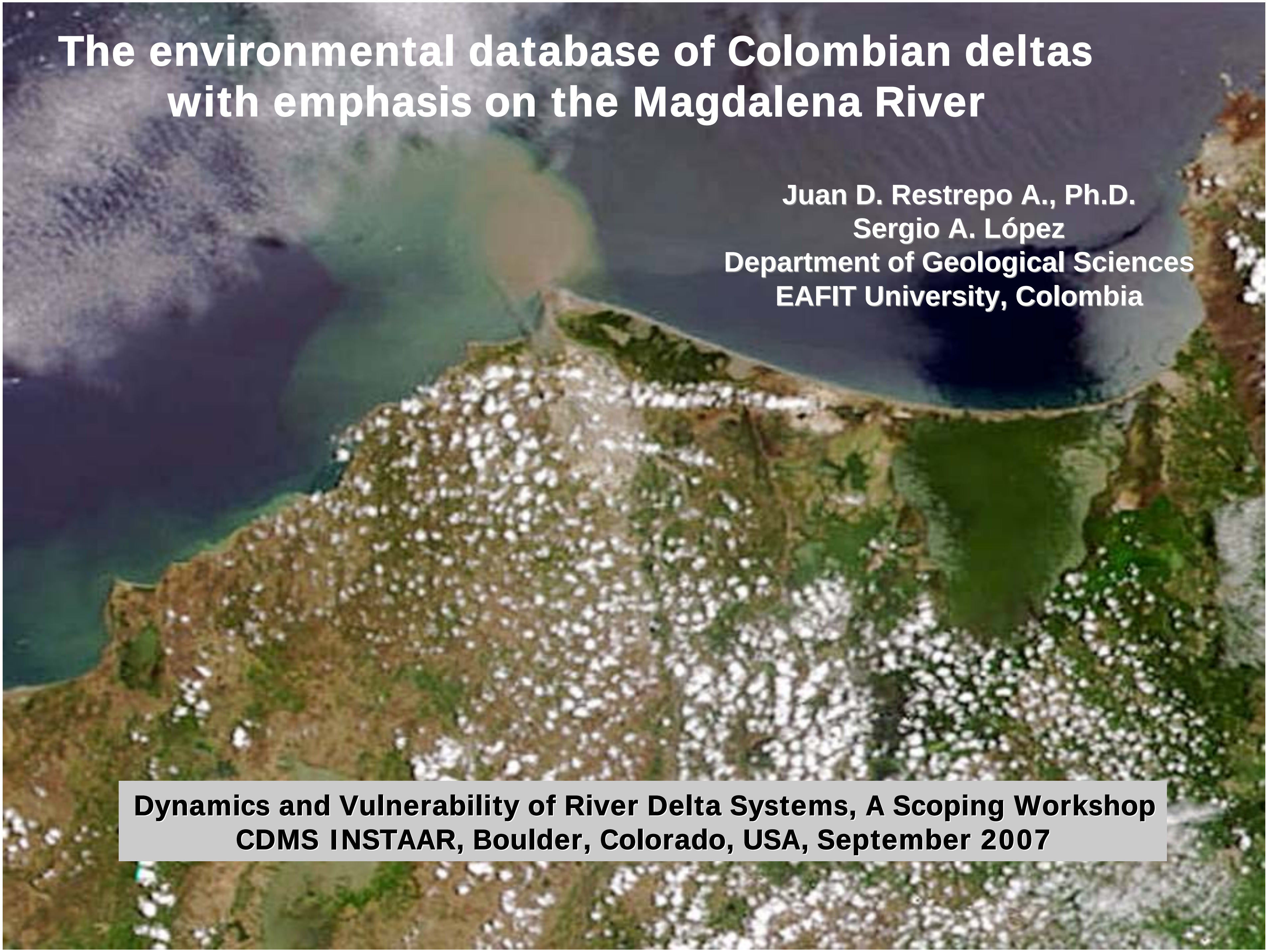

The environmental database of Colombian deltas with emphasis on the Magdalena River

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Dynamics and Vulnerability of River Delta Systems, A Scoping Workshop
CDMS INSTAAR, Boulder, Colorado, USA, September 2007

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2. Environmental database for the Colombian deltas with emphasis on the Magdalena River delta
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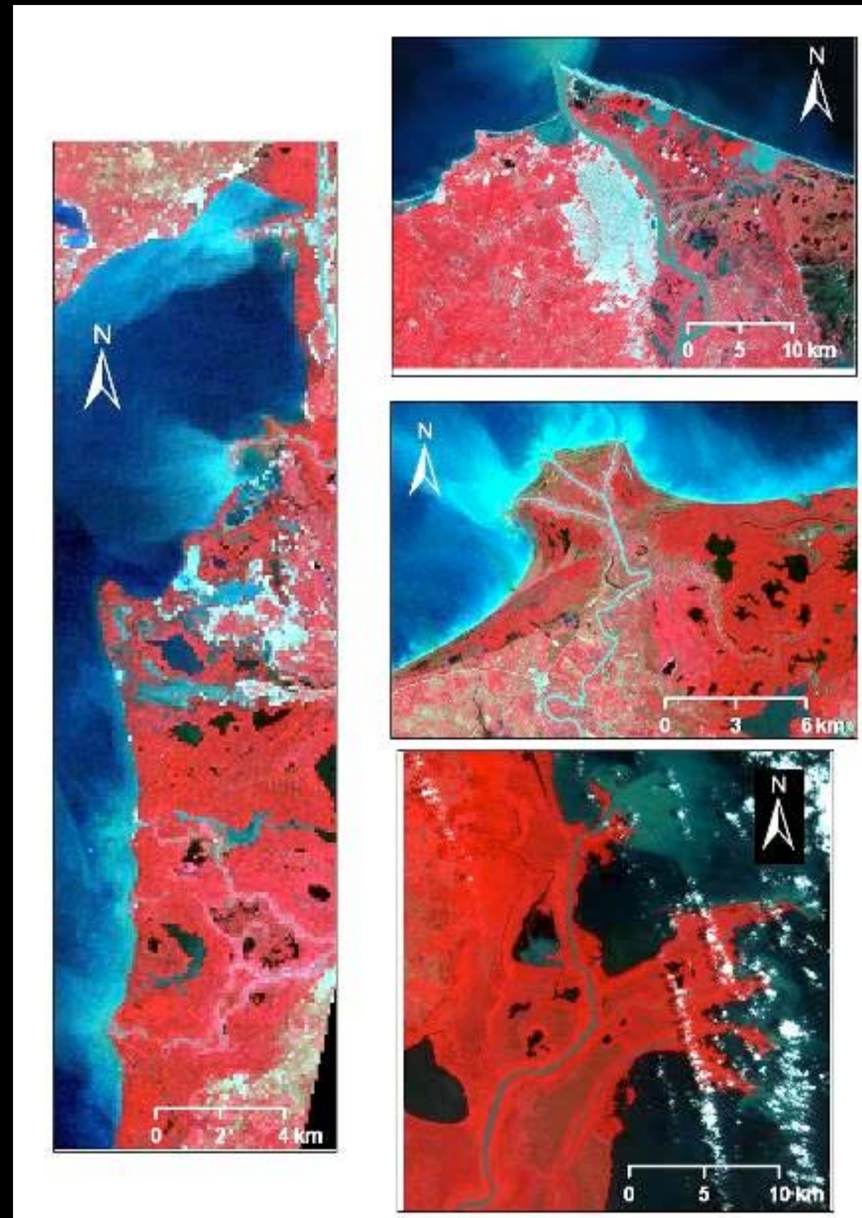
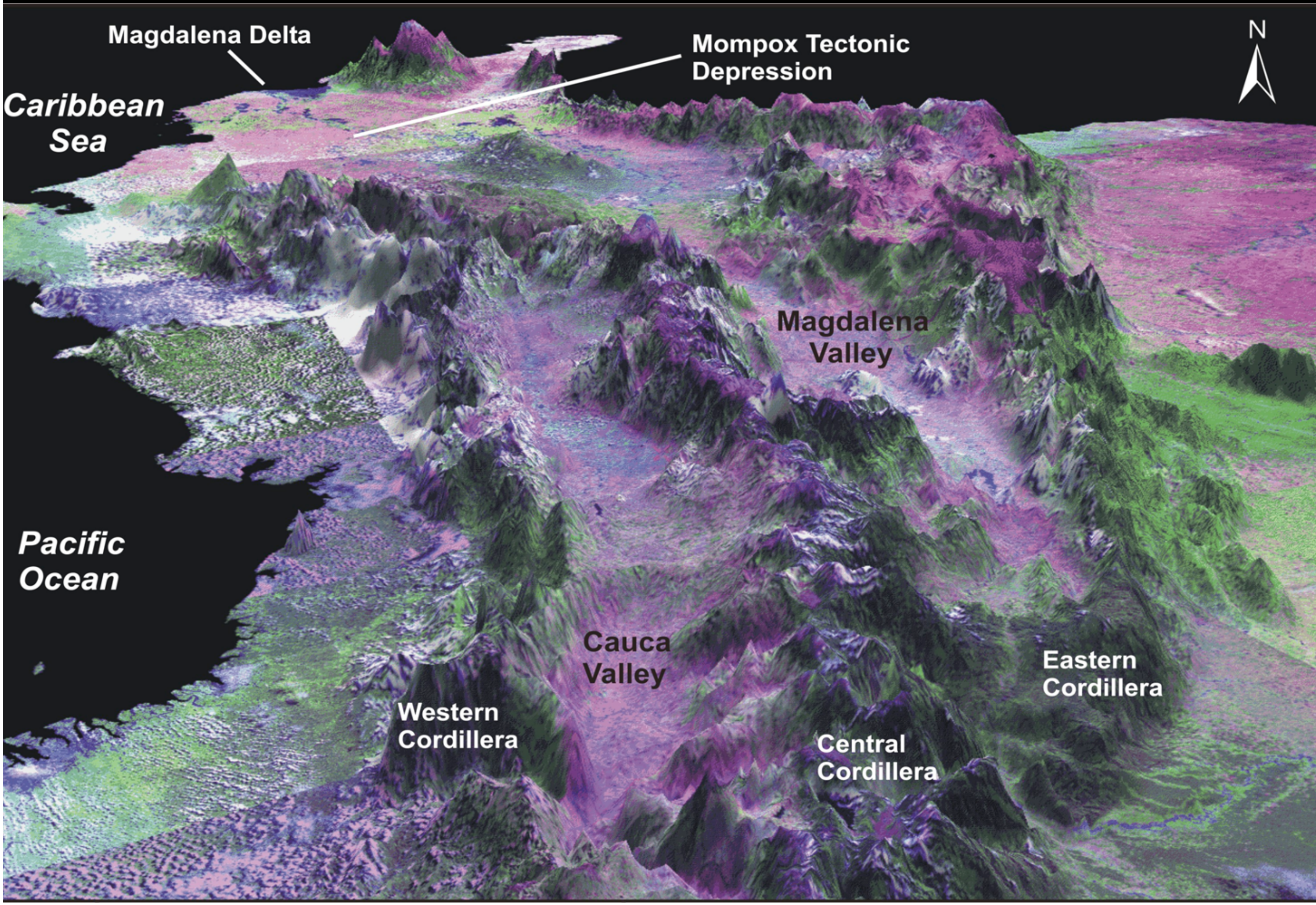
   - Fluxes into the Caribbean
   - Tidal characteristics
   - Wave climate
   - Shoreline changes
   - Morphodynamic indicators

