Backwater Effects in the Amazon River Basin of Brazil

ROBERT H. MEADE
U.S. Geological Survey
MS 413, Box 25046
Denver, Colorado 80225, U.S.A.
JOSÉ M. RAYOL
Companhia de Pesquisas de Recursos Minerais
Av. Carvalho Leal 1017, Cachoerinha
69000 Manaus, AM, Brazil
SYLVIO C. Da CONCEICÃO
Companhia de Pesquisas de Recursos Minerais
Av. Dr. Freitas 3645
66000 Belém, PA, Brazil
JOSÉ R. G. NATIVIDADE
Departamento Nacional de Aguas e Energia Eletrica
Av. Gentil Bittencourt 46
66000 Belém, PA, Brazil

ABSTRACT / The Amazon River mainstem of Brazil is so regulated by differences in the timing of tributary inputs and by seasonal storage of water on floodplains that maximum discharges exceed minimum discharges by a factor of only 3. Large tributaries that drain the southern Amazon River basin reach their peak discharges two months earlier than does the mainstem. The resulting backwater in the lowermost 800 km of two large southern tributaries, the Madeira and Purús rivers, causes falling river stages to be as much as 2–3 m higher than rising stages at any given discharge. Large tributaries that drain the northernmost Amazon River basin reach their annual minimum discharges three to four months later than does the mainstem. In the lowermost 300–400 km of the Negro River, the largest northern tributary and the fifth largest river in the world, the lowest stages of the year correspond to those of the Amazon River mainstem rather than to those in the upstream reaches of the Negro River.

Introduction

Hydrologic data have been collected routinely in the Amazon River basin at least since the earliest years of this century. The longest continuous record of daily river stage in the Amazon River basin, that of the Negro River at Manaus, began in 1902 and continues to the present day. This and other records of river level served as the basis of early summaries by Pardé (1936, 1954, 1958) of the hydrology of the Amazon River and its tributaries. Following the pioneering measurements of river discharge made in 1963–1964 (Oltman and others 1964; Oltman 1968; Sternberg and Pardé 1965), a comprehensive program of regular discharge measurement along the Amazon River mainstem and along selected tributaries was begun during the early 1970s by Brazil's Departamento Nacional de Aguas e Energia Eletrica (DNAEE) with the collaboration of Companhia de Pesquisas de Recursos Minerais (CPRM) and Hidrologia S.A. (Divisão de Aguas 1968). This program was expanded during the late 1970s to include discharge measurements along the Negro River, the last major tributary to be gaged regularly in the Amazon River basin. Stage and discharge data collected at stations shown in Figure 1 are the basis of this report. Unless otherwise noted, all data in this report were collected for DNAEE by CPRM and Hidrologia S.A.

The purpose of this report is to use the newer data to demonstrate some of the hydrologic characteristics of the world's largest river system. Our approach is descriptive and pictorial. The first four figures and the accompanying discussion describe some of the general features of the hydrology of the Amazon River mainstem and two of its major tributaries. The remaining figures and discussion focus on some of the impressive effects of backwater—especially the extent to which the Amazon River mainstem causes backwater in other rivers that themselves rank among the half dozen largest in the world.

Hydrologic Setting

On the basis of the average discharge at its mouth (200,000 m^3/sec), the Amazon ranks as the world's largest river. On the same basis, two of its tributaries, the Negro and Madeira rivers, rank as fifth and sixth largest. Second, third, and fourth in the same ranking are the Congo (Zaire), Orinoco, and Yangtze (Changjiang) rivers. The Mississippi River ranks about tenth and has an average discharge (including that of the Red and Atchafalaya rivers) about one-twelfth the discharge of the Amazon. The total area drained by the Amazon River and its tributaries is about 6.15×10^6 km^2. Recent summaries of the hydrology and hydrography of the Amazon basin have been published by Sternberg (1975), Sioli (1984), and Salati (1985).

