Discharge and Other Hydraulic Measurements for Characterizing the Hydraulics of Lower Congo River, July 2008

Kevin Oberg[1], John M. Shelton[2], Ned Gardiner[3], and P. Ryan Jackson[4]

[1]Hydrologist, U.S. Geological Survey, Office of Surface Water, 1201 W. University Ave., Suite 100, Urbana, IL 61801; PH: (217) 328-9727; kaoberg@usgs.gov
[2]Hydrologist, U.S. Geological Survey, SC Water Science Center; jmshelto@usgs.gov
[3]Research Associate, American Museum of Natural History; egardiner@amnh.org
[4]Hydrologist, U.S. Geological Survey, IL Water Science Center; pjackson@usgs.gov

ABSTRACT

The first direct measurements of discharge of the Lower Congo River below Malebo Pool and upstream from Kinganga, Democratic Republic of Congo (DRC) were made in July 2008 using acoustic Doppler current profilers, differential GPS, and echo sounders. These measurements were made in support of research that is attempting to understand the distribution of fish species in the Lower Congo River and reasons for separation of species within this large river. Analyses of these measurements show that the maximum depth in the Lower Congo River was in excess of 200 m and maximum water velocities were greater than 4 m/s. The discharge measured near Luozi, DRC was 35,800 m^3/s, and decreased slightly beginning midway through the study. Local bedrock controls seem to have a large effect on the flow in the river, even in reaches without waterfalls and rapids. Dramatic changes in bed topography are evident in transects across the river.

INTRODUCTION

The Congo River stretches from the Great Rift Valley in eastern Africa to the Atlantic Ocean in the west and has a drainage basin 3.8 million km^2. It is the second longest river in Africa and is the second largest river in the world as measured by discharge. The Congo River basin is home to one of the largest intact rain forests in the world, is one of the world's most biologically diverse river systems, and is an important freshwater supply for millions of people in central Africa.

The American Museum of Natural History (AMNH) is leading a major taxonomic collection effort in the Lower Congo River. As a part of this work, more than 300 species of fish have been identified, 30% of which are found nowhere else on the planet. This large diversity may be caused by the river's unique geology, geomorphology, and hydraulic conditions. Analysis of fish tissues collected between 2006 and 2008 shows that morphologically similar fishes found in close proximity are genetically distinct, implying long-term separation of fish populations (Stiassny, M., AMNH, 2008, written comm.). For example, on north and south banks of the Lower Congo River just below Malebo Pool, collections within the genus *Teleogramma* are clearly separable on the basis of mitochondrial DNA (Schelly, R., AMNH, 2009, written comm.). Although they subsist within a few hundred meters of one another, the two lineages apparently exchange less than one individual per three generations. This separation of species may be caused by hydraulic conditions between collection locations which prevent movement of fishes across the channel. As a result, it is important to collect and analyze data on the hydraulics in the Lower Congo River in order to understand causes for species isolation.

Despite its geologic, geomorphic, biologic, and economic significance, there is little basic hydrologic and hydraulic data available for the Lower Congo River. In July 2008, a synoptic survey of a reach of the Lower Congo River below Malebo Pool and upstream of Kinganga, DRC was made. The objectives for this synoptic survey were (1) to make direct measurements of discharge in this reach, (2) to provide information that would help researchers begin to characterize the velocity distributions in the river, and (3) to document geomorphic and hydraulic features that may be related to patterns of freshwater fish biodiversity observed in the Lower Congo River. The work was accomplished by a team of researchers, including staff from the American Museum of Natural History, the U.S. Geological Survey (USGS), the University of Kinshasa, and the University of Marien Ngouabi (Brazzaville).

The purpose of this paper is to describe the study reach, the methods and instruments used in the synoptic survey of the Lower Congo River, and present some selected, preliminary results of the survey. The synoptic survey described herein was conducted from below Malebo Pool to a point in the river about half way between Kinganga and Luozi, Democratic Republic of Congo (DRC). The focus of this paper is to document the discharges measured during the synoptic survey; however, selected results of velocity and bathymetry measurements are also presented.