3. Further comments



Colombia: Research interest

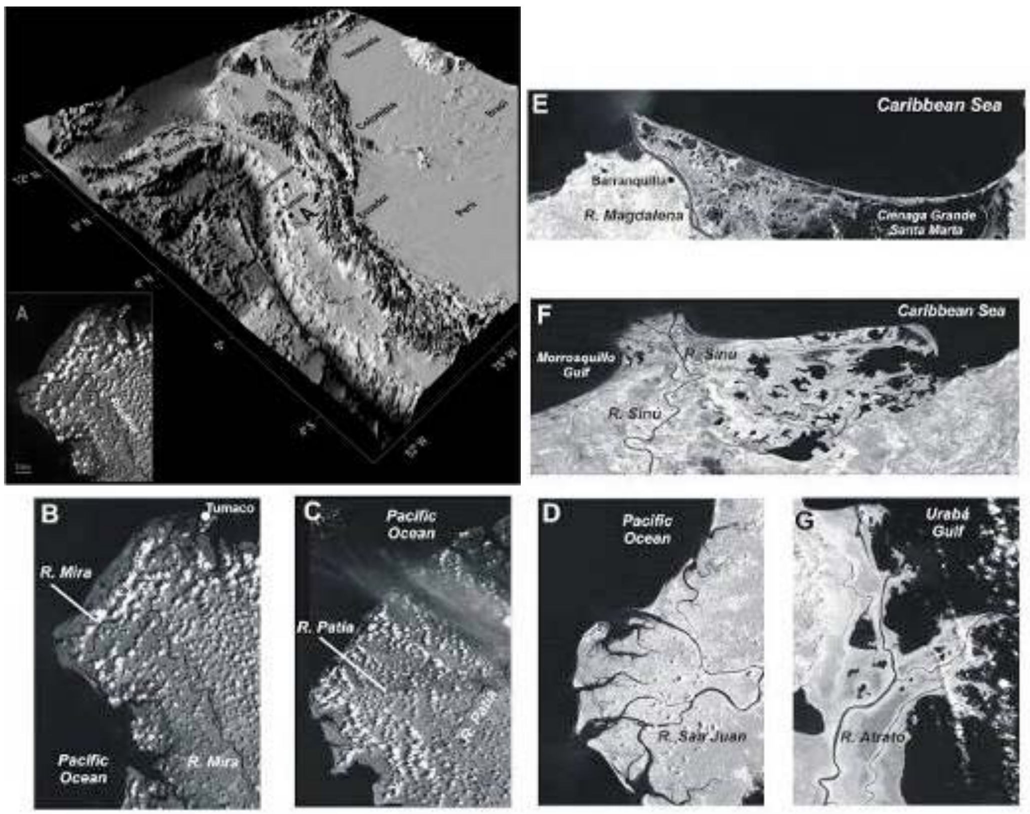


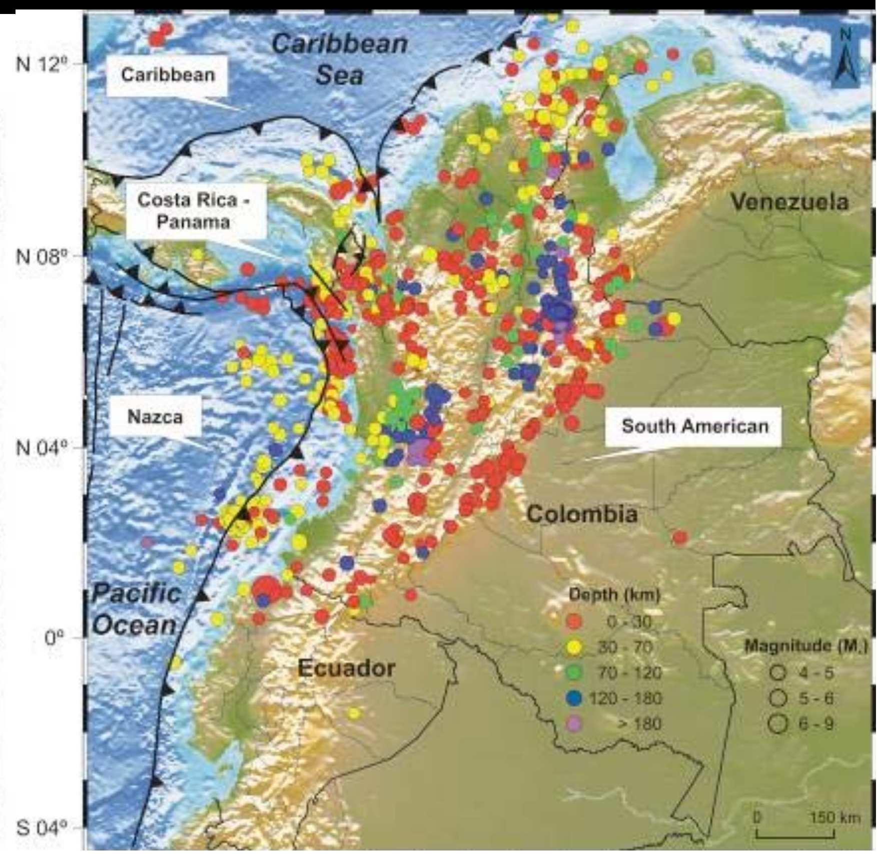
Research interest: Pacific and Caribbean deltas of Colombia

- The morphology has been described in a qualitative manner and there are no quantitative databases of key morphodynamic factors.

- Colombian deltas have not been included in global databases.

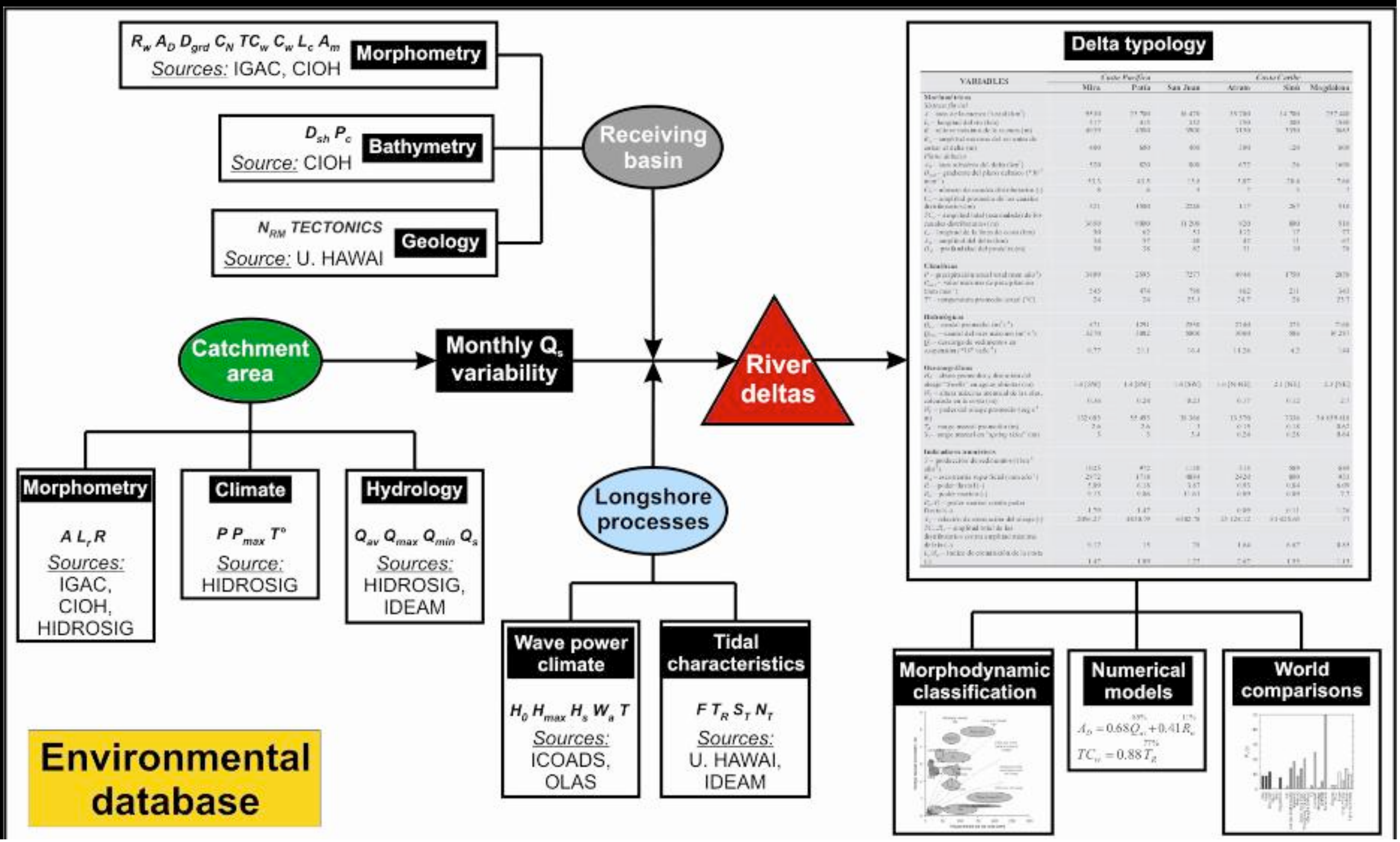
- Compared to other South American deltas, Colombian systems are built under the unique combination of extreme climatic, geological, and oceanographic conditions.





Building the environmental database

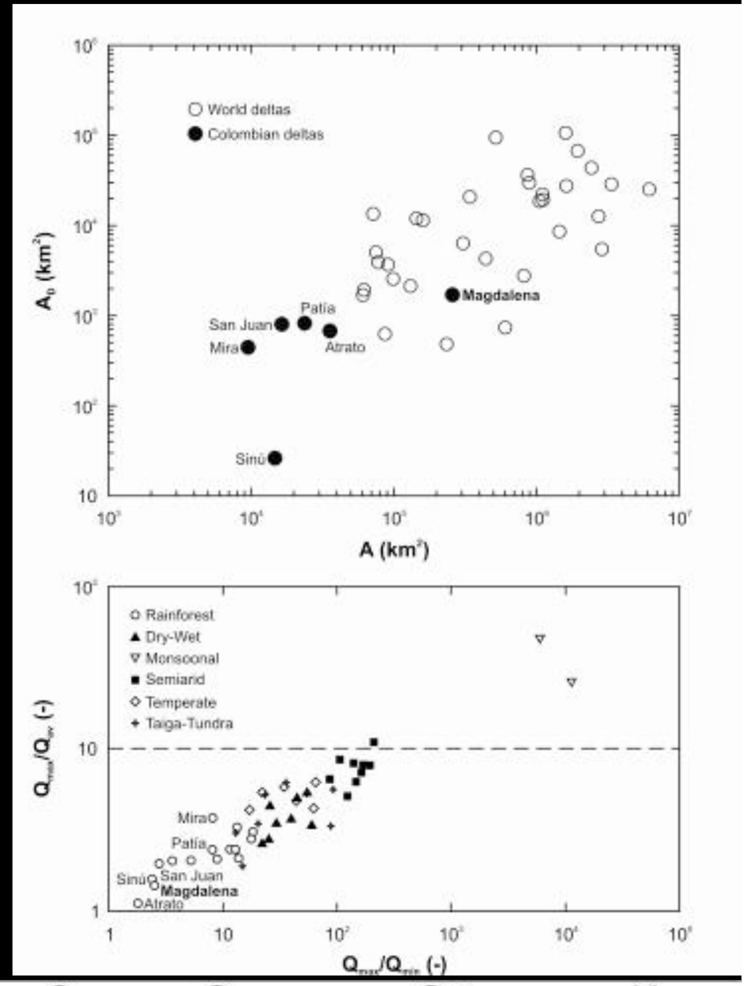
To address the morphodynamic characteristics of Colombian deltas, we developed a database of key physical variables according to the environmental factors established by Syvitski (2005) and Syvitski et al. (2005).



Database: The drainage basin

(Restrepo and López, in press. J. of South American Earth Sciences)

- **Location in the tropical zone**
- **Small drainage basins**
- **Presence of active fault systems**
- **High precipitation rates**
- **Slopes frequently steeper than 35°**
- **Low variability of Q and Qs**
- **High sediment yield**

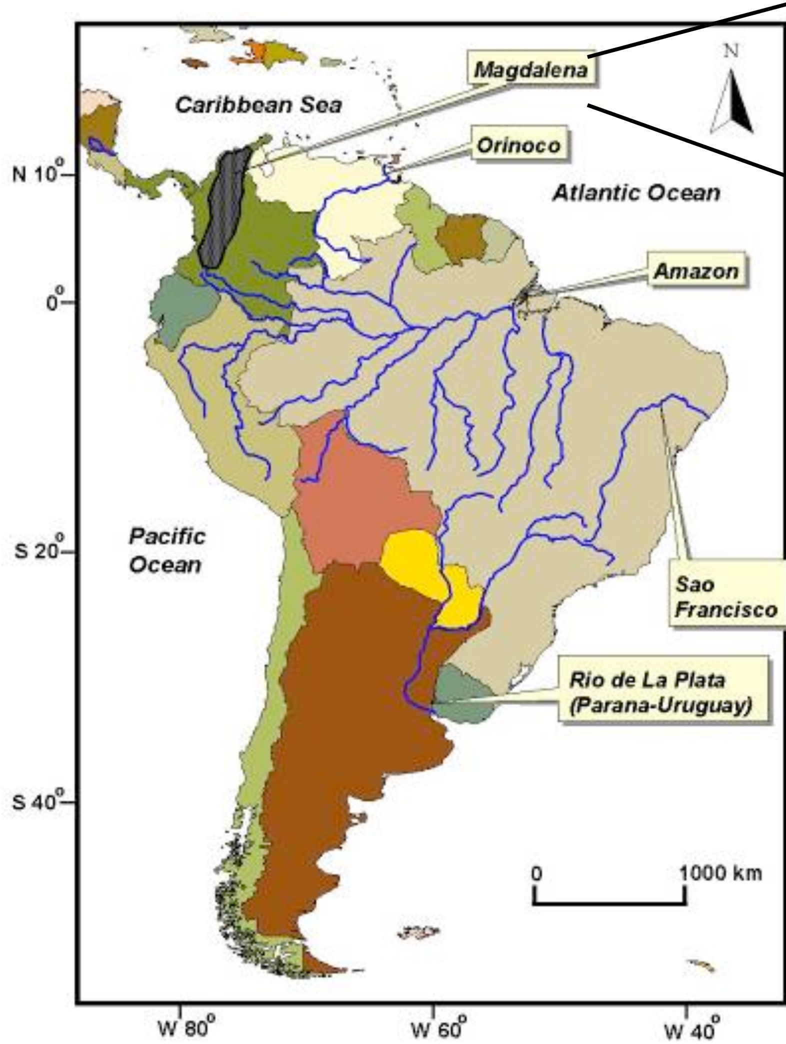


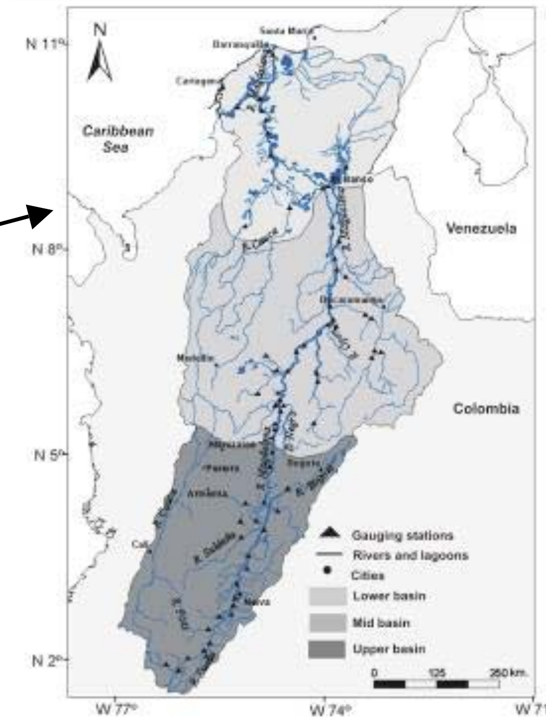
Fluvial system / Delta	L (km)	A (km^2)	R (m)	r (mm yr^{-1})	f (mm yr^{-1})	f/r (-)	Q (m^3 s^{-1})	Q_{max} (m^3 s^{-1})	Qs (x 10^6 t yr^{-1})	Y (t km^{-2} yr^{-1})
Pacific coast										
Mira	272	9530	3346	4703	2872	0.61	868	3270	9.7	1025
Patia	415	23700	4580	3296	1718	0.52	1291	3082	21.1	972
San Juan	352	16470	3900	7277	4884	0.67	2550	5000	16.4	1150
Caribbean coast										
Atrato	700	35700	3150	4944	2420	0.49	2740	3060	11.3	315
Sinu	300	14700	3350	1750	800	0.46	373	586	4.2	589
Magdalena	**1540**	**257440**	**3300**	**2050**	**886**	**0.43**	**7232**	**10287**	**144**	**560**

