



Some Hydraulic Characteristics of Three Mega-Rivers: Amazon, Congo and Orinoco [†]

Carlo Gualtieri *  and Paola Gualtieri 

Department of Structures for Engineering and Architecture, University of Naples Federico II, Via Claudio 21, 80135 Naples, Italy; paola.gualtieri@unina.it

* Correspondence: carlo.gualtieri@unina.it

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Abstract

The present study compares the results from field studies conducted over several years using ADCP profiling to identify basic hydraulic characteristics in some locations of the Amazon River, Congo River and Orinoco River, which rank as the three largest rivers in the world in terms of discharge. The results highlighted some temporal trends among years and seasons in terms of discharge, cross-sectional average velocity and water depth and demonstrated that the classical power laws between discharge and water depth are reasonably valid even in those mega-rivers.

Keywords: mega-rivers; hydraulics; field measurements; discharge; velocity

1. Introduction

The world's large rivers, such as the Yellow River, Indus, Nile, Tigris and Euphrates, and their floodplains have historically been key locations for the establishment of human civilization [1]. Nowadays, large rivers are threatened by several anthropogenic stressors, operating on a range of timescales, such as large-scale damming, rapid urbanization, sea-level change, deforestation, hydrological change, pollution, introduction of non-native species and sediment mining [2–4]. Latrubesse [5,6] defined as *mega-rivers* those with an average annual discharge $Q_{avg} > 17,000 \text{ m}^3/\text{s}$. There are 11 *mega-rivers* on Earth: Amazon, Congo, Orinoco, Yangtze, Madeira, Negro, Brahmaputra, Japurá, Paraná, Mississippi and Yenisei. *Mega-rivers* were investigated in the Earth Sciences community [4,5,7–9], but few studies have focused on their hydrodynamics and sediment transport [10–12]. Some field studies were conducted at *mega-river* confluences, such as Jamuna/Ganges-Brahmaputra [13], Paraná-Paraguay [14], Negro/Solimões [15–18] and Yangtze/Poyang Lake [19–21], and diffuence–confluence units, such as in the Paraná River [22–24], Yangtze River [25,26] and Mississippi River [27], but further research is needed to address the complex interaction between hydrodynamic and morphodynamic processes in such very large systems.

The present study compares the results from field studies conducted over several years under different flow conditions using ADCP profiling to identify basic hydraulic characteristics in some reaches of the Amazon River, Congo River and Orinoco River, which rank as the three largest rivers in the world for discharge. The results highlighted some temporal trends among years and seasons in terms of discharge, cross-sectional average velocity and water depth and demonstrated that the classical power law between discharge and water depth is reasonably valid even in those mega-rivers.



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2. Materials and Methods

The Amazon River (Figure 1a) is the longest and largest river by discharge in the world (average annual discharge of about $209,000 \text{ m}^3/\text{s}$). Such discharge is up to 18% of the global riverine discharge into oceans [28]. The Amazon basin is the largest worldwide drainage basin (approximately $7.0 \text{ km} \times 10^6 \text{ km}$) and hosts 4 mega-rivers: Amazon, Madeira, Negro and Japura rivers. The Congo River (Figure 1b) has the second largest discharge ($40,500 \text{ m}^3/\text{s}$) with a basin area of $3.7 \text{ km} \times 10^6 \text{ km}$. Its center (Central Basin), is a depression, flooded according to the hydro-rainfall cycle and covered by a great rainforest, which together with the Amazon River basin plays a key role in regulating the world's climate [29–32].