STUDY AREA

There is some evidence that the Congo River was once a closed basin. At some point it began to flow into the Atlantic Ocean, however the mechanism and timing of this is in dispute (Runge, 2008). Regardless, the river upstream from Kinshasa, the capital of the DRC and Brazzaville, the capital of the Republic of Congo (RC), is quite different than the river below these cities. The Malebo Pool, located upstream from Kinshasa and Brazzaville (Fig. 1), is as wide as 24 km in places and may be a remnant of the once landlocked basin. The Malebo Pool forms the downstream end of the Middle Congo River.

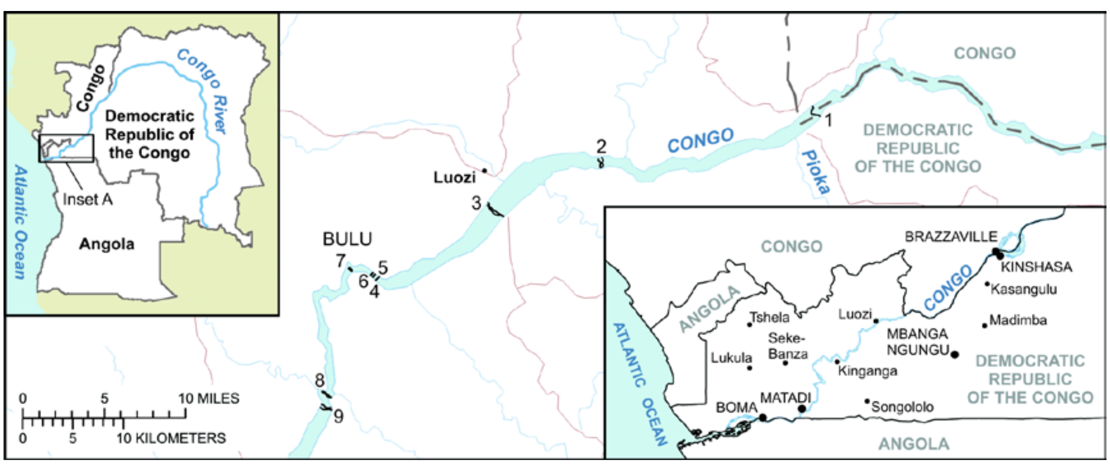

Figure 1. Location of ADCP measurements on Lower Congo River, July 2008.

The Lower Congo River drops 280 m in 350 km between Kinshasa and the Atlantic Ocean (Fig.2). In the first 130 km below Malebo Pool are a series of extreme rapids that no one had successfully descended and documented until 2008. Nearer to the mouth are Matadi and Boma, the largest trading cities for the DRC. Matadi and Boma are located 134 km and 100 km upstream from the mouth, respectively. The river is not navigable between Matadi and Kinganga because of the steep bed slope and numerous rapids and waterfalls. The channel is primarily bedrock, but there are some areas with substantial alluvial deposits. In addition to the steep bed slope in the first 130 km below Malebo Pool, the river is characterized by many channel expansions and contractions.

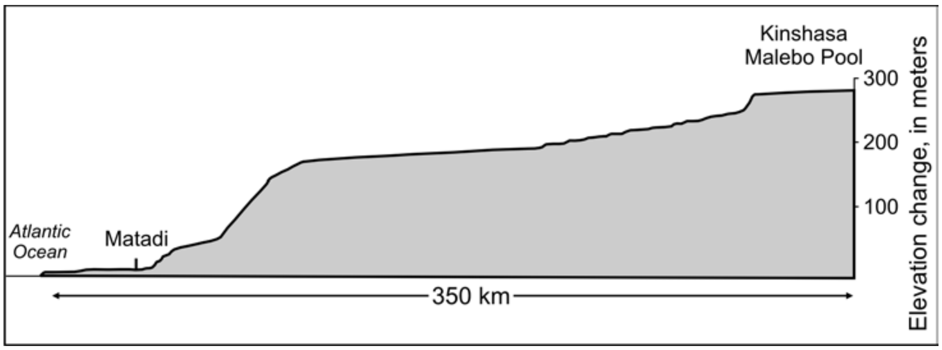

Figure 2. Bed slope of the Lower Congo River from Kinshasa to the mouth, modified from Robert (1946).