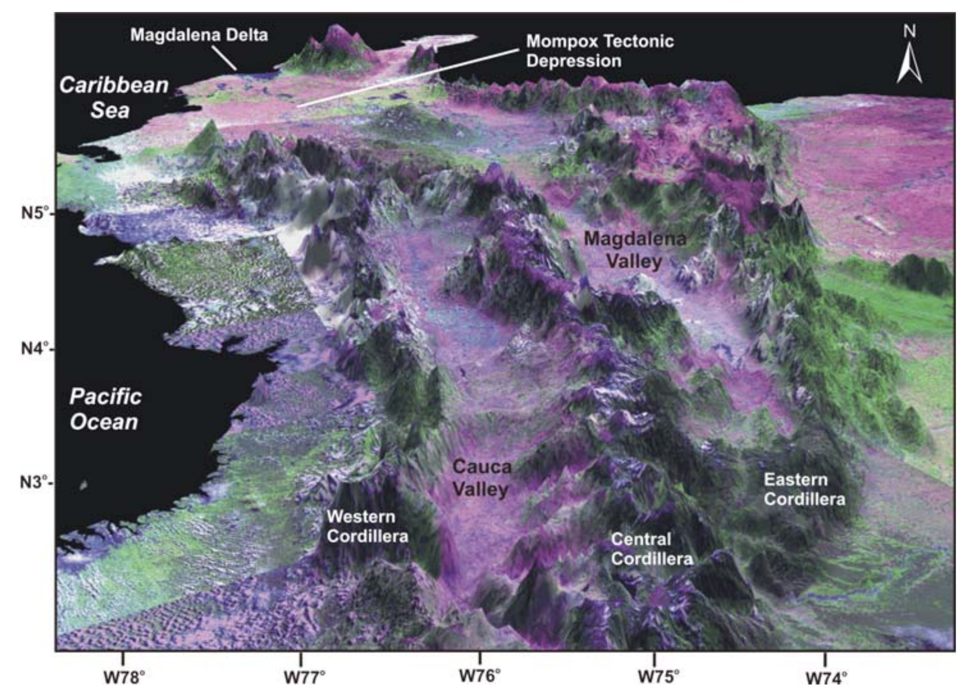
The Magdalena drainage basin

(Restrepo and Syvitski, 2006. Ambio)

- Drainage basin area of 257 438 km^2
- 24 % of the Colombia
- 151 sub-catchments (42 second order)
- Head waters at an elev of 3 685 m



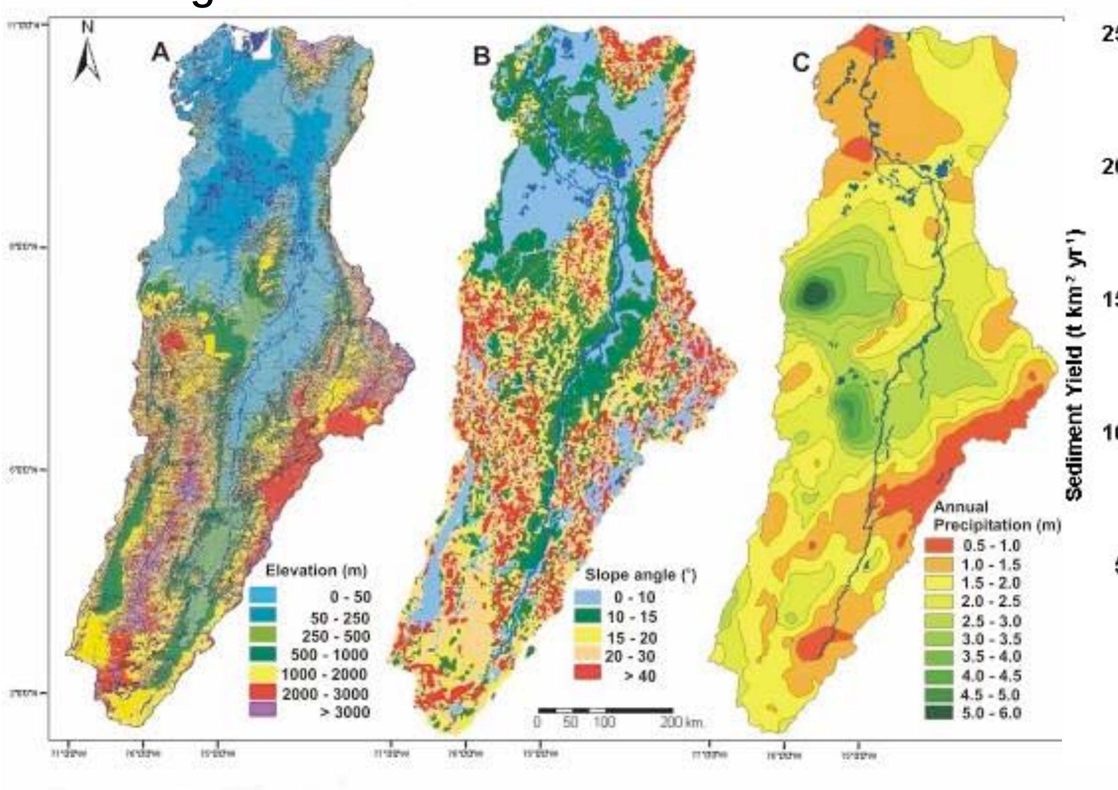




Sediment yield (Y) estimates

Drainage basin characteristics

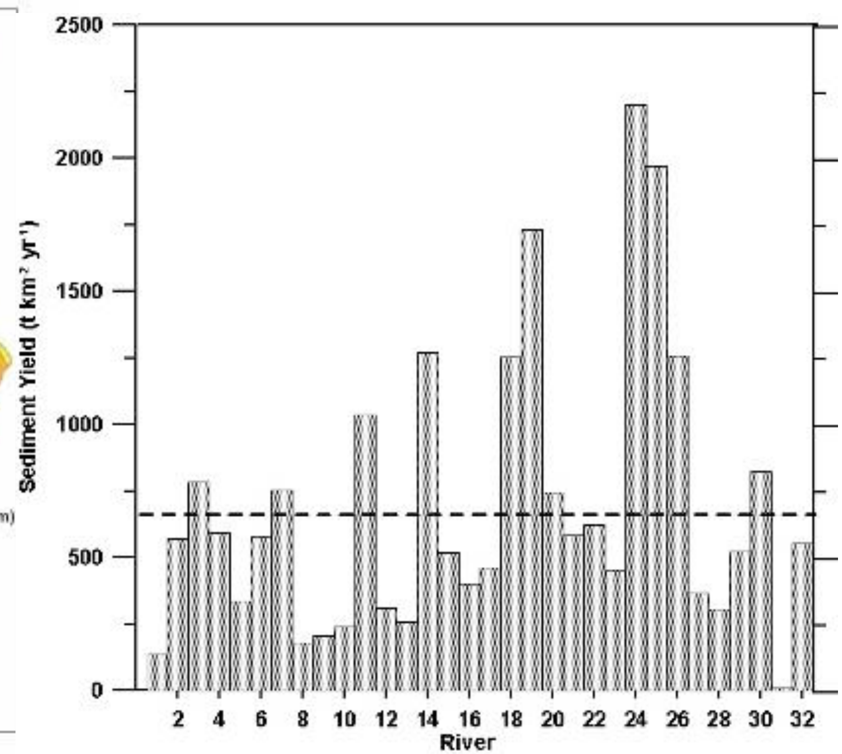
- •19% with hillslopes > 35°
- •71% with elev. > 1000 m
- •Average rainfall of 2 050 mm yr^{-1}
- •Average runoff of 953 mm yr^{-1}
- •Average Δf is 0.54



(Restrepo and Syvitski, 2006. Ambio)

Spatial variability in Y

- •Average Y of 689±528
- •128 to 2200 t km^{-2} yr^{-1}
- •Max values of Y in the middle basin (Eastern Cordillera)



Natural factors controlling sediment yield

- $\triangle f$ y Q_{max}
- R^2 of 0.51 ($\triangle f$) and 0.32 (Q_{max})
- Both variables explain 58%
- of the data variance

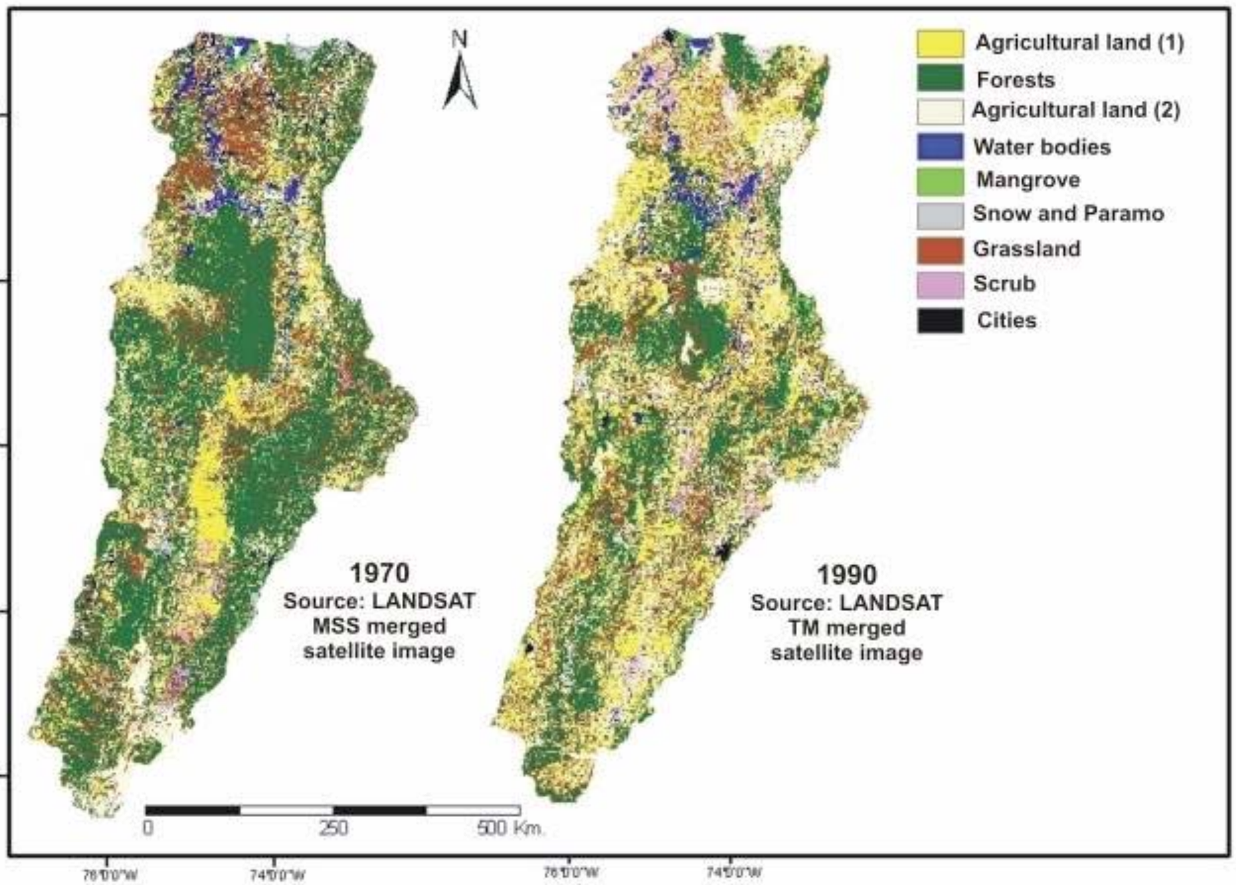
Multiple regression models

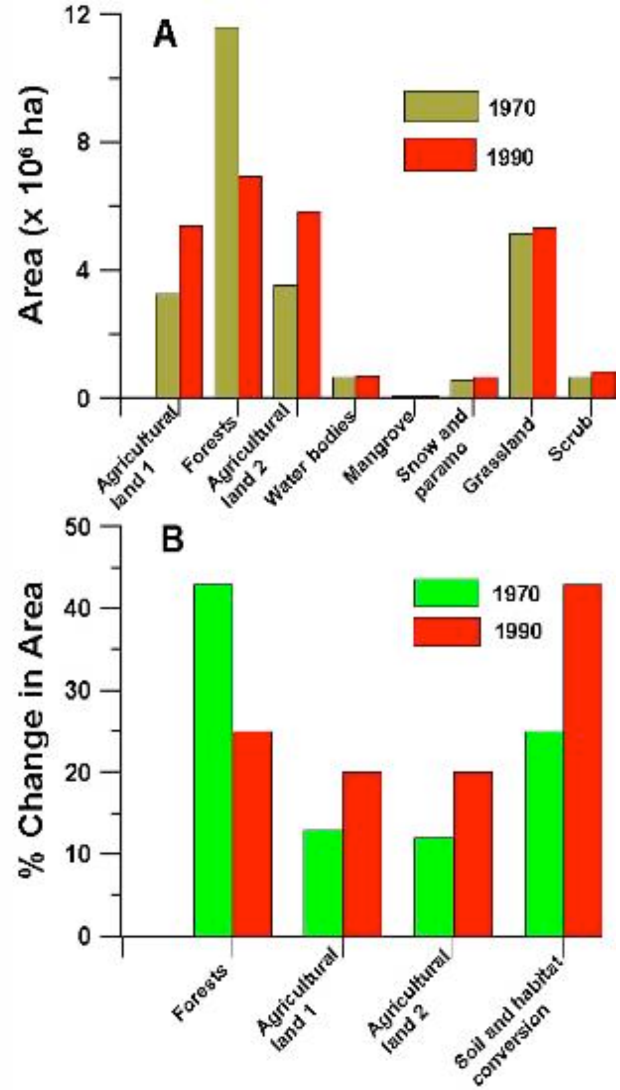
Morphometric classification	Regression equation	N	R^2	F-value
Basin	(1) $Y = 0.13\ \Delta f^{\,0.81} Q_{max}^{-0.39}$	32	0.58	16.15
Upper Basin	(2) $Y = 107.092 + 0.4227\ Q_{max}$	13	0.75	33.23
Mid Basin	(3) $Y = 3484.95 - 0.5042\ H - 38.1722\ H_r - 2.3837\ Q$	10	0.77	6.71
Eastern Cordillera	(4) $Y = 5.4\ H^{-2.1}\ Q^{0.78}\ r\ A^{-0.4}$	12	0.82	202.13
A > 10 000 km^2	(5) $Y = 4.4\ \Delta f^{\,0.9}\ r_{pk}^{-4.9}$	3	0.78	19.83

