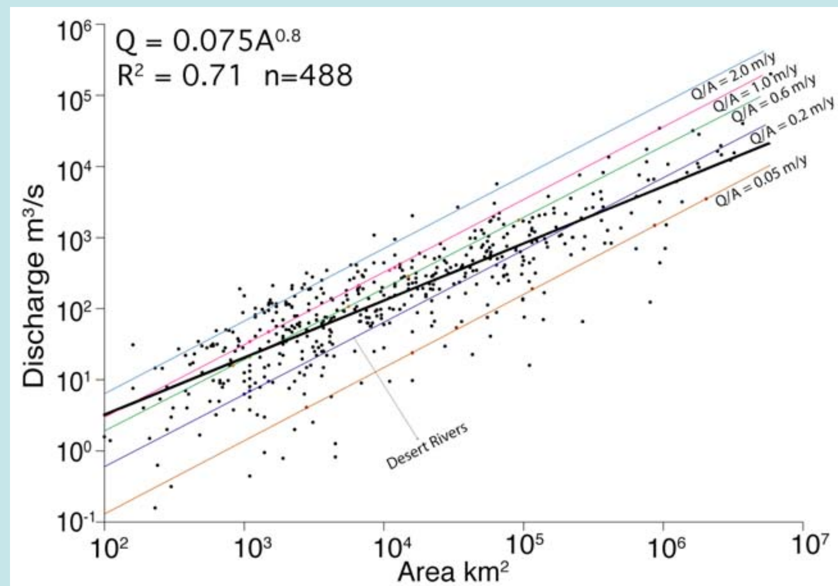
$\mathbf{Q_s=\omega BQ^{0.31}A^{0.5}RT}$ ***for T ≥ 2°C***

$\mathbf{Q_s=\omega BQ^{0.31}A^{0.5}R}$ ***for T < 2°C***

where "B" is a term capturing human and geological factors.



