5

Rivers

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River basins and river characteristics are controlled in part by their tectonic setting, in part by climate, and increasingly by human activity. River basins are defined by the tectonic and topographic features of a continent, which determine the general pattern of water drainage. If a major river drains to the ocean, its mouth is usually fixed by some enduring geologic structure, such as a graben, a downwarp, or a suture between two crustal blocks. The largest river basins constitute drainage areas of extensive low-lying portions of Earth's crust, often involving tectonic downwarps. The magnitude of river flow is determined by the balance between precipitation and evaporation, summed over the drainage area. Seasonality of flow and water storage within any basin are determined by the seasonality of precipitation in excess of evaporation, modified in some regions by water stored in snow packs and released by melting, and by water stored in wetlands, lakes, and reservoirs. Increasingly the flows of rivers are influenced by human land use and engineering works, including dams, but in South America these anthropogenic influences are generally less intense and widespread than in North America, Europe, and much of Asia. Thus the major rivers of South America can be viewed in the context of global and regional tectonics and climatology (see chapters 1, 2, and 3). For reference, figure 5.1 outlines South America's three largest river basins—the Orinoco, Amazon, and Paraguay-Paraná systems—while figure 5.2 shows the locations of rivers referred to in the text against a background of the continent's density of population per square kilometer.

5.1 Structural Controls over River Basins

The geologic history of South America has bequeathed to the continent a number of structural elements that are relevant to the form and behavior of its three major river systems (fig. 1.2). These structural elements are (1) the Andes; (2) a series of foreland basins, approximately 500 km wide immediately east of the Andes and extending southward from the mouth of the Orinoco to the Chaco-Paraná basin, where the crust is depressed by the weight of the Andes and the sediment derived from the mountains; (3) the Guiana and Brazilian shields reflecting Precambrian cratons and orogenic belts of mostly crystalline metamorphic rocks, partly covered with flat-lying sedimentary rocks and deeply weathered regolith; and (4) the Central Amazon Basin, a large cratonic downwarp with some graben structures dating back to early Paleozoic time, which runs generally east-west between the two shields, connecting the foreland basins to the west with a graben that localizes the Amazon estuary at the Atlantic coast.

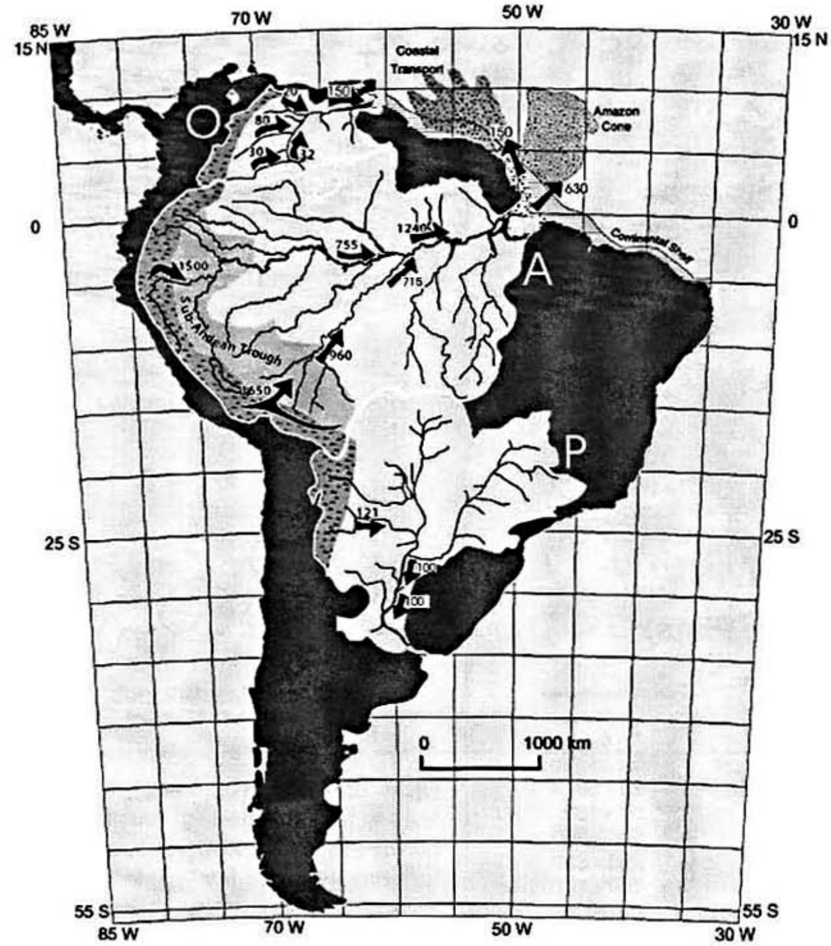

Figure 5.1 The three largest river basins of South America: Orinoco (O), Amazon (A), and Paraguay-Paraná or Rio de la Plata system (P). Data for suspended sediment transport are shown for each river (Orinoco, R.H. Meade, personal communication; Amazon—Subandean Trough and Madeira River, Aalto et al., 2006; Amazon mainstem, Dunne et al., 1998).

In the above context, the assembly and development of these river basins have been plausibly linked to several tectonic and climatic factors. The Mesozoic opening of the Atlantic Ocean fixed the mouths of the Amazon and Paraguay-Paraná systems in rifts that extended into the continent (Potter, 1978). The Oligocene-Pliocene rise of the Andes then closed off the marine embayments in the Central Amazon Basin from former outlets westward to the Gulf of Guayaquil and northward to the Gulf of Maracaibo. This closure caused the drainage of a vast area (soon to be the modern Amazon Basin) to seek a path eastward towards the topographic low provided by the still active graben that presently localizes the mouth of the Amazon (fig. 5.1). Simultaneously, orogenic uplift also created the foreland basins east of the Andes, as the mountains pushed over the downwarping cratons, thereby forming a partial trap for a large fraction of the sediment emanating from the mountains. Meanwhile, mantle-plume driven fracturing of the crust at triple junctions and aulacogens, and hotspot doming during continental separation, caused topographic highs to develop near the rifted margin of southeast Brazil, producing a drainage system that converges first inland into the Paraná basin before leaving the continent through the Río de la Plata estuary (Cox, 1989). Within the cratonic shields, transcurrent sets of faults at angles of 90 to 100° to one another appear to have resulted from crustal tension since at least Miocene time when collapse of the Nazca and Caribbean plates began. Most rivers and lakes on the central Brazilian Shield are aligned with these fracture systems and have reticulated courses with sharp bends (Sternberg and Russell, 1952). Finally, tilting and folding have occurred within the basins between the cratons, as exemplified by the presence of structural highs or arches along the Amazon River valley (Tricart, 1977; Caputo, 1984, 1991). These apparently ongoing structural processes have been shown to impact the fluvial geomorphology in their vicinity, with the arches associated with the narrowing of the valley and changes in modern water-surface gradients (Birkett et al., 2002; Dunne et al., 1998; Latrubesse and Franzinelli, 2002; Mertes et al., 1996).

