

Factors controlling sediment yield in a major South American drainage basin: the Magdalena River, Colombia

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Abstract

The Magdalena River, a major fluvial system draining most of the Colombian Andes, has the highest sediment yield of any medium-sized or large river in South America. We examined sediment yield and its response to control variables in the Magdalena drainage basin based on a multi-year dataset of sediment loads from 32 tributary catchments. Various morphometric, hydrologic, and climatic variables were estimated in order to understand and predict the variation in sediment yield. Sediment yield varies from 128 to 2200 t km⁻² yr⁻¹ for catchments ranging from 320 to 59,600 km². The mean sediment yield for 32 sub-basins within the Magdalena basin is ~690 t km⁻² yr⁻¹. Mean annual runoff is the dominant control and explains 51% of the observed variance in sediment yield. A multiple regression model, including two control variables, runoff and maximum water discharge, explains 58% of the variance. This model is efficient (ME=0.89) and is a valuable tool for predicting total sediment yield from tributary catchments in the Magdalena basin. Multiple correlations for those basins corresponding to the upper Magdalena, middle basin, Eastern Cordillera, and catchment areas greater than 2000 km², explain 75, 77, 89, and 78% of the variance in sediment yield, respectively. Although more variance is explained when dataset are grouped into categories, the models are less efficient (ME<0.72). Within the spatially distributed models, six catchment variables predict sediment yield, including runoff, precipitation, precipitation peakedness, mean elevation, mean water discharge, and relief. These estimators are related to the relative importance of climate and weathering, hillslope erosion, and fluvial transport processes. Time series analysis indicates that significant increases in sediment load have occurred over 68% of the catchment area, while 31% have experienced a decreasing trend in sediment load and thus yield. Land use analysis and increasing sediment load trends indicate that erosion within the catchment has increased over the last 10–20 years.

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1. Introduction

South America measures 17.8×10^6 km² and accounts for the 12% of the global land surface.

However, the continent delivers a disproportionately larger water discharge and suspended sediment load into the oceans as compared to its area. The three largest rivers, the Amazon, the Orinoco, and the Paraná, deliver only 7300 km³ yr⁻¹ of water or 24% of the global runoff (Probst and Tardy, 1989), and with respect to suspended sediment load, northeastern

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South America alone contributes 13% of the global sediment load into the oceans. The Amazon, Orinoco, and Paraná rivers are responsible for most of the water discharge and sediment load from the South American continent (Milliman, 1990; Milliman and Syvitski, 1992), but a relatively smaller system in Colombia, the Magdalena River (Fig. 1), carries a significant share of the sediment load from the continent (Milliman and Meade, 1983).

Restrepo and Kjerfve (2000a,b) have shown that the Magdalena River contributes approximately 9% of the total sediment load discharged from eastern South America and appears to have the highest sediment yield ($560 \text{ t km}^{-2} \text{ yr}^{-1}$) of the large rivers along the Caribbean and Atlantic coasts. It is almost three times greater than the yield of the Amazon, $190 \text{ t km}^{-2} \text{ yr}^{-1}$, Orinoco, $150 \text{ t km}^{-2} \text{ yr}^{-1}$, Negro (Argentina), $140 \text{ t km}^{-2} \text{ yr}^{-1}$ (Milliman and Syvitski, 1992) and is much greater than the yield of the Paraná, $30 \text{ t km}^{-2} \text{ yr}^{-1}$ (Milliman and Syvitski, 1992; Goniadzki, 1999), Uruguay, $45 \text{ t km}^{-2} \text{ yr}^{-1}$, and São Francisco, $10 \text{ t km}^{-2} \text{ yr}^{-1}$ (Milliman and Syvitski, 1992) (Fig. 2).

Sediment yield 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).

In addition, sediment yield studies for small catchments in particular, are very important for studying linkages between soil erosion and suspended sediment transport in large rivers (Verstraeten and Poesen, 2001). 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). Since river fluxes are sensitive indicators of global change either related to climate change or to direct human

impacts on continental aquatic systems, a comprehensive analysis of drainage basin behavior in terms of sediment yield appears warranted from a large global change perspective (Vörösmarty and Meybeck, 2000). Further, sediment yield is a key estimate to understanding relationships between natural variability and the anthropogenic changes having taken place in catchments during the past century, on one hand, and how these factors influence the delivery of water and sediment to receiving basins, on the other.

Scientists 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). 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).

Previously, the three largest river systems draining South America have received most attention, i.e. the Amazon (e.g. Meade et al., 1979; Meade et al., 1985; Richey et al., 1986, 1989, 1991), Orinoco (e.g. Eisma et al., 1978; Paolini and Ittekkot, 1990; Depetris and Paolini, 1991), and Paraná (e.g. Depetris, 1976; Depetris et al., 1996; Depetris and Gaiero, 1998; Goniadzki, 1999). These studies focus on estimates of water discharge, suspended sediment concentrations, sediment load, and biogeochemical fluxes from the three rivers and their interannual variability, but there has been no research on sediment yield and its response to climatic, hydrologic, topographic, and land cover variables in any major river basin of South America. Overall, the flux of sediment from continents into continental basins by intermediate and large fluvial systems remains poorly understood.

The Magdalena is a major river for which until now little data has been published. It is one of the more important rivers on a worldwide basis due to (1) its

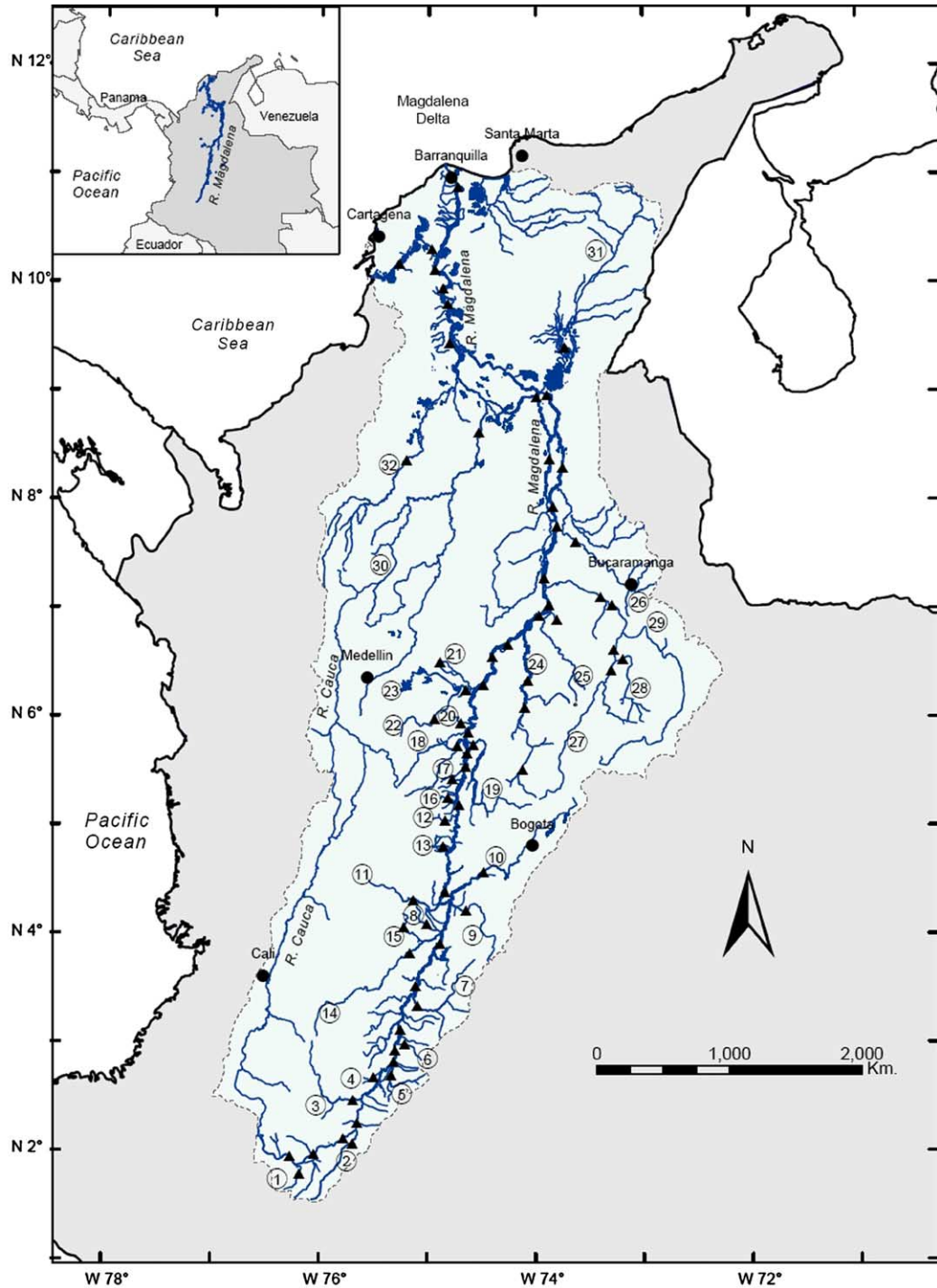


Fig. 1. Map of the Magdalena River drainage basin, Colombia, showing the principal tributaries (numbers and circles), hydrological stations (solid triangles), where sediment load and water discharge were measured. The name of each tributary corresponding to each number is shown on [Table 2](#).