Latitude



Basin-averaged climate incorporates spatially variable rainfall and temperature

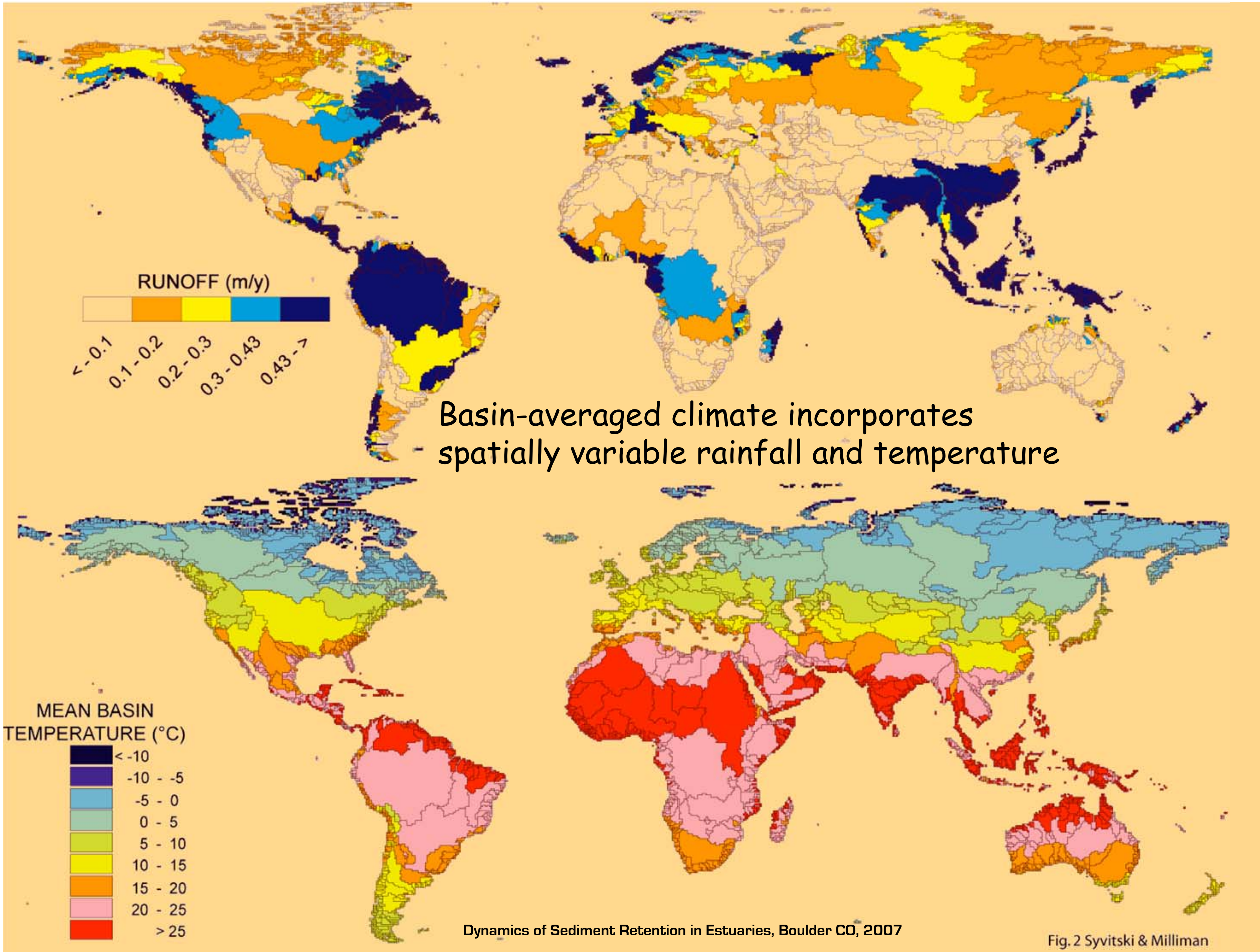


Fig. 2 Syvitski & Milliman

The "***B***" was defined as

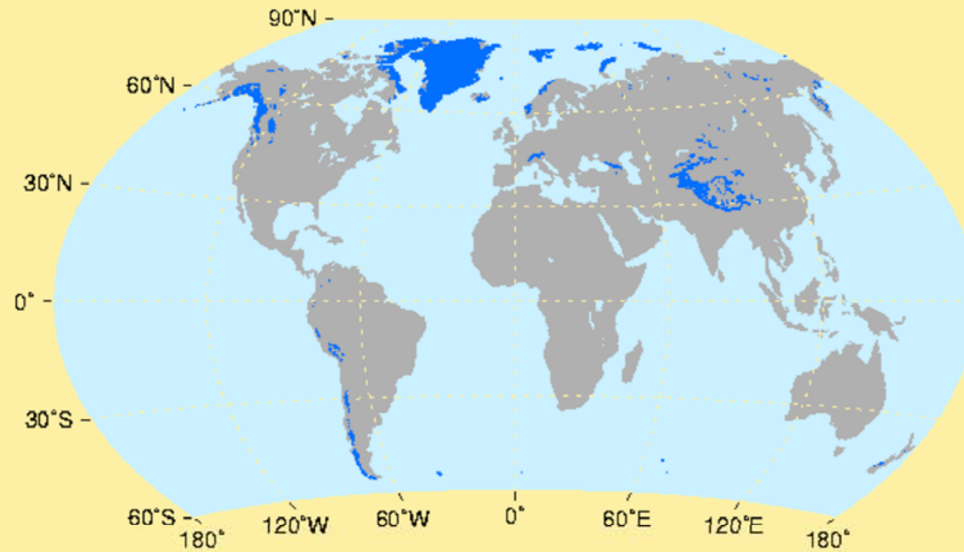
$B = I\,L\,(1-T_E)\,E_h$

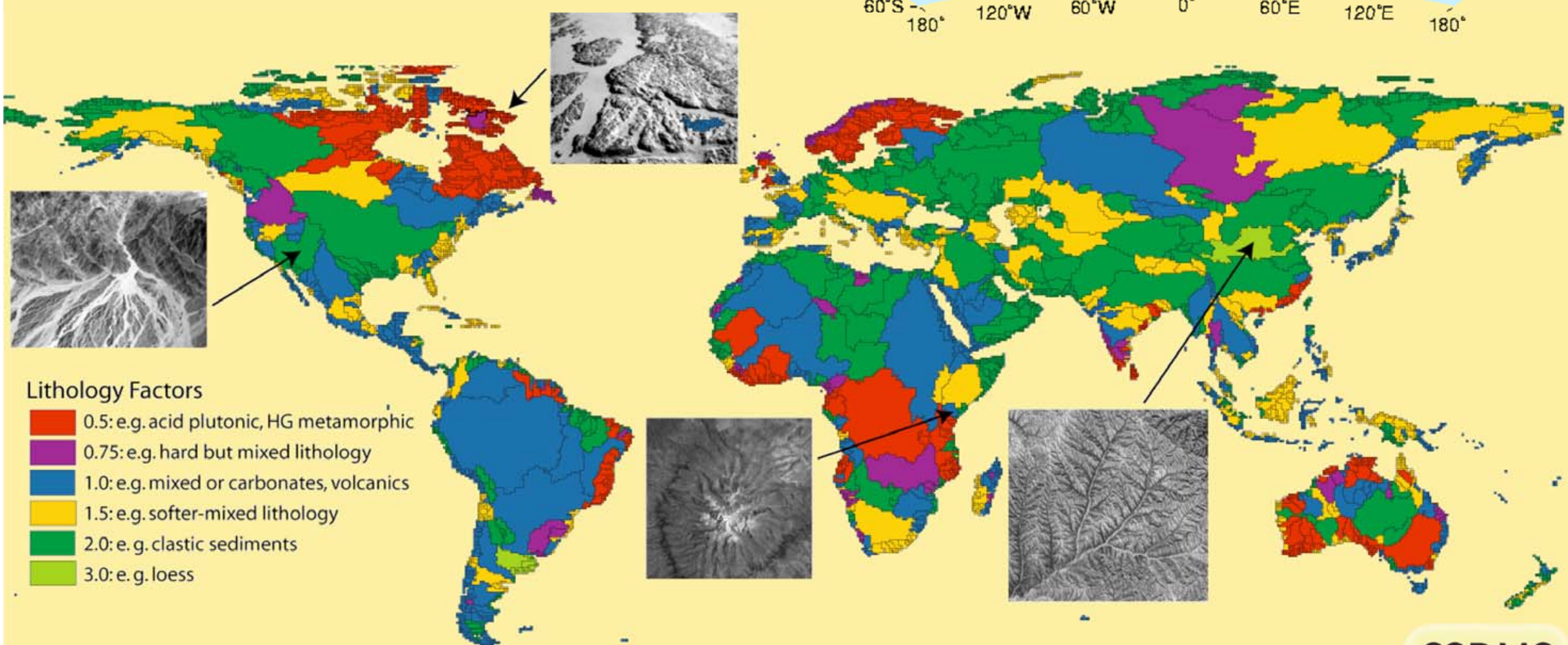
With the geological "***B***" terms

$I = 1 + 0.09A_g$

A_g is % basin glaciated

L=Lithology

