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THE EFFECTS OF GEOMORPHIC CONTROLS ON SEDIMENT YIELD IN THE ANDEAN RIVERS OF COLOMBIA

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Abstract: This paper examines sediment yield rates and its response to control variables in the principal rivers of Colombian draining into the Caribbean and Pacific coasts. Based on a multi-year dataset of sediment load from six rivers, including Mira, Patía, and San Juan on the Pacific margin, and Magdalena, Atrato, and Sinú, on the Caribbean basin, various morphometric, hydrologic, and climatic variables were estimated in order to understand and predict the variation in sediment yield. A multiple regression model, including two control variables, runoff and relief ratio (the ratio of the maximum height of the drainage basin and the basin length), explains 83% of the variance in sediment yield. This model is efficient (ME = 0.93) and is a valuable tool for predicting total sediment yield from Colombian rivers. These two selected estimators refer to the relative importance of the fluvial transport component in the sediment routing system. Thus, regional-scale variance of sediment yield in the Andean basins of Colombia seems to be explained by the combined influence of tectonics (relief) and surface runoff available for weathering and transport processes. In general, high sediment yielded rivers are high runoff systems with narrow alluvial plains (i.e. Pacific rivers), while low sediment yielded rivers like the Caribbean systems, contain large sections with not significant gradient in their longitudinal profiles. These sections coincide with large floodplains, which all provide sediment storage capacity within the catchments. When considering the three gauged Pacific rivers at their furthest downstream stations, the combined annual sediment load from these rivers into the Pacific Ocean is ~40 Mt yr^{-1}. In contrast, the Magdalena, Atrato and Sinu rivers deliver ~173 Mt yr^{-1} into the Caribbean. Overall, Andean rivers of Colombia exhibit the highest sediment yields of all medium-large sized rivers of South America due to the interplay of (1) high rates of runoff (1,750-7,300 mm yr^{-1}), (2) steep relief within catchments, (3) low values of discharge variability (Q_{max}-Q_{min}), and (4) episodic sediment delivery due to either geologic events or climatic anomalies.

Resumen: En este estudio se analizan los factores físicos que controlan la producción de sedimentos de los principales ríos andinos de Colombia que drenan hacia las costas Pacífica y Caribe. Con base en datos multi-anuales de caudal y transporte de sedimentos en suspensión en las estaciones de aforo aguas debajo de los ríos San Juan, Patía y Mira, en la margen Pacífica, y Atrato, Sinú y Magdalena, en la cuenca Caribe, además del cálculo de variables hidrológicas, climáticas y morfométricas en cada cuenca de drenaje, se realizaron análisis de regresión potencial y multivariada. Los resultados indican que la escorrentía y el coeficiente de relieve (cociente entre la altura máxima y la longitud total

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de la cuenca), explican el 83% de la variabilidad regional en la producción de sedimentos. El modelo multivariado compuesto por estos dos estimadores es estadísticamente significativo al 95% de confiabilidad y presenta una eficiencia ME = 0,93. Por lo tanto, la varianza regional en la producción de sedimentos de los principales ríos andinos colombianos parece ser explicada por la interacción entre las condiciones tectónicas (relieve) y la cantidad de escorrentía disponible para los procesos del lavado de suelos y del transporte de sedimentos. En general, los ríos con altas tasas de producción (cuenca Pacífica) son sistemas caracterizados por altos valores de escorrentía y estrechos planos fluviales de inundación. En contraste, los ríos de la margen Caribe, con menores valores de producción de sedimentos, son ríos que tienen gran parte de su perfil topográfico sin gradientes significativos. Estas áreas coinciden con amplios planos de inundación para la captación de sedimentos. Al evaluar las descargas totales de sedimentos, los tres principales ríos de la margen Pacífica aportan al océano un total de ~40 Mt año^{-1}. Los ríos del Caribe, incluyendo Magdalena, Atrato y Sinú, aportan al Mar Caribe ~173 Mt año^{-1}. En conclusión, los ríos andinos de Colombia presentan las tasas más altas de producción de sedimentos de todos los ríos suramericanos que drenan hacia las márgenes Atlántica y Pacífica debido a la interacción de (1) altos niveles de escorrentía (1,750-7,300 mm año^{-1}), (2) relieves pronunciados y reducidos planos de inundación en las cuencas de drenaje, (3) bajos valores de variabilidad de descarga (Q_{max}-Q_{min}) y (4) altos aportes de sedimentos durante eventos geológicos de alta energía y anomalías climáticas.

Keywords: sediment yield, runoff, relief, Andes, Colombia.
Palabras clave: producción de sedimentos, escorrentía, relieve, Andes, Colombia.

INTRODUCTION

Sediment yield (or sediment production) is the sediment load normalized for the drainage area and is the net result of erosion and deposition processes within a basin. Thus, it is controlled by those factors that control erosion and sediment delivery, including local topography, soil properties, climate, vegetation cover, catchment morphology, drainage network characteristics, and land use (Walling, 1994; Hovius, 1998). Knowledge of sediment yield and the factors controlling it provides useful information for quantitative models of landscape evolution and geochemical and sediment mass balance studies, and for estimating net erosion intensities within river basins (Pinet and Souriau, 1988; Summerfield and Hulton, 1994; Walling, 1994; Harrison, 2000). Measurements of sediment yield are also key elements for understanding the impacts of past land-use or climate changes (e.g. Dearing, 1992; Walling, 1997; Verstraeten and Poesen, 2001).

Previous studies have attempted to explain the global pattern of sediment yield in terms of climatic factors (Langbein and Schumm, 1958; Fournier, 1960; Douglas, 1967, 1973; Wilson, 1973; Ohmori, 1983; Walling and Webb, 1983), the role of relief and elevation of drainage basins (Ahnert, 1970; Pinet and Souriau, 1988; Milliman and Syvitski, 1992; Summerfield and Hulton, 1994), vegetation as controlled by climate (Douglas, 1967; Jansen and Painter, 1974), and land use (e.g. Trimble, 1975; Dunne, 1979; Verstraeten and Poesen, 2001; Molina *et al.*, 2008). Other investigations have tried to explain sediment yield in terms of the combined effect of morphometric, climatic, and hydrologic variables of drainage basins. These relations have often been presented as single or multiple regression models (e.g. Pinet and Souriau, 1988; Summerfield and Hulton, 1994; Hovius, 1998; Ludwig and Probst, 1998; Harrison, 2000; Aalto *et al.*, 2006).

