Earth-surface Dynamics Modeling & Model Coupling

A short course

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Module 2: Modeling discharge and Sediment Flux

ref: Syvitski, J.P.M. et al., 2007. Prediction of margin stratigraphy. In: C.A. Nittrouer, et al. (Eds.) Continental-Margin Sedimentation: From Sediment Transport to Sequence Stratigraphy. IAS Spec. Publ. No. 37: 459-530.

DEM to flow paths (3)
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U.S. East Coast Example
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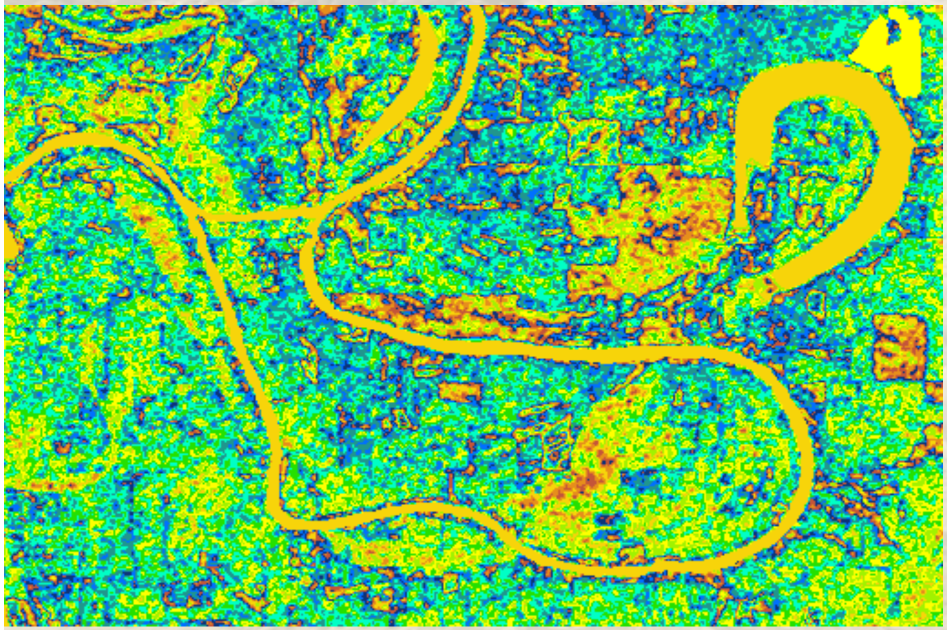
Summary (1)

Step 1): use an appropriate topographic DEM: LIDAR (1-5 m), SRTM (30-90m), GLOBE & GTOPO30 (1km), ETOPO2/5 (4-10km)

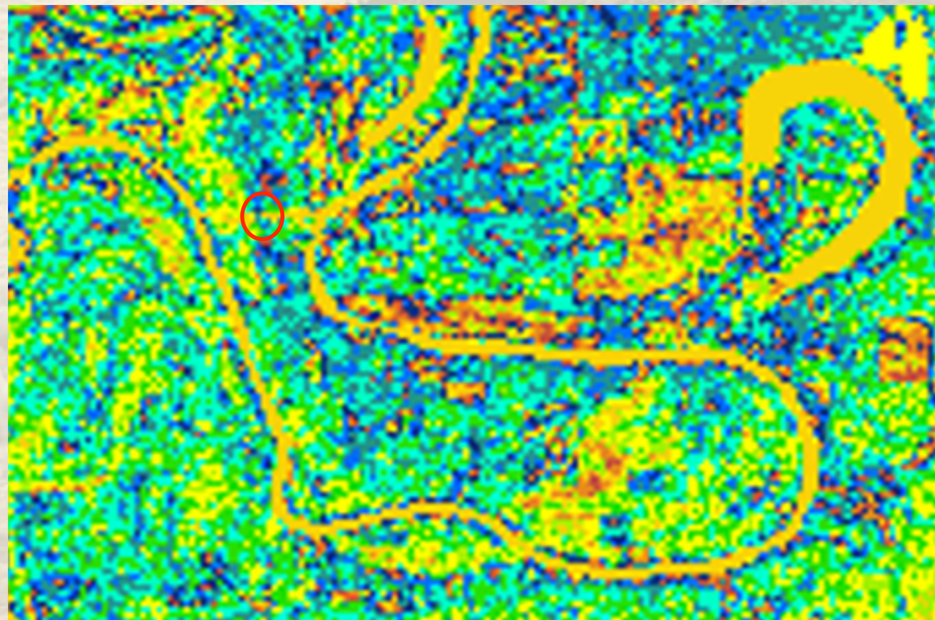
SRTM Data Resolution

- A horizontal pixel is 1-arc or 3-arc seconds, depending on data availability

Mississippi floodplain detail



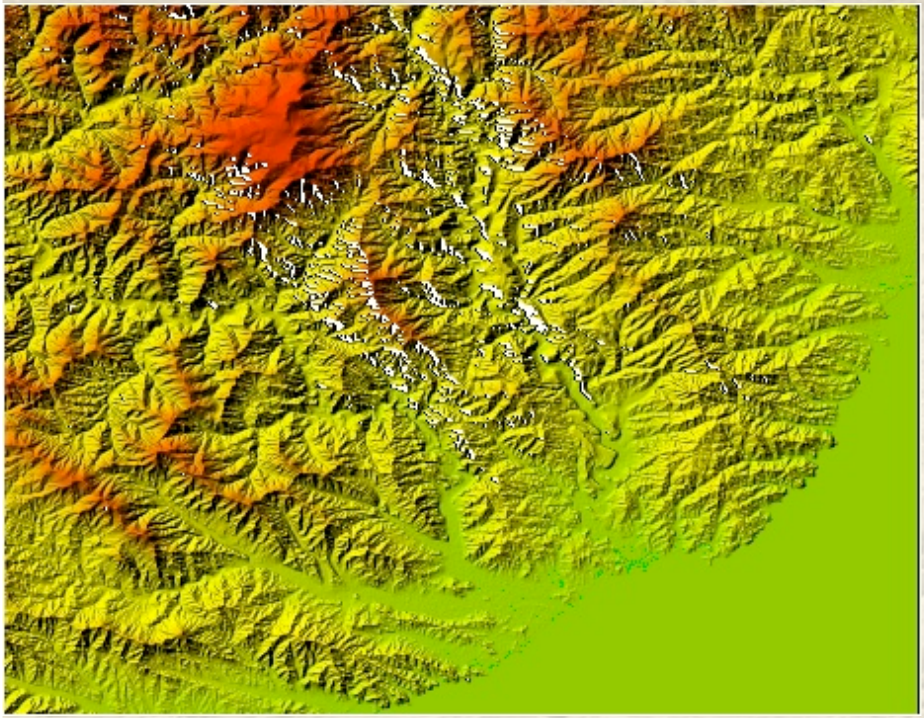
30 m horizontal resolution



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



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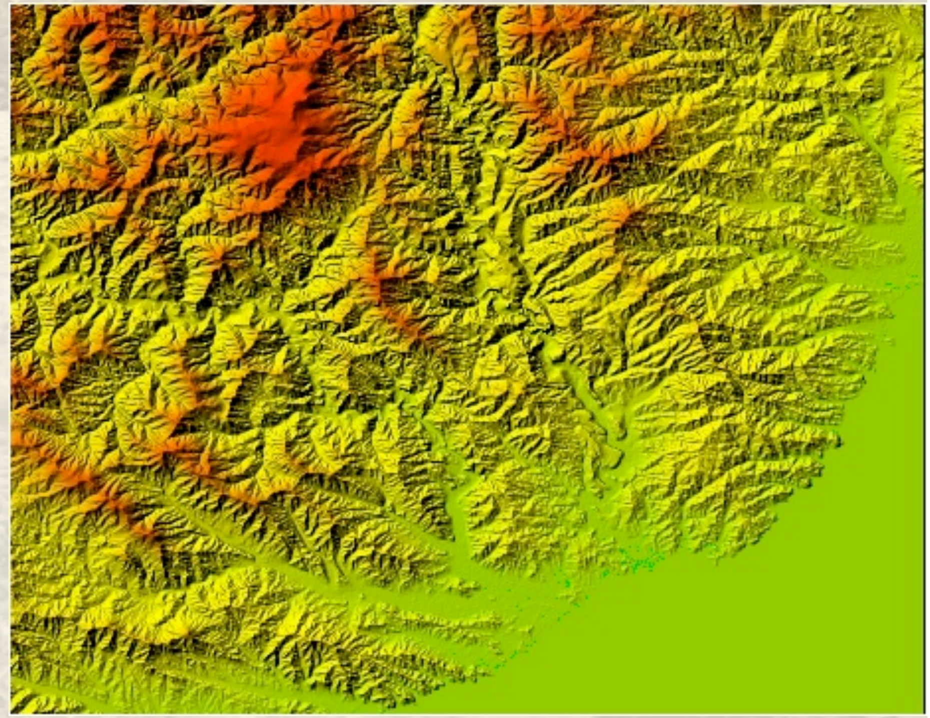
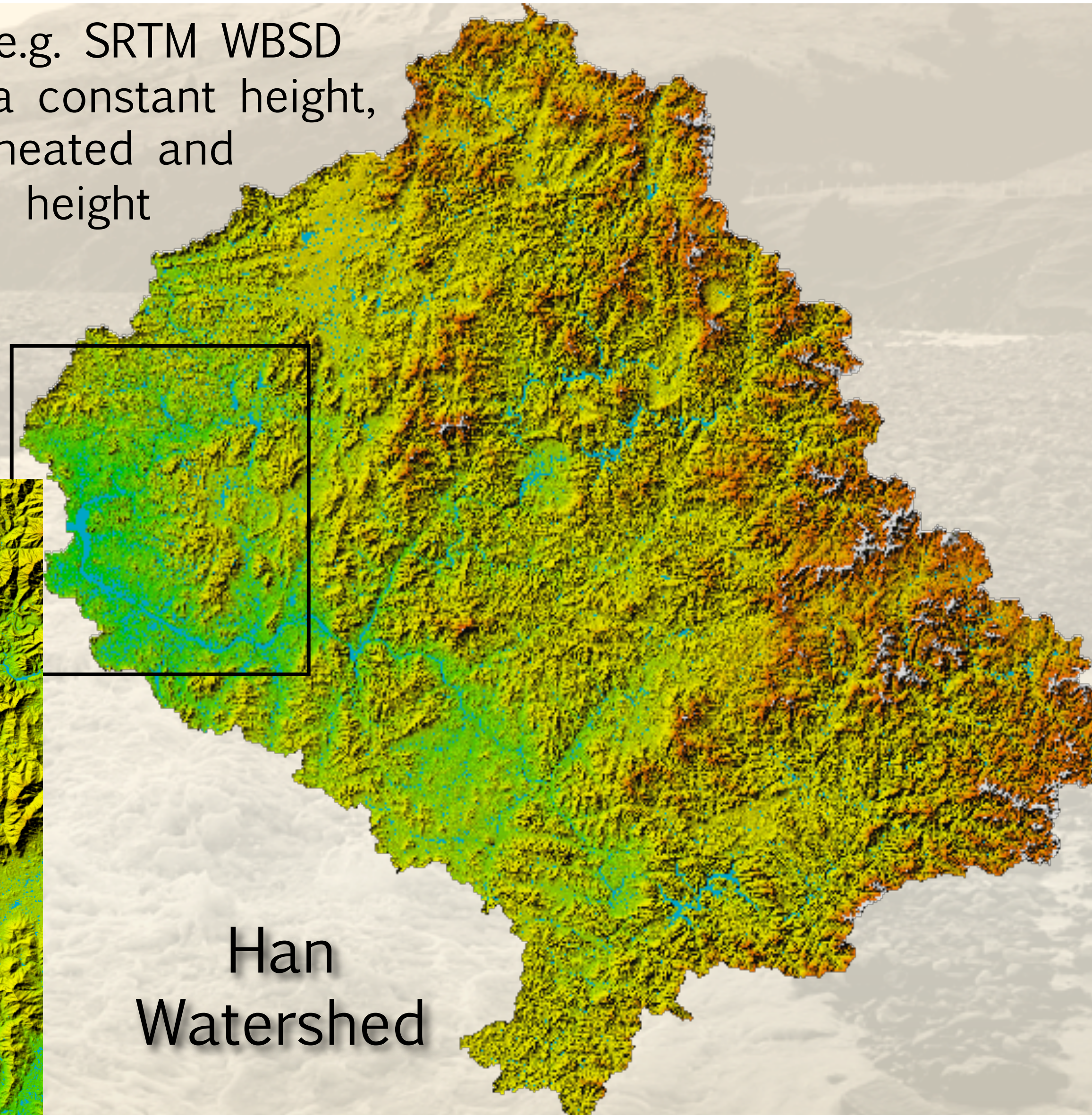
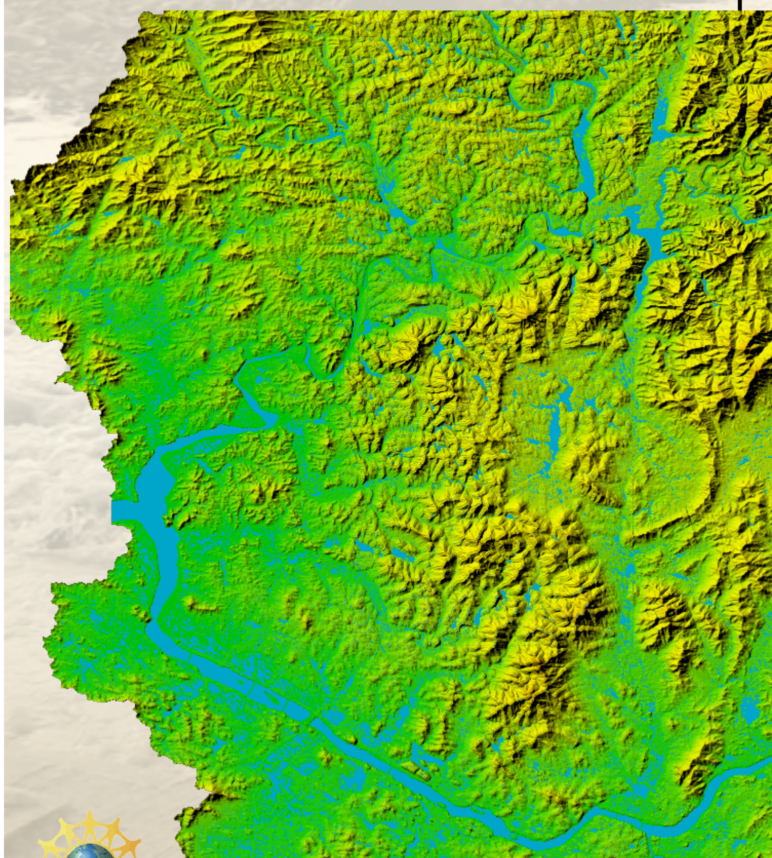