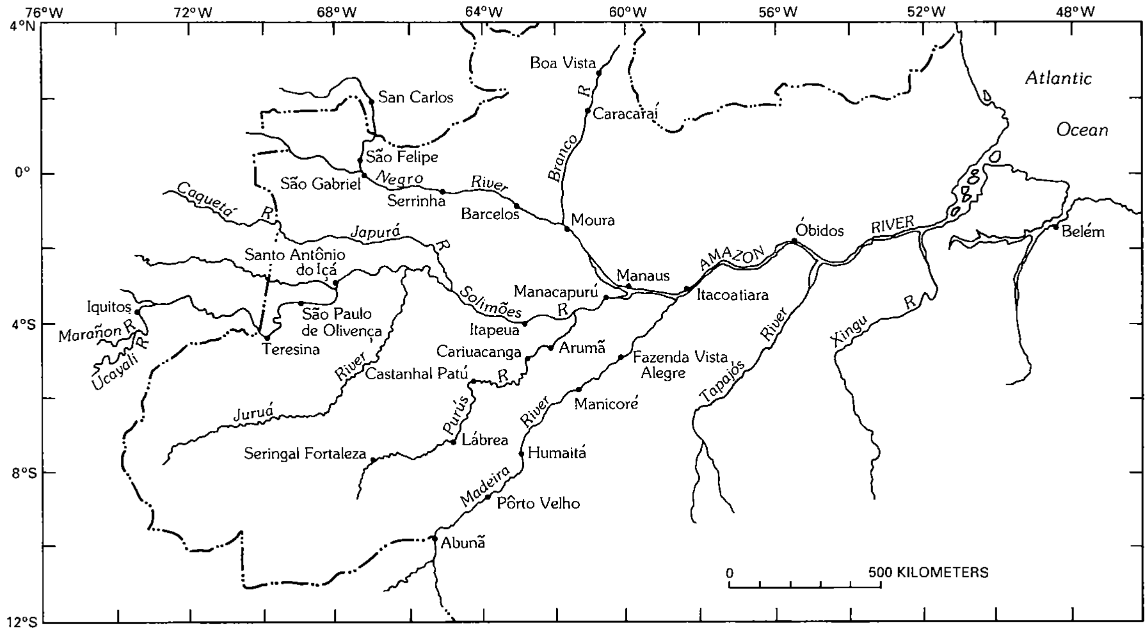

Figure 1. Map of Amazon River basin of Brazil, showing locations of major rivers and gaging stations (● Manaus). Broken line is international boundary between Brazil and neighboring countries. In Brazilian usage, the mainstem river is called Amazon River downstream from the confluence with the Negro River at Manaus, and Solimões River upstream from this confluence. In Peruvian usage, the mainstem river is called Amazon River everywhere downstream from the confluence of the Marañon and Ucayali Rivers.

Nomenclature of the Amazon River mainstem is somewhat confusing. In Peru, the mainstem river is called the Ucayali River until it is joined by the Marañon River, at which confluence (according to Peruvian and Colombian usage) it is first called the Amazon River. When it flows across the Peru–Brazil border, the local name becomes Solimões. According to Brazilian usage, the mainstem river is called the Solimões River until it is joined by the Negro River; downstream from this confluence, it is called the Amazon River. In our article, we follow the Brazilian usage.

Stage and Discharge

Although the water level in the Solimões–Amazon mainstem will fluctuate 10 m or more during an average year, the discharge will vary only by a factor of 2 or 3. This is shown in Figure 2 by the plotted positions of the discharge measurements, which cover nearly the full range of discharge for the indicated periods (see also Figure 3a of Meade and others 1979). This extraordinarily small range of variation in mainstem discharge is due to two principal factors. First in importance are the large seasonal time differences between peak discharges from the northern and southern tributaries. Because of the seasonal shift of the intertropical convergence zone, the maximum rainfall in the southernmost parts of the Amazon River basin usually occurs two months earlier (December–January–February) than maximum rainfall in the central basin along the Solimões–Amazon mainstem (February–March–April), and six months earlier than maximum rainfall in the northernmost parts of the basin (June–July–August). Likewise, minimum rainfall in the southern half of the Amazon River basin (June–July–August) occurs half a year earlier than minimum rainfall in the northernmost regions of the basin (January–February–March). (Maps showing the temporal distributions of maximum and minimum rainfalls in the Amazon River basin are presented by Hjelmfelt 1978, p. 891, and SUDAM/PHCA 1984, p. 19–20.) Figure 3 shows that the lowest stages in the Madeira River, the largest southern tributary of the Amazon, occur four to five months earlier than the lowest stages in the Negro River, the largest northern tributary. Highest stages in the Madeira River occur two to three months earlier than highest stages in the Negro River. Even though the discharges by the tributaries at their mouths may vary by factors of 10 or more (see Figs. 6e and 9e), the offset timing of inputs from northern and southern tributaries keeps the variation in mainstem discharges within a factor of 3.

A second principal factor that damps the extremes of discharge in the Solimões–Amazon River mainstem

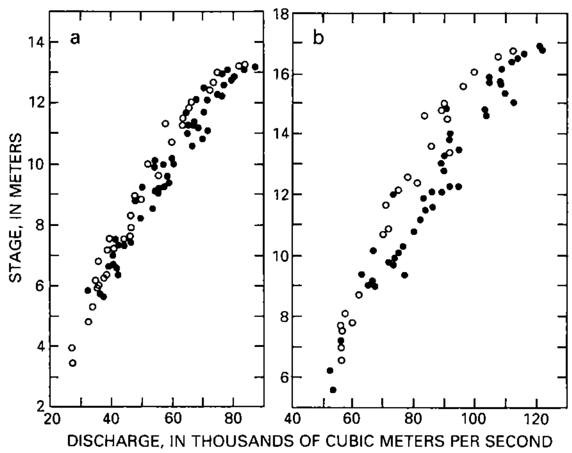

Figure 2. Stage–discharge relations in the Amazon mainstem. **(a)** Solimões River at Santo Antônio do Içá, February 1974 through November 1983. **(b)** Solimões River at Itapeua, February 1974 through February 1983. Ordinate scales refer individually to local datum; zero stages in this figure correspond to the arbitrarily assigned elevations of 9.5 m (Itapeua) and 46.5 m (Santo Antônio do Içá) in Figure 4. Solid circles represent measurements made during rising stages of the rivers; open circles represent measurements made during falling stages. Differences between rising and falling stages are related to positions on the annual flood wave, which proceeds downriver, peaking at Santo Antônio do Içá nearly one month earlier than at Itapeua (Figure 4). The steeper river slopes on the front of the flood wave (rising stages) versus those on the back of the flood wave (falling stages) cause at least some of the differences in stage–discharge relations between rising and falling stages. Similar differences were noted in the Mississippi River during the late 1850s by Humphreys and Abbot (1861, plates 14–17).