The mean annual discharge of the Lower Congo River at Kinshasa, measured from 1932 to 1959, is 46,200 m^3/s and the highest recorded discharge at this same location is 64,900 m^3/s (Runge, 2008). According to Runge (2008), "Hydrological data on the Congo River are often limited to documents that date back to the colonial times and for a brief period after that … Many Congolese gauging stations, mainly those in rural areas, were abandoned after independence." More recent, satellite-derived estimates have indicated that the river can be very deep (greater than 100 m), and that velocity may be in excess of 7 m/s, suggesting extreme hydraulic conditions. Field data collected in 2007 with an inexpensive echo sounder and a Price AA current meter confirmed depths in excess of 70 m and measured velocities in excess of 5 m/s (Bjerklie, D., USGS, 2008, written comm.). The flow in this reach is unregulated and is subject to seasonable fluctuations largely driven by the tropical climate of central Africa.

APPROACH FOR CHARACTERIZING THE HYDRAULICS OF THE LOWER CONGO RIVER

A synoptic survey of the Lower Congo River was conducted from just below Malebo Pool to a point about half way between Kinganga and Luozi, DRC. A team of kayakers equipped with an echo sounder and a differential Global Positioning System (dGPS) surveyed the first 130 km of this reach through the series of rapids below Malebo Pool. Another team made a more detailed survey of the reach between Pioka, DRC and the end of the study reach.

A single-line longitudinal bathymetric survey from Malebo Pool to Pioka was made by a team of kayakers. A kayak was outfitted with a Trimble[1] AgGPS 132 dGPS, a 200 kHz Lowrance LCX-15MT digital echo sounder, and an RS-232 datalogger. The dGPS was configured to obtain differential corrections via the OmniStar subscription service available for central Africa. The team of kayakers was also outfitted with video recorders and some limited water-quality sampling supplies. The kayakers put in just below the Malebo Pool near Kinshasa and traveled approximately 130 km downstream in 5 days. The data recorded for this survey consist of a record of position and depth at every point along the route taken by the kayak equipped with the echo sounder and dGPS. No attempt was made to map the bathymetry of the channel from bank to bank using kayaks.

Acoustic Doppler current profilers (ADCPs), dGPS receivers, echo sounders, multi-parameter water-quality meters, and a water-quality sampler were used to make hydraulic and water-quality measurements in the reach from below the Pioka to about half way between Luozi and Kinganga, DRC (Fig. 1). In order to measure in a variety of conditions expected in the Lower Congo River, three different ADCPs were used, a 1200 kHz and a 600 kHz Teledyne RD Instruments (TRDI) Rio Grande ADCP, and a 300 kHz TRDI Workhorse ADCP.

A dug-out canoe equipped with an outboard motor, known as a pirogue, was used both for transport between sites and for ADCP surveys. The ADCPs were mounted in a tethered catamaran that was attached to the boat via a line. Position information was obtained using the Trimble dGPS receiver with the OmniStar service. The ADCP was used to measure profiles of velocity and backscatter, along with depths from each of the four ADCP beams. These data and the external echo sounder data were synchronized in real time with dGPS data via TRDI's WinRiver II software.

Prior to the field work, 10 locations along the river were randomly chosen for data collection. Locations were rejected if they were inaccessible due to large rapids or if they were deemed inordinately difficult to measure due to logistics and coordination with ichthyology teams. At each site, the discharge of the river was measured using procedures outlined in Oberg et al. (2005). If possible, additional measurements of velocity were to be made using procedures described by Dinehart and Burau (2005). At sites of particular interest, more detailed velocity and bathymetry mapping were to take place, based on the flow conditions and depths observed.

