Chapter 14

The Pacific and Caribbean Rivers of Colombia: Water Discharge, Sediment Transport and Dissolved Loads

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14.1 Introduction

Although the South American continent includes three of the largest river basins in the world, the Amazon, the Orinoco, and the Paraná, with some of the highest discharges and sediment loads, a number of comparatively smaller systems in Colombia carry a significant share of the sediment load from the continent. Our objective is to synthesise the role and contribution of river systems in Colombia.

South America measures 17.8×10^6 km^2 and accounts for 12% of the global land surface. However, the continent delivers a disproportionally larger water discharge and suspended sediment load into the oceans as compared to its area. The three largest rivers only deliver 7 300 km^3 yr^{-1} or 24% of the global water runoff. With respect to suspended sediment load, the South American continent contributes 13% of the global load into the oceans. Although most of the discharge and sediment load are due to the Amazon, Orinoco, and Paraná Rivers (Milliman 1990; Milliman and Syvitski 1992), the Magdalena River, which empties into the Caribbean Sea (Fig. 14.1), transports more sediment than either the Orinoco and Paraná Rivers (Milliman and Meade 1983), although it has much smaller water discharge and drainage area.

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 (Kellog and Mohriak 2001) (Fig. 14.1). However, the discharge of suspended sediment into the oceans from many smaller Colombian rivers may have greater impact on the world sediment budget than previously thought (Milliman 1990; Milliman and Syvitski 1992). Further, land use in South American basins is changing rapidly and is seemingly causing changes in water, sediment, and nutrient transports, resulting in regional impacts. From the perspective of ecology and to understand change impact, there is a need to understand better the geochemistry of these rivers (Richey et al. 1991).

Water discharge, sediment load, and physical characteristics for the major Pacific and Caribbean rivers of Colombia have been reported during the past few years (e.g. Restrepo and Kjerfve 2000a,b, 2002). However, until now data for the dissolved load of these rivers have not been reported.

Due to the importance of Colombian rivers in the global budgets (Milliman and Meade 1983; Milliman and Syvitski 1992; Restrepo and Kjerfve 2000a,b), we synthesise data on water discharge, sediment load, and dissolved load of the principal rivers along the Pacific and Caribbean coasts of Colombia, make comparisons to other major fluvial systems draining into the Atlantic Ocean and elsewhere, and present some result-

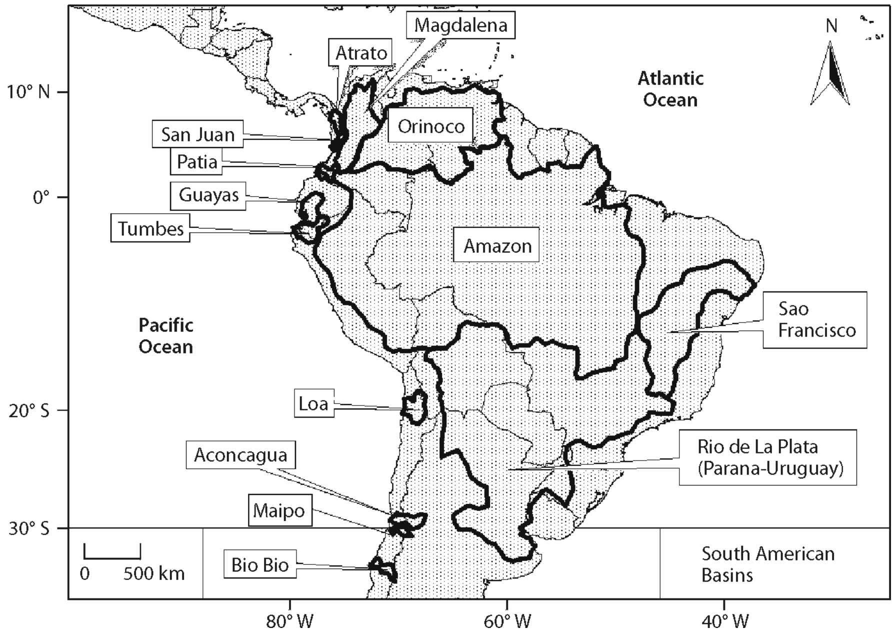

Fig. 14.1. Map showing the major basins in South America draining into the Atlantic Ocean and the smaller Pacific and Caribbean basins of Colombia

ing environmental implications and impacts along the Caribbean. This information is a significant addition to the understanding of (1) chemical weathering processes occurring on a regional scale, (2) the nature of the organic matter from autochthonous and allochthonous sources, (3) fluvial fluxes to oceans and the context of Colombian rivers in the global budgets, and (4) human impacts on continental and coastal water systems.

14.2 Water Discharge and Sediment Load

14.2.1 The Pacific Rivers

Climate, geology, relief, and size of the drainage basin are critical factors that determine river discharge. 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 characterised by the presence of active fault systems, high precipitation rates, slopes frequently steeper than 35°, and dense tropical rain forests. These conditions are favourable 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 principal rivers from north to south are the Baudó, San Juan, Patía, and Mira (Fig. 14.2).

The Pacific basins are located within the humid tropics, characterised by high but relatively constant temperature, high rainfall rates, and high humidity. Average rainfall ranges from 2 000 to 12 700 mm yr^{-1} (Eslava 1992). The rainfall distribution is bi-