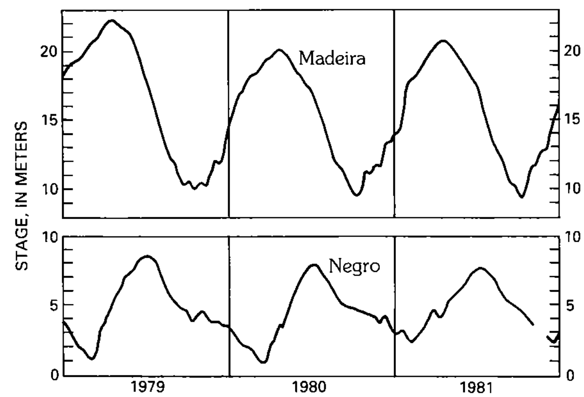

Figure 3. Daily river stages, Madeira River at Fazenda Vista Alegre and Negro River at Barcelos, 1979–1981, showing the different timing of maxima and minima of annual discharge from southern (Madeira) and northern (Negro) tributaries of the Amazon River. Ordinate scales refer individually to local datum.

is the seasonal storage of water on the floodplain. The largest tract of such floodplain in Brazil lies adjacent to the Solimões River between Santo Antônio do Içá and Itapeua. Hydrographs of river stage at these two locations, both of which are constructed from measurements made daily, are shown in Figure 4. The increased smoothness of the stage hydrograph at Itapeau, relative to that of the hydrograph at Santo Antônio do Içá, reflects the seasonal storage of large quantities of water that flow onto the intervening floodplain during rising stages and flow slowly back into the river channel during falling stages. Richey and others (1989a) "... estimate that up to 30% of the water in the mainstem is derived from water that has passed through the floodplain."

River Slopes

The river elevations expressed in the ordinate scale of Figure 4 are only approximate. No comprehensive spirit leveling or satellite geodesy has been used to determine elevations along the Solimões–Amazon mainstem, and the elevations of such places as Manaus and Iquitos have been measured only by aneroid barometer. Although the river slopes implied by the elevations in Figure 4 could be in error by a factor of 2 or more, they are not unreasonable when compared with measured slopes in other large rivers. According to unpublished spirit-leveling data in possession of the Venezuelan Ministerio del Ambiente y de los Recursos Naturales Renovables, the slope of the Orinoco River in the 800-km reach between Puerto Ayacucho and Puerto Ordaz, parts of which are controlled by bedrock and minor rapids, ranges consistently between 0.00004 and 0.00005. According to Stroebe (1925), the slope of the Yangtze River in the 600-km alluvial reach between the upriver city of Hankow and the landward limit of oceanic tides at Wuhu ranges between about 0.000025 at high river stages and about 0.000015 at low river stages. According to data presented by Gannett (1901, p. 39) and the Mississippi River Commission (1988, sheet 1), the slope of the Mississippi River averages about 0.00006, at both high- and low-water stages, in the 1540-km alluvial reach between Cairo, Illinois (the junction of the Ohio and Mississippi rivers) and the Gulf of Mexico. In the 840-km reach between Cairo and Vicksburg, the slope of the Mississippi River averages about 0.00008 at bankfull stage and 0.00009 at low-water stage. In the 700-km reach between Vicksburg and the Gulf of Mexico, the mean river slope is 0.00004 at bankfull stage and 0.00002 at low-water stage. Considering the greater size (and presumably the lower slope) of the