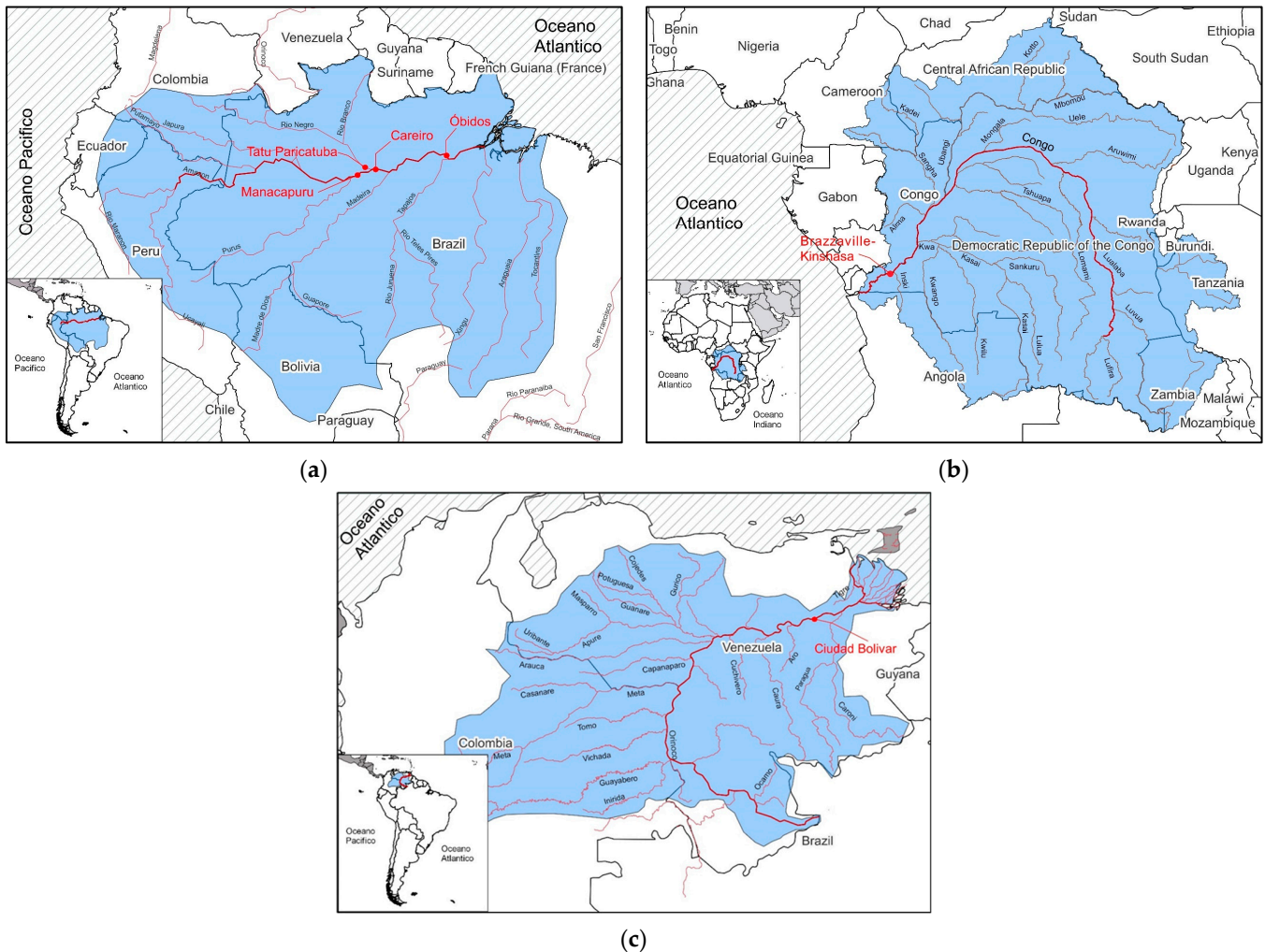


Figure 1. (a) Amazon River basin; (b) Congo River basin; (c) Orinoco River basin.

The Orinoco River (Figure 1c) has the third largest average annual discharge ($37,600 \text{ m}^3/\text{s}$). Its basin covers about $1.1 \text{ km} \times 10^6 \text{ km}$ and is divided into three large zones: (1) the Andes and Caribbean Coastal Ranges, where most suspended sediments originate; (2) the Llanos (floodplain area), which are crossed by all major tributaries coming from the Andes and (3) the Precambrian Guiana Shield with black water and low TSS content [33–37].