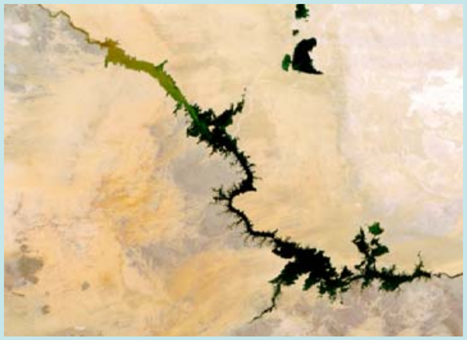




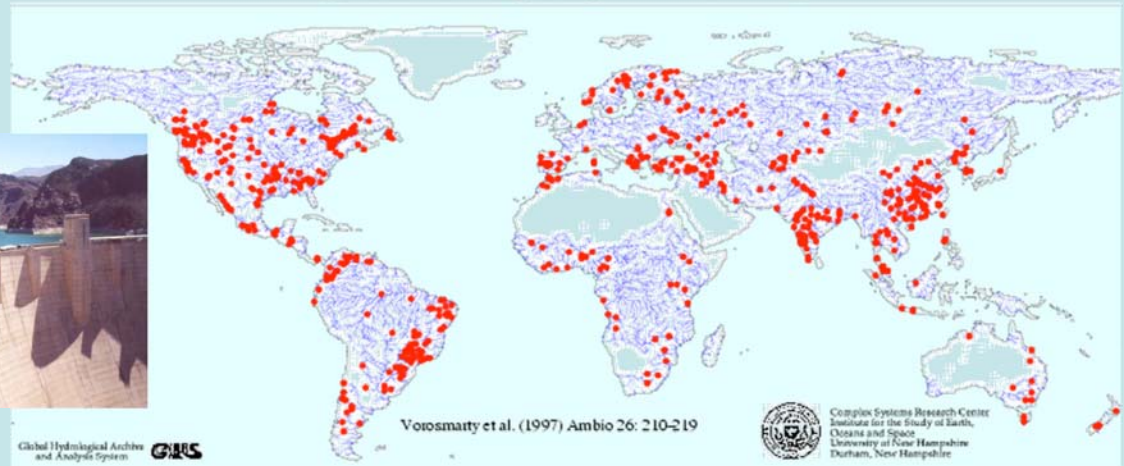
Two human "*B*" terms are defined :

$$T_E = 1 - \left(0.05 \Big/ \sqrt{\frac{V_{res}}{\overline{Q_m}}}\right) \qquad \overline{Q_m} = \overline{Q_{up}}\left(A_R \big/ A_{up}\right) \qquad T_E = 1 - \frac{A_R}{1.00021 V_R}$$

1) $1\text{-}T_E$ for sediment trapping.



LARGE RESERVOIRS
(Maximum Capacity >= 0.5 km3)