(Restrepo and Syvitski, 2006. Ambio)

Land cover change, 1970-1990

- Forest cover decrease by 40% in 20-yr period
- Annual deforestation rate of 1.9%
- Agriculture and pasture cover increase by 65% during the same period
- Agricultural lands doubled their areas in 20 yrs



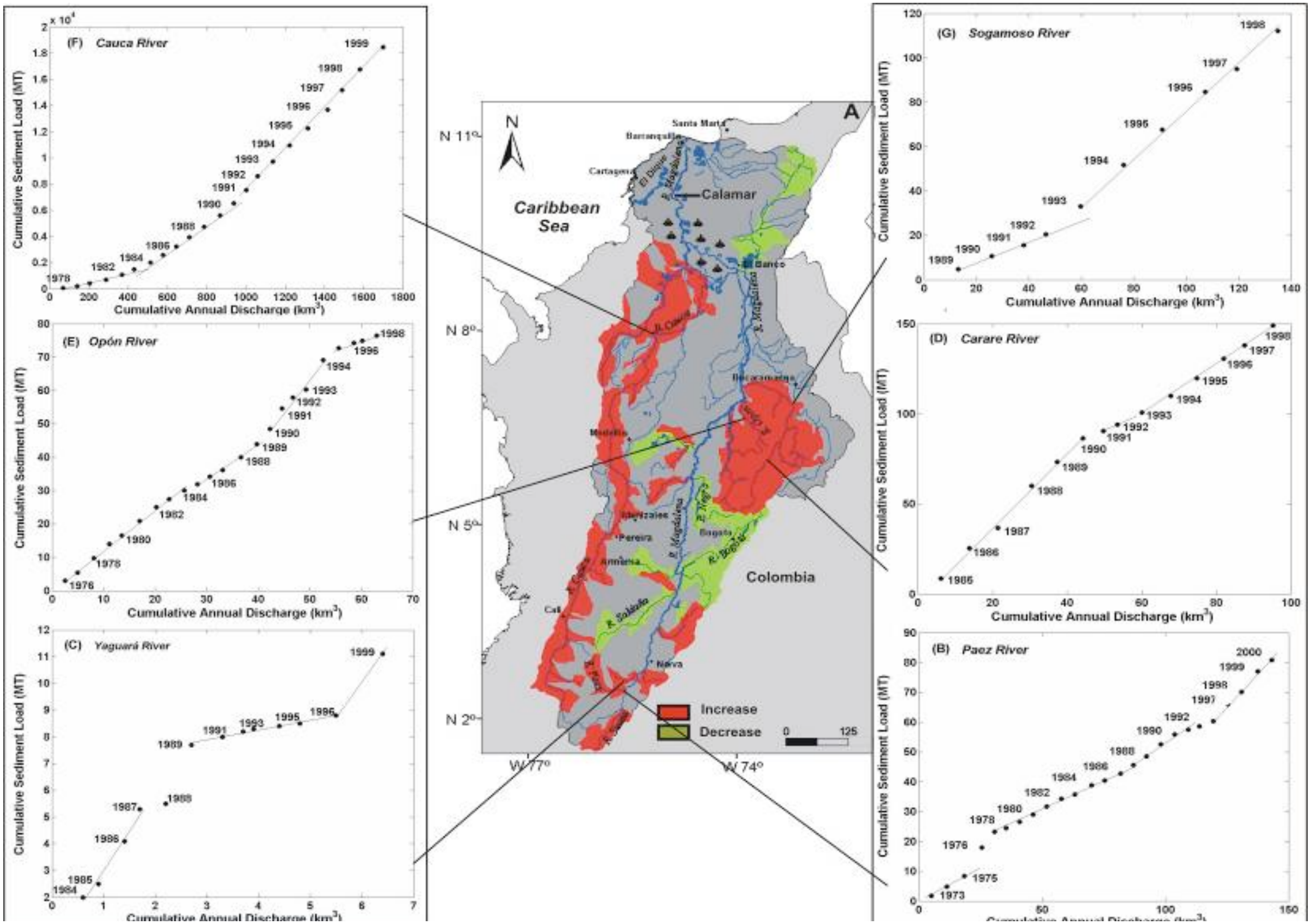


(Restrepo and Syvitski, 2006. Ambio)

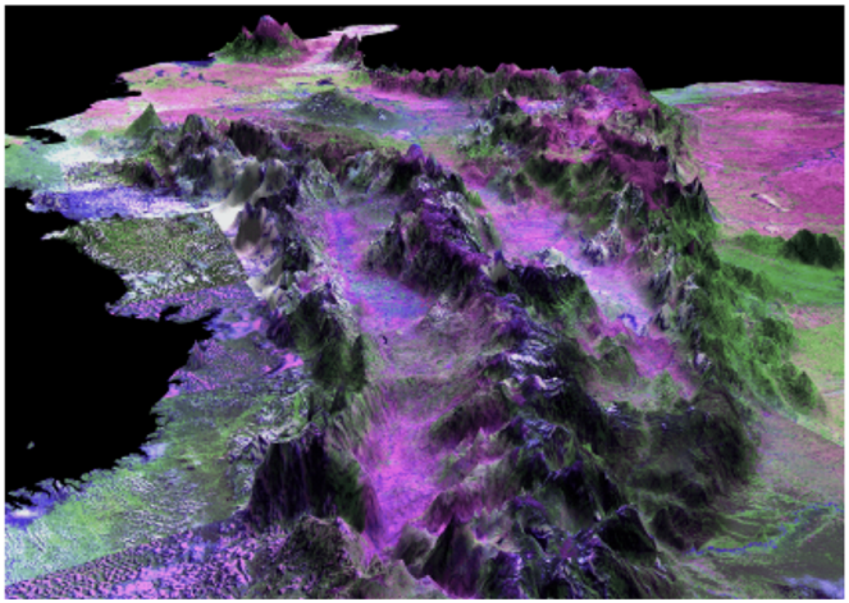
Recent trends in sediment loads

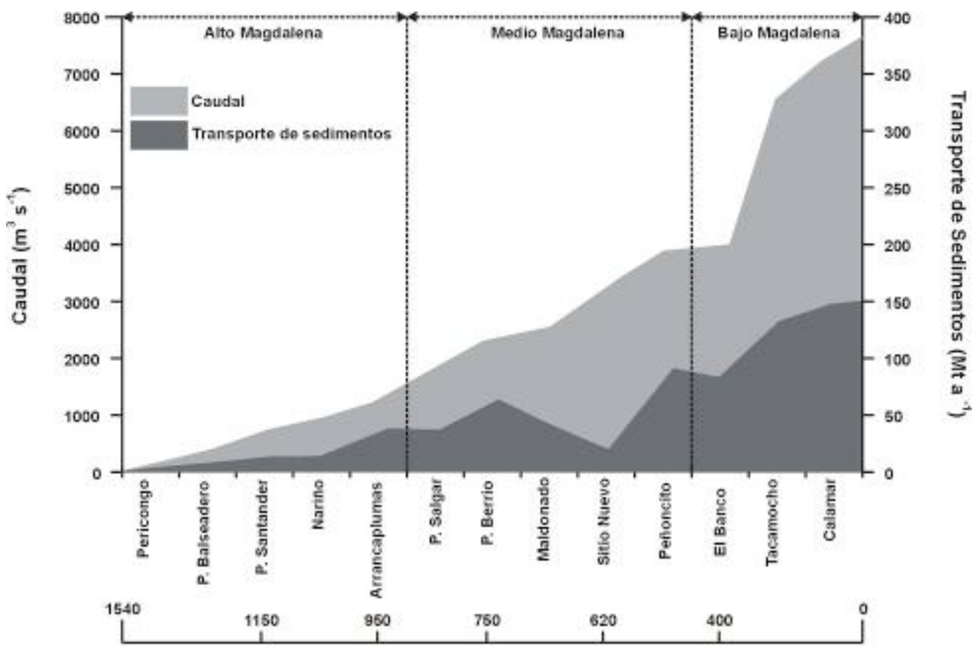
(Restrepo and Syvitski, 2006. Ambio)

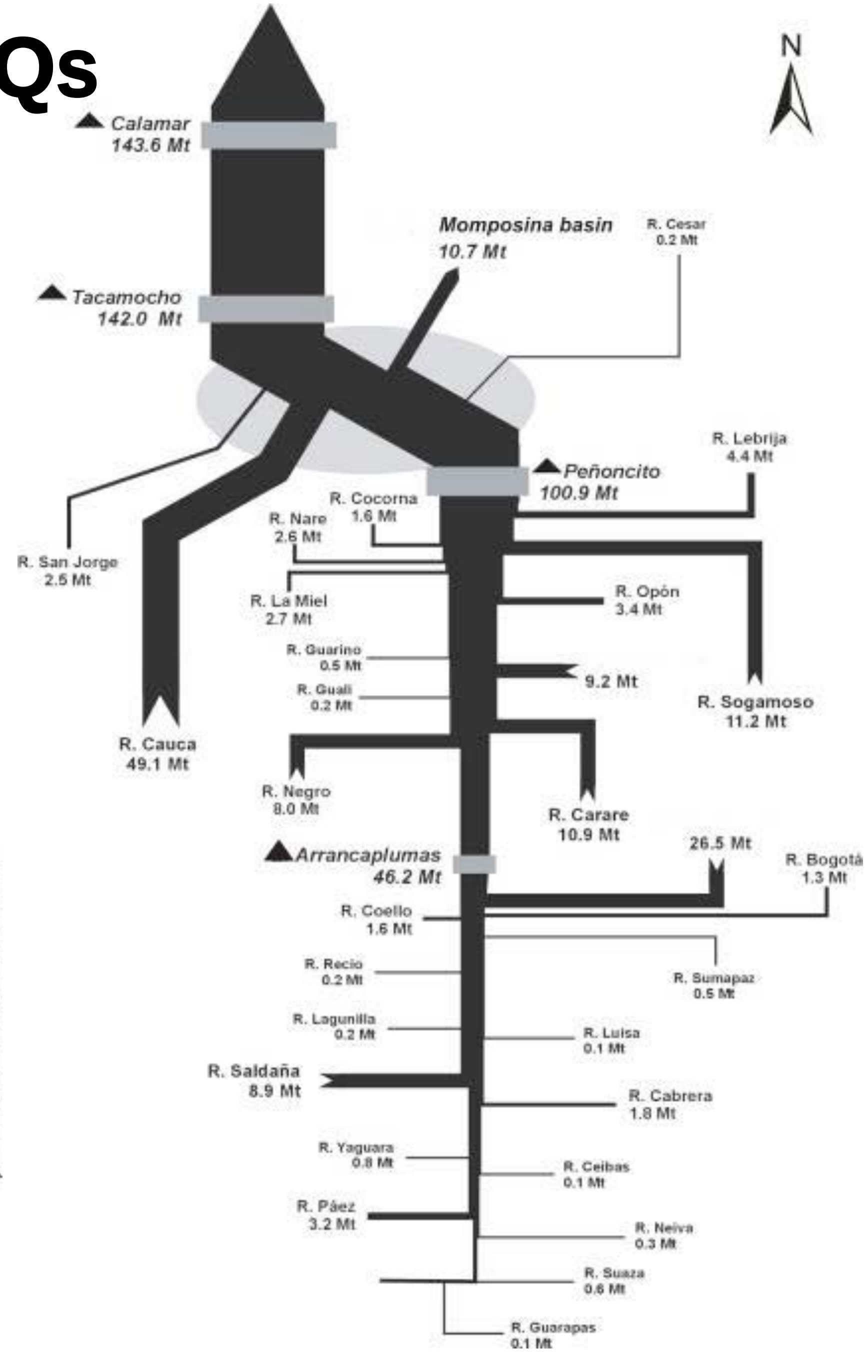
- 68% of the drainage basin area show increasing trends
- The Cauca River saw its Qs increase by ~30% from 1979-1999
- Annual Qs of the Sogamoso River have increased by ca. 43% (1990-2000)