The Andes is a tectonically active region characterized by active volcanism, ongoing uplift, earthquakes (Fig. 1), and high magnitude mass movements (Vanacker *et al.*, 2003; Harden, 2006; Molina *et al.*, 2008). Uplift has caused rivers to incise and denudation rates to be high. In this region of steep slopes, mass movements are triggered by wet conditions and by earthquakes (Aalto *et al.*, 2006; Harden, 2006). Thus, tropical catchments located in the cordilleras of the Andes are highly susceptible to soil erosion due to their topography and erosive climate, and the occurrence of extreme geologic

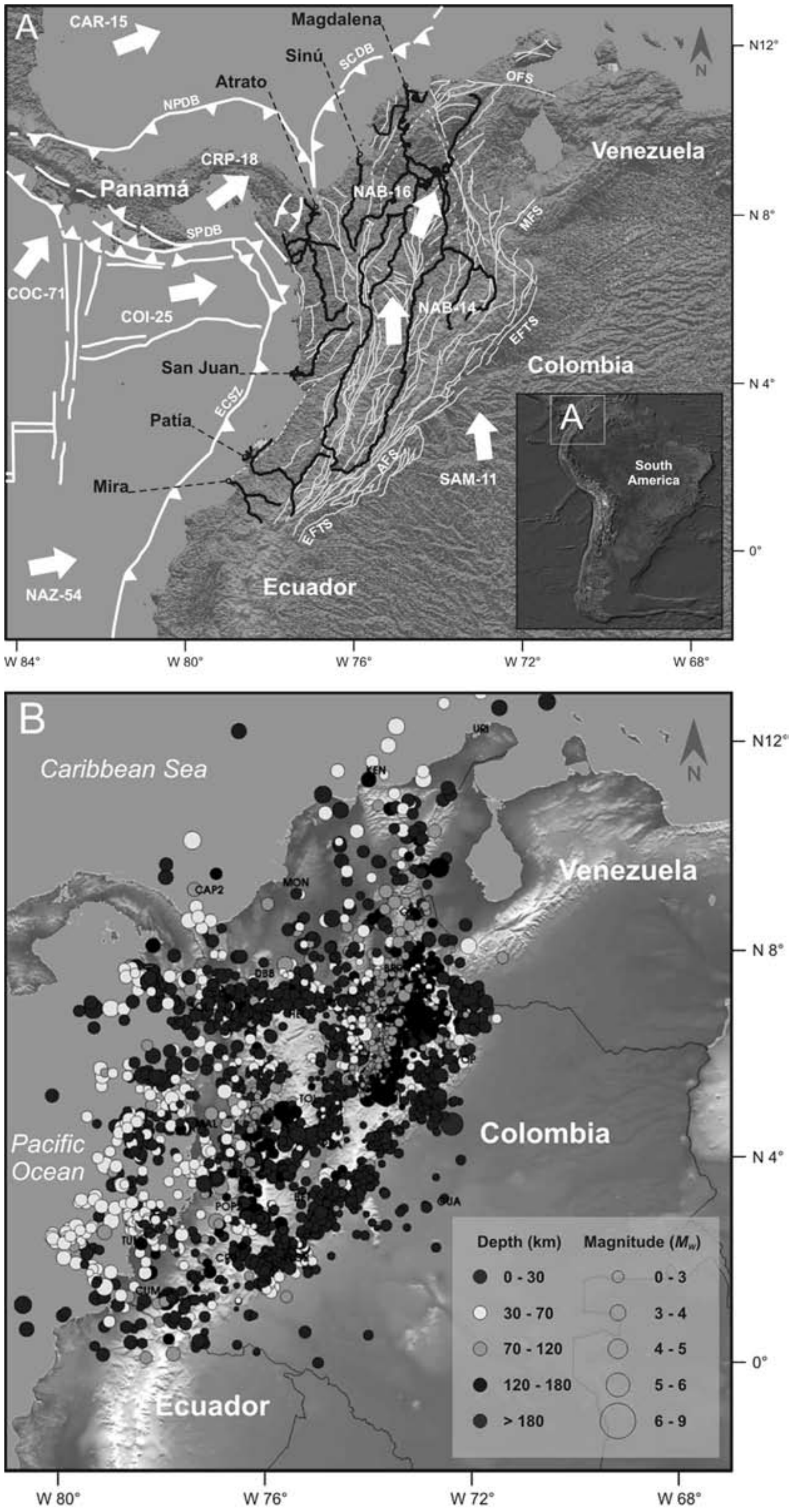

Figure 1. a) Regional tectonic features and major neotectonic structures of the northern Andes, showing the main Andean rivers of Colombia draining into the Pacific and Caribbean coasts. Arrows denote relative motion of tectonic plates (mm yr^{-1}): Caribbean (CAR), Cocos (COC), Nazca (NAZ), South American (SAM), Costa Rica - Panama (CRP) and Coiba (CO). Major structural blocks and fault systems are also shown, including: North Andean Block (NAB), East Frontal Thrusts (EFTS), Algeciras (AFS), Maracaibo (MFS), Oca (OFS). Other features include Ecuador - Colombia Suture Zone (ECSZ), North Panama Deformed Belt (NPDB), South Caribbean Deformed Belt (SCDB), and South Panama Deformed Belt (SPDB) (Modified from Gómez *et al.*, 2008). b) Location and magnitude of earthquakes that occurred in Colombia between 1993 and 2008. Codes indicate the location of seismic sensors (Courtesy of the Colombian Seismological Network, INGEOMINAS).

events (Hess, 1990; Milliman and Syvitski, 1992; Wunder, 1996; Dadson *et al.*, 2003).

Studies analyzing physical and anthropogenic controls on sediment yield at the scale of small-medium sized Andean catchments (101-103 km^2), have shown that sediment yield is controlled by (1) slope movement on hillslopes (Vanacker *et al.*, 2003), vegetation cover and lithology in the Ecuadorian basins (Molina *et al.*, 2008), (2) lithology, catchment slope, climate (Aalto *et al.*, 2006), and landsliding (Safran *et al.*, 2005) in the Bolivian Andes and (3) runoff and maximum water discharge in the

Magdalena drainage basin (Restrepo and Syvitski, 2006). However, there are no studies analyzing on a preliminary basis the environmental factors controlling regional variations in sediment yield in the main Andean rivers of Colombia. It has been already demonstrated that the Colombian Pacific and Caribbean rivers (Fig. 1) are important rivers on a worldwide basis due to (1) their contribution of sediment fluxes for the global budgets (Milliman and Meade 1983; Milliman and Syvitski 1992; Restrepo and Kjerfve 2000a,b), (2) their high sediment yields, the largest for the Atlantic and Pacific coasts of South America (Restrepo and Kjerfve, 2000a), (3) their high spatial variability of geologic, climatic and anthropogenic factors within drainage basins (Restrepo and Syvitski, 2006), and (4) the occurrence of extreme episodic geologic and climate events that are important in delivering sediment to the coastal ocean (Restrepo and Kjerfve, 2000b; Restrepo and López, 2008).

This paper aims to synthesize and update the status of the main Andean rivers of Colombia draining into the Pacific and Caribbean margins (Fig. 1) with respect to sediment yield. It provides the first attempt to analyze the main physical variables explaining most of the spatial variation in observed sediment yields in the Colombian Andes. This synthesis, which is based on previous results presented by Restrepo and Kjerfve (2000a,b), Restrepo (2005), Restrepo *et al.* (2006) and Restrepo and Syvitski (2006), shows new analysis and discussions in terms of: (1) analysis of environmental factors controlling sediment yield on a regional scale; (2) discharge variability and comparisons to other tropical rivers; (3) sediment load trapping by floodplains; and (4) further comparisons to other systems in South America and elsewhere. This information is a significant addition to the understanding of (1) The denudation of the continents and the transfer of sediments to new depositional environments; (2) The spatial variability of sediment yield through rivers, which provides the information for better management decisions; (3) Fluvial fluxes to oceans and the context of Colombian rivers in the global budgets; (4) The functioning of coastal ecosystems and the evolution of deltas and other coastal landforms; and (5) Future scenarios of sediment flux under different conditions of climate change and human perturbations (Syvitski *et al.*, 2003; Morehead *et al.*, 2003, Syvitski and Milliman, 2007).

