Reconnaissance Investigations of the Discharge and Water Quality of the Amazon River

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Prepared in cooperation with the Ministerio da Marinha do Brasil, University of Brazil

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By Roy E. Oltman

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By ROY E. OLTMAN

Abstract

Selected published estimates of the discharge of Amazon River in the vicinity of Óbidos and the mouth are presented to show the great variance of available information. The most reasonable estimates prepared by those who measured some parameters of the flow were studied by Maurice Parde, who concluded that the mean annual discharge is 90,000 to 100,000 cms (cubic meters per second) or 3,200,000 to 3,500,000 cfs (cubic feet per second). A few published estimates of discharge at mouth of 110,000 cms (3,900,000 cfs) based on rainfall-runoff relationships developed for other humid regions of the world are available.

Three measurements of discharge made at the Óbidos narrows in 1963–64 by a joint Brazil-United States expedition at high, low, and medium river stage are referred to the datum used at the Óbidos gage during the period of operation, 1928–46, and a relationship between stage and discharge prepared on the basis of the measurements and supplementary data and computations. Recovery of the original Óbidos gage datum is verified by referring the 1963–64 concurrent river stages at Manaus, Óbidos, and Taperinha to gage relation curves developed for Manaus-Óbidos and Óbidos-Taperinha for periods of concurrent operation, 1928–46 and 1931–46, respectively. The average discharge, based on the stage-discharge relation and record of river stage for the period 1928–46, is computed to be 5,500,000 cfs (157,000 cms) for the Óbidos site.

The greatest known flood at Óbidos, that of June 1953, is computed to have been a flow of 12,500,000 cfs (350,000 cms) at stage of 7.6 meters (24.9 feet) in the main channel and an indeterminate amount of overflow which, under the best assumed overflow conditions, may have amounted to about 10 percent of the main channel flow. Overflow discharge at stage equivalent to mean annual discharge is judged to be an insignificant percentage of flow down the main channel.

Miscellaneous data collected during the flow measurements show that the tidal effect reaches upstream to Óbidos at extremely low flows, the distribution of velocities in stream verticals is affected by large-scale turbulence, the standard procedure of basing mean velocity in vertical on the average of point velocities measured at 20 and 80 percent of the total depth is valid, and there is a low Manning roughness coefficient of 0.019 (English units).

Samples of suspended sediment taken with a point sampler at various depths in selected verticals show, for the Óbidos site, a variation in concentration from 300 to 340 mg/l (milligram per liter) near the streambed to 50 to 70 mg/l in the upper part of the verticals. Median diameter of bed material at Óbidos averaged about 0.20 mm (millimeter) in a range of 0.15 to 0.25 mm. Analyses of water samples collected at Óbidos in July and November 1963 and August 1964 are presented.

The reconnaissance measurements of 1963–64 provide a well-supported value of mean annual water discharge of Amazon River at Óbidos and the mouth. Many more measurements of flow and water-quality characteristics are needed to obtain more exact values of discharge, suspended sediment, and salt loads.

INTRODUCTION

When the International Association for Scientific Hydrology (IASH) in 1957 began a program for assessment of river-borne dissolved solids from all sources carried to the oceans, the investigators found little published information on the Amazon River. The information on the water discharge of the Amazon River, because of the wide range in published values, did not provide a reliable estimate of average annual discharge upon which a computation of the annual dissolved-solids load of the river could be made. On the basis of the scanty information available to the investigators, the Amazon River appeared to supply about 10 percent of the total continental water discharge into the world's oceans. However, if the estimated Amazon River discharge was in error by as great a percentage as appeared probable, the calculated annual salt discharge to the oceans could be seriously affected.

This situation led, in May 1961, to a joint proposal by Luna B. Leopold, then chief hydrologist of the U.S. Geological Survey, Walter B. Langbein, staff scientist of the U.S. Geological Survey, and Professor H. O'R. Sternberg, then Director, Centro de Pesquisas de Geografia do Brasil, Universidade do Brasil, for measuring the flow, solute load, and sediment concentration of the Amazon River. Professor Sternberg gained the backing of Vice Adm. Helio Garnier Sampaio, Directoria de Hidrografia e Navegaçao, Ministerio da Marinha, for logistic support. The Marinha do Brasil would supply the necessary gaging vessel and the Geological Survey would provide the gaging manpower and equipment. Arrangements for the first of three reconnaissance expeditions (July 1963, October-November 1963, and August 1964) to the lower Amazon River were completed in the spring 1963. Space does not permit acknowledgement of the assistance of the many other individuals and organizations that helped in carrying out the reconnaissance work.

Four engineers of the U.S. Geological Survey—Frank C. Ames, Luther C. Davis, George R. Staeffler, and the writer—composed the gaging team, which was most ably assisted by several Brazilian naval officers. Professor Sternberg assisted the team during much of the second expedition.

It is the purpose of this paper to present a few of the notable results and conclusions obtained by the joint expedition for the Óbidos location and other pertinent sites on the lower Amazon River. A similar paper was presented at the "Simposio Sobre A Biota Amazonica" Belém, Pará, Brazil, June 6–11, 1966. Information in regard to Selfridge, not available in June 1966, has been added to table 1. All quantities were given in metric units at the Belém symposium. Quantities are expressed here in both English and metric units, with the quantities first listed in the system of units as originally published, measured, or calculated, followed by the equivalent in the other system enclosed in parentheses. A final report, in preparation, will provide information on all the work done, including that in the Manaus vicinity.

ESTIMATES OF AMAZON RIVER DISCHARGE

Scientists conducting a literature search for information on the discharge of the lower Amazon River may become confused by the many different estimates of discharge published by investigators of South American or world river discharge.

Table 1 contains a list, from 14 sources, of selected published estimates of some aspect of the Amazon River discharge, such as stream geometry, mean velocity, and total discharge made at the general location of Óbidos or the mouth. The earliest estimate in the list is that of Spix and Martius published in 1831. The latest estimate in the list is that of the eminent hydrologist Maurice Parde published in 1955. One may note the wide range of listed values for the average annual discharge at mouth—a range from 2,400,000 cfs (cubic feet per second) or 68,000 cms (cubic meters per second) by Siemens (1896) to 7,200,000 cfs (204,000 cms) (Military Engineer).

Upon inspection of the source documents one finds such perplexing circumstances as the following:

The published estimate for discharge at mouth in the "Military Engineer" is credited to Dr. H. P. Guppy. Upon examination of Dr. Guppy's tabulation of discharge of large rivers of the world as found in "Nature," one finds that he credited his value for Amazon River discharge (at mouth) to Elisee Reclus. Thus, the real source of the estimate published in the "Military Engineer" is Reclus. However, during the compilation of estimates by Guppy and those in "Military Engineer," the original Reclus estimate of 100,000 cms (3,500,000 cfs) for the average annual discharge at Óbidos became 2,458,026 cfs (70,000 cms) at mouth of river in Guppy's table and 7,200,000 cfs (204,-000 cms) at mouth in the table in "Military Engineer." Furthermore, upon examination of Reclus' work one finds the width at the Óbidos narrows quoted as 5,000 to 6,000 ft (1,520 to 1,830 meters) and mean depth quoted as about 250 ft (76 meters), which would provide a cross-sectional area of 1,250,000 to 1,500,000 sq ft (116,000 to 140,000 square meters). Using Reclus' value of velocity of 8,000 yards an hour equivalent to 2.04 meters per second, one would compute an average discharge at Óbidos of 8,400,000 to 10,000,000 cfs (237,000 to 286,000 cms). Thus, the whole chain of published estimates—Reclus, Guppy, "Military Engineer"—is a compounding of errors.