Conceptual model of Qs

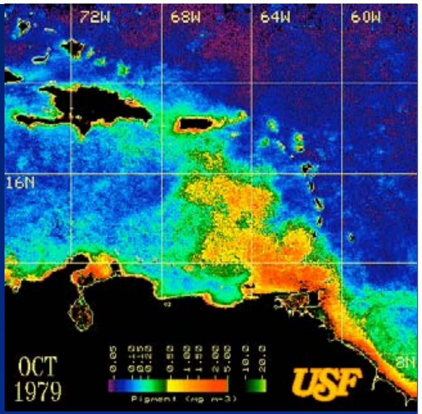




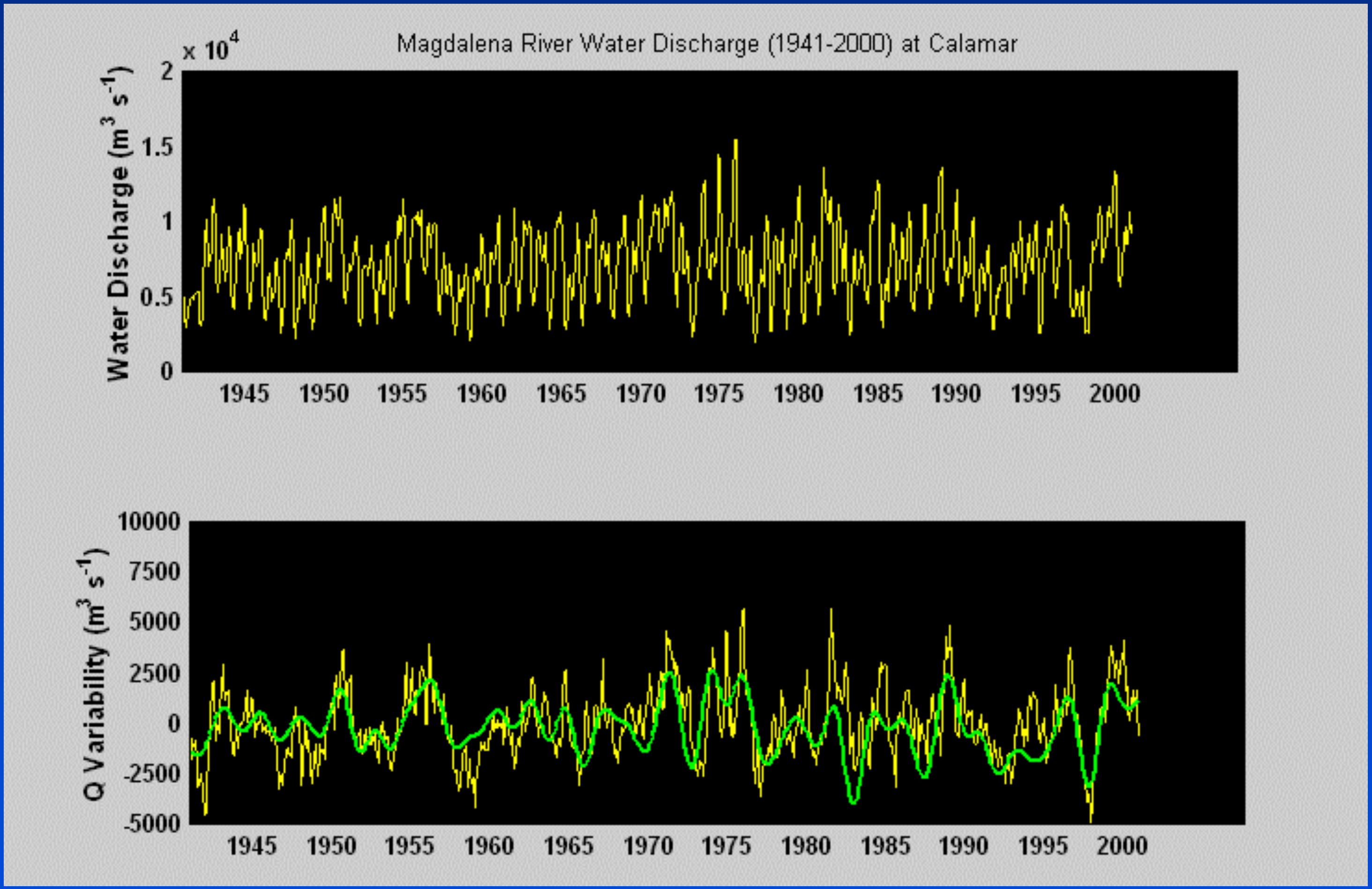


(Restrepo, in press. Estuarine, Coastal and Shelf Science)

Fluvial fluxes into the Caribbean (Q)

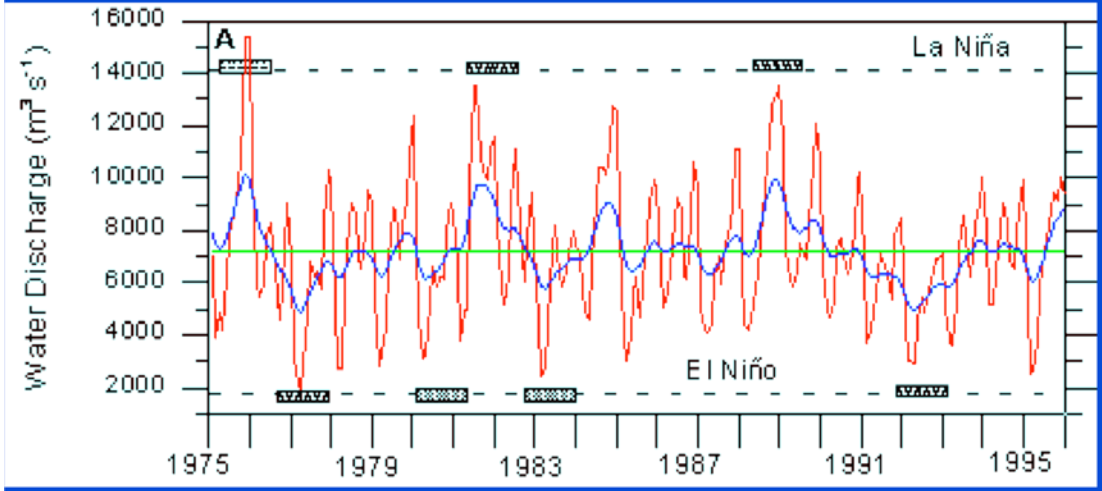


High interannual variability

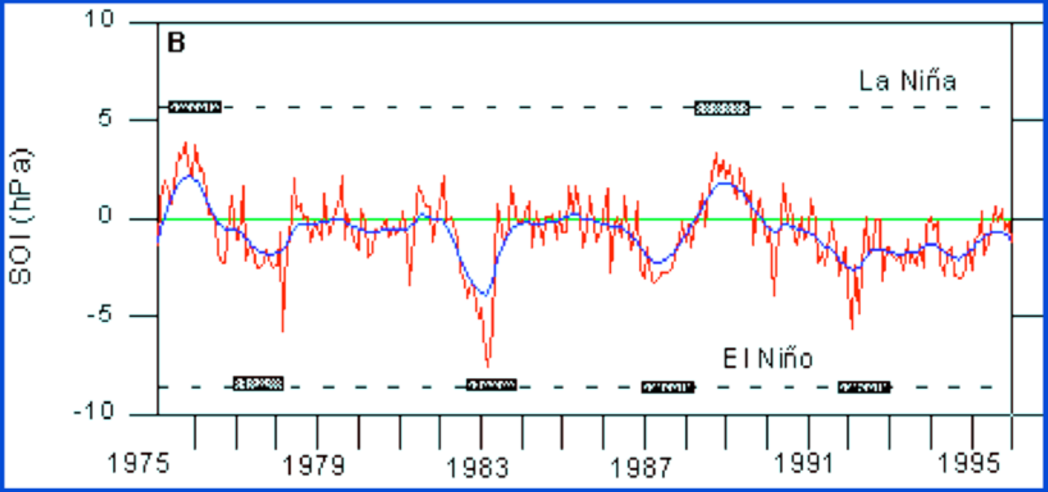


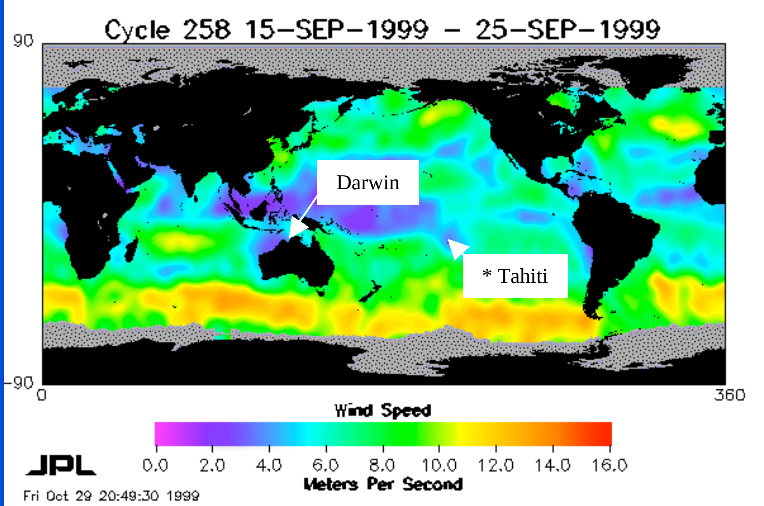
(Restrepo et al., 2006, Global & Planetary Change)

Magdalena River: Inter-annual variability 1975-1995, water discharge – El Niño Cycle



- Interannual mean = 7,200 $m^3 s^{-1}$
- La Niña: 12,000 $m^3 s^{-1}$
- El Niño: 2,000-3,000 $m^3 s^{-1}$
- Mean - El Niño = 5,512 $m^3 s^{-1}$
- Mean - La Niña = 8,747 $m^3 s^{-1}$
- Regression analysis, R^2 = 0.69

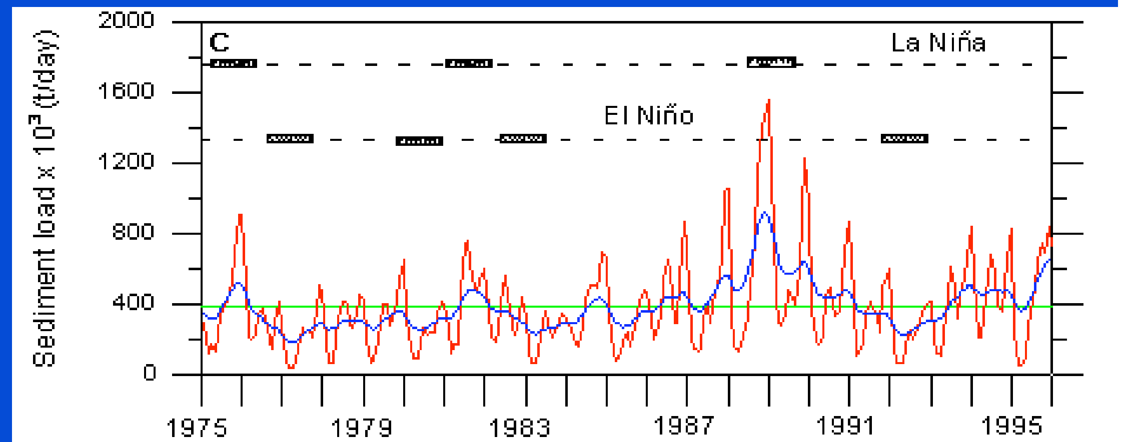


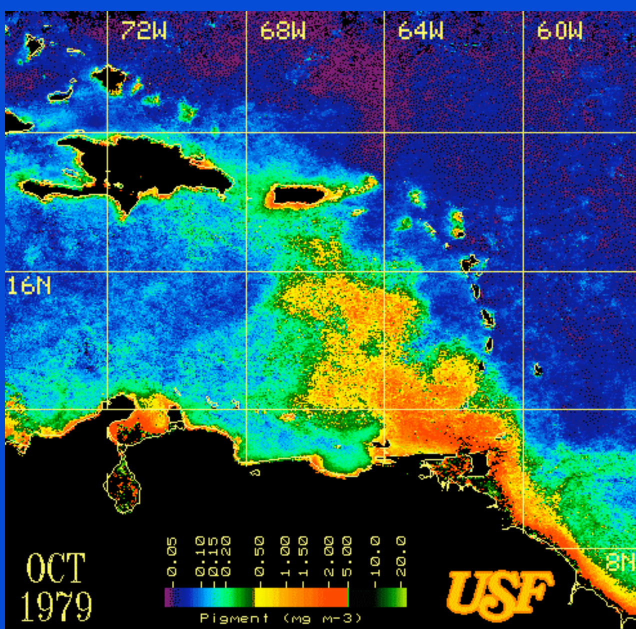


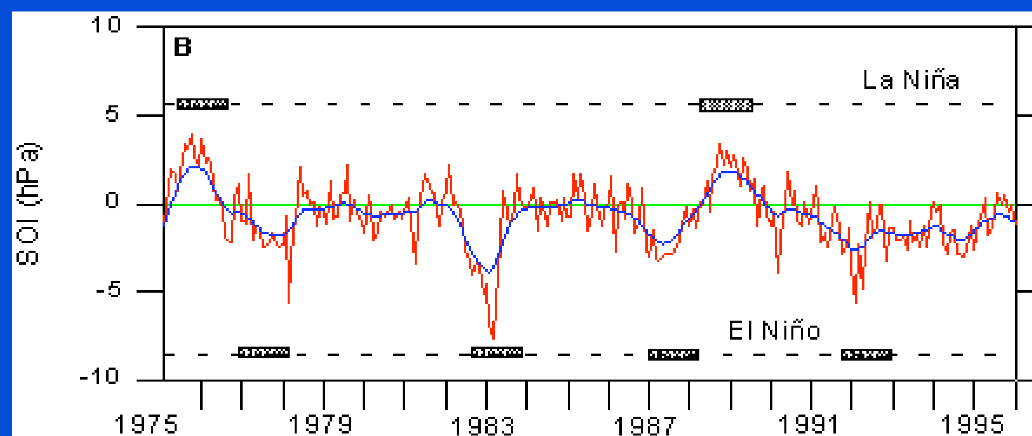
(Restrepo and Kjerfve, 2000. Journal of Hydrology)

Magdalena River: Inter-annual variability 1975-1995, sediment load – El Niño Cycle

- La Niña: high flow in 1988-89, caused a prominent peak of 1,600 t day^{-1}
- Mean - El Niño = 256 t day^{-1}
- Mean - La Niña = 511 t day^{-1}
- R^2 = 0.54





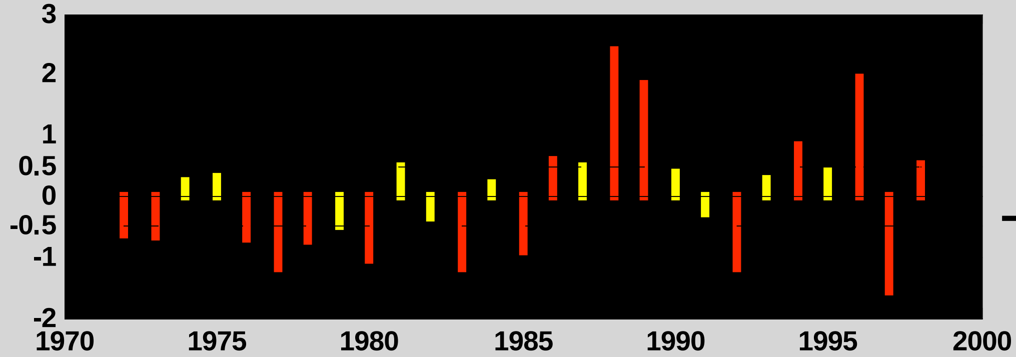


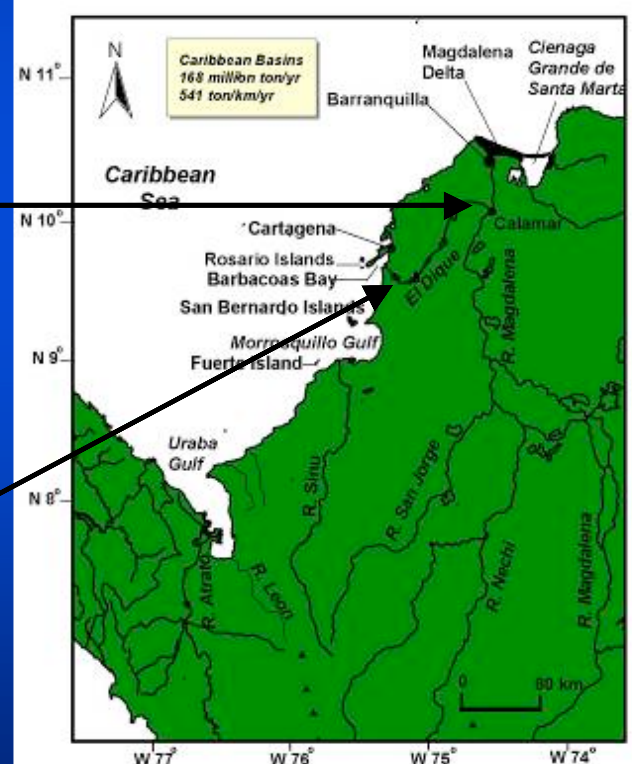
(Restrepo and Kjerfve, 2000. Journal of Hydrology)

Fluvial fluxes (Qs)

•The analysis of annual deviations from the 27-year mean sediment load indicates that 59% of the total sediment load variability of the Magdalena at Calamar could be attributed to peak events. The sediment load experienced 16 deviations from the interannual-year mean.