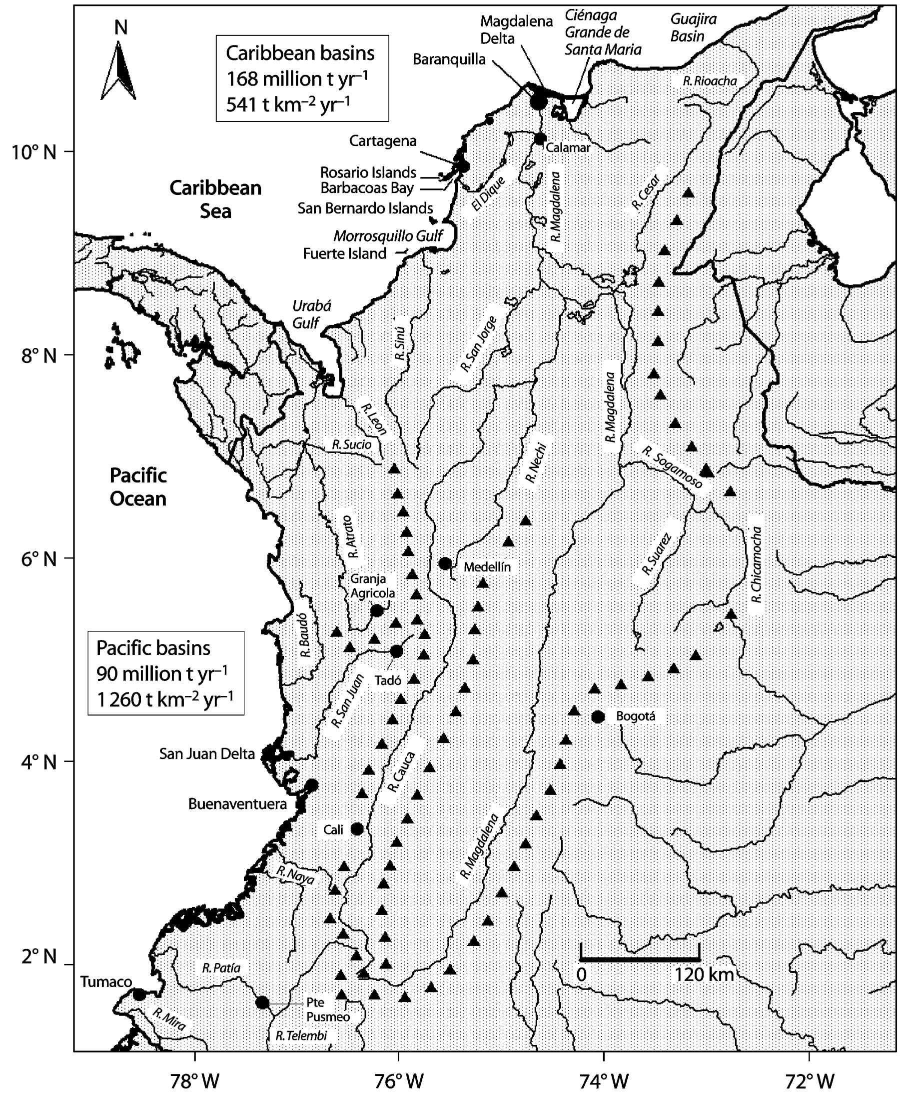

Fig. 14.2. Map of the Pacific and Caribbean coasts of Colombia showing the principal rivers, the main drainage basins indicated in Tables 14.1 and 14.2, the Western, Central, and Eastern Cordilleras (solid triangles), and the estimates of total sediment load and, accordingly, sediment yield into the Pacific Ocean and Caribbean Sea

modal with the highest rainfall occurring from September to November and a secondary rainy season from April to June. The least rain falls from December to March, and rainfall is also moderately low from July to August (Snow 1976; Lobo-Guerrero 1993). Based on rainfall distribution, the Pacific basins are divided into three zones: the northern, central, and southern basins. The northern zone, including the watersheds of the Atrato, Baudó, and San Juan Rivers (Fig. 14.2), receives on average 5 600 mm of rainfall annually. The central zone, which includes the watersheds of the Dagua, Anchicayá, Cajambre, Raposo, Yurumanguí, San Juan de Micay, Iscuandé, Amarales, Satinga, and Sanguianga Rivers, receives on average 4 100 mm of rainfall annually. The southern zone, consisting of the drainage basins of the Patía and Mira Rivers, receives on average 2 000 mm of rainfall annually.

The drainage areas, water and sediment transports for the largest Pacific rivers are synthesised in Table 14.1. Four rivers provide most of the freshwater discharge into the Pacific. The largest is the San Juan River with a mean discharge of 2 550 $m^3 s^{-1}$. The Patía, as gauged at Puente Pusmeo, discharges on average only 328 $m^3 s^{-1}$, but the mean river basin discharge is 1 291 $m^3 s^{-1}$ because of the large contribution from the Telembí River, the last tributary before the delta. The Mira River contributes an average 839 $m^3 s^{-1}$, and the Baudó 782 $m^3 s^{-1}$ (Table 14.1). The annual water discharge into the Pacific Ocean from these four larger rivers and the many smaller Pacific rivers measures 8 020 $m^3 s^{-1}$ or annually 254 km^3.

The Patía has the largest drainage basin of the Colombian rivers draining into the Pacific (23 700 km^2). From the upper river, sediment loads measure 0.88, 15.39, 13,71 and 8.82×10^6 t yr^{-1}, as gauged at La Fonda, Puente Guascas, Puente Pusmeo, and Los Nortes, respectively (Table 14.1). Based on daily measurements from 1988 to 1995 by IDEAM, Instituto de Estudios Ambientales de Colombia (IDEAM 1995), at Los Nortes, 9 km downstream of Puente Pusmeo, and representing an upstream basin area of 14 500 km^2, the maximum recorded sediment load was 245.8×10^3 t d^{-1} in November 1993, and the monthly mean sediment load measured 57.76×10^3 t, corresponding to an annual sediment load of 21.1×10^6 t yr^{-1}. The sediment yield for the Patía River ranges from 972 t $km^{-2} yr^{-1}$ at Puente Pusmeo to 1 714 t $km^{-2} yr^{-1}$ at Puente Guascas, for the upstream-most portion of the river, the highest yield of any measured river in Colombia.

The upper portion of the Mira River has an annual sediment load of 0.234×10^6 t yr^{-1} as gauged at Pipiguay and a sediment yield of 856 t $km^{-2} yr^{-1}$. Because this gauging station is located 130 km upstream and represents only 4% of the total basin area, the load is not included in the Pacific budget. Considering the two gauged rivers at their furthest downstream stations, San Juan and Patía, the measured annual sediment loads of these rivers into the Pacific Ocean is 30.13×10^6 t yr^{-1} (Table 14.1). The Atrato River is a special case. Although the Atrato has its watershed west of the Cordilleras, and thus have many common characteristics with the Pacific rivers, it discharges into the Caribbean Sea (Figs. 14.1 and 14.2). Thus, we did not include the Atrato in the Pacific budgets.

