

Numerical modeling of Earth systems

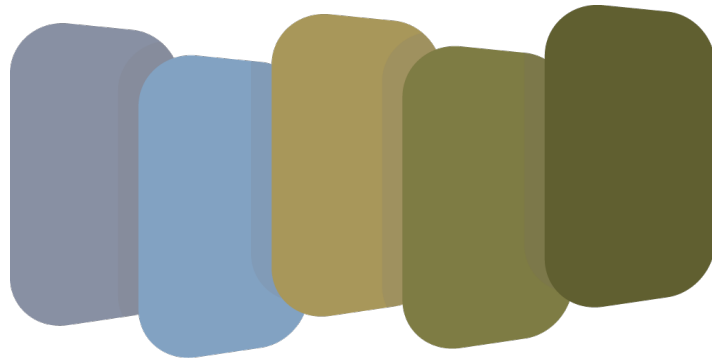
On the flux of fluvial sediments to the oceans

Albert Kettner

Associate Professor – Research, INSTAAR, CU-Boulder



University of Colorado
Boulder



CSDMS

community surface
dynamics modeling system



CSDMS supports computational modeling in earth-surface science by engaging **community**, providing **computing** resources, and promoting **education**

Earth-surface processes



*share resources,
collaborate*



**COMMUNITY
SUPPORT**

*create, run, test, analyze,
and apply models*



**COMPUTING
RESOURCES**

learn and teach



**EDUCATION
OPPORTUNITIES**

2,300+ members
75 countries
several hundred institutions



<https://csdms.colorado.edu>

What can CSDMS do for you?

- Providing a community of model developers and users
- Free available model codes and metadata in model repository
- Free access to cloud and supercomputer for members
- Define model standards and coupling protocols
- Access to educational resources on surface process modeling

<https://csdms.colorado.edu>

Earth Surface community: CSDMS Model Domains & Scales

Cryosphere: glaciers, permafrost, snow

Hydrology: watershed, reach to global, discharge and sediment transport

Terrestrial: hillslope processes, landslides, river processes, coupling to tectonics

Coastal: wetlands, estuarine processes, beach and barriers, storm erosion

Marine: circulation, surges, tides, waves, gravity flows, turbidity currents



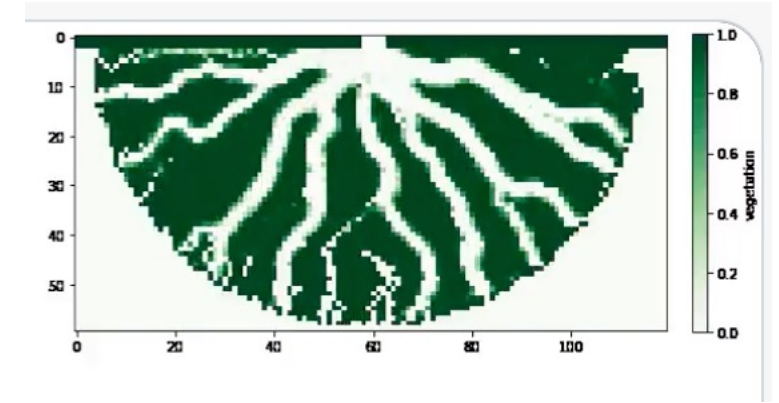
*River discharge and Delta Plume Dynamics,
Greenland*



*Floodplain and coastal aggradation and degradation,
Ganges delta, Bangladesh*

<https://csdms.colorado.edu>

Earth Surface Processes Institute (ESPIIn) and Roadshows provide hands-on cyber-skills training



Example project from 2022: impact of mangroves on river delta morphology



<https://csdms.colorado.edu>

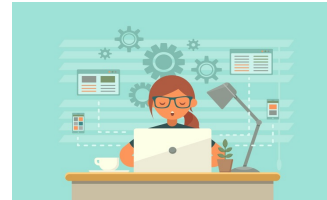
Online resources for learning

The CSDMS Help Desk

The **CSDMS Help Desk** is where you can get answers for questions about the products and services of the [Community Surface Dynamics Modeling System](#). The Help Desk provides tracking and an audit trail for your questions. Plus, the responses are searchable, so the questions you ask may help another CSDMS member in the future.

The Help Desk uses [GitHub](#), so if you don't yet have an account, please [sign up](#).

Ask a question



CSDMS Ivy

CSDMS Ivy is a collection of instructional materials on

- modern, collaborative, scientific software development, and
- use of community cyberinfrastructure tools

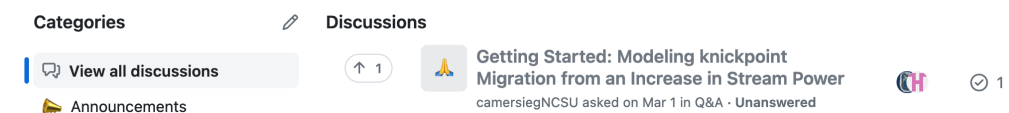
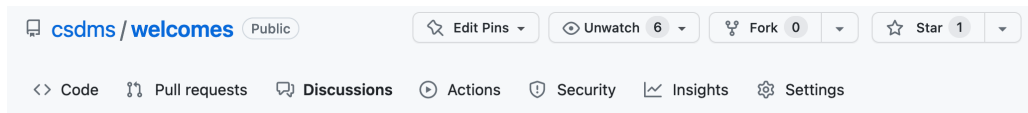
for researchers in earth and planetary surface processes.

CSDMS Ivy is written and maintained by the [Community Surface Dynamics Modeling System](#) (CSDMS).

Lessons

CSDMS Ivy lessons are modular and independent, although the ordering below represents a typical progression.

1. [Project Jupyter](#)
2. [Introduction to the Shell](#)
3. [Text Editors and Development Environments](#)
4. [Python Fundamentals](#)
5. [Anaconda and conda](#)
6. [Version Control with git and GitHub](#)
7. [Python for Modeling](#)
8. [Landlab](#)
9. [The Basic Model Interface \(BMI\)](#)
10. [The Python Modeling Toolkit \(pymt\)](#)
11. [Permamodel Toolkit](#)
12. [Introduction to Cluster Computing](#)
13. [Best Practices in Scientific Software Development](#)



Upcoming

Presenter	Title
-----------	-------

<https://csdms.colorado.edu>

Numerical modeling of Earth systems

On the flux of fluvial sediments to the oceans

Albert Kettner

Associate Professor – Research, INSTAAR, CU-Boulder



University of Colorado
Boulder

Outline

- **Why studying fluvial sediment fluxes to the oceans?** Anybody?
- Human impact on fluvial systems
- Numerical modeling of fluvial sediment fluxes at basin scale

Coastline retreat



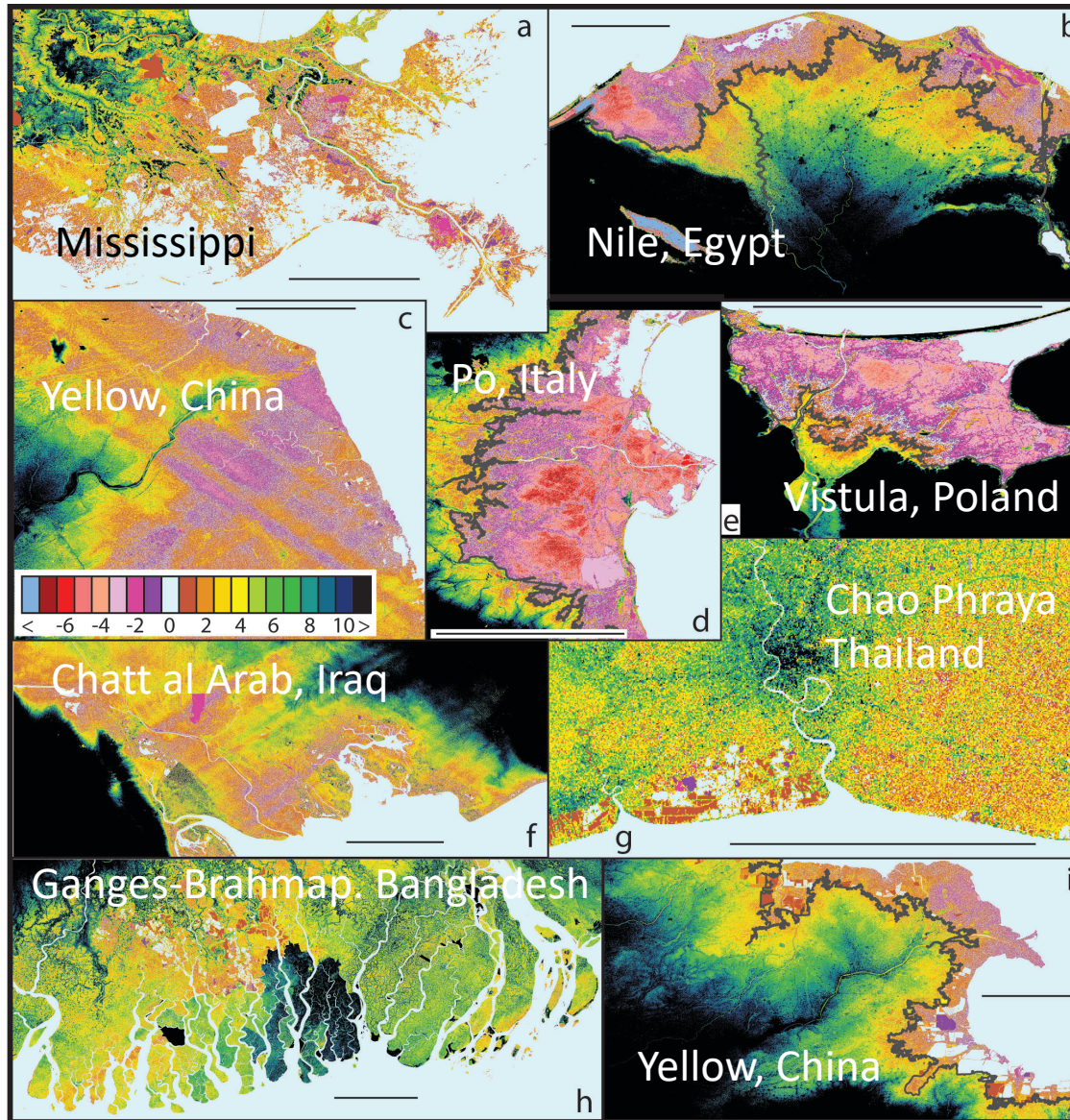
Texas Gulf coast is retreating $\sim 1.6\text{m/yr}$

Causes of coastline retreat for Texas:

- Lack of sediment supply
- Sea level rise
- Changes in local circulation patterns
- High intensity storms (Katrina, 2005; Ike, 2008; Andrew, 1992; etc)



Sinking deltas due to humans



85% of the deltas experienced severe flooding, resulting in lives lost & people that need to be displaced.

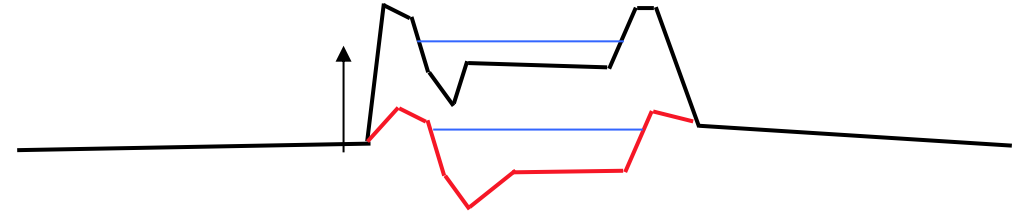
- Aggradation rate decrease due to:
 - Dams & reservoirs
 - Levees
 - Distributary channel reduction
- Natural compaction
- Accelerated compaction
- Sea level rise

Syvitski et al, Nature Geoscience, 2009

Super-elevation on e.g. deltas

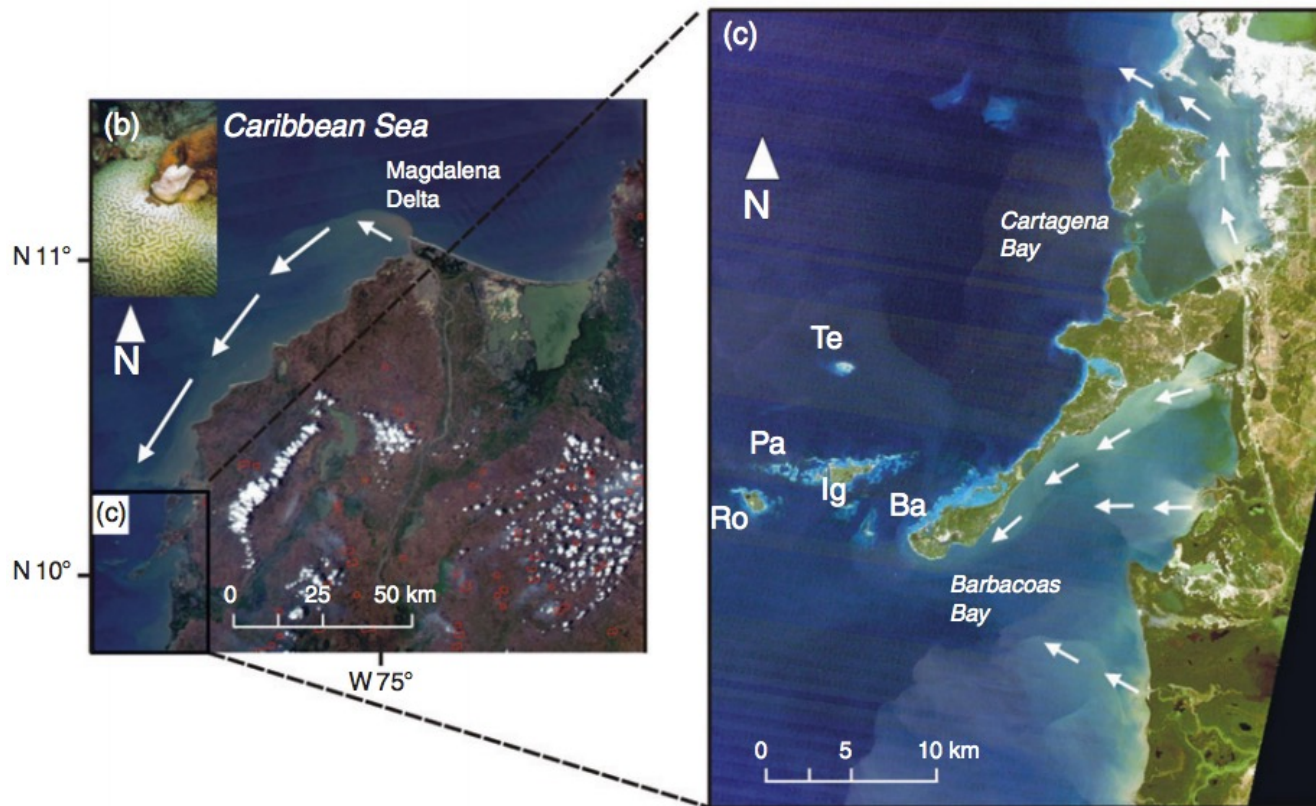


In courtesy of Heezik, 2007



Levees can cause super-elevation of the channels above the surrounding floodplain.