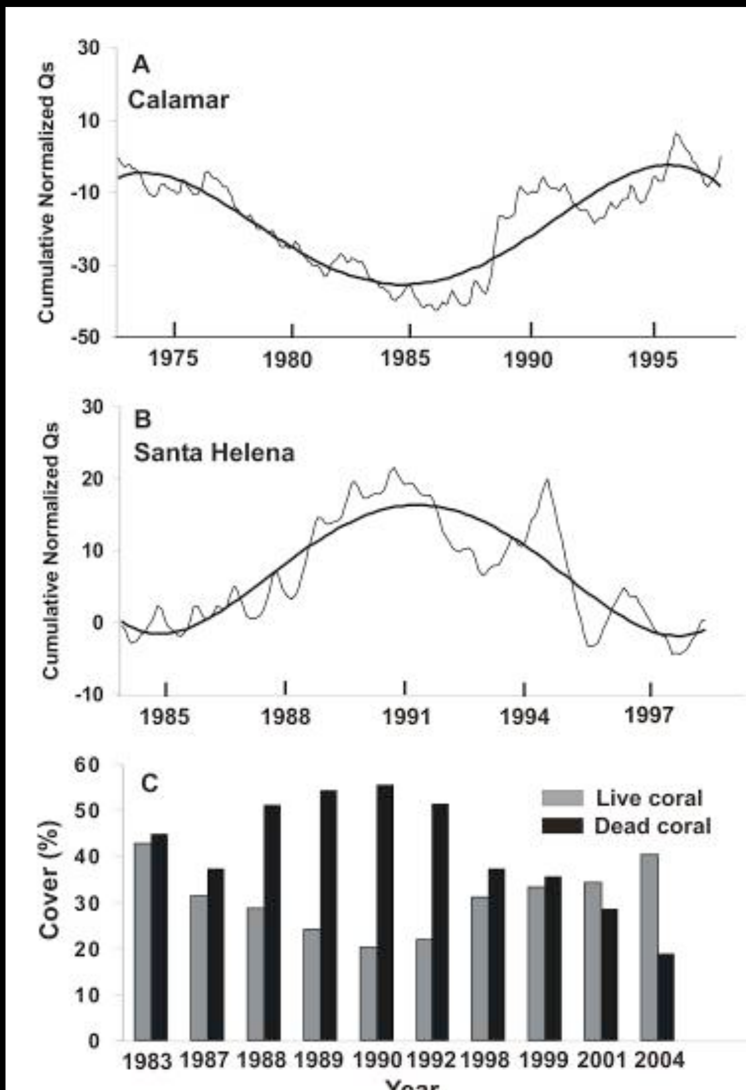
•The smaller Canal del Dique experienced 7 years, or 50% of the total sediment load variability, in which the annual sediment load exceeded 50% of the mean.

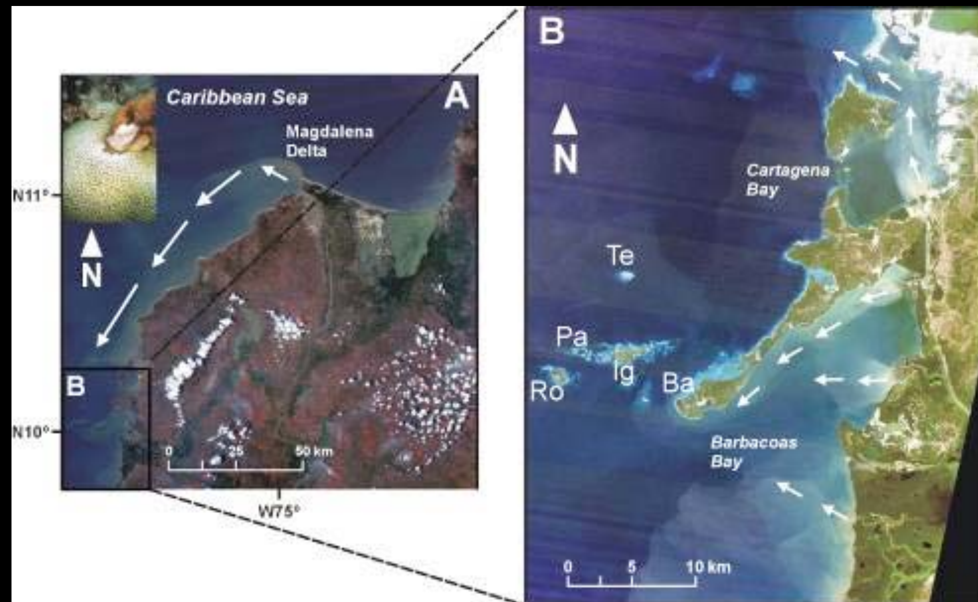


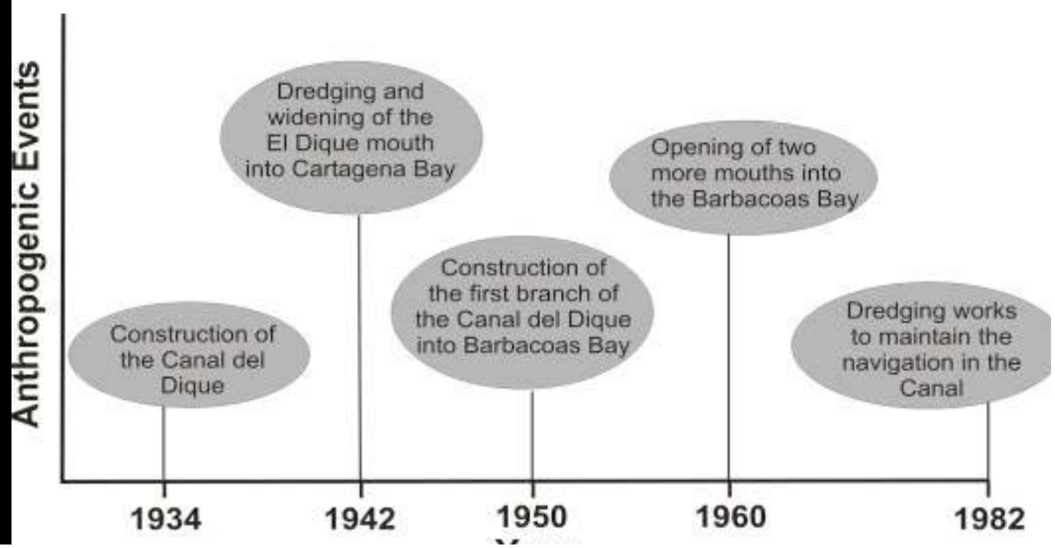


(Restrepo et al., 2006, Global & Planetary Change)

Fluvial fluxes (Qs) and impact on the coastal zone







(Restrepo et al., 2006, Global & Planetary Change)

Database: The Magdalena delta

(Restrepo and López, in press. J. of South American Earth Sciences)

- Arcuate delta with an emergent area of 1,690 km^2.
- Classified as a wave dominated system (Coleman, 1981).
- Receiving basin characterized by sedimentation, slumping and compressional tectonics that cause mud diapirism.
- The delta empties into an offshore canyon (slope of 40°).

- Caribbean deltas have micro-tidal range, ranging from 62 to 15 cm.
- The tide in the Magdalena is a mixed primariliy diurnal tide (F=1.9)

Constituent	Origin	Period (solar hours)	Pacific coast: Mira H_n (cm)/g_n(°)	Pacific coast: San Juan H_n (cm)/g_n(°)	Pacific coast: Atrato H_n (cm)/g_n(°)	Caribbean coast: H_n (cm)/g_n(°)	Caribbean coast: Magdalena H_n (cm)/g_n(°)
Diurnal							
Q_1	Larger elliptical lunar	26.87	0.7/293	6/161	1/72	6/254	13/269
O_1	Principal lunar	25.82	0.5/256	6/240	33/299	33/300	23/258
K_1	Principal solar-lunar	23.93	0.6/101	25/039	33/301	36/289	35/270
Semidiurnal							
N_2	Larger elliptical lunar	12.66	4/185	25/169	10/251	5/222	9/126
M_2	Principal lunar	12.42	6/98	137/323	7/259	8/302	28/21
S_2	Principal solar	12.00	116/198	31/208	5/230	6/86	4/211
L_2	Smaller elliptical lunar	12.19	20/53	6/266	15/55	1/61	9/76
K_2	Declinational lunar-solar	11.97	32/177	8/199	1/228	2/97	1/198
Shallow water							
MK_3			0.7/22	7/196	133/198	115/14	140/172
MN_4			0.6/44	16/338	104/89	59/94	70/63
M_4	Principal lunar over-tide	6.21	0.3/359	55/117	157/110	163/92	178/100
MS_4		6.10	1.5/13	26/360	23/342	43/340	17/255
M_6			0.2/98	13/073	28/236	35/254	57/245
$2MS_6$			0.2/56	9/313	21/333	17/346	32/78
M_8			0.2/96	8/068	43/339	48/300	65/41
$3MS_8$			0.1/61	11/325	43/11	33/292	27/14
Tidal statistics	Formula						
Form number (-)	$(K_1 + O_1)/(M_2 + S_2)$		0.09	0.18	5.5	4.93	1.81
Inequality phase (°)	$M_2^\circ \quad (K_1^\circ + O_1^\circ)$		-259	43	-341	-287	-507
Phase age (°)	$0.98*(S_2^\circ - M_2^\circ)$		98	- 112	28.4	-211.68	186.2
Mean tidal range (m)	$2.2*(M_2)$		1.3	3.0	0.15	0.18	0.62
Spring tidal range (m)	$2.0*(M_2 + S_2)$		2.4	3.4	0.24	0.28	0.64
Neap tidal range (m)	$2.0*(M_2 - S_2)$		1.1	2.1	0.04	0.04	0.48

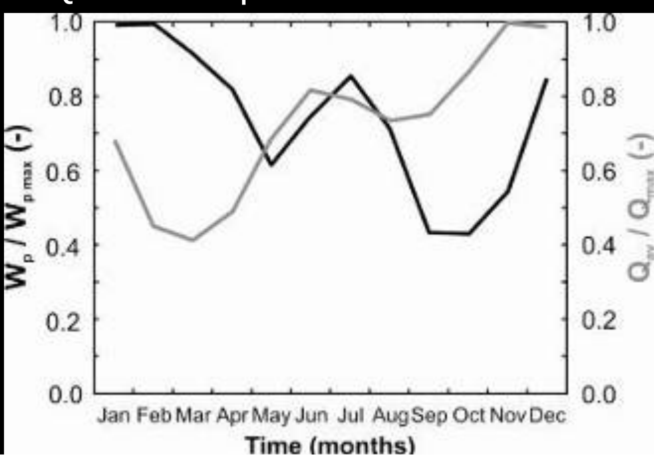
Data base: Wave climate and depth of the delta front

- Higher nearshore wave power with 35 x 10^6 erg s^{-1}

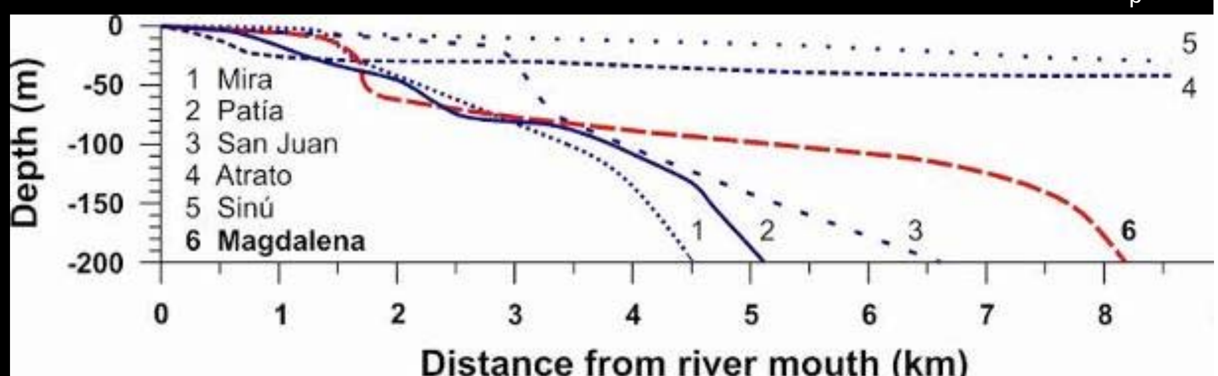
Wave characteristics	Pacific coast			Caribbean coast		
	Mira		San Juan	Atrato		Magdalena
Seas	Sea/swell wave	direction				
Predominant Sea direction (1963-2000)	SW	SW	SW	NW	NE	**NE**
Mean height (m)	0.9	0.9	0.9	0.8	1.4	**1.6**
Maximum height(m)	3.0	2.5	2.7	1.5	6.5	**6.5**
Significant height (m)	2.0	2.1	1.4	1.8	3.3	**3.6**
Mean period (s)	5.2	5.5	5.6	5.0	6.0	**6.1**
Swells						
Predominant Swell direction (1963-2000)	SW	SW	SW	NE	NE	**NE**
Mean height (m) - rms	1.4 - 0.6	1.4 - 0.7	1.4 - 0.7	1.6 - 0.8	2.1 - 1.3	**2.3 - 1.2**
Maximum height (m)	4.5	6.5	7.5	6.5	9.0	**9.0**
Significant height (m)	3.0	3.1	1.7	3.6	4.9	**5.1**
Mean period (s) - rms	6.3 - 2.6	6.3 - 2.4	6.1 - 2.6	6.3 - 2.5	6.5 - 2.3	**6.7 - 2.3**
Wavelength (m)	61.9	61.9	58.0	61.9	48.9	**70.0**
% Swell direction (1963-2000)	64.2	67.8	63.2	36.0	74.5	**77.9**
Other wave parameters (shallow water)						
x -Incremental linear distance (m, from *d* = *L* / 2 to *d* = 9 m)	529	1167	1250	4375	1818	
Wave height after frictional attenuation (m, *x* to *d* = 9 m)	1.3	1.3	1.3	1.4	1.8	**2.1**[1]
W_P-Wave power (10^6 erg s^{-1}, *d* = 9 m)	16.2	16.0	15.8	18.5	34.4	**45.4**[1]
x -Incremental linear distance (m, from *d* = *L* / 2 to *d* = 0.3 m)	1765	2833	3250	5417	5727	
Wave height after frictional attenuation (m, *x* to *d* = 0.3 m)	0.25	0.26	0.21	0.14	0.11	**4.0**[1]
W_P-Wave power (10^6 erg s^{-1}, *d* = 0.3 m)	0.13	0.14	0.10	0.04	0.02	**34.9**[1]
A_P-Attenuation index (-)	2056	1894	2454	7676	25 376	**24**[1]