The relation between sediment yield and basin area for the Pacific rivers were determined by log-linear regression of sediment yield on basin area (Restrepo and Kjerfve 2000a). The analysis included only data for the most downstream gauging locations on the San Juan, Patía, and Atrato Rivers (Tables 14.1 and 14.2), and in devel-

Table 14.1. Drainage basin, annual rainfall, measured water and sediment transports, and calculated yields for Colombian rivers draining into the Pacific Ocean

River	Basin area ($\times 10^3$ km^2)	Annual rainfall (mm)	Water discharge (km^3 yr^{-1})	Sediment discharge ($\times 10^6$ t yr^{-1})	Sediment yield (t km^{-2} yr^{-1})	Years of data
Pacific basin						
North basin	21.8	5 600				
R. Baudó	5.4	6 373	23.68	…	…	1980–84
R. San Juan	16.4	7 277	82.1			1970–96
Tadó	1.6	7 410	8.23	2.6	1 570	1986–94
Malaguita	14.3	8 117	82.1	16.42	1 150	1978
Central basin	26	4 100				
R. Dagua	1.7		3.97	…	…	1982–93
R. Anchicayá	1.1		3.53	…	…	1982–93
R. Cajambre	1.9		8.64	…	…	1980–84
R. Naya Yurimangui	2		13.15	…	…	1985–93
R. Yurumangui	1.4		…	…	…	1985–93
R. Sn. Juan Micay	4.4		19.11	…	…	1981–93
R. Saija	1.4		5.23	…	…	1981–93
R. Timbiquí	1.2		4.64	…	…	1981–93
R. Guapi	2.9		11.26	…	…	1981–93
R. Iscuandé	2.1		6.71	…	…	1980–84
R. Tapaje	2.1		5.52	…	…	1980–84
R. Sanguianga	1.5		2.76	…	…	1980–84
Others	2.2			…	…	1980–84
South basin	28.5	2 000				
R. Patía	23.7	2 821	40.74			1972–93
La Fonda	1.8	1 877	1.8	0.88	478	1981–93
Pte Guascas	8.9	833	7.1	15.39	1 714	1972–93
Los Nortes	14.5	1 410	10.39	8.82	608	1985–93
Pte Pusmeo	14.1	1 410	10.34	13.71	972	1972–93
R. Chagui/Cuna		3 054	4.21	…	…	1968–93
R. Mira	4.8	5 546	23.43	0.234		1980–93
Pipiguay	0.2	8 838	3.56	0.234	856	1982–93
Total Pacific	76.3	5 900	254.37	30.13	1 053	

oping this regression, we did include the Atrato. Regression of sediment yield on basin area yielded a decreasing trend for larger basins with a coefficient of determination, $r^2 = 0.97$.

Table 14.2. Drainage basin, annual rainfall, measured water discharge, sediment load, and calculated yields for the Caribbean Rivers of Colombia

River	Basin area ($\times 10^3$ km^2)	Annual rainfall (mm)	Water discharge (km^3 yr^{-1})	Sediment discharge ($\times 10^6$ t yr^{-1})	Sediment yield (t km^{-2} yr^{-1})	Years of data
Caribbean basin						
Urabá Gulf						
R. Atrato	35.7	5318	81.08	11.26	315	1982–93
R. Chigorodó	0.1	2485	0.46	0.2153	1088	1977–93
R. León	0.7	2485	2.01	0.7701	1007	1978–93
R. Vijagual	0.04	2485	0.06	0.0219	548	1977–93
R. Grande	0.07	2485	0.13	0.0438	626	1978–93
R. Zungo	0.05	2485	0.07	0.0292	584	1977–93
R. Apartadó	0.16	2485	0.14	0.0620	585	1984–93
R. Carepa	0.15	2485	0.16	0.3175	2048	1978–93
R. Currulao	0.23	2485	0.31	0.2373	1023	1979–93
R. Guadalito	0.08	2485	0.08	0.0310	369	1979–93
R. Turbo	0.16	2485	0.12	0.0730	445	1966–93
Caribbean basin						
R. Mulatos	1.02	2485	.33	0.2117	208	1978–93
R. Sinú	10.18	1750	11.76	6.1	589	1963–93
R. Canal Dique		1750	9.43	4.76	…	1981–93
R. Magdalena	257.43	1700	228.1	143.9	559	1975–95
Guajira basin						
R. Piedras	0.14	850	0.15	…	…	1974–93
R. Gaira	0.03	850	0.08	0.0014	42	1978–93
R. Guachaca	0.26	450	0.45	0.0113	43	1973–93
R. Don Diego	0.52	450	1.14	0.0226	43	1973–93
R. Ancho	0.54	450	0.47	0.0288	53	1971–93
R. Palomino	0.68	450	0.80	0.0511	75	1973–93
R. Ranchería	2.24	450	0.39	0.1022	46	1976–93
Total Caribbean	311.06		337.68	168.25	541	

The sediment load for the non-gauged area of the Pacific coast was obtained from the regression of sediment yield on basin area, using the gauged data and data for the San Juan, Patía, and Atrato Rivers (Tables 14.1 and 14.2). The mean sediment yield for the non-gauged watersheds is 1827 t km^{-2} yr^{-1}, occupying a combined area of 36100 km^2, and with a calculated sediment load of 66×10^6 t yr^{-1}. The best estimate of total sediment load into the Pacific Ocean from both gauged and non-gauged rivers is 96×10^6 t yr^{-1}. These results in a sediment yield estimate of 1260 t km^{-2} yr^{-1}, very similar to the yield of 1 200 t km^{-2} yr^{-1} proposed by Milliman and Syvitski (1992), based on extrapolation of data for a single river in Peru.

The sediment yields of the upstream San Juan River at Tadó (1 570 t km^{-2} yr^{-1}) and the upstream Patía River at Puente Guascas (1 714 t km^{-2} yr^{-1}) (Table 14.1) are substantially higher than the averages calculated for the entire Pacific coast, and are among the highest values anywhere in the world. The corresponding drainage areas are 1 661 km^2 and 8 900 km^2, respectively. Both rivers descend rapidly from the high Cordilleras to the alluvial plain. Over a distance less than 75 km, the San Juan River falls abruptly from an elevation of 3 900 m to 100 m at Tadó (Fig. 14.2), and the tribute basin descends from elevations between 4 200 and 2 500 m in less than 50 km to join the San Juan River in the upper watershed at an elevation of 90 m. Likewise, the Patía River descends from its headwaters at 4 580 m elevation to 400 m over a distance of 150 km. Since the San Juan drainage basin as a whole has a greater sediment yield compared to the Patía drainage basin (Table 14.1), the explanation for the higher yield of the upstream portions of the Patía implies greater sediment deposition (storage) on the alluvial plains of the Patía. In the case of the San Juan River, the control exerted by the Tertiary formations in the middle and lower courses of the river results in a much narrower alluvial plain as compared to Patía River, and thus less sediment deposition/storage within the drainage basin.