Sediment impact on coral reefs



Deforestation, changes in land-use, mining all **increase sediments** towards to coast

Effects coastal systems:

- a) Blocking sun light,
 - b) Increase in pollutants,
 - c) Increase in macro algae
- direct threat on health of coral reefs.

Sediment run-off is the major stressor to reefs

Restrepo, J.D., Alvarado, E.M., Treatise on Estuarine and Coastal Science, 2011.

Prouty et al., coral reefs, 2014; Jokiel et al., PeerJ, 2014; Stender et al., PeerJ, 2014; Restrepo, 2019; Restrepo et al., XIX. Fishes of the Magdalena river basin, 2020

Summarize

Quantifying sediment fluxes towards the oceans can give you better insights in

- **Changes in coastline (e.g. coastal retreat),** which is directly influenced by river sediment supply
- Reduction in **delta aggradation** rates; which are linked to changes in sediment fluxes towards the deltas
- **Stress on coral reefs:** reefs suffer from increasing sediment supplies
- **Nutrients delivered to oceans,** which effecting coastal fisheries (Sediments are an important source of nutrient to the oceans)
- **Harbor maintenance** and e.g. the potential for burial of pollutants
-



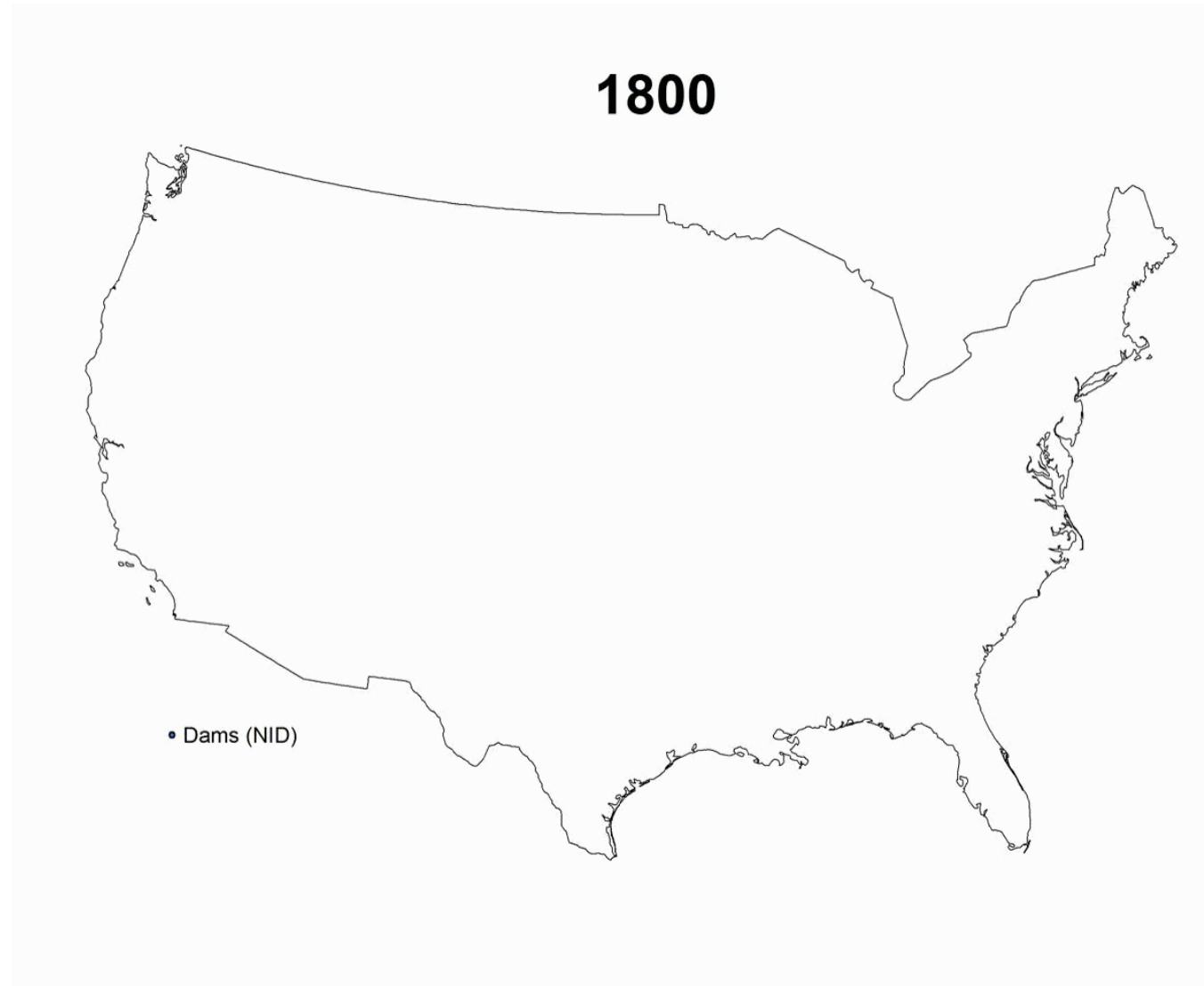
Outline

- Why studying fluvial sediment fluxes to the oceans
- **Human impact on fluvial systems**
- Numerical modeling of fluvial sediment fluxes at basin scale

Human impact on fluvial systems

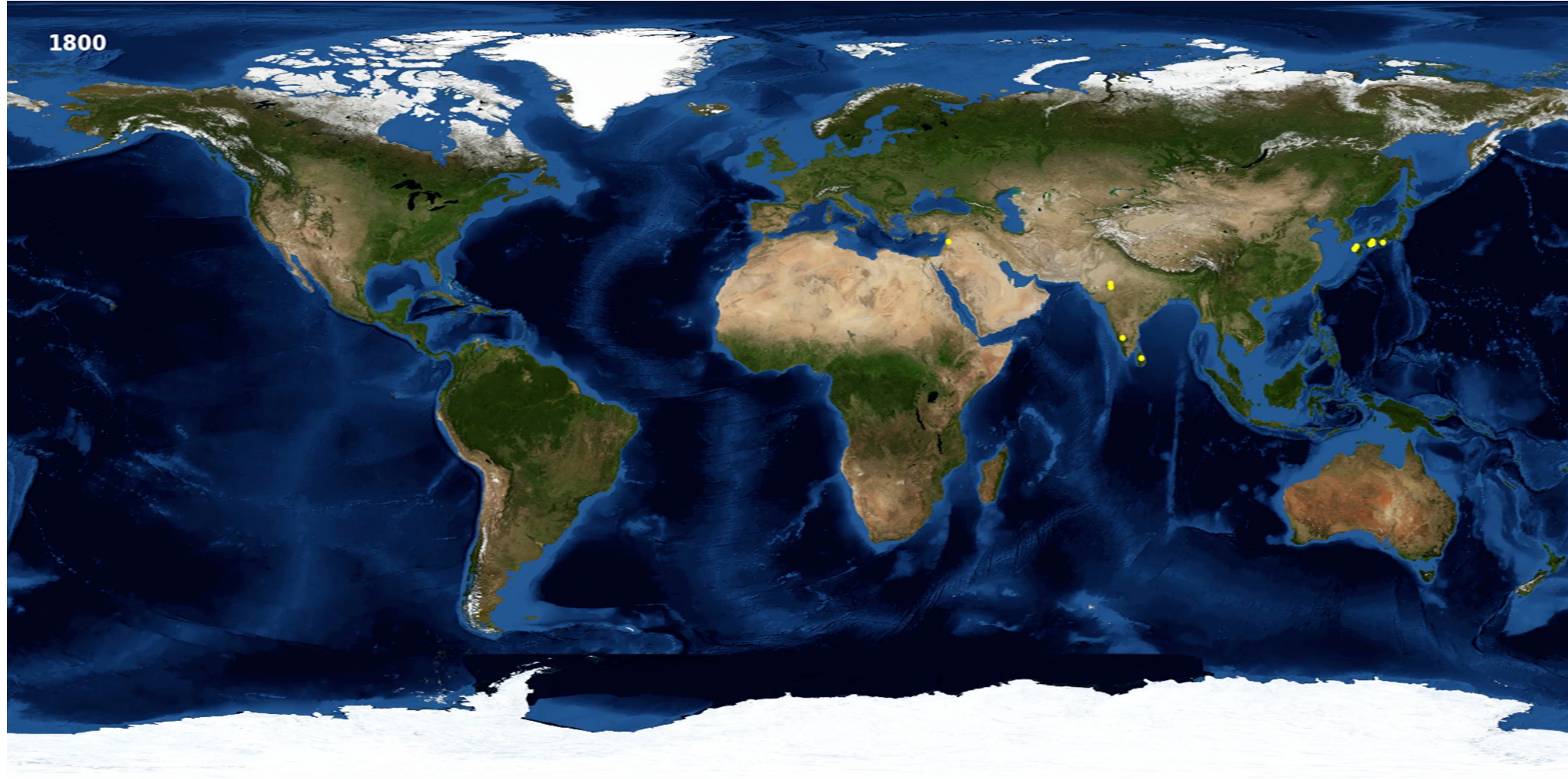
How do humans change the water discharge and sediment load to the ocean?

Dams in the US



National Inventory of Dams (NID, USA); shown are dams ≥ 2 meter

Large dams of the world

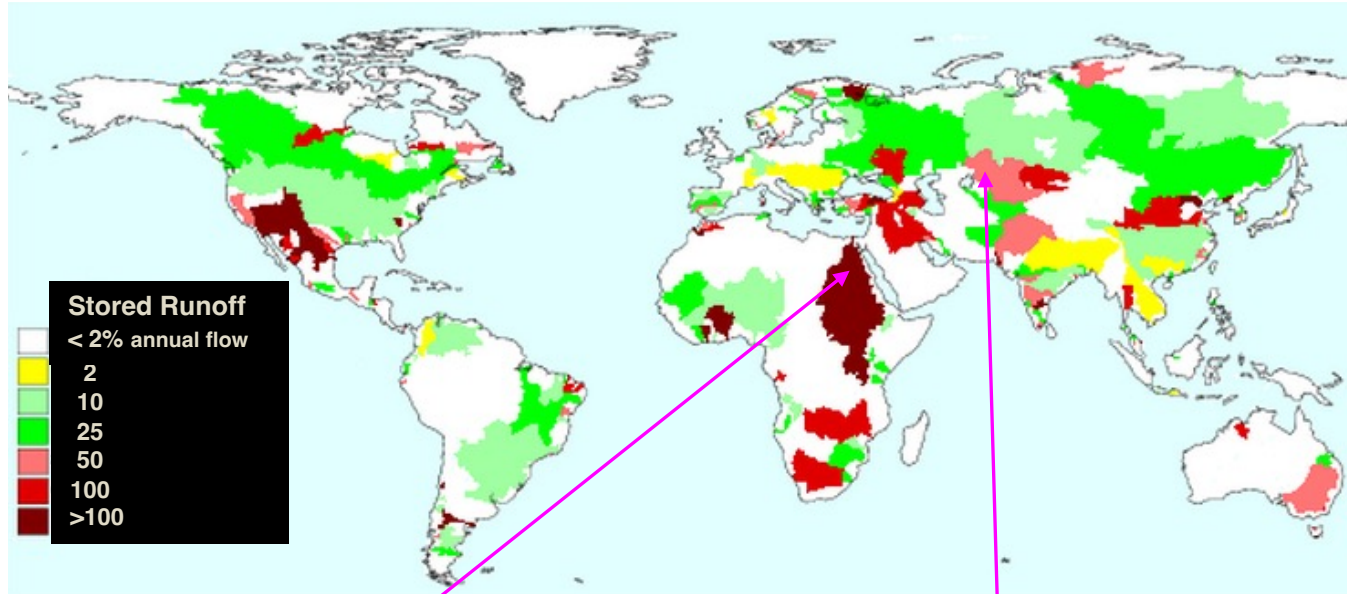


GRanD data from: Lehner et al, Frontiers in Ecology and the Environment, 2011.