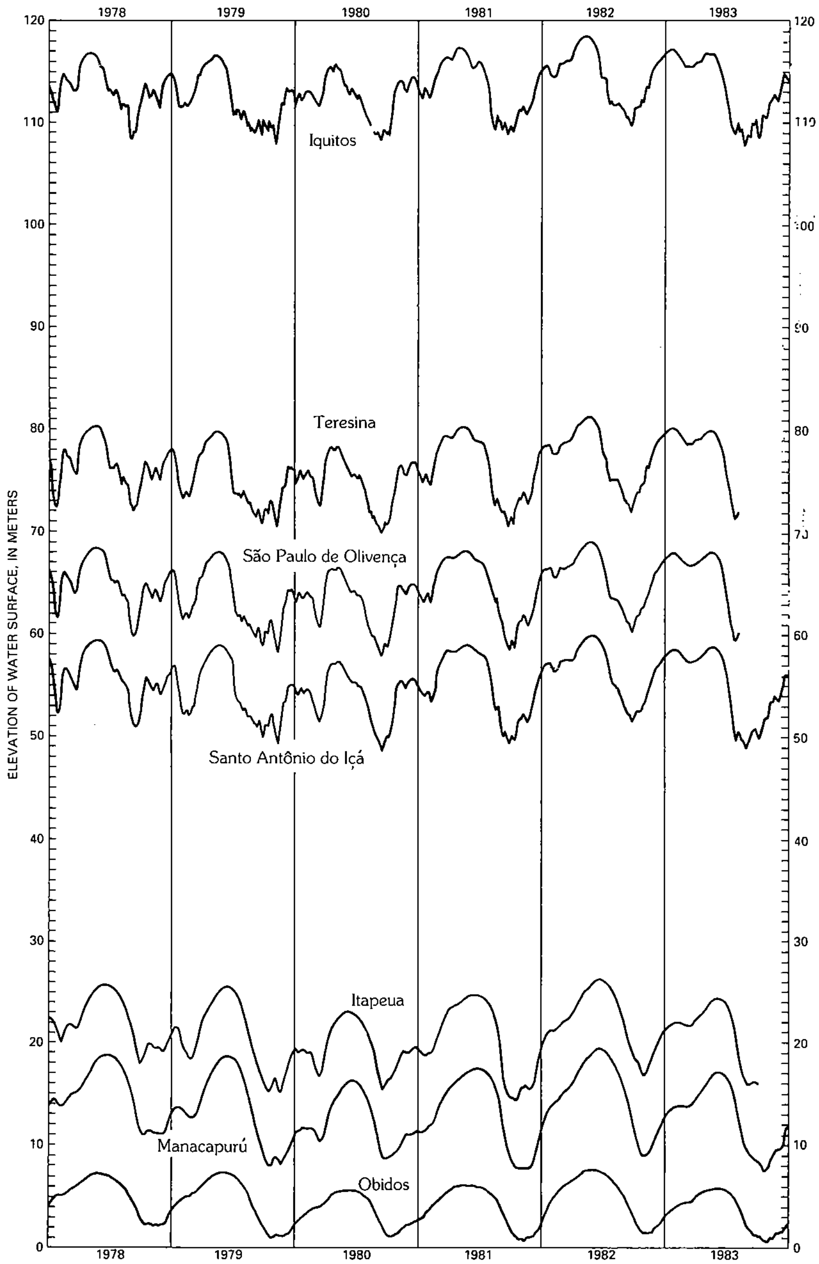

Figure 4. Fluctuations in river stage at seven gaging stations along the Solimões–Amazonas River mainstem of Peru and Brazil, 1978–1983. This six-year record contains a year of exceptionally low water (1980) and one of unusually high water (1982). The peak annual stages during these two years were the third lowest and eighth highest in 87 years of record (1903–1989) collected at the gage at Manaus. Data for Iquitos provided by Empresa Nacional de Puertos, S.A. The individual stage curves are internally accurate, based on twice-daily readings of a gage relative to a fixed local datum. However, the numbers assigned to the ordinate scale, the vertical locations of the stage curves within the graph, and the vertical distances between the stage curves are all arbitrary. Zero elevation was assumed to coincide with the zero datum of the gages at Iquitos, Manacapurú, and Obidos, and the other stage curves were located by assuming an average river slope of 0.00006 between Iquitos and Santo Antônio do Icá, 0.00004 between Santo Antônio do Icá and Itapeua, and 0.00002 between Itapeua and Manacapurú.

Amazon River, and that its mainstem channel is formed almost entirely in its own alluvium, the mean slope of the Solimões–Amazon River might be expected to be within the range between 0.00001 and 0.00006.

Backwater Effects

Madeira River

The Madeira River, whose most distant sources lie in the Andes of Bolivia, drains an area of about 1.35×10^6 km^2 and discharges an average of about 25,000 m^3/sec at its mouth. The river reaches its highest stage some two months earlier than the Amazon River into which it flows (Fig. 5). This two-month difference in peak stage causes distinctive backwater effects in the relations between river stage and water discharge in the lower Madeira River.

Figure 6 shows the expected downstream increase in backwater effects. In the gaging records collected at stations on the upper reaches of the Brazilian portion of

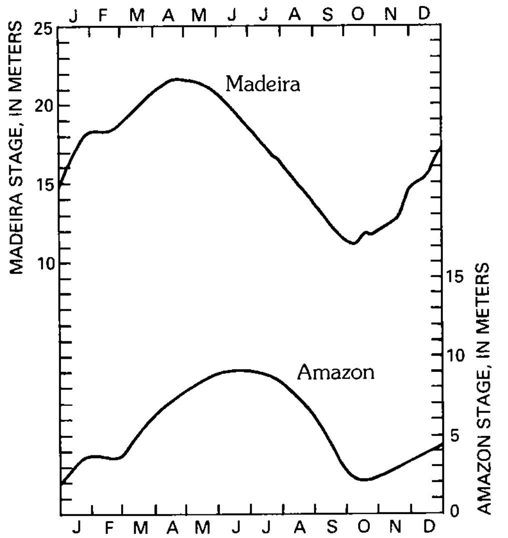

Figure 5. Daily river stages, Madeira River at Fazenda Vista Alegre and Amazon River at Itacoatiara, 1977, showing time lag between peak discharges. Fazenda Vista Alegre is about 260 km up the Madeira from the Madeira–Amazon confluence, and Itacoatiara is about 40 km down the Amazon from the Madeira–Amazon confluence. Stage data at Itacoatiara were collected by Capitania dos Portos and reported by Smith (1981, p. 133–137). Ordinate scales refer individually to local datums. The vertical distance between stage curves is based on an assumed average river slope of 0.00006.

the Madeira (Fig. 6a and 6b), the relation of stage to discharge during rising river stages is not substantially different from the relation during falling stages. At Humaitá, which is about 810 river km upriver of the mouth of the Madeira (Fig. 6c), the river level is a few tenths of a meter higher during falling stages than during rising stages at the same discharge. At Manicoré, about 460 km upriver of the mouth (Fig. 6d), the difference between river levels during rising stages and those during falling stages at the same discharge is about 1 m. At Fazenda Vista Alegre, which is about 260 km upriver of the mouth (Fig. 6e), this difference is 2–3 m.

These shifts in the stage–discharge ratings are due to the time lag between the peak discharges of the Madeira and Amazon rivers. Early in the calendar year, when both rivers are rising, the slope of the lower Madeira River (judging from the vertical distance between the two hydrographs in Fig. 5) is at a maximum, mean velocities are greater (Fig. 7a and 7b), while mean depths are smaller (Fig. 7c and 7d) at a given stage or discharge. After the Madeira has begun to fall and the Amazon has reached its peak stage for the year, the slope of the lower Madeira becomes smaller (smaller vertical distance between the two hydrographs in Fig. 5), and mean velocities are smaller while mean depths are greater at a given stage or discharge (Fig. 7a–d).