3-arcsecond SRTM, Korea

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

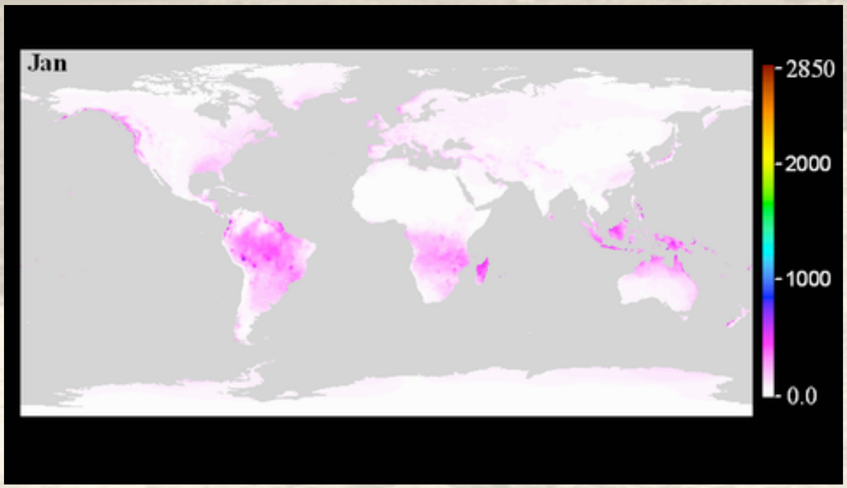




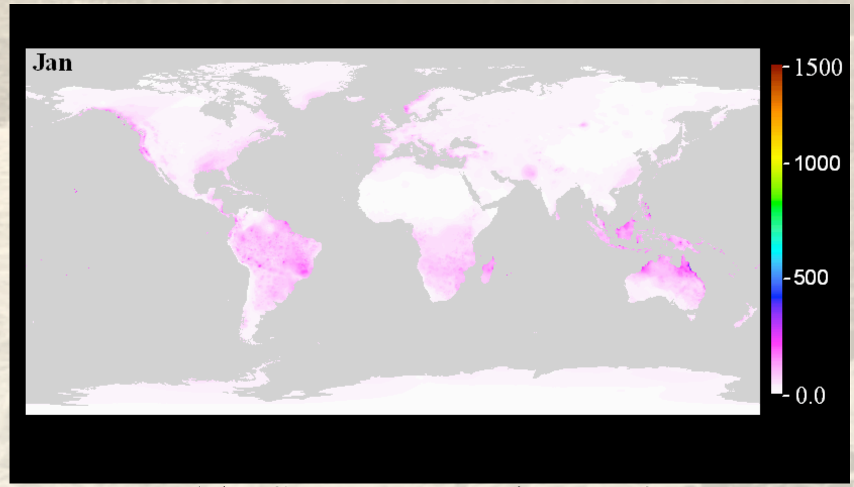
Han Watershed

Precipitation

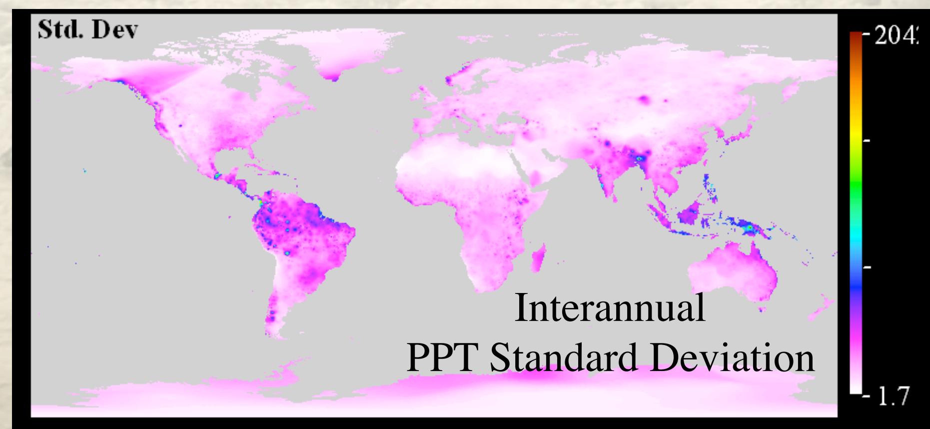
1. Gridded 0.5° by 0.5°: CRU or U. Delaware rain gauge data, based on: NSDC Global Historical Climatology Network 1,870 to 16,360 stations between years 1950-1999; Legates and Willmott archive 26,858 precipitation stations

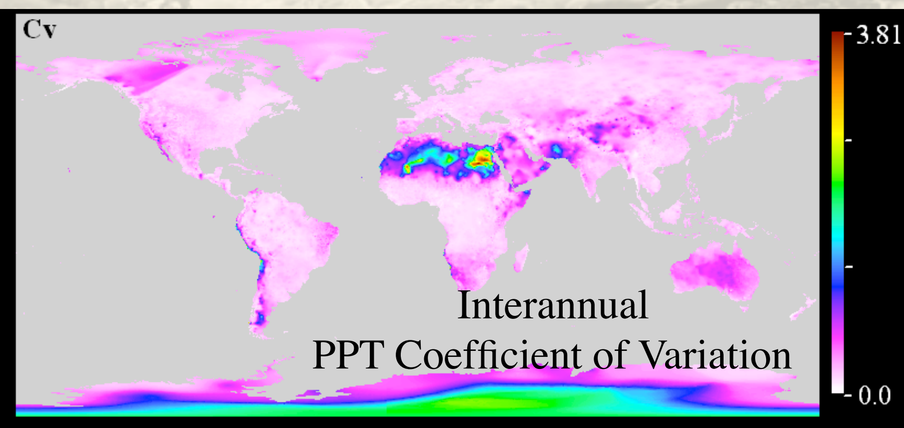


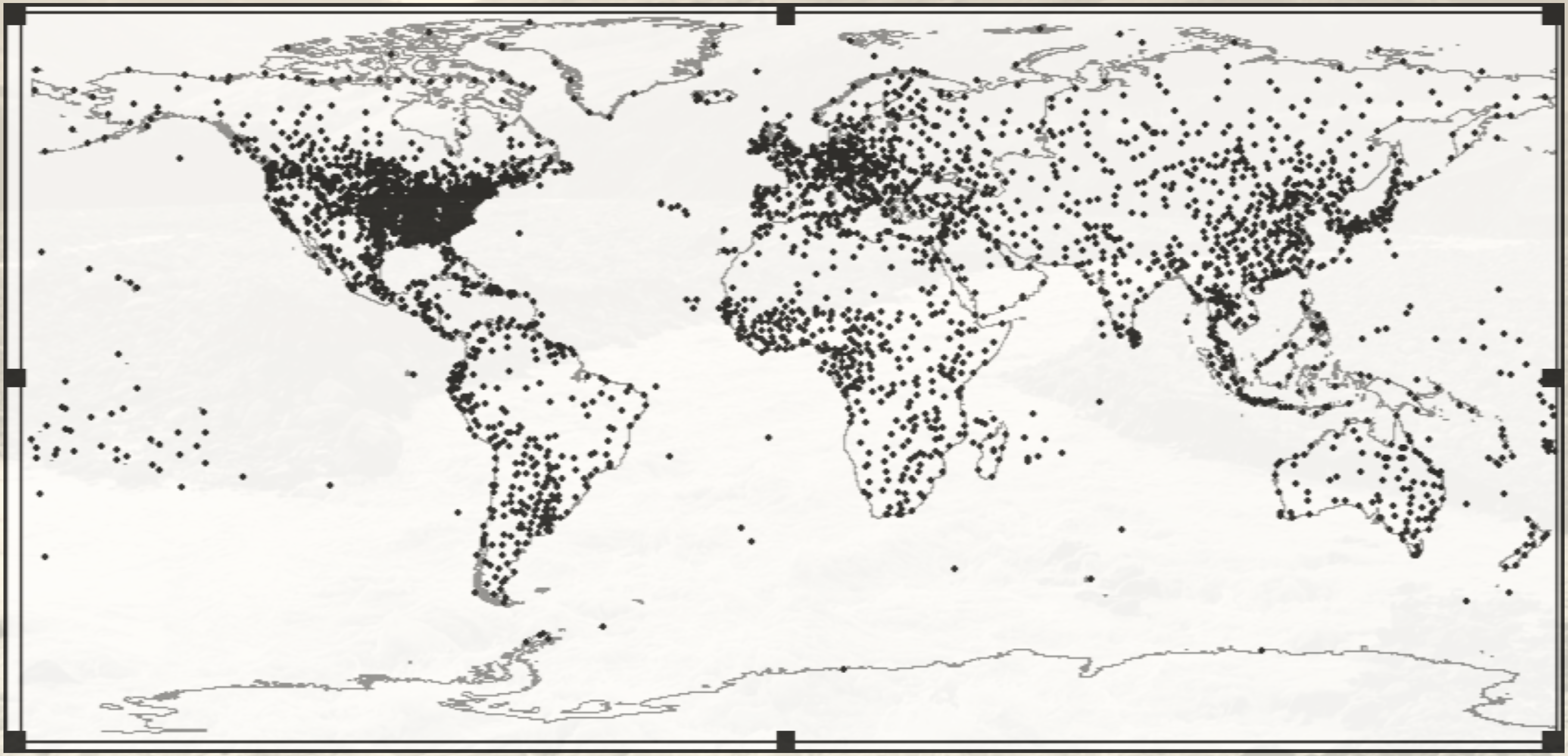
Monthly Mean Precip mm/mo



Monthly St. Dev. Precip mm/mo



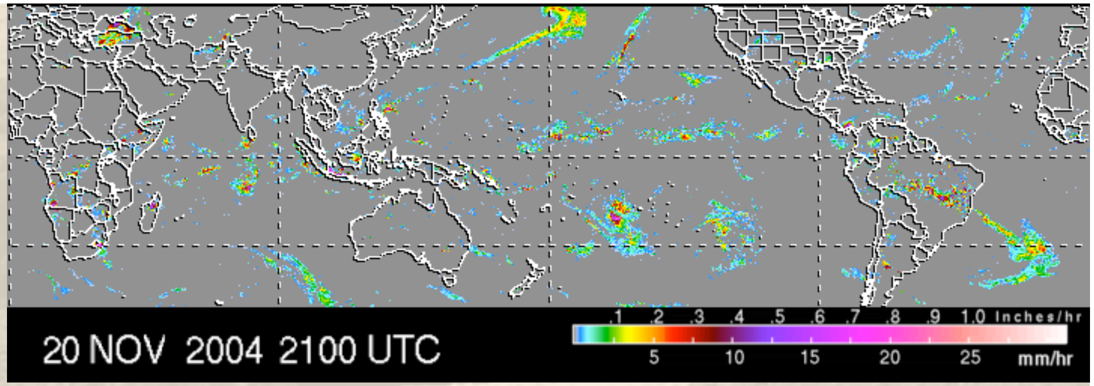


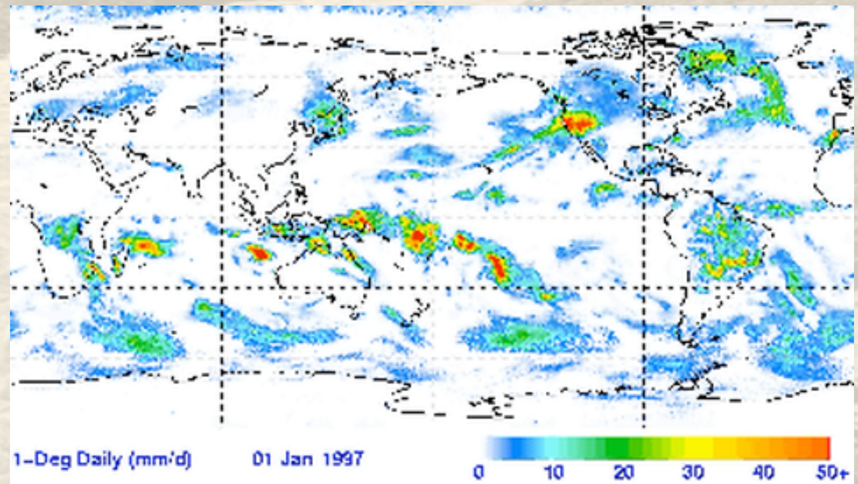


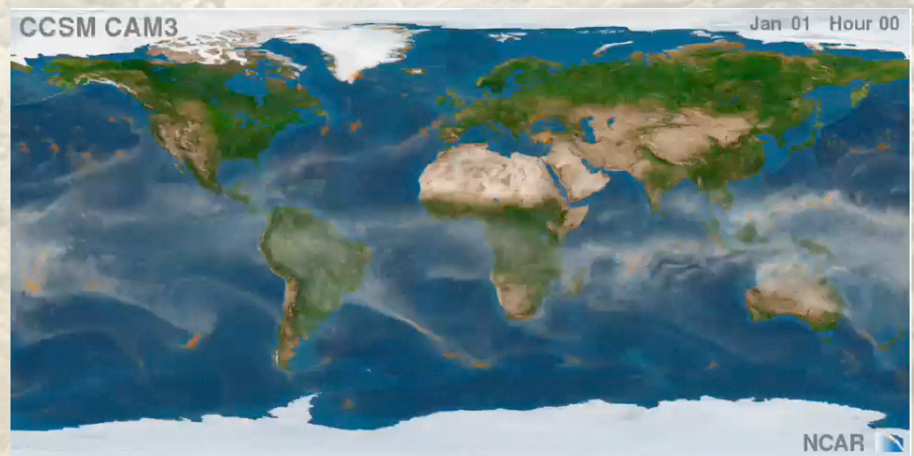
Global distribution of 3423 met stations providing monthly averages on precipitation and temperature, with most stations reporting between 50 and 100 years of observations.

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

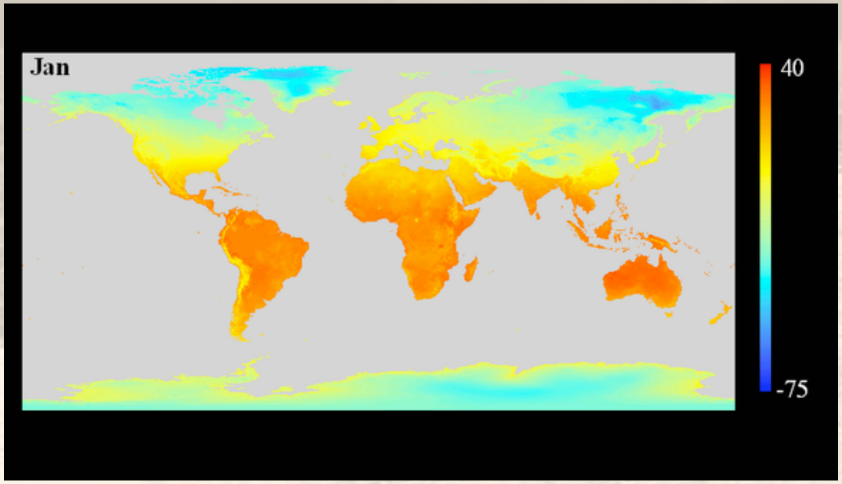




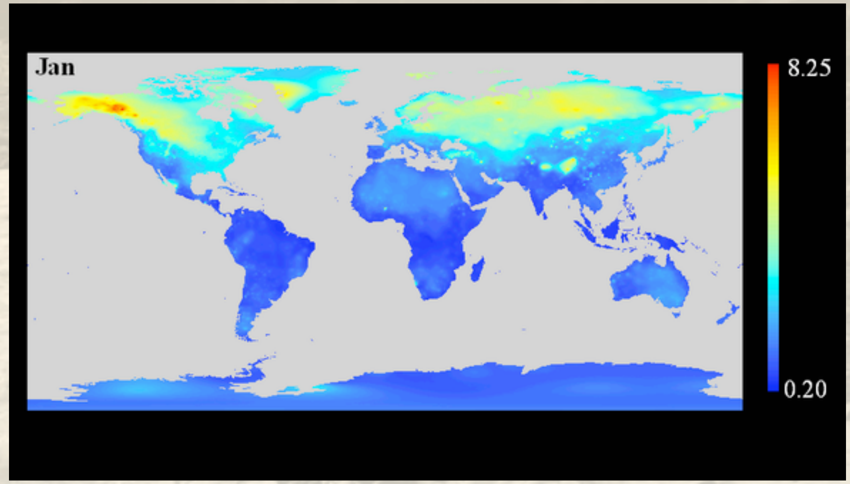


Precipitation to Discharge

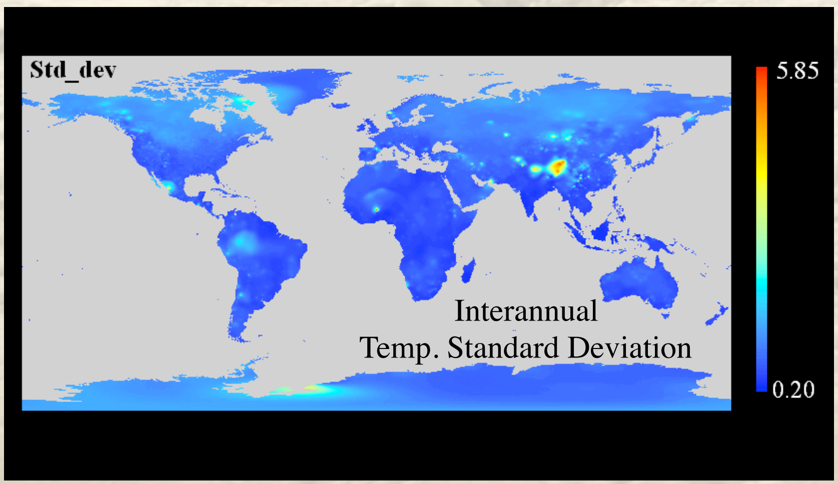
1. Precipitation as rain or snow: Need DEM, gridded temperature, lapse rates
2. Snow to glacial ice: Need DEM, equilibrium line altitude of glaciers and ice sheets
3. Snowmelt, glacial melt: Need DEM, gridded temperature, lapse rates