If one accepts the estimates published by scientists who actually visited Óbidos and vicinity and made personal observations of channel geometry and stream velocity as reliable estimates, the data would be narrowed down to that of Katzer, Selfridge, Spix and Martius, Wallace, Smith, LeCointe, and Lallemant. (See table 1.) (Note: Carvalho's estimate may also be valid.) These valid estimates apply to differing river stages; for example, Katzer's observation was made in early July 1896; Selfridge's (at Parintins) in early August 1880. LeCointe appears to be the most helpful. He provides for Óbidos a measured width at the narrows of 1,890 meters (6,200 ft) (obtained by triangulation), low-water cross section of 105,-000 square meters (1,130,000 sq ft), high-water cross section of 117,500 square meters (1,260,-000 sq ft), and discharges ranging from 63,000 cms (2,200,000 cfs) (low water) to 146,775 cms (5,200,000 cfs) (high water). Parde, in his study, based his estimate of the average annual discharge at Óbidos largely on LeCointe's data and reported it as from 90,000 to 100,000 cms (3,200,000 to 3,500,000 cfs).

One may wonder why estimates only, instead of measurements, of the Amazon River dis-

Table 1.--Selected published estimates of flow of the lower Amazon River

Source[1]	Date	Location	Date or season	Cross-section area: Square meters	Cross-section area: Square feet	Width: Meters	Width: Feet	Mean velocity: Meters per second	Mean velocity: Feet per second	Discharge: Cubic meters per second	Discharge: Cubic feet per second	Remarks
Spix and Martius	1831	Óbidos	Low water	------	-------	---------	----	0.7	2.3	14,000	500,000	
Wallace---------	1853	Óbidos	Low water	------	-------	---------	----	1.62	5.3	-------	----------	Velocity estimate attributed to Wallace by F. Katzer.
Ave-Lallemant (in Reclus, 1877, 1895).	1860	Óbidos	High water	------	-------	---------	----	----	---	319,476	11,000,000	Value of 319,476 cms appears in "The Earth and Its Inhabitants" by Elisee Reclus (1895). Value of 243,875 cms appears in "La Terre" by Elisee Reclus (1877, v.1, p. 514).
Guppy-----------	1880	Mouth	Annual----	------	-------	---------	----	----	---	70,000	2,458,026	Estimate attributed to Reclus by H.P. Guppy.
Smith-----------	1880	Óbidos	Annual----	22,500	240,000	1,892 (from Penna)	6,200	1.0	3.3	21,500	760,000	Based on data reported by Penna, Wallace, and Martius.
Selfridge-------	1882	Parintins	Aug. 7, 1879.	------	-------	---------	----	----	---	110,404	3,899,149	Aug. 7, 1879, is date given for actual measurement in report of Secretary of Navy for 1879.
Reclus----------	1895	Óbidos	June------	116,000-140,000	1,250,000-1,500,000	1,520-1,830	5,000-6,000	2.04	6.7	(100,000), 237,000-286,000	8,400,000-10,000,000	Figure in parenthesis is published but is apparently in error.
Siemens---------	1896	Mouth	Annual----	------	-------	---------	----	----	---	68,000	2,400,000	Basis of estimate unknown.
Katzer----------	1898	Óbidos	Early July 1896.	100,000	1,080,000	1,890	6,200	1.2	3.9	120,000	4,200,000	From article: "Die Stromenge des Amazonas bei Óbidos."
Le Cointe-------	1922	Óbidos	End of May 1918.	------	-------	---------	----	3.15	---	-------	----------	Float observation at crest of flood.
			Low water	105,000	1,130,000	1,890	6,200	.6	2.0	63,000	2,200,000	Area based on soundings of others.
			High water	117,500	1,260,000	1,890	6,200	1.25	4.1	146,775	5,200,000	
Carvalho--------	1942	Mouth	Low water	-------	---------	---------	----	----	---	60,000	2,100,000	
			High water	-------	---------	---------	----	----	---	140,000	4,900,000	
Jarvis----------	1945	Óbidos	Annual----	-------	---------	---------	----	----	---	85,000	3,000,000	Computed on basis of rainfall-runoff relation.
Parde-----------	1955	Óbidos	Annual----	-------	---------	---------	----	----	---	90,000-100,000	3,200,000-3,500,000	Based mainly on Le Cointe's data.
Military Engineer.	1958	Mouth	Annual----	-------	---------	---------	----	----	---	204,000	7,200,000	Value of 204,000 cms attributed to Guppy.

[1]See list of references.

charge at Óbidos are available. The techniques for gaging large rivers were well developed during the 19th century. Revy reported application of completely satisfactory methods in measurements of the Rio Paraná at Rosario made in 1871. Although the maximum depth of the Rosario cross section was only 72 feet (22 meters)—shallow in comparison with the 201-foot (61-meter) maximum depth found in the discharge measurement at Óbidos on July 16, 1963—the same procedures used for holding the measuring vessel in place at Rosario would have worked at Óbidos, and the current-meter suspension for measurement of velocities at Rosario would have been satisfactory at Óbidos. After establishment of the river gage at Óbidos in 1928 by the Brazilian Government and the commencement of daily river-stage readings, the attraction to measure the flow and develop a stage-discharge relation for Óbidos was stronger, for then the annual flow regime could be completely charted. The task of determining the geometry of a selected cross section on the Amazon River at Óbidos was relatively simple. Although complete information is not available on the techniques used by the scientists who have reported measured cross-sectional area, it is probable that the method fully described by Revy, as used on the Rio Paraná work for obtaining measured depths, was used on the Amazon River. Depth measurements of a selected cross section are made, following Revy's method, by sounding with a weighted line from a ship drifting with the current. In this way, the sounding line remains nearly vertical because there is only minor current drag on it near the bed. As the ship drifts across the desired measuring section, the sounded depth is observed and the location of ship on the cross section (distance from either bank) is determined by standard surveying methods (sextant readings on flags located on the ends of a measured base line established on shore, or theodolite readings taken to the ship from a shore-based instrument). With great care and replication, a very reliable cross section could be so measured. The measurement of stream velocities could have been obtained by anchoring the gaging vessel to permit observations of subsurface velocities with standard current meters or by using subsurface floats. If a few such measurements, referenced to the Óbidos gage, had been made to cover the range of discharge from low to high water and an approximate stage-discharge relation established for the Óbidos location, a much better estimate of the average annual discharge at Óbidos could have been computed.

Although Jarvis' discharge (table 1) for the Amazon River at Óbidos is the only tabulated one that is known specifically to be based on rainfall-runoff relationships, the map of world runoff, published by L'Vovich (1945) and also based on hydrologic calculations, permits an estimate of the discharge at mouth to be measured. Jarvis, using data then available to him, computed the average annual precipitation for the drainage area tributary to Óbidos as 62 inches (1,570 mm). He based his average annual runoff estimate on a ratio of runoff to precipitation of 34 percent. The estimate one may derive from L'Vovich's map is equivalent to about 110,000 cms (3,900,000 cfs) for either the Óbidos or at-mouth location. Precipitation data in the Amazon River basin are presently much more adequate for assessment of basin average annual rainfall then was the case for Jarvis or L'Vovich. Using Thornthwaite's potential evapotranspiration approach and the presently available climatic data, the writer has calculated average annual runoff for area above mouth as 31.5 inches (800 mm), equivalent to average annual discharge of 5,300,000 cfs (150,000 cms).

RESULTS OF RECONNAISSANCE WORK

As discussed in Geological Survey Circular 486, "Amazon River Investigations—Reconnaissance Measurements of July 1963", the lack of data for discharge and dissolved solids of the Amazon River hampered work on the project of the International Association of Scientific Hydrology (IASH) for calculation of the salt balance of the oceans. The Amazon River was known to be the world's largest in terms of discharge, but the degree of uncertainty in the available estimates of the discharge led to the investigations jointly sponsored by the Brazilian Navy, the University of Brazil, and the U.S. Geological Survey. The results collected during the first measurements (July 1963) reported in Circular 486 have been supplemented by results obtained in October-November 1963 and August 1964 and will be discussed in detail in a final report (in preparation). The results of the measurements of flow at Óbidos are discussed in this section; the measurements of water quality and sediment are discussed in a later section.