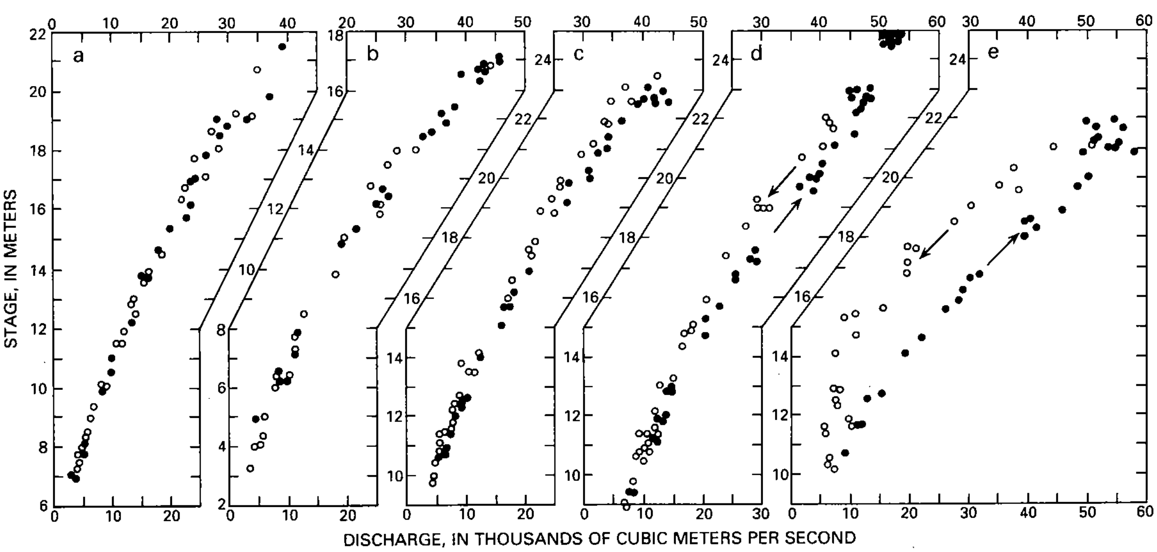

Figure 6. Stage–discharge relations at gaging stations along the Madeira River, showing the different relations on rising (solid circles) versus falling (open circles) stages. **(a)** Abunã, 1320 km upriver of mouth (river distances, rounded to nearest 10 km, are measured from side-looking-radar mosaics published at a scale of 1:250,000 by RADAM BRASIL), June 1976 through January 1983. **(b)** Pôrto Velho, 1060 km upriver of mouth, July 1977 through January 1983. **(c)** Humaitá, 810 km upriver of mouth, January 1974 through December 1980. **(d)** Manicoré, 460 km upriver of mouth, July 1972 through November 1979, August 1981 though April 1982. **(e)** Fazenda Vista Alegre, 260 km upriver of mouth, March 1975 through November 1979. Ordinate scales refer individually to local datums.

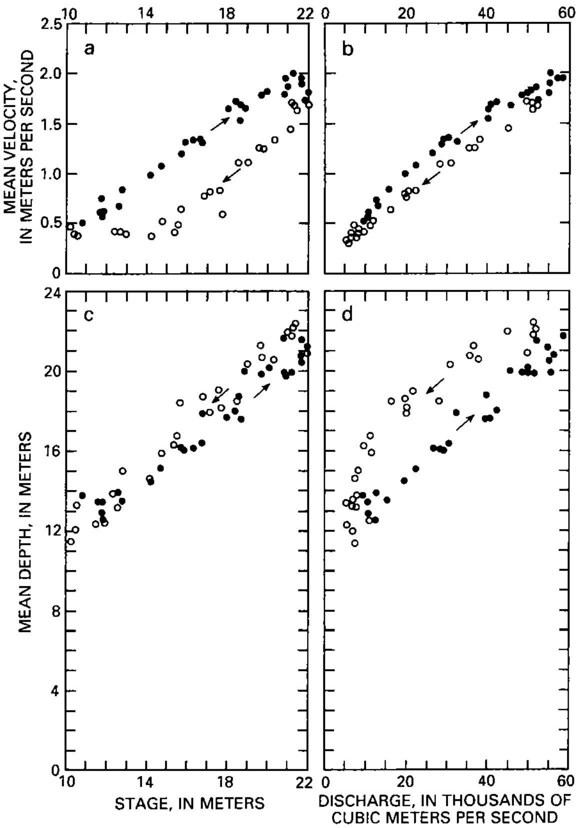

Figure 7. Relations of mean velocity and mean depth to stage and discharge, Madeira River at Fazenda Vista Alegre, March 1975 through November 1979, showing greater mean velocities and smaller mean depths during rising stages and discharges (solid circles) versus those during falling stages and discharges (open circles). **(a)** Mean velocity versus stage. **(b)** Mean velocity versus discharge. **(c)** Mean depth versus stage. **(d)** Mean depth versus discharge.

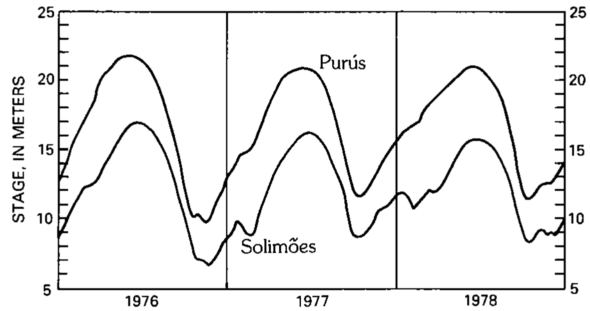

Figure 8. Daily river stages, Purús River at Arumã and Solimões River at mouth of Purús River, 1976–1978. Arumã is approximately 190 km upriver of mouth of Purús River. The stage curve for the Solimões River at the mouth of Purús River was constructed by graphically averaging the daily stage data from the gages at Itapeua and Manacapurú. The ordinate scale for both stage curves refers to the datum at Arumã. Vertical distance between stage curves is based on an assumed average slope of 0.00002 between Arumã and the mouth of the Purús.