14.2.2 The Caribbean Basins

Caribbean Colombia is principally drained by the Magdalena and Sinú Rivers, and also receives the Atrato drainage from west of the Cordilleras (Figs. 14.1 and 14.2). The Magdalena River measures 1 612 km and drains a 257 438 km^2 basin, which occupies a major portion of the Colombian Andes. It is the largest fluvial system in Colombia and originates from headwaters in the Andean Cordillera at an elevation of 3 300 m. The Sinú River empties into the Morrosquillo Gulf. The Atrato, draining a basin of 35 700 km^2, occupies a considerable portion of the Pacific basin, but the river empties into the Caribbean via the Urabá Gulf (Fig. 14.2).

Analysis of 22 rivers draining into the Caribbean Sea indicates that the combined water discharge and sediment load are 338 km^3 yr^{-1} and 168×10^6 t yr^{-1}, respectively, corresponding to a sediment yield for the Colombia Caribbean drainage basins of 541 t km^{-2} yr^{-1}, or approximately half of the yield for the Pacific basins of Colombia (Table 14.2).

Based on discharge gauging and sediment concentration measurements, the sediment load of the Atrato River is 11.3×10^6 t yr^{-1}, and the corresponding sediment yield 315 t km^{-2} yr^{-1}. The sediment yield is comparatively low because of the large size of the drainage basin and the extensive low-lying Urabá alluvial flood plains, with an area of 5 500 km^2, where significant sediment deposition and storage occur. Besides the Atrato, several other rivers discharge into the Urabá Gulf (Fig. 14.2). These rivers are characterised by having small drainage basins and high sediment yields (Table 14.2). The Sinú River empties into the Golfo de Morrosquillo (Fig. 14.2) and drains an area of 10 180 km^2. Based on monthly data from 1963 to 1993, the annual discharge of the Sinú is 373 m^3 s^{-1}. The sediment load is 6×10^6 t yr^{-1}, based on data from 1972 to 1993, with a sediment yield of 589 t km^{-2} yr^{-1} at Montería (Table 14.2).

The Magdalena River is the largest river system with a length of 1 500 km. It drains the Andes Cordillera, which forms the Western, Central, and Eastern Cordilleras. The drainage basin area measures 257 438 km^2 and occupies a considerable part of the Colombian Andes. Daily water discharge measurements from 1975 to 1995 at Calamar indicate an annual discharge of 7 232 $m^3 s^{-1}$. Load measurements during the 21-year period yielded an annual sediment load of 144×10^6 t yr^{-1}. The calculated sediment yield for the drainage basin area upstream of Calamar is 559 t $km^{-2} yr^{-1}$. The Canal del Dique (Fig. 14.2) is a 114 km long man-made channel from the Magdalena River at Calamar to Bahía de Cartagena and was constructed in 1514 by native slaves by order of Spanish conquistadors. The mean annual water discharge and sediment load through this channel are currently 299 $m^3 s^{-1}$ and 4.8×10^6 t yr^{-1}, respectively (Table 14.2).

The Magdalena River contributes 9% of the total sediment load discharged from the east coast of South America. The 144×10^6 t yr^{-1} estimate of sediment load is higher than the 133×10^6 t yr^{-1} reported by Marín (1992) but considerably lower than the estimate by Milliman and Meade (1983) of 220×10^6 t yr^{-1}. Our sediment load estimate sediment implies a sediment yield of 559 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).

14.3 Dissolved Load

Major natural origins and controls of river-borne materials include atmospheric inputs, chemical weathering of mineral, mechanical erosion of rock and soil particles, and soil leaching. As a result, rivers contain naturally occurring compounds, e.g. major ions (i.e. Ca^{2+}, Mg^{2+}, and HCO_3^-), plant nutrients (e.g. SiO_2, NO_3^-, NH_4^+, and orthophosphates), organic compounds (e.g. humic acids and hydrocarbons), and xenobiotic substances synthesised by humans (Meybeck 2001b).

In the Andes, sedimentary rocks constitute the principal basement lithology, and the river chemistry agrees with basin geology (Stallard 1980, 1985; Stallard and Edmond 1983). The concentrations of major dissolved constituents and mass transport rates for major Colombian rivers including the larger Magdalena, El Dique, Sinú, Atrato, Mira, and Patía (Fig. 14.2) are shown in Table 14.3. Estimates are based on averages calculated from monthly samples from 1990 to 1993 (IDEAM 1995). Ca^{2+} and Mg^{2+} are the dominant ions (Table 14.3), indicating that the water corresponds to the rock-dominated type.

The inorganic carbon concentration was well within the common range of river pH values, which vary between 6 and 8.2. It is 100% due to atmospheric CO_2 and soil weathering in non-carbonate basins, whereas in carbonate basins 50% comes from the dissolution of carbonates and other rocks (Meybeck 1996; Knighton 1998). Dissolved inorganic carbon, present mostly as bicarbonate ions, constitutes almost 50% of the TDS in the Colombian rivers (Table 14.3). High values of alkalinity seem to be well explained by high rates of total dissolved solids (TDS) in all Colombian rivers. Regression of alkalinity concentration (mg l^{-1}) on TDS (mg l^{-1}) yielded a coefficient of determination of 0.98, accentuating the predominance of bicarbonates.

Values of solute concentrations show that the Sinú and Magdalena have the highest dissolved solute content followed by the El Dique canal and Patía River (Table 14.3). The Atrato is by far the most dilute river, four times less mineralised than the larger

Table 14.3. Basic hydrochemical data and dissolved solutes of major Caribbean and Pacific rivers of Colombia for the period 1990–1993. Solute values are expressed as discharge-weighted mean. *TSS* = total suspended solids; TDS = total dissolved solids (*Source:* IDEAM 1995)

Parameter	**River**					
	Caribbean			**Pacific**		
	Magdalena	**Dique**	**Sinú**	**Atrato**	**Mira**	**Patía**
pH	7.1	7.1	7.0	5.9	6.1	6.7
Na^+ (mg l^{-1})	4.6	3.9	4.6	1.1	4.2	9.5
K^+ (mg l^{-1})	1.7	2.0	1.6	1.6	0.8	1.9
Mg^{2+} (mg l^{-1})	11.7	11.6	22.0	1.5	3.1	4.1
Ca^{2+} (mg l^{-1})	36.2	30.1	34.0	4.4	7.0	17.4
Cl^- (mg l^{-1})	9.0	7.2	9.4	2.8	5.2	5.7
SO_4^{2-} (mg l^{-1})	6.0	8.5	8.4	0.2	3.2	15.5
Total ALKAL (–)	60.8	59.7	62.5	18.9	29.3	57.2
SiO_2 (mg l^{-1})	…	…	…	…	…	…
TDS (mg l^{-1})	131	123	142.3	30.5	52.8	111.4
Transport TSS ($\times 10^6$ t yr^{-1})	144	4.8	6.1	11.3	0.2	13.7
Transport TDS ($\times 10^6$ t yr^{-1})	30.0	1.6	1.7	1.1	1.5	0.8
Transport TSS/TDS	4.8	3.0	3.6	10.3	0.1	17.1
Net CO_2 (mg l^{-1})	1.6	7.9	18.1	4.6	7.4	14.8

… = No available data.