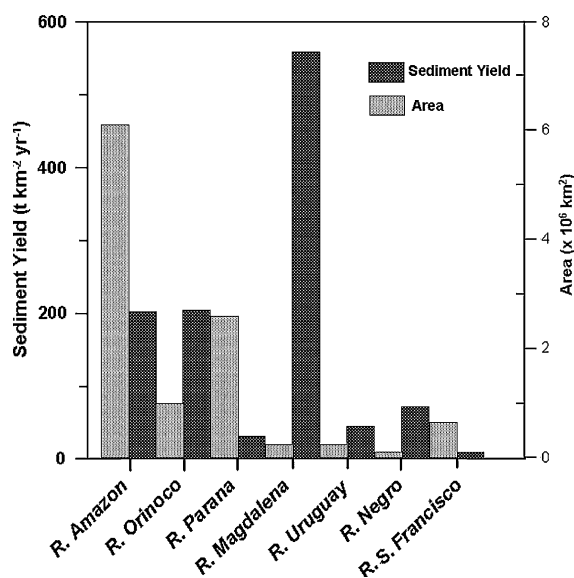


Fig. 2. Sediment yield and basin area for selected rivers in South America (Normalized sediment yield for the river basins was estimated by dividing sediment load (ton yr⁻¹) by drainage areas (km²). Data were gathered from Milliman and Syvitski (1992), Ludwig and Probst (1998), Goniadski (1999), and Restrepo and Kjerfve (2000b).

contribution of fluxes for the global budgets (Milliman and Meade, 1983; Milliman, 1990; Milliman and Syvitski, 1992; Ludwig and Probst, 1998); (2) its high sediment yield, the largest for the Atlantic coast of South America (Restrepo and Kjerfve, 2000a, b); (3) the size of the drainage basin: it is the largest of any Andean river, and (4) the significant contribution of material fluxes into the Caribbean Sea (Restrepo and Kjerfve, 2002).

It is our objective to present sediment yield data from small catchments in the Magdalena drainage basin and to explore the factors that control the observed patterns of sediment yield based on a substantial data set of multi-year measurements. We will then assess the extent to which a model of sediment delivery for the Magdalena drainage basin can adequately explain the observed spatial and temporal variability of sediment yield.

2. The Magdalena River basin

The Magdalena River is the largest river system in Colombia, extending for 1612 km. Its headwaters are

located at the Magdalena's lake at an elevation of 3685 m. The river drains the Andes, which are formed in Colombia by the Western, Central, and Eastern Cordilleras. The drainage basin area covers 257,438 km², 24% of the territory of Colombia, and occupies a considerable portion of the Colombian Andes (Fig. 1). The basin is formed by 151 sub-catchments of which 42 are second-order watersheds. The main tributaries are the Cauca (second largest river in Colombia), Sogamoso, San Jorge, and Cesar rivers (Fig. 1). The basin is characterized by high tectonic activity, hillslopes commonly exceeding 45°, landslides, steep gradients, and high relief tributary basins.

According to Potter (1997), Late Miocene deposits in the Magdalena Valley between the Eastern and Western Cordilleras indicate a Late Miocene initial age for the Magdalena River. Both the paleo-Magdalena, and its principal tributary, the paleo-Cauca, developed in tectonic lows when the Eastern and Central Cordilleras were uplifted. Thus tectonic control is evident in the entire Magdalena watershed.

The Magdalena basin is characterized by high precipitation with an average rainfall of 2050 mm yr⁻¹ for the basin as a whole (Instituto de Hidrología, Meteorología y Estudios Ambientales, IDEAM, 2001). Annual distribution is similar throughout the watershed. There are two wet and two dry seasons. December–March and June–September are low rainfall periods and March–May and October–November are high rainfall periods. The two wet seasons are comparable in length and intensity, except in the upper Magdalena valley, where the early first wet season is more prolonged.

The complex topography along the basin makes it difficult to present generalizations of rainfall patterns. Nevertheless, some characteristics and similarities are present throughout the drainage basin (López, 1966; López and Howell, 1967; Snow, 1976; IDEAM, 2001). (1) The basin would be considerably drier if there were no avenues through which moist air penetrates deeply into the section. The principal avenue is the Magdalena valley and secondarily the Cauca valley; (2) comparing opposite slopes of major valleys, the windward slope receives approximately twice the rainfall of the leeward slopes. In both major valleys, the Magdalena and Cauca, between 6 and 7° N, the highest rainfall values, more than

3000 mm yr⁻¹, are received at intermediate elevations, normally below 1500 m. The floor of the Magdalena valley receives 1700 mm yr⁻¹, windward slopes 3000 mm yr⁻¹, and leeward slopes 1500 mm yr⁻¹; (3) the higher the elevation of the floor of the Magdalena basin, the lower the total rainfall, specifically if the floor elevation is greater than 1000 m, the annual rainfall is less than 1000 mm; and (4) above 3000 m the annual rainfall is less than 1000 mm.

Daily water discharge measurements, 1975–1995, at Calamar, the most downstream station before the Magdalena delta on the Caribbean, indicate an average annual discharge of 7232 m³ s⁻¹. Load measurements during the 21-year period yielded an annual sediment load of 144 × 10⁶ t yr⁻¹. The calculated sediment yield for the whole drainage basin area upstream of Calamar is 559 t km⁻² yr⁻¹ (Restrepo and Kjerfve, 2000b).

The large-scale changes associated with land use practices and resource exploitation in the Andes section are particularly significant for the Magdalena basin. Besides steep slopes that lead to excessive erosion, tectonic activity and morphological factors, forest cover in the Colombian Andes has greatly decreased due to population expansion and change in land use. The main cities of Colombia, including Bogotá, Medellín, Cali, Bucaramanga, and Barranquilla are located in the Magdalena basin (Fig. 1). Seventy nine percent of the population of Colombia lives in the Magdalena watershed, corresponding to a density of 120 inhabitants/km² (IDEAM, 2001), which is very high when compared to 0.24 inhabitants/km² in the Amazon basin as a whole (Serruya and Pollinger, 1984; Depetris and Paolini, 1991).

Current trends for the Magdalena drainage basin, including increasing population densities, accelerating upland erosion rates due to poor agricultural practices and widespread deforestation and mining have distorted the natural hydrographs, in turn leading to further loss of critical habitats and biodiversity, and altering sediment transport (Colciencias-Fen, 1989; Himat-Ingeominas, 1991; Restrepo and Kjerfve, 2000b; IDEAM, 2001). Although these facts have been widely recognized, until now there have been no studies examining sediment yield and its response to environmental variables and catchment disturbances in the Magdalena River basin.

3. Data and methods

3.1. Sediment yield data

We have obtained daily water and suspended sediment load data for more than 40 sites (Fig. 1) in the Magdalena basin from the Instituto de Hidrología, Meteorología y Estudios Ambientales, IDEAM (1995, 2003). Bed load transport is not included in the analysis since this contribution to total load is less than 15% and probably much smaller than 15% (IDEAM, 2001). The gauging stations in each major tributary system correspond to the lowest point in the sub-basin for which water discharge and sediment load data are available, although this is not always near where the tributary joins the main course of the Magdalena or the Cauca. Simultaneous measurements of water level, river discharge, and sediment concentration were done on several occasions by the IDEAM during high, intermediate, and low river discharge conditions at each gauging station. The daily stage readings for the whole year records were converted to discharges via the established rating curve. Thus river discharge measurements are based on daily water stage (level) measurements and the application of rating curves (Buchanan and Somers, 1969; Gregory and Walling, 1973). Sediment load measurements are based on daily sediment concentration measurements and cross-multiplication with water discharge (Colby, 1956; Jansen et al., 1979).