RESULTS OF SELECTED HYDRAULIC MEASUREMENTS

Measurements made by the kayak team from the reach between Malebo Pool and Pioka are presently (2009) being analyzed but initial analyses indicate depths in excess of 220 m in one reach of the river. Although hundreds of measurements were made, they are being verified because these data may indicate that the Lower Congo River is the deepest river on Earth.

Discharge measurements were made at nine locations shown on Fig. 1 from Pioka (Map ID 1) to below Bulu (Map ID 9). The measured discharges ranged from 30,600

[1] Any use of trade, product, or firm names in this document is for descriptive purposes only and does not imply endorsement by the U.S. Government.

m^3/s to 36,800 m^3/s and tended to decrease between July 9 – 13, 2008 (table 1). The discharge measurement with the deepest measured depth (118 m) and the largest cross-sectional area (110,000 m^2) was near Pioka; just below the last major rapids above Luozi. The cross-sectional area there is approximately double that of the largest measurement section downstream. From Pioka, the cross-sectional area steadily decreases until the Bulu reach (locations 4-7) and below.

Table 1. Summary of discharge measurements, Lower Congo River, July 2008

Location	Date	Discharge (m^3/s)	Width (m)	Area (m^2)	Depth (m) Mean	Depth (m) Maximum	Velocity (m/s) Mean	Velocity (m/s) Maximum	Aspect Ratio
1	07/07/08	36,700	1,460	110,000	75.3	118.	0.33	4.60	19.4
2	07/05/08	33,900	1,010	34,200	33.9	78.2	0.99	2.97	29.8
3	07/04/08	35,800	2,190	25,700	11.7	24.2	1.39	3.19	187
4	07/09/08	36,500	540	23,800	44.1	79.2	1.53	2.87	12.3
5	07/09/08	36,800	388	17,100	44.1	78.5	2.15	3.29	8.8
6	07/09/08	34,400	384	16,600	43.2	78.1	2.07	3.31	8.9
7	07/11/08	34,200	429	26,700	62.3	102.	1.28	5.89	6.9
8	07/13/08	32,700	1,020	58,500	57.4	92.9	0.56	3.41	17.8
9	07/13/08	30,600	1,070	52,800	49.3	87.1	0.58	3.04	21.7

In addition to the discharge measurements summarized above, velocity and bathymetry data were collected especially in the bends near Bulu, using ADCPs and echo sounders equipped with dGPS. Although these data are still being analyzed, measurements in the second bend near Bulu indicate water depths of 164 m.

DISCUSSION

All of the discharges reported in table 1 were collected using dGPS as the velocity reference (not bottom track) except for location 1, where the dGPS data were not of acceptable quality. Ratios of discharge computed with dGPS as the reference to discharge with bottom track as the reference ranged from 1.01 to 1.13, with most values ranging from 1.01 to 1.05. These values indicate that a small moving bed condition was present in most measurements. However, because the mean number of transects obtained for each location was only 2, the magnitude of the moving bed condition is in question.

Some compass errors are also evident in the data collected. Even though compass calibrations were done at each site and estimates of local magnetic variation were validated with on-site measurements, for some measurements the magnetic variation was modified to remove directional bias evident in the dGPS discharge measurements. There are two possible reasons for these compass issues; (1) despite our best efforts the compass was not well calibrated, and/or (2) there are significant local magnetic anomalies that affected compass performance.

From the data in table 1 and other measurements, it is clear that the Lower Congo River is quite different from many large rivers in the world. River depths as deep as

164 m were observed in the area around Bulu, and depths greater than 220 m were observed below Malebo Pool by the kayak team. The depths recorded in the reach below Malebo Pool are not compensated for pitch and roll; however, the depths measured using the ADCP and echo sounder near Bulu are compensated. Not only is the Lower Congo River deeper and narrower in the lower reaches than expected for a river of its size, the bed topography can change dramatically, both locally and in a given reach. The channel is more like a high-gradient mountain stream with a very large discharge; which is consistent with the theory that a short mountain river eroded through the divide and reached Malebo Pool, forming the present Lower Congo River. For example, Fig. 3b shows a cross section measured at location 8 in which there is a maximum 35-m variation between ADCP beam depth measurements. In contrast, at Luozi (Fig. 3a), there is much less variation in beam depths (4 m maximum).