DATA AND ANALYSIS

Monthly water discharge and sediment load data were obtained from the Hydrological Institute of Colombia-IDEAM for the most downstream station at each river (IDEAM, 2003) (Fig. 1), or from various studies (Restrepo and Kjerfve, 2000a,b; Restrepo *et al.*, 2002; Latrubesse *et al.*, 2005; Restrepo, 2005).

Morphometric and climatic variables for the analyzed catchments (Table 1) were obtained by using an ARCINFO® database (IDEAM, 2001) and a GIS software, HidroSig Java® (version 1.8) (HIDROSIG, 2001), which includes all existing hydrological and meteorological databases of Colombia. An available 30 arc second Digital Elevation Model (DEM) with a resolution of 1 x 1 km, supplemented by 1:1,000,000 maps (IDEAM, 2001), was used in HidroSig Java® to calculate morphometric variables such as watershed boundaries, area, river length, indices of slope, maximum elevation, relief ratio, topographic profiles, and also climatic parameters, including mean and maximum annual precipitation and precipitation ratios. Definition and derivation of hydrologic, morphometric, and climatic controlling variables used in correlation and multivariate analysis were obtained from Summerfield and Hulton (1994), Hovius (1998), and Harrison (2000).

To obtain predictive relationships and examine which environmental factors control sediment yield, series of correlation calculations were done using the database from the six rivers (Table 1). Both single and multiple correlations were performed. Pearson correlation coefficients were calculated for some variable pairings for catchment properties and for the neperian logarithm of delta variables. To analyze if a significant component of the regional variation of sediment yield can be explained by a combination of several controls, a step-wise regression was implemented on data listed in Table 1. This multivariate regression approach has been used to analyze global and regional variations in sediment yield, where individual catchments are represented by a single sediment yield value (e.g. Hovius, 1998; Ludwig and Probst, 1998; Harrison, 2000). Here we examine a set of estimator variables, select those that are most efficient at explaining the variance in a response variable, and build them into a model. The predictive efficiency of the regression model was evaluated based on the Root Mean Square Error (RMSE) and the adjusted R-square. In order to compare Colombian rivers with South American and major fluvial systems, we used databases of river properties from Milliman and Syvitski (1992), Ludwig and Probst (1998), Latrubesse *et al.*, (2005), and Syvitski (2005).

RESULTS AND DISCUSSION

Fluvial Fluxes and Sediment Yield

The Pacific Rivers. In general, the drainage basins on the eastern side of South America are large, whereas the numerous basins with discharge into the Pacific are comparatively small because of the crowding of the drainage basins west of the Andes imposed by regional geology and tectonics.

The basins of the Pacific coast of Colombia, measuring 76,365 km^2 and extending from latitude 00°36’ N to latitude 07°45’ N and from longitude 75°51’ W to longitude 79°02’ W, are characterized by the presence of active fault systems (Fig. 1), high precipitation rates, slopes frequently steeper than 35°, and dense tropical rain forests. These conditions are favorable for the occurrence of rapid mass wasting, caused by slope erosion processes and thus high sediment loads. The basins extend inland 60-150 km and comprise all of Colombia west of the Cordillera Occidental of the Andes, linking Panama and Ecuador. They consist of a broad coastal plain and the western slopes of the Cordilleras. The

Table 1. Summary list of some analyzed environmental variables of major Andean rivers draining into the Pacific and Caribbean coasts of Colombia. River length (L), drainage basin area (A), maximum elevation (H), relief ratio (H_r), average annual precipitation (P), maximum monthly precipitation (P_{max}), precipitation peakedness (P_{pk}), runoff (Δf), runoff coefficient ($\Delta f/P$), mean annual temperature (T), mean annual water discharge (Q_{av}), monthly maximum water discharge (Q_{max}), monthly minimum water discharge (Q_{min}), water discharge peak (Q_{pk}), suspended sediment load (Q_s), and basin wide sediment yield (Y). The location of each river is shown in figure 1. Definition and derivation of hydrologic, morphometric, and climatic controlling variables used in correlation and multivariate analysis were obtained from Summerfield and Hulton (1994), Hovius (1998) and Harrison (2000).

[a] Sediment load estimates were obtained from the regression equation of annual suspended sediment load on basin area for orogenic continental rivers of South America and Asia with precipitation rates higher than 700 mm yr^{-1} (Latrubesse *et al.*, 2005).

Fluvial System	L (km)	A (km^2)	H (m)	H_r (m km^{-1})	P (mm yr^{-1})	P_{max} (mm yr^{-1})	P_{pk} (-)	Δf (mm yr^{-1})	$\Delta f/P$ (-)	T (°C)	Q_{av} (m^3 s^{-1})	Q_{max} (m^3 s^{-1})	Q_{min} (m^3 s^{-1})	Q_{pk} (-)	Q_{max} / Q_{av} (-)	Q_{max} / Q_{min} (-)	Q_s (Mt yr^{-1})	Y (t km^{-2} yr^{-1})
Pacific margin																		
Mira	317	9530	4939	15.61	4703	545	6.98	2872	0.61	24.3	868	3270	402	0.27	2.75	8.13	9.7[a]	1018[a]
Patía	415	23700	4580	11.32	3296	474	5.47	1718	0.52	24.1	1291	3082	382	0.42	2.38	8.07	21.1	972
San Juan	352	16470	3900	11.06	7277	790	9.21	4884	0.67	23.1	2550	5000	1802	0.51	1.96	2.77	16.4	1150
Caribbean margin																		
Atrato	700	35700	3150	4.20	4944	862	5.73	2420[b]	0.49	24.7	2740	3060	1694	0.90	1.12	1.81	25[a]	700[a]
Sinú	300	14700	3350	11.16	1750	211	8.29	800	0.46	28.1	373	586	244	0.64	1.47	2.40	4.2	589
Magdalena	1540	257440	3300	2.39	2050	343	5.97	886	0.43	23.7	7232	10287	4068	0.70	1.52	2.53	144	560

principal rivers from north to south are the San Juan, Patía, and Mira (Fig. 1).

The extreme climatic conditions along the Pacific basins of Colombia are responsible for the high water discharge into the Pacific. The largest is the San Juan with a mean discharge of 2,550 m^3 s^{-1}. The Patía has a mean river basin discharge of 1,291 m^3 s^{-1}, and the Mira River contributes an average 868 m^3 s^{-1}. Table 1 shows the main climatic and morphologic characteristics, and water discharge and sediment load for the largest Pacific and Caribbean rivers.