This study reports the results of 18 fieldworks conducted in the Amazon from 2010 to 2023 under different flow conditions by the CPRM (Geological Survey of Brazil) and HYBAM Observatory (HYdro-geochemistry of the AMazonian Basin) at four different key locations, Manacapuru, Careiro, Obidos and Tatu Paricatuba, which is in the Negro River, a major tributary of the Amazon River (Figure 1a). A Teledyne Rio Grande ADCP (600 kHz) was used. For the Congo River, 8 fieldworks carried out from 2011 to 2024 under different flow conditions at the key Brazzaville–Kinshasa section with a Teledyne Rio Grande ADCP (600 kHz) by SCVN-GIE (Groupement d’Intérêt Economique pour le Service Commun d’Entretien des Voies Navigables, Republic of Congo) are reported. Finally, for the Orinoco River, the results of 4 fieldworks conducted from 2012 to 2018 under different flow conditions by Hybam Observatory at Ciudad Bolivar using a RiverRay II (600 kHz) are reported. In all field studies at least 4 transects were collected at each location.

3. Results and Discussion

The post-processing of the raw ADCP velocity data obtained basic hydrodynamic parameters such as area, wetted perimeter, hydraulic ratio, average/median water depth, aspect ratio, cross-sectional average velocity, and median/maximum depth-averaged velocity measured in each vertical. Tables 1 and 2 list the median value from each field study. Further information was derived using the Velocity Mapping Tool software (VMT) 4.09 [38].

In the Amazon River at Manacapuru, the discharge from low- to high-flow conditions was in the range from 31,000 to 143,000 m³/s. The water depth varied from 14 to 30 m, accordingly, while the maximum depth-averaged velocity was in the range from 1.1 to 2.2 m/s. In the Negro River at Tatu Paricatuba, discharge and water depth were in the range from 33.000 to 57.000 m³/s and from 30 to 39 m, respectively. In the Amazon River at Careiro, discharge and water depth varied from 17.000 to 25.000 m³/s and from 21 to 25 m in low- and high-flow conditions. Finally, in the Amazon River at Obidos, the largest change in discharge and maximum depth-averaged velocity between low- to high-flow conditions were found as they varied from 74,000 to 223,000 m³/s and from 1.0 to 2.7 m/s.

In the Congo River at Brazzaville–Kinshasa, the flow discharge was in the range from 24,000 to 66,000 m³/s. Velocities up to almost 3 m/s were observed, while water depth ranged from 9 to 13 m from low- to high-flow conditions.

In the Orinoco River at Ciudad Bolivar, from low-flow to high-flow conditions, the cross-sectional velocity and the maximum depth-averaged velocity increased from 0.4 to 2.5 m/s and 1.1 to 3.8 m/s, while water depth and width increased from 25 to 35 m.

Figure 2 presents the cross-sectional distribution of velocity magnitude with secondary flow vectors calculated using the Rozovski method [39,40] at Manacapuru on 25 October 2010 and on 12 June 2017 under low- and high-flow conditions, respectively. Velocity magnitude was in the order of 1 to about 2.3 m/s from low- to high-flow conditions, mostly located about the channel centerline where secondary flow was also stronger.

There is a long history of attempts to predict the depth of alluvial channels. Leopold and Maddock used regression analysis to find a power law such as $h \propto Q^{0.40}$ [41–44]. The data collected in the three *mega-rivers* support such power law with an exponent often close to that suggested by Leopold and Maddock, for example 0.49, 0.38 and 0.44 in the Amazon River at Manacapuru and Careiro and in the Congo River at Brazzaville–Kinshasa, respectively (Figure 3), while in Tatu Paricatuba it was 0.25 and in the other stations (Obidos and Ciudad Bolivar), it was <0.20. The latter is probably due to the distance (about 1 km) among the locations where the transects were collected.