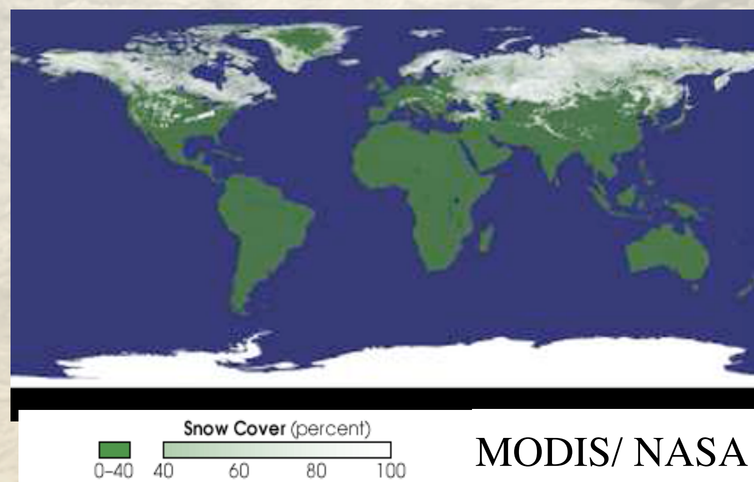


Monthly Mean Temperature °C (U. Delaware)



Monthly St. Dev. Temperature °C

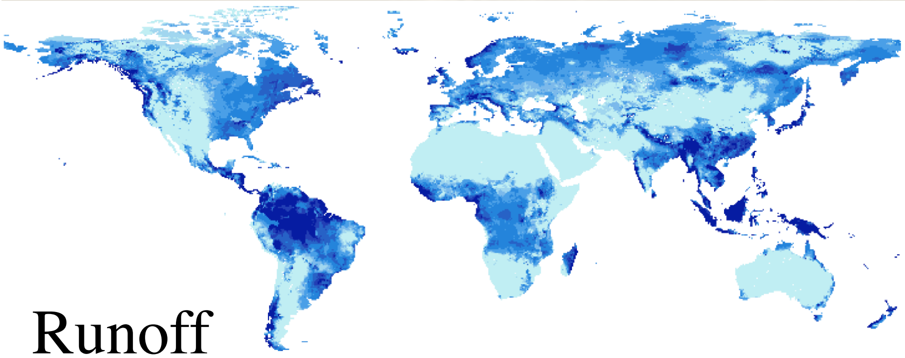


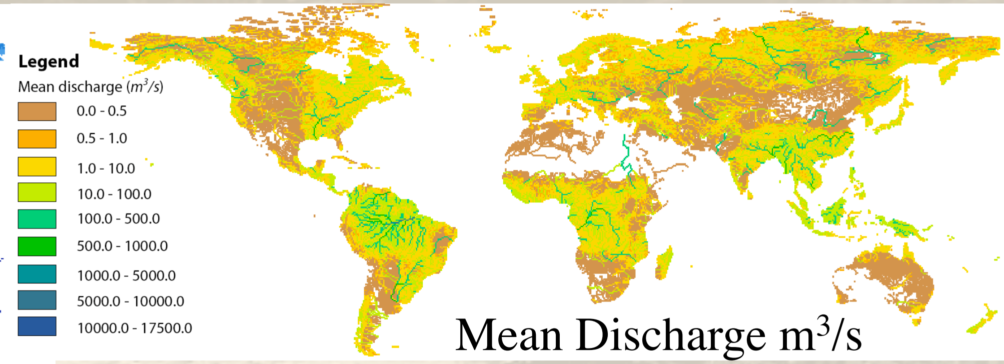


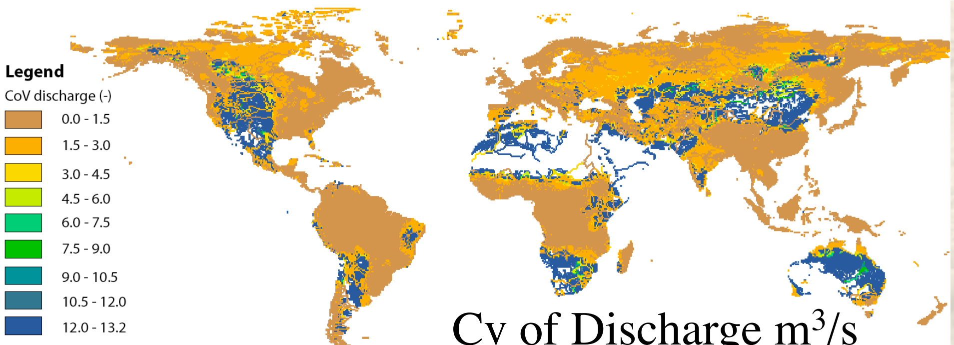
MODIS/ NASA

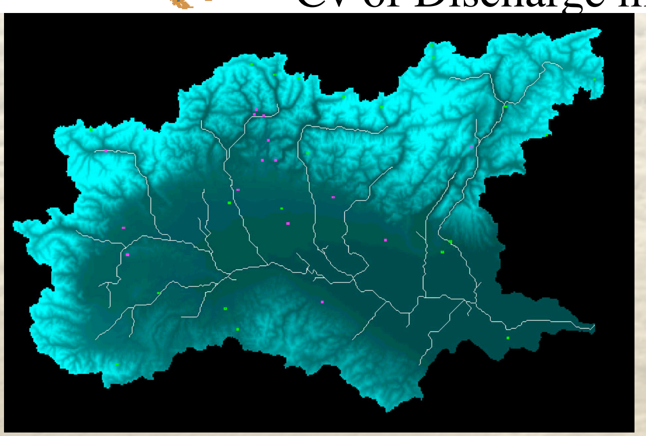
Precipitation to Discharge

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









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

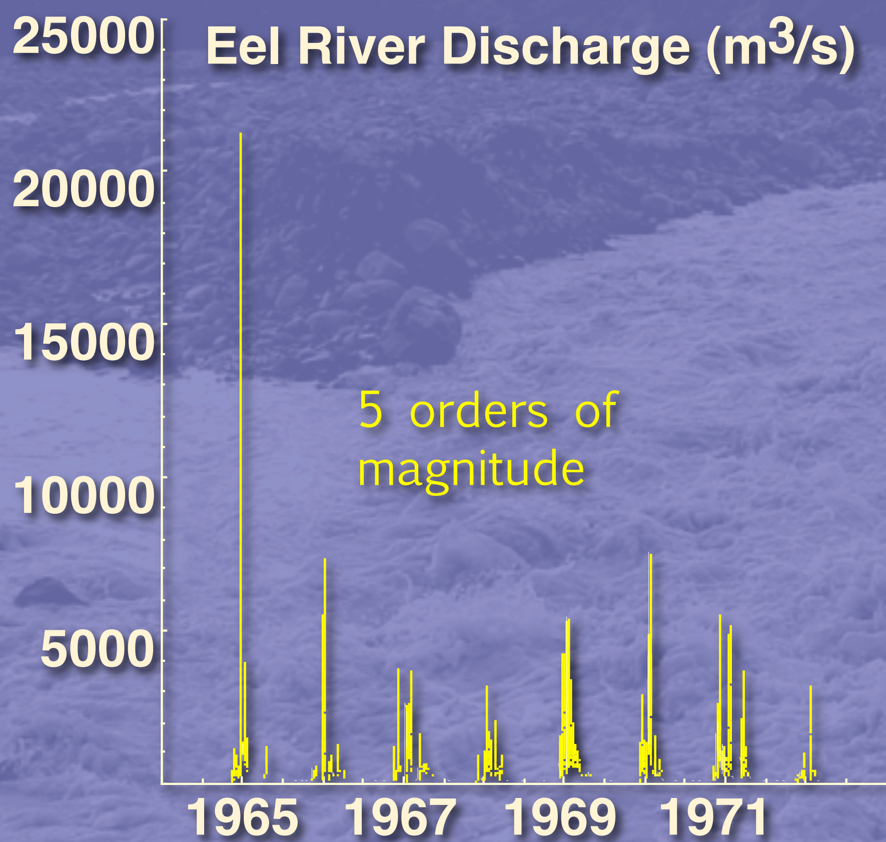
3. INSTAAR-TopoFlow: local to regional, 100m resolution, minutes, for weeks to year, functional routing.

Polar zones: low frontal rainfall; large contribution from snow & ice meltwater; short runoff season; low lapse rates; high inter annual variability; permafrost

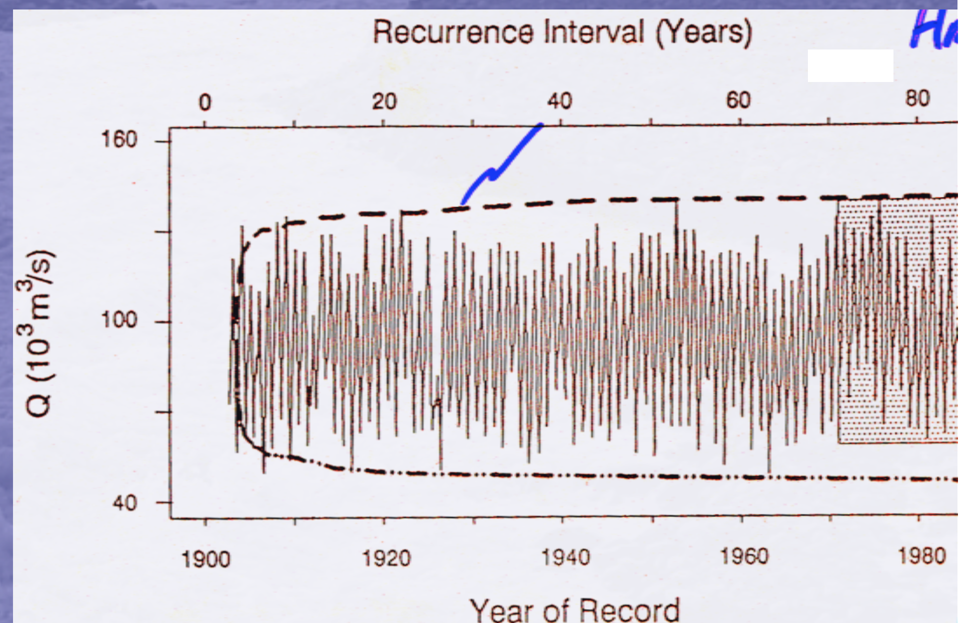
Temperate zones: discharge from springtime snowmelt, summer convective rainfall, and fall time frontal rainfall; high alpine freeze-thaw cycles; highly industrialized hinterland

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.