Sediment flux to the coastal ocean is conditioned by geomorphic and tectonic influences (basin area and relief), geography (temperature, runoff), geology (lithology, ice cover), and human activities (reservoir trapping, soil erosion) (e.g. Milliman and Syvitski, 1992; Syvitski and Milliman, 2007). On a global basis, the warm temperate region has the highest sediment yield of all the climate zones and accounts for nearly 2/3 of the global sediment delivery. Also, river basins draining high mountains (>3,000 m) contribute 60% of the global sediment flux to the coastal zone (Syvitski *et al.*, 2005a,b).

The Pacific basins are characterized by small rivers with high sediment yield (Table 1). The San Juan occupies a 16,465 km^2 basin with the highest mean sediment load (16 Mt yr^{-1}) and basin-wide sediment yield (1,150 t km^{-2} yr^{-1}) on the entire west coast of South America (Restrepo and Kjerfve, 2000a). The Patía River, with a drainage area of 23,700 km^2, has a sediment load and basin-wide sediment yield of 14 Mt yr^{-1} and 972 t km^{-2} yr^{-1}, respectively. Based on daily measurements from 1,982 to 2,000 by IDEAM at Pipiguay, which only covers 4% of the upstream basin, the upper portion of Mira River has an annual sediment load of 213,160 t yr^{-1} and a sediment yield of 507 t km^{-2} yr^{-1}. This sediment yield is much lower than the yield of 856 t km^{-2} yr^{-1} estimated by Restrepo and Kjerfve (2000a), which only included 10 years of data 1982-1992. To remedy this, sediment load for the Mira River catchment was estimated from the regression of sediment load on basin area for tropical rivers with precipitation rates higher than 700 mm yr^{-1} (Latrubesse *et al.*, 2005). The best estimate for the total sediment load into the Pacific Ocean from the Mira is 9.7 Mt yr^{-1}. This results in a sediment yield estimate of 1,018 t km^{-2} yr^{-1}, very similar to the yields of 1,150 t km^{-2} yr^{-1} and 972 t km^{-2} yr^{-1} estimated for the San Juan and Patía rivers, respectively. The total measured sediment load into the Pacific from gauged Colombian rivers is ~40 Mt yr^{-1}.

In general, climate determines where tropical weathering occurs, while tectonics increase erosion rates and dictate the composition of erosion products (Stallard, 1988). Catchments with intense tectonic activity usually have high sediment yields (Meade 1988; Milliman and Syvitski 1992), as in the case of San Juan and Patía rivers (Fig. 1). Furthermore, the presence of unstable and cation-rich minerals in the suspended load and bedload of rivers draining the Andean basins suggests that rapid erosion is indeed occurring. Thus, along the slopes of the Pacific basins, high temperatures, humid conditions, and abundant vegetation in these high-rainfall basins promote rapid chemical weathering and high denudation rates (Restrepo and Kjerfve, 2000a).

Besides climate and weathering factors, other processes such as landslides lead to slumps that increase sediment loads. In humid uplands, landslides are the dominant mass-wasting process (Hovius *et al.* 1997, 1998). The Colombian Pacific basins are characterized by the presence of active fault systems, high precipitation rates (reaching as much as 12 m in the Atrato watershed), slopes frequently steeper than 35°, and dense tropical rain forests (Restrepo and Kjerfve, 2000a). According to Hovius *et al.* (1997), these conditions are favorable to the occurrence of rapid mass wasting caused mainly by hillslope erosion processes such as landslides, slumps, and slides.

The Caribbean Rivers. Caribbean Colombia is principally drained by the Magdalena and Sinú Rivers, and also receives the Atrato drainage from west of the Cordilleras (Fig. 1). The drainage basins are characterized by high and moderate rainfall patterns averaging 4,944, 1,750, and 2,050 mm yr^{-1} in the Atrato, Sinú, and Magdalena watersheds, respectively (Table 1). The climate of the region is modulated by the geographical position of the Intertropical Convergence Zone (ITCZ). The seasonality of the position of the ITCZ corresponds to the windy and dry (December-April) and rainy (August-October) seasons. The rest of the year is transitional between these two seasons. In the dry season the ITCZ resides at its southernmost position (0-5°S). At that time the northern trade winds dominate the area (Andrade, 1993). During the rainy season the ITCZ moves over the southwestern Caribbean, decreasing the wind speed of the southerlies there and promoting the highest rate of precipitation anywhere in the western hemisphere (Andrade and Barton, 2000).

The Magdalena River is the largest river system with a length of 1,612 km. The drainage basin area measures 257,438 km^2 and occupies a considerable part of the Colombian Andes. Daily Magdalena water discharge measurements from 1942 to 2002 at Calamar indicate an annual discharge of 7,176 m^3 s^{-1}. Load measurements during the 1975-1998 period yielded an annual sediment load of 144 Mt yr^{-1}. Based on this sediment load value, Restrepo and Kjerfeve (2000b) estimated that the Magdalena River contributes 9% of the total sediment load discharged from the east coast of South America. The current 144 Mt yr^{-1} estimate of sediment load is higher than the 133 Mt yr^{-1} value reported by Marín (1992), but considerably lower than the estimate by Milliman and Meade (1983) of 220 Mt yr^{-1}. This sediment load estimate implies a sediment yield of 560 t km^{-2} yr^{-1} for the Magdalena, which is more realistic than the previously reported values of 1,000 t km^{-2} yr^{-1} (Meybeck 1976, 1988), 900 t km^{-2} yr^{-1} (Milliman and Meade 1983), and 920 t km^{-2} yr^{-1} (Milliman and Syvitski 1992).

Because there is no measurement of sediment load of the Atrato River at its lower course, we estimated sediment flux from the regression of annual suspended sediment load on basin area for orogenic continental rivers of South America and Asia (Latrubesse *et al.*, 2005). The best estimate for the total sediment load into the Caribbean from the Atrato is ~25 Mt yr^{-1}. This results in a more reliable sediment yield estimate of ~700 t km^{-2} yr^{-1}. A previous sediment yield value of 315 t km^{-2} yr^{-1} (Restrepo and Kjerfve, 2000a), which was based on sediment load data from an upstream station covering only 14% of the Atrato catchment, does not reflect the denudation rates present in this humid drainage basin of western Colombia. Finally, the annual discharge and sediment load of the Sinú River are 373 m^3 s^{-1} and 4.2 Mt yr^{-1}, respectively, with a basin-wide sediment yield of 589 t km^{-2} yr^{-1} (Table 1). The total sediment flux into the Caribbean from the three main Andean rivers of Colombia is ~177 Mt yr^{-1}.

Relation between Sediment Yield and Geomorphic Variables

Univariate regression analyses indicate that the control variables explaining most of the variation in observed sediment yield are mean annual runoff (Δf) and to a lesser extent maximum elevation (H). Curvilinear regression of sediment yield on mean annual runoff and maximum elevation yielded a coefficient of determination of 0.79 and 0.40, respectively, both regressions significant at the 95% level (Fig. 2a, b). Thus, at the regional scale, 79% of the observed variance in sediment yield can be explained by runoff. Other estimators such as mean slope, drainage area, mean annual precipitation, and maximum water discharge are not significantly linked to sediment yield.