Table 1. Flow properties measured in the Amazon River during the 2010–2023 field studies.

Location	Date	Flow	Q (m ³ /s)	A (m ²)	W (m)	R _h (m)	h _{med} (m)	W/h _{rect} (-)	V _{avg} (m/s)	V _{depth-avg} (m/s)	V _{max} (m/s)
Amazon River at Manacapuru	25 October 2010	Low	30,578	44,368	3031	14.4	14.2	207	0.690	0.723	1.089
	24 July 2011	High	122,812	90,945	3265	25.6	28.3	117	1.349	1.362	2.086
	26 January 2017	High	95,981	78,789	2960	23.6	24.9	111	1.218	1.177	1.794
	10 April 2017	High	123,789	90,626	3052	26.8	28.5	103	1.368	1.291	2.041
	12 June 2017	High	142,922	96,408	3064	28.2	30.2	98	1.482	1.349	2.202
	12 August 2017	High	109,531	87,923	2967	27.5	27.6	100	1.244	1.200	2.006
Amazon River at Tatu Paricatuba	20 September 2010	Low	35,588	67,580	2394	27.6	34.8	85	0.527	0.529	0.789
	14 July 2013	High	57,252	97,105	2736	34.9	37.2	77	0.590	0.546	1.013
	7 February 2017	Low	33,102	86,496	2496	29.4	30.5	72	0.383	0.363	0.593
	12 April 2017	Low	37,968	94,492	2494	35.0	37.5	66	0.402	0.365	0.841
	13 June 2017	High	48,997	98,012	2540	35.2	38.6	66	0.500	0.445	0.807
Amazon River at Careiro	7 February 2017	Low	16,265	16,752	749	19.3	20.7	34	0.971	0.872	1.231
	24 May 2017	High	25,236	20,380	763	22.0	24.8	28	1.236	1.098	1.584
	27 July 2017	High	21,252	19,074	758	21.1	23.2	30	1.114	1.058	1.504
Amazon River at Obidos	23 November 2010	Low	73,719	110,606	2292	41.9	46.2	48	0.667	0.630	0.962
	29 July 2011	High	188,260	131,049	2773	37.2	48.2	59	1.446	1.472	2.284
	21 June 2013	High	207,936	133,207	2760	38.6	47.0	57	1.562	1.477	2.381
	14 July 2023	High	222,916	132,950	2377	44.9	64.5	43	1.677	1.658	2.713

Legend: Q = discharge; A = cross-sectional area; W = transect width; R_h = hydraulic radius; h_{med} = median depth; W/h_{rect} = aspect ratio; V_{avg} = cross-sectional velocity (Q/A); V_{depth-avg} = median depth-averaged velocity; V_{max} = maximum depth-averaged velocity.

Table 2. Flow properties measured in the Congo River during the 2011–2024 field studies and in the Orinoco River during the 2012–2018 field studies.

Location	Date	Flow	Q (m ³ /s)	A (m ²)	W (m)	R _h (m)	h _{med} (m)	W/h _{rect} (-)	V _{avg} (m/s)	V _{depth-avg} (m/s)	V _{max} (m/s)
Congo River at Brazzaville–Kinshasa	14 July 2011	Low	24,822	28,563	3208	7.6	9.03	361	0.869	1.185	2.220
	28 November 2012	High	49,758	39,323	3210	10.2	11.02	262	1.265	1.485	2.476
	28 March 2013	Low	37,627	35,576	3195	9.9	10.42	287	1.058	1.185	2.239
	10 June 2013	Low	36,980	36,025	3327	9.8	10.87	296	0.990	1.147	2.135

Table 2. Cont.