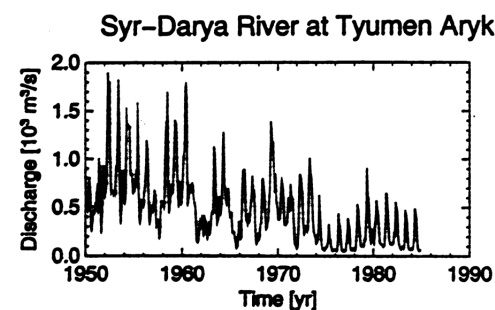
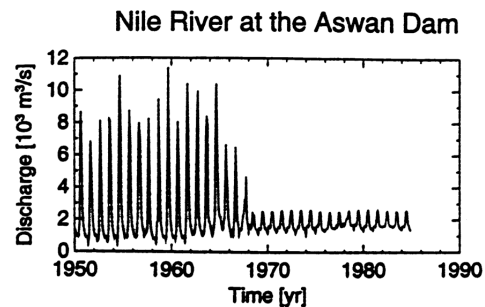
Global Reservoir and Dam database (GRanD): 6,862 dams (Typically dams with a reservoir volume of $> 0.1 \text{ km}^3$)

Total large dams of the world according to International Commission on Large Dams (ICOLD) $> 58,000$

Due to dams: distortion of Natural Hydrographs

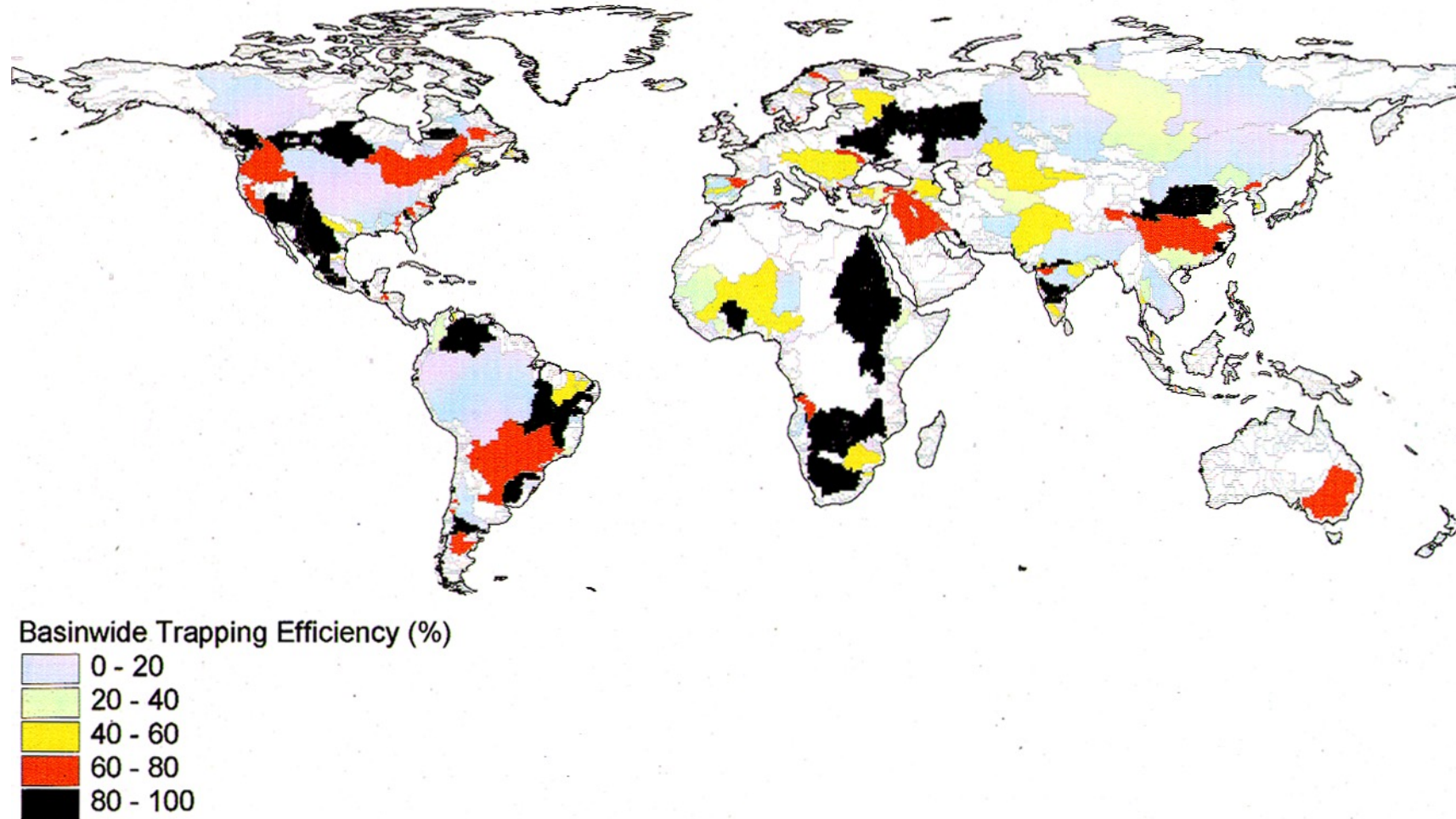


- 700% increase in water held by river systems
- Several years of residence time change in many basins
- Tripling of river runoff travel times globally (from 20 up to 60 days)



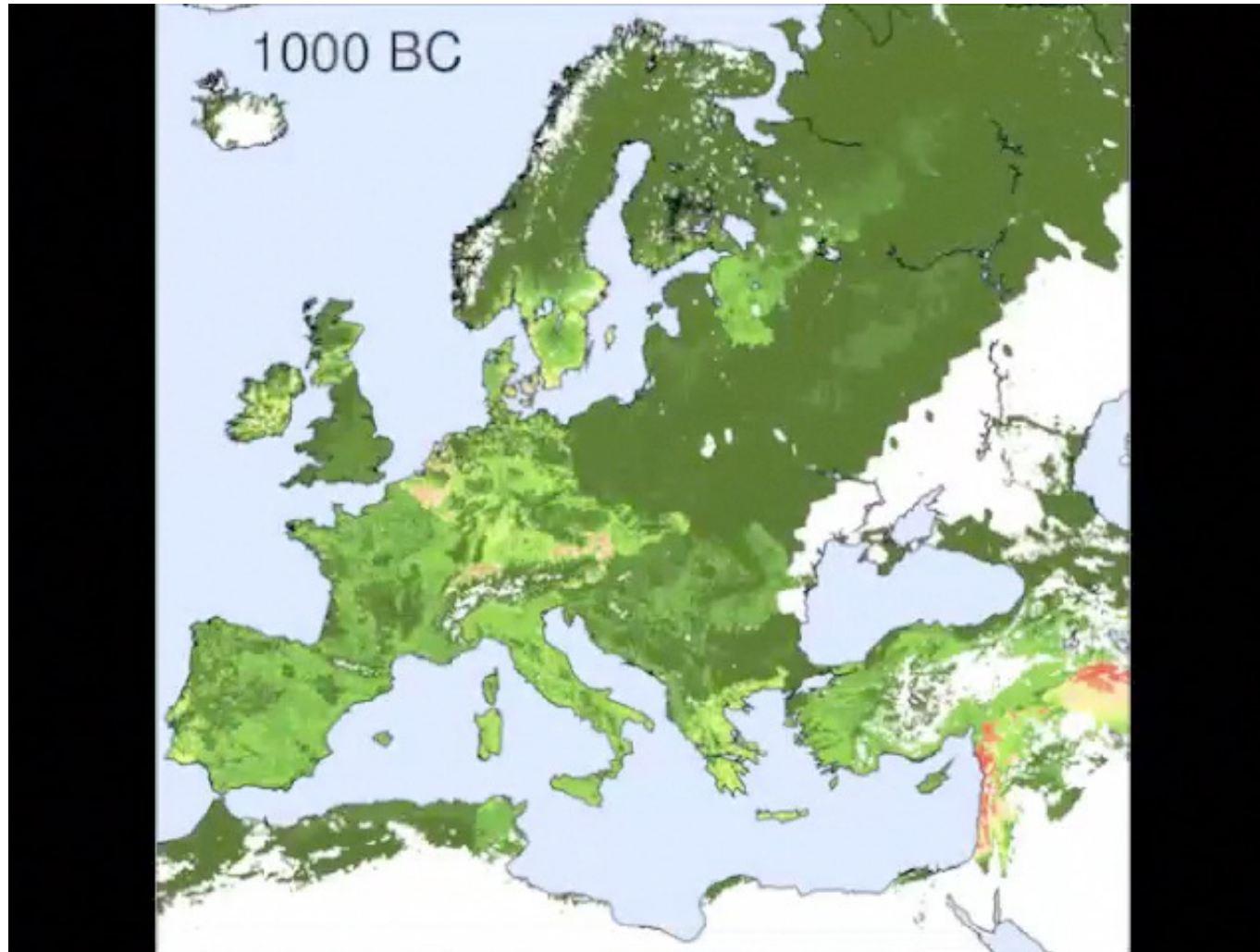
*Vörösmarty et al.,
Global and Planetary Change, 2003*

Sediment trapping efficiencies of world's largest dams



Vörösmarty et al., Global and Planetary Change, 2003

Human causes: Vegetation change



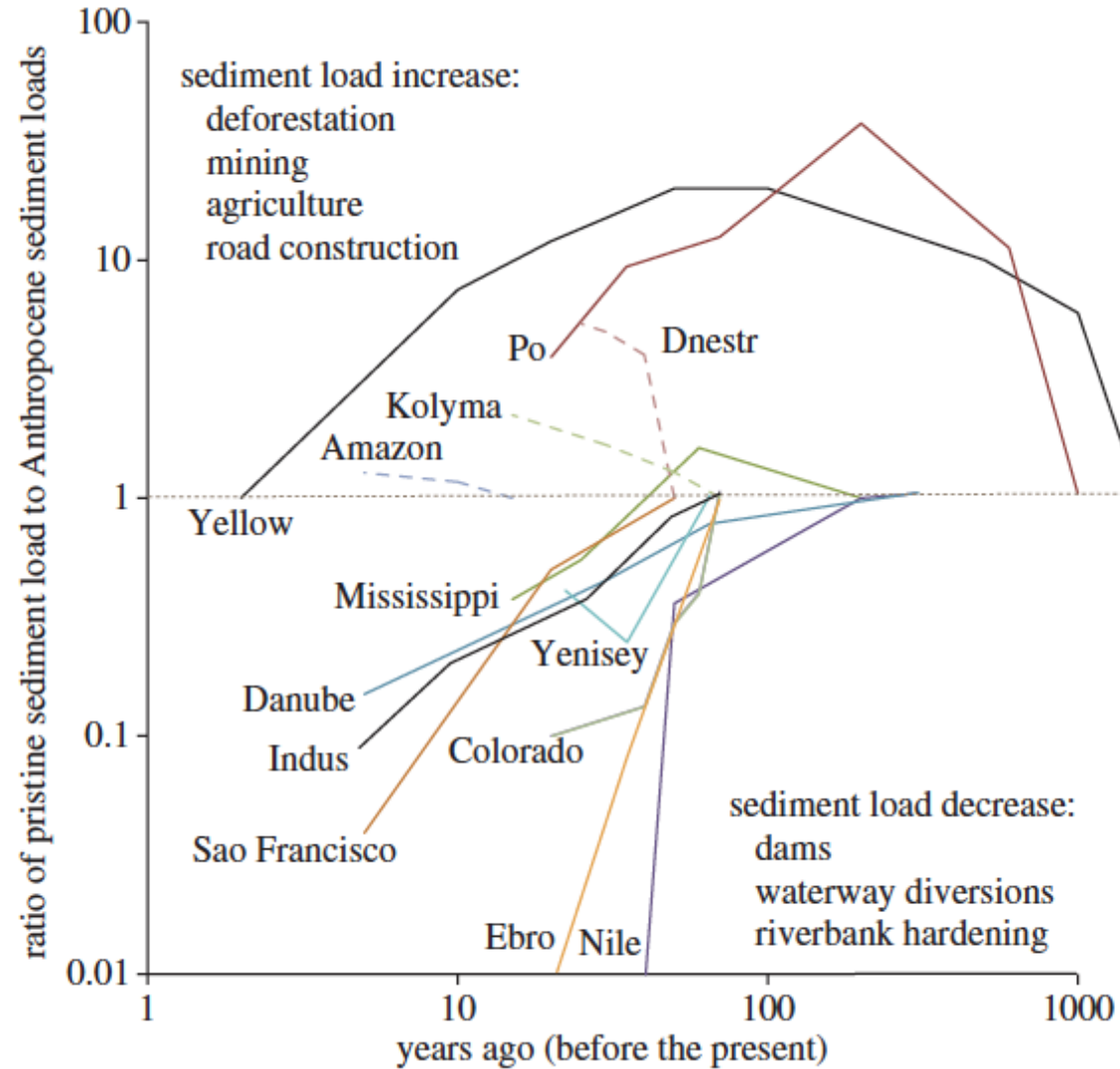
% forest cover on usable land

1000 BC: 75%

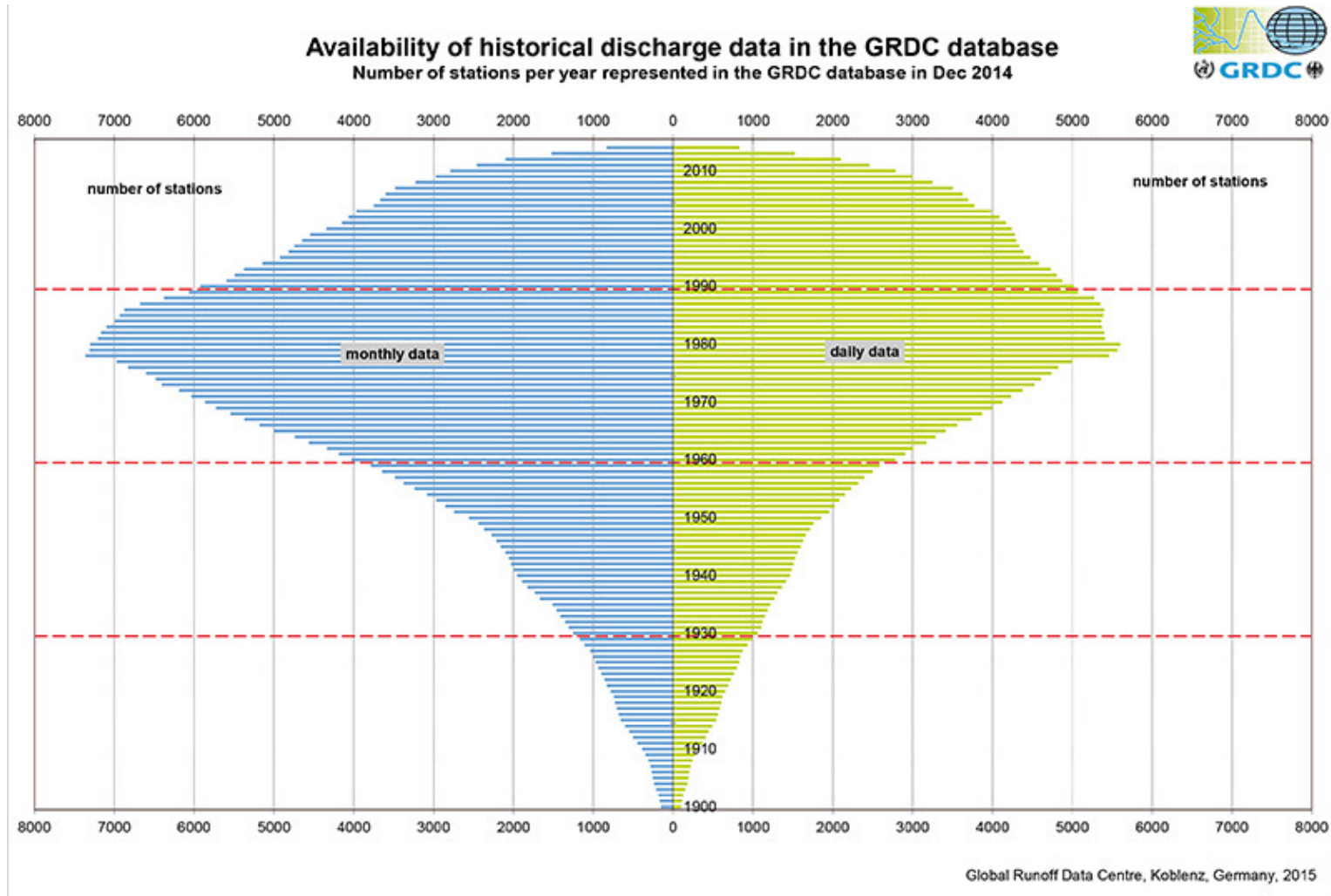
AD 1850: 21%

Kaplan et al., 2009

Human impact on sediment flux to the oceans



What we (don't) measure: a plea for models



Source: *The Global Runoff Data Centre (GRDC), 2014.*

Other human impact not included in this lecture:

Environmental impact - plastics to oceans



From rivers



To oceans



Plastic in the ocean has increased **100-fold** in the past 40 years. The Great Pacific Garbage Patch covers 1.6 million square km = an area 2 x Texas or 3 x France.