Magdalena and the other Caribbean rivers, as a result of its location in a very humid environment. The upper and middle sections of the Atrato are located in regions with very high annual rainfall. The meteorological station at Granja Agrícola Lloró in the upper Atrato basin at an elevation of 120 m has an annual rainfall rate of 12 717 mm, based on data from 1952 to 1989 (Eslava 1992). This, to the best of our knowledge, represents the highest rainfall rate anywhere in South America.

Also, depending on local or regional conditions, natural chemical water composition can differ by two or three orders of magnitude between basins. As a consequence of multiple controls on river chemistry including lithology, climate, and topography, it is inappropriate to refer to any continental or regional averages for comparisons to local data (Meybeck 1996, 2002). In heterogeneous mountains basins, e.g. in the Colombian Andes, stream and river chemistry are highly variable. More detailed studies are needed to establish the natural controls on solute concentrations by each rock type.

Chemical weathering of rocks still remains the main source of dissolved substances. Climate determines where tropical weathering occurs, while tectonics increase erosion rates and dictate the composition of erosion products. In the humid tropics, the primary factor that distinguishes different weathering regimes is tectonic setting. In tectonically active areas, easily weathered lithologies are exposed on steep slopes and weathering rates are lithology dependent (Stallard 1988). Where carbonates and cations are present, their weathering products dominate the river solution chemistry (Table 14.3). Furthermore, the presence of unstable and cation-rich minerals in the suspended load and bedload of rivers draining the Andean basins indicates that rapid erosion is indeed occurring. Thus, along the western portion of the Pacific basins, high temperature, humid conditions, high rainfall, and abundant vegetation promote rapid chemical weathering and high denudation rates (Table 14.1).

The hydrological regime of rivers is a major regulator of their chemical composition. For each chemical element or TDS value, concentrations and fluxes are discharge dependant (Meybeck 1996, 2001a,b). The estimates of dissolved materials exported to the Caribbean and Pacific basins are mainly controlled by water discharge. Thus, the Magdalena transports 30×10^6 t yr^{-1} of dissolved materials into the Caribbean (Table 14.3). The specific transport rate is highest in the Sinú basin, 167 t km^{-2} yr^{-1}, followed by that of the Magdalena (117 t km^{-2} yr^{-1}). The Atrato, Mira, and Patía Rivers have values ranging between 31 and 90 t km^{-2} yr^{-1}.

14.4 Interannual Variability

All South American rivers, independent of size, display a strong seasonal signal of discharge and sediment load variability, typically a factor of 5–10 comparing low monthly to high monthly discharge (Fig. 14.3). The interannual variability of discharge and sediment load associated with the ENSO or El Niño-La Niña cycle can be almost equally great, typically a factor of 2–4, comparing low annual to high annual discharges (Richey et al. 1986, 1989; Depetris et al. 1996; Vörösmarty et al. 1996). This variability can be quantified by the southern oscillation index (*SOI*), which is defined as the difference in atmospheric sea-level pressure between Tahiti and Darwin (Glantz 1997). The cold La Niña phase of the *SOI* is characterised by a positive peak *SOI* of approximately +5 hPa, whereas the warm El Niño phase is characterised by a negative peak *SOI* of approximately –5 hPa (Fig. 14.3a). The El Niño-La Niña cycle gives rise to a significant variability in regional rainfall, river discharge, and sediment load. However, the northern and southern portions of the South American continent have a response that is completely opposite in phase.

El Niño brings about heavy rainfall south of a hypothetical line from Quito, Ecuador, to São Paulo, Brazil. The rivers respond with large increases in both water discharge and sediment load during the Southern Hemisphere's late summer, when extensive river flooding impact Paraná and Santa Catarina, Brazil, the delta of the Paraná River in Argentina, and many other river basins in the south of the continent (Mechoso and Perez-Iribarren 1992; Probst and Tardy 1989). This causes destructive and costly flooding of cities, roads, and agricultural fields and brings about much hardship. At the same time, river basins in South America, north of the front, suffer from drought conditions and low river discharges, which have negative impacts on the regional agriculture and water resources.

In contrast, during the La Niña phase, the southeast trade winds are well developed, and the intertropical convergence zone (ITCZ) remains north of its typical position in the Eastern Pacific. This results in drier than normal conditions in the southern