3.2. Obtaining physical catchment variables

Physical variables for the main tributary catchments of the Magdalena basin (Tables 1 and 2) were obtained by using an ARCINFO[®] database (IDEAM, 2001) and a GIS software, HydroSig 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 × 1 km, supplemented by 1:1,000,000 maps (IDEAM, 2001), was used in HydroSig Java[®] to calculate morphometric variables such as watershed boundaries, area, river length, indices of slope, relief ratio, hypsometric curve and integral (Strahler, 1952), and also climatic parameters, including mean and maximum annual precipitation and precipitation ratios. Table 1 lists

Table 1

Definition, derivation and source of Hydrologic, Morphometric, and Climatic controlling variables used in correlation and multivariate analysis (after Strahler, 1952; Fournier, 1960; Summerfield and Hulton, 1994; Hovius, 1998; Harrison, 2000)

Variable (symbol, unit)	Definition	Source
Hydrologic		
Mean water discharge (Q , $\text{m}^3 \text{s}^{-1}$)	The long term average water discharge at the most downstream station	Colombian Hydrological Institute Database (IDEAM, 2003)
Maximum water discharge (Q_{\max} , $\text{m}^3 \text{s}^{-1}$)	The long term average maximum water discharge corresponding to the month of greatest discharge in the time series	(IDEAM, 2003)
Water discharge peak (Q_{pk} , –)	The ratio of the average water discharge and the maximum water discharge	(IDEAM, 2003)
Mean annual runoff (R , mm yr^{-1})	Calculated from the mean water discharge and the catchment area	HidroSIG Java Database (2001), IDEAM (2001)
Mean annual sediment load (Sa, Mt yr^{-1})	The long-term average of suspended sediment load at the most downstream station	IDEAM (2003)
Morphometric		
Catchment area (A , km^2)	Basin area above gauging station	HidroSIG Java Database (2001), IDEAM (2001)
Catchment length (L_b , km^2)	Straight-line distance from the most remote point on the water divide to the basin mouth	HidroSIG Java Database (2001), IDEAM (2001)
River length (L_r , km^2)	The length of the main stream of the basin (distance between headwaters and the basin mouth)	HidroSIG Java Database (2001), IDEAM (2001)
Mean height (H , m)	The mean modal elevation of all cells within the basin perimeter	HidroSIG Java Database (2001), IDEAM (2001)
Maximum height (H_{\max} , m)	The value of maximum basin elevation	HidroSIG Java Database (2001), IDEAM (2001)
Minimum height (H_{\min} , m)	The value of the lowest elevation in the drainage basin	IDEAM (2001)
Relief peakedness (H_{pk} , –)	The ratio of the mean height and the maximum height of the catchment	HidroSIG Java Database (2001), IDEAM (2001)
Relief ratio (H_r , m km^{-1})	The ratio of the maximum height of the drainage basin and the basin length	Calculated from H_{\max} and L_b variables
Hypsometric integral (HI, –)	Given by: $(H - H_{\min}) / (H_{\max} - H_{\min})$ (Strahler, 1952)	Calculated from variables in the data set
Mean slope (α , m km^{-1})	The ratio of the maximum elevation of the catchment and the length of the river. It defines the mean slope angle of the riverbed	HidroSIG Java Database (2001), IDEAM (2001)
Slope 1 (α_1 , m km^{-1})	The ratio of the mean height of the drainage basin and the square root of the basin area as calculated by Fournier (1960) and Harrison (2000)	Calculated from variables in the data set
Climatic		
Mean annual precipitation (P , mm yr^{-1})	The total annual precipitation as calculated by Hovius (1998)	HidroSIG Java Database (2001)
Maximum monthly precipitation (P_{\max} , mm yr^{-1})	The long term mean value of precipitation for the wettest month of each year (Hovius, 1998)	HidroSIG Java Database (2001)
Precipitation peakedness (P_{pk} , –)	Given by the mean annual precipitation divided by the maximum monthly precipitation for the whole period of measurements	Calculated from P and P_{\max} variables
Mean annual temperature (T , $^{\circ}\text{C}$)	The mean annual daytime temperature as calculated by Hovius (1998)	HidroSIG Java Database (2001)
Temperature range (Tr , $^{\circ}\text{C}$)	The difference between the mean daytime temperatures for the hottest and coldest months	HidroSIG Java Database (2001)
Drainage basin/sediment		
Specific sediment yield (S_y , $\text{t km}^{-2} \text{yr}^{-1}$)	Total sediment outflow from the catchment. It is defined as annual sediment load per unit area	Calculated from Sa and A variables
Mechanical denudation rate (D , mm/ka)	The average mechanical denudation per unit time of the land surface	Calculated from S_y

Note. HidroSIG Java (Version 1.8) is a GIS software including all existing hydrological and meteorological database of Colombia. An available 120 arc second digital elevation (DEM) was used for morphological and climatic analysis. (National University of Colombia, 2001). Other calculated morphometric variables have not been shown in Table 1.

Table 2

Morphometric, hydrologic, and climate data for the 32 studied tributaries in the Magdalena River basin. Definition and source of catchment variables used in correlation and multivariate analysis are shown in Table 1

River	A (km ²)	Lb (km)	Lr (km)	Sa (Mt yr ⁻¹)	Sy (t km ⁻² yr ⁻¹)	D (mm/ ka)	Q (m ³ s ⁻¹)	Q _{max} (m ³ s ⁻¹)	Q _{pk} (-)	R (mm yr ⁻¹)	H (m)	H _{max} (m)	H _{min} (m)	H _{max} * (m)	H _{pk} (-)	Hr (mkm- 1)*	$\alpha_1(H/\sqrt{A})$ (m km ⁻¹)	α (mkm ⁻¹)*	HI	P (mm yr ⁻¹)	P _{max} (mm yr ⁻¹)	P _{pk} (-)	Years of Data (Sa)
1.Guarapas	503	49	56	0.1	138	91.9	8	144	0.055	495	1730	2200	1259	941	0.786	19	77.1	16.8	0.50	1460	172	8.51	1990–2000
2.Suaza	989	62	89	0.6	572	381.4	44	745	0.059	1390	1640	2450	845	1605	0.669	26	52.1	18.0	0.50	1576	180	8.74	1981–2000
3.Paez	4078	85	127	3.2	782	521.5	185	1694	0.109	1429	2330	4200	587	3613	0.555	42	36.5	28.4	0.48	1495	173	8.62	1972–2000
4.Yaguara	1386	61	59	0.8	593	395.0	15	458	0.033	343	1770	2260	505	1755	0.783	29	47.5	29.7	0.72	1611	258	6.25	1983–1999
5.Neiva	756	44	71	0.3	338	225.3	17	375	0.045	702	1640	2600	468	2132	0.631	49	59.6	30.0	0.55	1773	215	8.25	1989–2000
6.Ceibas	220	36	38.6	0.1	581	387.1	5	118	0.041	694	1600	1650	443	1207	0.970	33	107.9	31.3	0.96	1451	160	9.09	1983–1999
7.Cabrera	2446	94	115	1.8	755	503.4	71	848	0.084	914	1750	4000	356	3644	0.438	39	35.4	31.7	0.38	1159	166	7.00	1982–1998
8.Luisa	342	80	98	0.1	181	121.0	9	725	0.013	836	830	3000	275	2725	0.277	34	44.9	27.8	0.20	1780	226	7.88	1990–1999
9.Sumapaz	2435	72	137	0.5	207	137.9	43	988	0.043	555	2120	4000	260	3740	0.530	52	43.0	27.3	0.50	1766	235	7.52	1980–1999
10.Bogotá	5544	167	305	1.3	239	159.3	39	606	0.064	220	2280	3200	258	2942	0.713	18	30.6	9.6	0.69	923	126	7.33	1976–1999
11.Coello	1580	78	108	1.6	1035	690.0	40	2202	0.018	802	2080	3750	252	3498	0.555	45	52.3	32.4	0.52	1346	163	8.26	1983–1999
12.Lagunilla	663	54	88	0.2	308	205.5	18	624	0.029	854	1900	5000	217	4783	0.380	88	73.8	54.4	0.35	1079	130	8.28	1990–1999
13.Recio	610	62	76	0.2	257	171.5	20	518	0.038	1011	2170	4900	221	4679	0.443	76	87.9	61.6	0.42	1993	267	7.46	1980–1999
14.Saldaña	7009	165	199	8.9	1271	847.1	320	2574	0.124	1441	1900	2060	275	1785	0.922	11	22.7	9.0	0.91	2316	353	6.56	1974–1999
15.Cucua	725	68	101	0.4	519	345.7	13	232	0.056	567	1950	3550	310	3240	0.549	47	72.4	32.1	0.51	1076	130	8.28	1976–1997
16.Gualí	480	77	96	0.2	403	268.7	23	1164	0.020	1514	1640	4800	193	4607	0.342	60	74.9	48.0	0.31	2053	296	6.93	1990–1999
17.Guarino	976	66	92	0.5	464	309.2	34	504	0.067	1085	2350	3100	188	2912	0.758	44	75.2	31.7	0.74	3853	521	7.40	1981–1999
18.La Miel	2121	86	104	2.7	1253	835.2	243	1903	0.128	3618	1560	2650	150	2500	0.589	29	33.9	24.0	0.56	4477	612	7.31	1975–1999
19.Negro	4604	111	214	8.0	1730	1153.2	136	1620	0.084	930	1200	3500	152	3348	0.343	30	17.7	15.6	0.31	1460	213	6.85	1975–2000
20.Cocorna	799	35	86	0.6	745	496.4	56	700	0.080	2203	530	2200	134	2066	0.241	59	18.8	24.0	0.19	3651	423	8.63	1978–1999
21.Nus	320	60	79	0.2	582	387.8	17	237	0.072	1682	1030	1200	575	625	0.858	10	57.6	7.9	0.73	3307	462	7.17	1983–1995