Potter (1978) originally systematized the relationships between large rivers and tectonic context, illustrating that

Figure 5.2 Locations of rivers discussed in text and table 5.1, overlain onto population density map of South America [Center for International Earth Science Information Network (CIESIN), 2000]. Small rivers are underlined, medium rivers are in italics; large rivers are normal.

not only their sizes but also other features such as their sediment loads and valley geomorphology could be related to their geological context. Figure 5.3 summarizes the classification scheme that Potter developed to express the tectonic contexts of certain kinds of rivers across the globe. Examples of each class in his scheme, which we have labeled with P-values in the figure, can be recognized in South America.

P1 rivers are those that flow from an active orogen that fringes a craton (Amazon) or a stable crustal platform such as Patagonia (Colorado). A large debris load is injected into the upper end of the river system, but little is supplied from the downstream parts of the basin. River systems transport a portion of their load across the lowland, depositing large fractions of it along the way, especially in foreland or intracratonic basins. Floodplains usually increase in width with distance downstream, but with significant variations in width because of structural patterns. Since the Amazon is exceptionally long, only a small fraction of the input reaches the ocean.

P2 rivers, such as the Paraguay, flow roughly parallel to an orogen and receive all their sediment loads from the tributaries on one bank. These rivers therefore often construct depositional wedges and large alluvial fans at tributary junctions, thereby diverting the main stem away from the mountain front. The Orinoco is intermediate between the P1 and P2 types.

P3 rivers flow in tectonic depressions along the strike of mountain ranges. South American examples include the Magdalena in Colombia, with an alluvial plain 30 to 100 km wide (Garcia Lozano and Dister, 1990), and the Marañon in Perú, which travels northwest through the high north-central Andes before crossing to the east to join the Amazon main flow.

P4 rivers are those that flow across mountain ranges, exemplified by the irregular courses of the Ucayali in eastern Perú and the Pilcomayo in eastern Bolivia, which flow through Subandean ranges toward the Amazon and Paraguay-Paraná systems, respectively.

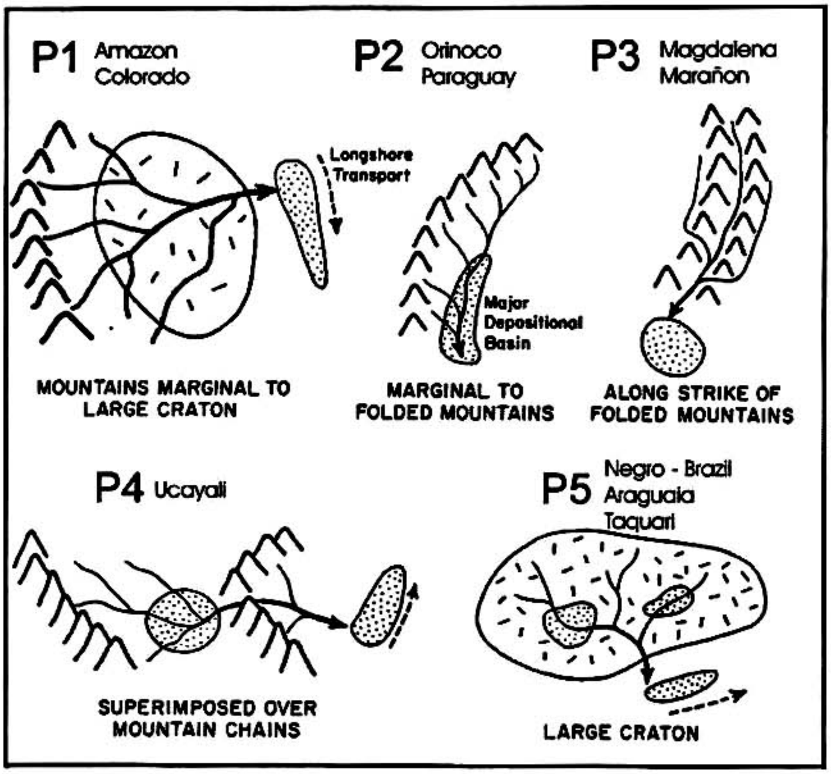

Figure 5.3 Potter classification for continental setting of large rivers (Potter, 1978, fig. 7). P1-P5 labels are assigned for reference. South American rivers cover all categories.

P5 rivers drain large cratonic areas without a significant mountain source. These rivers, such as Brazil's Negro, Araguaia, and Taquari, have relatively low sediment loads and thus narrow or no floodplains, except where they flow into large structural depressions, such as the Taquari, which flows into the Pantanal wetland before reaching the Paraguay River (Ussami et al., 1999).

5.2 Long-term Climate Controls over River Basins

Late Cenozoic climate changes have directly affected the modern form and behavior of South American rivers. Glacial-interglacial cycles of the past few million years have influenced the magnitude, frequency, and seasonality of precipitation and runoff, the nature of sedimentation on the megafans of the Andean foreland and in river floodplains, and the vegetation cover of river basins (see chapters 2 and 9). The growth and decay of glaciers in the tropical Andes have affected the Amazon system (see chapter 4), just as the waxing and waning of the Patagonian ice cap have shaped proglacial lakes and drainage systems in the southern Andes (Clapperton, 1993).

Indirectly, the late Cenozoic eustatic sea-level changes that accompanied these climate cycles have had major impacts on the mouths of most rivers, and these have been transmitted upstream for varying distances. The low sea levels that coincided with Pleistocene glacial stages lowered the base levels of erosion for rivers, causing them to scour sediment from their estuaries and floodplains. Many of the river valleys on the western slopes of the Andes in central and southern Chile were also deeply scoured by glaciers and then dammed by glacial debris, causing modern rivers to flow through glacial lakes into fjords (see chapter 15; Clapperton, 1993). In contrast, the higher sea levels of warm interglacial stages raised base levels and favored sedimentation in these scoured lower reaches. Thus, in response to high Holocene sea level, the scoured depression of the lower Orinoco floodplain and delta, which lies relatively close to its Andean sediment source, has filled with sediment. Similar infilling is occurring in the lower reaches of many smaller rivers flowing from the Andes.

By contrast, the mouth of the Amazon, though having a huge sediment source in the Andes, has not yet filled during the Holocene because the mountains are far from the coast and separated from it by large foreland basins that trap sediment. During episodes of low sea level in the lower Amazon valley, knickpoint recession appears to have extended upstream at least to the vicinity of the Purús arch, a structural high several hundred kilometers above Manaus (Mertes and Dunne, in press; Mertes et al., 1996), and up each of the tributaries farther downstream (Tricart, 1977), and to have removed a wedge of sediment that exceeded 100 m thick at the coast. Postglacial sea-level rise has caused sedimentation in the lower river valley, but this reach remains underfilled with sediment, with large irregular lakes and a large delta plain several hundred kilometers from the mouth of the estuary, in which 300–400 × 10^6 t yr^{-1} of sediment are being trapped (Dunne et al., 1998). Rapid aggradation of the lower Amazon floodplain has also raised the base level of major tributaries draining the forested cratons. However, because these rivers supply only small amounts of sediment, they are unable to fill in behind the natural dams produced by main-stem sedimentation, thereby forming ria lakes with small deltas at their heads (Siolli, 1968; Tricart, 1977).