(Restrepo and López, in press. J. of South American Earth Sciences)

- Qs – Wave power climate

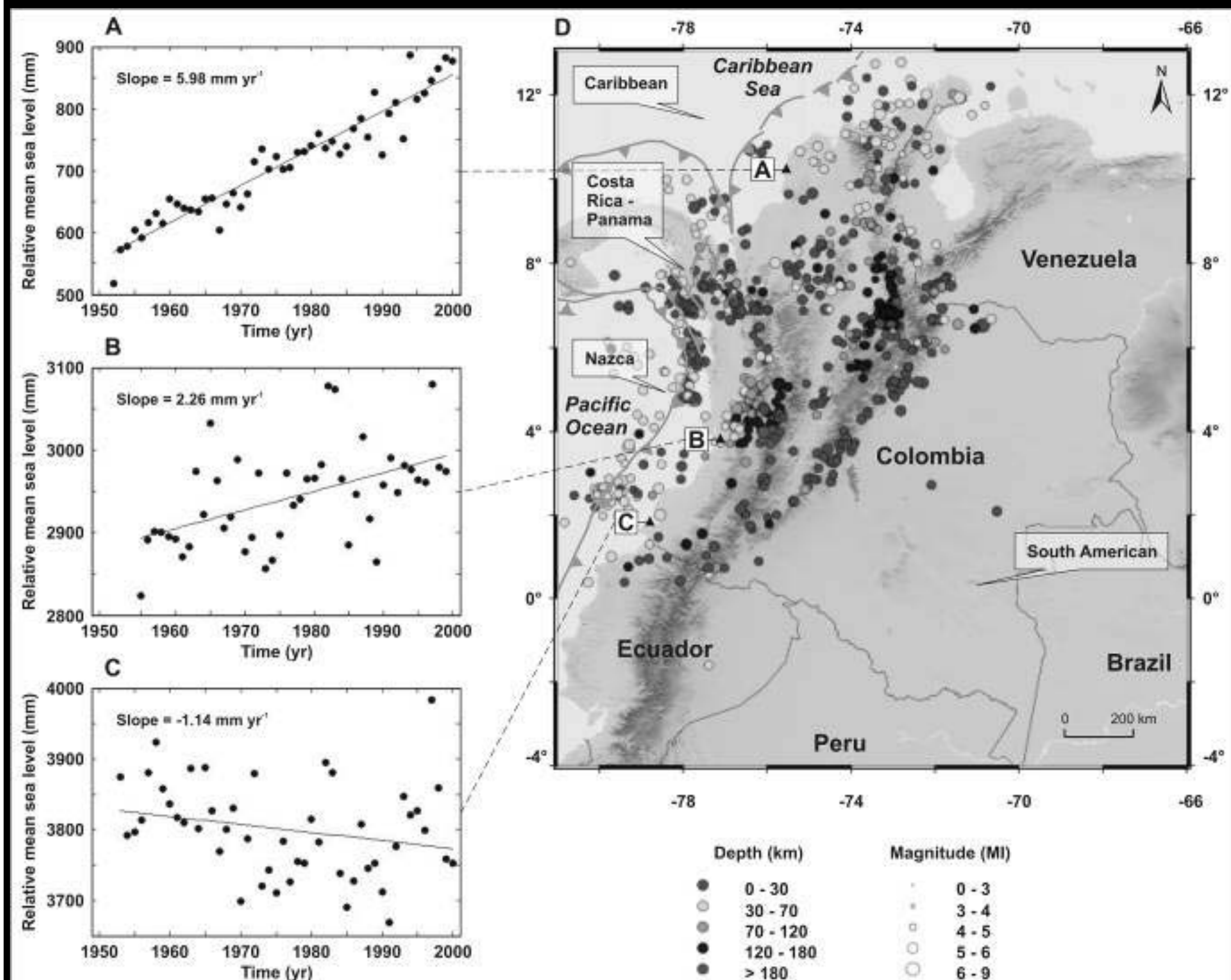


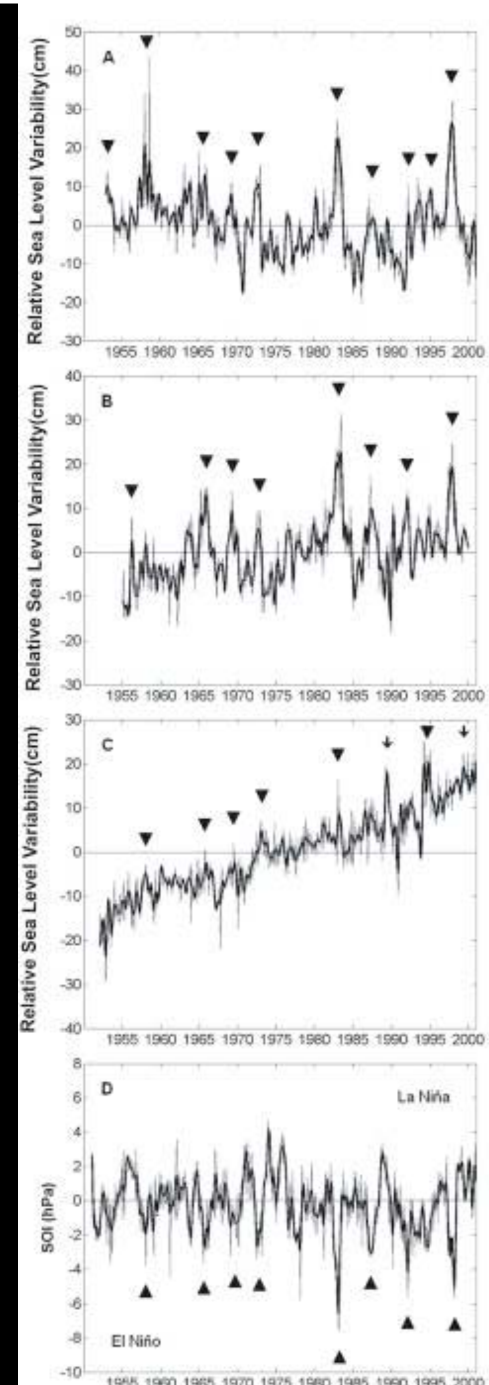
- Angular-shaped subaqueous delta and lower attenuation ratio (A_p)



Relative sea level and relationship with the ENSO cycle

•ENSO raises sea level by 15-25 cm in the Magdalena delta

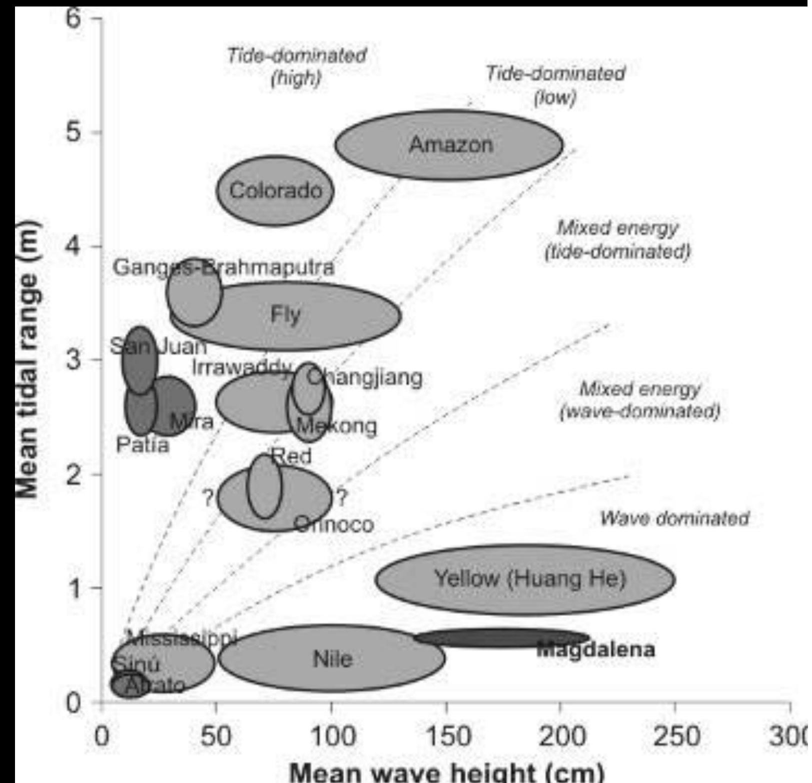




(Restrepo and López, in press. J. of South American Earth Sciences)

Delta classification and morphodynamic indicators

- Quantitative relationship between mean wave height and mean tidal range shows that the Magdalena is the most wave influenced Colombian delta.
- Increasing trend in relative sea level of 5.98 mm yr^{-1}.
- High marine power index.
- Highest river power index (P_r = 0.79).
- Highest maximum monthly wave height of all Colombian deltas (W_a = 2.70 m).



Delta	A_D (km^2)	D_{grd} ($\times10^{-5}$ m m^{-1})	C_N (-)	D_W (km)	C_W (m)	R_W (m)	Sw (km)	L_C (km)	T_i (m)	W_a (m)	P_r	P_m	Q_s:P_m	P_m:P_r	S_L (mm yr^{-1})	S_{LA} (cm)
Pacific coast																
Mira	443	4.85	5	34	617	400	11.4	50	3.0	0.36	0.35	9.13	0.0008	26.09	-1.14	28-32
	820	15.48	6	57	1500	600	10.0	62	3.0	0.24	0.25	9.06	0.074	36.24		
San Juan	800	13.79	5	40	2240	400	6.7	51	3.4	0.23	0.69	11.60	0.045	16.81	2.26	27-33
Caribbean coast																
Atrato	672	4.87	7	42	117	500		112	0.24	0.17	0.15	0.09	5.10	0.60		
Sinu	26	20.40	3	11	267	120		17	0.28	0.12	0.12	0.09	1.48	0.75		
Magdalena	**1690**	**7.66**	**3**	**67**	**510**	**600**	**2.0**	**77**	**0.64**	**2.70**	**0.79**	**7.86**	**8.02**	**9.95**	**5.98**	**15-25**

(Restrepo and López, in press. J. of South American Earth Sciences)

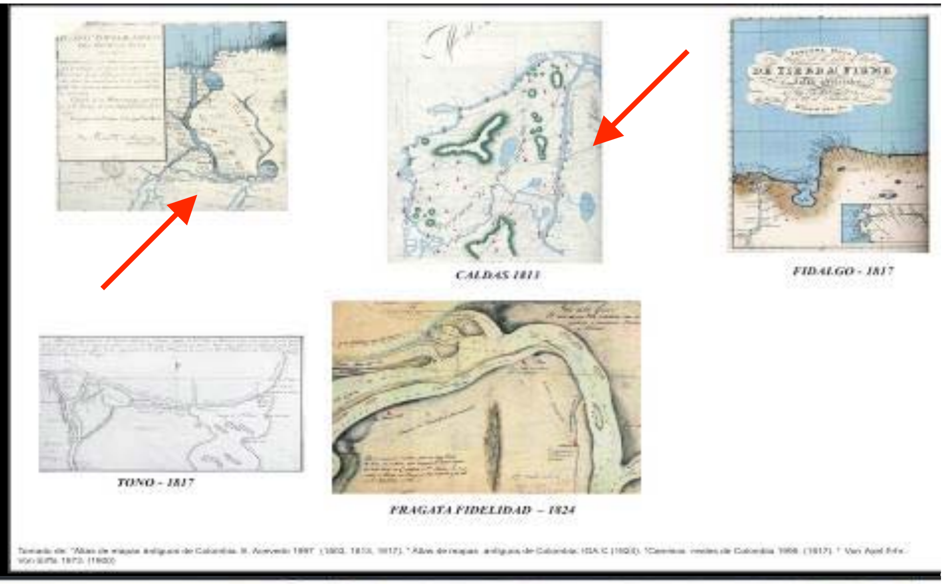
Shoreline changes 1936-2002

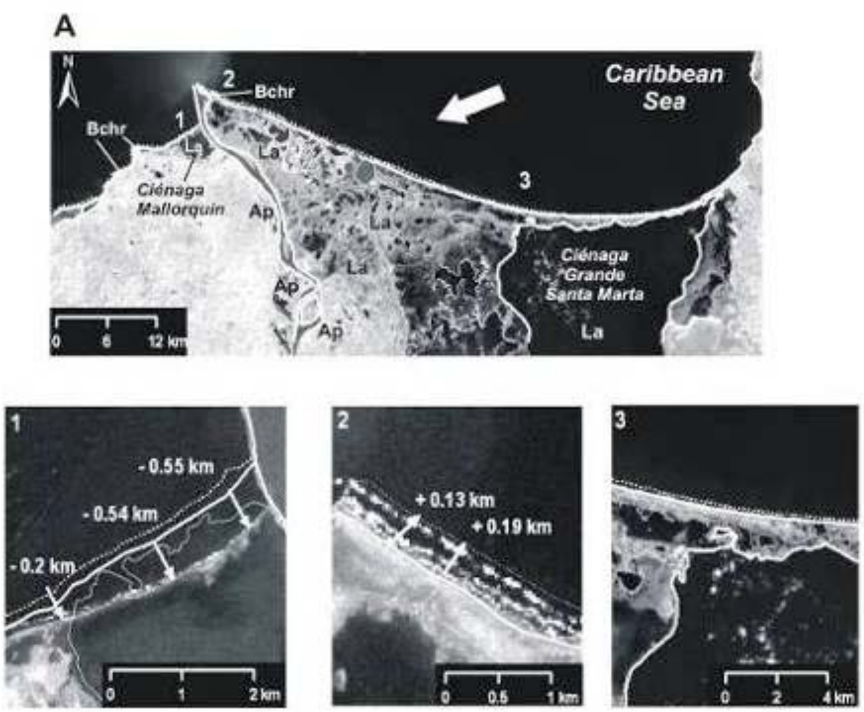
- Levees constructed in 1900's have confined the fluvial sediment to the river channel and delivered the Qs offshore rather than deposition in the delta shoreline.

