SOURCES AND ROUTING OF THE AMAZON RIVER FLOOD WAVE

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Abstract. We describe the sources and routing of the Amazon River flood wave through a 2000-km reach of the main channel, between São Paulo de Olivença and Obidos, Brazil. The damped hydrograph of the main stem reflects the large drainage basin area, the 3-month phase lag in peak flows between north and south draining tributaries due to seasonal differences in precipitation, and the large volume of water stored on the floodplain. We examined several aspects of the valley floor hydrology that are important for biogeochemistry. These include volumes of water storage in the channel and the floodplain and the rates of transfer between these two storage elements at various seasons and in each segment of the valley. We estimate that up to 30% of the water in the main stem is derived from water that has passed through the floodplain. To predict the discharge at any cross section within the study reach, we used the Muskingum formula to predict the hydrograph at downriver cross sections from a known hydrograph at upstream cross-sections and inputs and outputs along each reach. The model was calibrated using three years of data and was successfully tested against an additional six years of data. With this model it is possible to interpolate discharges for unsampled times and sites.

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INTRODUCTION

The water and dissolved and particulate materials observed in the main channel of the Amazon and other large floodplain rivers are the products of drainage basin processes occurring across widely varying temporal and spatial scales [Welcomme, 1979; Richey et al., 1989a]. An understanding of how these substances are routed from precipitation through their drainage systems to the oceans would yield important information on the processes controlling regional-scale hydrological and biogeochemical cycles [Gildea et al., 1986; Richey and Ribeiro, 1987; Vorosmarty et al., 1986]. Of particular importance for biogeochemistry are the storage of water in various parts of the drainage system for time periods of weeks, and the transfer of this water between the various physiographic reservoirs. Analyses of routing done on spatial scales of tens to hundreds of kilometers over time periods of weeks would be compatible in scale with the land-atmosphere interfaces represented by general circulation models [Dooge, 1982].

Data on the chemical composition of large rivers are increasing [Degens and Kempe, 1982; Meybeck, 1982; Naiman, 1983; Sedell et al., 1989; Degens et al., 1989; Richey et al., 1989a]. However, little progress has
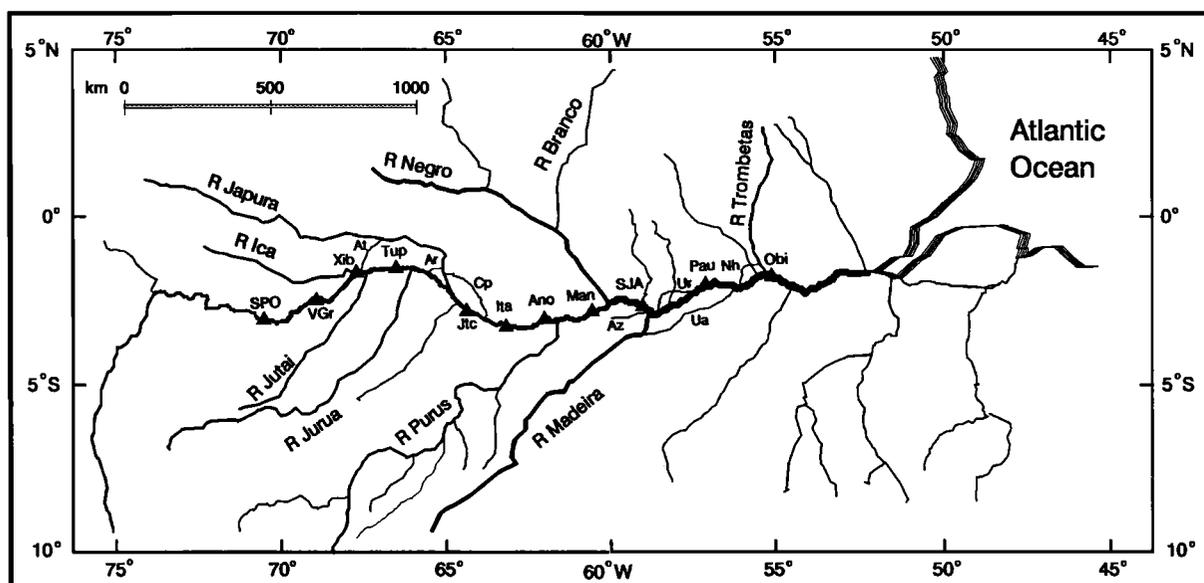
Fig. 1. The Amazon drainage basin. CAMREX main stem sampling stations include Vargem Grande (VGr), Santo Antônio do Içá (between Vargem Grande and Xibeco, not shown), Xibeco (Xib), Tupé (Tup), Jutica (Jtc), Itapeua (Ita), Anori (Ano), Manacapurú (Man), São José do Amatari (SJA), Paura (Pau), and Obidos (Obi). DNAEE gaging stations include São Paulo de Olivença (SPO), Santo Antônio do Içá, Itapeua, Manacapurú, and Obidos. Major tributaries are indicated by name. Ungaged channels and small tributaries passing through the floodplain include the Auati (At), Aranapu (Ar), Copea (Cp), Autaz (Az), Urucara (Ur), Uraria (Ua), and Nhamunda (Nh).

been made to date on studies of large-scale catchment behavior, particularly in tropical basins. Heterogeneity of the environment with regard to runoff-producing mechanisms, measurement and logistic realities, and differences in response between smaller and larger catchments make it difficult to extrapolate from one site to larger areas [Pilgrim et al., 1982; Beven, 1983; Dooge et al., 1982; Richey et al., 1989b].

In this paper we analyze the sources and routing of water in the Amazon River flood wave over a 2000-km reach of the main stem (Figure 1). This study reach includes most of the important tributaries of the Brazilian Amazon, and is demarcated by the last upriver and downriver gaging stations, at São Paulo de Olivença and Obidos. Our overall emphasis is on developing flow-routing models for the main stem which summarize information on sources of water and can be readily incorporated into analyses of carbon and nutrient cycling. Concentrating the analysis on the main stem is a logical step toward understanding basin-wide flow regimes under natural and perturbed conditions.

To assess the flux balance of water which constitutes the basis of our analysis, we (1) define the discharge regime of the main stem and major tributaries by compiling discharge hydrographs at four gaging stations on the main stem and at the most downriver stations of eight of its major tributaries; (2) estimate the magnitude of inputs from ungaged channels and the net exchange of water between the

main stem and its extensive floodplain from computations of potential runoff, change in storage, and isotopic $\delta^{18}O$ mass balances; and (3) use a Muskingum model as a summary flow model to calculate the time rate of change of flow in the Amazon main stem at 20 cross-sections over the length of the study reach.