Summarize

Human impact to Earth's freshwater system to the ocean

- >40% of global water discharge is presently intercepted by reservoirs (1950 ->)

*Vörösmarty et al.,
Global and Planetary Change, 2003*

- ~20% of riverine sediment is trapped by reservoirs

*Syvitski, Kettner et al.,
Science, 2005*

Outline

- Why studying fluvial sediment fluxes to the oceans
- Human impact on fluvial systems
- **Numerical modeling of fluvial sediment fluxes at basin scale**

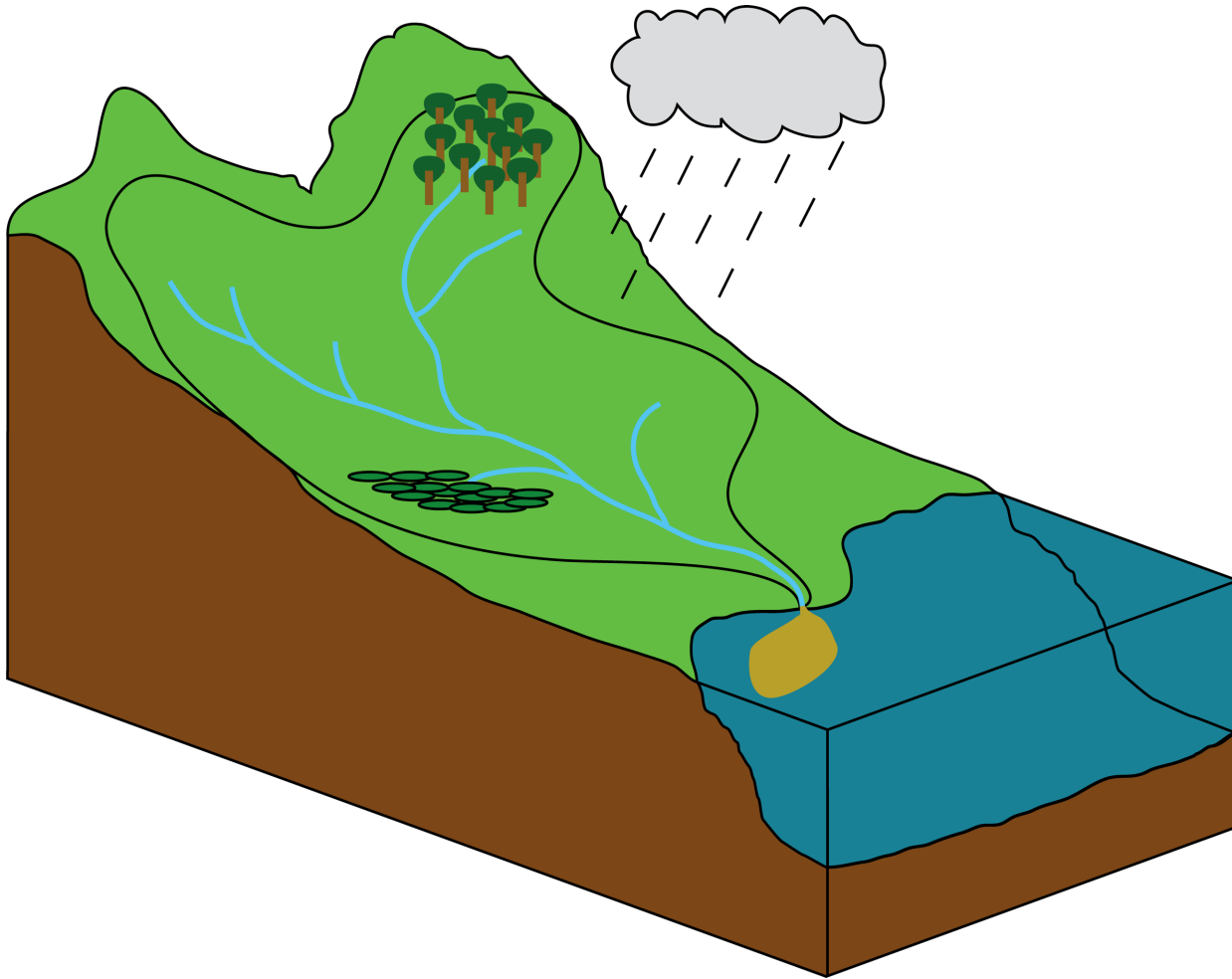
What are the advantages of using numerical models

Anybody?

Models typically represent a simplification of reality

- Models can simulate riverine fluxes where there are no gauging stations
- Models can simulate the past, present or future fluxes
- With models you can eliminate processes to study their impacts on fluxes

Model: HydroTrend



Climate driven hydrological transport model

Point source model (fluxes at the ocean)

Simulates daily water and sediment load

Generic model; not specific to a certain river basin; no 'tuning' needed to apply

Water discharge (Q) is a function of precipitation (P) per unit area (A) reduced by evaporation (Ev) and modified by water storage and release (Sr), computed through 5 water components

$$Q = A(P_i - Ev_i \pm S_r i)$$

$$Q = Q_r + Q_n + Q_{ice} - Q_{evap} \pm Q_g$$

Kettner and Syvitski,, Computers & Geosc., 2008

Long term **suspended** sediment load (Q_s)

$$Q_s = BQART$$

Q_s (sediment load (kg/s))

B (Lithology, Anthropogenic, Trapping efficiency, glaciers)

Q (Water discharge)

A (Area)

R (Relief)

T (Temperature)

Syvitski & Milliman, Journal of Geology, 2007

Sediment variability

Classic method to determine
Sediment flux per unit discharge

$$Cs_{[i]} = aQ_{[i]}^c$$

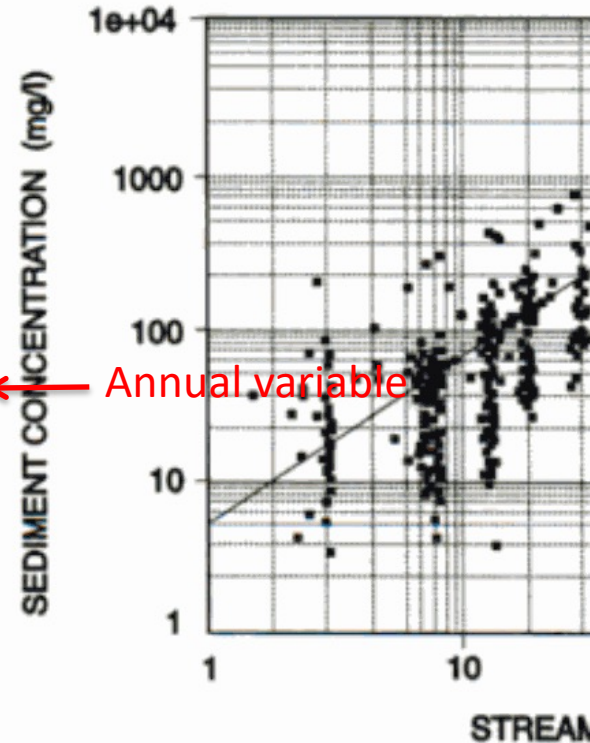
HydroTrend

$$\left(\frac{Qs_{[i]}}{\overline{Qs}}\right) = f\psi_{[i]}\left(\frac{Q_{[i]}}{\overline{Q}}\right)^{C_a}$$

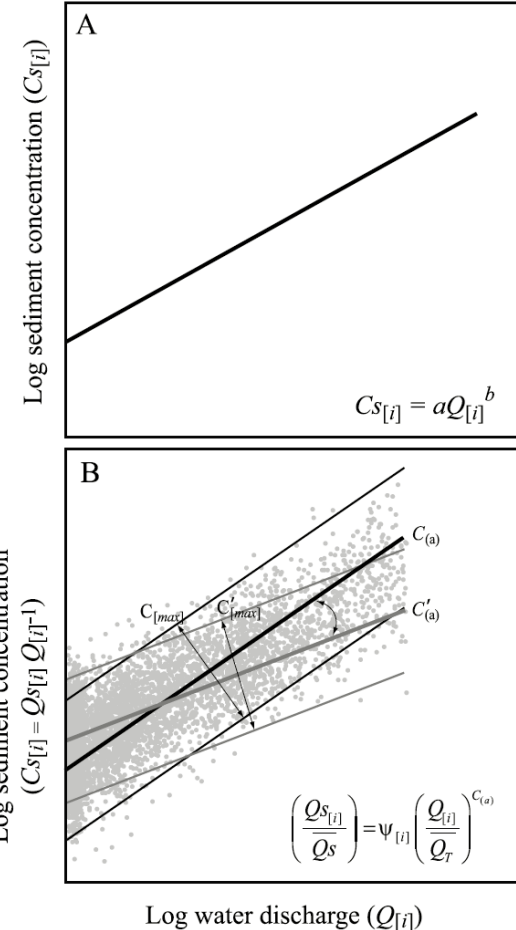
Daily variable

$$Cs_{[i]} = Qs_{[i]} / Q_{[i]}$$

Morehead et al.,
Glob. and Plan. Chan., 2003



Lopes and Folliott,
WRB, 1993



Kettner et al., WRR, 2007

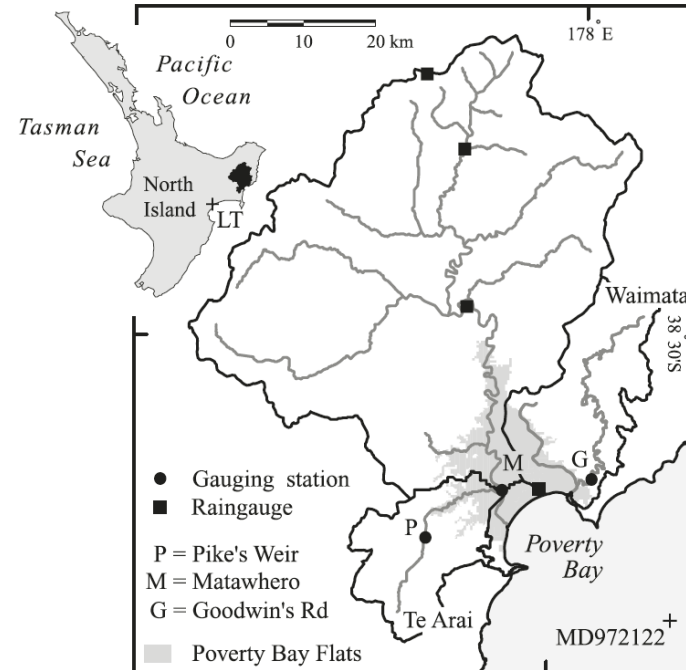
HydroTrend

Does this model obey the laws Andrew talked about earlier this morning?

- Conservation of mass
- Conservation of momentum

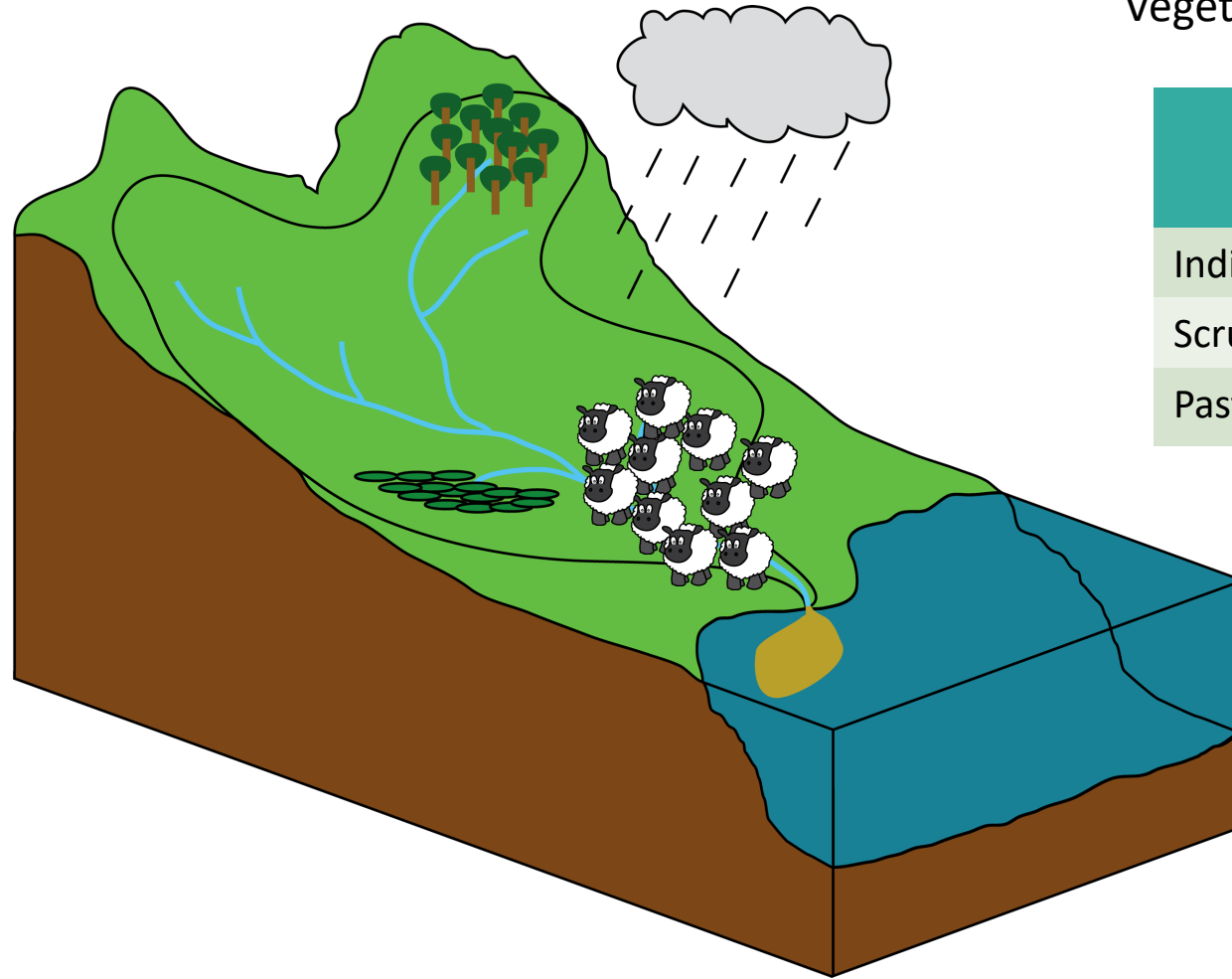
Case study Waipaoa River.