Table 2 (continued)

River	A (km ²)	Lb (km)	Lr (km)	Sa (Mt yr ⁻¹)	Sy (t km ⁻² yr ⁻¹)	D (mm/ ka)	Q (m ³ s ⁻¹)	Q _{max} (m ³ s ⁻¹)	Q _{pk} (-)	R (mm yr ⁻¹)	H (m)	H _{max} (m)	H _{min} (m)	H _{max} * (m)	H _{pk} (-)	Hr (mkm- 1)*	$\alpha_1(H/\sqrt{A})$ (m km ⁻¹)	α (mkm ⁻¹)*	HI	P (mm yr ⁻¹)	P _{max} (mm yr ⁻¹)	P _{pk} (-)	Years of Data (Sa)
(continued on next page)																							
22.Samana	1490	71	111	0.9	625	416.4	181	846	0.214	3828	1310	2800	145	2655	0.468	37	33.9	23.9	0.44	4114	488	8.44	1983–1999
23.Nare	5711	110	187	2.6	452	301.7	396	2850	0.139	2189	1410	3000	125	2875	0.470	26	18.7	15.4	0.45	2594	320	8.10	1976–1999
24.Carare	4943	173	274	10.9	2200	1466.5	232	2476	0.094	1479	1010	3600	88	3512	0.281	20	14.4	12.8	0.26	2638	348	7.58	1985–1998
25.Opón	1698	91	179	3.4	1973	1315.5	90	566	0.159	1670	790	2000	79	1921	0.395	21	19.2	10.7	0.37	3212	301	10.6	1976–1998
26.Lebrija	3500	150	258	4.4	1258	838.5	90	1000	0.090	813	1030	3700	49	3651	0.278	24	17.4	14.2	0.27	2442	324	7.54	1979–1998
27.Suárez	9312	183	220	3.4	367	244.6	300	2332	0.129	1016	2460	3800	300	3500	0.647	19	25.5	15.9	0.62	3066	442	6.94	1974–1998
28.Fonce	1849	67	106	0.6	306	204.0	84	947	0.089	1435	2040	3800	650	3150	0.537	47	47.4	29.7	0.44	1598	232	6.88	1976–1998
29.Sogamo	21513	219	348	11.2	522	347.8	488	4343	0.112	715	2200	3800	70	3730	0.579	17	15.0	10.7	0.57	1997	289	6.92	1989–1998
30.Cauca	59615	789	1183	49.1	823	549.0	2373	4985	0.476	1255	1440	4200	20	4180	0.343	5	5.9	3.5	0.34	1887	243	7.77	1978–1999
31.Cesar	16657	232	379	0.2	10	6.4	53	199	0.268	101	500	1850	27	1823	0.270	8	3.9	4.8	0.26	1575	154	10.2	1977–1998
32.S.Jorge	4463	274	395	2.5	554	369.1	198	958	0.207	1400	240	3150	18	3132	0.076	11	3.6	7.9	0.07	1670	248	6.72	1981–1995

Numbers indicate the location of each tributary on Figs. 1 and 4

definitions, derivations and sources of the main morphometric, climatic and hydrologic variables calculated for the 32 main sub-catchments of the Magdalena River. In our analysis, we compared normalized sediment yields ($\text{t km}^{-2} \text{yr}^{-1}$) for the river basins by dividing sediment load (t yr^{-1}) by drainage basin areas (km^2).

3.3. Physical factors controlling sediment yield

To explore which factors control sediment yield in the Magdalena basin, series of correlation calculations were done using data from the 32-second order river catchments (Table 2). Both single and multiple correlations were performed. Pearson correlation coefficients were calculated for all variable pairings for catchment properties and for the neperian logarithm of catchment variables (Table 3). 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 Tables 1 and 2. This multivariate regression approach has been used to analyze global 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.

3.4. Trends in sediment load and land use

There are large variations in the spatial distribution, length of the time series, and the catchment area of gauging stations, which have implications for the statistical analysis. Of the 32 gauging stations, 35% represent upstream areas less than 1000 km^2 , 55% represent upstream areas between 2000 and $10,000 \text{ km}^2$, and 10% represent upstream areas greater than $10,000 \text{ km}^2$. Twenty-three of the gauging stations have continuous records for 15 years or longer. These 23 sub-catchments were used in the more detailed analysis of sediment yield variability.

The trend in sediment load thus sediment yield was estimated by using 3-year equally weighted running mean filters and least squares linear regressions for the time series for each gauging station. Land use, and in

Table 3
Correlation matrix between the neperian logarithm of catchment properties and sediment yield

	Sy	A	Q	Q _{max}	Q _{pk}	R	H	H _{max}	H _{pk}	H _r	α_r	P	P _{max}	P _{pk}
A	0.049													
Q	0.434	0.844												
Q _{max}	0.604	0.558	0.806											
Q _{pk}	0.080	0.792	0.789	0.273										
R	0.717	-0.153	0.400	0.530	0.100									
H	0.117	-0.103	-0.117	0.163	-0.361	-0.040								
H _{max}	0.214	0.178	0.269	0.522	-0.104	0.191	0.183							
H _{pk}	0.025	-0.117	-0.181	-0.054	-0.239	-0.134	0.855	-0.314						
H _r	0.092	-0.765	-0.586	-0.208	-0.737	0.277	0.357	0.309	0.154					
α_r	0.067	-0.808	-0.637	-0.229	-0.798	0.206	0.434	0.256	0.241	0.956				
P	0.340	-0.043	0.287	0.197	0.263	0.604	-0.202	-0.117	-0.051	0.008	-0.031			
P _{max}	0.431	-0.016	0.321	0.307	0.204	0.620	-0.120	-0.014	-0.030	0.015	0.016	0.949		
P _{pk}	-0.317	-0.083	-0.131	-0.365	0.165	-0.099	-0.241	-0.316	-0.063	-0.025	-0.150	0.078	-0.239	
α_l	0.038	-0.779	-0.677	-0.296	-0.794	0.084	0.703	-0.011	0.622	0.772	0.851	-0.096	-0.064	-0.092

This correlation matrix is between the log-transformed variables. Definition of each variable is explained in Table 1.

particular differences between forest-dominant, agricultural land, and other land uses, were assessed by analyzing a land-use map of the Magdalena basin. This map was derived by classification of two composite LANDSAT images from 1970 and 1990, using the maximum likelihood procedure (IDEAM, 2001). With ARCINFO®, we calculated the land use distribution for the Magdalena basin (% agricultural land, forest, pasture, deforestation).