The relationship between sediment yield and mean annual runoff (Fig. 2a) has been demonstrated in many studies examining global sediment yields. Summerfield and Hulton (1994) showed that for hydrological and climatic variables, only mean annual runoff, and to a lesser extent mean annual precipitation, were strongly associated with denudation rates. Further, the increase of sediment yield for precipitation rates higher than 700 mm yr^{-1} runoff is a feature that has already been described (Langbein and Schumm, 1958; Wilson, 1973; Walling and Webb, 1983; Latrubesse *et al.*, 2005).

According to Syvitski and Milliman (2007), when two basins with similar size, relief, and temperature are compared, the wetter one will be more able to erode and transport sediment downstream. In contrast, drier basins produce less sediment through mechanical and chemical weathering, and more of this sediment load will be stored between the source area and the receiving basin. Similar comparison can be made in the Andean rivers of Colombia. High runoff systems are clearly grouped as high sediment yield rivers while Caribbean systems, that are comparable in drainage area and elevation (i.e. Atrato and Sinú), exhibit much lower yields (Fig. 2a).

According to Milliman and Syvitski (1992), topography and basin area exert the major controls on sediment yield of most rivers, with climate, geology, and land use being second-order influences. They demonstrated a robust correlation between sediment yield and maximum elevation for mountainous rivers in North and South America, Asia, and Oceania, and showed that mountainous rivers have greater loads and yields than do upland rivers, which in turn have higher loads and yields than lowland rivers. Other studies simulating sediment load to the coastal ocean have shown that sediment flux is conditioned by

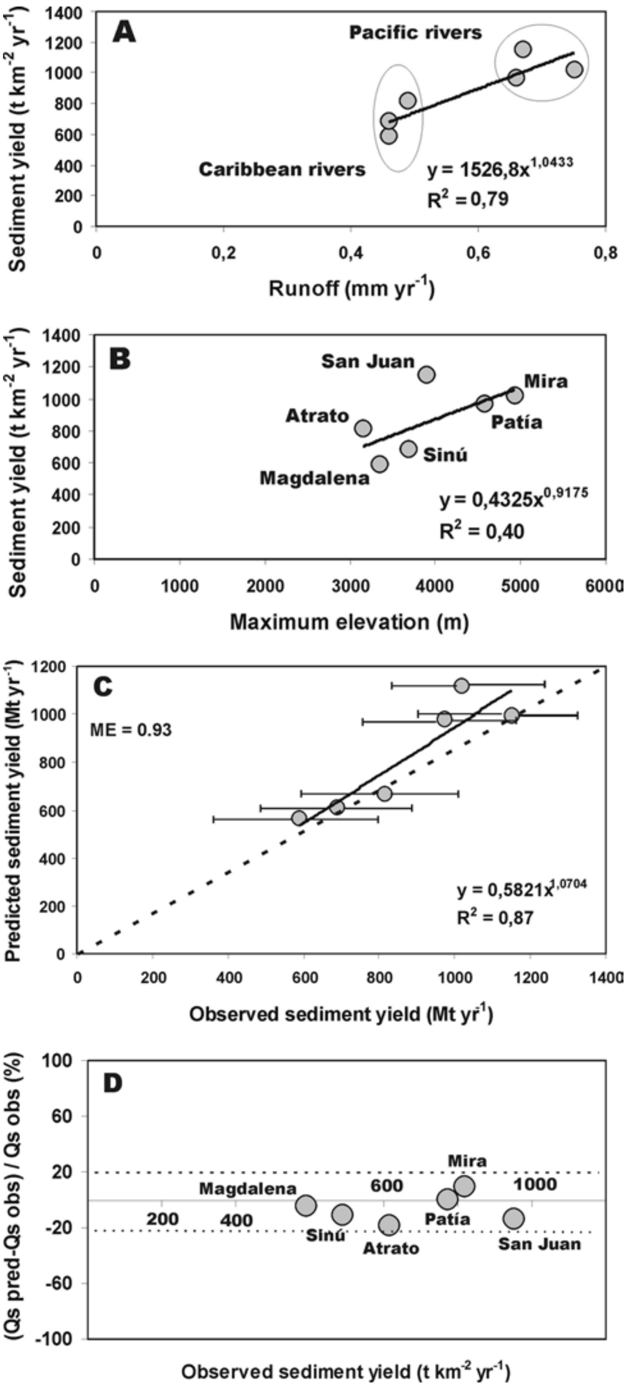

Figure 2. Relation of sediment yield versus mean annual runoff (a) and maximum elevation (b) for the main Andean rivers of Colombia listed in Table 1. c) Model (eq. 1) predictions compared to sediment yield (*Y*) observations from six analyzed Andean rivers within the Pacific and Caribbean basins, showing the model efficiency value (ME). d) Scatter plot of observed Y versus model (eq. 1) performance.

geomorphic and tectonic influences, including basin area and relief (Moulder and Syvitski, 1996; Sytitski *et al.*, 2005a; Syvitski and Milliman, 2007). Our data also indicate that maximum basin elevation shows some degree of association (Fig. 2b). This is probably due to the fact that some of the analyzed rivers have their headwaters at high elevations and others are lowland rivers (Fig. 3). In fact, high sediment yielded rivers which descend rapidly from high Cordilleras to their limited alluvial plains (i.e. Pacific rivers) have tributary basins (70-90% of the drainage area) in elevations higher than 1,000 meters. Low sediment yielded rivers like the Atrato, Magdalena and Sinú (Table 1), are characterized by large sections with a very gradual gradient in their longitudinal profiles. These sections coincide with large wide floodplains, which all provide sediment storage capacity within the catchments (Fig. 3c).

A multiple regression of sediment yield was obtained following the stepwise procedure. The two estimators, which predict sediment yield (*Y*) for the main Andean catchments draining into the Pacific and Caribbean margins, are runoff (Δf) and relief ratio (H_r), such that:

$$Y = 1530.55 + 2643.36 \log (\Delta f) - 70.256 \log (H_r) \quad (1)$$

This multiregression equation accounts for 83% of the total observed variance in sediment yield from these drainage basins. The two independent variables are statistically significant at $\alpha = 0.01$ (Fig. 2c). One of the selected estimators, runoff, refers to the relative importance of the fluvial transport component in the sediment routing system. According to Hovius (1998), specific runoff determines to a certain extent the transport capacity of the fluvial system and may also refer to the amount of water available for hillslope erosion. It is relatively well correlated with mean annual precipitation (P) and maximum monthly precipitation (P_{max}).