2) E_h for human effects on erosion

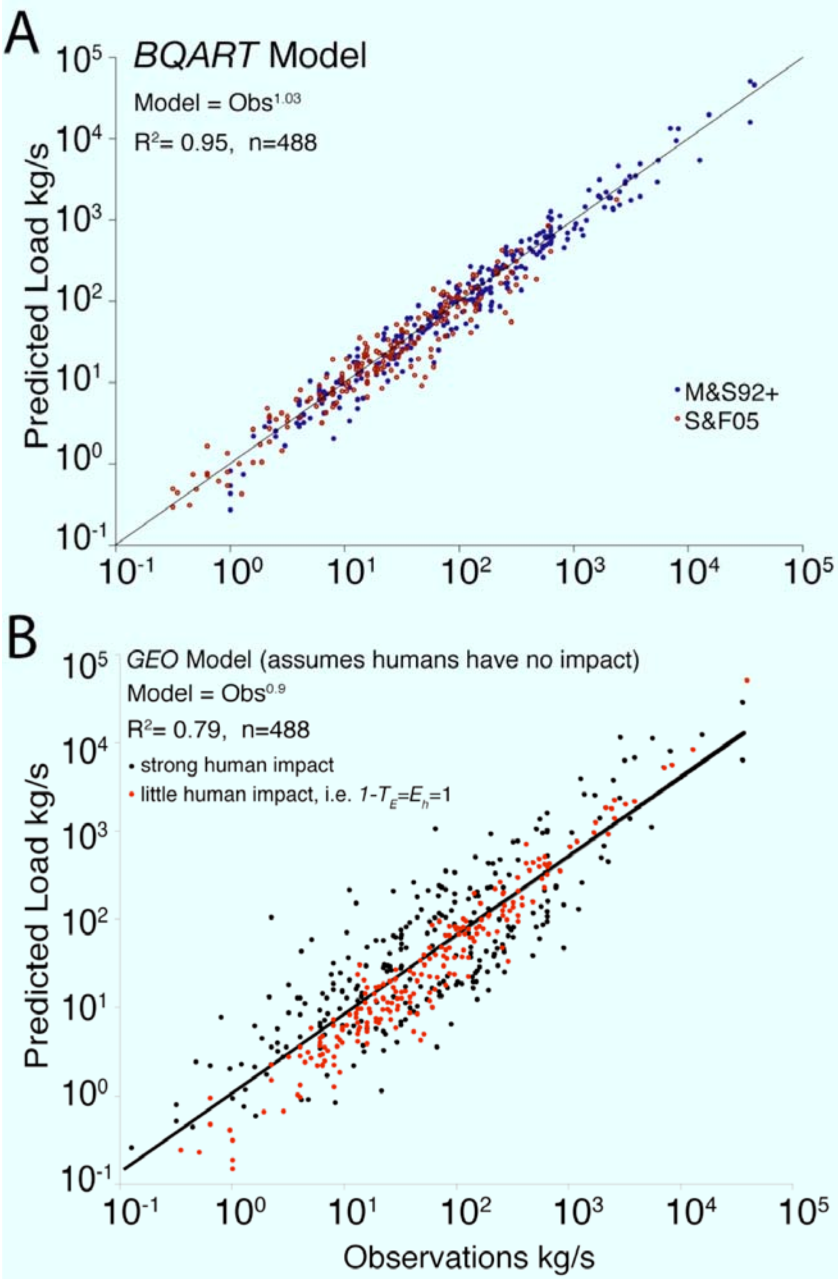
E_h factors

0.5 = hardened

1.0 = mixture or pristine

2.0 = softened

>3.0 = devastation



- Applied to 488 rivers, BQART showed no ensemble over- or under-prediction, had a bias of just 3%, across 6 orders-of-magnitude in observational values, and accounted for 96% of the between-river variance in sediment load observations.
- Sediment yields can be equally predicted with BQART.
- A blind application of BQART to load observations from 200 rivers had a similar success.
- On individual rivers, human impacts can alter loads by >10x.

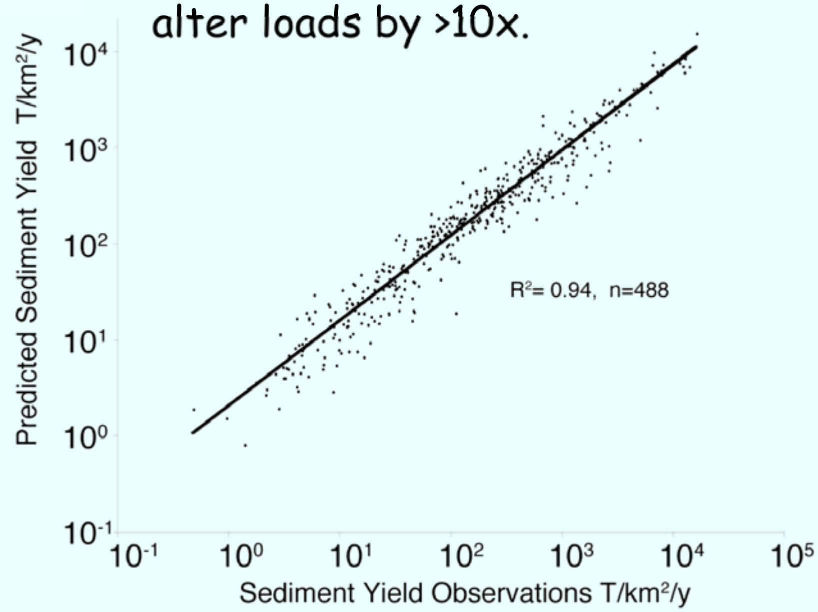
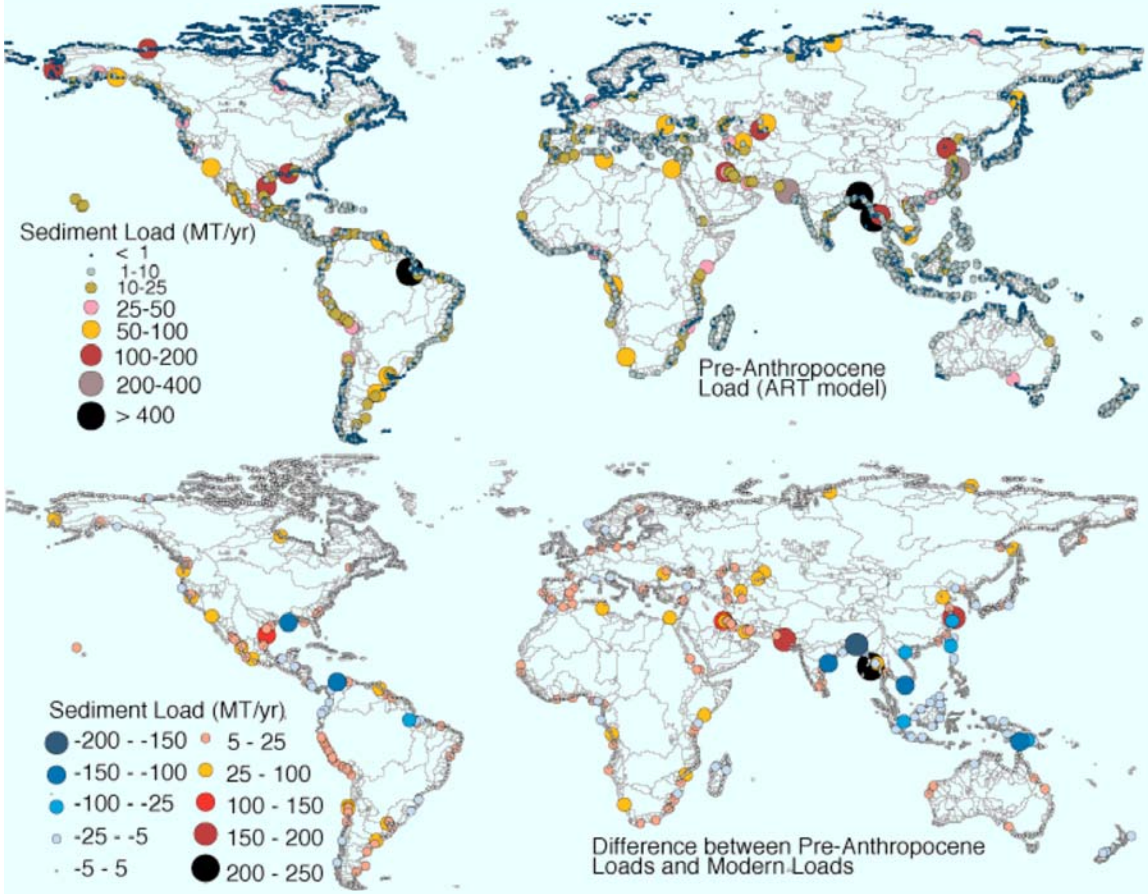
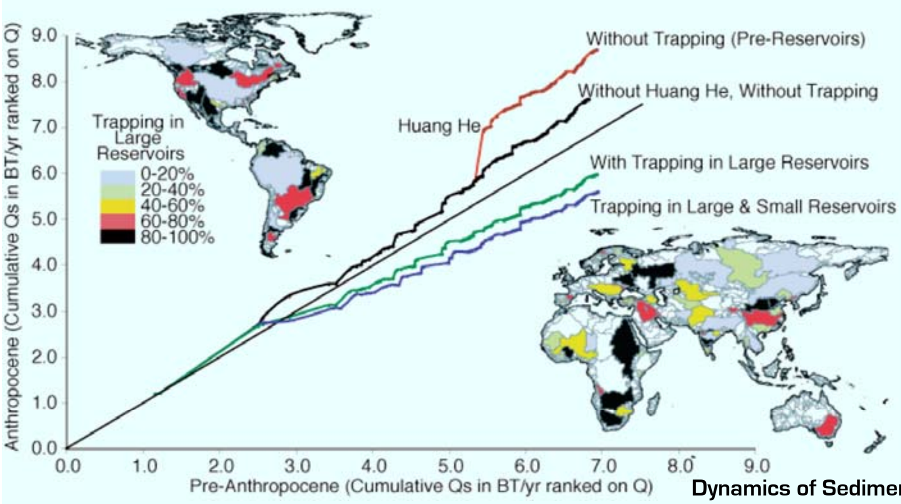