4. Results and discussion

4.1. Relation between sediment yield and control variables

Close examination of data indicates that associations between sediment yield and basin variables are more adequately described by the log-transformed data (Table 3). The control variables that explain most of the variation in observed sediment yield are mean annual runoff (R) and to a lesser extent peak maximum annual water discharge (Q_{\max}) (Table 3). Specific sediment yield for the whole Magdalena basin increases following a power function with increasing catchment runoff. Curvilinear regression of sediment yield on mean annual runoff and maximum water discharge yielded a coefficient of determination of 0.51 and 0.36, respectively, both regressions significant at the 99% level (Fig. 3). We conclude that none of the other variables defined in Table 2 can be regarded as prime controls on sediment yield on a regional scale (Table 3).

The relationship between sediment yield and mean annual runoff is noteworthy (Fig. 3(A)). Many studies examining global sediment yields have explored this relationship. 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. In addition, high sediment yields for low values of runoff are consistent with the Langbein and Schumm (1958) model. Further, the increase of sediment yield for precipitation in excess of 700 mm runoff is a feature that has already been described (Wilson, 1973; Walling and Webb, 1983).

The sediment load at the mouth of a river reflects the sum of all erosional and depositional processes

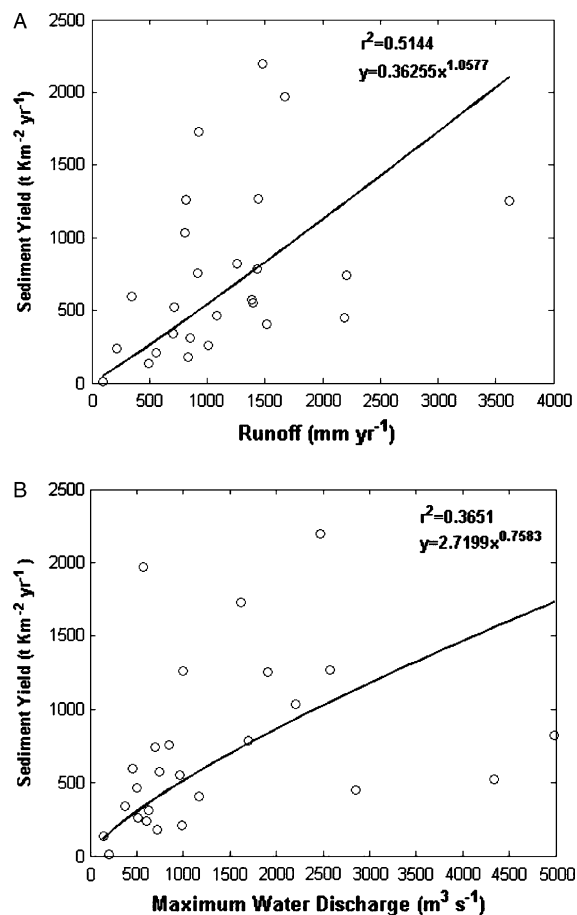


Fig. 3. Relation of sediment yield versus mean annual runoff (A) and maximum water discharge (B) for the second order tributary basins on the Magdalena River drainage basin listed in Table 2.

occurring within the drainage basin. With an increase in catchment area, there is an increase of the relative importance of depositional processes (Hovius, 1998). This is illustrated by the inverse relationship between specific sediment yield and drainage basin area, noted in several global studies (Milliman and Meade, 1983; Milliman and Syvitski, 1992) and for the Pacific and Caribbean basins of Colombia (Restrepo and Kjerfve, 2000a, 2002, 2004). Contrary to what we expected, there is no relationship between sediment yield and drainage area for the Magdalena sub-basins (Table 3). This may be due to the small range of basin sizes within the Magdalena drainage basin. This range spans less than one order of magnitude.

In addition, analyses of sediment yield and denudation processes in some tropical and sub-tropical catchments (e.g. Hagget, 1961; Trimble, 1975; Dunne, 1979) show that extensive storage of sediment is not feasible in catchments smaller than 2000 km². In the Magdalena watershed, these basins constitute 51% of the drainage area and are high-relief basins with steep slopes and limited floodplains in which sediment can be stored. Thus, it is unlikely that catchment area has any important effect on the statistical analyses.

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. In contrast, our data indicate that none of the topographic variables is associated with sediment yield; only maximum basin elevation shows some degree of association (Table 3). Thus elevation does not explain sediment yield from the second order tributary basins of the Magdalena catchment. This is probably due to the fact that most of the analysed tributaries have their headwaters at high elevations and because we did not analyse lowland rivers. In fact, most rivers which descend rapidly from high Cordilleras to their limited alluvial plains and tributary basins (71% of the drainage area) are in elevations > 1000 m.

4.2. Multiple regression models

Using step-wise regression, two control variables were selected of the 21 listed in Table 2. These two estimators, which predict sediment yield for the whole Magdalena basin (Table 4, Eq. (1)), are mean annual runoff, R , and peak maximum water discharge, Q_{\max} . The resulting regression equation is based on data from the 32 sub-catchments included in Table 2, and no outliers have been excluded from the analysis. It explains 58% of the variance in sediment yield from these drainage basins. Using one or more additional

variables does not contribute significantly to the explanatory power of the model.

The two selected estimators, R and Q_{\max} , refer 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}). Thus, the regional-scale variance of sediment yield in the Magdalena basin seems to be explained by the combined influence of precipitation, storminess and surface runoff available for weathering and transport processes.

Since the model explains 58% of variance in sediment yield from small catchments in the Magdalena basin, 42% of that variance is not explained in terms of variables listed in Tables 1 and 2. According to Hovius (1998) this may either be due to the use of incorrect data or data that reflect strong human influence, or may be partly due to the fact that the variables do not cover all aspects of weathering, hillslope erosion, and fluvial transport processes that are most relevant to sediment yield. In addition, sediment loads may not always reflect contemporary environmental conditions, responding instead to previous episodes of landscape evolution. These factors may cause considerable scatter in the dataset, but it seems unlikely that the combination of these factors is responsible for all unexplained variance.

The prediction of sediment yield is complicated by the interaction of controlling variables, human impact on the hydrological system, and by scale effects associated with different basin sizes (Walling and Webb, 1983). The high degree of spatial variability in sediment yield and catchment characteristics causes difficulty in modeling the controlling relationships across the whole dataset. Previous studies on global and regional sediment yield variations have used the strategy of grouping dataset into suitable categories to reduce scatter (e.g. Dunne, 1979; Summerfield and Hulton, 1994; Ludwig and Probst, 1998; Higgitt and Lu, 2001). Based on tributary groupings in the Magdalena basin, including those watersheds corresponding to the upper and middle basin, the Central

Table 4

Models and estimator variables predicting suspended sediment yield in the Magdalena River basin

Classification/model equation	r^2	p -value	F -ratio
<i>Basin</i>			
(1) $\log Sy = -0.8838 + 0.8140 \log R - 0.3906 \log Q_{\max}$	0.5840	0.0001 ^a	16.15
<i>Upper basin</i>			
(2) $Sy = 107.092 + 0.4227 Q_{\max}$	0.7513	0.0001 ^a	33.23
<i>Middle basin</i>			
(3) $Sy = 3484.95 - 0.5042 H - 38.1722 Hr - 2.3837 Q$	0.7704	0.0241 ^b	6.71
<i>Central cordillera</i>			
(4) $\log Sy = 1.3576 + 0.4401 \log A$	0.4823	0.0122 ^b	9.32
<i>Eastern cordillera</i>			
(5) $\log Sy = 12.733 - 2.1389 \log H + 0.7755 \log Q - 0.9718 \log P - 0.4048 \log A$	0.8950	0.0001 ^a	202.13
Area < 2000 km ²			
(6) $\log Sy = -3.8038 + 1.4439 \log Q - 1.1147 \log R - 0.5314 \log H_{pk}$	0.8629	0.0000 ^a	69.40
2000 km ² < Area < 10,000 km ²			
(7) $\log Sy = 1.7233 + 0.5424 \log Q$	0.3071	0.0769 ^c	3.99
Area > 10,000 km ²			
(8) $\log Sy = 4.4063 + 0.9013 \log R - 4.9426 \log P_{pk}$	0.7828	0.0002 ^a	19.83

A step-wise regression analysis was implemented on data listed in Tables 1 and 2. Correlation coefficients between controlling variables and sediment yield are shown in Table 3. r^2 = coefficient of determination of multiple regression; p = p -value on the independent variable.