This research is part of the CAMREX (Carbon in the Amazon River Experiment) project, a joint U.S.-Brazil study of the hydrology, sediment transport, and biogeochemistry of the Amazon River basin [Richey et al., 1980; Meade et al., 1985; Richey et al., 1986; Richey and Ribeiro, 1987; Hedges et al., 1986a,b; Ertel et al., 1986].

THE AMAZON RIVER

The Amazon basin, with an area of 6 million km^2 containing the largest stand of tropical rainforest in the world, contributes 20% of the global river discharge to the oceans, and condensational energy release from convective precipitation is of sufficient magnitude to influence global climatic patterns [Paegle, 1987]. Fluctuations in the Intertropical Convergence Zone induce wet and dry seasons in alternating seasons in the northern and southern sides of the basin [Hjemfelt, 1978; Salati et al., 1979]. Precipitation ranges from less than 2000 mm/yr in the extreme northeastern and southern parts of the basin, to more than 3500 mm/yr in the northwest lowlands, and

increases to 7000 mm/yr on the east side of the Andes. South of the equator there is a distinct dry period from June to August, whereas north of the equator the dry period lasts from January to March. Approximately fifty percent of rainfall is transformed into runoff; the balance is recycled via evapotranspiration from the forest [Villa Nova et al., 1976; Salati et al., 1979; Lettau et al., 1979].

The River System: São Paulo de Olivença - Obidos

The main channel of the Amazon (the Rio Solimões above the confluence with the Rio Negro] at São Paulo de Olivença carries water primarily of Andean origin. Of the northern tributaries downriver of São Paulo de Olivença, the Rios Içá and Japurá originate in the Andes and cross the Subandean Trough and central plain to reach the main stem. The Rio Negro drains primarily the caatinga [Sioli, 1975] forest on the Planalto das Guianas, and its major tributary, the Rio Branco, drains a drier savannah region. Of the southern tributaries, the Rios Jutaí, Juruá, and Purús drain the Subandean Trough and the central plain, while the Rio Madeira originates in the Bolivian Andes and then passes across the Planalto Brasileiro and the central plain. The Rio Trombetas drains crystalline shields, and enters the main stem via a large "mouthbay" [Sioli, 1975]. Numerous smaller tributaries drain exclusively lowland regions into the main channel or into the floodplain, while large "paranas" act as diversion canals between the main channel, floodplain, and tributaries, with the flow direction often depending on river stage.

In the reach between São Paulo de Olivença and Obidos, floodwaters and direct precipitation regularly inundate about 40,000 km^2 of floodplain ("varzea") [Iriondo, 1982; Mertes, 1985] through an extensive network of drainage channels ("paranas") and overbank flow during the 7- to 10-m rise and fall of the river over the course of a year. Approximately 10,000 km^2 are covered by thousands of permanent lakes that range in size from less than a hectare to over 600 km^2, and are typically 6-8 m deep at high water [Melack, 1984]. As the river falls, land is reexposed and the lakes become isolated from the main channel, with depths decreasing to 1-2 m. Determining the relative distribution of main stem versus local sources of water for the varzea is important in analyzing the nutrient cycling of the region [Forsberg et al., 1988] and for estimation of the extent of biogenic gas fluxes; floodplains are an important source of methane to the troposphere [Richey et al., 1988; Devol et al., 1988]

Discharge Regime: Measurements and Data Sources

The overall flux balance we wish to evaluate over the study reach is

$$Q_{sm} = Q_{in} + Q_{tr} + Q_{ex} - Q_{ot} \qquad (1a)$$

where the flows include import from upriver (Q_{in}), import from major (gaged) tributaries (Q_{tr}), net water exchange between the varzea and main channel (Q_{ex}), output at the downriver cross section (Q_{ot}), and change in main stem storage (Q_{sm}).

The exchange between the main stem and varzea is

$$Q_{ex} = Q_{vm} - Q_{mv} \qquad (1b)$$

where Q_{vm} is flow from the varzea to the main stem and Q_{mv} is flow from the main stem to the varzea. The flux balance for the varzea is

$$Q_{sv} = Q_p - Q_{ex} - Q_{ev} \qquad (1c)$$

where Q_{sv} is storage on the varzea, Q_p is import from ungaged paranas or minor tributaries to the varzea and precipitation directly on the varzea and adjacent local drainage areas, and Q_{ev} is evaporation from the varzea. We now evaluate the terms in (1).

Main stem and major tributary discharge. Daily measurements of river stage in the Amazon basin were started in 1972 by the Departamento Nacional de Aguas e Energia Elétrica (DNAEE), following the pioneering measurements of Oltman et al. [1964]. Gaging stations have been maintained for varying periods of time at six sites along the main stem and at sites along major tributaries (Table 1). Stage heights at these stations are recorded twice daily by local observers, and are archived in the Sistema de Informações Hidrometeorológicas (SIH) of DNAEE. We converted the stage heights into water discharge (Q_{in}, Q_{ot}, Q_{tr}) using rating curves based on bimonthly or trimonthly current meter measurements of discharge by DNAEE field crews and by CAMREX (see below). Use of the term "discharge" in this paper implies a daily average value.

The main stem DNAEE gaging stations are not close enough to each other to determine either the details of input from local ungaged tributaries and channels or the magnitude of water exchange between the floodplain and main channel. To provide finer-scale resolution of discharge, we made current meter measurements at eleven stations along the main stem and at seven tributary stations (located less than 100 km upriver of the main stem of the Amazon (Figure 1)) on nine cruises over a three-year period (1982-1984) at different parts of the annual hydrograph [Richey et al., 1986]. For subsequent mass balance calculations, errors (1 σ) associated with the water discharge measurements and with dissolved chemical flux measurements are 2.5% and 5%, respectively [Richey et al., 1986, 1989a].

Ungaged flows: storage, paranas and varzea exchange. We made several direct measurements of the discharge of the smaller ungaged paranas and tributaries, but not with sufficient frequency to determine annual patterns. Here we estimate these ungaged flows from basin area, precipitation, and a rainfall-runoff coefficient.