Hillslope erosion processes are controlled in part by topographic variables such as mean modal elevation, maximum elevation, relief ratio, and slope angle of the riverbed. The relief ratio and slope angle of the river are possibly more relevant to the fluvial transport of sediment (Hovius, 1998). A high relief ratio corresponds to a more pronounced topography and thus to higher erosion. Similar observations have been reported from catchments in Colorado, USA (Schumm, 1954), for continental scale basins (Summerfield and Hulton, 1994), and in the Magdalena drainage basin (Restrepo and Syvitski, 2006). Thus, the second estimator, relief

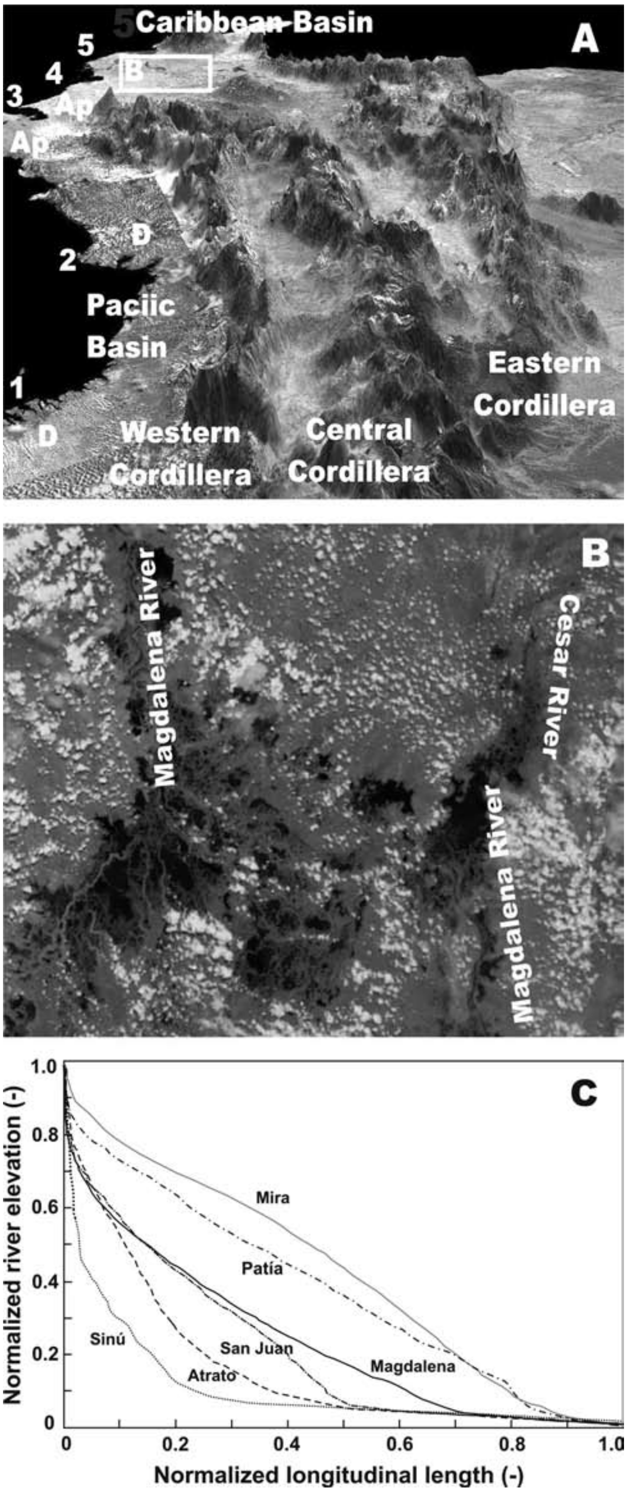

Figure 3. a) Digital elevation model (DEM) of the Andean region of Colombia, showing the Western, Central, and Eastern Cordilleras, the Pacific and Caribbean basins, the floodplains (Ap) within the lower course of the Atrato (3), Sinú (4) and Magdalena (5) rivers. We also show the location of the Patía (1) and San Juan rivers (2) and their deltas (D). b) Near infrared Aqua MODIS satellite image during July 24th, 2008. Black indicates water bodies surrounding the Mompox tectonic depression within the lower course of the Magdalena River. c) Longitudinal river profiles of systems that trap sediment through their extended floodplains (Atrato, Sinú and Magdalena) and rivers along the Pacific basin that have limited alluvial plains and the highest sediment yield.

ratio, represents the potential energy available for soil erosion.

Summerfield and Hulton (1994) noted the strong role of relief and runoff in influencing denudation rates for major basins worldwide. Jansen and Painter (1974) showed that climate and topography were the most important controls on sediment yield from catchments globally, and Restrepo and Syvitski (2006) demonstrated the combined effect of relief and runoff on sediment yield from tributaries within the Magdalena drainage basin. Also, our data show that relief and climate account for a remarkably high amount of explained variance from main Colombian rivers given the fact that only natural variables are included.

Comparison between observed and predicted sediment yield of Andean rivers indicates that the model (eq. 1) replicates successfully the spatial distribution of sediment load and captures for 83% of the between-river spatial variation (Fig. 2c). To validate the model, simulated sediment yield was compared to measured sediment yield for the same model by calculating model efficiency (ME) relationship. ME is 0.93 and the agreement indicates that the model is robust and predicts well sediment yield for the studied rivers in the Pacific and Caribbean basins. When evaluating model performance, sediment yields are well predicted within ~20% bias over one order of magnitude (Fig. 2d).

Comments on Discharge Variability, Runoff, and Floodplains

Rainforest rivers show high but variable peak discharges during the rainy season. Similar to other world rainforest rivers, Andean rivers of Colombia display two annual flood peaks, in agreement with bimodal distribution of rainy periods in summer (main) and fall (secondary). However, when analyzing discharge variability for world tropical rivers in different hydrologic and morphoclimatic zones (Latrubesse *et al.*, 2005), Colombian rivers show the lowest values of Q_{max}/Q_{mean} and Q_{max}/Q_{min} ratios compared to other rainforest rivers (Fig.