The principle holds regardless of the true difference in elevation and the true slope of the water surface between the gaging stations. For example, if the difference in elevation between the two stage hydrographs were twice the distance portrayed in Figure 5 (that is, if the mean slope between the gages were 0.00012 rather than 0.00006), the river slope would still be greater during March than during August; the difference then would be a factor of 1.2 rather than a factor of 1.4. On the other hand, if the difference in elevation between the two stage hydrographs were actually smaller than portrayed in Figure 5 (that is, if the mean slope were substantially less than 0.00006), the slope of the lowermost Madeira River during March would be two to three times greater than the slope during August.

Purús River

The Purús River drains about 375,000 km^2 of western Brazil, and its discharge is probably less than half that of the Madeira River. Peak stages in the Purús River precede those in the Solimões River by a month or two (Fig. 8), and this difference in the arrival times of the peak stages causes substantial backwater effects in the relations between river stage and water discharge in the lower Purús (Fig. 9).

As in the Madeira, the backwater effects in the Purús River become progressively more pronounced with increasing proximity to the confluence with the Solimões River. At Seringal Fortaleza and Lábrea, 1860 and 1300 km upriver of the confluence (Fig. 9a and 9b), the stage–discharge relations during rising stages are not substantially different from those during falling stages. At Castanhal Patú, about 890 km upriver of the mouth (Fig. 9c), the river level is a few tenths of a meter higher during falling stages than during rising stages at the same discharge—much the same as at Humaitá, which is located a similar distance upstream from the mouth of the Madeira River (Fig. 6c). With increasing distance downstream along the Purús River (increasing proximity to the mouth), the differences between rising-stage and falling-stage river levels at the same discharge become progressively larger (Fig. 9d and 9e).

The wide scatter of points in Figure 9e is a reflection of the year-to-year differences in the relations between stage and discharge. The looped patterns become clearer and more coherent when the data are graphed by individual years, as they are in the upper row of

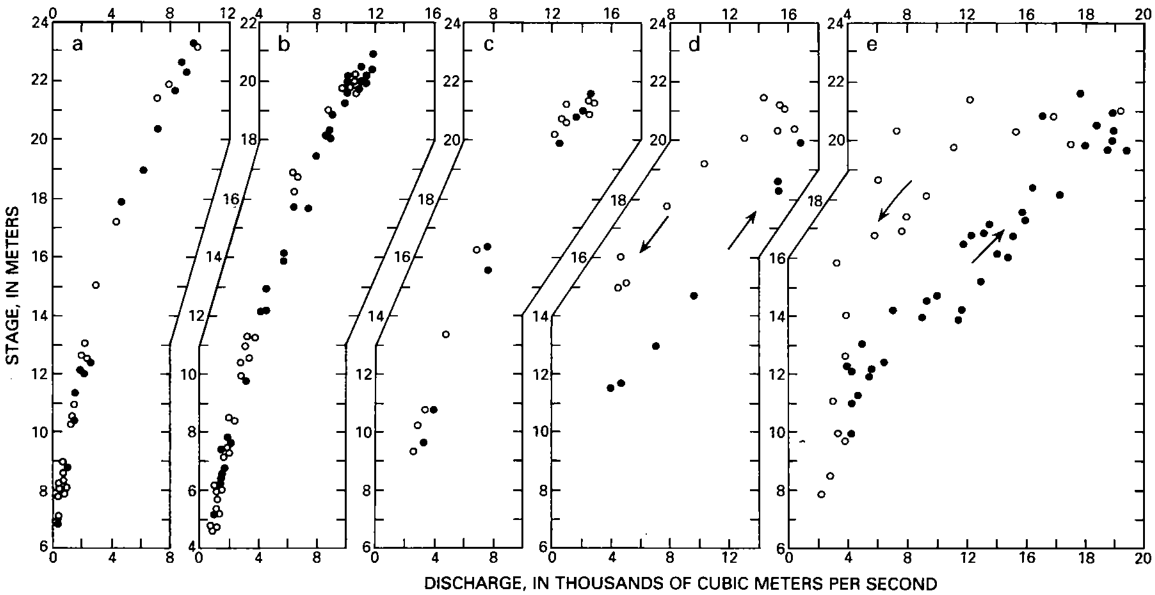

Figure 9. Stage–discharge relations at gaging stations along the Purús River, showing the different relations during rising (solid circles) versus falling (open circles) stages. **(a)** Seringal Fortaleza, 1860 km upriver of mouth (river distances, rounded to nearest 10 km, are measured from side-looking-radar mosaics published at a scale of 1:250,000 by RADAM BRASIL), June 1972 through October 1976. **(b)** Lábrea, 1300 km upriver of mouth, December 1977 through October 1982. **(c)** Castanhal Patú, 890 km upriver of mouth, June 1972 through September 1975. **(d)** Cariuacanga, 390 km upriver of mouth, August 1972 through September 1975. **(e)** Arumã, 190 km upriver of mouth, November 1975 through February 1982. Ordinate scales refer individually to local datum.

Figure 10. Note that backwater effects at Arumã are so pronounced that the river stage might continue to rise for a month or two after the discharge has begun to fall.