TABLE 1. DNAEE Gaging Stations

Station[a]	Period of Record	Drainage Area,[b] 10^3 km^2	Distance,[c] km	% of Basin Downriver of Station
São Paulo de Olivença (3°27'S 68°55'W)	1974-1985	990	0	
Santo Antônio do Içá (3°02'S 67°53'W)	1974-1985	1163	140	
Itapeua (4°02'S 63°00'W)	1975-1985	1821	994	
Manacapurú (3°19'S 60°33'W)	1973-1985	2233	1306	
Obidos (1°56'S 55°30'W)	1972-1985	4640	2039	
Rio Içá (2°59'S 69°35'W)	1980-1985	150	260	10.1
Rio Jutaí (2°48'S 67°05'W)	1979-1983	65	30	0.0
Rio Juruá (4°50'S 66°45'W)	1973-1985	1865	83	14.7
Rio Japurá (1°48'S 66°33'W)	1974-1985	331	340	5.3
Rio Purús (4°41'S 62°07'W)	1977-1985	358	187	2.6
Rio Negro (00°27'S 64°50'W)	1978-1985	468	590	50.8
Rio Branco (1°48'N 61°08'W)	1974-1984	217	660	38.8
Rio Madeira (4°54'S 60°01'W)	1976-1985	1306	258	2.8
Rio Trombetas (1°05'S 57°02'W)	1972-1985	151	165	38.8

[a]Terezinha, upriver of São Paulo de Olivença, is not included here because of its shorter period of record and proximity to São Paulo de Olivença.
[b]Drainage area refers to the area upriver of the station.
[c]Distance refers to the distance downriver from São Paulo de Olivença (main stem) or upriver from confluence with main stem (tributaries).

The ungaged drainage areas were outlined on 1:5,000,000 and 1:1,000,000 scale U.S. Air Force navigation charts and, for smaller-scale features near the Amazon main stem, on 1:250,000 Radambrasil charts [Radambrasil, 1972]. Each drainage area was identified as contributing to an ungaged tributary or parana or as floodplain which directly contributes to the main Amazon channel. The drainage areas for paranas and varzea were divided according to the corresponding subdivisions along the main stem. All the areas were planimetered, and recorded as the average of three measurements which differed by no more than 1 cm^2; i.e., at most 2500 km^2 on the 1:5,000,000-scale maps.

Daily data from 19 precipitation stations monitored by DNAEE in the Amazon basin were used to construct monthly hyetographs for each station for each year with a complete rainfall record. The number of years of complete records for the precipitation stations that were available for this study ranged from one to 11, with 1972 the earliest year and 1982 the most recent. The measurements from each station were averaged to obtain mean monthly hyetographs. Since only data from a few stations were used, it was necessary to assume that precipitation is uniformly distributed over areas at large distances from the precipitation stations. To account for water loss due to evapotranspiration, these precipitation numbers were adjusted by a coefficient of 0.5, which is in accord with approximations of water loss in Amazonian environments determined by Salati et al. [1979].

Monthly water input, Q_p, from each ungaged source was then calculated by multiplying the ungaged drainage area by the adjusted average monthly value of precipitation for the nearest precipitation station. At the level of resolution of these calculations, we include evaporation from lakes, Q_{ev}, which is on the order of 4 mm/day over open water [S. MacIntire, University of California at Santa Barbara, personal communication, 1989], as part of the precipitation reduction factor of 50%.

Change in the volume of water stored in the main stem, Q_{sm}, was approximated as the product of change in stage and reach surface area. The change of water storage on the varzea, Q_{sv}, was calculated as the product of the change in depth on the varzea and the area inundated (40,000 km^2 periodically inundated and 10,000 km^2 of large lakes). The depth change was calculated from the change in stage levels averaged for each month for 1982-1984. The minimum stage heights correspond to a floodplain depth of less than 0.5 m, and at high water they correspond to maximum depths of about 9 m upriver and 7 m downriver; these depths are consistent with those observed. The change in inundated area was assumed to be a linear function of depth on the varzea. Change in lake area was included in the change in inundated area.

Isotope ratio $\delta^{18}O$ measurements. We measured the isotope ratio $^{18}O/^{16}O$ ($\delta^{18}O$) in river and floodplain waters on the CAMREX cruises as a tracer of different water masses [Gat and Gonfiantini, 1981]. Samples were taken from the main stem and

tributaries as part of the routine chemical sampling on the CAMREX cruises, and were analyzed by mass spectrometry (Finnegan MAT 251 fitted with water CO_2 equilibration system at the University of Washington and a MAT 230 at the Centro de Energia Nuclear na Agricultura). Isotope results are reported as relative deviations ($^o/_{oo}$) from the standard mean ocean water (SMOW) standard, defined by Craig [1961] as

$$\delta^{18}O = ((^{18}O/^{16}O_{sample})/(^{18}O/^{16}O_{SMOW}) - 1) \times 10^3 \quad (2)$$

THE DISCHARGE REGIME

Main Stem and Major Tributary Hydrographs: 1972-1985

Though differences in stage of 7-10 m are common along the main stem, there is only a twofold to threefold difference between low and high discharge (Figure 2). São Paulo de Olivença has average minimum and maximum discharges of 20,000 m^3/s and 60,000 m^3/s, Manacapurú averages 70,000 m^3/s and 130,000 m^3/s, and Obidos averages 100,000 m^3/s and 220,000 m^3/s, respectively. The total Amazon input to the Atlantic includes the Rios Tapajos, Xingu, and Tocantins, for a mean annual input of about 200,000 to 220,000 m^3/s. The damped hydrograph of the main stem reflects in part the offset input from tributaries. The peak flows from the northern and southern tributaries are typically three months out of phase as a result of the seasonal differences in precipitation.

The data from the DNAEE records represent a short period of time. In order to determine whether the data from the detailed discharge records of 1972 to 1985 are representative of longer time periods, the discharge history must be considered. The only long-term discharge record available for the Amazon is a record of the stage of the Rio Negro at Manaus, covering the period 1903-present. Richey et al. [1989c] showed that these data could be used to calculate a discharge time series for Manacapurú (Figure 3). They found that the predominant interannual variability occurs on the 2 to 3 year time scale, and that the oscillations in the hydrograph are coupled to the El Niño-Southern Oscillation cycle, with a lag of about five months. Recurrence intervals (the average interval in years between events equaling or exceeding a given magnitude) for those years include values that range from 2 years to 80 years (Figure 3). Therefore, it can be assumed that the pattern of the hydrographs for 1972 to 1984 is representative of the historical pattern, and results obtained from these data could be applied to the longer-term record.

Ungaged Flows

On the basis of the siting of sampling stations and the locations of tributaries and paranas, we evaluate the ungaged flows for upriver (São Paulo do Olivença - Itapeua), midriver (Itapeua - Manacapurú), and downriver (Manacapurú - Obidos) reaches.

Storage and runoff calculations. The change in channel storage, Q_{sm}, is greatest downriver (Manacapurú- Obidos), ± 3,500 m^3/s, less upriver (São Paulo do Olivença-Itapeua), ± 3,000 m^3/s, and about ± 1,500 m^3/s midriver (Itapeua - Manacapurú) (Figure 4). When the change in storage is calculated per unit reach length, it is greatest downriver, ± 5 m^3 s^{-1} km^{-1}, and decreases upriver to ± 2.5 m^3 s^{-1} km^{-1}.