During episodes of low sea level, the Amazon flushed sediment across the continental shelf to feed the massive Amazon Cone beyond the continental slope (fig. 5.1; Damuth and Kumar, 1975; Manley and Flood, 1988; Milliman et al., 1975; Nittrouer et al., 1986b). In contrast, under present high sea level at the mouth of the Amazon, deltaic sedimentation is minimal owing to the strength of tidal currents and littoral drift on the shelf, with currents transporting the majority of the sediment plume to the north (see chapter 15; Augustinus, 1982; Kuehl et al., 1982, 1986; Nittrouer et al., 1986a, 1986b; Pujos et al., 1997). Similarly, in the lower Paraguay-Paraná valley, modern sedimentation is focused on the delta at the head of the Río de la Plata estuary, hundreds of kilometers from the open ocean.

5.3 Patterns of River Flow

A convenient separation of the rivers of South America occurs at about 15°S latitude, dividing rivers flowing northward from those flowing to the south. The northern rivers drain a very wet region which, together with the sizes of the tectonic basins, creates rivers with exceptionally large discharge, width, depth, and extensive floodplain inundation lasting for months, particularly for the Amazon, Orinoco, Tocantins, Magdalena, and São Francisco rivers. Lewis et al. (1989) calculated that the northern region of 12 × 10^6 km^2, with a mean annual precipitation of 1,700 mm, generates more river runoff (averaging 850 mm) than any other comparably sized region in the world. The southern portion of the continent is smaller and drier, and therefore its rivers are generally smaller, and the largest by far, the Paraguay-Paraná system, drains the subtropical and tectonically most active southern basin. For present purposes, we will compare rivers according to their annual volume of flow, expressed as depth of runoff (annual runoff as volume per unit area of drainage basin in table 5.1); their mean annual discharge; and their seasonality, expressed in terms of the range and timing of monthly flows. Table 5.1 presents these statistics for a sample of rivers, selected to illustrate differences within the continent.

5.3.1 *Inter-Annual Variability*

Even in the largest rivers of the continent, there is a significant and persistent deviation from average annual flows (fig. 5.4). Richey et al. (1989) demonstrated that low annual flows for the Amazon have occurred during El Niño years when ocean circulation anomalies associated with El Niño–Southern Oscillation modify both the intensity and location of the energy source for atmospheric heating and circulation (see chapter 19; Molion, 1990). The ascending east-west branch of the Walker Circulation that usually covers the Amazon basin is displaced westward over the abnormally warm east Pacific Ocean, and intensifies. The descending branch of the circulation then covers the Amazon, reducing rainfall. Molion (1990) quotes reduc-

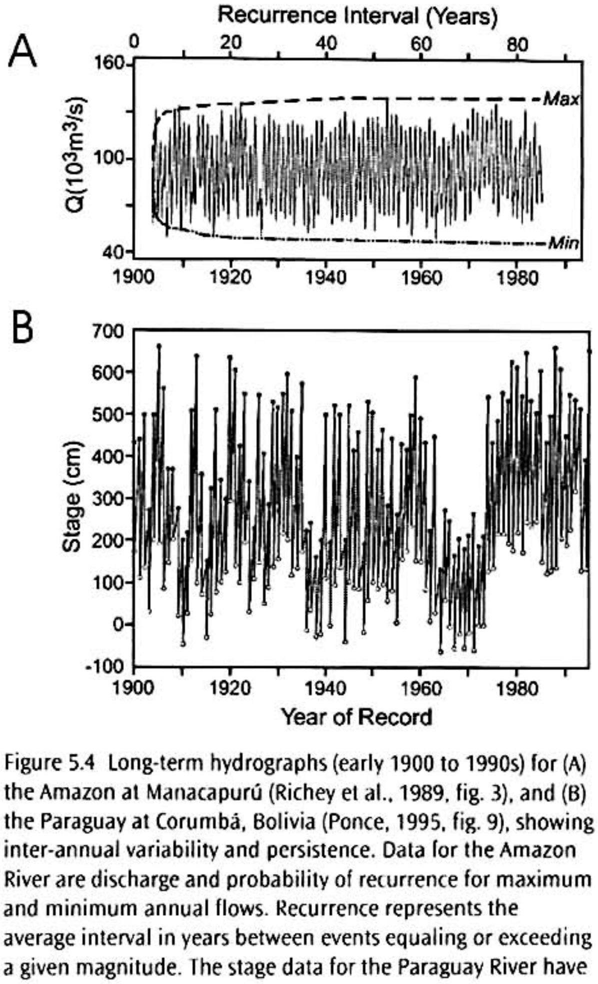

Figure 5.4 Long-term hydrographs (early 1900 to 1990s) for (A) the Amazon at Manacapurú (Richey et al., 1989, fig. 3), and (B) the Paraguay at Corumbá, Bolivia (Ponce, 1995, fig. 9), showing inter-annual variability and persistence. Data for the Amazon River are discharge and probability of recurrence for maximum and minimum annual flows. Recurrence represents the average interval in years between events equaling or exceeding a given magnitude. The stage data for the Paraguay River have not been transformed to discharge.

Table 5.1 Flow characteristics of selected South American rivers

Scale	Basin area [km²]	Country	River	Mean annual flow [m³ s⁻¹]	Annual runoff [mm]	Maximum monthly discharge [m³ s⁻¹]	Minimum monthly discharge [m³ s⁻¹]	Source
Large								
	4,620,000	Brazil	Amazonas	173,167	1182	229,000	103,000	5
	3,100,000	Argentina	Rio de la Plata	18,200	185			4
	2,300,000	Argentina	Paraná	20,663	283	23,700	17,350	4
	1,306,000	Brazil	Madeira	29,300	707	54,000	5,400	5
	1,100,000	Venezuela	Orinoco	38,000	1300	81,100	1,330	1
	1,095,000	Argentina	Paraguay	4,550	130			4
	727,900	Brazil	Tocantins	8,318	360	16,657	2,053	4
	510,800	Brazil	São Francisco	2,162	133	3,799	1,163	4
	468,000	Brazil	Negro	29,560	1990	58,000	13,200	5
	320,290	Brazil	Araguaia	6,100	601	23,000	800	4
	266,600	Colombia	Magdalena	7,018	830	11,374	1,800	2
	199,200	Colombia	Caquetá	13,180	2090			2
	166,200	Colombia	Guaviare	8,200	1560			2
Medium								
	95,000	Argentina	Negro	581	193	934	373	4
	69,000	Bolivia	Beni	2,274	1039	5,388	728	4
	63,000	Uruguay	Negro	1,139	570	3,749	285	4
	53,160	Colombia	Putumayo	6,250	3707			2
	35,700	Colombia	Atrato	4,155	3670			2
	35,000	Brazil	Taquari	732	659	4,470	92	3
	29,000	Argentina	Salado	12	13	40.5	0.5	4
	24,300	Chile	Bio Bio	1,014	1300	2,000	230	4
	22,300	Argentina	Colorado	85	120	288	31	4
Small								
	13,100	Colombia	Patia	205	491	310	105	4
	2,300	Ecuador	Zapotal	297	4072	627	64	4