^a Significant at the 90% confidence level.

^b Significant at the 95% confidence level.

^c Significant at the 99% confidence level.

and Eastern Cordilleras, and the three categories of catchment areas, different multiple correlations were estimated (Table 4).

Multiple regressions for the upper and middle parts of the Magdalena basin indicate that 75 and 77% of the variance in sediment yield, respectively, is explained by maximum water discharge (Q_{\max}) in the upper part and by mean modal elevation (H), relief ratio (Hr), and mean water discharge (Q) in the middle basin (Table 4). The grouping strategy also suggests that most of the variability in sediment yield in the eastern Magdalena basin (Eastern Cordillera) can be explained in terms of 'natural' catchment characteristics, including mean elevation (H), mean water discharge (Q), mean annual precipitation (P), and drainage area (A). In contrast, only 48% of the variance in the central part of the basin (Central Cordillera) is explained by drainage area (A) as a result of a larger size range of tributary catchments present in this part of the basin. Also, when grouping the dataset in the three categories according to drainage area, 86% of the variance in sediment yield for basins with drainage areas < 2000 km² is explained by runoff (R), mean water discharge (Q),

and precipitation peakedness (P_{pk}), while 78% of the variance for basins > 2000 km² is explained by R and P_{pk} (Table 4).

One of the common features arising from these models, after grouping the dataset into categories, is the combination of seven catchment variables, including runoff, precipitation, precipitation peakedness, mean elevation, mean water discharge, relief ratio, and drainage area. Similar combinations have been found on a regional scale in the upper Yangtze basin (Higgitt and Lu, 2001) and Kenyan catchments (Dunne, 1979), and on a global basis (Fournier, 1960; Milliman and Syvitski, 1992; Summerfield and Hulton, 1994; Hovius, 1998). These seven selected estimators represent different controls on the processes determining sediment yield. As expressed in previous studies (e.g. Milliman and Meade, 1983; Milliman and Syvitski, 1992), there is an inverse relationship between specific sediment yield and drainage basin area in the equation predicting sediment yield for the Eastern Cordillera (Eq. (5); Table 4). In contrast, sediment yield and drainage area follow a direct relationship in the Central Cordillera (Eq. (4); Table 4). One of the reasons for this

relationship is the reduced storage capacity of sediment in these high relief basins. The six remaining predictors capture the relative importance of climate and weathering, hillslope erosion, and fluvial transport components.

Several studies have analyzed and discussed the relationship between denudation rates and mean annual precipitation (Langbein and Schumm, 1958; Douglas, 1967; Wilson, 1973; Hovius, 1998). Some results show the existence of peak erosion rates in semi-arid environments and how denudation increases above a mean annual precipitation rate of 1000 mm. However, Ahnert (1970) and Pinet and Souriau (1988) found a weak correlation between denudation rates and mean annual precipitation. According to Hovius (1988), most hillslope erosion processes are dependent on instantaneous rates of precipitation rather than mean annual rates. Fournier (1960) showed that precipitation peakedness (P_{pk}) is one of the main factors controlling denudation rates on a global scale. In the Magdalena basin precipitation peakedness is one of the variables predicting sediment yield for catchments $>2000 \text{ km}^2$, including the larger tributaries, the Cauca, Sogamoso and Cesar rivers.

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) and for continental scale basins (Summerfield and Hulton, 1994). In the Magdalena, both mean modal elevation and relief ratio, which represent the potential energy available for soil erosion, are estimators predicting sediment yield (Table 4). If two catchments with similar areas are compared, the expected influence of topography is observed. The catchment areas of the Negro and San Jorge rivers are 4604 and 4463 km^2 , respectively (Table 2). The relief ratio in the Negro catchment is 30 m km^{-1} , compared to only 11 m km^{-1} in the San Jorge watershed. The sediment yield of the Negro River is nearly three times higher ($1730 \text{ t km}^{-2} \text{ yr}^{-1}$ compared to $554 \text{ t km}^{-2} \text{ yr}^{-1}$).

Summerfield and Hulton (1994) noted the strong role of relief and runoff in influencing denudation rates for major basins worldwide. Also, Jansen and Painter (1974) showed that climate and topography were the most important controls on sediment yield from catchments globally. In the Magdalena drainage basin, the combined effect of relief and runoff can clearly be seen in the multiple regression for the classification of catchments with an area $<2000 \text{ km}^2$ (Table 4). The two variables together with mean annual water discharge account for more than 86% of the variance in sediment yield. This is a remarkably high amount of explained variance given the fact that only natural variables are included.

4.3. Model validation

To validate each multiple regression model shown in Table 4, simulated sediment yield was compared to the measured sediment yield for the same model by applying a paired two-tailed *t*-test (Moore and McCabe, 1993) and by calculating the model efficiency (ME) relationship (Verstraeten and Poesen, 2001). The ME can range from $-\infty$ to 1 and indicates the proportion of the initial variance accounted for by the model. The closer the value of ME approaches 1, the more efficient the model is. Values of $\text{ME} < 0$ (or closer to 0) means that the model produces more variation than could be observed: the model is inefficient. The sediment yield calculated from the basin model (Eq. (1); Table 4) was not significantly different at the 95% confidence level ($t = 7.26 \times 10^{-6}$; $p = 2.07$; $p > 0.05$; paired two-tailed *t*-test, Moore and McCabe, 1993) than from measured sediment yield. For Eq. (1) (Table 4), ME is 0.89 and the agreement indicates that the model is robust and predicts well sediment yield for the studied sub-basins in the Magdalena catchment (Fig. 5). Only three rivers, including the Cesar, Luisa and Nare, are not well predicted in terms of sediment yield. This is due to the presence of low alluvial plains where sediments are stored in each tributary margin, and therefore, the model produces more variance in these systems. We also compared measured and predicted sediment yield for the other model equations after grouping the dataset. Although these equations explain more variance in sediment yield (Table 4), values of ME are much lower (0.72–0.67) and indicate that the

models produce more variation than could be observed (Fig. 5).

The variation in observed sediment yield that cannot be explained by each model can be attributed to: (1) errors in measured sediment yield; (2) the fact that not all controlling physical properties are known and analyzed; (3) the fact that time periods for which sediment yield was calculated differ between basins; and (4) that no quantitative relationship has been established between sediment yield and land use changes caused by human influences. Thus spatially distributed models of sediment yield are needed to overcome these constraints. Extended data sets on sediment yield and the inclusion of more sophisticated analysis on land use, as one of the dominant controls, are necessary to validate these models.

4.4. Spatial variability and trends

Tributaries with significantly higher sediment yield are distributed throughout the Magdalena basin and include the Coello, Saldaña, La Miel, Negro, Carare, Opon, and Lebrija rivers. The mean sediment yield for all the sub-basins within the Magdalena systems is

$\sim 690 \text{ t km}^{-2} \text{ yr}^{-1}$, and values range from ~ 160 to $2200 \text{ t km}^{-2} \text{ yr}^{-1}$. Maximum values of sediment yield are observed in the Negro, Carare and Opon rivers, with 1730, 2200, and $1973 \text{ t km}^{-2} \text{ yr}^{-1}$, respectively (Fig. 4). These three catchments are located in the middle Magdalena basin and correspond to tributaries descending from the Eastern Cordillera (Fig. 1).

Analysis of annual trend in sediment load and thus sediment yield provides evidence that most of the tributaries in the upper Magdalena basin have been experiencing significant increases in sediment load over the last 10 years (Fig. 6). Also, rivers in the middle and eastern basins, such as the Carare, Opon, and Sogamoso, have witnessed significant increases since the 1990s. The largest tributary of the Magdalena River, the Cauca River, has experienced a dramatic increase in sediment load during the last 20 years. The rate of increase in sediment load has been more accentuated since 1990 (Fig. 6). This increasing trend in sediment load for the Cauca River, which represents 25% of the Magdalena drainage basin area, is strong evidence of the erosional conditions in the catchment (Fig. 6).