Storage of water on the floodplain, Q_{sv}, is considerably greater than in the main channel. The increase in storage over the 8-month period of rising water is greatest during the mid-rising water phase in the upriver reach of the main stem, approaching 15,000 m^3/s, with maximum rates in the midriver and downriver reaches of 3,000 m^3/s and 9,000 m^3/s, respectively. The decrease in storage during the 4-month falling water period is greatest during mid-falling water, ranging from -18,000 m^3/s upriver to -8,000 m^3/s at midriver.

Ungaged flows from paranas, small tributaries, and direct precipitation, Q_p, upriver and downriver range from 3,000 m^3/s during the dry season to 7,000 m^3/s during the wet season; midriver flows are about half of these values (Figure 4). These estimates of flow for individual paranas and ungaged tributaries from the area precipitation calculations compare reasonably well to the few CAMREX discharge measurements on those rivers (3,000 to 6,000 m^3/s, unpublished data).

Water exchange between the varzea and the main stem, Q_{ex}, is the difference between parana and precipitation inputs Q_p and the change in storage on the varzea. Overall, exchange was greatest during early-falling to mid-falling water in the upriver and downriver reaches, with a net flow from the floodplain to the main stem of about 20,000 m^3/s. Net exchanges were generally lower in the midriver reach, where the area of the floodplain is relatively small.

Floodplain exchange is therefore a significant component of the water budget of the main stem. These flows correspond to about 30% of the flow at Itapeua, and cumulatively to about 25% of the flow at Obidos. Through input from local sources (paranas, direct precipitation) there is generally a net positive flow into the river. Discharge measurements made during the CAMREX cruises confirmed that the main stem gained water in excess of that contributed from the major tributaries, even when water from the main stem was flowing onto the varzea [Richey et al., 1986].

The $\delta^{18}O$ signal of main stem and floodplain waters. We have calculated that the exchange of water between the main stem and floodplain could be quite large. Martinelli et al. [1989] and Mortatti et al. [1985] found that the $\delta^{18}O$ of local precipitation inputs was seasonally variable and enriched relative to river water. Hence, if these local inputs do constitute a significant input to the main stem, then the main stem should reflect their isotopic composition. To provide an independent assessment of the magnitude of Q_{ex} and to begin to separate it into its separate flow components, we calculated the $\delta^{18}O$ expected for Q_{ex}
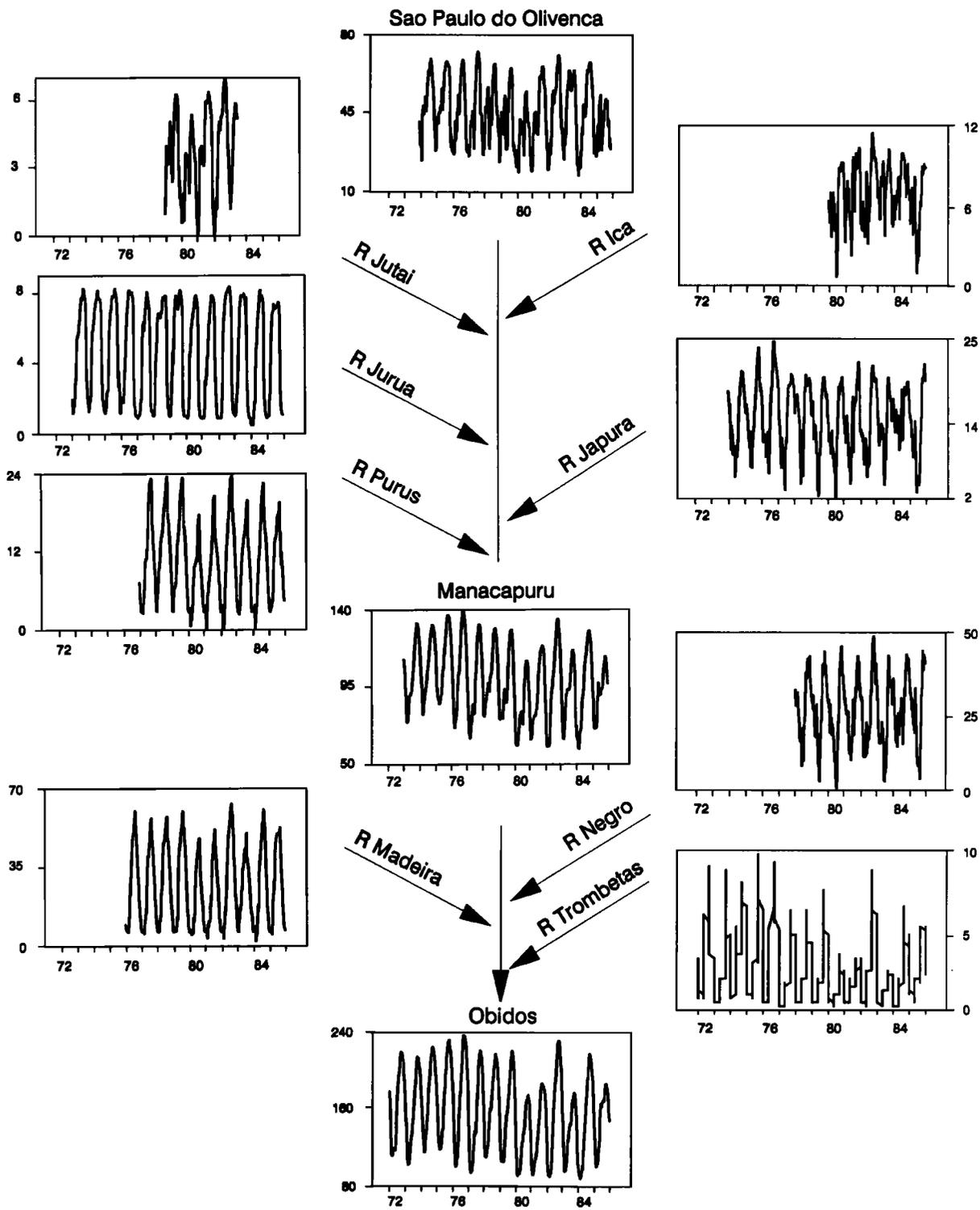
Fig. 2. Discharge (10^3 m^3/s), along ordinate, calculated from DNAEE stage records for main stem (Santo Antônio do Içá and Itapeua are not shown) and tributary gaging stations. Years indicated by abscissa scale are from September 1 through August 31 (the water year for São Paulo de Olivença).
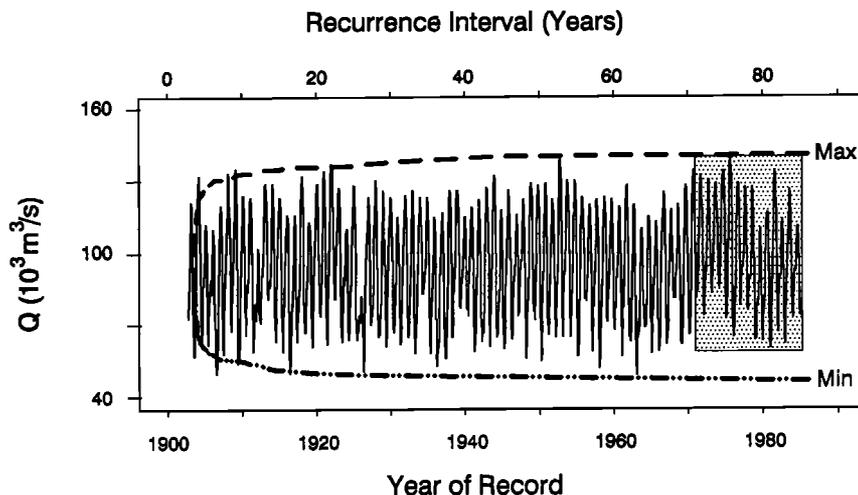
Fig. 3. Long-term discharge record (solid line) for Manacapuru, 1903-1985, (adapted from Richey et al. [1989c]). The dashed lines refer to the upper abscissa and represent the average recurrence interval of a particular discharge being equaled by either the maximum flow event or minimum flow event in a year. The shaded portion represents the years for which detailed discharge records are available.