Data sources: 1. Warne et al. (2002); 2. Garcia Lozano and Dister (1990); 3. Souza et al. (2002); 4. Vörösmarty et al. (1996, 1998); and 5. Richey et al. (1989).

tions of up to 1.8 standard deviations in rainy season totals in the northwest Amazon basin (the wettest region) and 0–1.2 standard deviations in the central and eastern portions of the basin. By contrast, the southwest Amazon basin, at 10°S latitude and closer to the perturbed offshore area of the east Pacific, shows an increase of up to 1.2 standard deviations in rainy season rainfall. In agreement with this pattern, figure 5.4A illustrates the trend in Amazon discharge at Manaus for much of the twentieth century, calibrated by Richey using modern discharge measurements. A more persistent, but still unexplained pattern of low- and high-flow years is exhibited by the record from the upper Paraguay River near Corumbá, Bolivia (fig. 5.4B).

5.3.2 Seasonality

Runoff responds to the seasonal pattern of rainfall (see chapter 3) but lags behind the rainfall record as a result of storage as groundwater and along the floodplains of large alluvial rivers. Figure 5.5 shows the mean monthly hydrographs for several of the rivers listed in table 5.1. The hydrographs are arranged to correspond generally to large (A), medium (B), and small (C) rivers. The largest rivers have discharge maxima ranging from 10,000 to 240,000 m³ s⁻¹, with marked seasonality that varies based on their locations relative to the Equator. With decreasing size, the yearly rise and fall observed for the largest rivers becomes more irregular, with the Negro in Argentina showing the greatest number of peaks.

The seasonality of precipitation over South America is controlled mainly by the annual north-south interhemispheric march of the insolation maximum and consequent land-surface heating (see chapter 3, especially fig. 3.2). This is the signal, lagged by one to three months as a result of groundwater and floodplain storage, that is reflected in the hydrographs of the largest rivers (fig. 5.5). The Tocantins River, a major Southern Hemisphere tributary of the Amazon, has a peak flow in March–April, soon after the rainfall

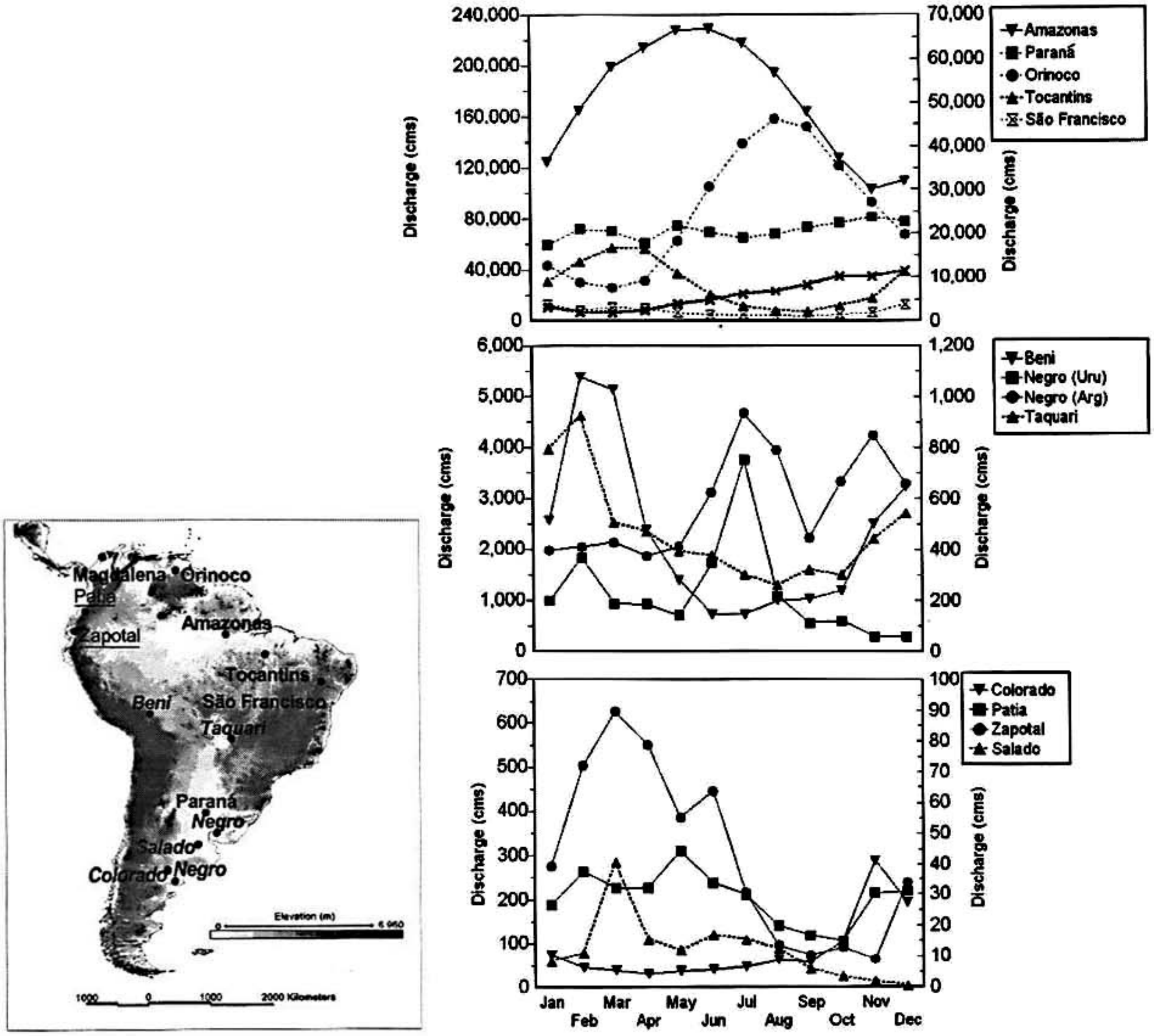

Figure 5.5 Seasonal hydrographs of mean monthly discharge for representative large, medium, and small rivers for which discharge data are available (see table 5.1). Solid lines relate to the left y-axis for the Amazonas, Beni, Negro (Uruguay), Colorado, Patia, and Zapotal rivers. Dotted lines relate to the right y-axis for the Paraná, Orinoco, Tocantins, São Francisco, Negro (Argentina), Taquari, and Salado rivers. The location map (based on USGS shaded relief map GTOPO30) shows gauging stations for which data are plotted (small rivers underlined, medium rivers in italics, and large rivers in normal font). Discharge data for the Taquari River are based on Souza et al. (2002) and for all other rivers on Vörösmarty et al. (1996, 1998).

peak, whereas the Orinoco River in the Northern Hemisphere peaks in August. The main-stem Amazon at Óbidos peaks in May–June because Southern Hemisphere tributaries contribute most of its drainage area and runoff. The regime of the Paraná is radically altered by storage in large reservoirs, which can accommodate up to 60% of the river's average annual flow.