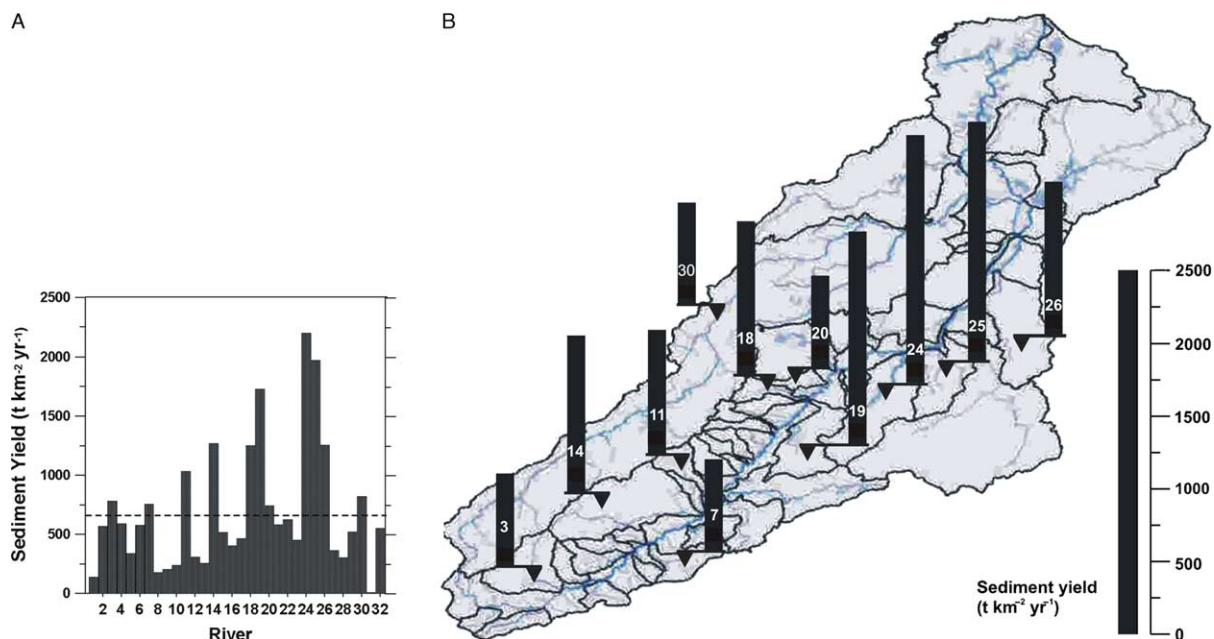
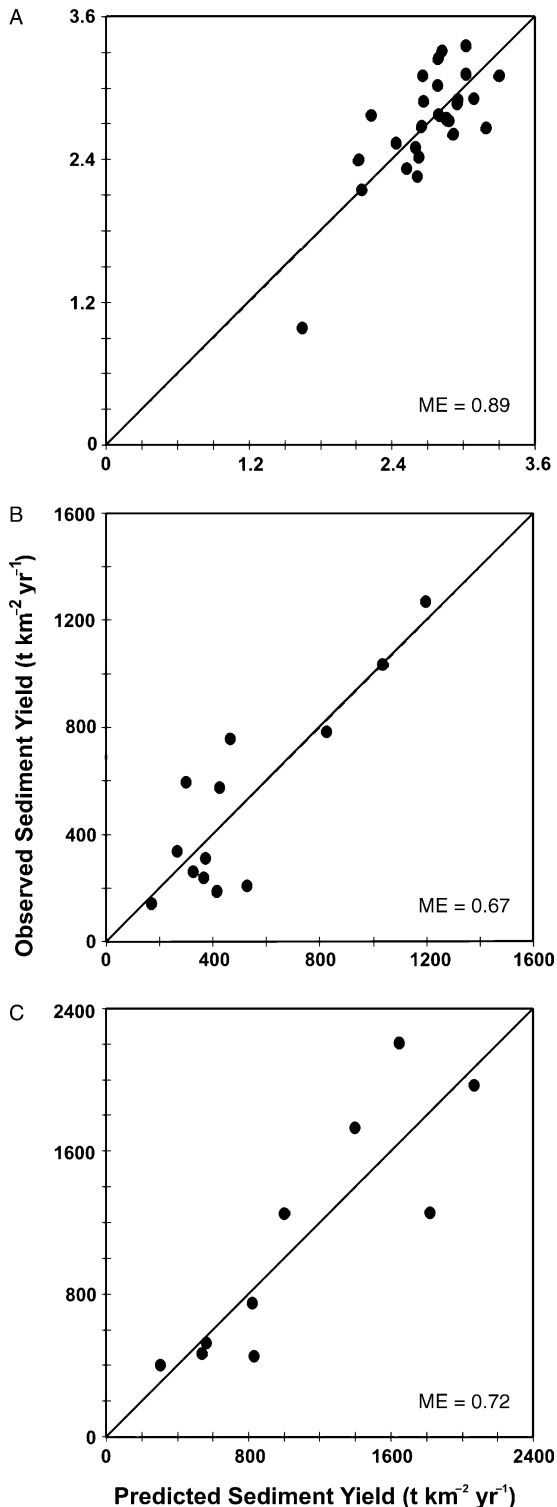


Fig. 4. (A) Calculated sediment yields for the 32-second order tributaries on the Magdalena River drainage basin. The mean sediment yield for the whole basin is $689 \text{ t km}^{-2} \text{ yr}^{-1}$ (dash line). (B) Map of sediment yields for some tributaries on the Magdalena catchment. The name of each tributary corresponding to each number is shown on Table 2.



The land use maps of the Magdalena basin, which were derived by classification of a composite set LANDSAT images dating from (i) 1970 and (ii) 1990 (IDEAM, 2001), indicate that during the past thirty years, the Magdalena basin has been under increasing environmental stress. Land use inventories carried out in the 1970s and 1990s indicate that forest cover was reduced from 71 to 54% in the Magdalena watersheds (Restrepo and Syvitski, *in press*). Deforestation has led to severe soil erosion. The only remaining rain forest area is located in the lower Magdalena valley, whereas most of the land on the lower and middle slopes is under cultivation. In addition, this period also witnessed an increase in habitat and soil conversion due to agricultural practices from 25 to 42% (Restrepo and Syvitski, *in press*). Notwithstanding the quality of the inventories, an increase in the extent of land change degradation is expected to show increasing trends in sediment load for the Magdalena basin.

Further time series analysis of sediment load for the 32 stations in the Magdalena basin indicates that 17 watersheds (68% of drainage basin area) exhibit increasing trends, while 12 locations (31%) display decreasing ones. Only three stations, representing 1% of the drainage basin area, show no significant change in sediment load. Thus, regional analysis of land use and sediment load indicates that erosion within the catchments has increased over the last 10–20 years.

Currently measured sediment loads do not represent only natural quantities. Human activities have caused both increases and decreases in sediment yield. Deforestation and poor soil conservation have enhanced soil erosion over the past several hundred years on a global scale. On the other hand, dams have acted to capture sediment, which might otherwise reach the lower river reaches and the coast. More recently, urbanization has locally induced subdued erosion rates. Large-scale river training, dredging and mining, irrigation, and hydroelectric works may also have dramatic influence on sediment yield (Milliman et al., 1987; Milliman and Syvitski, 1992; Hovius,

Fig. 5. Observed versus predicted specific sediment yield for various models: (A) Magdalena basin without including the Cesar, Nare, and Luisa Rivers, (B) upper Magdalena basin, and (C) middle Magdalena basin. The equations describing these models are presented on Table 4.

1998). Although many workers have documented changes in sediment flux caused by human activities (e.g. Dunne, 1979; Meade, 1982; Milliman et al., 1987; Vörösmarthy and Meybeck, 2000; Yang et al., 2002; Nixon, 2003), it is often impossible to calculate their combined effect on the sediment yield from a drainage basin. Depending on the character and relative importance of human activities, their net effect may be to increase or decrease sediment load with respect to natural factors (Hovius, 1998).

In the Magdalena basin, the evidence for trends in sediment load at individual gauging stations provide some insight into the changing nature of sediment delivery. For the upper basin tributaries, many natural and anthropogenic factors may be responsible for the increasing trends. (1) These are small ($220 \text{ km}^2 < \text{catchment area} < 1400 \text{ km}^2$) and high relief basins with

narrow alluvial plains and less sediment deposition/storage within the drainage basin. (2) The catchments are characterized by the occurrence of strong storms and erratic rains. Between 21 and 55% of the total sediment load could be attributed to a few extreme rain events (Fig. 6). (3) According to the last national inventory of land use (1990–1998) (IDEAM, 2001), much of the natural vegetation in the upper Magdalena basin has been removed to promote agriculture.