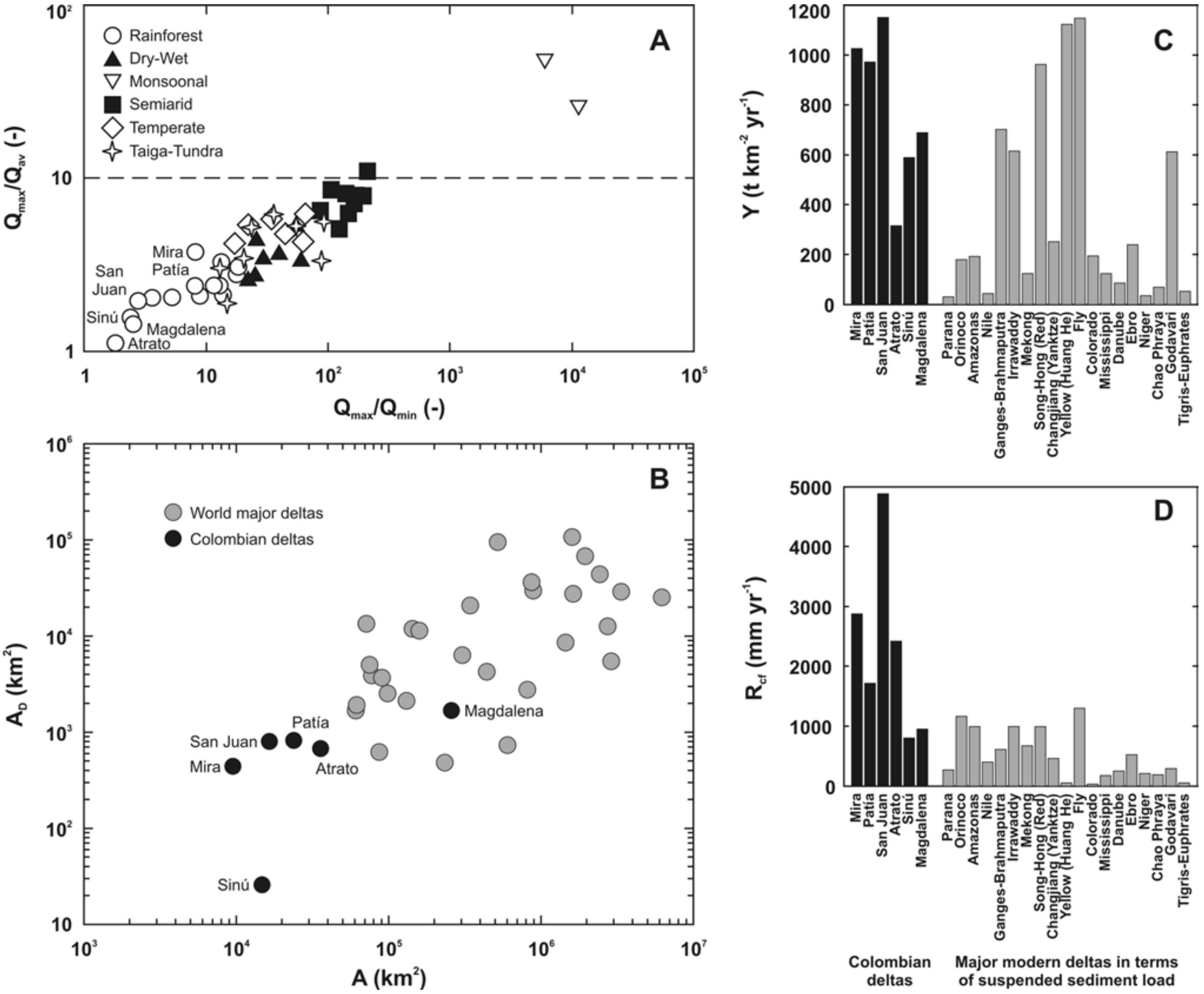

Figure 4. a) Discharge variability for world tropical rivers in different hydrologic and morphoclimatic zones. Colombian rivers show the lowest values of Q_{max}/Q_{mean} and Q_{max}/Q_{min} ratios compared to other rainforest rivers (modified from Latrubesse *et al.*, 2005). (b) Relationship of drainage basin area (km^2) and delta area (km^2) for the major Colombian and global river deltas. Data for the world's major rivers were obtained from Syvitski (2005). Further comparisons between Colombian and major global rivers in terms of sediment yield (c) and runoff (d) are shown. Note that major South American rivers, including Amazon, Orinoco, and Paraná, are also shown. Data from Milliman and Syvitski (1992), Syvitski (2005), Latrubesse *et al.* (2005), and this study.

4a). Thus, Andean Pacific and Caribbean rivers are high runoff systems (Fig. 4d) with low discharge variability and more water available for hillslope erosion and sediment transport.

The Pacific and Caribbean drainage basins are characterized by strong tectonic activity (Fig. 1b), high rates of runoff, low discharge variability, and steep slopes that promote high sediment yields. Even though these rivers drain small basins, with the exception of the Magdalena, this unique combination of geomorphic factors promote high sediment delivery and the construction of extensive deltas under destructive geologic and oceanographic conditions, including (1) high tectonic activity in the receiving basins (Fig. 1b), (2) drainage basin divides close to the ocean (Fig. 3a), (3) narrow continental shelves, (4) moderate to high marine energy conditions, (5) increasing trends in relative sea level, and (6) strong oceanographic manifestations associated with the ENSO cycle, causing sea-level rises during El Niño years (Restrepo and López, 2008). Figure 4b shows the trend between drainage basin area and delta area for the Colombian rivers determined by log– log regression of basin area on delta area. It indicates that Colombian deltas fit the global trend well and are comparable with major world rivers within two orders of magnitude. The small Pacific rivers, including the Atrato, show a clear cluster. Although the Atrato discharges into the Caribbean Sea (Figs. 1, 3), its drainage basin is located west of the Cordilleras and has the same drainage basin characteristics as the San Juan and Patía rivers (e.g., headwaters at high elevations, high rainfall rates, and high tectonic activity).

It is well recognized that natural lakes, wetlands, and floodplains are also of prime importance in predicting river basin delivery (Stallard, 1998; Vörösmarty *et al.*, 2003). Rivers with lower values of sediment yield like the Sinú and Magdalena (Table 1) contain large sections with not significant gradient in their longitudinal profiles. These sections coincide with large floodplains, which all provide sediment storage capacity within the catchments (Fig. 3c). The lower course of the Magdalena River has large floodplains known as the Mompox tectonic depression, a "natural dam" of 6,000 km^2 in which much of the sediment load is stored for long time periods. The Mompox basin concentrates around 80% of the total number of "ciénagas", depressions in the Cretaceous-Tertiary bedrock with stagnant or river-dependent bodies of water that accumulate sediments (Van der Hammen, 1986). Findings of Plazas *et al.* (1988) and Modis images support that this region gets flooded for up to 8-9 months of the year and acts as natural lakes, trapping significant amounts of sediment (Kettner *et al.*, in press) (Fig. 3b). According to Restrepo (2008), 14% of the Magdalena sediment load, approximately 21 Mt yr^{-1}, is trapped in the Mompox tectonic depression basin with a sedimentation rate of 2.0 mm yr^{-1}.

Based on monthly values of sediment load for the Atrato River (1982-1993), Restrepo and Kjerfve (2000a) estimated that the sediment load of the Atrato is 11.3 Mt yr^{-1}, and the corresponding sediment yield 315 t km^{-2} yr^{-1}. As mentioned before, this sediment load is very low and rather uncertain, considering that the Atrato partially drains the western slopes, a region characterized by the presence of active fault systems (Fig. 1), high precipitation rates (reaching as much as 12 m within the Atrato watershed), slopes frequently steeper than 35°, and dense tropical rain forests. Nevertheless, the sediment yield appears to be comparatively low because of the large size of the drainage basin and the extensive low-lying alluvial flood plains (Fig. 3), with an area of 5,500 km^2, where significant sediment deposition and storage occur.