The most influential alteration of a river regime through wetland storage occurs in the Pantanal of Mato Grosso, which delays the flow of the upper Paraguay River between Cáceres, Brazil, and Concepción, Paraguay, by about six months. From March to August, the river floods into the Pantanal, and drains out through a system of distributary channels, including the Taquari River (Souza et al., 2002), between September and February. In the central Pantanal, the river usually peaks in June, but in exceptionally high-flow years, the maximum flow is advanced to May or April, roughly in proportion to the magnitude of the flood stage; the flood also occurs earlier in exceptionally dry years when the water remains within the river banks. The smaller rivers, with less wetland storage to modify their regimes, respond more directly to the seasonality of rainfall, with for example the Salado River of southern Argentina exhibiting a March runoff peak of 25 $m^3 s^{-1}$, and the Zapotal River of Ecuador also showing a March peak of 650 $m^3 s^{-1}$.

5.3.3 Inundation

The generally low gradients (1–10 cm km^{-1}) of the continent's large rivers, the breadth of their structurally controlled alluvial valleys with extensive floodplains, inland deltas, and alluvial fans, and the limited extent of channel engineering or impoundment all favor massive overbank flows and seasonal storage of water in wetlands (Junk and Furch, 1993; Richey et al., 1989). Inundation thus occurs from the lower Paraná delta plain in Argentina to the *várzeas* of the central Amazon basin (Mertes et al., 1996), the *ciénagas* and lakes of the Magdalena valley (Garcia Lozano and Dister, 1990), the *llanos* of the western Amazon in Bolivia and Peru (Goulding et al., 2003), and the fringing floodplains, inland delta, and coastal delta of the Orinoco basin (Hamilton and Lewis, 1990). Hamilton et al. (2002) used satellite technology to monitor seasonal changes in the extent of inundation in six large wetlands in South America (fig. 5.6). Large seasonal changes in inundated area correlated well with water levels in adjacent rivers, and averaged a continent-wide total of 187,000 km^2, with a nonsynchronous maximum exceeding 500,000 km^2, although the passage of the annual flood wave exaggerates this flooded area above that which is flooded simultaneously (463,000 km^2). Maximum depths of inundation range up to 15 m. Inundation is also caused at the mouths of the many tributaries entering the major rivers through the backwater effects of large seasonal changes in water levels (e.g., Meade et al., 1991).

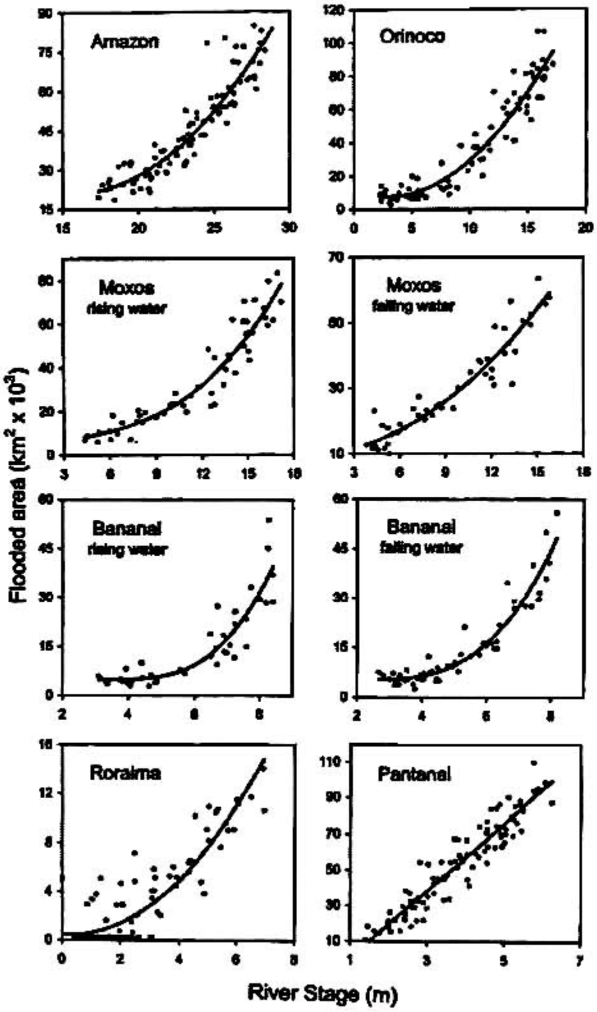

Figure 5.6 Seasonal variations of inundated area in South American wetlands (Hamilton et al., 2002, fig. 7)

5.4 Sediment Supplies and Transport

Sufficient data are available to report on sediment transport for very few South American rivers, but a useful sample of annual sediment yields per unit area of drainage basin is presented in table 5.2. As with large rivers everywhere, the quantity of sediment supplied to the rivers reflects mainly the lithology and topography of their drainage basins. Thus most sediment enters the large rivers of the continent from the mechanically weak rocks and steep topography of the Andes. The most extensive dataset presently available on sediment fluxes in South America was compiled by Bolivian and French hydrologists, and summarized by Guyot and his colleagues (Guyot, 1993; Guyot et al., 1988, 1990). Aalto et al. (2006) made a statistical summary of these data, correlating long-term annual sediment yields in the east-flowing Andean tributaries of the Madeira River in Bolivia with indices of basin-averaged hillslope steepness and of lithologic resistance to weathering and erosion. Yields range from 30 to 8000 t $km^{-2} yr^{-1}$ on igneous rocks, from 100 to 10,000 t $km^{-2} yr^{-1}$ on metasedimentary rocks, and from 200 to 18,000 t $km^{-2} yr^{-1}$ on weakly consolidated sediments. More than 70% of the annual load carried by these tributaries leaves the Andes in a three-month period from January to March.

Deposition of much of this sediment in structural basins adjacent to the Andes and in the long floodplain reaches of the major rivers alters the sediment transport patterns and limits the amount of sediment reaching the ocean. Guyot (1993) estimated that, of the annual sediment load of 550 Mt (million tonnes) leaving the Eastern Cordillera of Bolivia for the Madeira River, about 60% is trapped in the floodplains of the foreland basin, with

Table 5.2 Sediment yields of selected South American rivers

River	Station	Country	Basin area [km^2]	Sediment yield [$t\ km^{-2}\ yr^{-1}$]	Source
Magdalena	mouth	Colombia	266,600	716	Garcia Lozano and Dister (1990)
Beni	Rurrenabaque	Bolivia	68,000	3220	Guyot (1993)
Beni	Cachuela Esperanza	Bolivia	282,500	570	Guyot (1993)
Madeira	Guayaramerin	Bolivia	903,500	250	Guyot (1993)
Negro	Manaus	Brazil	691,000	10	Dunne et al. (1998)
Orinoco	Ciudad Bolivar,	Venezuela	1,100,000	140	Warne et al. 2002)
Pilcomayo	Villamontes,	Bolivia	81,000	1000	Guyot et al. (1990)
Paraguay	Paraná confluence	Paraguay	1,095,000	100	Anderson et al. (1993)
Upper Paraná	Porto São Jose	Brazil	670,000	30*	Orfeo & Stevaux (2002)
Middle Paraná	Corrientes	Argentina	1,950,000	80	Orfeo & Stevaux (2002)

*after impoundments

the amount retained ranging from 80% in the Mamore basin to 43% in the steeper Beni River with its narrower floodplain.