The major features of the three measurements of discharge at Óbidos are presented in table 2.

The methods used in collecting the data for the measurements have been discussed in Circular 486. All three discharge measurements were made at the same cross section. The August 1964 measurement used subsurface velocities after loss of 300-pound (136-kilogram) sounding weight and current meter on an underwater obstruction led the gaging party to conclude it would be prudent to conserve the

Table 2.--Discharge measurements at Óbidos
[Quantities listed in system of units as originally published, measured, or calculated; equivalents in the other system enclosed in parentheses]

Date	Stage	Width		Area		Mean depth		Mean velocity		Discharge	
	Meters	Feet	Meters	Square feet	Square meters	Feet	Meters	Feet per second	Meters per second	Cubic feet per second	Cubic meters per second
7-16-63	5.8	7,500	(2,290)	1,184,000	(110,000)	158	(48.0)	6.45	(1.97)	7,640,000	(216,000)
11-20-63, 11-21-63	-.5	7,410	(2,260)	990,000	(92,400)	134	(41.0)	2.59	(.79)	2,560,000	(72,500)
8-9-64	4.76	7,450	(2,280)	1,145,000	(106,000)	154	(46.5)	5.08	(1.55)	5,810,000	(165,000)

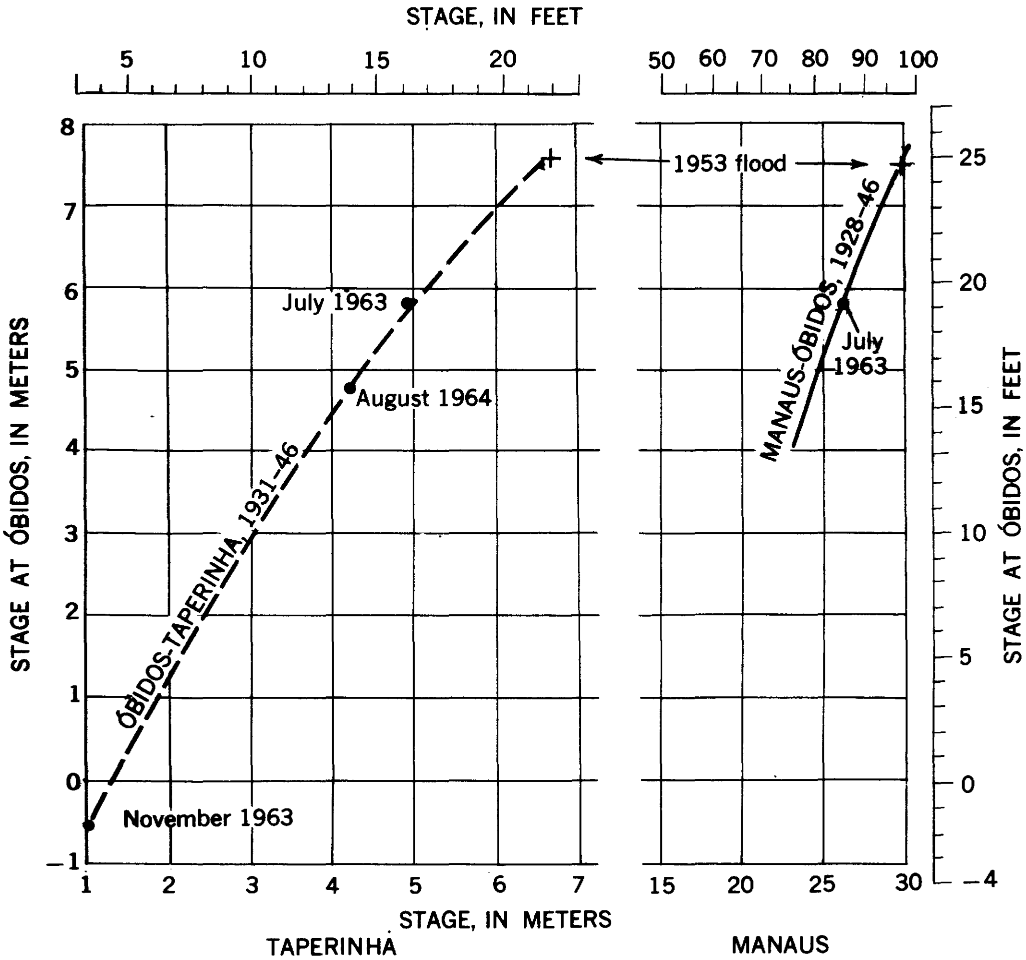

Figure 1.—Relation of concurrent readings on gages, Amazon River at Óbidos, Manaus, and Taperinha.

remaining equipment. However, the depths for the measurement were taken with a sonic sounder and the results should be nearly as reliable as are those of the first two measurements. The width of section, ranging from 7,410 to 7,500 feet (2,260 to 2,290 meters) is different from that measured by LeCointe (1922)—1,890 meters (6,100 feet)—because the cross section selected for the 1963–64 work was about 1¼ miles (2 kilometers) downstream from LeCointe's section.

The datum of the gage used at Óbidos in 1928–46 and destroyed (according to local information) during the great flood of 1953 was recovered by reference to a photograph (courtesy of Departmento Nacional de Producao Mineral, Divisao de Agua) of the location of the original high-water staff-gage section. Fortunately, the Óbidos municipal warehouse, against which the original staff section had been photographed, existed during the 1963–64 visits, and by careful measurements the datum was recovered within a possible error range of 10 centimeters (4 inches). Fortunately, also, overlapping records of river stage are available at Manaus and Taperinha.

Figure 1 shows the good agreement of the concurrent 1963–64 Óbidos readings with those from Manaus and Taperinha where daily gage readings were available. The stage graphs showing the relationship of concurrent readings for the periods 1928–46 (overlapping records Óbidos and Manaus) and 1931–46 (Óbidos and Taperinha) were prepared by plotting selected concurrent readings for the three gages and fitting the curves to the scatter plot. There can be no question that the Óbidos gage datum was recovered with reasonable accuracy, as the concurrent readings 1963–64 lie on the curves developed from data taken in 1928–46 (1931–46 in the Óbidos-Taperinha comparison). For example, the relationship curve Manaus-Óbidos shows that a stage of about 7.5 meters (24.6 feet) would have occurred at Óbidos at the crest of the great 1953 flood, which reached 29.7 meters (97.4 feet) at Manaus. Similarly, the Taperinha-Óbidos relation curve shows that a stage of about 7.6 meters (24.9 feet) would have occurred at Óbidos during the 1953 flood, which reached 6.65 meters (21.8 feet) at Taperinha. Discussion with Óbidos inhabitants who remembered the 1953 flood and showed the survey party the level it reached in the vicinity of the gage location verified the approximate Óbidos stage of 7.5 meters (24.6 feet) for the 1953 event. Thus, significant evidence indicates reliable recovery of the Óbidos gage datum used in 1928–46.

A rating curve (curve showing relationship of stage to discharge) prepared for Óbidos on the basis of the three available measurements of discharge and other data is shown in figure 2.

The stage-discharge relation at Óbidos may be affected at times by variable slope caused by inflow from the Rio Tapajós. Additional discharge measurements will be required to define the magnitude of any backwater effects.

Guidance in drawing the curve through the discharge measurements and extending it to the greatest known stage of 7.6 meters (24.9 feet) was obtained from a study of conveyance and slope. The slope computed by use of the Manning formula with a Manning coefficient of 0.020 (derivation of the Manning coefficient from a vertical velocity curve is explained later) varied among the three measurements as follows:

July 1963	8.75×10^{-6}
November 1963	1.74×10^{-6}
August 1964	5.65×10^{-6}

It is the author's opinion that the square root of the slope varies linearly with stage at and above the stage of the two higher measurements of discharge. Thus, the slope estimated for a stage of 7.6 meters (24.9 feet) at Óbidos is 16.0×10^{-6}. The stage-conveyance relation for Óbidos does not vary much with stage. Conveyance, K, in English units, may be calculated as follows:

$$K = \frac{1.486\ AR^{2/3}}{n}$$

where

A=cross-sectional area,
R=hydraulic radius, and
n=Manning coefficient.