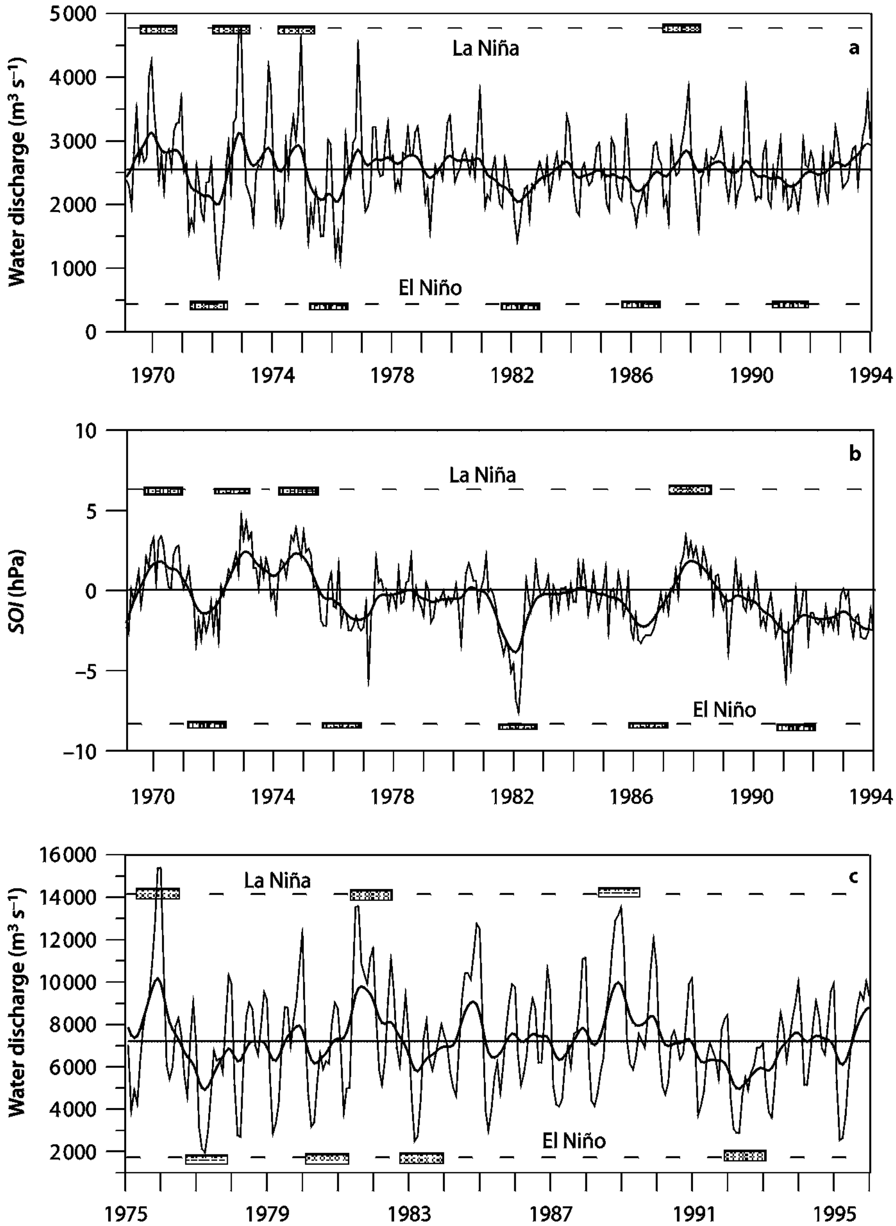

Fig. 14.3. Time series plots of mean monthly (*thin lines*) and low-frequency pass filter with zero phase (*bold lines*); **a** water discharge for San Juan River 1970–1994; **b** the southern oscillation index (*SOI*) (National Oceanic and Atmospheric Administration, NOAA, 1999; data-base on the internet at http://ftp.ncep.noaa.gov/pub/cpc/wd52dg/data/indices); **c** water discharge for Magdalena River 1975–1995 (modified from Restrepo and Kjerfve 2000a,b)

portion of the South American continent but brings about intense rainfall in the northern parts of the continent (Ropelewski and Halpert 1987). Rivers in Colombia (Figs. 14.3a and 14.3c) and Venezuela, in particular, experience catastrophic flood conditions, which often have drastic social and economic impacts.

The San Juan River discharge and the smoothed monthly values of the *SOI* showed very good coherence for the 25-year period from 1970 to 1994 (Fig. 14.3a). Peak flow exceeds 5 000 $m^3 s^{-1}$ during La Niña years and low discharges of 600–1 500 $m^3 s^{-1}$ were observed during El Niño years. Mean annual discharge during El Niño and La Niña years are 3 625 $m^3 s^{-1}$ and 1 490 $m^3 s^{-1}$, respectively. Regression analysis of smoothed *SOI* on smoothed discharge yielded a coefficient of variation of $R^2 = 0.60$, which indicates that variations in the *SOI* explain 60% of the variability in discharge, with high values of the *SOI* corresponding to peak La Niña conditions and peak San Juan discharge. This relationship is similar to the response of Rio Orinoco but contrary to rivers in Perú, Rio Guaiba (Brazil), Rio Paraná (Argentina) (Goniadzki 1999), and other rivers, which experience significantly higher discharges during the warm El Niño phase.

In the Magdalena River, water discharge varies significantly interannually. The mean discharge is 7 200 $m^3 s^{-1}$, and the seasonal root mean square (rms) variability is 2 020 $m^3 s^{-1}$. The Magdalena discharge at the Calamar station (Fig. 14.2) and the smoothed monthly values of the *SOI* show very good coherence for the 21-year period from 1975 to 1995. Peak flows usually exceed 12 000 $m^3 s^{-1}$ during La Niña years, and low discharges of 2 000–3 000 $m^3 s^{-1}$ are observed during El Niño years (Fig. 14.3c). Mean annual discharges during El Niño and La Niña years are 5 512 $m^3 s^{-1}$ and 8 747 $m^3 s^{-1}$, respectively.

14.5 The Colombian Rivers and the Global Trend

Rivers with smaller basins have less area to store sediments, and the sediment yield of smaller basins increases as much as sevenfold for each order of magnitude decrease in basin area. The result is that many rivers draining smaller basins can have higher yields than rivers draining larger basins (Milliman 1990; Milliman and Syvitski 1992).

In comparing rivers with small basins in high rainfall areas in both Colombia and Asia/Oceania (Fig. 14.4), the San Juan and Patía Rivers are similar in terms of water discharge, sediment load and yields, to the Purari and Fly Rivers in Papua New Guinea. Average annual rainfall ranges from 2 000 mm 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 2 390 $m^3 s^{-1}$ and a sediment yield of 1 500 t $km^{-2} yr^{-1}$ (Pickup et al. 1981). 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 76 000 km^2 size of the Fly, it has greater water discharge. The yield of the Fly, 1 500 t $km^{-2} yr^{-1}$, is very similar to the yield of the upper San Juan and Patía Rivers (Table 14.1).

Mountainous rivers with basin areas of ~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 2–3 than rivers draining most other mountainous areas of the world. The Pacific basins of Colombia have yields between 1 150 and 1 714 t $km^{-2} yr^{-1}$, which are very simi-