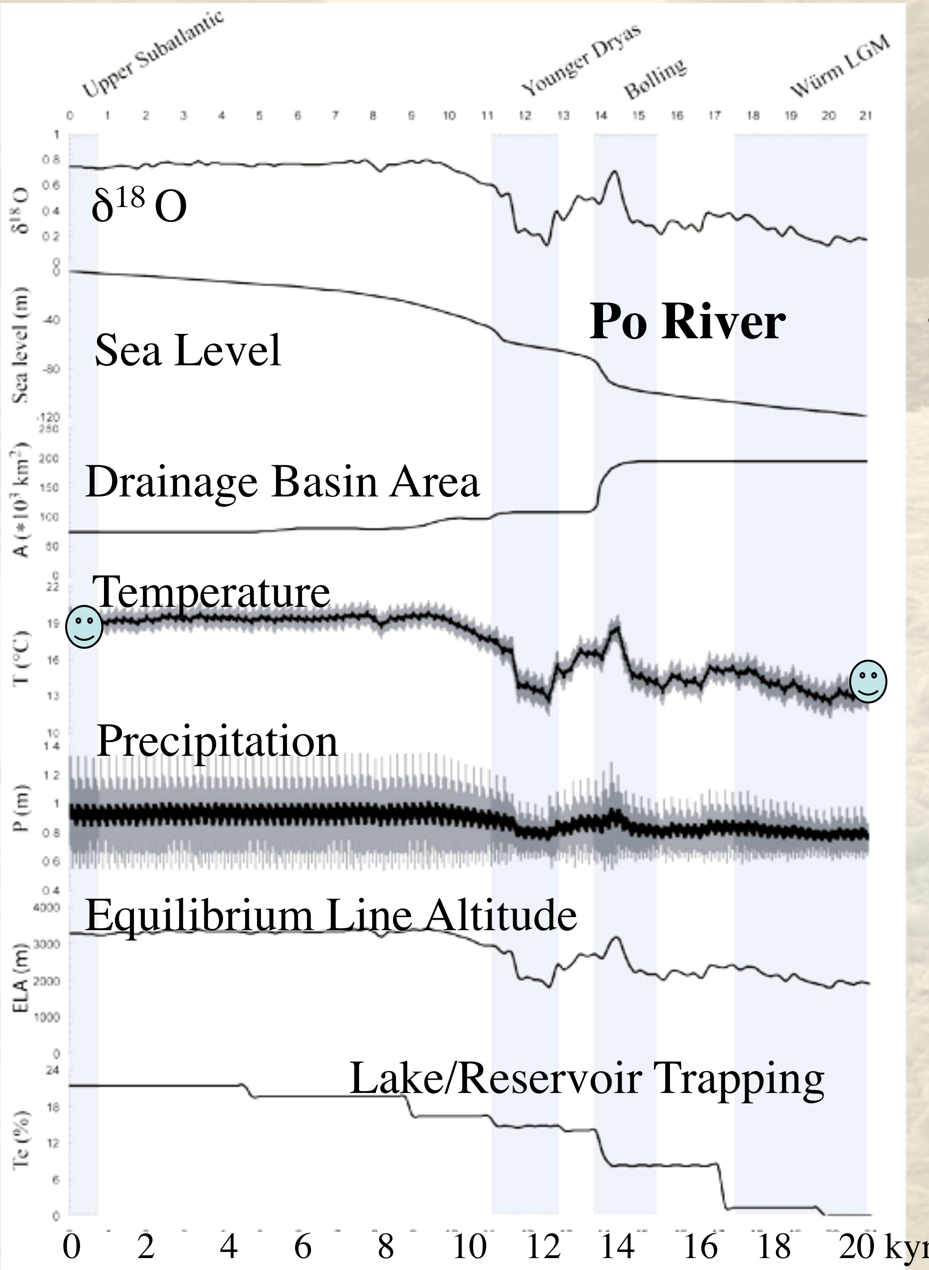


5 orders of magnitude



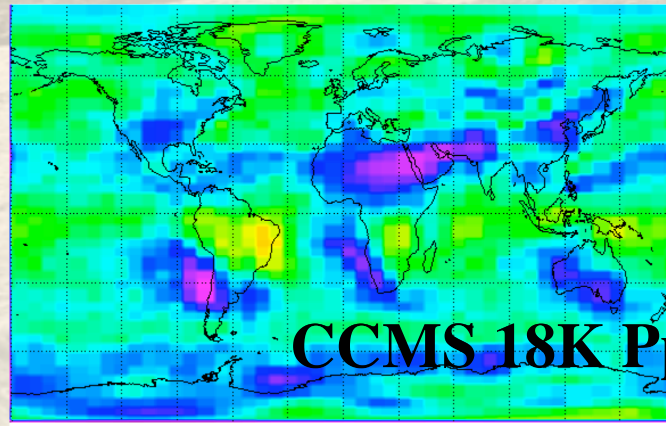
Amazon River 10^3 m^3/s

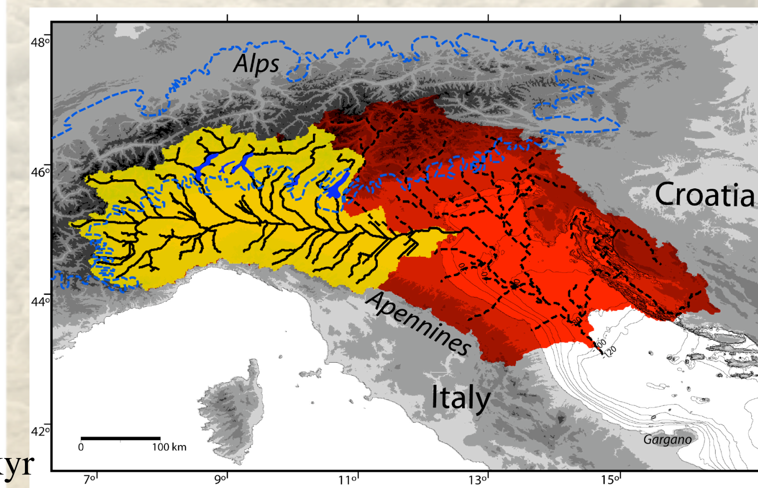
1 order of magnitude



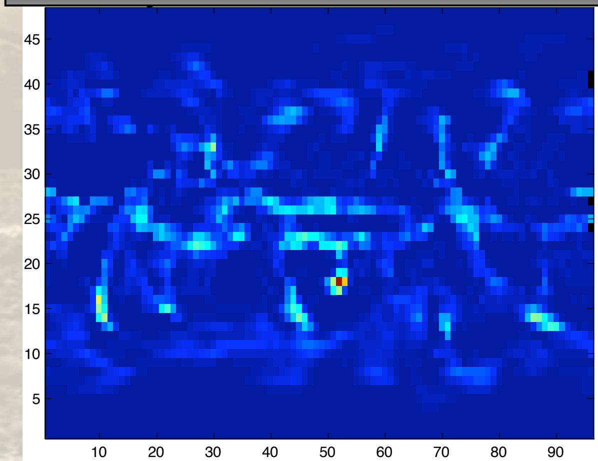
Paleo-discharge

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

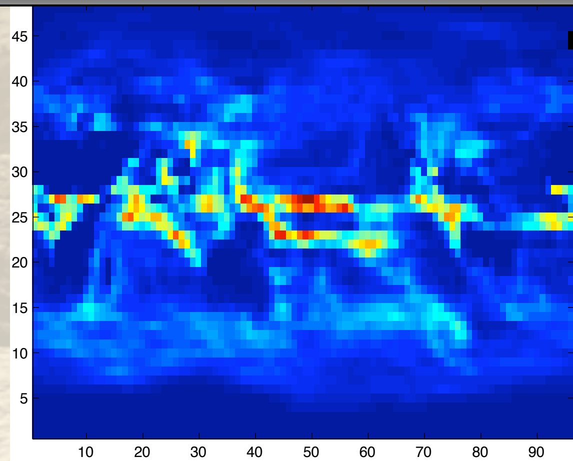




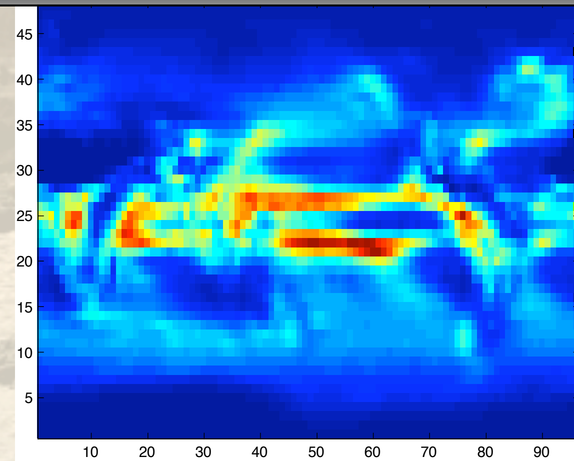
June 1, 18kaBP Prec. m



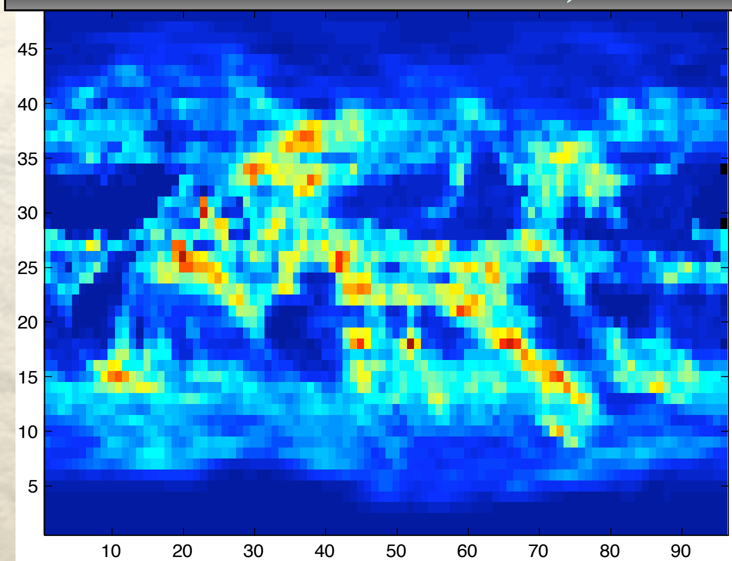
Mean June Prec. m, 18ka



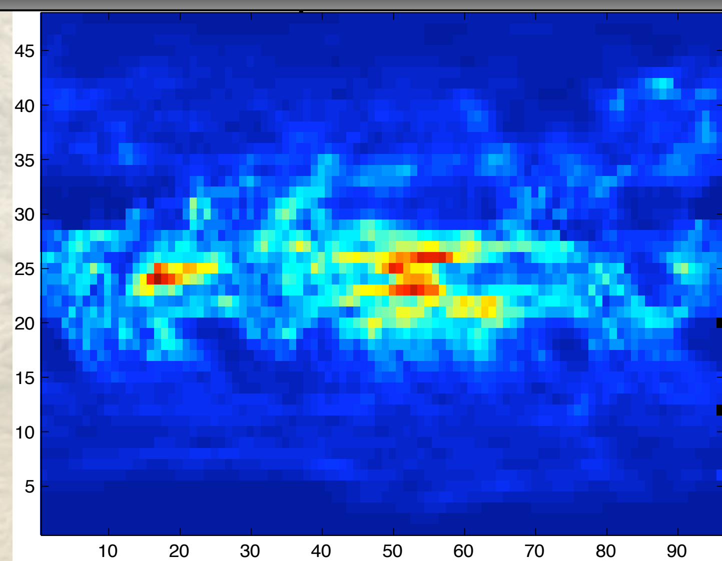
Mean Annual Prec. m,



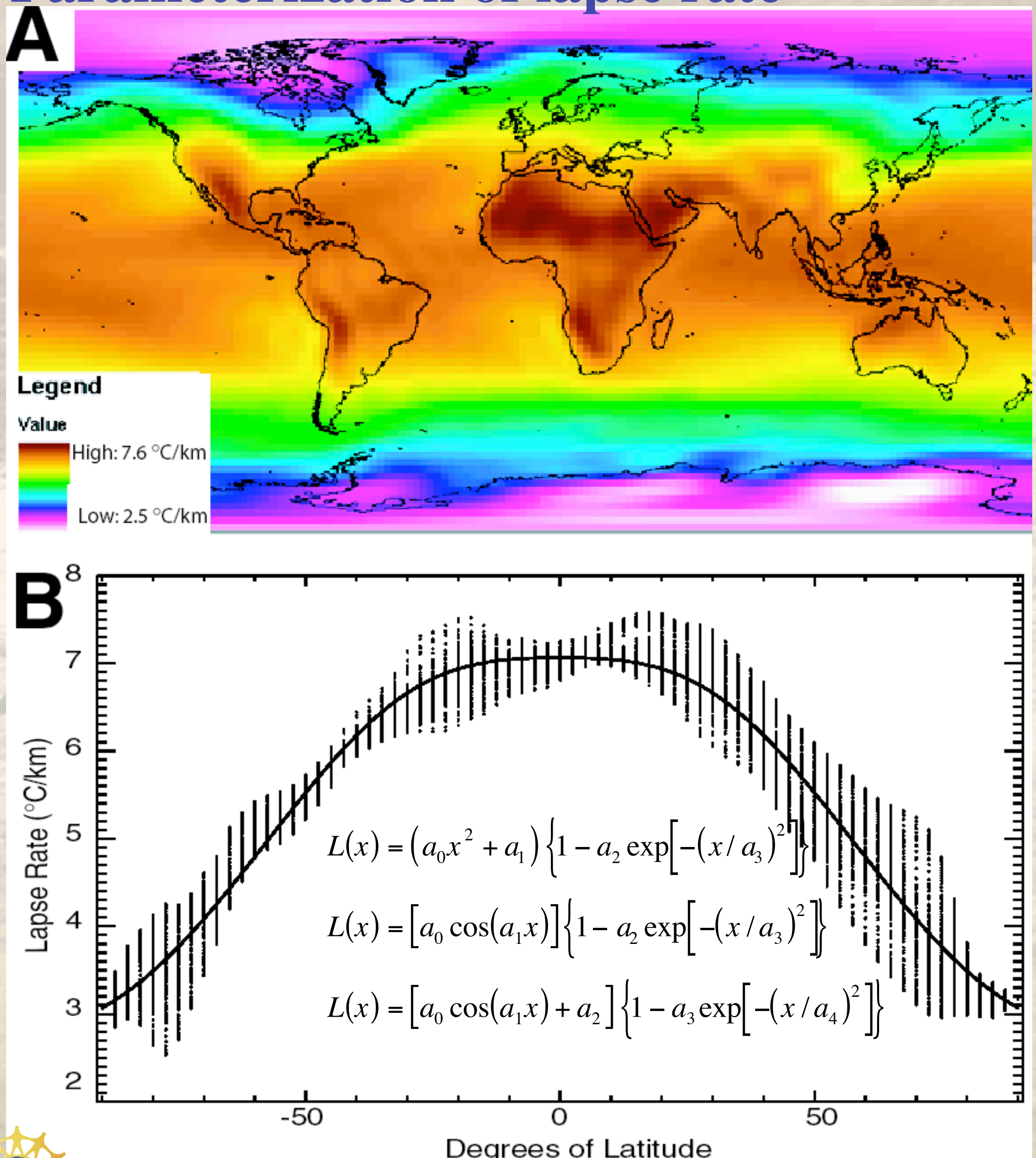
1 June Prec. m - Std. Dev., 18ka

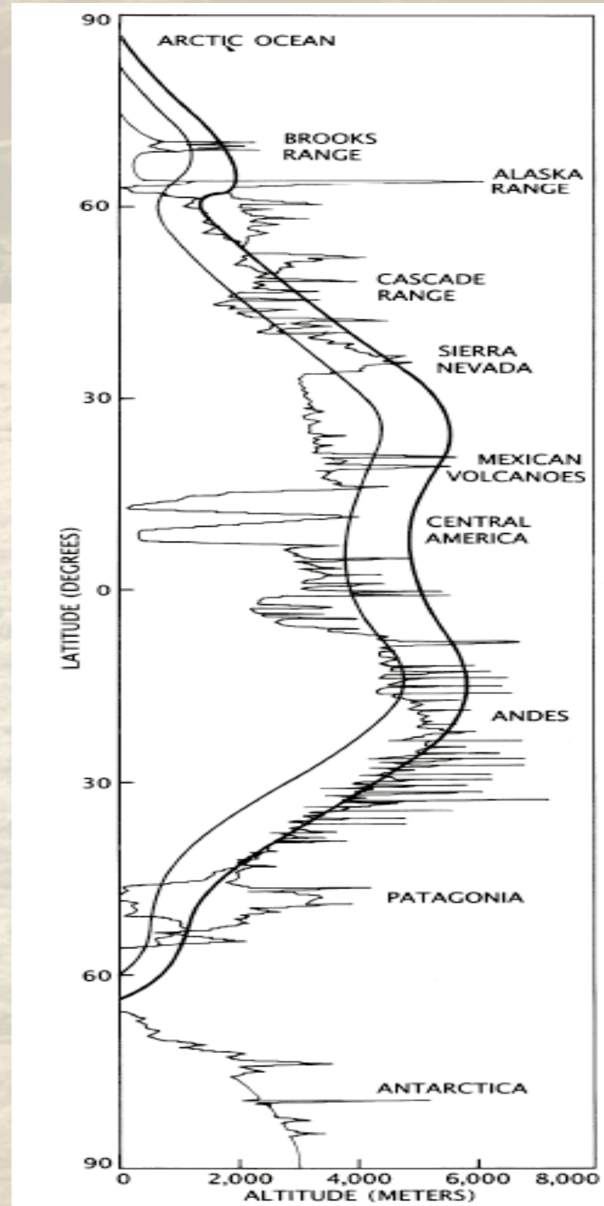


Annual Prec. m Std.Dev. 18ka

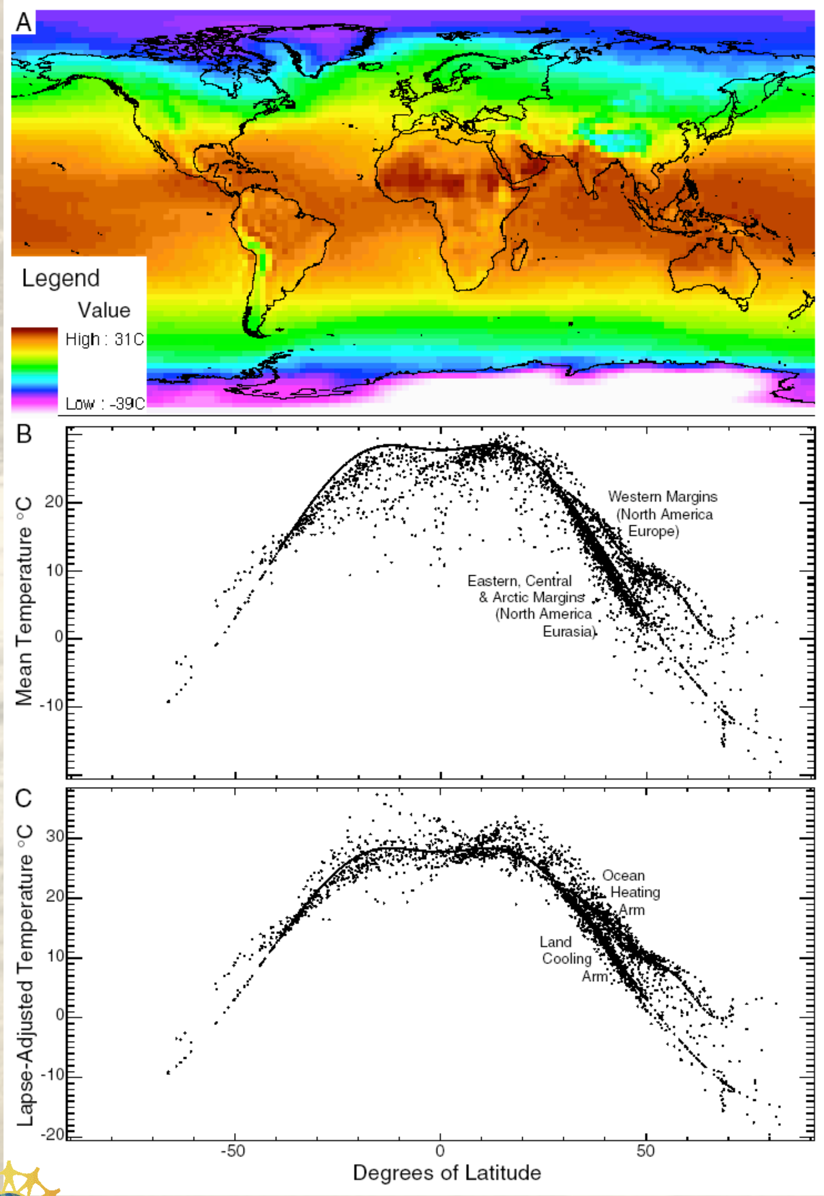


Parameterization of lapse rate





Parameterization of basin-averaged temperature



A) 2.5° grid of surface temperatures

Syvitski et al, Sedimentary Geology, 2003

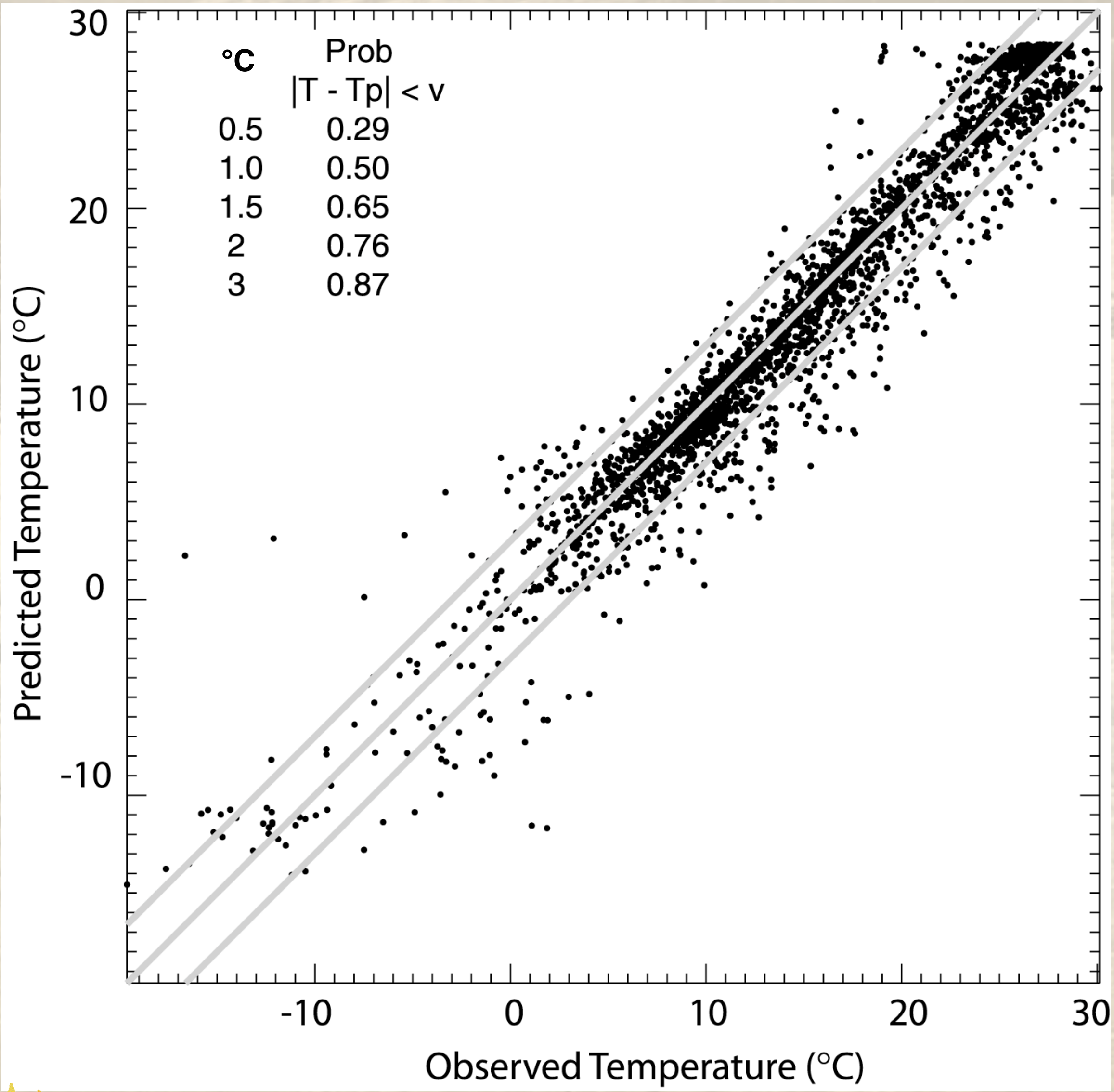
B) Global station temperature versus latitude and the best-fit model.