Location	Date	Flow	Q (m ³ /s)	A (m ²)	W (m)	R _h (m)	h _{med} (m)	W/h _{rect} (-)	V _{avg} (m/s)	V _{depth-avg} (m/s)	V _{max} (m/s)
Congo River at Brazzaville–Kinshasa	19 December 2014	High	59,235	49,423	3445	N/A	13.76	249	1.073	1.286	2.335
	23 December 2019	High	66,976	49,896	3493	11.4	13.03	231	1.564	1.621	2.830
	27 December 2023	High	73,187	58,498	3771	13.0	15.79	244	1.232	1.477	2.385
	10 January 2024	High	74,696	57,541	3586	14.5	14.12	223	1.297	1.488	2.335
Orinoco River at Ciudad Bolivar	14 August 2012	High	64,821	41,783	1278	27.6	34.71	38.18	1.519	1.164	2.768
	25 April 2013	Low	10,515	24,563	995	21.6	25.16	40.74	0.428	0.399	1.074
	11 November 2014	Medium	39,722	32,218	1206	22.0	25.46	45.19	1.227	1.089	2.049
	19 August 2018	High	85,472	35,205	915	28.1	34.97	23.00	2.469	2.054	3.833

Legend: Q = discharge; A = cross-sectional area; W = transect width; R_h = hydraulic radius; h_{med} = median depth; W/h_{rect} = aspect ratio; V_{avg} = cross-sectional velocity (Q/A); V_{depth-avg} = median depth-averaged velocity; V_{max} = maximum depth-averaged velocity.