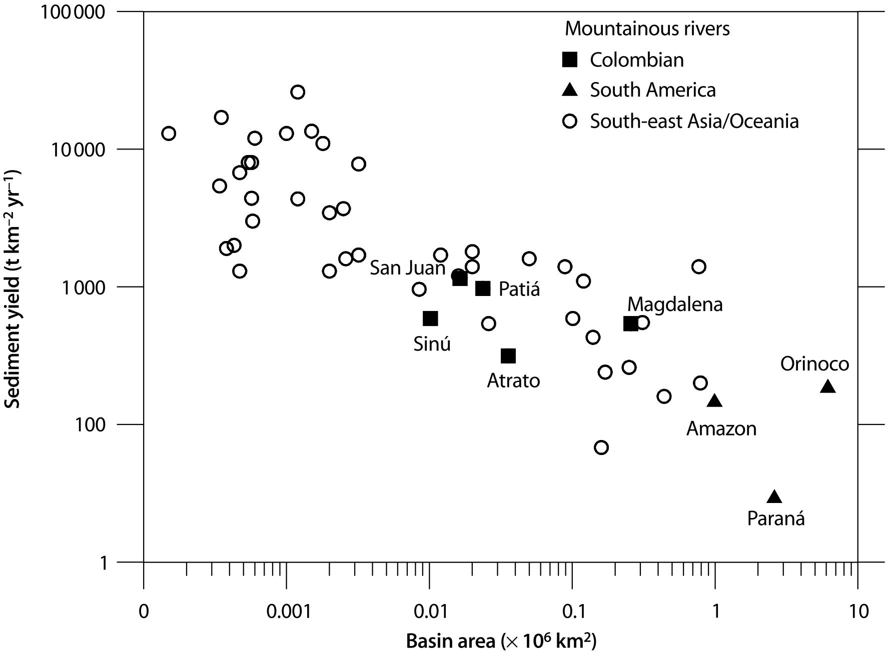

Fig. 14.4. Variation of sediment yield with basin area for several mountainous rivers of Asia/Oceania, South America (Amazon, Orinoco, and Paraná) and Colombian rivers draining into the Caribbean Sea (Magdalena, Sinú, and Atrato) and into the Pacific Ocean, San Juan and Patía

lar to rivers draining mountainous terrain and high rainfall areas in South Asia and Oceania (Fig. 14.4).

The data shown in Tables 14.1–14.3 confirm that the Pacific rivers have smaller drainage basins but much higher yields than the Caribbean rivers and those draining eastern South America (Amazon, Orinoco, Paraná) (Fig. 14.4). The Patía and San Juan Rivers appear to have the highest sediment yields of any river in South America, and have many characteristics comparable to the rivers of Papua New Guinea and Taiwan, based on rainfall, mountainous terrain, small river-basin area, and high sediment transport.

The Magdalena River has the highest sediment yield of the large rivers along the Caribbean and Atlantic coasts of South America. Its yield is almost three times greater than the yield of the Amazon, 190 t $km^{-2} yr^{-1}$, Orinoco, 150 t $km^{-2} yr^{-1}$, or Negro (Argentina), 140 t $km^{-2} yr^{-1}$ (Milliman and Syvitski 1992), and much greater than the yield of the Paraná, 30 t $km^{-2} yr^{-1}$ (Milliman and Syvitski 1992; Goniadzki 1999), Uruguay, 45 t $km^{-2} yr^{-1}$, and São Francisco, 10 t $km^{-2} yr^{-1}$ (Milliman and Syvitski 1992) (Table 14.4).

The dissolved load for the Magdalena, 30×10^6 t yr^{-1} (Table 14.3), is of the same magnitude as the Orinoco (30.5×10^6 t yr^{-1}; Depetris and Paolini 1991), ten times lower than that of the Amazon (259×10^6 t yr^{-1}; Meybeck 1976), and similar to the Parana River (38.3×10^6 t yr^{-1}; Depetris 1976; Depetris and Paolini 1991) (Table 14.4).

Table 14.4. Drainage basin, water discharge, sediment and dissolved loads, calculated yields, and receiving basin for some rivers of South America (from Depetris 1976; Meybeck 1976; Milliman and Meade 1983; Depetris and Paolini 1991; Milliman and Syvitski 1992; Goniadzki 1999; Restrepo and Kjerfve 2000a,b)

River	Basin area ($\times 10^3$ km^2)	Water discharge (km^3 yr^{-1})	Sediment load ($\times 10^6$ t yr^{-1})	Sediment yield (t km^{-2} yr^{-1})	Dissolved load TDS ($\times 10^6$ t yr^{-1})	Receiving basin
R. Amazon (Brazil)	6.15	6300	1200	190	290	N. Atlantic
R. Orinoco (Venezuela)	0.99	1100	150	150	30	N. Atlantic
R. Paraná Argentina)	2.60	470	79	30	38	S. Atlantic
R. Magdalena (Colombia)	0.25	228	144	560	30	Caribbean
R. Atrato (Colombia)	0.035	81	11	315	1.0	Caribbean
R. Uruguay (Uruguay)	0.24	253	11	45	6(?)	S. Atlantic
R. Negro (Argentina)	0.10	30	13	140	…	S. Atlantic
R. S. Francisco (Brazil)	0.64	97	6	10	…	S. Atlantic
R. San Juan (Colombia)	0.014	82	16	1150	…	N. Pacific
R. Patía (Colombia)	0.014	10	14	972	0.8	N. Pacific
R. Chira (Peru)	0.020	5	20	1000	…	S. Pacific

The major rivers of Colombia fit well into the global river chemistry classification developed by Gibbs (1970), with Ca^{2+} and HCO_3^- dominating the ionic composition. Also, values of dissolved solutes are in the range of the most common natural concentration (MCNC) found in most rivers. This classification was proposed by Meybeck and Helmer (1989) to replace the "average world river," which is greatly influenced by a few rivers of extreme concentrations. Thus MCNC is simply the median value of the distribution of concentrations found in pristine major rivers, weighted by the river discharge. The ionic natural composition by Colombian rivers with respect to $Ca^{2+} > Mg^{2+} > Na^+ > K^+$ and $HCO_3^- > SO_4^{2-}$ is similar to the MCNC of other world rivers (cf. Meybeck 1996).

14.6 Environmental Implications

During the past fifty years, the Caribbean rivers and downstream coastal areas have been under increasing environmental stress. Economic development in Colombia between the 1970s and 1980s increased demand for river control and utilisation. Ongoing trends in the drainage basins include (1) escalating population densities along the basins and at the river mouths. The main cities of Colombia, including Bogotá, Medellín, Cali, and Barranquilla are located in the Magdalena basin (Fig. 14.2). As much as 80% of the entire population of Colombia lives in the Magdalena watershed, leading to a demographic density of 54 inhabitants km^{-2}, which is very high when compared to 0.24 inhabitants km^{-2} in the Amazon basin (Serruya and Pollingher 1984; Depetris and Paolini 1991); (2) accelerating upland erosion rates due to poor agricultural practices, increasing deforestation and gold mining; and (3) as a result of poor agricultural practices and deforestation, increasing levels of water pollution. As a result, river-induced impacts have produced distortion of natural hydrographs, in turn leading to the loss of critical habitat, biodiversity, and altered material transport (Colciencias-Fen 1989; HIMAT-INGEOMINAS 1991; Restrepo and Kjerfve 2000b). Although these facts have been widely recognised, there are until now no quantification of the fluxes for the Magdalena River.