3kyrs →



Waipaoa River basin	
Area	1987 km ²
Relief	1190 m
Precipitation	1.59 m
Temperature	11.8 °C
Mean water discharge	~48 m ³ /s
Average sediment load	13.4 Mt/yr

Model modifications

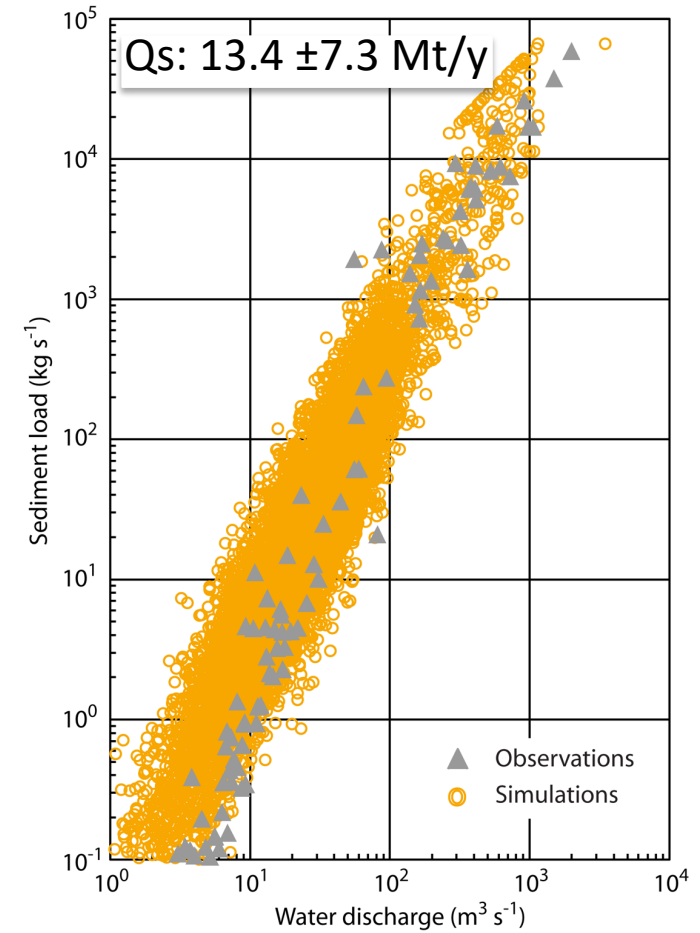
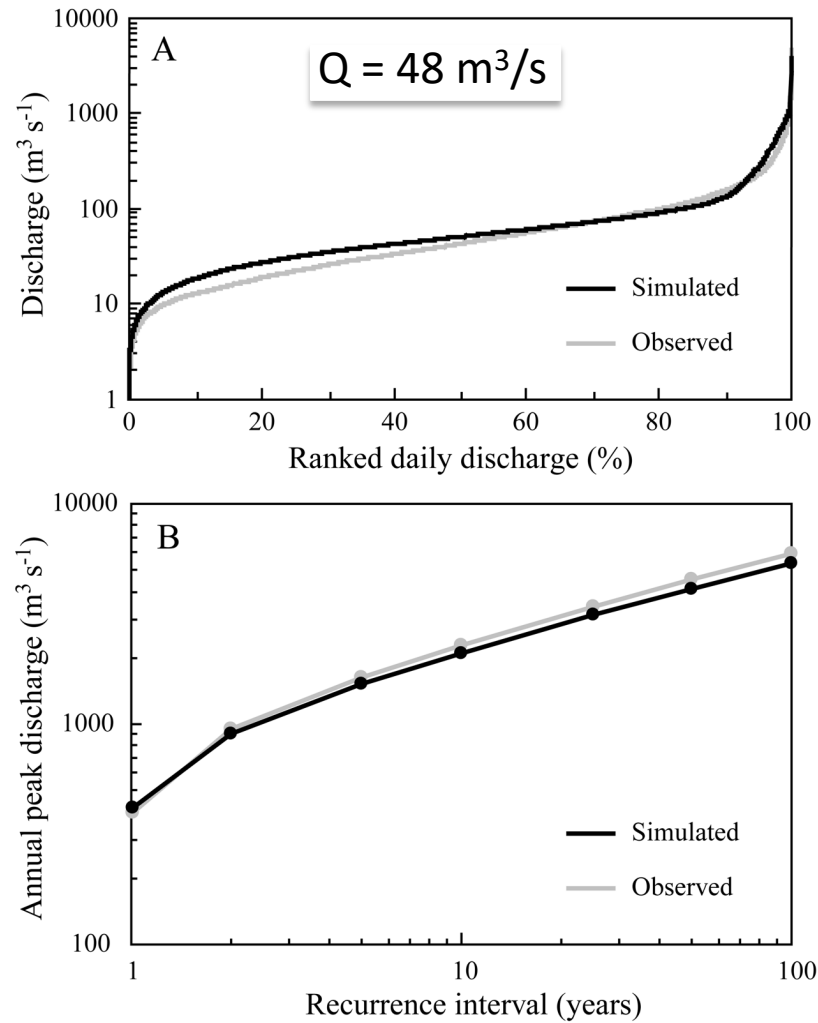


Vegetation driven sedimentation rates

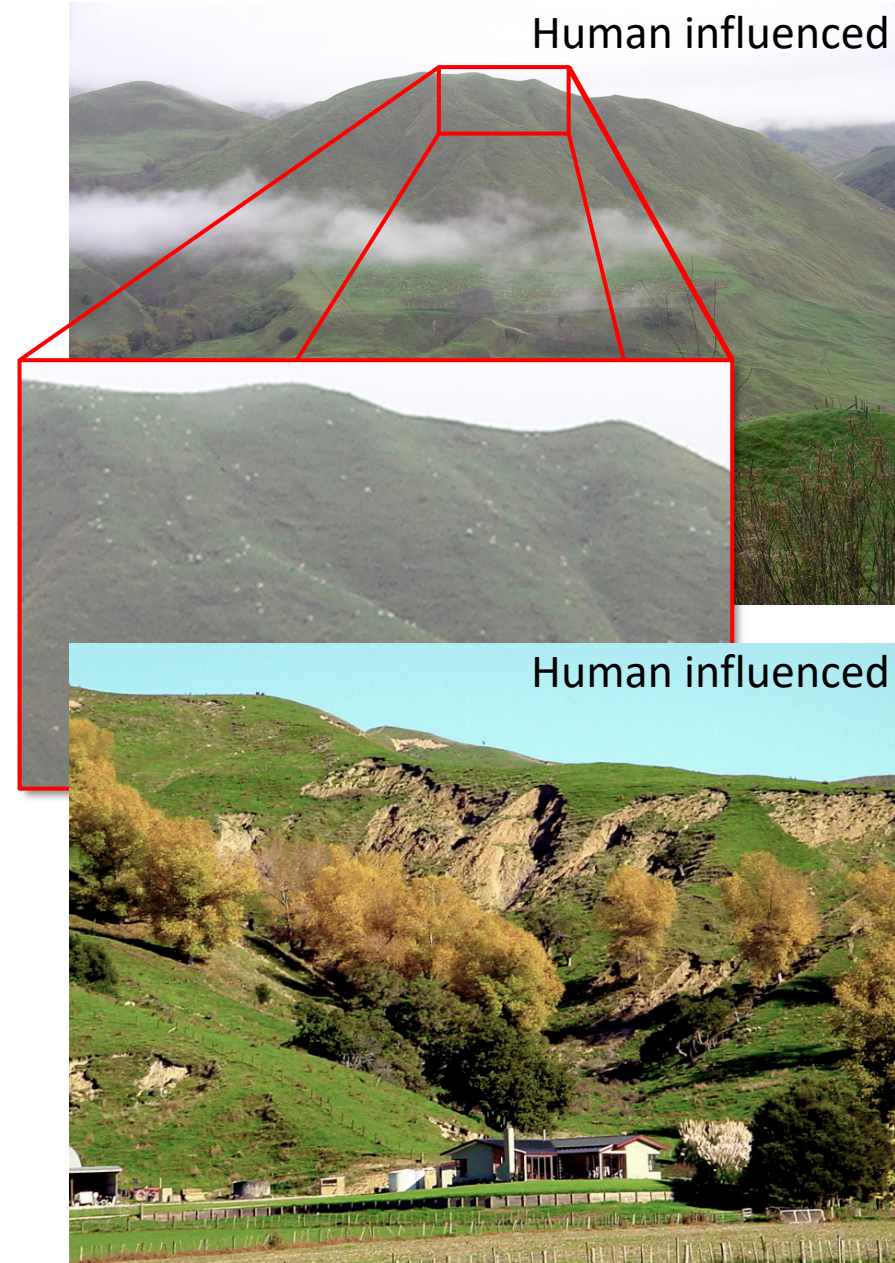
Vegetation erosion index / Sheep index	
Indigenous Forest	1
Scrub/Secondary Forest	2
Pasture / Bare ground / Crops	10

In this case study we adjusted the model to local circumstances (sheep)

Model validation



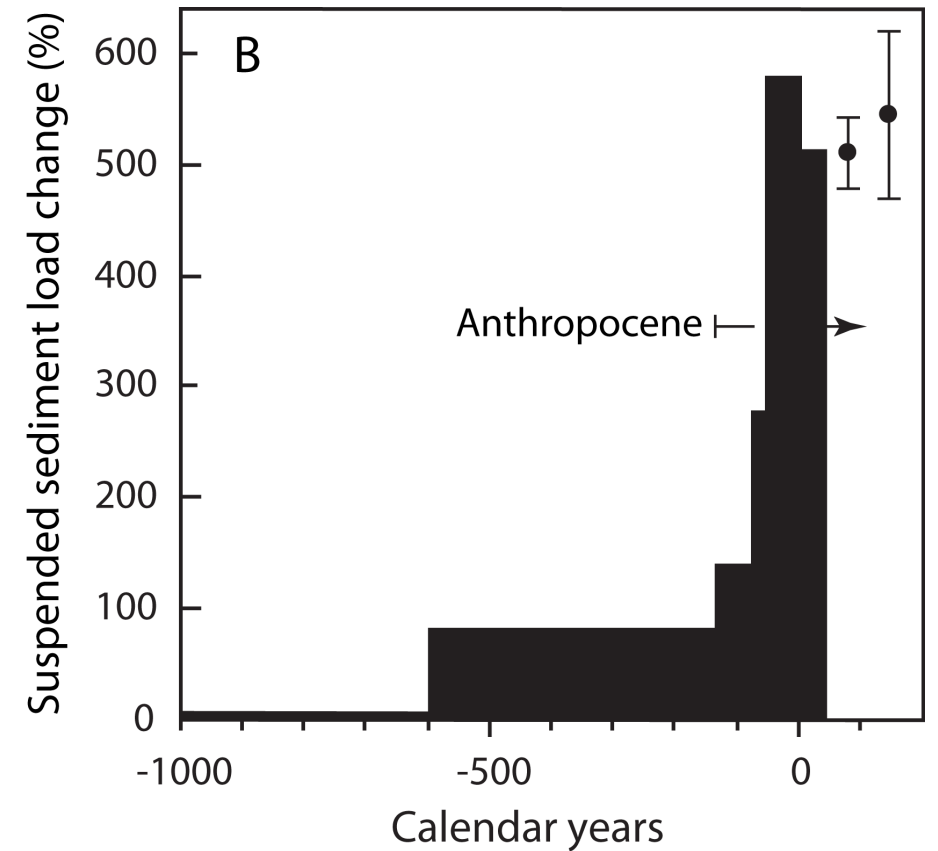
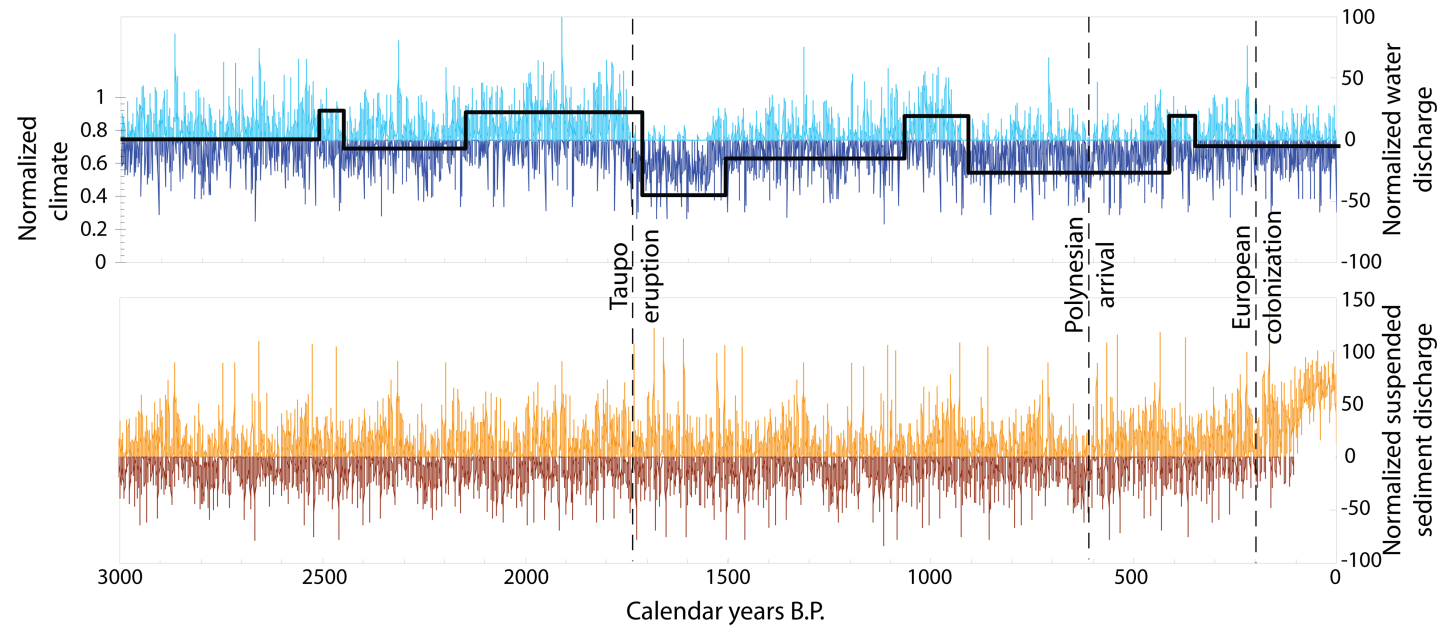
Vegetation change