Fig. 9 Syvitski & Milliman

Fig. 10 Syvitski & Milliman





Syvitski et al, *Science*, 2005, set the human influence factors to 1 to globally predict the flux of sediment to the coastal zone under pristine conditions for >6000 river basins.

They compared these fluxes to modern observations and determined the difference in load being delivered to the coast under human influence showing zones of increased load (blue) and decreased load (orange). These differences are continually changing.

On average, earth rivers are getting dirtier, yet less and less sediment is getting to the coastal ocean.

Values are dated and ever changing

Landmass	Area	Discharge	Runoff	Yield	Pristine Qs	Modern Qs	Change	Retention in Reservoirs
	Mkm^2	km^3/yr	Q/A	$MT/km^2/y$	MT/y	MT/y	%	%
Africa	20	3,799	190	66	1,312	801	-39	35%
Asia	31	9,812	317	176	5,446	4,740	-13	37%
Australasia	4	608	152	104	415	392	-6	10%
Europe	10	2,682	268	92	922	682	-26	14%
Indonesia	3	4,254	1,418	300	900	1,625	81	1%
N America	21	5,823	277	112	2,345	1,914	-18	16%
Oceans	0.01	20	2,000	400	4	8	100	0%
S America	17	11,537	679	158	2,684	2,446	-9	16%
Global	**106**	**38,537**	**364**	**132**	**14,029**	**12,608**	**-10**	**26%**

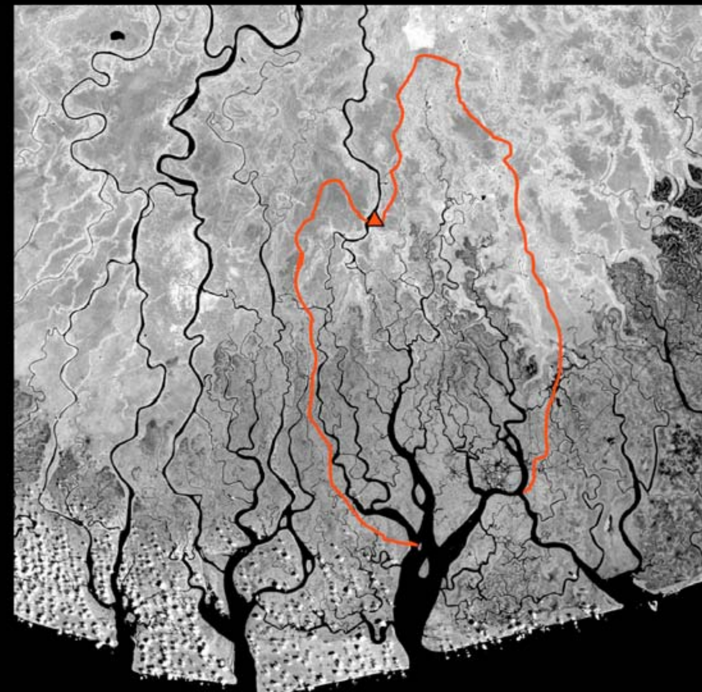
Syvitski et al, *Science*, 2005,

- Less sediment delivered to the coast
- More sediment delivered to the coast
- Decrease in delivery not accounted just by reservoirs
- Reservoir trapping not able to keep up with increased loads