Sediment load of the Magdalena River has strongly impacted the coastal ecosystems. Since 1954, the government of Colombia has dredged the El Dique Canal, a 114 km man-made channel from the Magdalena River at Calamar to Cartagena Bay (Fig. 14.2). Because of increased sedimentation in Cartagena Bay during the 1970s, new canals were constructed from El Dique to Barbacoas Bay, and since then, the suspended sediment load in Barbacoas has reached and impacted the El Rosario Islands (Fig. 14.2), a 68 km^2 coral reef ecosystem in the Caribbean Sea. Sediment load is responsible for most of the observed coral reef mortality, with dead coral reef cover reaching 58% (Vernette 1985; INVEMAR 2000b). Also, the suspended sediment load from the Sinú River is probably responsible for the impact on the largest coral reef on the Colombian Caribbean coast, the San Bernardo and Fuerte Islands, a 135 km^2 coral reef community north and south of the Morrosquillo Gulf (Fig. 14.2). Live coral has, in some areas, decreased 25% of the 1995 cover (INVEMAR 2000b).

Water diversion due to the construction of a highway in the Magdalena delta/lagoon complex, the Ciénaga Grande de Santa Marta, has resulted in hypersalinisation of mangrove soils and the consequent die-off of almost 270 km^2 of mangrove forests during the past 39 years. Between 1956 and 1995, 66% of the original mangrove forest died (Botero 1990; Cardona and Botero 1998). Recent estimates indicate that for the whole Magdalena lagoon/delta complex and associated coastal zones, the mangrove area has been reduced from 62 000 ha in 1991 to 52 478 ha in 1996, almost 2 000 ha yr^{-1} (INVEMAR 2000b). In addition, freshwater input from the Magdalena River to the lagoon was also diverted for irrigation purposes and interrupted by dikes built along the delta distributaries to prevent flooding of farmlands. The changes in the hydrological regime have also caused water quality changes in the lagoons and canals, resulting in low dissolved oxygen concentration, fish kills, and eutrophication (Botero 2000).

Fluvial geochemistry and material fluxes have already been much altered on the global scale by agriculture, deforestation, mining, urbanisation, industrialisation, irrigation, and damming. The continental aquatic systems are now affected by hypoxia, eutrophication, salinisation, and contamination by nitrate, metals, and persistent organic pollutants. Phosphate (PO_4^{3-}) and nitrate (NO_3^-) increases are observed in most rivers exposed to human pressure (Meybeck 2001b). Their sources are multiple. Since the 1950s, the use of nitrogen and of phosphorous, both as fertilizers, and in the food, detergent, and other industries, have resulted in a rapid increase of fluvial N and P fluxes, now exceeding the pristine levels by a factor of ten in some world rivers (Meybeck 2002).

In Colombia, pristine fluvial systems like those draining the Pacific basins have much less PO_4^{3-} and NO_3^- loads when compared to the Caribbean rivers (Table 14.5). The Magdalena and Atrato Rivers are the Colombian systems that contribute by far the highest P and N fluxes to the sea, with total phosphate and nitrate fluxes up to 186×10^3 t yr^{-1} and 47×10^3 t yr^{-1}, respectively (Table 14.5). Many causes are responsible

Table 14.5. Nutrient fluxes of phosphate (PO_4^{3-}) and nitrate (NO_3^-) in pristine Pacific rivers and non-pristine fluvial systems of the Caribbean basins of Colombia. Nutrient values are based on averages calculated from monthly samples covering the three-year period 1998–2000 (*Source:* INVEMAR 2000a, 2001; Restrepo and Kjerfve 2000a)

River	Water discharge ($km^3 yr^{-1}$)	Total nitrate (NO_3^-) ($\times 10^3$ t yr^{-1})	Total phosphate (PO_4^{3-}) ($\times 10^3$ t yr^{-1})
Caribbean			
Magdalena	228	186	47
Dique	9.4	12	3.0
Sinu	11.8	1.5	0.07
Leon (Uraba Gulf)	2.1	2.5	0.7
Atrato (Uraba Gulf)	81	58	2.4
Turbo (Uraba Gulf)	12	0.1	0.003
Pacific			
San Juan		25	4.0
Anchicaya	3.5	1.5	0.1
Dagua	3.9	1.5	0.1
Raposo	5.6	1.4	0.1
Guapi	11.2	9.5	0.01
Iscuande	6.7	9.5	0.01
Mira	23.4	14	0.2
Micay	19.1	9.9	0.02

for these high nutrient loads, including massive sewage collection in cities and towns for NH_4^+ and PO_4^{3-}, mainly in the Magdalena basin, and also due to fertilization of banana plantations in the lower course of the Atrato River.

Magdalena is the major collector of municipal and industrial waste waters in Colombia. Urban, agricultural, mining, and industrial waste inputs from the Magdalena basin have aggravated the conditions of the Ciénaga Grande lagoon and coastal ecosystems. Biodiversity has been reported to be considerably lower in the area affected by mangrove mortality as well as in the coastal zone (Botero 2000; INVEMAR 2000a). Declining fisheries from 63 700 tons in 1978 to 7 850 tons in 1998, an approximate decline of eight times in less than 20 years, is a strong declination for any living resource, and indicates low environmental and water quality conditions as well as the absence of policies and management (Beltrán et al. 2000). The fluvial inputs of the Magdalena River into the Caribbean have great environmental and economic impacts on the coastal ecosystems.

14.7 Conclusions

The results indicate that the sediment yield in the smaller Pacific rivers, San Juan and Patía (Figs. 14.1 and 14.2), is significantly higher than for larger river basins draining into the Caribbean and Atlantic Oceans (Table 14.4). However, the Magdalena, the largest river discharging directly into the Caribbean Sea, has the highest sediment yield of any medium-sized or large river along the entire east coast of South America. This is consistent with the global trend of sediment yield decreasing for larger basins.

The data also confirm that the San Juan River appears to have the highest yield of any documented river in South America and has many characteristics comparable to rivers in Papua New Guinea and Taiwan, based on drainage basin characteristics, rainfall, relief, area, and sediment load. The rivers in Colombia exhibit significant discharge variability as a result of ENSO.

Many Colombian rivers, including the larger Magdalena, are affected by deforestation and rapid changes in land use, thus accelerating the transfer of particulate and dissolved organic and inorganic matter from the river basins to the sea. Due to the magnitude of fluvial fluxes to the oceans from the Colombian rivers (Tables 14.4 and 14.5), the fluctuations of dissolved and suspended loads need to be monitored for a period of at least ten years, in order to be able to quantify the influences of man's activities and assess global climate.

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