Erosion

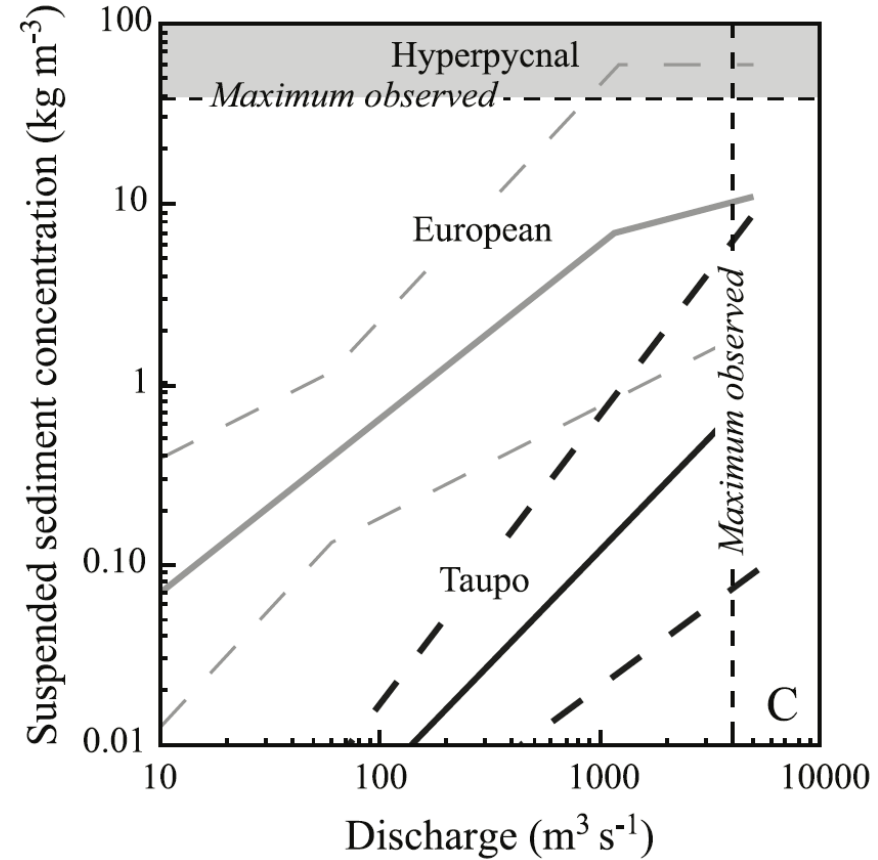
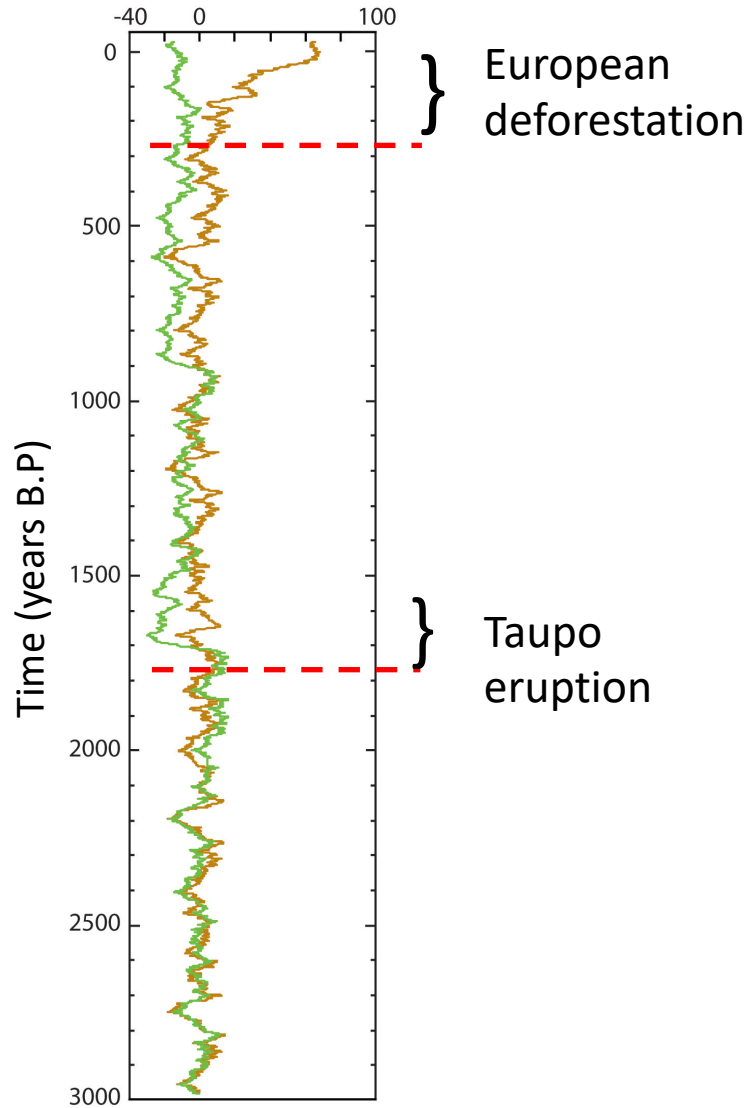


Simulated sediment flux of the Waipaoa



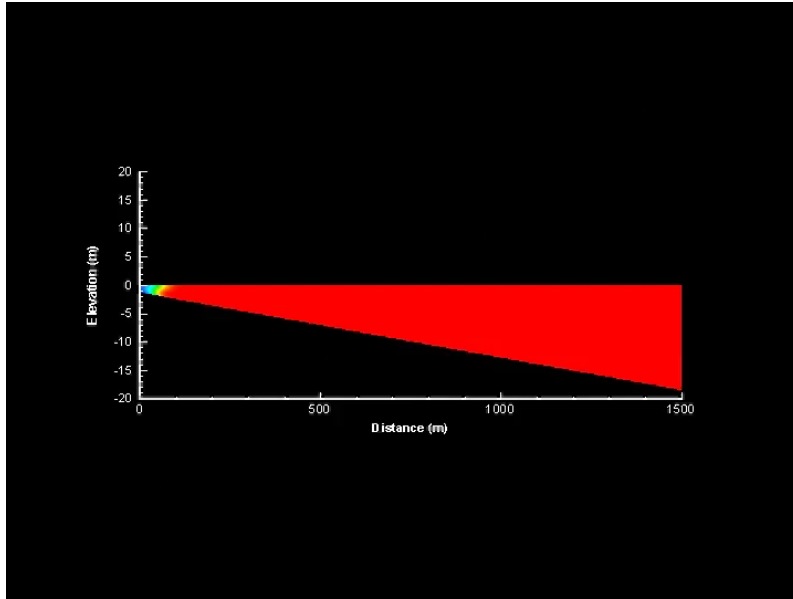
Changes in outflow regime Waipaoa River

25 yr running mean Water and Sediment



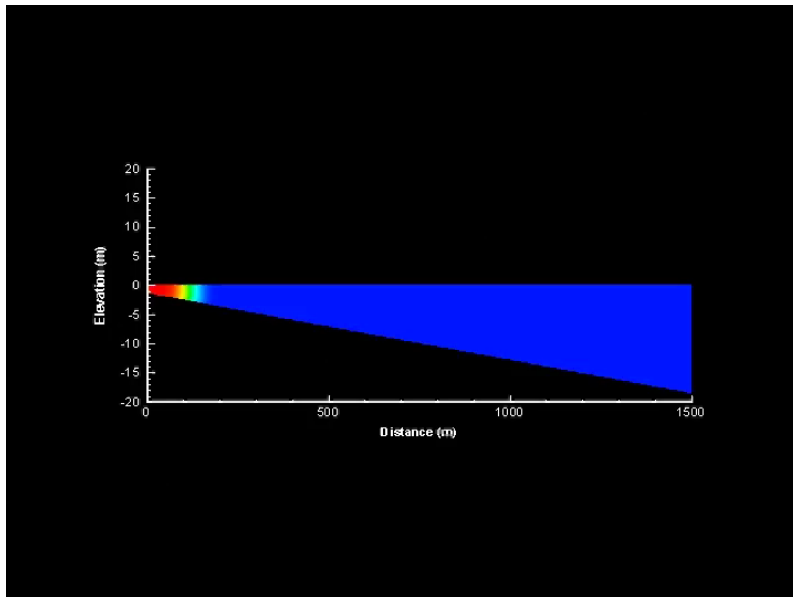
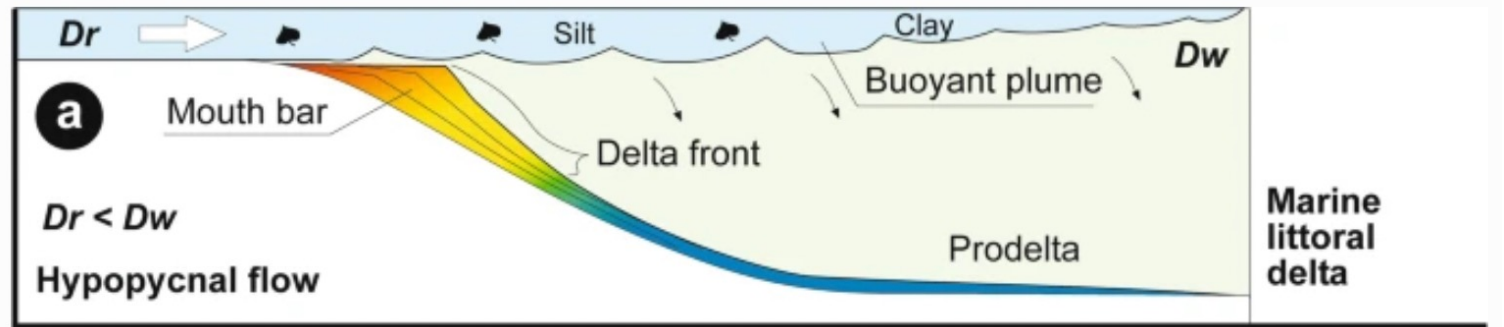
Kettner et al., WRR, 2007

Potential impact of Changing outflow regime Waipaoa River



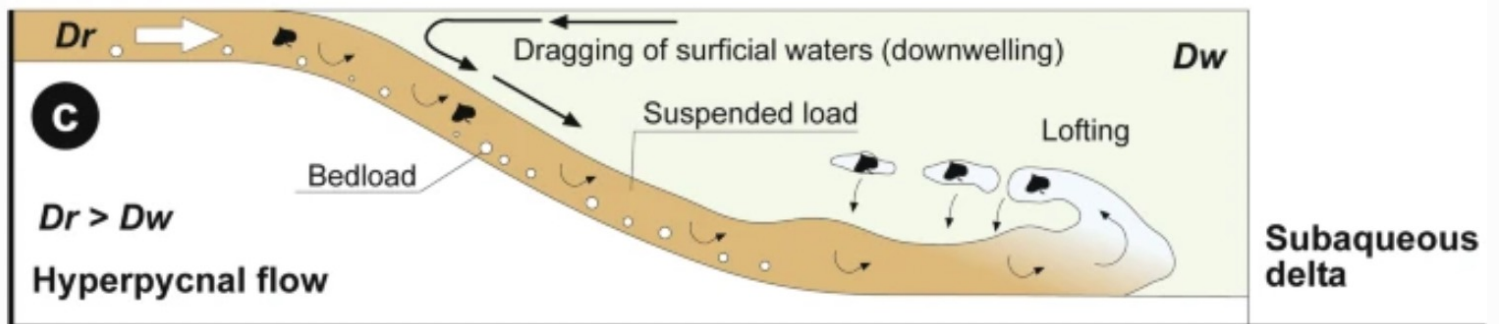
HYPOpycnal flows: *River outflow is less dens than ocean*

Sediment concentration $< 40 \text{ kg/m}^3$



HYPERpycnal flows: *River outflow is more dens than ocean.*

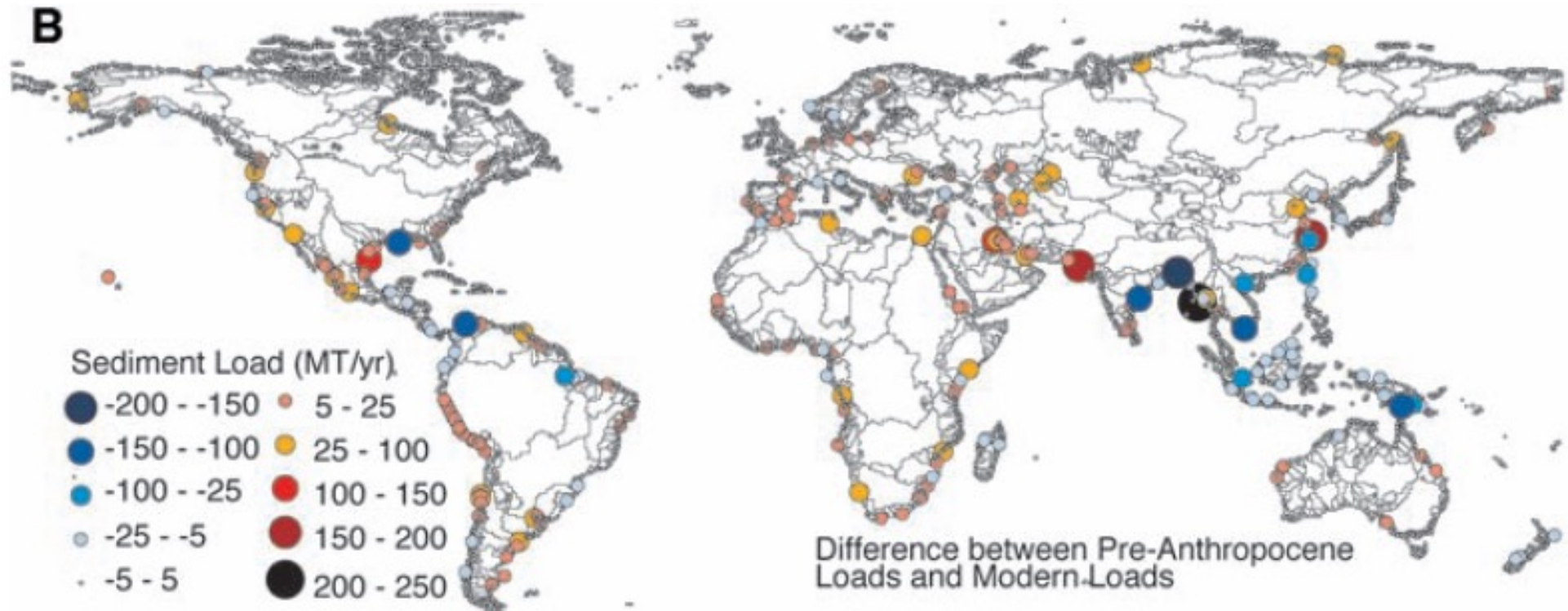
Sediment concentration $> 40 \text{ kg/m}^3$