Hence, the increase in discharge with stage is mainly a result of increase in slope through the Óbidos narrows. An observation by Le Cointe of the high velocity through the Óbidos narrows concurrent with the crest of the flood of May 1918 (3.15 meters, or 10.33 feet per second from float observation) supports the extrapolation of the stage-discharge relation to 12,500,000 cfs (350,000 cms) at stage 7.6 meters (24.9 feet). Figure 3 shows the small variation in cross section measured in the Óbidos discharge measurements. The cross-sectional area of the main channel for a stage of 7.6 meters (24.9 feet) would be but 45,000 sq ft (4,150 meters²) larger (about 4 percent larger) than that of the discharge measurement of July 1963.

During the three trips for collection of reconnaissance data, limited time did not permit an investigation of the overflow situation at Óbidos. Maps (see fig. 4) clearly show the area subject to overflow between the main channel opposite Óbidos and the terra firma about 32 km (20 miles) south of Óbidos. The flood plain, judging by available maps and air photos, is covered with shallow lakes, swamps, scrub trees, and grass, and the drainage channels and

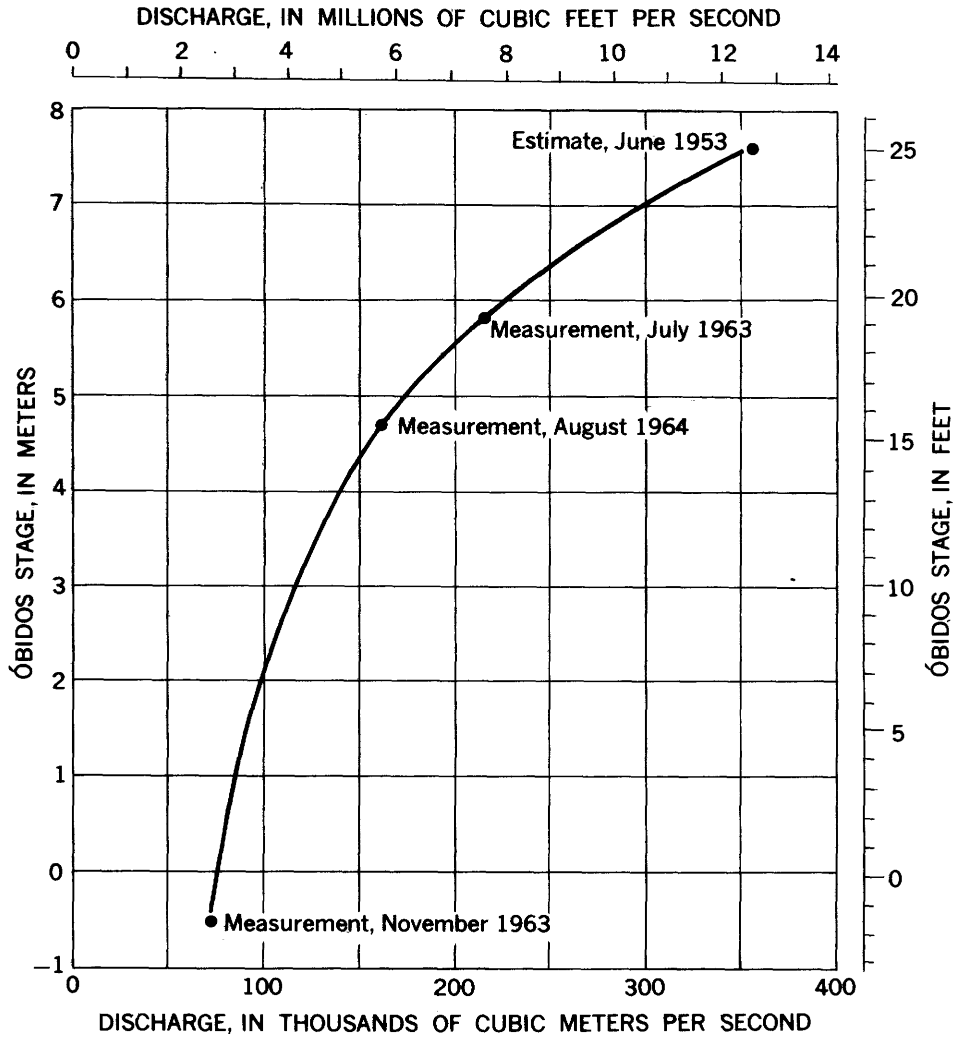

Figure 2.—Stage-discharge relation, Amazon River at Óbidos.

abandoned meanders indicate the localized flow directions during floods. A set of levels run from the water surface as far inland on the flood plain as limited time would permit shows the top of the natural levee and flood plain adjacent to the right bank of the main channel opposite Óbidos to be about at elevation 6.9 meters (22.6 feet) (Óbidos gage datum). Thus, significant overflow covering the entire flood plain opposite Óbidos would occur any time the Óbidos stage exceeded 6.9 meters (22.6 feet). It is of interest that the former Óbidos gage observer (Mrs. Platt) made a notation in the gage records that overflow would begin at Óbidos when the river level reached 7.5 meters (24.6 feet).

Although overflow directly opposite Óbidos might not begin until the river stage reached 6.9 meters (22.6 feet), it is very likely that significant overflow would exist at a 6.9-meter (22.6 foot) stage through the channels and lakes—Lago do Pocao, Lago Grande do Curuaí (Lago Grande de Vila Franca), and connecting small lakes—occupying roughly a strip of the flood plain 15 km (9 miles) wide immediately adjacent to terra firma. A computation of possible range in discharge over the flood plain at the stage ((7.6 meters) 24.9 feet) of the 1953 flood was made by (1) assuming the worst possible hydraulic conditions of shallow depth, water-surface slope equal to the main channel water-surface slope, and maximum natural roughness and (2) assuming the best possible hydraulic conditions of average depth of overflow equal to 6.5 feet (2 meters), water-surface slope increased 50 percent over the main chan-

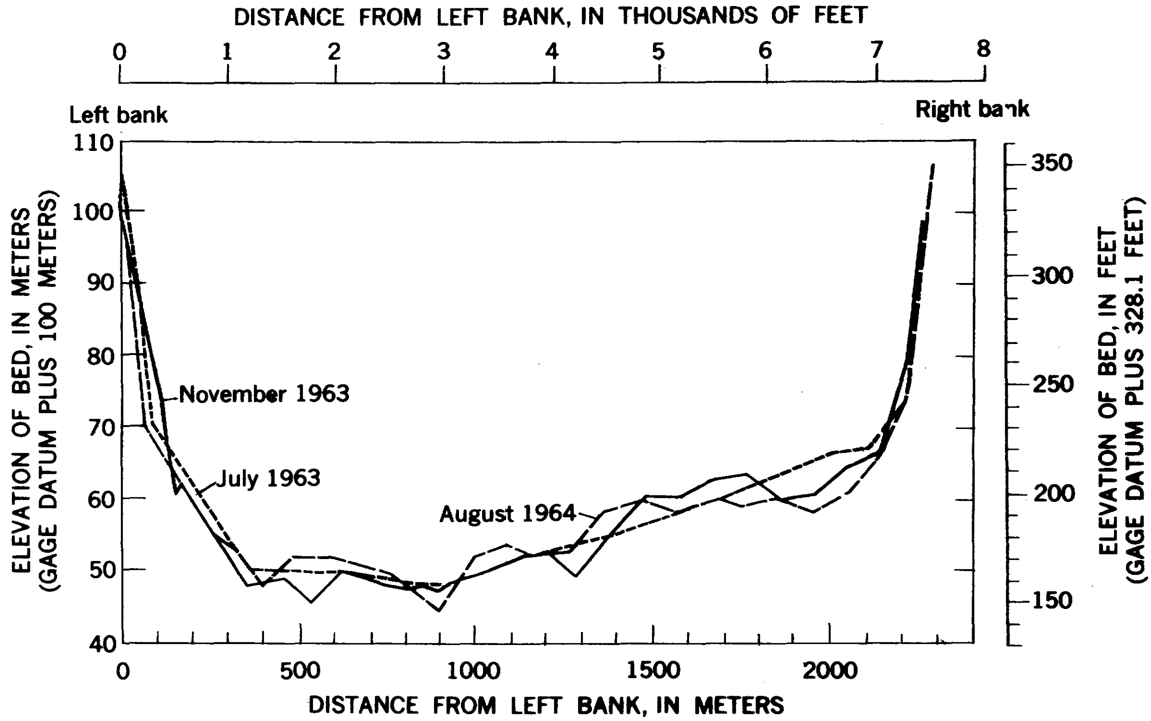

Figure 3.—Measured cross sections from three discharge measurements, Amazon River at Óbidos.