The main-stem Amazon carries a load of more than 1000 Mt yr^{-1}, with an irregular downstream reduction due to variations in channel gradient, valley width, and tributary input. Dunne et al. (1998) calculated sediment budgets for the various processes (bar deposition, bank erosion, and diffuse and channelized overbank deposition) exchanging sediment between the channel and the floodplain along a 2,010-km reach of the Amazon. These lateral exchanges exceed the total annual sediment load moving past Óbidos at tidewater (~1200 Mt yr^{-1}), and a further 300–400 Mt yr^{-1} of deposition was estimated to occur in a delta plain at the head of the estuary.

In the lowland Amazon basin, erosion rates on the forested Brazilian and Guiana shields are very slow. Guyot (1993) estimated a sediment yield of 16 t km^{-2} yr^{-1} for the Río Guaporé in southeast Bolivia, and Dunne et al (1998) reported a yield of 10 t km^{-2} yr^{-1} for the Río Negro in Brazil. Latrubesse and Stevaux (2002) reported a yield of 49 t km^{-2} yr^{-1} from the 364,000 km^2 Araguaia River basin, which drains the ecotone between savanna and seasonally dry forest into the Tocantins River on the eastern Brazilian Shield. Thus the Andes remain the dominant sediment source of the main-stem Amazon all the way to the Atlantic Ocean.

The interacting effects of runoff, lithology, gradient change, and to some extent impoundment are reflected in the contrasting sediment transport regimes feeding into the Río de la Plata system, between those tributaries emerging from the Andes and those draining from the more resistant rocks of the upper Paraná Highlands and the Brazilian Shield (Orfeo and Stevaux, 2002). Downstream of large dams, the upper Parana River has suspended sediment concentrations of only 6–30 mg L^{-1} (Orfeo and Stevaux, 2002), and 90–200 mg L^{-1} at the confluence with the Paraguay River (Drago and Amsler, 1988, 1998). The river's large annual discharge transports about 15 Mt yr^{-1} of measured fine washload, and a calculated sandy bed-material load of about 5 Mt yr^{-1}, the coarser component of which travels as large sand waves on the wide channel bed. The smaller Paraguay River, at its confluence with the Paraná, has an average flow of about 4,500–5,000 m^3 s^{-1} and a sediment yield of 1,188 Mt yr^{-1} of finer sediment and a sandy bed–material load of about 40 Mt yr^{-1}. Most of this load derives from the Andean tributaries: the Río Pilcomayo (81,300 km^2) with a sediment load averaging 80 Mt yr^{-1} (Guyot et al., 1990), and the Río Bermejo (16,000 km^2), where concentrations average about 6,000 mg L^{-1} (Drago and Amsler, 1988). The wave of suspended sediment enters the middle and lower Paraná weeks after the main flood wave from the upper Paraná.

5.5 Fluvial Geomorphology

In order to illustrate the variety of riverscapes of the Amazon basin, figure 5.7 presents schematically a generalized cross-section showing the distinctive fluvial geomorphology of various sectors from the headwaters to the downstream delta plain near the Xingu confluence.

On the forested Brazilian and Guiana shields (exemplified by the northeast corner of figure 5.7D), most rivers receive small sediment loads, mostly silt and clay, and little bed material, so that they flow in bedrock channels that exhibit strong structural control along fractures or faults, irregular alignments, and rapids with intervening sand bars and little if any floodplain. However, some structural basins within the shields have extensive alluvial plains with actively meandering rivers and floodplains that contain paleo-channels and various other off-channel water bodies and marshes, some of them supplied only by local runoff. Latrubesse and Stevaux (2002) described one example in the alluvial plain of the middle Araguaia, central Brazil, which drains about 200,000 km^2 of savanna that is being aggressively deforested for agriculture. An extreme example of a sediment-starved river with a bedrock-dominated