From local to global fluvial sediment flux simulations

Semi global

Sediment fluxes towards the coast. Difference between Pre-Anthropocene and Modern Sediment load



Syvitski, Kettner et al., *Science* 2005

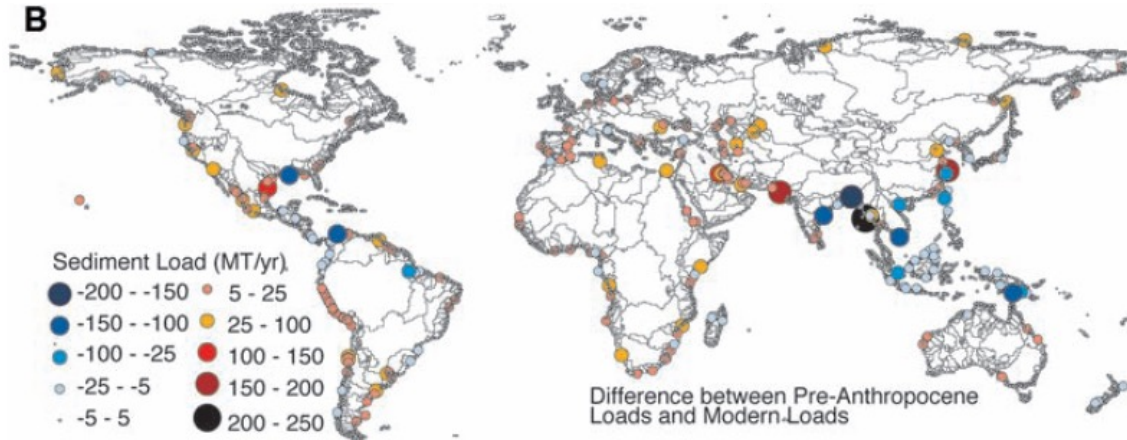
$$Q_s = BQART$$

Human induced sediment retention

	Area (Mkm ²)	Discharge (km ³ /year)	Prehuman load Qs (MT/year)	Modern suspended sediment load Qs					Load retained in reservoirs
				Annual (MT/year)	Seasonal percentages				
					DJF	MAM	JJA	SON	
Landmass									
Africa	20	3,800	1,310 ± 250	800 ± 100	30%	28%	22%	20%	25%
Asia	31	9,810	5,450 ± 1,300	4,740 ± 800	8%	12%	49%	31%	31%
Australasia	4	610	420 ± 100	390 ± 40	26%	27%	26%	21%	8%
Europe	10	2,680	920 ± 210	680 ± 90	29%	40%	18%	13%	12%
Indonesia	3	4,260	900 ± 340	1,630 ± 300	31%	28%	19%	21%	1%
North America	21	5,820	2,350 ± 610	1,910 ± 250	15%	24%	33%	28%	13%
Ocean islands	0.01	20	4 ± 1	8 ± 3	25%	13%	38%	25%	0%
South America	17	11,540	2,680 ± 690	2,450 ± 310	21%	32%	29%	18%	13%
Ocean basin									
Arctic Ocean	17	3,570	580 ± 120	420 ± 60	2%	20%	63%	15%	5%
Atlantic Ocean	42	18,480	3,850 ± 800	3,410 ± 420	20%	30%	27%	23%	14%
Indian Ocean	15	5,060	3,810 ± 1,020	3,290 ± 410	12%	12%	46%	30%	15%
Inland seas (endorheic)	5	400	470 ± 180	140 ± 30	13%	51%	28%	8%	30%
Mediterranean and Black Seas	8	710	890 ± 280	480 ± 60	43%	42%	9%	7%	30%
Pacific Ocean	18	10,320	4,430 ± 1,100	4,870 ± 910	18%	23%	33%	26%	26%
Climate zone									
Tropical (>25°C)	17	7,110	1,690 ± 480	2,220 ± 360	22%	17%	29%	32%	16%
Warm temperate (10–25°C)	47	21,110	9,070 ± 2,600	8,030 ± 1,250	18%	22%	35%	25%	15%
Cold temperate (0–10°C)	17	4,760	1,940 ± 250	1,460 ± 160	17%	35%	30%	19%	47%
Polar (<0°C)	24	5,560	1,330 ± 170	900 ± 120	2%	24%	58%	17%	6%
Elevation class									
High mountain (>5000 m)	21	12,500	5,120 ± 1,600	4,100 ± 740	11%	18%	44%	27%	31%
Mountain (3000–5000 m)	30	6,420	2,970 ± 610	2,190 ± 340	20%	28%	31%	21%	22%
Low mountain (1000–3000 m)	36	12,790	4,670 ± 1,030	4,800 ± 630	20%	23%	31%	25%	12%
Upland (500–1000 m)	10	3,670	910 ± 180	1,060 ± 110	24%	24%	28%	23%	4%
Lowland (100–500 m)	8	2,560	330 ± 70	360 ± 50	21%	34%	26%	19%	2%
Coastal plain (<100 m)	1	600	30 ± 10	100 ± 20	27%	40%	20%	13%	0%
Global	106	38,540	14,030	12,610	18%	23%	35%	25%	20%

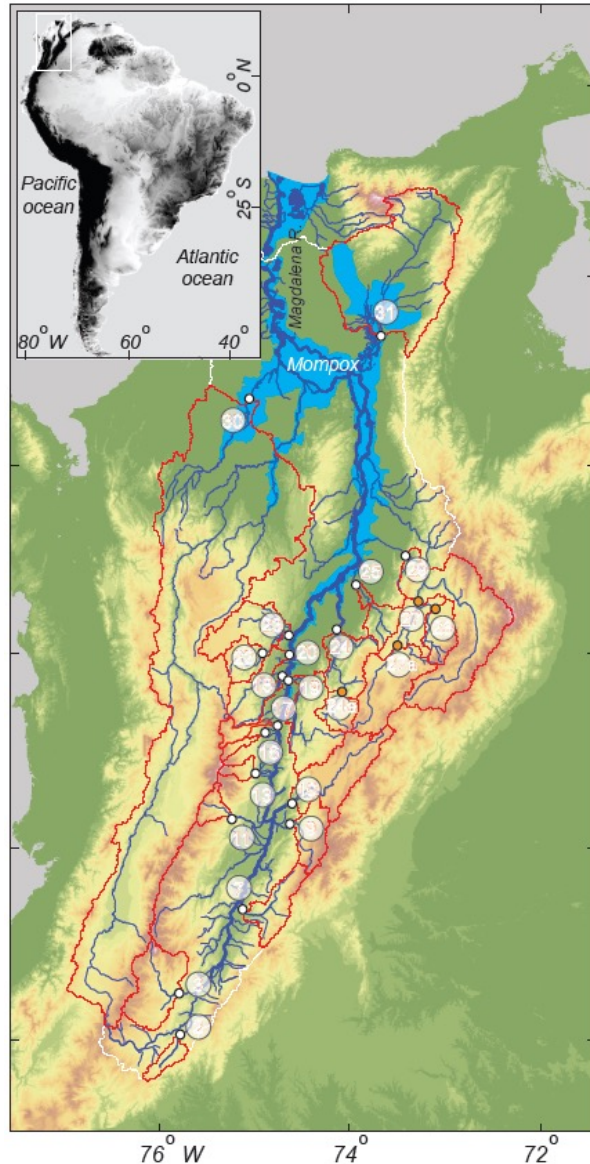
Syvitski, Kettner et al., Science, 2005

Limitations of 1D models



- Where on land happens the sediment retention e.g. behind dams, or will erosion occur due to e.g. vegetation change? What are the hotspots?
- Where on the land does climate (change) have a big impact on the sediment flux?

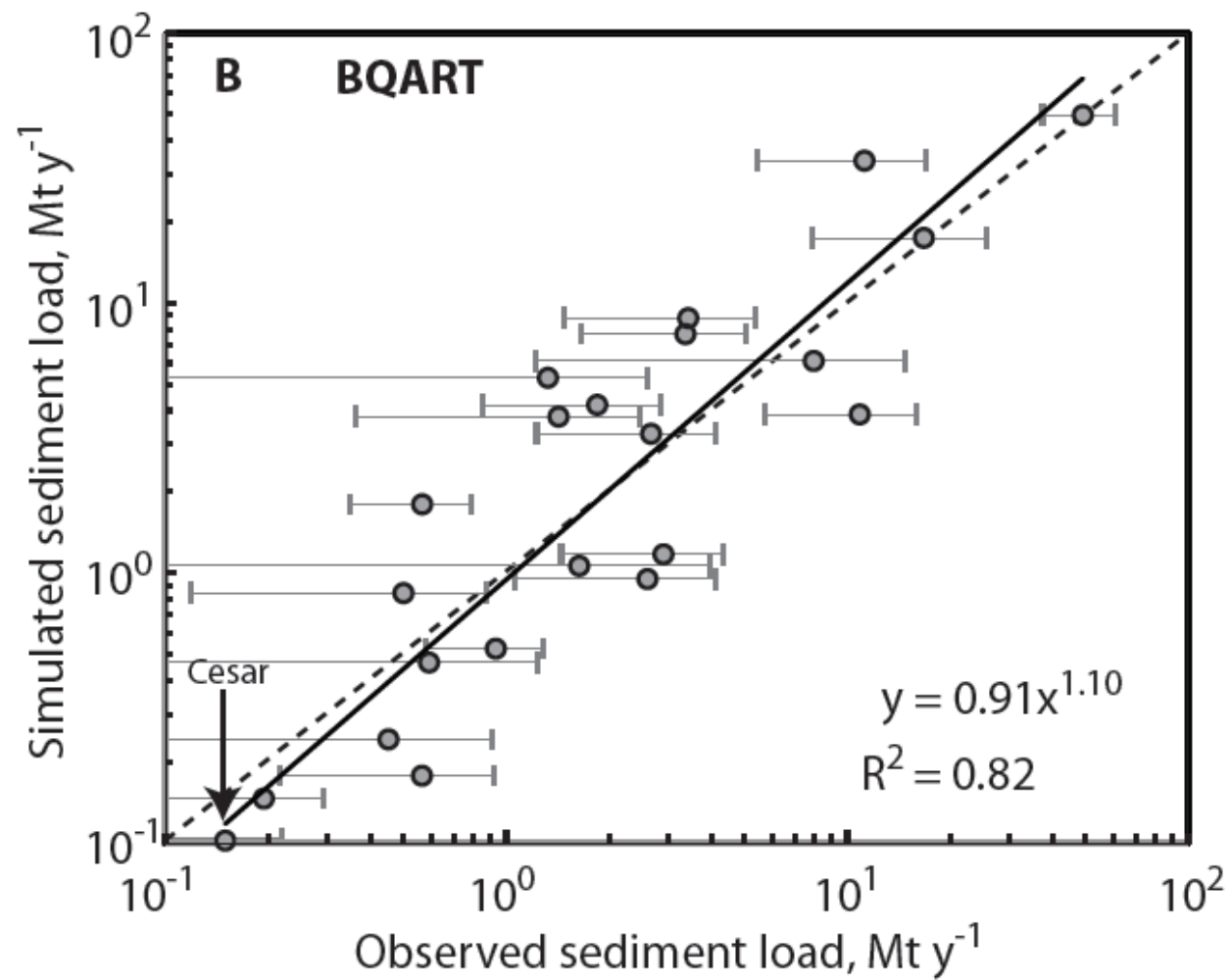
First step towards within basement simulation of sediments



Tributary	Discharge (km ³ yr ⁻¹)	Area (km ²)	Relief (km)	Temperature (°C)	Observed sediment load (Mt yr ⁻¹)	Simulated sediment load (Mt yr ⁻¹)
Magdalena River	226.3	257,438	5.4	21.8	144.2 ± 48.37	183–207
2. Suaza	1.4	1014	1.6	17.9	.57 ± .35	.18
3. Páez	5.7	4760	3.6	12.9	2.89 ± 1.44	1.17
7. Cabrera	2.2	2713	3.6	20.0	1.85 ± 1.00	4.20
9. Sumapaz	1.3	2433	3.7	10.8	.50 ± .38	.84
10. Bogotá	1.2	5409	2.9	12.3	1.32 ± 1.28	5.29
11. Coello	1.3	1041	3.5	17.1	1.64 ± 2.34	1.06
13. Recio	.6	643	4.7	4.3	.16 ± .11	.05
16. Gualí	.7	458	4.6	12.7	.19 ± .10	.15
17. Guarino	1.0	840	2.9	14.9	.45 ± .46	.24
18. La Miel	7.7	2363	2.5	19.9	2.66 ± 1.43	3.28
19. Negro	4.3	4575	3.3	21.9	7.97 ± 6.75	6.11
20. Cocorna	1.8	790	2.1	27.6	.59 ± .64	.47
22. Samana	5.7	1713	2.7	18.7	.93 ± .35	.52
23. Nare	12.5	5564	2.9	21.3	2.59 ± 1.53	.95
24. Carare:						
Downstream	8.3	4909	3.6	20.1	16.76 ± 8.85	17.45
Upstream (24a)	7.3	1607	3.1	19.1	10.87 ± 5.09	3.87
25. Opón	2.8	1752	1.9	22.8	3.35 ± 1.70	7.68
27. Suárez:						
Downstream	9.5	9775	3.7	13.9	3.41 ± 1.93	8.80
Upstream (27a)	6.2	5115	2.9	11.7	2.64 ± 1.06	3.80
28. Fonce	2.7	2083	3.2	14.0	.57 ± .22	1.80
29. Sogamoso	13.7	21,211	3.7	12.3	11.22 ± 5.75	33.70
30. Cauca	75.2	66,751	4.2	21.6	49.05 ± 11.7	49.73
31. Cesar	1.7	18,827	1.8	25.0	.15 ± .07	.10
Sum catchments					121	151.43