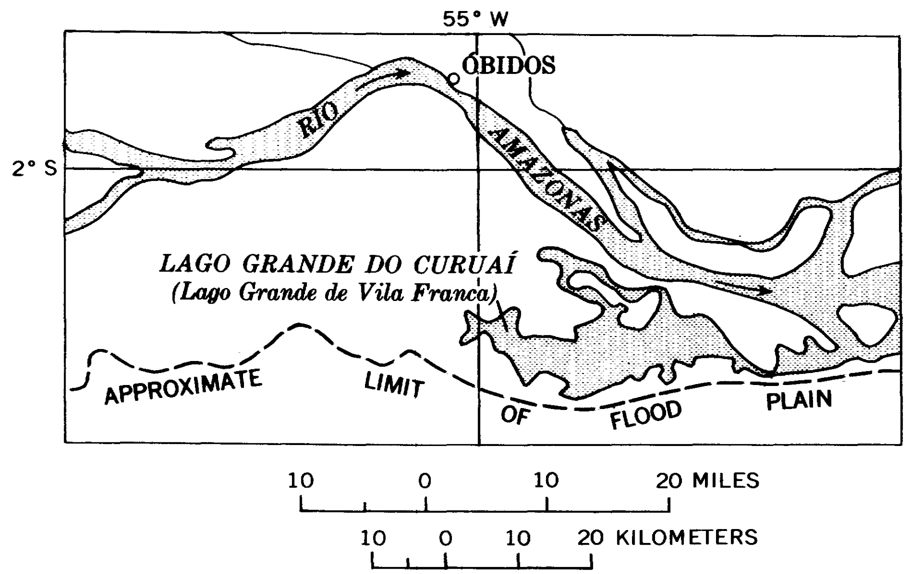

Figure 4.—Amazon River in vicinity of Óbidos.

nel slope, and minimum probable roughness (Manning coefficient 0.030). The result based on assumed worst hydraulic conditions showed that the overflow could be ignored without seriously affecting the accuracy of the estimated maximum discharge. The computation based on best conditions showed that a flow equal to about 10 percent of the main channel discharge might bypass the main channel at a stage equal to that of the 1953 flood. It is likely that the actual overflow discharge in June 1953 was somewhere between the two results.

Katzer's interpretation of the overflow situation at Óbidos is not favorable for accuracy of flow measurements. He wrote (1897): "Unfortunately the narrows at Óbidos is not suitable for this purpose as long as the entire quantity of water is to be determined, because only a part of the Amazon's total water passes at this point. Another part flows into a number of arms in the lowland north of the Serra do Valaio and helps to fill the large lake, Lago Grande do Curuaí, which forms a wide water zone with its numerous lagoons and their connecting channels. This water zone stretches like a bowstring across the main arm of the Amazon River, which bends north, and below whose zenith the city of Óbidos is situated."

Several strips of overlapping aerial photographs taken on flight lines across the flood plain from east to west and north to south from the terra firma to the Amazon River were available to the writer for study. It is unlikely that the overflow situation intimated by Katzer could exist. However, if great accuracy of measurement of the total discharge of a subsequent flood of the size of the 1953 event is desired, the overflow depths and current velocities should be measured and the quantity of flow computed. It is the writer's opinion that the quantity of flow bypassing the main channel at the stage equivalent to average annual discharge at Óbidos is an insignificant percentage of the main channel flow.

Some questions may be raised about the fact that the two higher discharge measurements were made on a falling river stage and hence the measured flows may be less than would occur at equal stage on the rising side of the hydrograph. A computation made by the Wiggin's formula,

$$\frac{Qc}{Qm}=\sqrt{1-\frac{1}{USc}\frac{dh}{dt}},$$

where

Qc=discharge corrected for changing stage,

Qm=discharge measured,

U=velocity of flood wave (assumed equal to 1.3 times mean velocity),

Sc=slope of energy gradient, and

$\frac{dh}{dt}$=rate of change of stage in feet per second,

showed the correction to be applied to the July 1963 measurement was less than 3 percent (which can be ignored in view of the reconnaissance nature of the work). The August 1964 measurement had a lesser correction computed for it.

Proof of tidal effect at Óbidos was obtained by stage readings at short intervals during the November measurement. (The existence of tidal effect was a moot point based on previous investigations.) The graphs of stage readings taken at ½-hour intervals on November 20 and 21, 1963, are shown in figure 5.

It should be kept in mind that the readings were taken during one of the lowest flows of the Amazon River at Óbidos when the upstream reach of tide effect would be a maximum. During the period 1928–46 no stage reading of less than 0.05 meter (1.6 feet) was recorded. The mean stage of the November 1963 discharge measurement is —0.5 meter (—1.6 feet), or one-half meter lower than zero datum. The

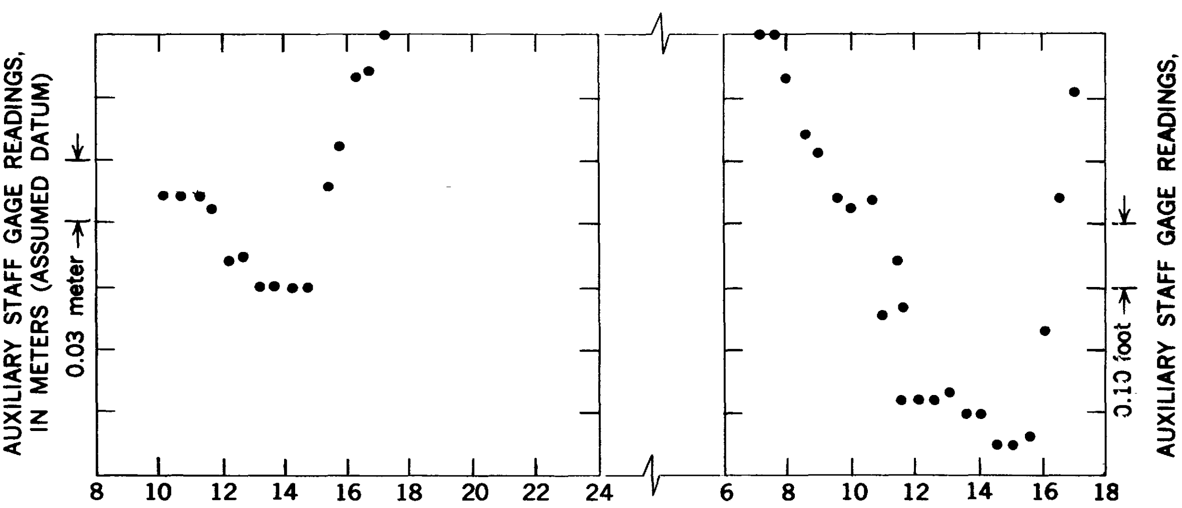

Figure 5.—Water level observations showing tidal effect at low flow, Amazon River at Óbidos. Auxiliary staff gage was moved at close of readings on November 20 and not set to same datum for readings of November 21.

effect of tide on the Óbidos stage-discharge relation is considered insignificant by the writer.