Negro River

The Negro River drains about 600,000 km^2 of Colombia, Venezuela, and northernmost Brazil. Although its drainage area is less than half that of the Madeira River, the Negro probably discharges more water than the Madeira. The uncertainty of this statement reflects the incompleteness of the gaging network and record in the Negro River basin. High-quality measurements of discharge are virtually impossible on a routine basis in the downstream reaches of the Negro River because the river is so wide and so broken by islands into multiple channels. The discharge-gaging station farthest downstream on the Negro River, at Serrinha, represents 250,000 km^2, or 40 percent of the total drainage area of the Negro River, and routine discharge measurements were begun at Serrinha only in 1977 (Fig. 11a). The only other significantly large fraction of the Negro River drainage area represented by gaging record is the 130,000 km^2 of the tributary Branco River basin above the gage at Caracaraí. The Branco River joins the Negro below Serrinha; the gaging record at Caracaraí spanned the decade 1967–1977, was discontinued, and then was resumed in 1983 (Fig. 11b). These two gaging records represent only 62% of the total drainage area of the Negro River (versus the 95% of the total drainage area of the Madeira River represented by the gaging record at Fazenda Vista Alegre), and estimating the runoff from the ungaged parts of the Negro River basin is complicated by the considerable spatial variability of rainfall. This variability is exemplified by the contrast between the mean annual rainfall of less than 1500 mm near Boa Vista (upper Branco River) and the more than 3500 mm that falls at San Carlos and in other parts of the Venezuelan and Colombian headwaters of the Negro (Boadas 1983, p. 38; IGAC 1983, p. 43; SUDAM/PHCA 1984, p. 17). At this time, a likely estimate for the mean annual discharge of the Negro River is about 30,000 m^3/sec. This impressive figure is considerably less than some previously reported estimates (for example, the figure of 67,000 m^3/sec, based on a single measurement made during a period of high discharge in 1963, and cited by Shoumatoff 1978, p. 98) which cannot be supported by the data that are now available.

The stage–discharge data that have been collected at gaging stations along the Negro River do not show

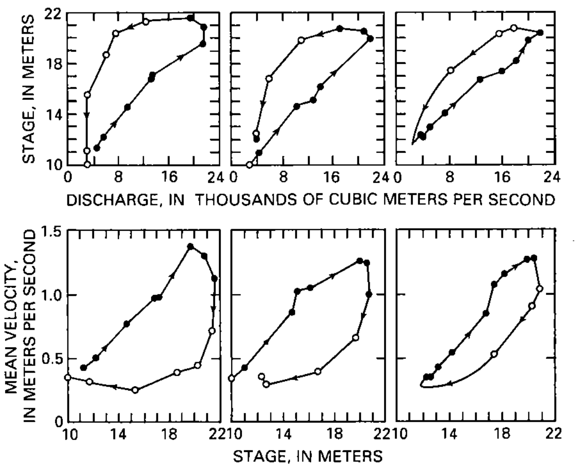

Figure 10. Stage–discharge relations (upper row) and velocity–stage relations (lower row) for three individual years, Purús River at Arumã. Points represent measurements made approximately one month apart: left graphs, November 1975 through November 1976; center graphs, November 1976 through October 1977; and right graphs, October 1977 through October 1978. Solid circles, rising-stage measurements; open circles, falling-stage measurements.

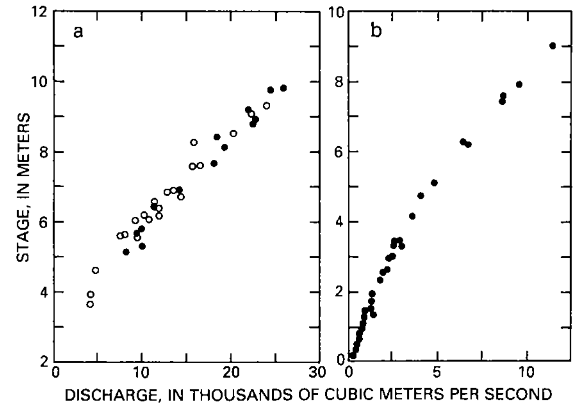

Figure 11. Stage–discharge relations in Negro River basin. **(a)** Negro River at Serrinha, approximately 700 km above mouth, February 1978 through August 1983, showing no apparent difference between relations during rising stages (solid circles) and falling stage (open circles). Rising and falling stages were sometimes difficult to distinguish because of short-term fluctuations (see Serrinha curve in Figure 12a). Zero stage on local gage corresponds to the arbitrarily assigned elevation of 37.0 m in Figure 12a. **(b)** Branco River at Caracaraí, September 1971 through November 1977, February 1983 through November 1983. No attempt was made to distinguish rising-stage data from falling-stage data at Caracaraí because of short-term fluctuations and because of the very small range of scatter in the stage–discharge relation. The stability of the stage-discharge rating probably is due to the strong bedrock control of the Branco River at Caracaraí (see the aerial photograph in the report by Johnstone 1986). Ordinate scales refer individually to local stage datums.

looped rating hydrographs such as those in Figures 6c–6e and 9c–9e. No routine measurements of discharge have been made in the Negro downriver of the station at Serrinha, which is about 700 km upriver of the mouth, and apparently too far upriver to show any effects of backwater from the Solimões or Amazon rivers (Fig. 11a).

Backwater effects are evident, however, in records of river stage collected along the lowermost 300–400 km of the Negro River (Fig. 12a). At least as far upstream as Moura, 300 km upriver of the mouth, the pattern of annual variation of river stage is more similar to that at the mouth than at stations farther upstream. At Moura and at stations farther downriver, the lowest stages of the year occur in October or November, whereas, at stations farther upriver (Barcelos and above, in Fig. 12a) the lowest stages occur in February or March. The upper and middle reaches of the Negro River, as far downstream as Barcelos, continue to fall in December and January while the lowermost river, downstream of Moura, has already begun to rise.

Comparison of the stage hydrograph for Manaus at the bottom of Figure 12a with the hydrographs for stations on the upper Negro River in the upper part of Figure 12a, and with the hydrograph for the mainstem Solimões River at Manacapurú in Figure 12b, shows that stages in the downstream reaches of the Negro reflect the stages of the mainstem. Although nominally in the Negro River, 17 km upstream from the confluence with the Solimões, the gage at Manaus measures fluctuations of the Solimões–Amazon mainstem to the virtual exclusion of fluctuations of the upper Negro. Therefore, the record of daily river stage at Manaus, continuous since 1902, can be considered a record of the stage fluctuations in the Solimões–Amazon mainstem (Sternberg 1987; Richey and others 1989b).