Kettner, Restrepo, et al., The J. of Geology, 2010

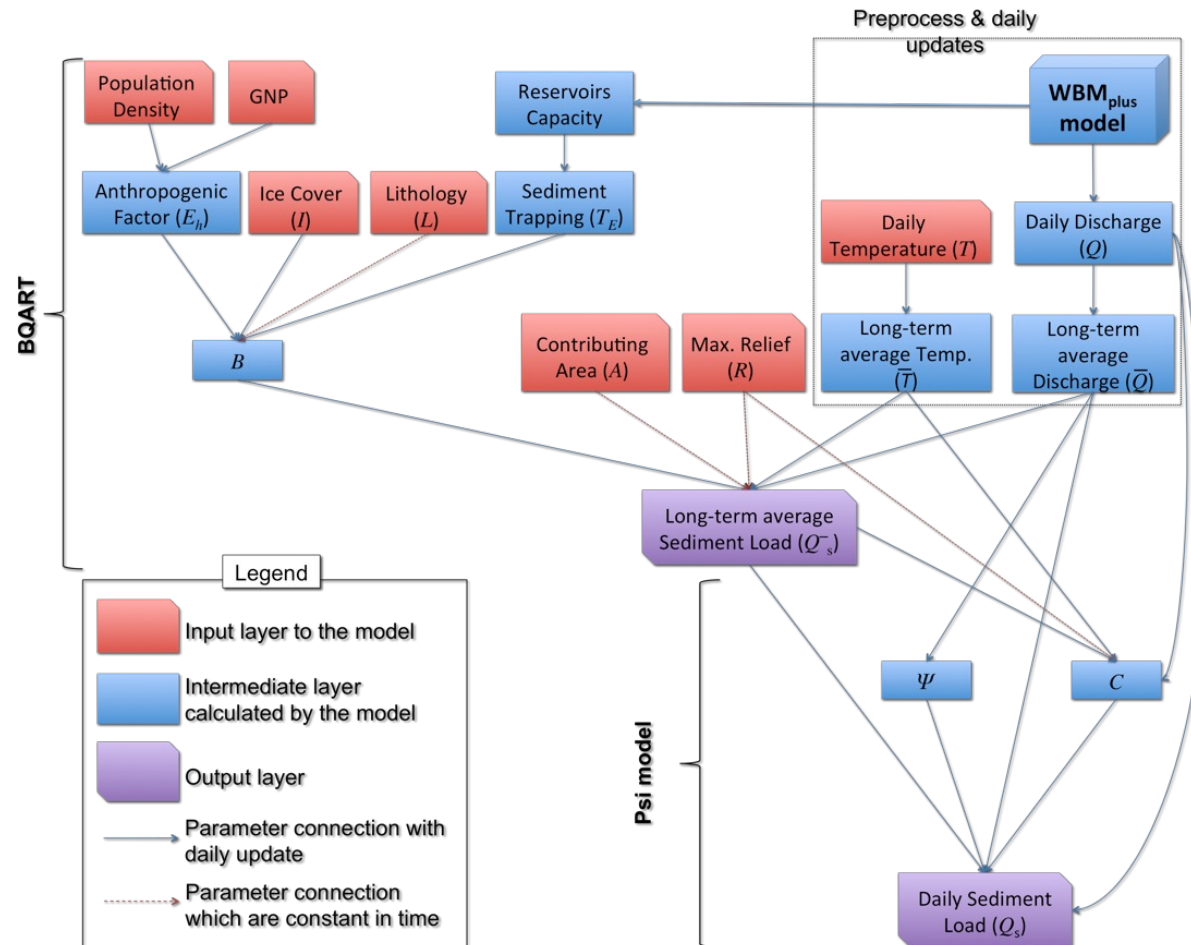
Sediment validation



Kettner, Restrepo, et al., The J. of Geology, 2010

WBM: fully 2D sediment routing model

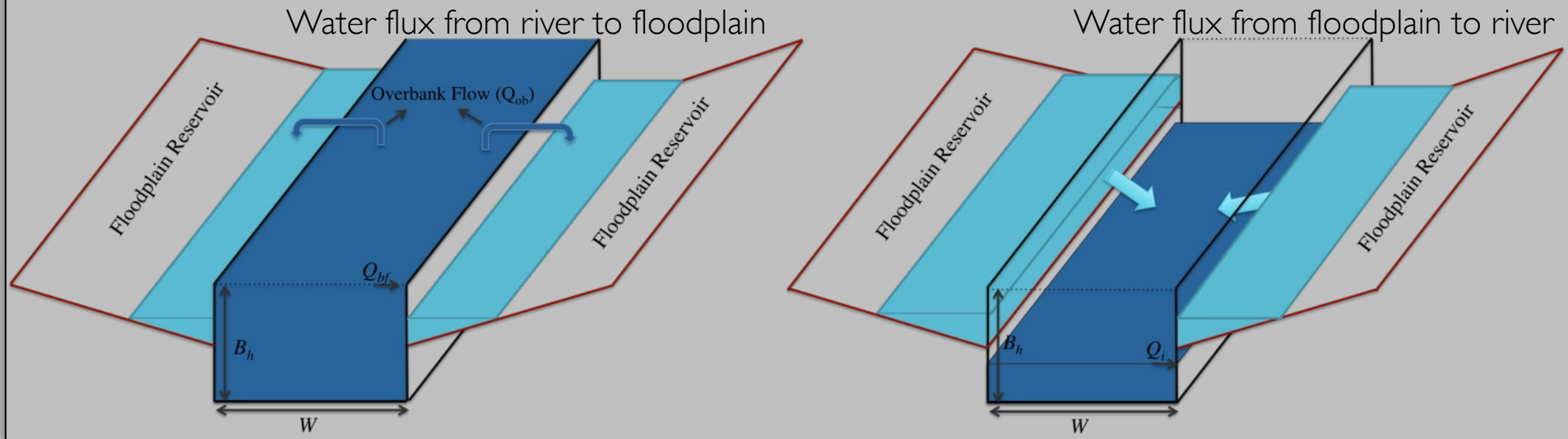
- WBMsed - a distributed global-scale riverine water, sediment and nutrients flux model (Cohen et al., 2013, 2014):



WBM: fully 2D sediment routing model

The WBMsed v2.0 model introduced an improved water routing scheme that account for **bankfull discharge and floodplain storage** of flood waters inspired by the *CaMa-Flood* model (Yamazaki et al., 2011).

Fig. 1: Schematics of the floodplain reservoir component in WBMsed v2.0.



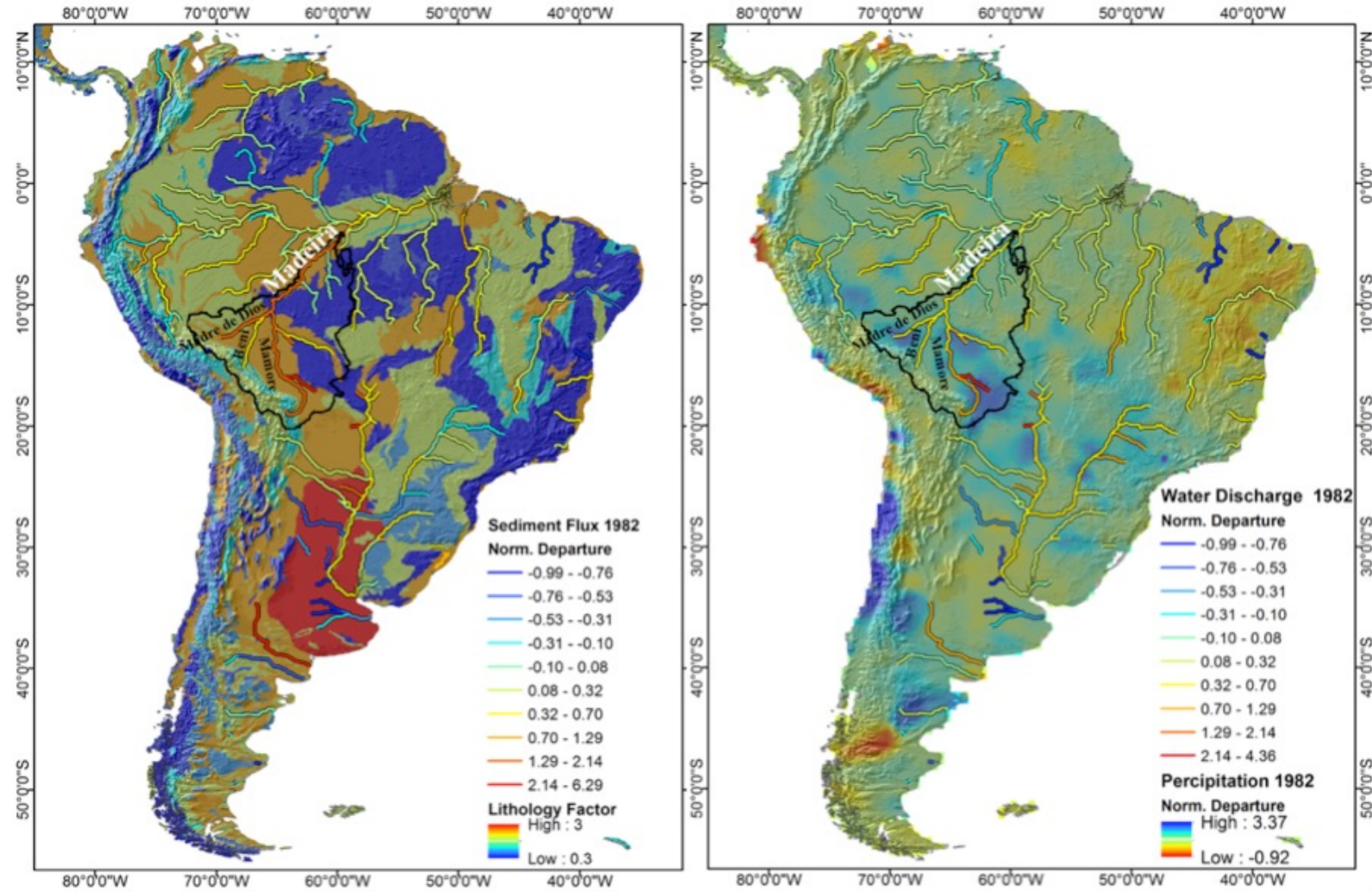
Key assumptions:

1. No additional loss of floodplain water to evaporation.
2. All sediment transported to the floodplain will be deposited.

Input data



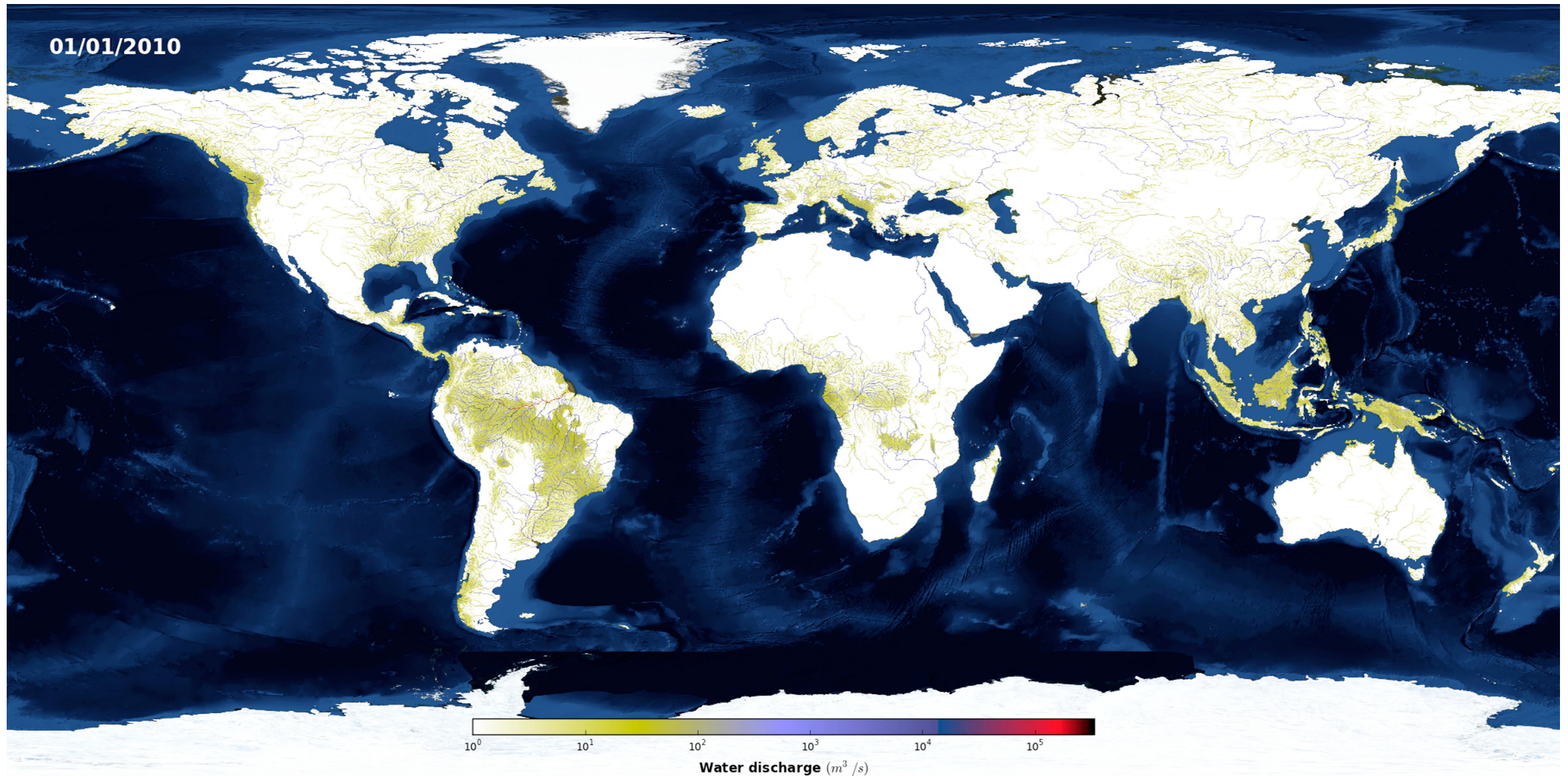
2D fluvial transport model



Background = Lithology

Background = 1982 annual precipitation

WBM – daily water discharge



Summary

- Fluvial Sediment fluxes change over time due to changes forced by:
 - Climate
 - human (deforestation / land use change, mining, emplacements of reservoirs)
 - Tectonics
- Changes in sediment flux have an impact on our environment:
 - Coastline (e.g. retreat with decreasing sediments)
 - Affect deltas
 - Stress on coral reefs; fisheries when there is an increase in sediments;
- Fluvial sediment transport models can provide insights in:
 - Quantifying the change in sediment flux towards the ocean
 - what causes changes in sediment fluxes
 - What are the consequences of human interference
 - With 2D models it is possible to detect local anomalies. Where are the hotspots.
- For many simulated basins we have found that due to human interference, sediment fluxes first increase (deforestation) where after fluxes decrease (dams)

Thank you for your attention!