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

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

$$T_0 = T + [L(x)H]$$

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.

Syvitski et al, Sedimentary Geology, 2003.

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

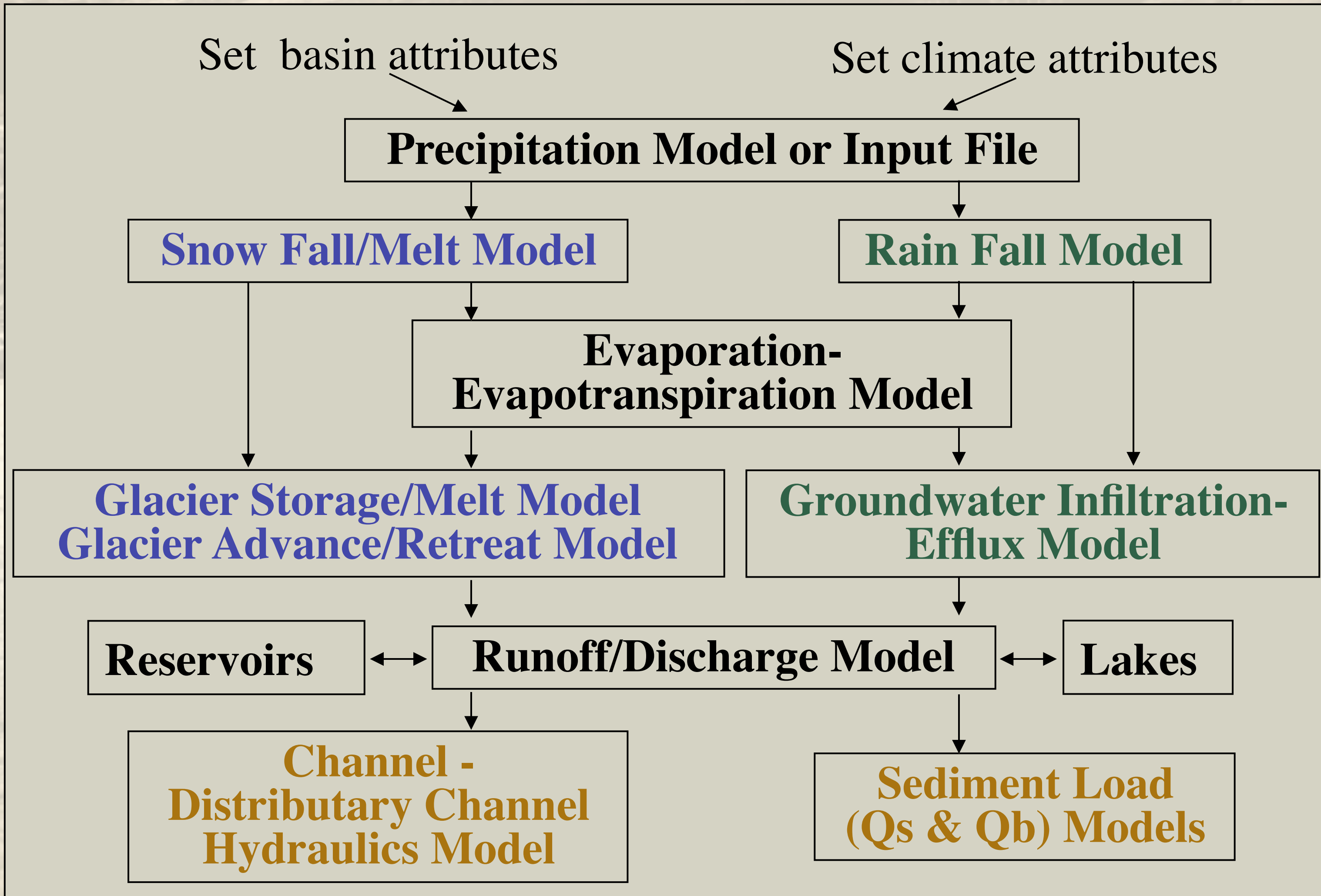
Variability vs. coherency

Drainage basin area vs. storm size and direction

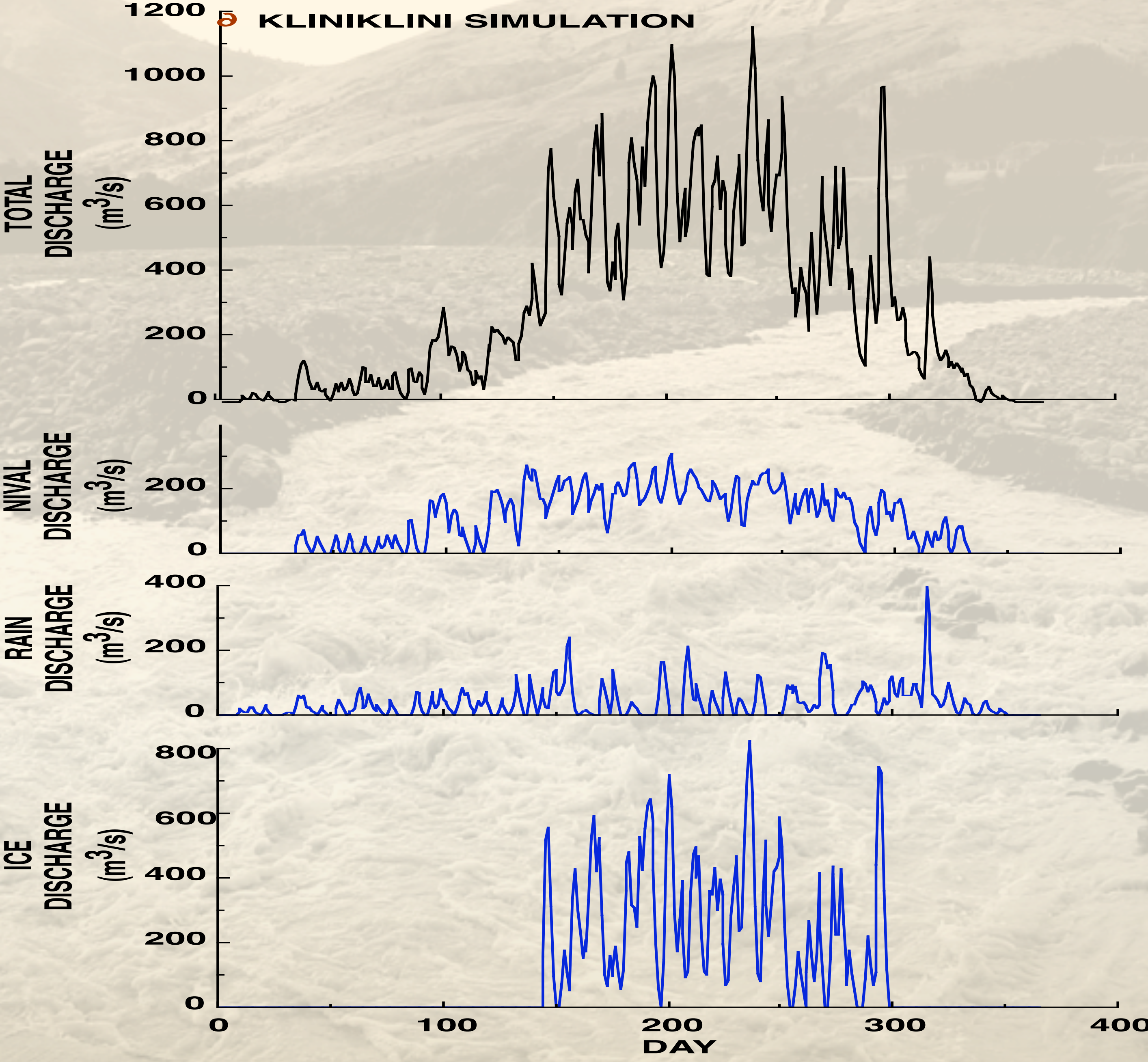
Interannual vs. intra-annual variability

Climate change effects and water storage changes

HydroTrend

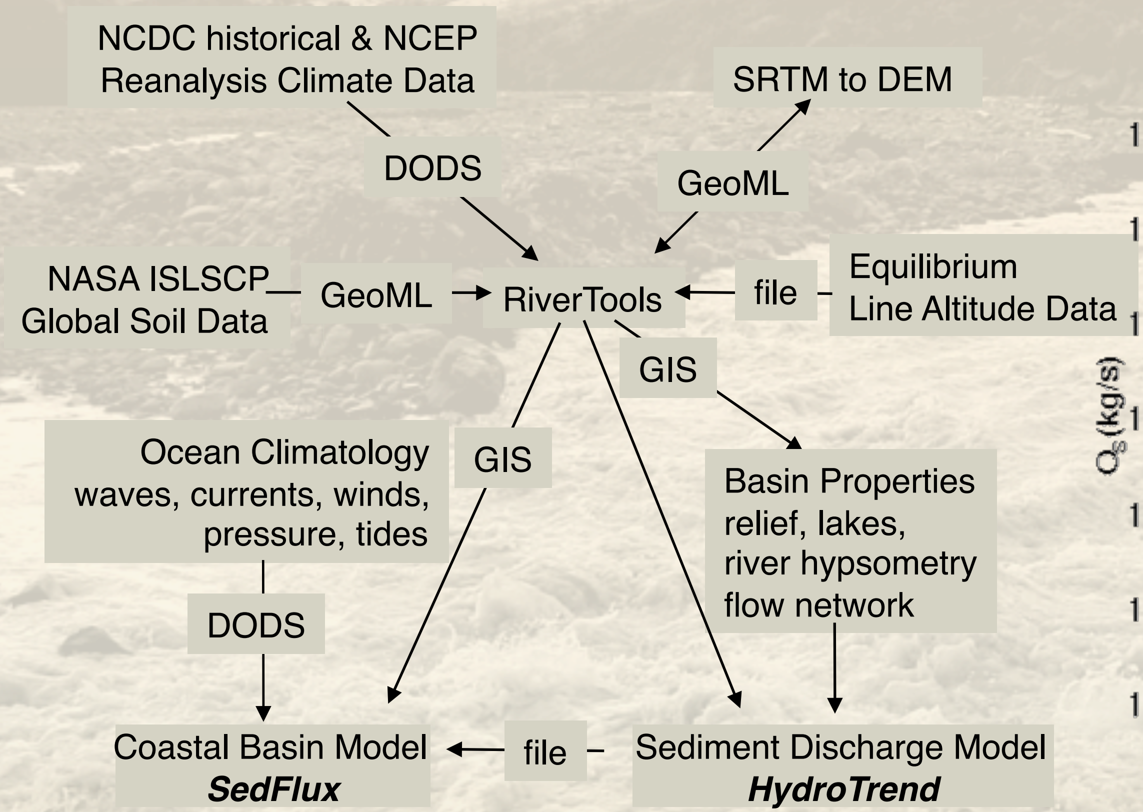


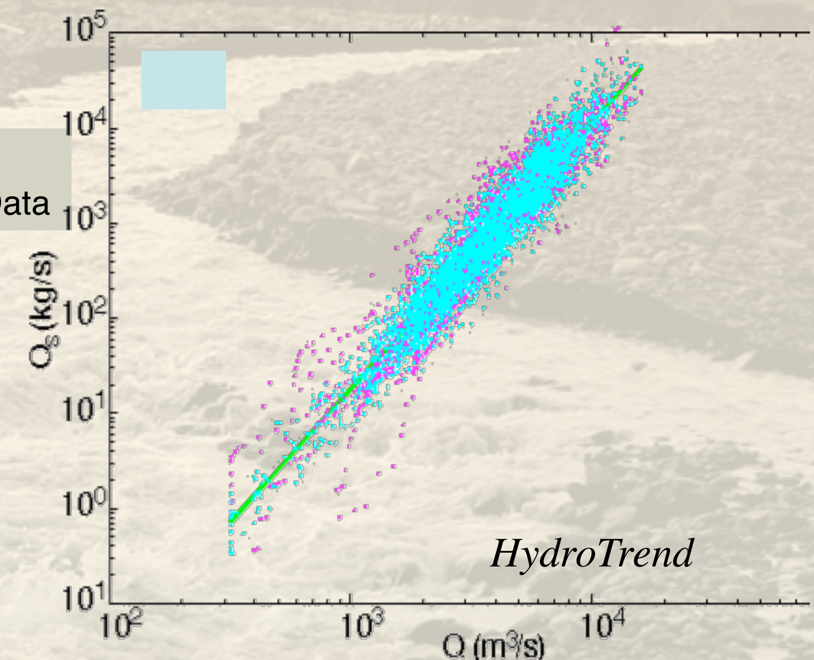
Set basin attributes
Set climate attributes
Precipitation Model or Input File
Snow Fall/Melt Model
Rain Fall Model
Evaporation-
Evapotranspiration Model
Glacier Storage/Melt Model
Glacier Advance/Retreat Model
Groundwater Infiltration-
Efflux Model
Reservoirs
Runoff/Discharge Model
Lakes
Channel -
Distributary Channel
Hydraulics Model
Sediment Load
(Qs & Qb) Models