On the basis of the recorded gage readings for the period 1928–46 and the rating curve in figure 2, mean monthly discharge has been computed as listed:

Month	*Average monthy discharge for period* (*1,000 cms*)[1]	(*1,000 cfs*)[1]
January	110	3,900
February	140	4,900
March	170	6,000
April	215	7,600
May	240	8,500
June	240	8,500
July	205	7,200
August	165	5,800
September	120	4,200
October	90	3,200
November	85	3,000
December	95	3,400

[1] Average rounded to nearest 5,000 cms and nearest 100,000 cfs.

The computed coverage discharge at Óbidos for the period is 5,500,000 cfs (157,000 cms). The average discharge computed for Óbidos on the basis of the three discharge measurements and Óbidos gage readings for the period 1928–46 is thus seen to be more than 50 percent greater than Parde's estimate of 90,000 to 100,000 cms (3,200,000 to 3,500,000 cfs).

Some observations on velocity distribution in selected verticals and in the complete cross section at Óbidos are shown in figure 6 and 7.

The point velocity observations for the vertical distribution of velocities observed on November 21, 1963, were measured while the corvette was anchored and should be reasonably free of errors caused by movements of the metering vessel during individual observations. Each point velocity observation is the average determined during a period of 40 or more seconds. The effects of natural stream turbulence are evident in the scatter of the observations about the arbitrarily placed distribution graph. It is evident that, because of the large scale of the turbulence, each point velocity observation should have been derived from a meter run of much longer duration—perhaps as long as 4 minutes. From a study of data from 23 United States rivers ranging in depth from 2.4 to 26.7 feet (0.73 to 8.1 meters), Carter and Anderson (1963) determined that an observation period of 4 minutes for the 20-percent depth location will yield a mean point velocity within 2 percent of the probable true average. As predicted by turbulence theory, the effect of turbulence at the Óbidos section is most pronounced in proximity to the channel bed and it decreases as the distance of observation point above the bed increases.

The vertical velocity curve data in figure 6 and the several other vertical velocity distribution curves developed for other locations and dates at Óbidos verify the essential correctness of the Geological Survey's standard procedure for computing the mean velocity in the vertical as the average of point velocity observations taken at 20 and 80 percent of the total depth. The mean in each vertical for the Óbidos discharge measurements of July and November 1963 was computed from the 20- and 80-percent depth observations—each corrected for movement of the measuring corvette during the period of observation, as explained in Geological Survey Circular 486. The mean in each vertical for the August 1964 measurement was obtained by applying an appropriate coefficient to the subsurface velocity.

The distribution of mean velocity in vertical across the Óbidos measuring section for the high-flow measurement of July 1963 is shown in figure 7. The distribution of velocities in the section is remarkably uniform, as would be expected from Geological Survey experience derived from thousands of discharge measurements made on deep, swift rivers in the United States with similar uniformity of measuring section and similar streambed conditions.

An analysis based on the vertical velocity distribution graph and the logarithmic velocity distribution law for wide channels (smooth or rough) follows.

$$\frac{v-V}{V\sqrt{f}} = 2 \log_{10}\left(\frac{y}{yo}\right) + 0.88$$

where

v=observed point velocity (all English units),
V=mean velocity in vertical,
f=Darcy-Weisbach friction coefficient,
y=depth of observation (measured from bed), and
yo=total depth of measured vertical.

This analysis yielded a Darcy-Weisbach friction coefficient of 0.008, equivalent to a Manning roughness coefficient for the depth investigated of 0.019.

This indication of a relatively smooth bed is borne out by the bed profile shown by sonic soundings and the bed material samples obtained. A section of fathometer chart taken November 21, 1963, during a run up the approximate middle of the channel and crossing the general location of the measured cross section is shown in figure 8.

The chart shows dunes with an approximate length of 200 meters (660 feet). (The illustration is a drafted reproduction of the fathometer chart. The explanation of the short period fluc-

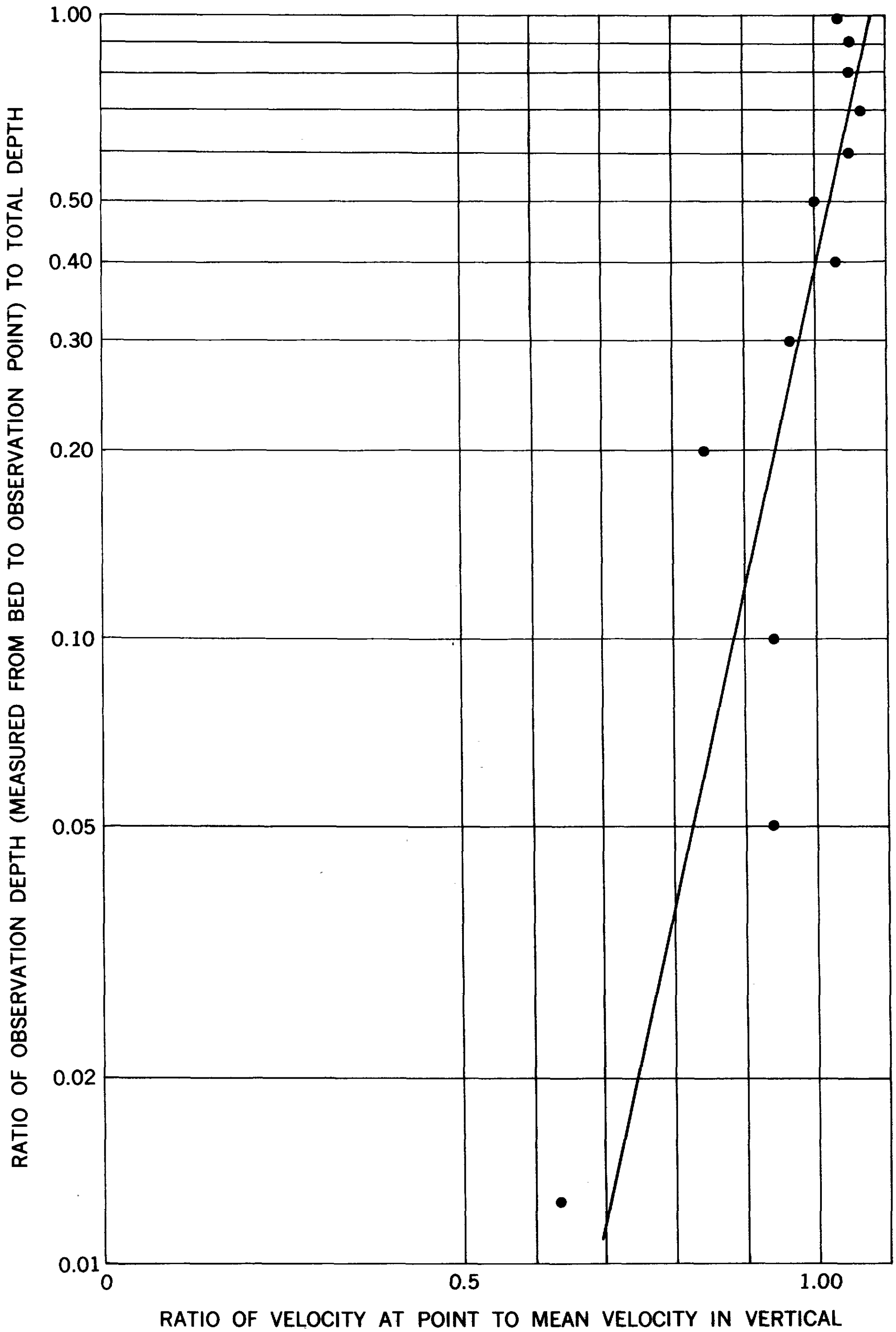

Figure 6.—Distribution of velocity in a selected vertical, Amazon River at Óbidos.