from the isotopic mass balance of the main stem and major tributaries for the CAMREX cruises:

$$\delta^{18}O_{ex} = (((^{18}O_{ot}Q_{ot} - {}^{18}O_{in}Q_{in} - {}^{18}O_{tr}Q_{tr})/ \quad Q_{ex}) -1) \times 10^3 \qquad (3)$$

where $^{18}O_i$ is the $^{18}O/^{16}O$ ratio of flow Q_i.

The distributions of $\delta^{18}O$ in the main channel ($\delta^{18}O_{in}$, $\delta^{18}O_{ot}$) and major tributaries ($\delta^{18}O_{tr}$) generally tracked the respective hydrographs (Figure 5). At Vargem Grande, where the river discharge is dominantly of Andean origin, the river was more isotopically depleted during high water, and more enriched during low water. Tributaries were enriched relative to Vargem Grande, by 1 to 2 °/$_{oo}$ in the Rios Içá and Japurá, to 2 to 3 °/$_{oo}$ in the Rio Içá. In the main stem and in all tributaries in 1983, a dry year, $\delta^{18}O$ was more enriched than in the other years; this trend was pronounced in the southern tributaries. As the composite of all inputs, the $\delta^{18}O$ signal at Obidos averaged about 2 °/$_{oo}$ more than, was offset from, and was more damped than the signal at Vargem Grande.

Computed values for $\delta^{18}O_{ex}$ and measured floodplain values ($\delta^{18}O_v$) were generally comparable, and always enriched relative to the main stem ($\delta^{18}O_{ms}$, as the reach average of $\delta^{18}O_{in}$ and $\delta^{18}O_{ot}$), by 0.3 to 2.7 °/$_{oo}$ (Table 2). Sufficient data to separate Q_{ex} into Q_{vm} and Q_{mv} and to calculate what the relative contribution of main stem water is to storage on the varzea are not available. However, the results of Table 2 suggest several trends. The smallest differences in isotopic composition between the varzea and main stem were at the time of late-falling and early-rising water. The largest differences were at late-rising and early-falling water. This implies that the relative

contribution of local sources of water to Q_{ex} increases with increasing stage.

These $\delta^{18}O$ calculations confirm that ungaged water sources from local drainage areas are indeed significant to the main stem, and the results are consistent with our previous estimates of Q_{ex}. The data also suggest that it should be possible to evaluate the relative magnitudes of water sources over time for the floodplain, when concurrent data are available on the change in $\delta^{18}O$ of the main stem, precipitation, and floodplain, and on the time rate of change of water storage on the floodplain.

FLOW ROUTING IN THE MAIN STEM

Our overall objective is to quantify the terms of (1) at cross sections at approximately every 100 km along the study reach (Figure 6). We used the Muskingum flow routing scheme to predict discharge for locations and times on the main stem for which there are no measurements. Elias and Cavalcante (1983) showed the potential for this approach for the Amazon by modeling the flood wave below Manaus.