KLINIKLINI SIMULATION
TOTAL DISCHARGE (m^3/s)
1200
1000
800
600
400
200
0
NIVAL DISCHARGE (m^3/s)
200
0
RAIN DISCHARGE (m^3/s)
400
200
0
ICE DISCHARGE (m^3/s)
800
600
400
200
0
0
100
200
300
400
DAY

Data Assimilation



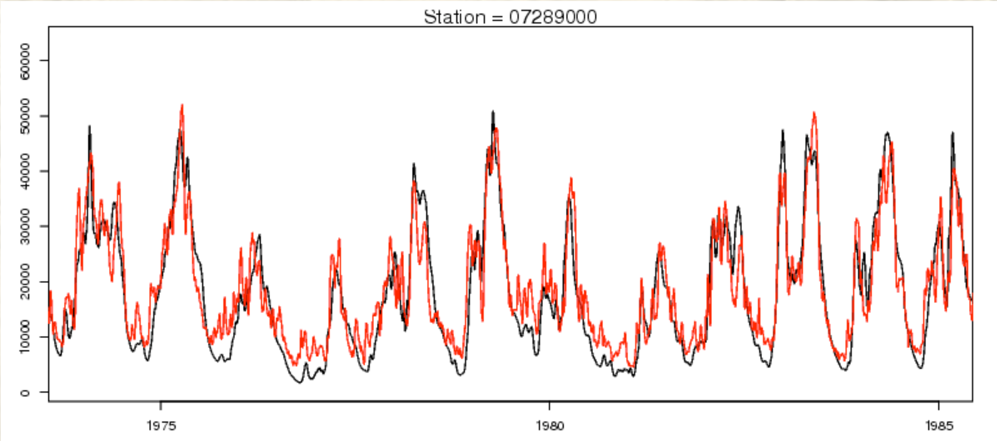


Syvitski et al, Terra Nostra, 2002

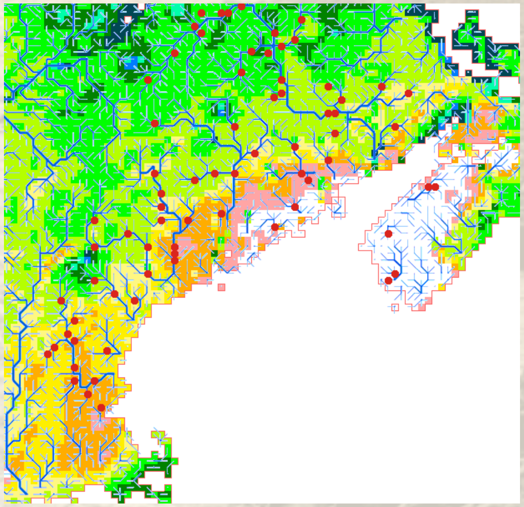
Hydrological Functionality

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

Mississippi time series



Gulf of Maine Daily Runoff



Wisser et al. In Preparation

Sediment Delivery

$$Q_b = \frac{\rho_s}{\rho_s - \rho}\frac{\rho g Q^{\beta} S e_b}{\tan\phi}$$ when $u \geq u_{cr}$ → $Q_b = (\Gamma)\, Q^{\beta}\, S$

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

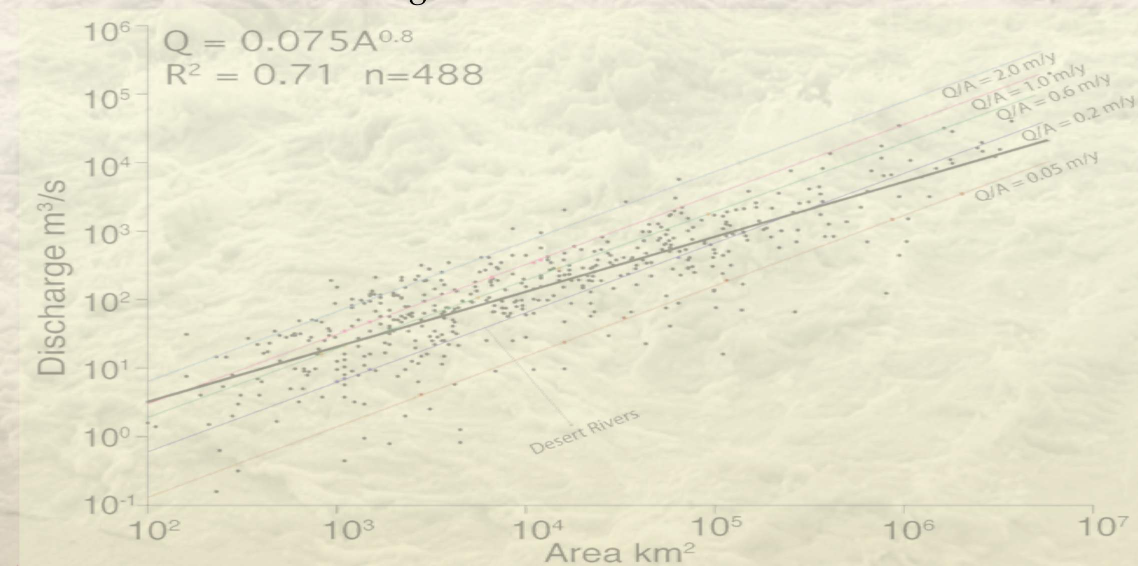
Using the globally-averaged value $n=1$, and the global relationship between Q, in m^3/s, and A, in km^2 ($Q = 0.075\, A^{0.8}$)

$Q_s = w\, B{\cdot}Q^{0.31} A^{0.5}\, R \cdot T$ for $T \geq 2°C$

→ $Q_s = (\mu)\, Q^{\beta}\, S$

$Q_s = 2\, w\, B{\cdot}Q^{0.31} A^{0.5}\, R$ for $T < 2°C$

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



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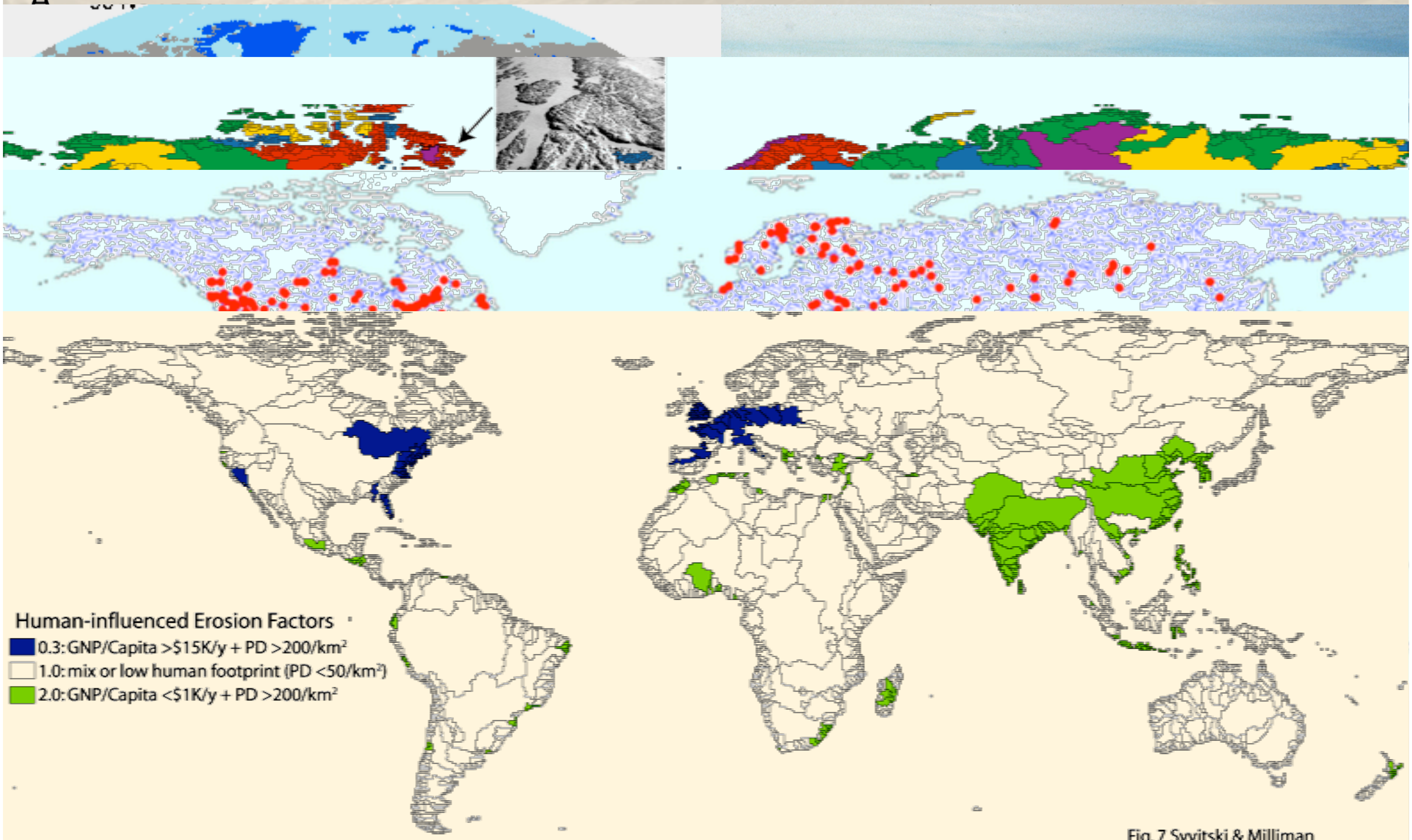
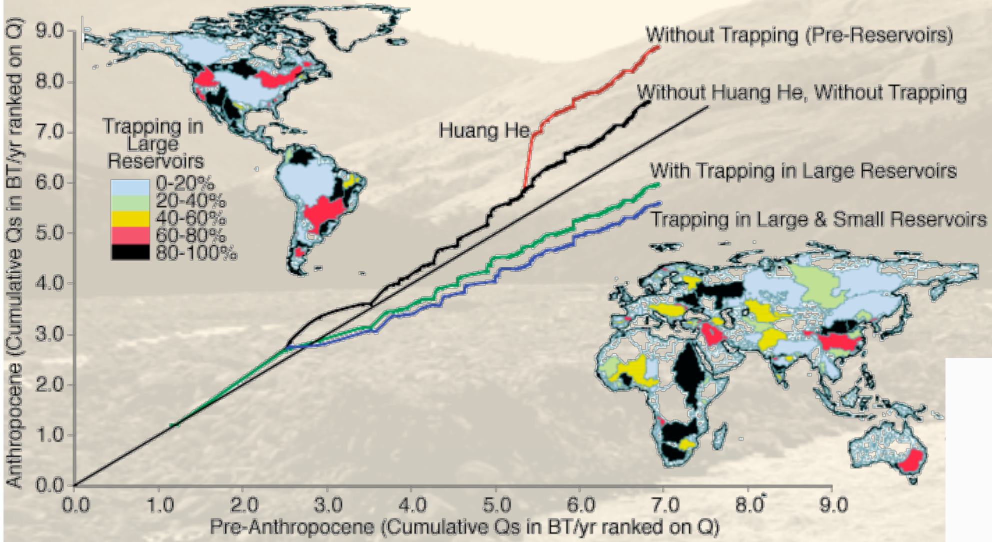
Sediment Delivery

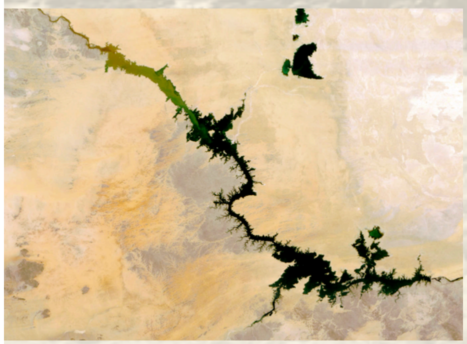
$$Q_s=[\omega\rho g^{0.5}]\,[1+0.09A_g]\,L\,(1-T_E)\,E_h\,Q^{0.31}\,A^{0.5}\,R\,T$$

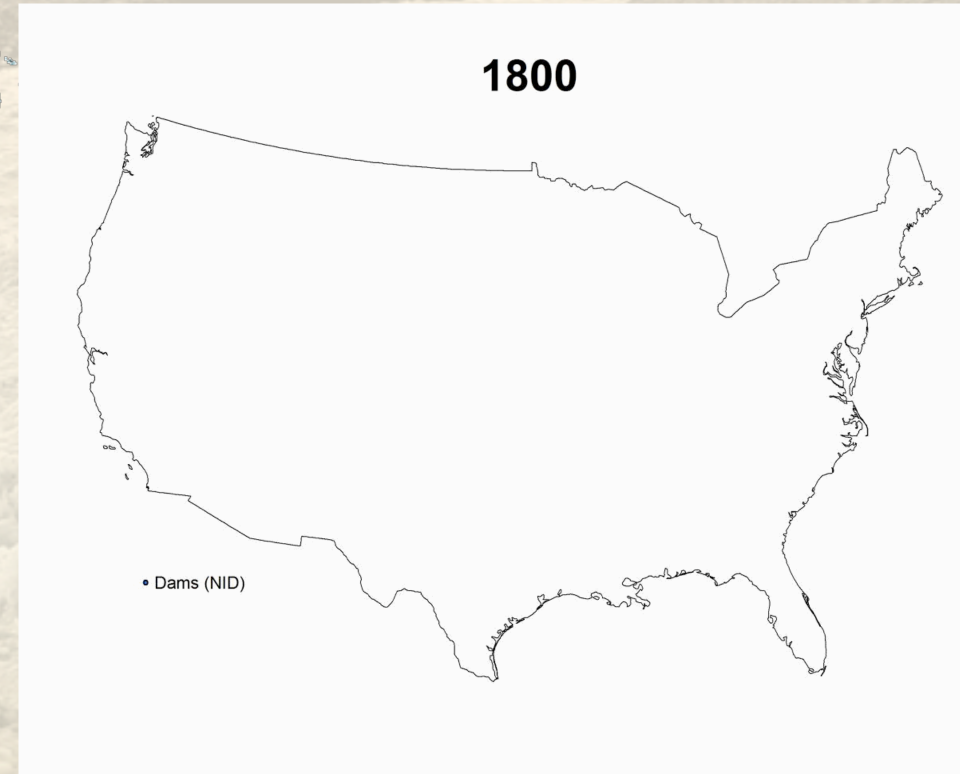




$$T_E = 1 - \left(0.05 \Big/ \sqrt{\frac{V_{res}}{Q_m}} \right) \qquad T_E = 1 - \frac{A_R}{1.00021 V_R}$$