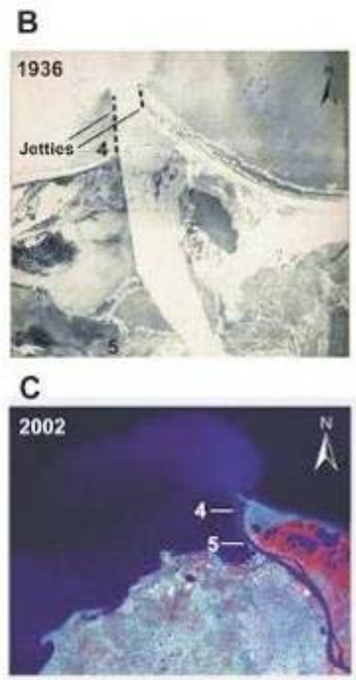
- Net estimate of beach erosion on the western part of the delta for the 1936-2002 yr period is 1,500 m.

- Further analysis indicate a coastal retreat of 55 m yr^{-1} in the western part for the 1989-2000 yr period.

- The number of distributary channels have decreased.





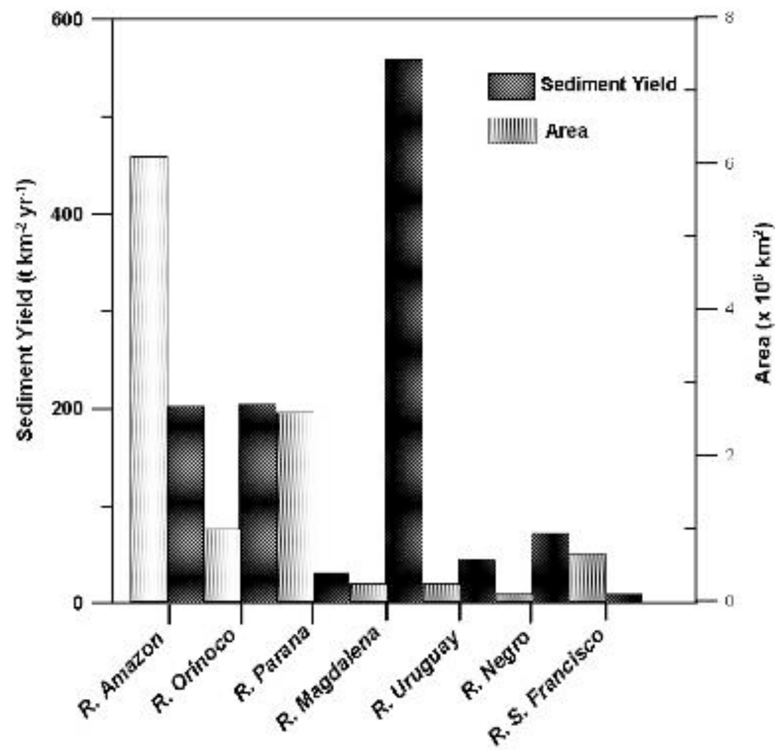


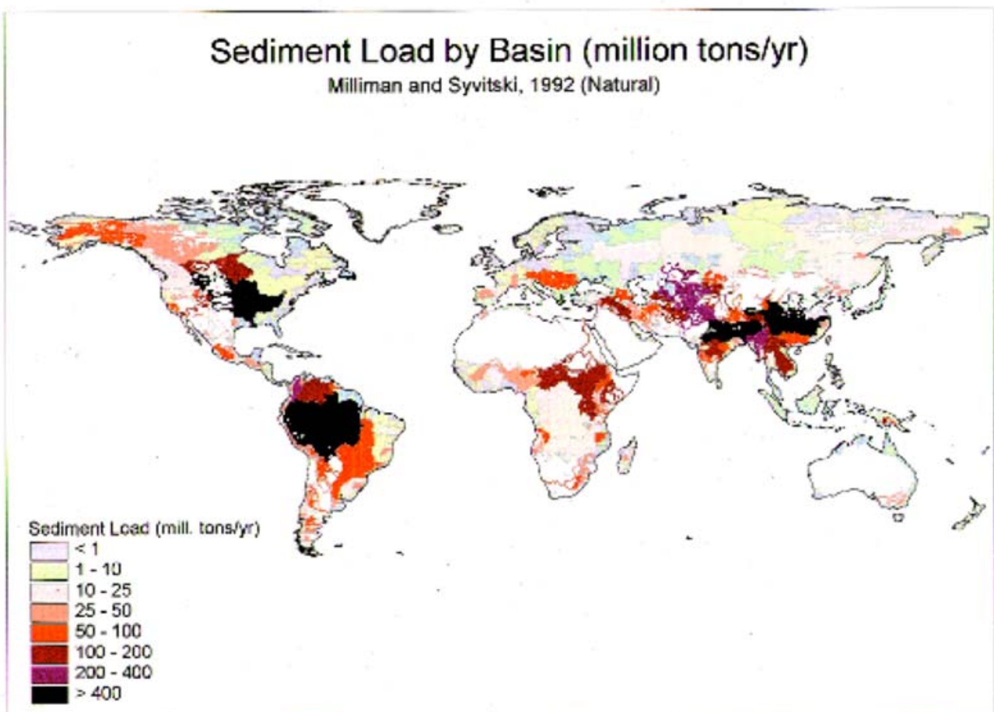
(Restrepo, in press. Estuarine, Coastal and Shelf Science)

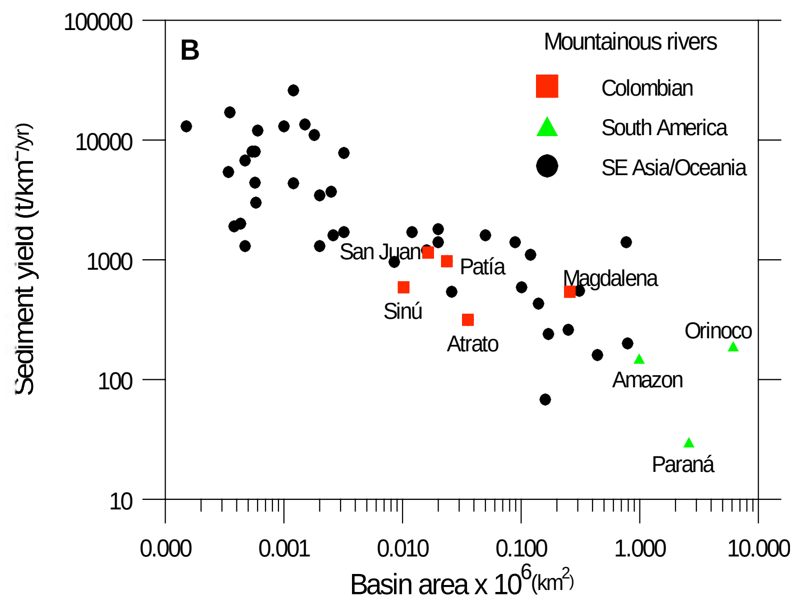
The Magdalena River and the global context

(Restrepo and Kjerfve, 2004)

- World-class river (~150 MT yr^{-1})
- The most significant contributor to the Caribbean Sea
- Largest sediment yield on the SA Atlantic seaboard (560 t km^{-2} yr^{-1})







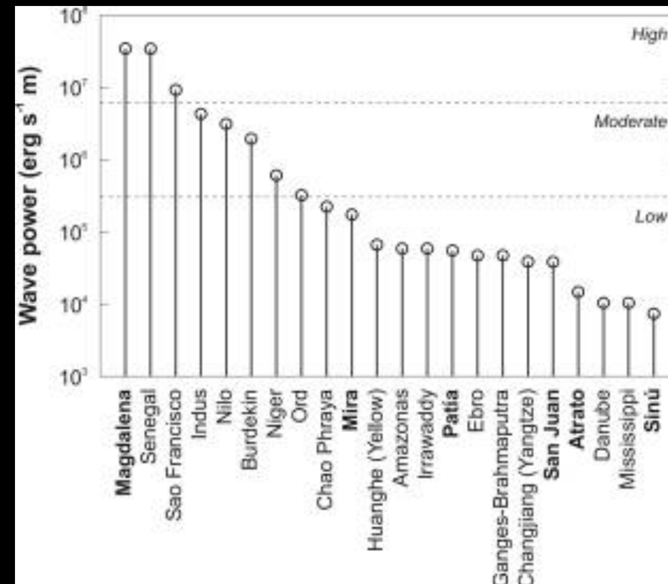
Data base: Magdalena and the global context

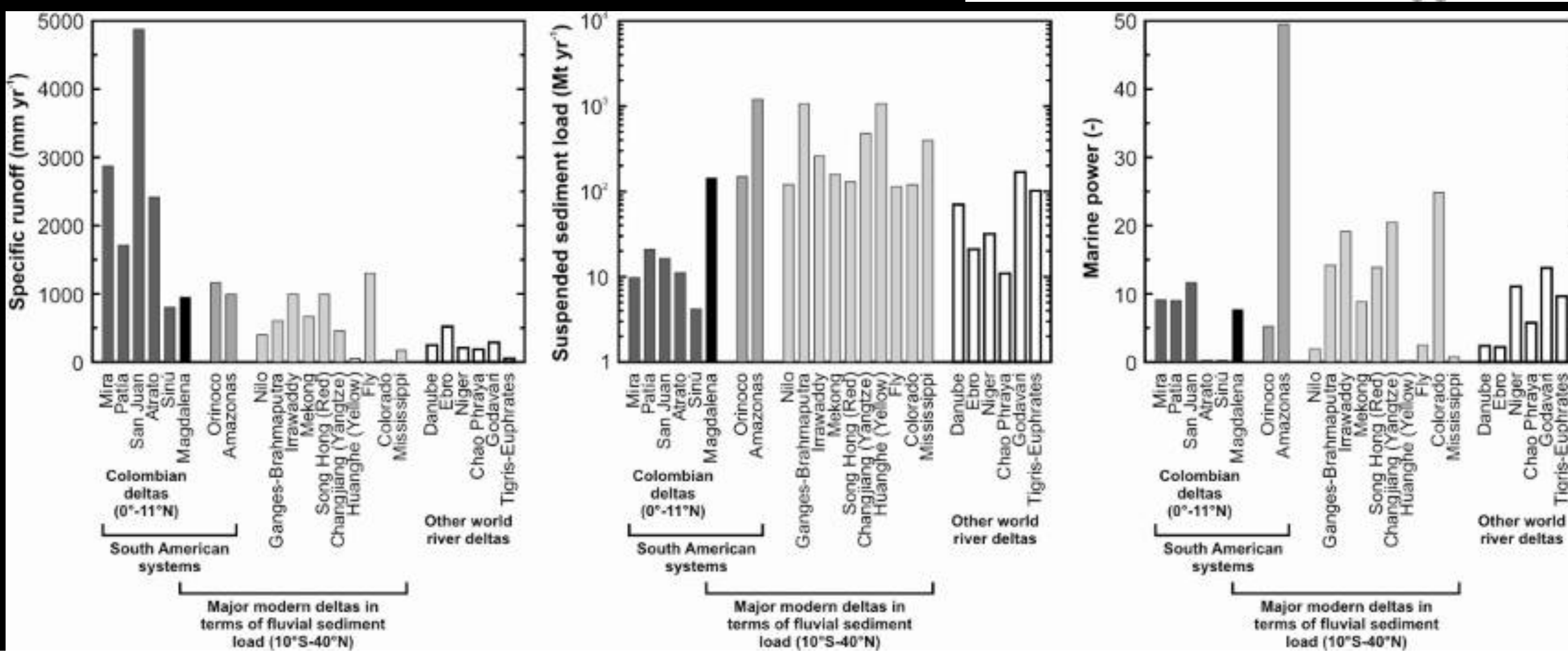
•Magdalena delta in the top 10 in terms of wave energy.

•Colombian rivers have large rates of specific runoff.

•Qs of the Magdalena River is of the same magnitude as the larger Orinoco and comparable to major modern deltas in terms of Qs.

•Excluding the Amazon, Colombian deltas have the highest marine power index compared to South American deltas.





Further comments

More and more deltas are moving away from their pre-Anthropocene morphology, as influenced by pristine sediment supply and sediment dispersal (Syvitski and Saito, 2007), and few systems can be studied under their natural settings (Ericson et al., 2006). Some Colombian deltas provide distinct examples as they are some of the few deltas worldwide exhibiting pristine characteristics and formed under the occurrence of high energetic and destructive conditions.

Questions

- **Since there are clear clusters of many global rivers in terms of Q and Qs variability due to climatic, geologic and lithologic conditions within drainage basins (e.g. Latrubesse, 2005), could the global database be grouped in different hydrologic-morphoclimatic zones?**

- **What would be the environmental variables controlling delta morphology for each morphoclimatic class?**

- **Include sea level anomalies related to ENSO or other oceanographic anomalies as a morphodynamic indicator?**

- **Many deltas in developing countries lack information of local relative sea level. What could be the best way to assess sea level change in these systems (interpolation, LOICZ typology, other databases?)**

- **Include wave power and attenuation index in the global database as one of the predictors of delta morphoilogy?**