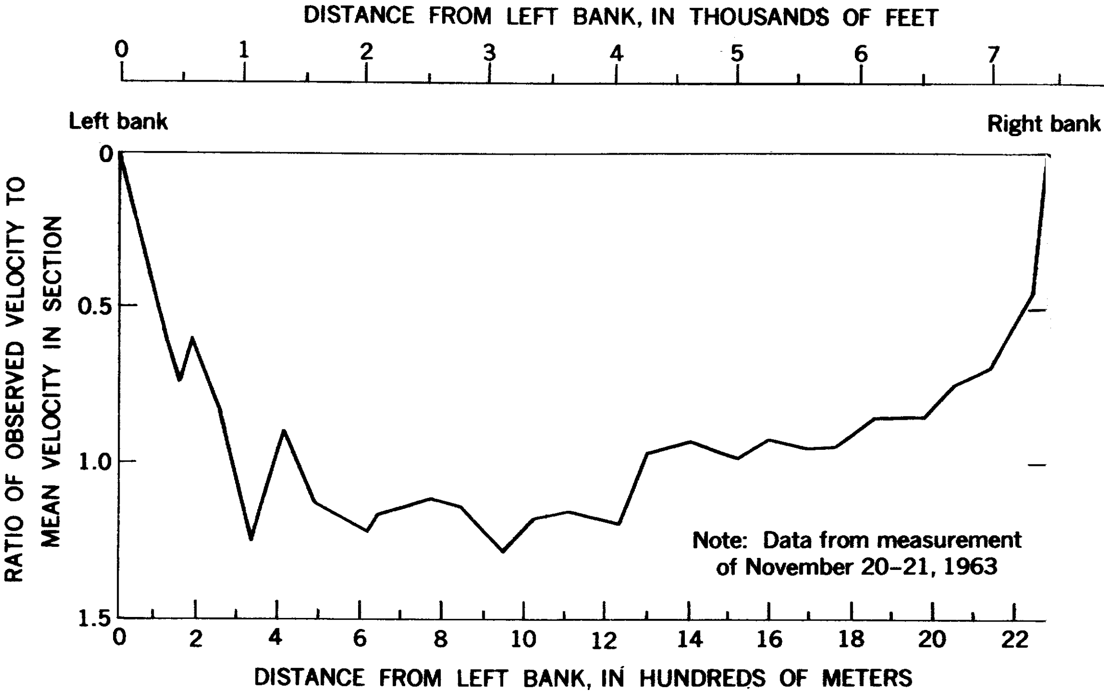

Figure 7.—Distribution of mean velocity in cross section, Amazon River at Óbidos.

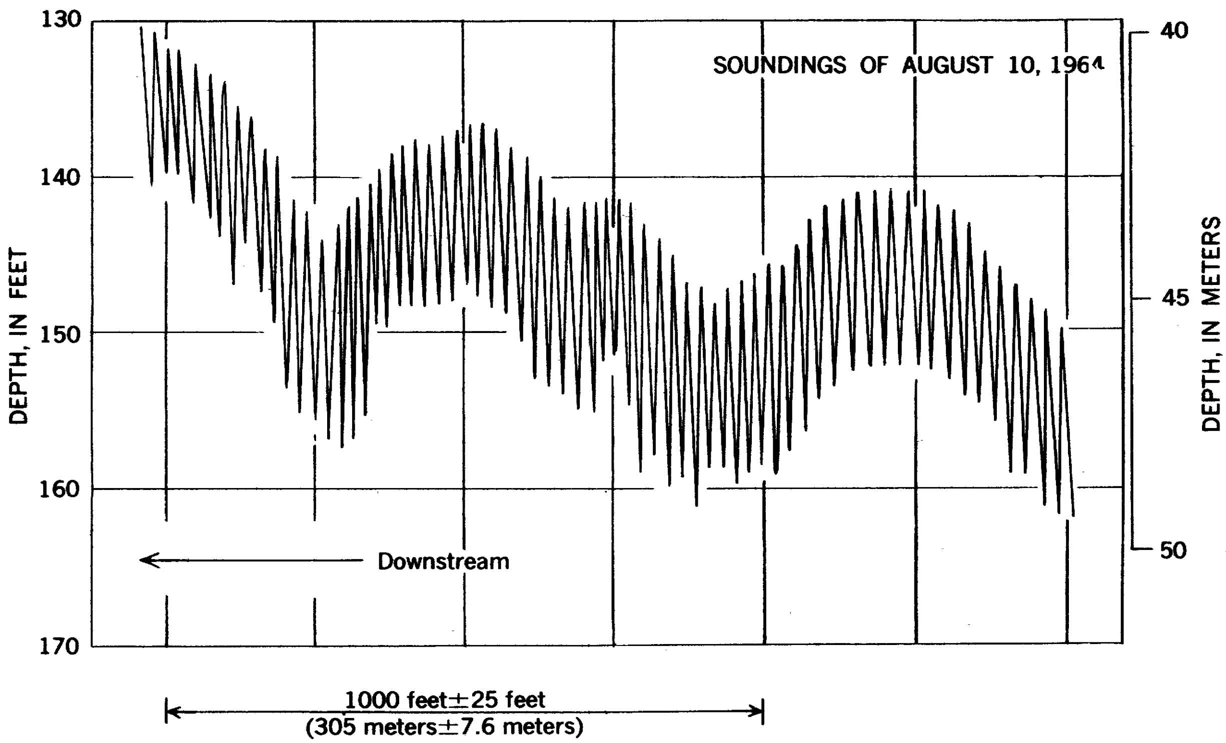

Figure 8.—Section of fathometer chart taken near midstream and crossing general location of measuring section, Amazon River at Óbidos.

tuations is unknown.) Experience with sand channels in the United States has led to assignment of Manning coefficients in the range 0.018 to 0.035 for such bed geometry. The size distribution of material determined from bed samples is discussed later.

QUALITY OF WATER

In contrast to the many published estimates of water discharge for the Amazon River, there is little published information on the suspended-sediment and dissolved-solids loads carried by the flow. Katzer (1897) and Sioli (1957) have published a few analyses of suspended sediment, total dissolved solids, and some other information on the chemical and physical nature of the Amazon River water in the general vicinity of Óbidos. Pinto computed a mean daily discharge of suspended load at mouth of Amazon to be 3 million metric tons (3.3 million tons).

Undoubtedly, the lack of means for collection of suspended-sediment samples from various depths at the relatively high velocities discouraged investigators from attempting to assess

Table 3.--Results of analyses of water samples from the Amazon River at Óbidos, Pará, Brazil
[Concentrations of dissolved and suspended material are in parts per million (ppm) except as indicated]

Constituent	July 16, 1963	November 20, 1963	August 9, 1964
Discharge cfs	7,640,000	2,560,000	5,810,000
(cms)	(216,000)	(72,500)	(165,000)
Silica (SiO_2)	7.0	9.0	9.0
Aluminum (Al)	.07	.02	.15
Iron (Fe)	.06	.06	.09
Calcium (Ca)	4.3	10	3.9
Magnesium (Mg)	1.1	.4	.6
Sodium (Na)	1.8	4.2	1.8
Potassium (K)	---	.4	.6
Bicarbonate (HCO_3)	19	32	16
Sulfate (SO_4)	3.0	6.4	1.0
Chloride (Cl)	1.9	4.5	1.6
Fluoride (Fl)	.2	0	0
Nitrate (NO_3)	.1	0	.1
Total dissolved solids	28	51	21
Hardness as $CaCO_3$	15	27	12
Dissolved oxygen	5.8	5.6	5.4
Specific conductance (micromhos at 25°C).	40	84	34
pH	6.5	7.1	6.5
Temperature (°F)	83	86	83
Suspended sediment	80	60	110
Upper part of verticals (mg/l)[1]	60	50	70
Near the bed	300	280	340

[1]Milligrams per liter.

the mean annual suspended-sediment discharge at Óbidos. Similar difficulties would have discouraged attempts to collect samples of the material in place on the streambed.