$$\overline{Q_m} = \overline{Q_{up}} \left(A_R \big/ A_{up} \right)$$

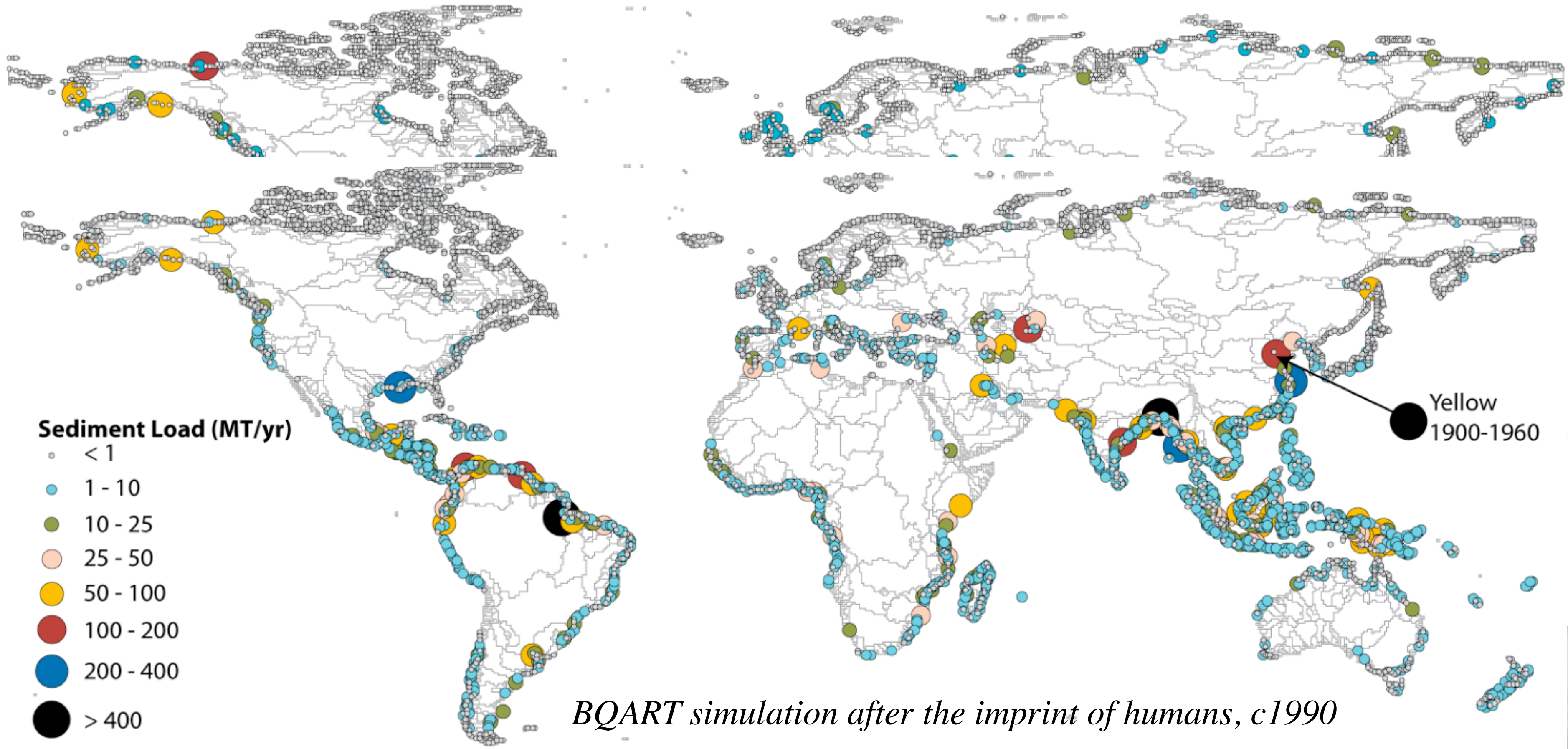




$$Q_s = [\omega \rho g^{0.5}]\,[1 + 0.09 A_g]\, L\, (1 - T_E)\, E_h\, Q^{0.31} A^{0.5} R\, T$$

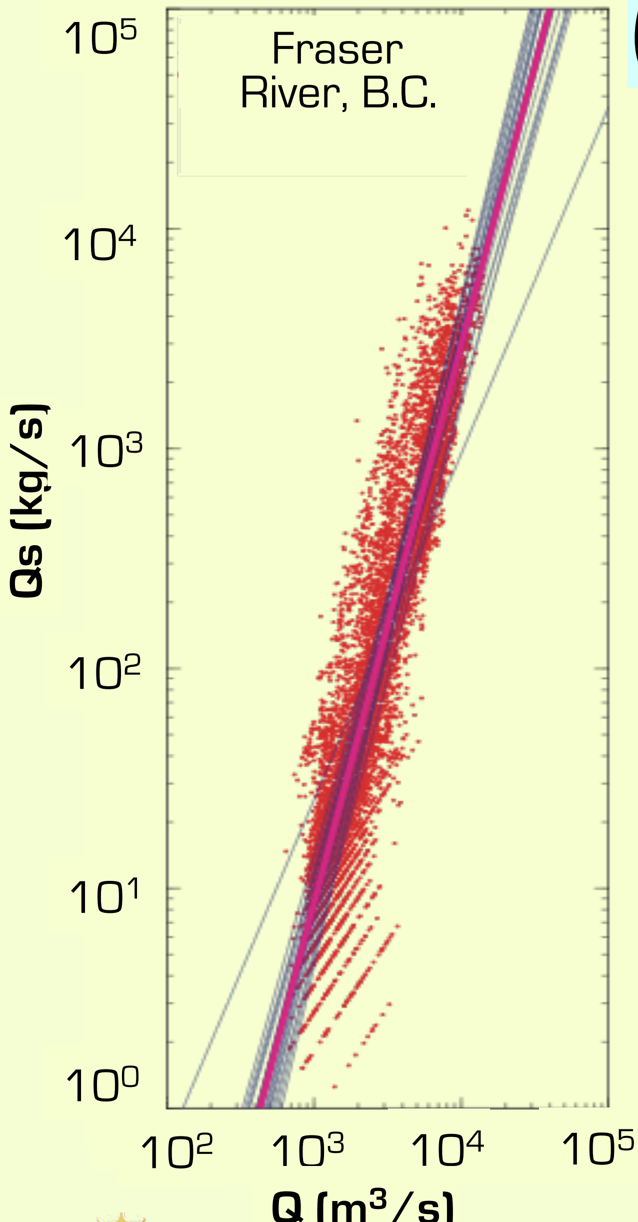
Sediment Delivery

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



BQART simulation after the imprint of humans, c1990

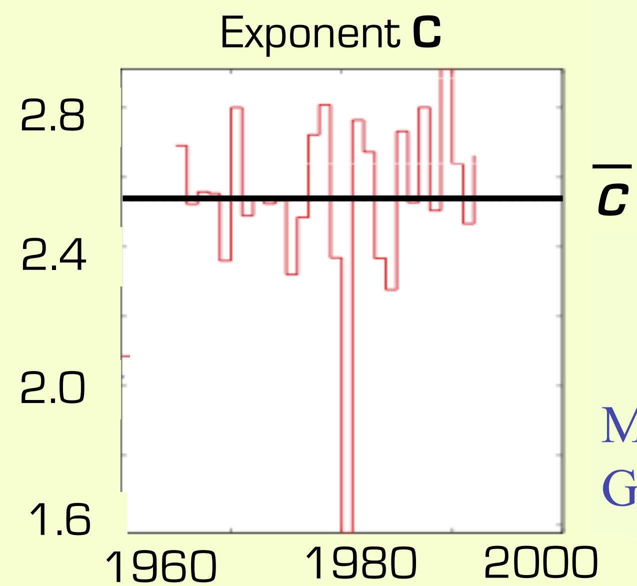
$$\left(Q_s/\overline{Q_s}\right) = \psi\left(Q/\overline{Q}\right)^C$$



$$E(C)=1.4\text{-}0.025T+0.00013R+0.145\ln(\overline{Q}_s)$$

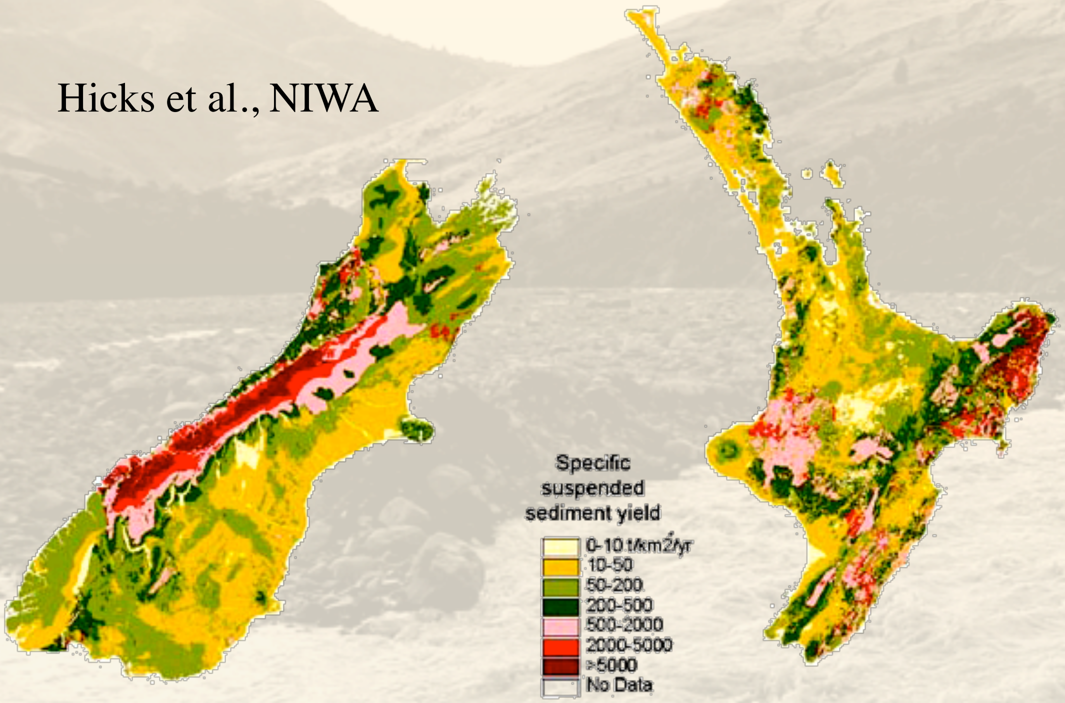
$$\sigma(C)=0.17+0.0000183\overline{Q}$$

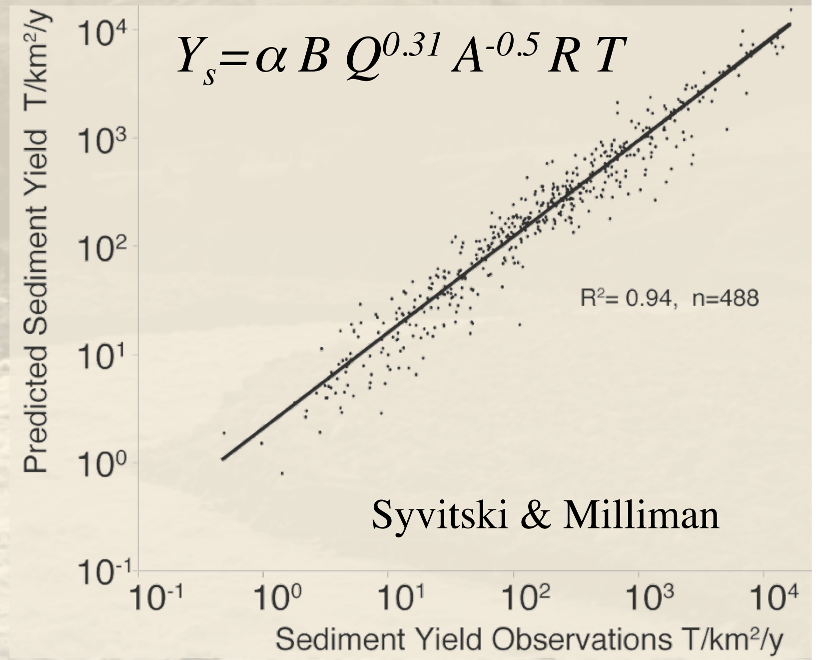
$$\sigma(\psi)=0.763(0.99995)^{\overline{Q}}$$

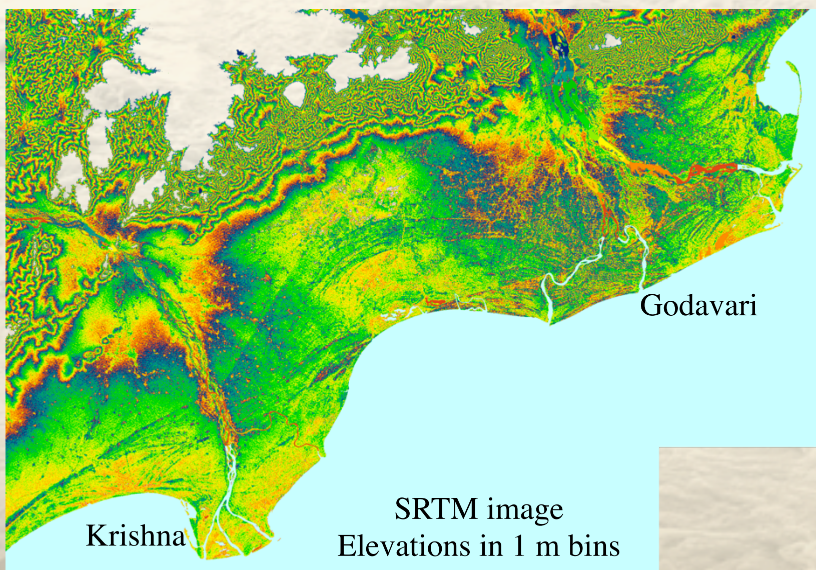


Morehead et al, GPC, 2003

Hicks et al., NIWA







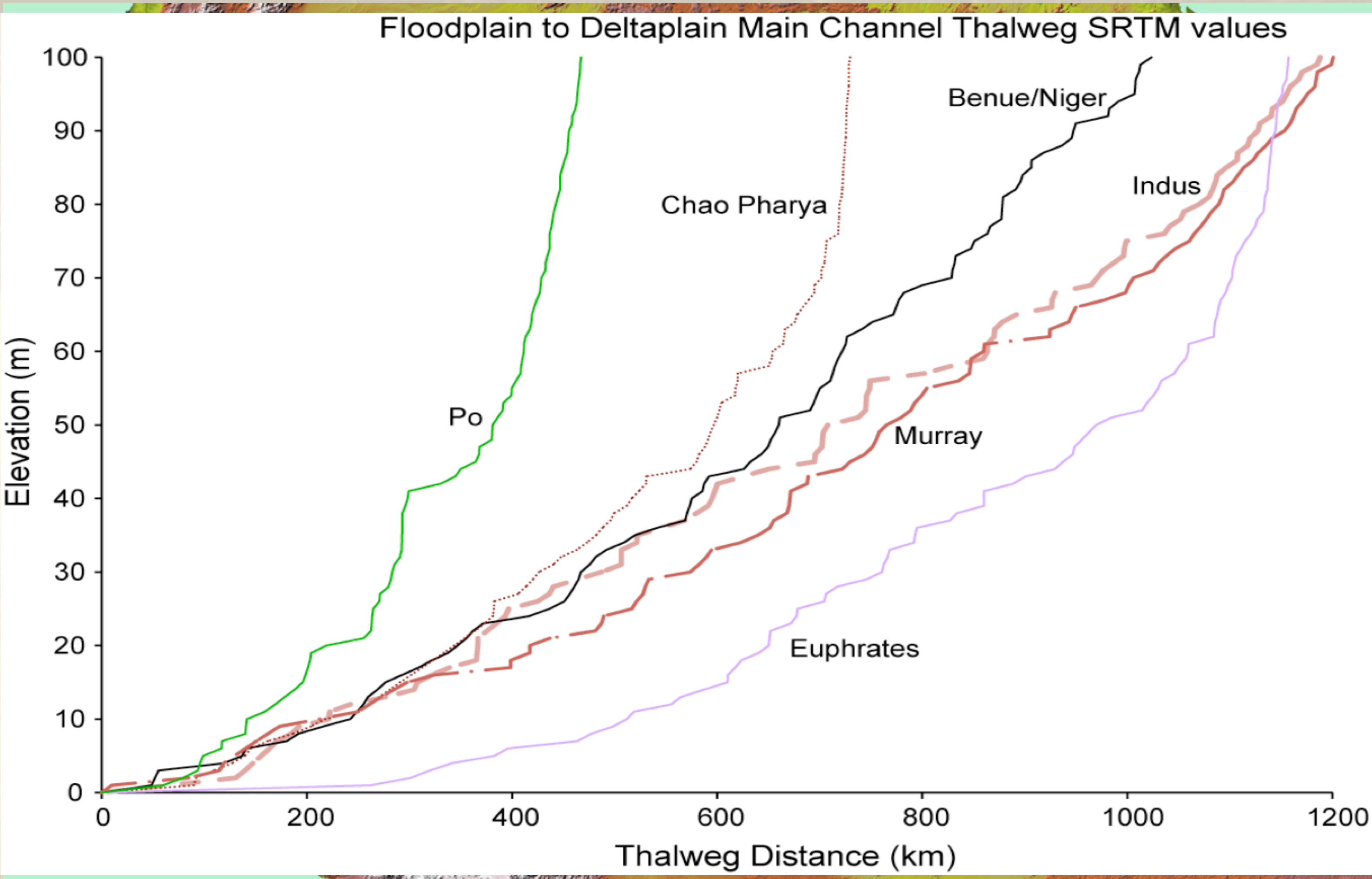
Sediment yield decreases away from highlands because:

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

$$Q_b = \frac{\rho_s}{\rho_s - \rho} \frac{\rho g Q^{\beta} S e_b}{\tan \phi} \quad \text{when} \quad u \geq u_{cr} \quad \longrightarrow \quad Q_b = (\Gamma)\, Q\, S$$

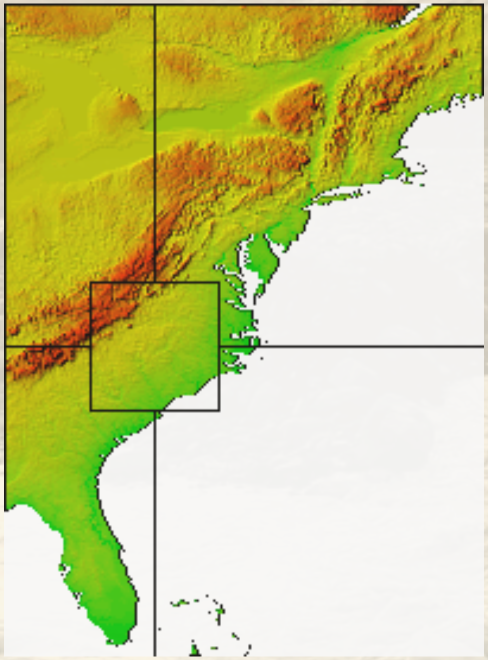


Sediment Delivery

$$Q_b = \frac{\rho_s}{\rho_s - \rho} \frac{\rho g Q^{\beta} S e_b}{\tan \phi} \quad \text{when} \quad u \geq u_{cr} \quad \longrightarrow \quad Q_b = (\Gamma)\, Q\, S$$

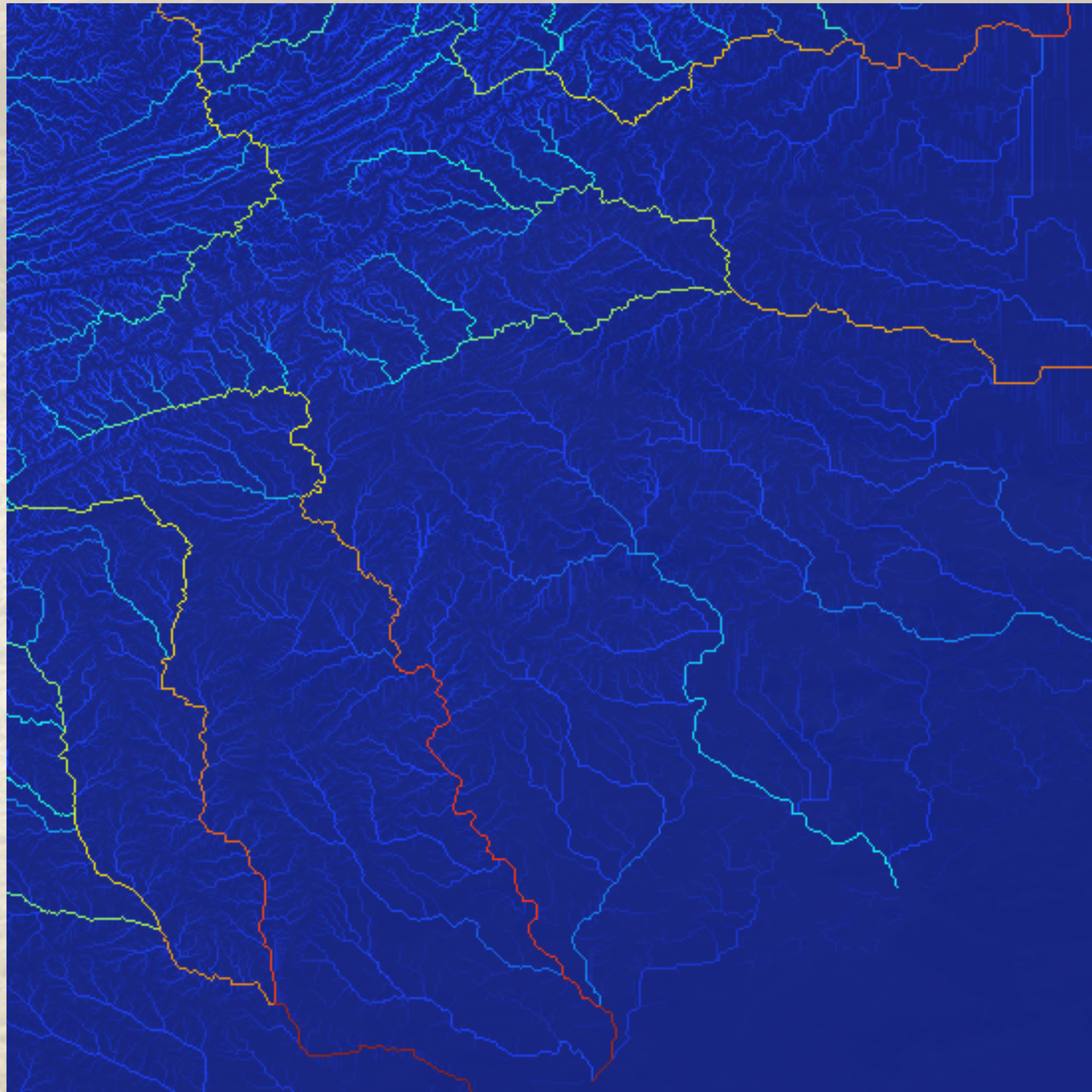
River	*A* km^2	*R* m	*Q* m^3/s	*Qs* kg/s	L km	L to 100m km	L to 10m km	Qb @100m kg/s	Qb @10m kg/s	Qb lost %	Qb loss per km kg/km·s
Chao Phrya (Thai)	160000	1920	963	349	1200	730	218	29	11	63	0.08
Fly (PNG)	64400	3990	2510	2219	1130	901	577	70	11	85	0.10
Godavari (India)	287000	1650	2650	5387	1450	513	95	137	69	50	0.72
Indus (Pak)	964000	7830	3171	12683	3180	1188	220	70	36	49	0.15
Irrawaddy (Burm)	430000	5881	13558	8239	2150	1078	337	338	99	71	0.71
Mekong (Viet)	811000	6100	14770	5070	4425	1008	566	783	64	92	1.27
Niger (Nig)	1240019	2130	6130	1268	4170	1023	242	182	63	66	0.49
Po (Ita)	70000	4800	1904	545	652	467	141	70	33	53	0.26
Rhone (Fr)	90000	4810	1700	1982	820	215	67	264	63	76	3.01
Euphrates (Iraq)	1050000	2960	1500	1680	2815	1157	511	48	7	85	0.08
Vistula (Pol)	200000	2500	1050	79	1091	547	86	42	30	28	0.14
Yangtze (PRC)	1958000	6800	28278	15210	4670	1771	840	642	83	87	0.67

East Coast Qs Grid

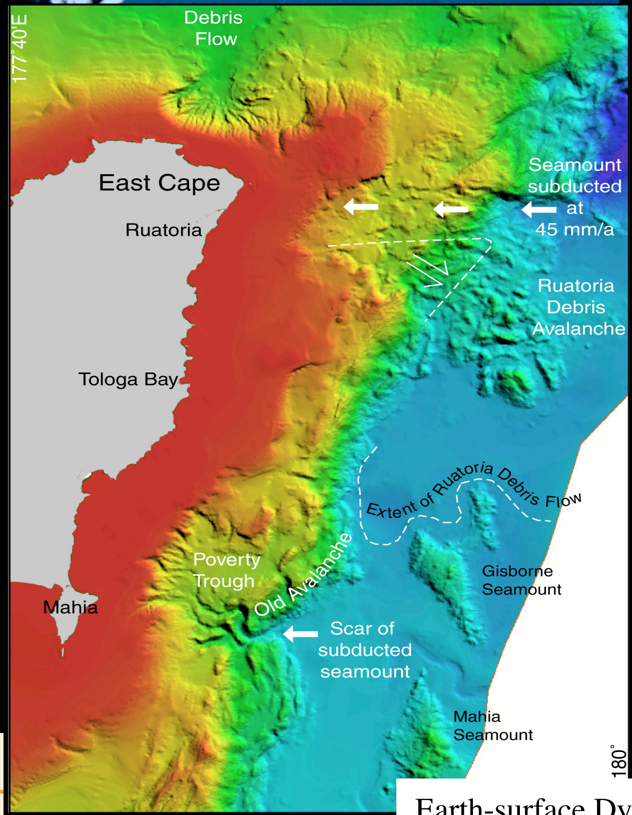


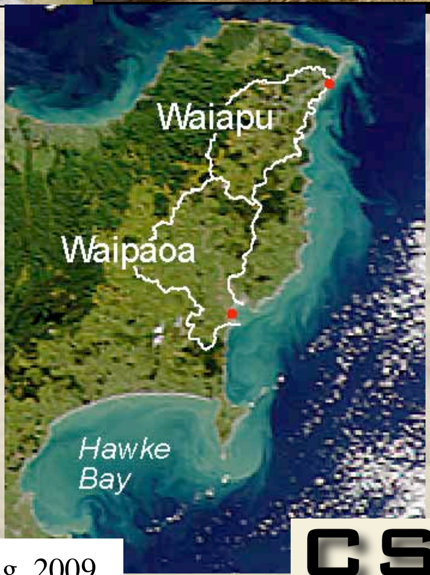
$$\overline{Qs} = \alpha R^{3/2} A^{1/2} e^{k\overline{T}}$$

Regression formula of Syvitski et al. (2002) for long-term average sediment discharge



MARGINS: Source to Sink - Waipaoa, NZ





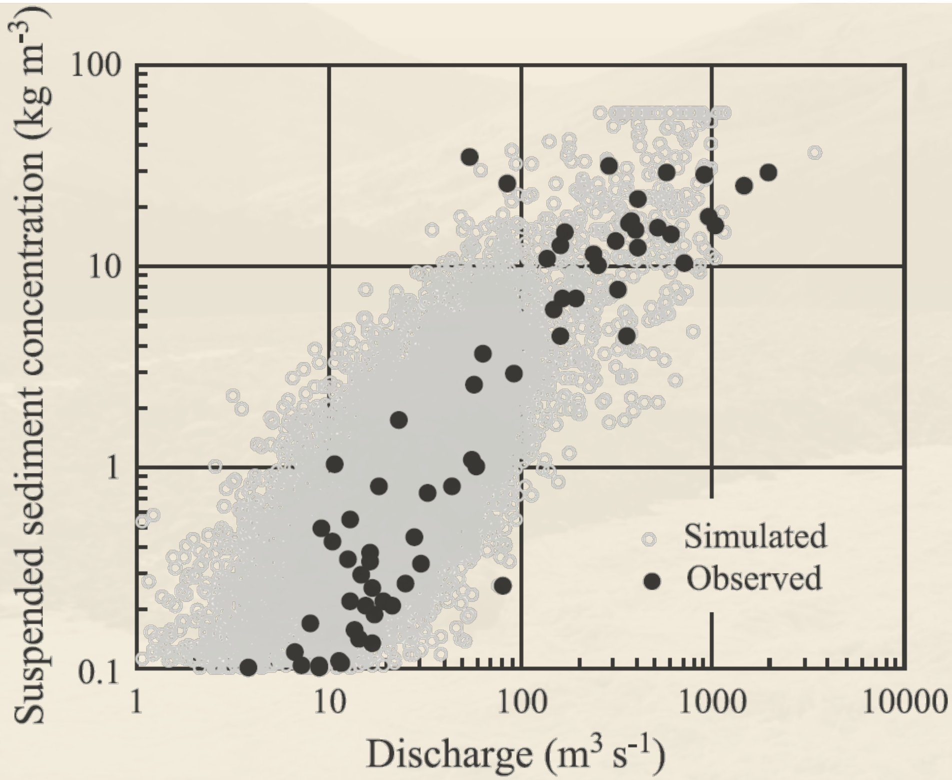


Figure 6. Comparison of 39 years of daily simulated and observed suspended sediment concentrations in the Waipaoa River at Matawhero.

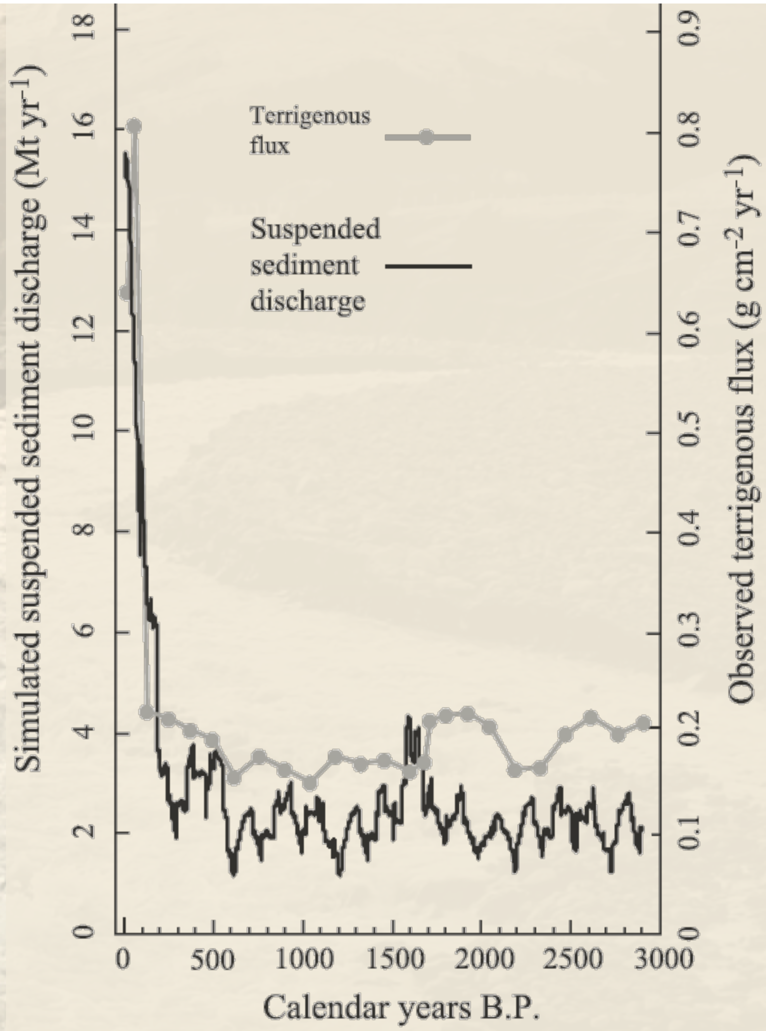
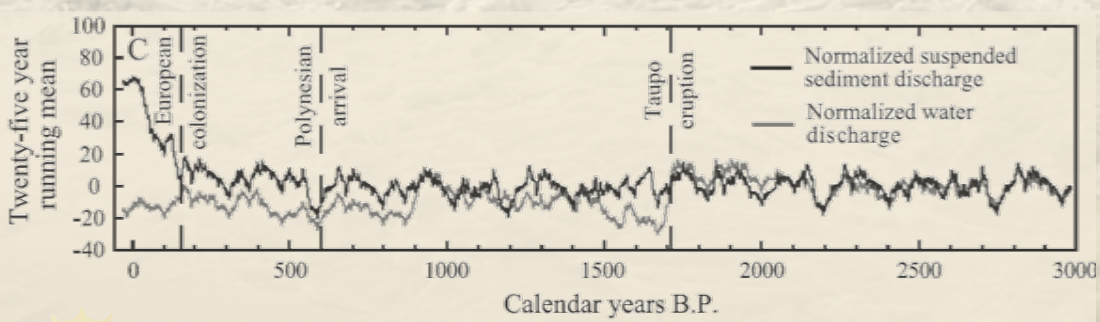


Figure 10. Comparison of the late Holocene suspended sediment discharge (99-yr running mean) from the Waipaoa River system computed using HydroTrend and the observed rate of terrigenous mass accumulation on the middle shelf at core site MD972122 [after *Gomez et al.*, 2007] (see Figure 1 for location).



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