Lithology differences between the various regions of the Magdalena catchment may play an important role in controlling sediment yield. The greater yields correspond to tributary basins located on the eastern central Magdalena catchment (Fig. 4). These systems are characterized by fissile sedimentary rocks and high erodable soils. In the eastern upper Magdalena basin and under the original forest cover, the soils have

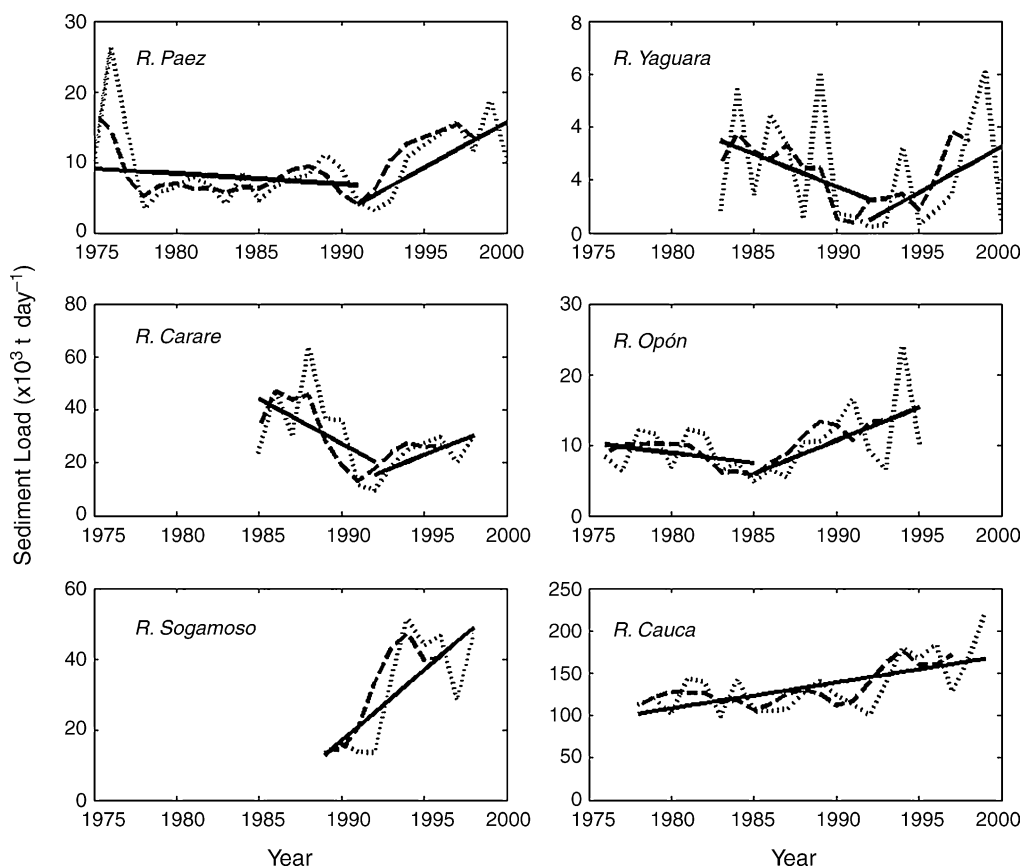


Fig. 6. Annual series plots of sediment load for selected tributaries in the Magdalena River drainage basin, showing mean sediment load (dotted line), three year running mean filter (dash line), and trend in sediment load estimated by least-square linear regression for each tributary time series (bold line).

moderate to high content of organic material (2–10% carbon) in the A-horizon, well-aggregated structure, and high infiltration characteristics; their resistance to erosion is high. When these soils are cultivated their organic content, infiltration capacities, and resistance to erosion are substantially decreased (IDEAM, 2001). In addition, other tributary basins in the western upper Magdalena do not have well established vegetation cover and a lithology characterized by marls and strongly weathered material (e.g. weathered granites). This lithological characteristic causes significant higher sediment yields in these basins compared to catchments with stable rocks in the western central Magdalena (e.g. metamorphic and volcanic rocks).

It has been shown on a global basis that it is probably the interaction of the soil erodibility of non-consolidated and unstable rocks together with extensive agricultural use that leads to high sediment loads (e.g. Ludwig and Probst, 1998). This interaction might be also one of the factors causing high sediment fluxes from the upper and middle tributaries of the eastern Magdalena (Fig. 4). Our data do not include any lithological parameter that gives some numerical indication of chemical or mechanical erosion. Probably, a numerical index characterizing the resistance of each rock type to mechanical erosion could have some weight in our regression models. Thus an important question is whether the regressions would change with a data set including the variable lithologies in the Magdalena drainage basin.

The Sogamoso River, a large tributary in the middle Magdalena basin, also exhibits an increasing trend in sediment load (Fig. 6). Several natural and human induced controls may explain this increasing trend in sediment delivery, e.g. (1) high rates of precipitation with an average annual rainfall of 1997 mm; heavier rainfall brings the available water and thus greater kinetic energy for hillslope erosion and stream transport of the eroded material; (2) 86% of the basin area is under strong erosional conditions (IDEAM, 2001); and (3) ongoing and increasing marble and emerald mining

The largest sub-drainage basin of the Magdalena River, the Cauca, shows a dramatic increase in sediment load over the last 20 yr (Fig. 6). The Cauca basin is characterized by active fault systems (e.g. Cauca-Romeral and Cauca-Patía systems),

overall moderate precipitation rates, and small tributary catchments (area <2000 km²) with slopes frequently steeper than 35°, erratic rains, and limited floodplains. According to Hovius et al. (1997, 1998), these conditions are favorable to the occurrence of rapid mass wasting caused mainly by hillslope erosion processes such as landslides, slumps and slides. In addition, most of the forests throughout the slopes of the Cauca valley have been removed to promote pasture growth. Also, one of the most extensive and profitable gold mining areas is located in the lower Cauca and its tributary, the Nechi River. According to the IDEAM (2001), gold extraction has increased from 15 ton yr⁻¹ of gold in 1990 to 20 ton yr⁻¹ in 1998. High concentrations of suspended sediments, often greater than 1800 mg l⁻¹, have resulted from the rapid erosion of the lowlands, partly because of ongoing gold mining.

5. Conclusions

A question for river basin managers and geomorphologists is whether the observed spatial and temporal variability of sediment yield can be explained adequately by a model of sediment delivery for a drainage basin under study. Analysis of sediment load and morphometric, hydrologic, and climatic variables from 32 tributary catchments in the Magdalena River indicates that the main physical control explaining most of the variation in observed sediment yield is mean annual runoff. No other catchment's properties explains more variation.

Multiple regression models used to predict sediment yield were constructed and validated. Sediment yield for the whole Magdalena basin can be simulated by two hydrological variables, including runoff and maximum water discharge. These two estimators explain 58% of variance in sediment yield. The importance of spatially distributed variables within drainage basins, including those controlling geomorphology, geology, hydrology, and land use, is one of the major reasons that the proposed model does not explain all observed variation in sediment yield. This stresses the need for spatially distributed models. When grouping the dataset into categories, more variance in sediment yield is explained by each correlation model (e.g. upper basin, 75%; middle

basin, 77%; Eastern Cordillera, 89%; area > 2000 km², 78%). The examination of spatial and temporal variability of sediment discharges and thus sediment yields indicates the main source areas where sediment loads are apparently increasing and the extent to which the pattern can be explained by a combination of hydroclimatic, topographic and land use variables. A large portion of the analyzed Magdalena drainage basin (68%) shows an increasing trend in sediment load. The extent of erosion within the catchment has increased over the last 10–20 years.

The analysis of sediment loads within a large basin such as the Magdalena has implications for management of potential sedimentation and for policy planning at the catchment scale. Critical areas of sediment control can be identified. Some of these are land areas in the upper basin and the catchments of the Sogamoso and Cauca rivers.

The precise influence of land use in the Magdalena basin remains somewhat inconclusive, but the increasing availability of environmental data sets will enable more sophisticated land use interpretation and associated modeling to be attempted. Work is now in progress to reconstruct the spatial and temporal patterns of agricultural intensification and deforestation in some pilot tributary basins across the central and western parts of the Magdalena basin in order to test the relationships between land use change and trends in sediment yield.

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