River Examples	ΔQ_{av} (%)	ΔQ_{mx} (%)	ΔQ_s (%)	ΔC_s (%)
Colorado CA 1904-23 vs. 1934-63	-76	-90	-100	-100
Danube (Ro) 1931-55 vs. 1956-96	0	0	-76	-76
Ebro (Sp) 1913-62 vs. 1965-83	-69	-73	-92	-8
Huanghe (PRC) 1921-60 vs. 1961-88	-20	-23	-50	-37
Indus (Pa) 1941-62 vs. 1974-90	-50	-44	-85	0
Kolyma (Ru) 1942-65 vs. 1965-89	0	0	98	89
Krishna (In) 1901-60 vs. 1965-79	-42	-19	-75	-61
Mekong (Viet) 1962-92 vs 1993-00	5	4	-19	-28
Mississippi (USA) 1940-60 vs. 1961-90	0	-2	-65	-65
Nile (Eg) 1871-98 vs. 1967-95	-64	-82	-98	-96
Po (It) 1933-39 vs. 1982-87	-19	-33	-65	-57
Yangtze (PRC) 1951-68 vs. 1986-04	0	0	-37	-36

Syvitski & Saito, *Global & Planetary Change*, 2007

Distributary Sediment Plumes, Dec 24, 2003, MODIS



May 3, 2002, Niger Delta, Landsat ETM+. Hydrological basin of the Brass estuary along with a major connection to the Niger River.

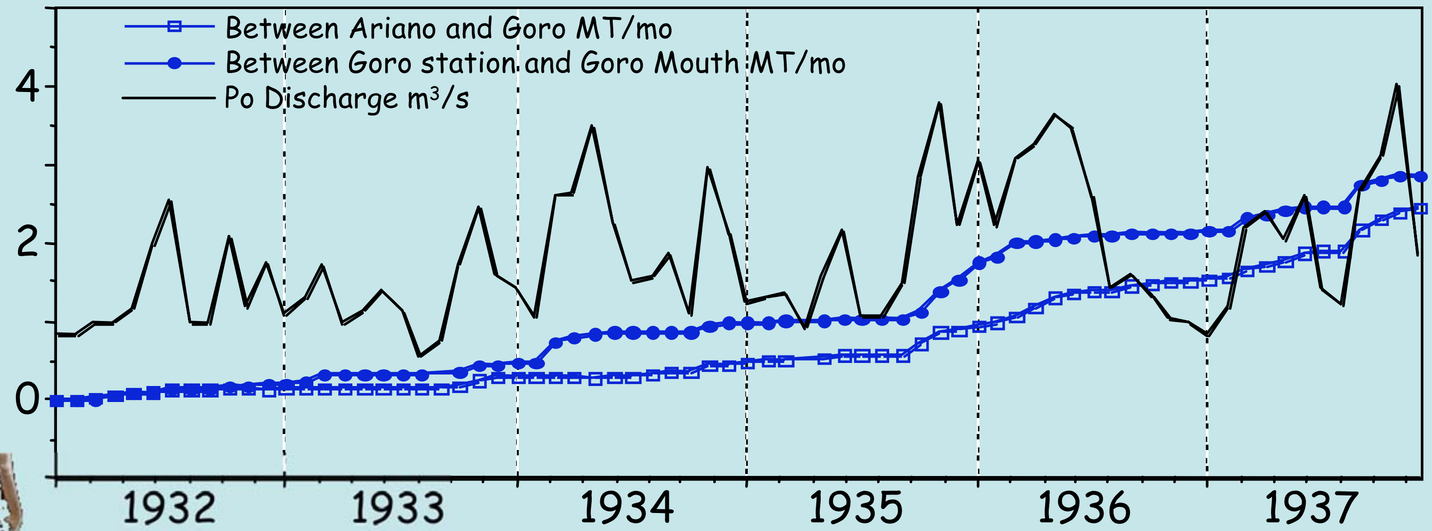
2007 Quickbird Image through Google Earth

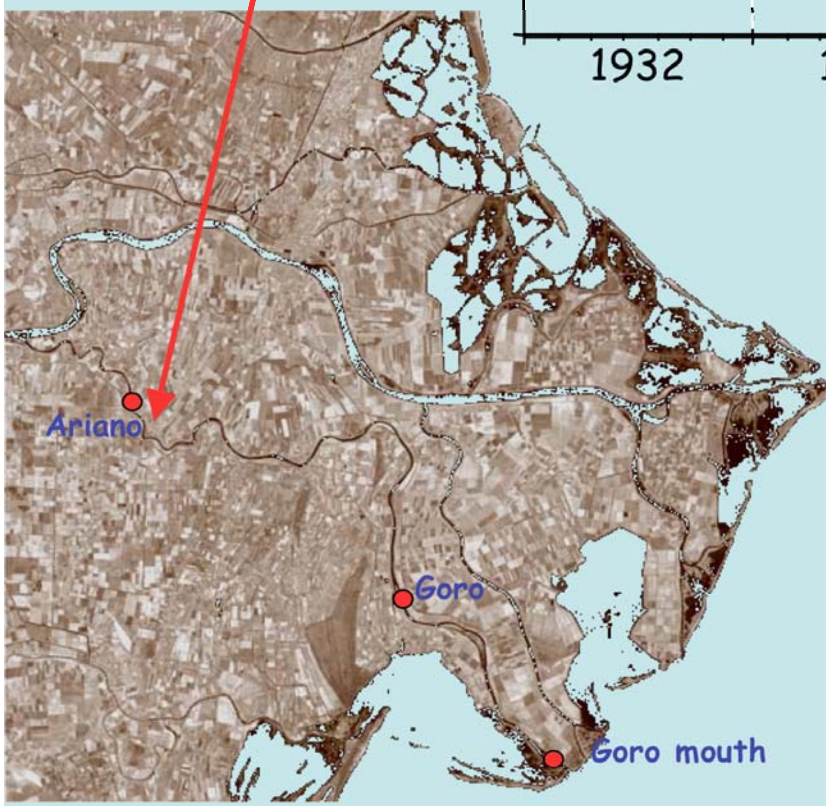
Once a river's sediment load reaches a delta, it is distributed into a number of estuaries.