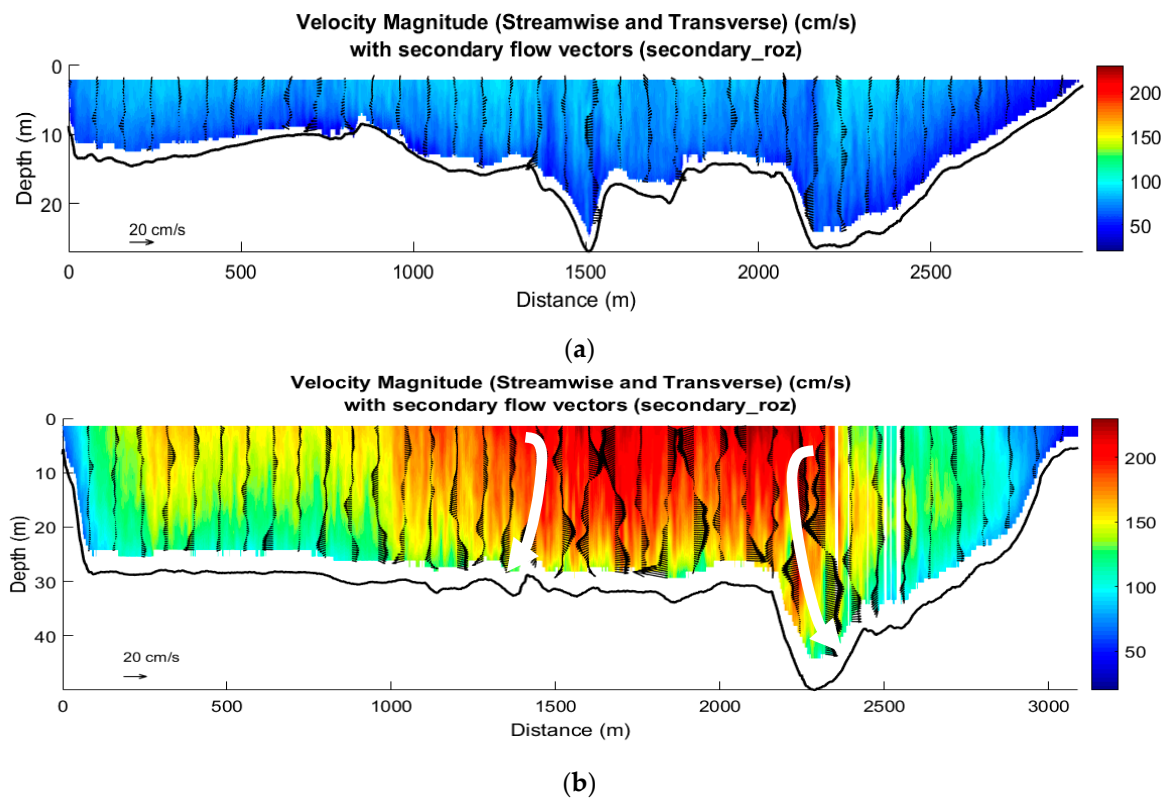


Figure 2. Amazon River Basin at Manacapuru (a) 25 October 2010 (low flow); (b) 12 June 2017 (high flow).

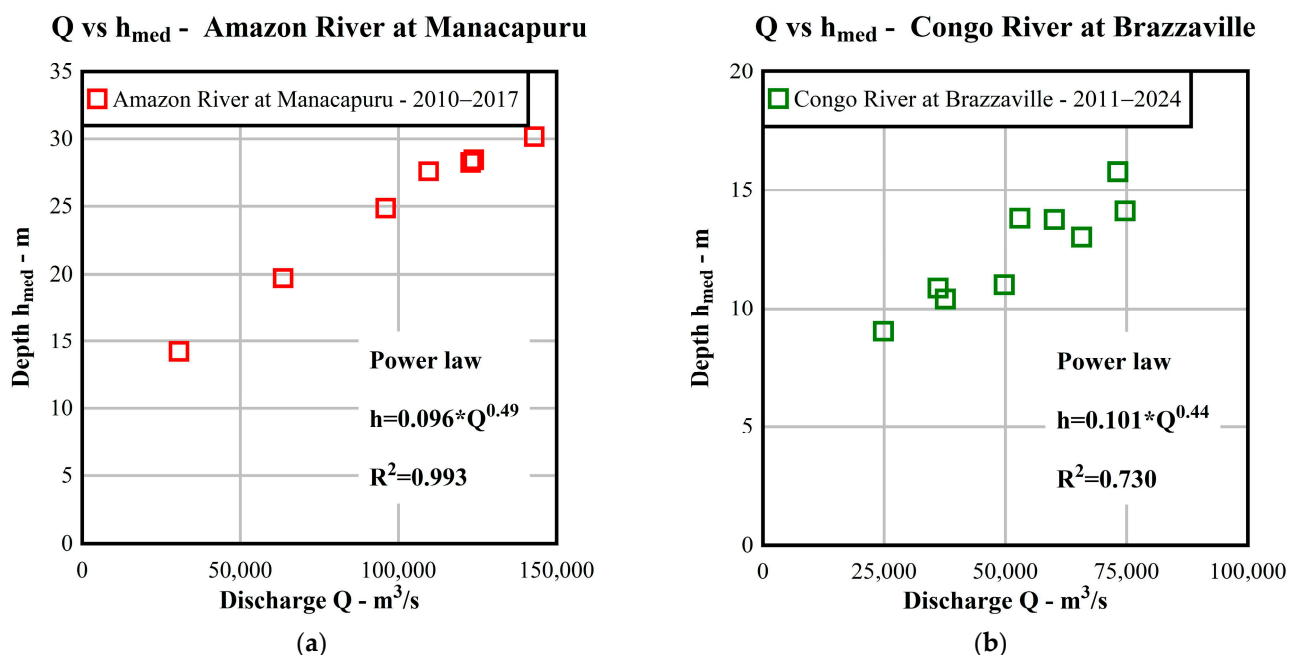


Figure 3. Relationship between discharge and water depth in the (a) Amazon River Basin at Manacapuru; (b) Congo River at Brazzaville–Kinshasa.

4. Conclusions

The analysis of ADCP data collected in some locations of the Amazon River, Congo River and Orinoco River identified some trends of the main hydraulic parameters from low- to high-flow conditions which might be applicable in the context of the global climate

change. In addition, it was found that the classical power law between discharge and water depth is reasonably valid even in those mega-rivers.

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