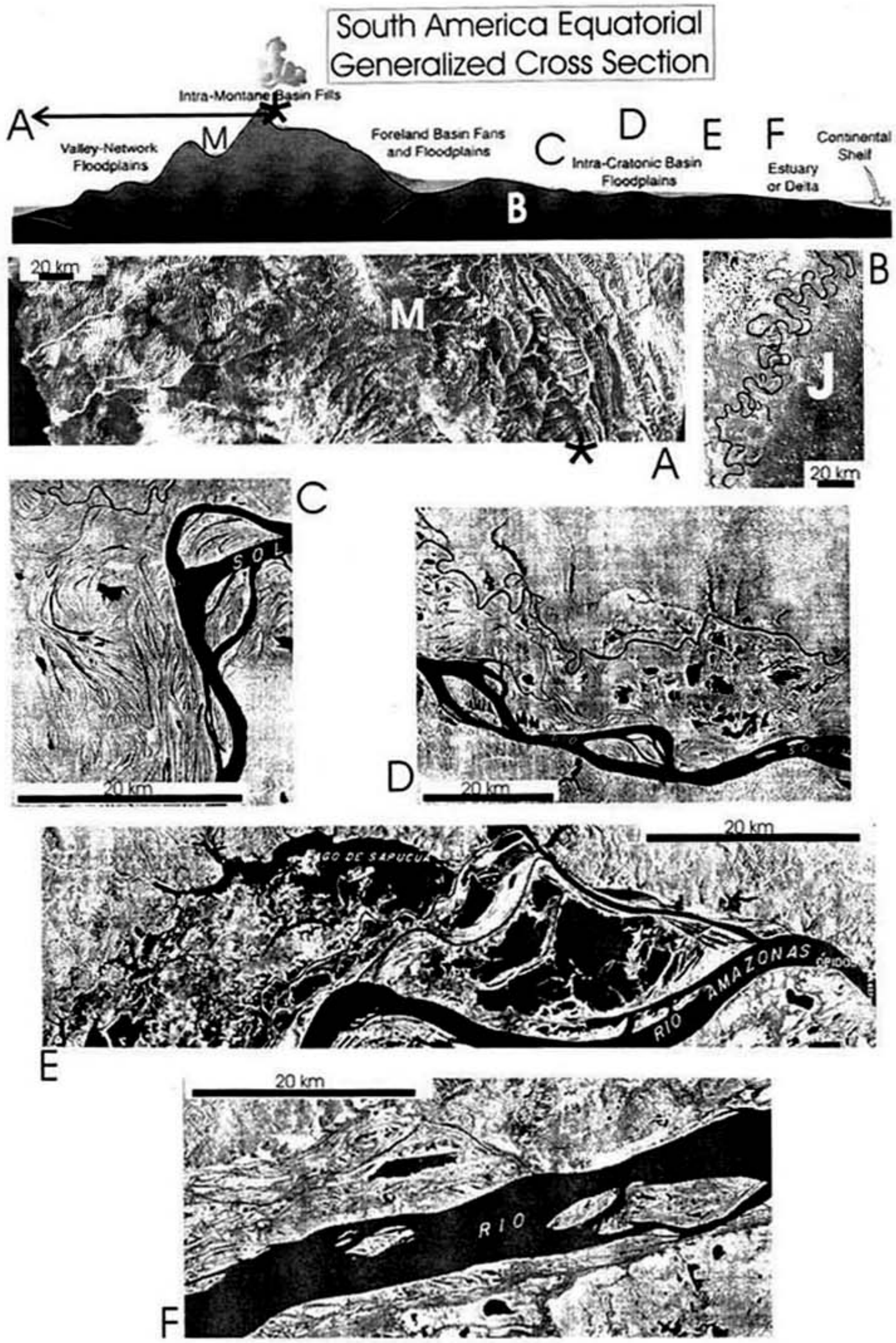

Figure 5.7 Regional variation in river character along an equatorial section across South America. A: Andean headwaters of Marañon (M) and Huallaga rivers (*), Perú (Landsat Thematic Mapper image, Band 4, 30 December 1989, centered ~9°S 78°W). B: Complex meanders of the Juruá River (J), Brazil, in an intracratonic setting just south of its confluence with the Amazon (Landsat Enhanced Thematic Mapper image, Band 4, 31 July 2001). C: Scroll-bar floodplain along upstream reaches of Amazon River near Xibeco. D: Transitional floodplain in middle reaches of Amazon River near Itapeua. E: Downstream floodplain of Amazon River near Óbidos. F: "Filled" delta-plain floodplain of Amazon River between Tapajós and Xingu confluences (figs. 5.7C–5.7F from Mertes et al., 1996).

channel is the lower Negro River in Amazonas state (Franzinelli and Igreja, 2002). The river, which exceeds 20 km in width in some reaches, flows in a half-graben between cliffs of friable sandstone and around long linear islands that are believed to be founded on up-faulted bedrock ridges. Blocks of bedrock and unconsolidated sediment also surrounded the wide bedrock channel in various attitudes and elevations. The river transports only enough sediment to maintain narrow beaches capping and lining the islands and in pockets where the valley-side alignment changes sharply.

Steep Andean rivers (fig. 5.7A) flow in narrow valleys, over bedrock and sparse gravel bars, occasionally interrupted by wider sand and gravel floodplains in intramontane basins that are also lined with gravel terraces reflecting the tectonic and climatic history of the range. When these rivers enter the Subandean basins, below the 500–m contour, they rapidly deposit sandy point and midchannel bars and crevasse-splay deposits, and overlay them with silt and clay levees and flood basin deposits. The rapid channel shifting and oxbow formations along the Beni and Mamore Rivers in the Beni Basin, for instance, create extensive and diverse habitats for fish and river dolphins (Lauzanne et al., 1990).

Larger rivers formed entirely within the Amazon lowland carry small sediment loads and have tortuous irregular planforms with sinuosities often exceeding 2.4, as exemplified by the Juruá River in western Amazonas state (fig. 5.7B; Latrubesse and Kalicki, 2002; Stölum, 1998). The rate of meander migration is generally unknown, but the Holocene floodplains are broad and contain many oxbow lakes that may be thousands of years old, since the rate of overbank sedimentation is probably limited by the small loads of these rivers.

Along the main-stem Amazon (figs. 5.7C–5.7F), deposition and channel migration have constructed an intricate valley-floor topography consisting of scroll-bar complexes, levees, and flood basins, many of them still occupied by perennial lakes. The main channel shifts at rates of <10 to >100 m yr^{-1}, depending on the degree to which the floodplain is confined between cohesive terraces. Mertes et al. (1996) described a structurally controlled alternating pattern of confined and freely meandering reaches with varying representation of alluvial features such as lakes and scroll bars (fig. 5.7C) that are scaled by three types of channel: the main Amazon channel, its occasional anabranches, and smaller floodplain channels that originate either in the main river (and therefore are sediment-rich) or in local floodplain or terrace drainage (and are sediment-starved). Latrubesse and Franzinelli (2002) emphasized the segmented alignment of the middle Amazon, which they attribute to neotectonic activity of tilted fault blocks. They also added detail and historical perspective concerning the development of the middle Amazon floodplain, differentiating between an older (late Holocene), smoother floodplain created dominantly by vertical accretion, and a later regime of lateral accretion of bars, levee complexes, channels, and lake deltas fringing the modern channel within the past millennium (fig. 5.7D).

Much of the Amazon valley downstream of Manaus was excavated of sediment as sea level fell to 120 m below the present during the Last Glacial Maximum, about 20 ka (Mertes and Dunne, in press). With the subsequent postglacial rise of sea level, sedimentation began refilling this valley, which may also still be subsiding due to continued graben dynamics (fig. 5.7E). The same lowering of base level scoured sediment from the lower reaches of each tributary entering the central and eastern Amazon, but the low sediment supply from these tributaries has not been able to keep pace with the rise of sea level and of the Amazon floodplain, leaving long bays at the mouths of all tributaries except for the sediment-rich Madeira (figs. 5.7E, 5.7F; Sioli, 1968; Tricart, 1975, 1977). At the mouth of the Amazon, a 25,000 km^2 delta plain and a subaqueous delta represent the continuing response of sedimentation to postglacial sea level rise (Nittrouer et al., 1986a, 1995).

The Orinoco River is confined to the southern edge of its valley by southeastward tilting associated with the uplift of the Venezuelan Andes and by the clastic wedge spreading from the mountains (fig. 5.8). This confinement forces the channel to cross eight bedrock outcrops that form rapids and reduce channel migration (Warne et al., 2002). The valley alluvium is thus limited to a narrow fringing floodplain with more extensive inland deltas at the mouths of left bank tributaries, such as the Apure and Arauca rivers, where deposition is induced by backwaters from the Orinoco as their flow is restricted by bedrock outcrops. Almost the entire sediment supply to the Orinoco is provided by left-bank tributaries draining from the Andes, but only after depositing much of their load on the gently sloping sedimentary wedge south and east of the mountains. The right-bank tributaries from the Guiana Shield have very low sediment loads. The Orinoco has built the continent's only large ocean-front delta, with a 22,000 km^2 plain consisting of sandy and silty fluvial deposits near its apex and southern margin, and along tributaries, grading into muddy and peaty inter-distributary plains with increasing tidal influence to the north and east (Warne et al., 2002).