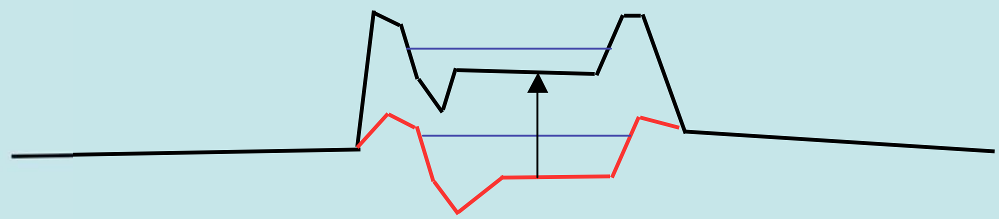
Humans have contributed to three problems with this natural distribution.

CSDMS
Community Surface Dynamics Modeling System

Distributary Channel Flood Control: Sediment Storage MT



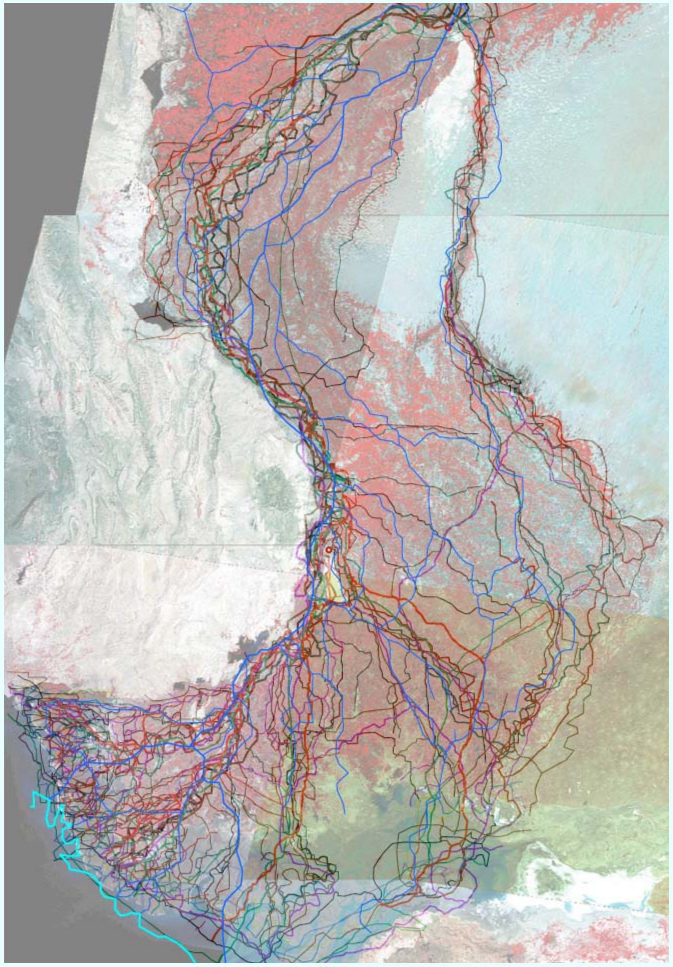


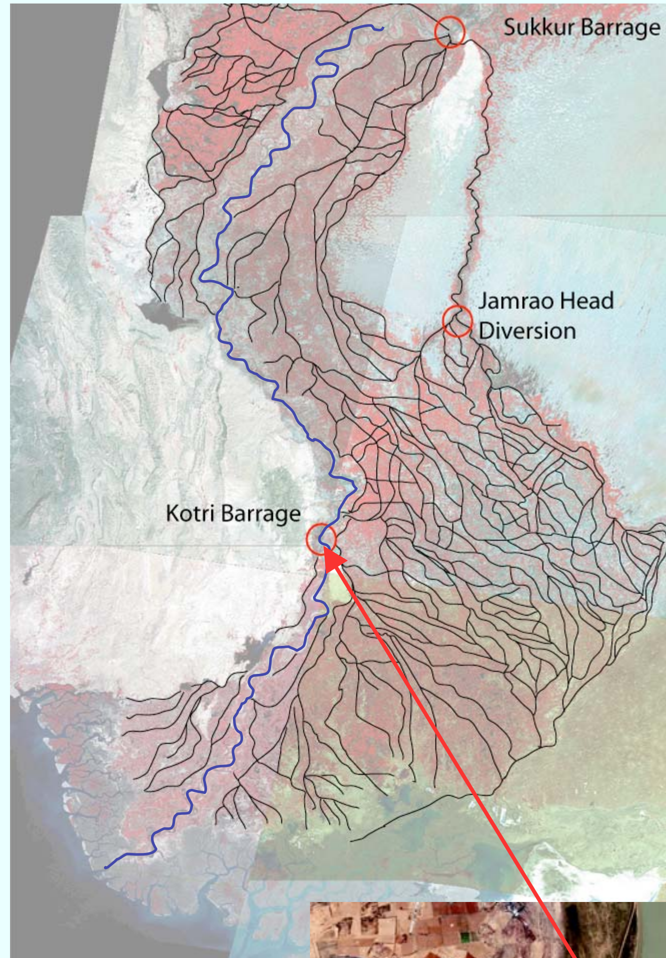


Problem 1: Stop-bank levees cause super-elevation of the estuary above the surrounding floodplain.