Amazon River

The Amazon River itself is subject to backwater effects from the combined effect of the discharges from large tributaries that flow into it from the south side, especially the Madeira, Tapajós, and Xingu rivers. Peak stages in the Tapajós and Xingu, as those in the Madeira (Fig. 5), precede peak stages in the Amazon mainstem by about two months. During April, when they have reached their maximum discharges for the year, these three tributaries combined can account for 40 percent of the total water being discharged by the Amazon River to the Atlantic Ocean. Their flows modify the annual rise and fall of the lower Amazon River in

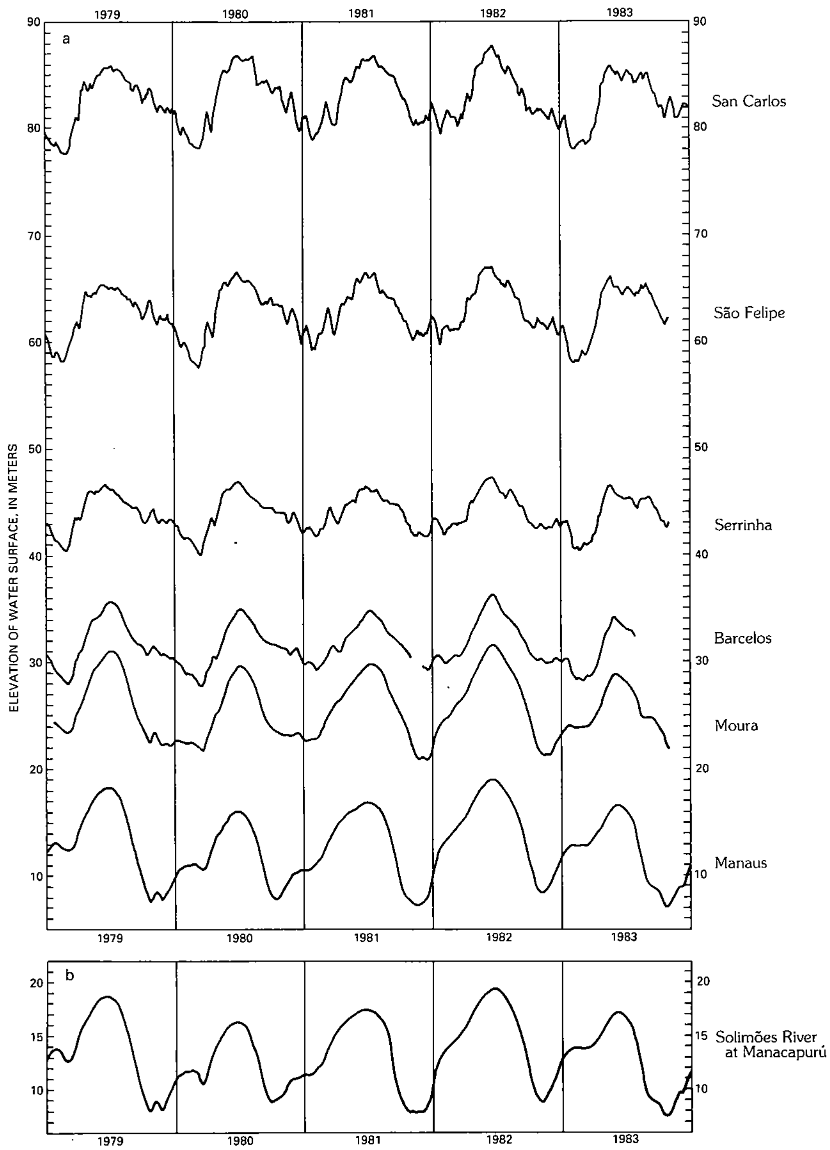

Figure 12. Fluctuations in river stage, Negro and Solimões rivers, 1979–1983. **(a)** At six stations on Negro River: data for San Carlos provided by Venezuelan Ministerio del Ambiente y de los Recursos Naturales Renovables; data for Manaus provided by PORTOBRAS. The individual stage curves are internally accurate, based on daily or twice-daily readings of a gage relative to a fixed local datum. However, the vertical distances between the stage curves and the numbers assigned to the ordinate scale are arbitrarily based on three assumptions: (1) that the mean low-water elevation at São Gabriel is 55 m above mean sea level (based on ten-year records of daily river stage and barometric pressure, 1933–1942, at the Salesian Mission in São Gabriel; U.S. Army Corps of Engineers, 1943, v. 1, pl. 21); (2) that the mean low-water elevation at Manaus is 8 m; and (3) that the mean water-surface slope between the river gages at São Gabriel and San Carlos is 0.000074 (as measured by the U.S. Army Corps of Engineers, 1943, v. 3, pl. 98–102). River distances upstream from mouth of Negro River (scaled from RADAM BRASIL mosaics and rounded to nearest 10 km): San Carlos, 1300 km; São Felipe, 1050 km; São Gabriel, 990 km; Serrinha, 700 km; Barcelos, 450 km; Moura, 300 km; Manaus, 20 km. **(b)** Solimões River at Manacapurú. Ordinate scale refers to same datum as in Figure 4.

such a way that the peak stage at Obidos usually precedes the peak stage 750 km upriver at Manacapurú (Fig. 4). This causes the mean river slope between Manacapurú and Obidos to be greater during falling stages than during rising stages, and it may account for the peculiar pattern in this same reach of storage of suspended sediment during rising stages and resuspension during falling stages (Meade and others 1985).

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