In contrast, high sediment yielded rivers in the Pacific margin (Table 1), contain less sections of low gradient slopes in their longitudinal profiles (i.e. Mira, Patía) (Fig. 3c). Over a distance less than 75 km,

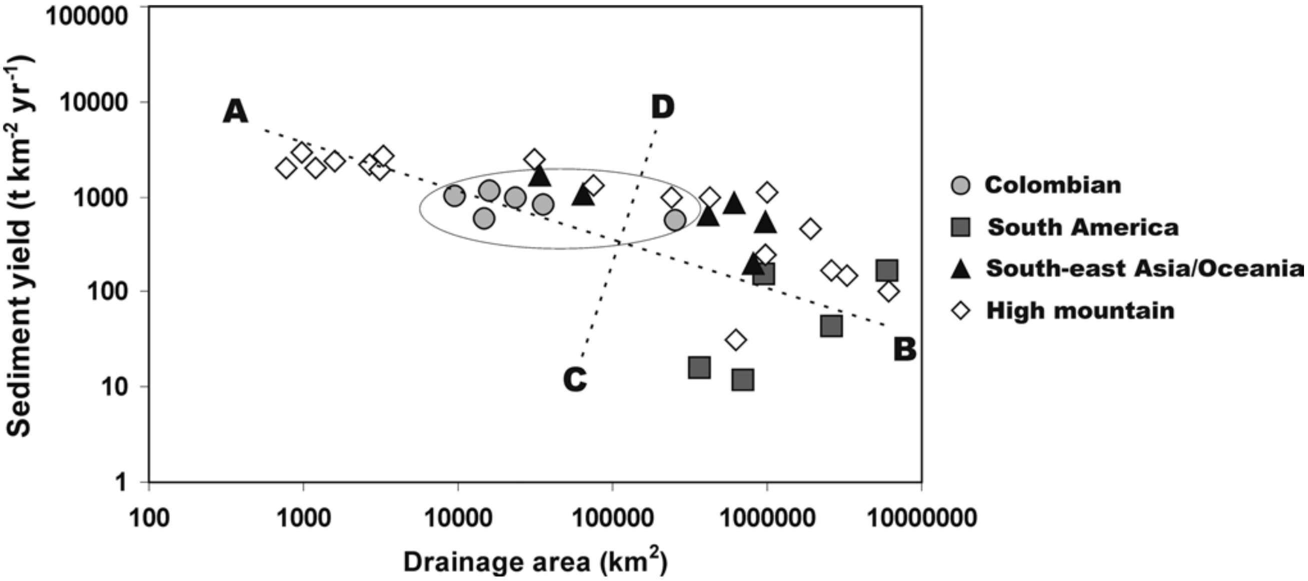

Figure 5. Variation of sediment yield with basin area for major tropical and mountainous rivers of Asia/Oceania, South America (Amazon, Orinoco, Paraná, Negro-Brazil) and Colombian rivers draining into the Caribbean Sea (Magdalena, Sinú, and Atrato) and into de Pacific Ocean (San Juan, Patía and Mira). Line A-B shows the global trend while line C-D indicates the scatter due to local effects caused by morphology, tectonism, rainfall, land use, and other effects. Data from Milliman and Syvitski (1992), Latrubesse *et al.* (2005), and this study.

the San Juan River falls abruptly from an elevation of 3,900 m to 100 meters. Likewise, the Patía descends from its headwaters at 4,580 m elevation to 400 m over a distance of 150 km. Although the San Juan shows large wide floodplains in its topographic profile compared to the lowlands of the Patía and Mira rivers (Fig. 3c), its lower course is highly controlled by Tertiary formations and structural highs. In addition, its flood plain is of limited size, and the bends of the river are frequently in direct contact with bedrock valley walls. Thus, the control exerted by narrow alluvial plains in the Pacific rivers results in less sediment deposition/storage within the drainage basins.

FURTHER COMPARISONS

According to Milliman and Syvitski (1992), basin area and morphology exert the major controls on sediment yield, with climate, geology, and land use being second-order influences. They demonstrated a robust correlation between sediment yield and basin area for mountainous rivers in North and South America, Asia, and Oceania. To illustrate the global trend, we replotted sediment yield on basin area on a log-log plot for several mountainous and tropical rivers of Southeast Asia, Oceania, and South America, using the data of Milliman and Syvitski (1992) and Latrubesse *et al.* (2005) and including our estimates for San Juan, Patía, Mira, Atrato, Magdalena, and Sinú. Figure 5 indicates that the Colombian rivers fit the global trend very well. The scatter reflects local effects caused by morphology, tectonism, rainfall, land use, and other effects.

The Atrato, Sinú, and Magdalena rivers have the highest sediment yield of the medium-large rivers along the Caribbean and Atlantic coasts of South America (Fig. 5). Their yields are almost four times greater than the yield of the Amazon, 167 t km^{-2} yr^{-1}, Orinoco, 158 t km^{-2} yr^{-1} (Latrubesse *et al.*, 2005), or Negro (Argentina), 140 t km^{-2} yr^{-1} (Milliman and Syvitski, 1992), and much greater than the yield of the Paraná, 43 t km^{-2} yr^{-1}, Uruguay, 16,4 t km^{-2} yr^{-1} (Latrubesse *et al.*, 2005), and São Francisco, 10 t km^{-2} yr^{-1} (Milliman and Syvitski, 1992) (Fig. 4c).

In comparing rivers with small basins in high rainfall areas in Colombia and Asia/Oceania, the San Juan, Patía, and Atrato rivers are similar, in terms of water discharge, sediment load, and sediment yields, to the Purari and Fly rivers in Papua New Guinea. Average annual rainfall ranges from 2,000 to 8,500 mm in the 33,670 km^2 catchment of the Purari, which has a mean discharge of 2,360 m^3 s^{-1} (Pickup, 1983). The Fly River has a mean discharge of 4,760 m^3 s^{-1} and a sediment yield of 1,087 t km^{-2} yr^{-1} (Latrubesse *et al.*, 2005). Although the San Juan drains a basin approximately half as large as the basin of the Purari (33,670 km^2) and far smaller than the 64,400 km^2 size of the Fly, it has greater water discharge than the discharge of the Purari and almost the same magnitude as the discharge of the Fly. In addition, the Atrato River is comparable to both the Purari and Fly rivers in terms of water discharge and sediment yield (Table 1).

Milliman and Syvitski (1992) stated that mountainous rivers with basin areas of approximately 10,000 km^2 in southeast Asia/Oceania have sediment yields between 140 and 1,700 t km^{-2} yr^{-1} and have higher yields by a factor of two to three than rivers draining other mountainous areas of the world. Taking the overall yields for the Pacific basins of Colombia to be between ~800 and 1,200 t km^{-2} yr^{-1}, it is apparent that rivers draining steep slopes in the western Andes have yields very similar to rivers draining mountainous terrain and high rainfall areas in South Asia and Oceania (Fig. 5).

The monsoonal influenced Pacific and Caribbean rivers of Colombia appear to have the higher runoff rates of the large world rivers in terms of sediment load (Fig. 4d) as a result of the combined influence of (1) the annual shift of the Inter Tropical Convergent Zone, (2) climatic anomalies due to the El Niño Sothern Oscillation during its positive phase of La Niña, (3) low pressure systems from the Caribbean Sea, (4) orographically driven rainfall within the Andes cordilleras, and (5) cold fronts from the Amazon basin.

Our conclusion is that the Andean rivers of Colombia exhibit the highest sediment yield rates of all medium-large sized rivers of South America due to the interplay of (1) high runoff conditions, (2) steep relief within catchments, (3) low discharge variability, and (4) episodic sediment delivery due to either geologic events or climatic anomalies.

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