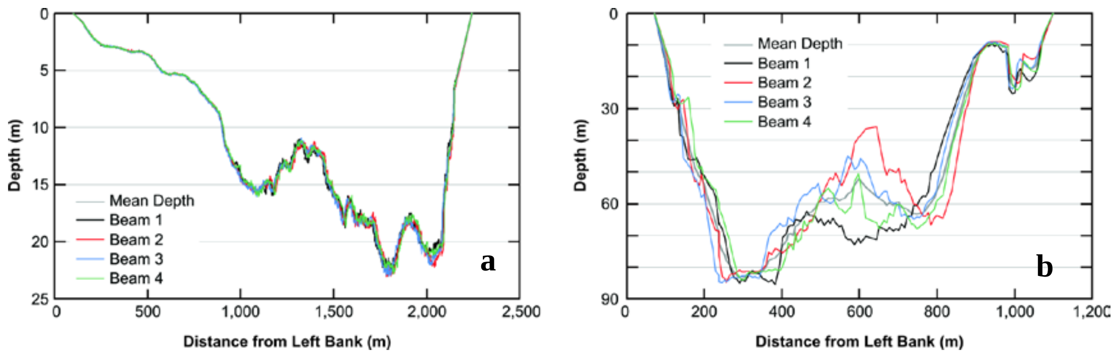

Figure 3. Cross sections of transects on the Lower Congo River at Luozi (a) at location 3 and below Luozi (b) at location 8, July 2008.

The aspect ratio for a river can be defined as the channel width divided by the mean depth. The aspect ratio of the lower Congo ranges from 7-8 near Bulu to 187 near Luozi (table 1). Four different discharge measurement sections (locations 4-7) had aspect ratios between 6.9 and 12.3. A transect made in the second bend near Bulu (as part of some velocity surveys not described herein) and downstream from locations 4-7 indicate that the aspect ratio for these flow conditions decreases to 5.1. An aspect ratio of 5-10 is quite small for a river the size of the Lower Congo. The aspect ratio for the lower Parana River, a large sand bed river in Argentina ranges from 60 to 100 (Szupiany et.al., 2009). The aspect ratio for the Mississippi River at Baton Rouge, LA is 60 for a similar discharge of 37,900 m^3/s, even though the Mississippi has levee systems that tend to confine the flow to a narrower channel. It appears that the aspect ratios of the Middle Congo (above Kinshasa) are much greater on average than in the Lower Congo River. This no doubt reflects the bedrock control on the channel shape and orientation, especially below Kinshasa. Even in some of the farthest downstream sections, such as at location 8 where the river is about 1 km wide and has an aspect ratio of 17.8, the effective width of the river is much smaller due to a large area of recirculation on the western shore (right bank) as indicated in Fig. 4b. Examination of the ADCP data for other sections suggests that the reduction in effective width is frequent for much of the Lower Congo River. With this in mind, it is apparent that even when the river widens, the downstream flow is often concentrated in a jet, the size and location of which is largely determined by the location and depth of the thalweg and the reach orientation of the channel. In contrast, the measurements made at location 3 near Luozi show that the depth-averaged velocities are all oriented in the downstream direction.

The nature of the field and river conditions along with time and logistical constraints made it difficult to completely adhere to standard protocols for measurement of discharge using ADCPs. The flows in some sections made navigation using the pirogue difficult. Large vortices, some of which were 3-4 m in diameter would open up under the pirogue making it difficult to adhere to a planned course. High velocities in the river, coupled with these vortices, made navigation from shore to shore a challenge.