The joint reconnaissance venture of 1963–64 was well equipped to collect water samples at any point in the measuring cross section at Óbidos. Samples of the material on the top of any part of the bed could also be taken with an oceanographic clamshell type sampler or standard U.S. BM–54 sampler. The U.S. P–61 suspended-sediment sampler (equipped with 3/16-inch (4.8-mm)-diameter intake nozzle), having an electrically controlled intake and closure valve, permitted water samples for analysis of suspended sediment to be taken at any location in the cross section of flow. Thus, the distribution of suspended-sediment concentration from bed to surface could be determined at any selected vertical. A bathythermograph furnished temperature-depth profiles at desired verticals. Chemical-quality samples were taken with an oceanographic sampler consisting of an open tube that allowed flow of water through it until it was closed, as desired, by ball-type valves.

The quality-of-water aspects of the investigation were conducted by Mr. F. C. Ames, U.S. Geological Survey, Denver, Colo. Mr. Ames (April 1966) furnished table 3, which shows the results of the three series of samplings made at Óbidos. The tabulated suspended-sediment concentrations are the calculated average concentration for the cross section. Suspended-sediment samples were taken at many points in each vertical sampled, so that the distribution suspended material in the vertical could be charted. Table 3 also includes information on the range of suspended-sediment concentrations measured in the cross section. As expected, the concentration of suspended sediment is high in the vicinity of the bed.

Ames reports (oral commun., May 1966) this information on the bed material at Óbidos:

"The median diameter of bed material averaged about 0.20 mm. The median diameters indicated by individual samples ranged from 0.15 to 0.25 mm. Only one to two percent of the bed material (by weight) was finer than 0.062 mm and only one or two percent was coarser than 0.4 mm."

Katzer reported total dissolved solids of 56 mg/l in a sample taken at Óbidos June 30, 1896. Because the turbulent mixing and lack of major tributary inflow in the vicinity of Óbidos (the discharge from the Rio Trombatas would have small effect) should guarantee uniformity of dissolved-solids concentration in a cross section of the stream, the minor differences in the four analyses can be attributed to seasonal variations. One would expect the total dissolved solids found by Katzer on June 30, 1896, to be more dilute than he reported unless the flow for that season was very low. The concentration of dissolved solids on August 9, 1964 (discharge 5,810,000 cfs = 165,000 cms), if there were a relatively fixed inverse curvilinear relation between total dissolved solids and water discharge, would be expected to be slightly higher than the concentration found on July 16, 1963 (discharge 7,640,000 cfs = 216,000 cms). The contrary findings, 21 mg/l and 28 mg/l, respectively, show the importance of seasonal variations in the proportions of total Óbidos flow contributed by "white water" and "black water" tributaries. It is apparent that a minimum of one water sample per month collected over several years would be necessary to describe accurately the dissolved-solids load variation at Óbidos.

The three determinations of mean concentration of suspended sediment in the Óbidos cross section also show the need for many more samples to be taken during several years before one could calculate a mean annual concentration of suspended sediment. However, on the basis of reconnaissance results at Óbidos, if the mean annual concentration were assumed to be 100 mg/l, one would arrive at a calculated mean daily suspended load at Óbidos (using 5,500,000 cfs = 157,000 cms) of about one-half that which Pinto (1930) computed for the mean daily load at mouth.

The dissolved-oxygen content is close to saturation level at the observed stream temperature. Bathythermograph results showed no detectable variation of temperature in any of the verticals where observations were taken from surface to bed and return. The pH was found to be as expected from the analyses reported by Sioli (1957) for the vicinity of Santarem.

ESTIMATED DISCHARGE AT MOUTH

The drainage area tributary to the Óbidos location is about 1,900,000 sq mi (5,000,000 square kilometers). The drainage area above the mouth is about 2,300,000 sq mi (6,000,000 sq km) or an increase of about 20 percent over that for Óbidos. If equal contribution of runoff existed for the basin above mouth, the mean annual discharge at mouth would be expected to be about 6,650,000 cfs (190,000 cms). However, there are several data that indicate the yield per unit drainage area from the approximately 400,000 sq mi (1,000,000 sq km) of drainage intervening between Óbidos and the mouth to be less than that occurring above Óbidos.

Only two large tributaries, the Rio Tapajós and the Xingu River, enter the Amazon River downstream from Óbidos. In August 1964, the gaging party measured the dry season discharge of the Rio Tapajós at Sao Luis, location of the first rapids, about 180 mi (300 km) upstream from Santarem. The discharge was found to be 99,000 cfs (2,840 cms). A stage-discharge relation for the Rio Tapajós gage at Fordlandia was drawn on the basis of the one discharge measurement, measured geometry of the high-flow cross section at Sao Luis, and a consideration of the apparent variation of water-surface slope with stage for the Rio Tapajós location at Sao Luis. On the basis of available daily gage readings from the Fordlandia gage and the constructed stage-discharge relation, a mean annual discharge for the Rio Tapajós has been calculated as 250,000 cfs (7,100 cms). No measurement was made on the Xingu River.

A low-water-season measurement made by the joint survey group on the Tocantins River (not considered an Amazon River tributary) at Maraba in October 1963 showed the discharge to be 52,800 cfs (1,500 cms). Using the cross-sectional area at Maraba that would be occupied by bankfull discharge and an estimated mean velocity at bankfull stage, the writer has calculated a bankfull discharge of 115,000 cfs (33,000 cms). No stage records are available at Maraba. The mean discharge for the Tocantins River was estimated, on the basis of the low-water measurement and the estimated bankfull discharge, as 400,000 cfs (11,000 cms).

The Tocantins River is not tributary to the Amazon River (its basin has a common drainage boundary with the Amazon River) but its estimated mean discharge and that of the Rio Tapajós permit a "bracketing" of an estimated mean annual discharge for the Xingu River. The sum of mean annual discharges for Tapajós and Xingu Rivers, and minor tributaries between Óbidos and the mouth is estimated to be 640,000 cfs (18,000 cms). On this basis, the partly estimated average annual discharge of the Amazon River at mouth is 175,000 cms (6,100,000 cfs).

Estimates of the runoff from the intervening area between Óbidos and the mouth based on the Thornthwaite potential evapotranspiration approach result in a discharge of about double that based on hydrometric data. The estimates based on hydrometric data are considered to be more reliable than those based on rainfall-runoff computations. The writer concludes that the most reliable value of average annual discharge for the Amazon River at its mouth is 6,100,000 cfs (175,000 cms)—about 10 times the average discharge of the Mississippi River at the mouth.

CONCLUSIONS

The results of the joint investigations show the previously published estimates of mean annual flow past Óbidos to be much too low. The average discharge computed on the basis of a stage-discharge relation developed from three complete discharge measurements and daily stage readings for the period 1928–46 is 5,500,000 cfs (157,000 cms). The great flood of 1953 which probably reached a stage of 7.6 meters (24.9 feet) at Óbidos is calculated to have discharged at 12,500,000 cfs (350,000 cms) through the main channel with an indeterminate quantity of overflow on the flood plain.

The observations of dissolved-solids, suspended-sediment, and other water-quality parameters provide much more information on these aspects for the Óbidos location than had been determined previously, but there is insufficient information to permit an accurate assessment of either the mean annual suspended load or the salt-load discharge. The bed material samples and fathometer charts provide much insight into the nature of the streambed at Óbidos.

The objective of the joint investigation to provide reconnaissance information on the flow and water quality of the Amazon River was achieved. If more refined determinations of the average annual flow and water quality characteristics are needed, it will be necessary to conduct intensive investigations at Óbidos and elsewhere in the basin. The maintenance of a river-stage gage at Óbidos—above tidal effects during all but extremely low flow—would provide valuable information at small expense.

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