Flow Routing Model

The Muskingum method uses the continuity equation for flow in a reach and a calibrated relationship between storage, inflow rate, and outflow rate to predict the hydrograph at a downriver cross section from a known hydrograph at the upriver end of the reach and inflows and outflows occurring along the reach. The downriver output is calculated as a function of a storage constant k, which is approximately equal to the travel time of the flood wave through the reach
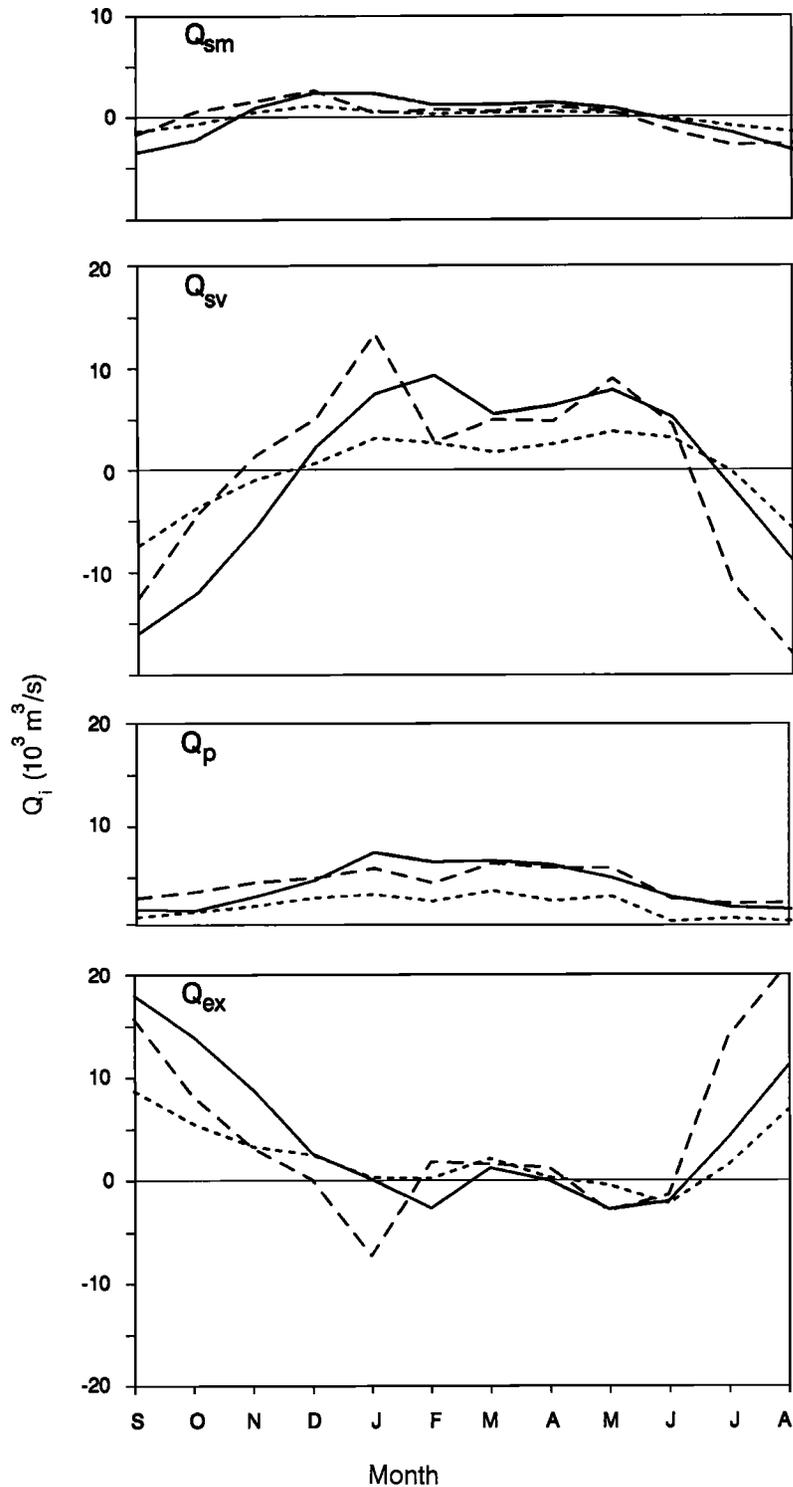
Fig. 4. Estimated annual cycle of ungaged flows for upriver (long dashes), midriver (short dashes), and downriver (solid line) reaches, including change in main stem storage (Q_{sm}), paranas and ungaged tributaries (Q_p), precipitation on the floodplain (Q_l), change in varzea storage (Q_{sv}), and net exchange between the main stem and varzea (Q_{ex}).
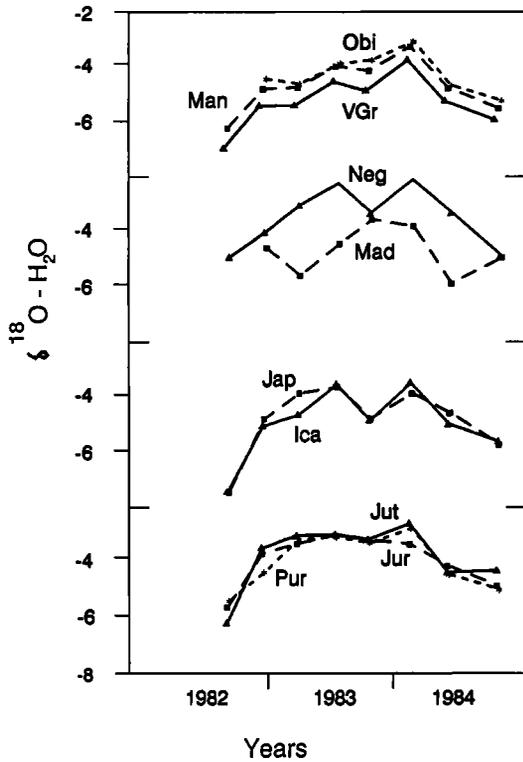
Fig. 5. The $\delta^{18}O$ of the main stem at Vargem Grande (Var Gr), Manacapurú (Manaca), Obidos and of the Rios Negro, Madeira, Japurá, Içá, Purús, Juruá, and Jutaí on CAMREX sampling cruises 1 through 8.

[Dooge et al., 1982], and a attenuation coefficient x, which indicates the relative importance of inputs and outputs in affecting storage [Dunne and Leopold, 1978]. The model is expressed as

$$Q_{ot(t)} = c_0 (Q_{in} + Q_{tr} + 0.5wQ_p)_{(t)} +$$
$$c_1 (Q_{in} + Q_{tr} + 0.5wQ_p)_{(t-1)} +$$
$$c_2 (Q_{ot} + 0.5wQ_p)_{(t-1)} \qquad (4a)$$

where

$$c_0 = (-kx + 0.5\Delta t)/(k - kx + 0.5\Delta t) \qquad (4b)$$
$$c_1 = (kx + 0.5\Delta t)/(k - kx + 0.5\Delta t) \qquad (4c)$$
$$c_2 = (k -kx - 0.5\Delta t)/(k - kx + 0.5\Delta t) \qquad (4d)$$

with Δt of 1 day. A weighting factor w is provided to adjust Q_p to account for interannual differences in precipitation. Dividing Q_p equally between the inflow and outflow terms accounts for the fact that water input from these sources occurs over the entire reach, not just as a point input at the head of the reach. The model was also applied to the lower 300 km of the Rio Japurá, to account for the effect on the Rio Japurá of water storage on the extensive floodplain at the lower end of that tributary.