In the upper Paraguay basin, between the Andes and the Brazilian Shield, the Pantanal of Mato Grosso do Sul, Brazil, comprises a series of low-gradient coalescing alluvial fans and inland deltas that cover nearly 200,000 km^2 and merge with the floodplain of the Paraguay River. Souza et al. (2002) described the downstream variation of channel form, inundation, and sedimentation along the largest of the fans, on the Taquari River. Near the fan apex, the channels are entrenched, single threaded, and sinuous, grading downstream to a multi-threaded channel more or less at the fan surface, which then merges with the Paraguay floodplain via fans, crevasses splays, and lakes. The

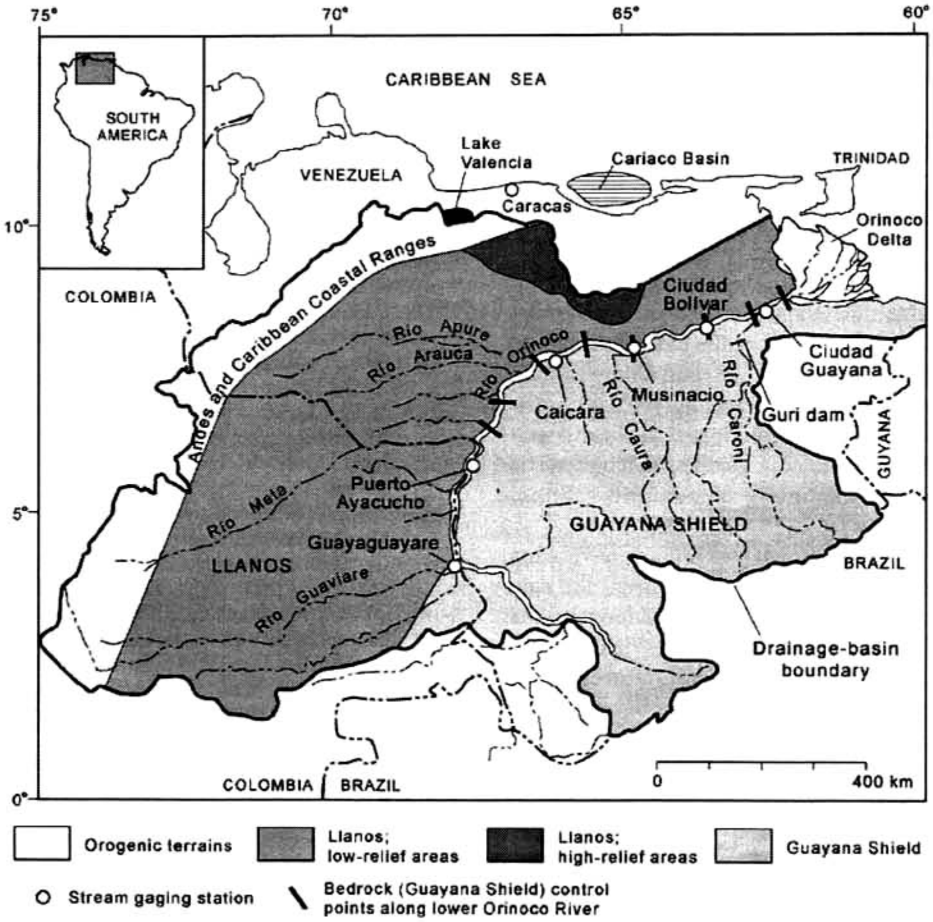

Figure 5.8 Orinoco River and delta plain (after Meade et al., 1983, in Warne et al., 2002, fig. 3)

lower Paraguay floodplain contains extensive sand-bar deposits, although significant meander activity also produces scroll bars and oxbow lakes. Older meander belts, now distant from the channel, receive only local sediment from smaller streams that are gradually resurfacing the plain (Drago, 1990).

The major channels of the upper and middle Paraná basin are exceptionally wide and shallow (width-depth ratio >100), with significant multi-thread reaches and frequent, complex sand bars, some of them eroded from older floodplain sediment and others deposited directly from the flow (Orfeo and Stevaux, 2002). Channel shifting by bend deformation occurs at rates of tens of meters per year, but chute cutoffs can displace the channel suddenly by several kilometers (Ramonell, 2002). The channel thalweg of the middle Paraná also shifts rapidly and erratically within its wide banks. As the bed narrows and widens, and scours and fills by up to 15 m in a flood season, the channel vacillates between single thread and multi-thread behavior, except where it impinges on resistant terrace materials of Neogene age (Drago, 1990). The modern floodplain consists of a complex of scroll bars, channels, lakes, lacustrine deltas, marshes, and islands, grading into a delta plain (Drago, 1990).

5.6 The Future of South American Rivers

The rivers of South America have as yet suffered relatively little disturbance from human activities, but this situation is likely to change in coming decades. The most pervasive changes are likely to arise through large impoundments, channel engineering works to improve navigation, forest and scrub clearance for agriculture, and urban and industrial pollution. Large dams have been spreading throughout the continent since the 1970s, mainly for hydroelectric power generation, and the potential for further development is large because of the generally high rates of runoff, the availability of favorable sites for large dams and reservoirs, and improvements in the efficiency of power transmission (Petts, 1990). The Paraná River is the basin most intensively developed for hydropower, with at least 20 dams on the main stem and tributaries of the upper Paraná already storing 60% of the mean annual flow. The seasonal flow pattern of the river has already been significantly altered, and together with toxic effluent from agriculture and industry, the regulation of the river-floodplain flow system appears to be reducing fish catches (Quiros, 1990). There are also major water impoundments in the São Francisco and Tocantins rivers in Brazil, and in the Andes where countries from Venezuela to Chile have constructed reservoirs in the face of high rates of sedimentation (see chapter 18) and where Bolivia, Perú, and Ecuador contain large canyons with attractive dam sites. It is likely that the alteration of flows and sediment dynamics downstream of large dams throughout the continent will change channel geometry and channel-floodplain connections.

The long rivers of the continent also provide navigation, but the frequent rapids, tortuous mobile bends, and sand bars limit the access of large modern barges. Several major dredging projects aimed at improving navigation have been initiated or proposed. The general nature of their impact is likely to be to deepen and simplify channels, thereby reducing connections with their floodplains and draining the wetlands of the major alluvial valleys. These events will likely have a major impact of aquatic and riparian ecosystems.

Deforestation for pasture and cultivation has spread widely through the continent and is likely to continue expanding through the Amazon basin for decades. Acceleration of sediment supply from deforested areas has appeared in savanna regions of the Brazilian Shield from widespread cultivation on the drier margins of Amazonia (Latrubesse and Stevaux, 2002), but sedimentation problems have not yet been reported in the wetter parts of the Amazon. However, pollution from urban and industrial development has already been recognized there (Biggs et al., 2004). Severe pollution problems also have been associated with urbanization and industrialization in more intensely developed drainage basins of the continent, notably along rivers flowing through the developed coastal regions of southeast Brazil, the Río del la Plata estuary of Argentina and Uruguay, central Chile, and the Caribbean coast (see chapter 20, Bartone, 1990; Filoso et al., 2003).

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