CSDMS
Community Surface Dynamics Modeling System

Indus distributary channels mapped out between 1829 and 1922. Note the many channels reaching the coastal estuaries.

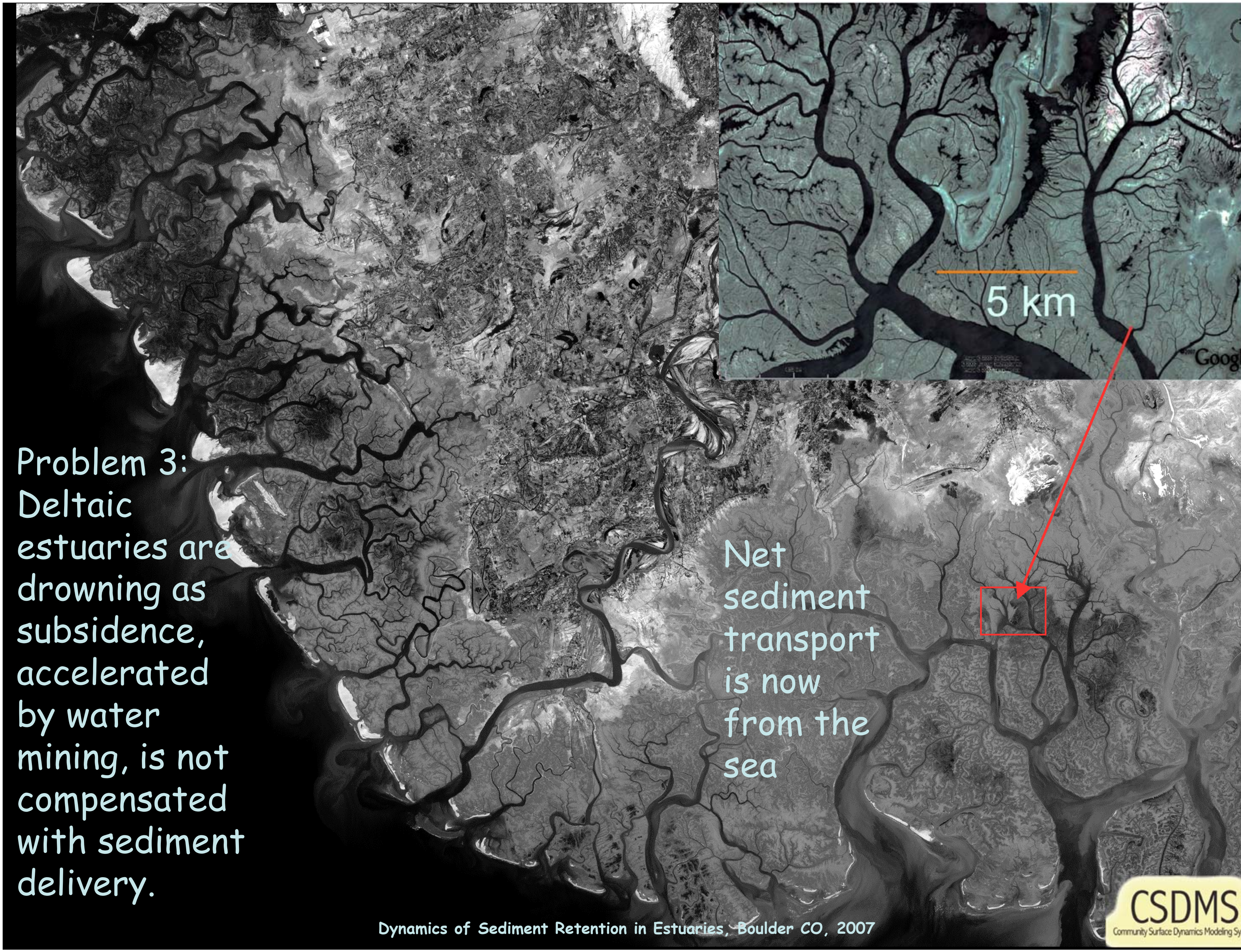




Barrages on the Indus now keep most of the water and sediment from reaching the coastal estuaries — one channel now reaches the coast delivering little water or sediment.

Problem 2: Humans often limit the number of distributary channels and thus leave deltaic estuaries with little water or sediment.

Problem 3: Deltaic estuaries are drowning as subsidence, accelerated by water mining, is not compensated with sediment delivery.



Suggested working group conclusions

1) In the battle for dominance over the delivery of fluvial sediment to coastal estuaries, humans are often winning over geology and geography — humans have become a dominating factor.
2) The new BQART model provides a useful tool in understanding changes in sediment delivery through human interference, whether as mitigators (e.g. impoundment) or accelerators (e.g. deforestation).
3) Once a sediment load nears a coast, new anthropogenic factors influence the sediment pathway to coastal estuaries:

i) stop bank levees increase sediment retention in main channels,
ii) fewer distributary channels, along with flow redistribution through diversion schemes, starve estuaries of fluvial sediment, and
iii) increased accommodation space (accelerated subsidence such as through water or gas mining) at a time of reduced sediment delivery, leads to the dominant sediment pathway to become landward.