Model Calibration and Results

With a floodplain that is inundated throughout the rise in river level, the Amazon does not have a clear onset of overbank flow until the river is at or near peak discharge; hence we used the same values of x and k for both within-channel and overbank flows at

TABLE 2. Values of $\delta^{18}O$ (‰) calculated for Total Ungaged Input Q_{ex} ($\delta^{18}O_{ex}$) Compared to Measured Varzea and Paranas ($\delta^{18}O_v$) and to Average Main Stem Values ($\delta^{18}O_{ms}$) for Upriver and Downriver sections for CAMREX Cruises 2-8 (Cr 2 - Cr 8)

	Cr 2	Cr 3	Cr 4	Cr 5	Cr 6	Cr 7	Cr 8
			Vargem Grande - Itapeua				
$\delta^{18}O_{ex}$	na	b	-4.4	-4.3	b	b	-6.2
$\delta^{18}O_v$	-5.2	na	-4.7*	-4.5	-3.7	-5.1	-6.8
$\delta^{18}O_{ms}$	-6.4	-6.4	-5.6*	-5.7	-4.3	-6.2	-7.2
			Manacapurú - Obidos				
$\delta^{18}O_{ex}$	na	-3.2	-2.6	b	-3.4	b	-6.1
$\delta^{18}O_v$	-5.0	na	-4.8*	-4.9**	na	na	na
$\delta^{18}O_{ms}$	-5.7	-5.8	-5.3*	-5.6**	-3.8	-5.9	-6.4

See Figure 7 for timing on hydrographs. Data are also from Martinelli et al. [1989], where a single asterisk denotes a cruise April-May 1987, and a double asterisk denotes a cruise July-August 1985, similar in hydrology to cruises 4 and 5, respectively. Here, b denotes sections where fluxes balanced within the 5% accuracy of the discharge measurements, and na denotes not available.
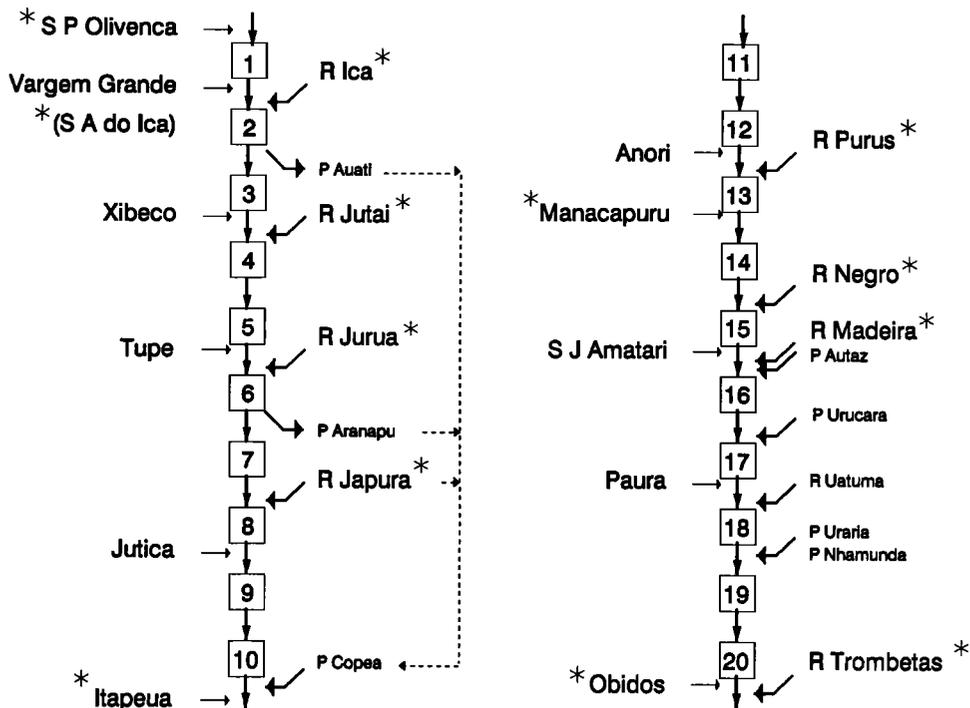
Fig. 6. Schematic representation of the 20-reach water routing model. Tributary (R) and parana (P) locations are shown to the right; dotted lines show parana connections. Stations marked with an asterisk are DNAEE gaging stations.

all stages. The value for x was set at 0.1 for all reaches; higher values increased differences between observed and predicted hydrographs, while lower values produced results insignificantly different from results at 0.1. Initial values for k were calculated from the hydrograph records as the residence time of the flood wave in each reach [Dunne and Leopold, 1978]. Final k values (respectively, k = 1.1, 1.0, 3.6, 4.2, 4.2, 4.2, 4.2, 4.2, 4.2, 4.2, 4.2, 2.9, 5.9, 2.3, 2.5, 2.3, 2.3, 2.3, 2.3, and 2.9 days for reaches 1 through 20 of the main stem, and 2.0, 4.5, and 4.5 days for the lower reaches of the Rio Japurá) were those that gave the best fit between observed versus predicted hydrographs for 1982-1984. These years were chosen for calibration of the model, because the CAMREX discharge measurements for that period allowed a more accurate definition of the hydrograph of the main stem flow between the DNAEE gaging stations, and hence provided more detailed comparisons. The annual precipitation weighting factors for Q_p (w = 1.1, 0.9, 1.0, 0.9, 0.8, 0.6, 0.8, 0.2, and 0.6 for 1976-1984, respectively) were ranked according to the relative magnitude of average precipitation for the years 1976-1983 at Santo Antônio do Içá, Manacapurú, and Oriximina (near Obidos). The weighting factor for 1984 could not be derived from the precipitation records (which extended only through 1983), so its rank was assigned according to the ranking of discharge at Manacapurú.

The k values used in this model are comparable to those calculated for other alluvial rivers. If it is assumed that the k values we used approximate the residence time of the flood wave in each reach (although the flood wave does not move uniformly downriver), then this yields a wave speed of approximately 0.3 m/s for the entire 2000 km reach. This compares with approximate wave speeds of 0.2 m/s for the lower Mekong River and the Brahmaputra River, 0.2 m/s for the Niger and Senegal Rivers, and 0.3 m/s for the middle Mekong River (calculated from data of Welcomme [1985]).

The agreement between predicted discharge for all the CAMREX and DNAEE cross sections when the measured flow was routed from São Paulo de Olivença during the calibration period and the observed discharge (i.e., DNAEE and CAMREX measured discharge) was very good (Figure 7). Comparison of the observed discharges and those predicted by the Muskingum model shows that the pattern of the residuals is similar for most of the cross sections. Generally, low flows are underestimated and high flows are slightly overestimated, but throughout most of the flow range the predictions are very close to observed values. Accuracy of the predicted discharge is increased when the flow is routed from the DNAEE station that is immediately upriver (Table 3). The average error is less than 10% of the observed flow for nearly all the stations.
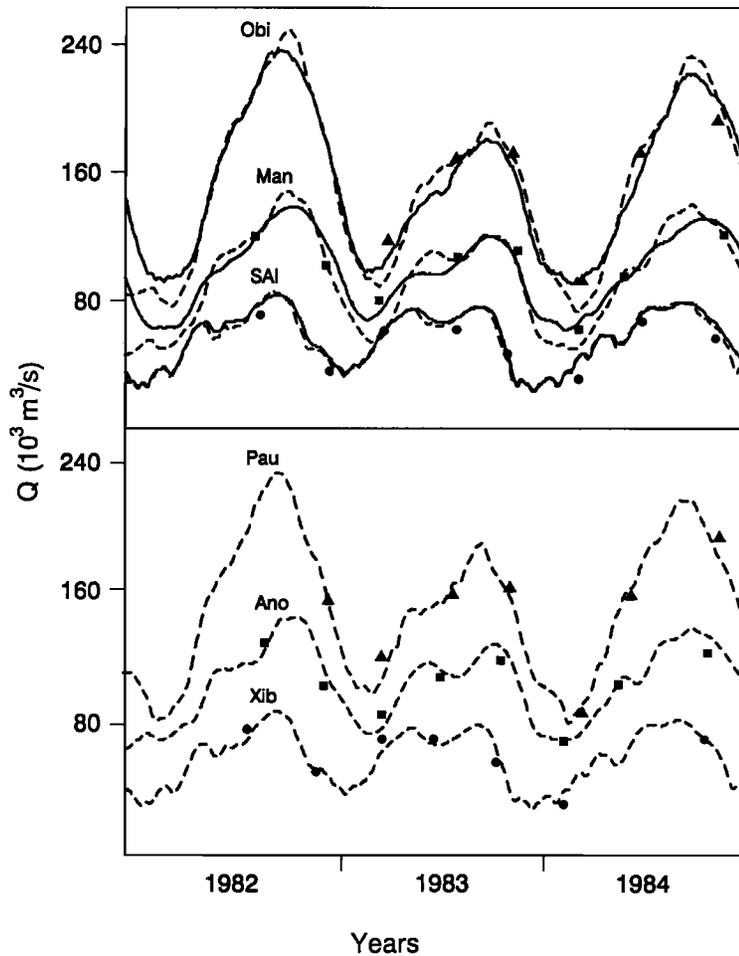
Fig. 7. Outputs of flood wave routing model for a flood wave initiated at São Paulo de Olivença: observed discharge from stage (solid curve) and predicted discharge from model (dashed curve) at Santo Antônio do Içá, Manacapurú, and Obidos (Itapeua not shown); and predicted only at Xibeco, Anori, and Paura (Tupé, Jutica, and São José do Amatari not shown). Symbols indicate CAMREX discharge measurement.

For further verification of the model, the k, x, and ungaged flow variables were retained and the model was run for the years 1976-1981 (Table 3). Predictions were comparable to or slightly less accurate than those for 1982-1984.

SUMMARY AND CONCLUSIONS

1. The damped hydrograph of the main stem reflects the large drainage basin area, the phase lag in peak flows between the north and south draining tributaries, and the large volume of water stored on the floodplain. Over a 15-year period, the average minimum and maximum discharges were about 20,000 m^3/s and 60,000 m^3/s upriver and 100,000 m^3/s and 220,000 m^3/s downriver, respectively.

2. The exchange of water between the floodplain and main stem is significant. Up to 30% of the flow of the main stem is derived directly from water stored on the floodplain and from flow from local sources passing through the floodplain.

3. The accuracy of the routing model predictions for six years based on a calibration for three years shows that the model and corresponding parameters are well-suited for flow routing in the reach of the Amazon between São Paulo de Olivença and Obidos. The stability of the main stem hydrograph since 1903 and the range of recurrence intervals for the years 1976 to 1984 (i.e., the years used in the Muskingum analysis and the years of the most recent series of sampling expeditions on the Amazon) indicates that the model is calibrated on the basis of a representative

TABLE 3. Summary Statistics for Muskingum Analysis of
Amazon Flows, 1976-1984

To	From	1982	1983	1984
SAI	SPO	4.7 (3.1)	3.4 (2.6)	3.5 (4.7)
Ita	SPO	9.2 (6.7)	9.0 (7.5)	9.5 (7.6)
Ita	SAI	7.0 (5.3)	6.8 (5.4)	7.7 (7.1)
Man	SPO	8.7 (6.4)	8.4 (6.8)	9.2 (6.3)
Man	Ita	4.7 (4.2)	3.9 (3.8)	4.1 (3.0)
Obi	SPO	5.9 (6.9)	5.7 (5.4)	6.3 (6.2)
Obi	Man	3.5 (3.1)	4.3 (2.7)	4.2 (3.4)

To	From	1976	1977	1978
SAI	SPO	7.4 (4.5)	5.9 (3.9)	6.7 (4.3)
Ita	SPO	8.3 (9.1)	8.2 (4.4)	7.9 (5.6)
Ita	SAI	5.9 (6.7)	5.6 (4.1)	6.3 (5.0)
Man	SPO	10.1 (12.6)	8.7(4.5)	8.8 (6.2)
Man	Ita	3.8 (2.8)	3.6 (2.3)	4.8 (3.2)
Obi	SPO	9.6 (11.6)	5.9 (6.1)	5.1 (4.4)
Obi	Man	4.1 (3.1)	6.3 (4.9)	4.4 (2.9)

To	From	1979	1980	1981
SAI	SPO	5.4 (4.0)	6.9 (3.6)	4.2 (3.6)
Ita	SPO	10.7 (7.9)	7.8 (6.3)	9.5 (7.1)
Ita	SAI	9.6 (7.4)	7.8 (5.9)	9.1 (8.3)
Man	SPO	11.7 (9.9)	9.7 (4.7)	8.9 (8.6)
Man	Ita	4.1 (2.5)	6.0 (3.0)	4.5 (3.6)
Obi	SPO	8.7 (8.4)	4.8 (3.4)	5.9 (5.2)
Obi	Man	4.1 (3.0)	3.8 (2.6)	2.8 (2.8)

Station abbreviations are SPO, São Paulo de Olivença; SAI, Santo Antônio do Içá;
Ita, Itapeua (Ita); Man, Manacapurú; and Obi, Obidos (Obi). Mean and standard
deviation (in parentheses) are based on the percent of the absolute values of the
residuals (observed minus predicted) normalized by the observed flow. Calibrated values
of k and x (equation (6)) from 1982-1984 used for 1976-1981.

range of flows and can be used to predict flows for years when detailed hydrological records are not available.

4. The discharge hydrographs describe the temporal sequence of water flow; they say little about the source of the water (for example, precipitation derived from recycled or marine water vapor in the tributaries, main stem river water or local precipitation on the varzea) or the time lag between a source and the point at which discharge is finally measured. In a continental-scale river system with little information available on rainfall-runoff relationships, it would be useful to identify tracers which indicate the source of runoff for each tributary drainage. With concurrent data on the $\delta^{18}O$ of precipitation, runoff, and groundwater, the isotopic signal may ultimately be of use in defining more clearly the routing of water within drainage basins from precipitation to major tributary discharge and between the main stem and floodplain.

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