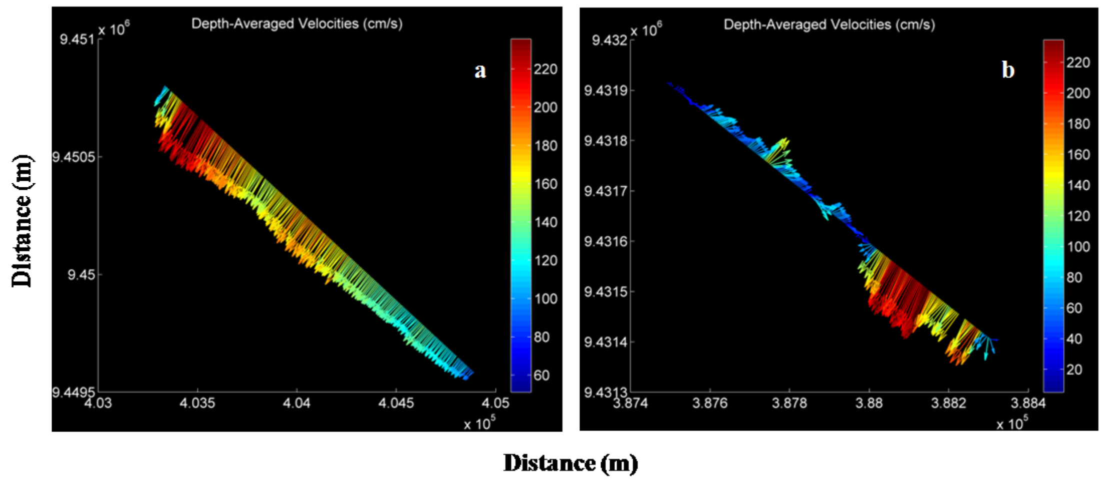

Figure 4. Depth-averaged velocities for transects on the Lower Congo River at Luozi (a) at location 3 and below Luozi (b) at location 8, July 2008.

Analyses of velocity and depth measurements in the area around Bulu are continuing. The authors are examining velocity gradients across the river and will explore whether or not these gradients could help explain patterns in fish speciation in the Lower Congo River. If future measurements of this reach of the Lower Congo River are possible, the following suggestions are offered:

- Use a dual frequency, survey-grade echo sounder.
- Use a boat operator experienced in velocity data collection in this environment and a boat suited to the conditions in the Lower Congo River.
- Identify and remedy the source of the compass problems experienced in this work.
- Include more transects across the stream at a given location using navigation software and pre-planned transects and, if possible, obtain stationary measurements at selected points in the cross section.
- Although not absolutely required, use an RTK dGPS system to provide accurate boat velocities for ADCP measurements and to help quantify local water surface slopes along the river.

SUMMARY

The Congo River is the second largest river in the world, by discharge. Personnel from the USGS and the American Museum of Natural History made direct measurements of discharge of the Lower Congo River below Malebo Pool and upstream from Kinganga, DRC in July 2008 using ADCPs, dGPS, and echo sounders. These measurements were made in support of research that is attempting to understand the distribution of fish species in the Lower Congo and reasons for separation of species within a reach of this large river.

Analyses to date have indicated that the maximum depth measured in the Lower Congo River was in excess of 220 meters and water velocities in excess of 4 m/s were measured. Measured discharge near Luozi was 35,800 m^3/s, and decreased slightly beginning midway through the study. Local bedrock controls seem to have a large effect on the flow in the river, even in reaches without waterfalls and rapids. Dramatic changes in bed topography are evident in repeated transects across the river. In relatively deep sections of the river, large vortices form as a result of these rapid changes in bed topography and channel orientation.

ACKNOWLEDGEMENTS

The authors acknowledge support for this work by the National Geographic Society's Waitt Foundation and the American Museum of Natural History's (AMNH) Ichthyology Department. We thank Melanie Stiassny for her generous support from the Axelrod endowment at AMNH. We acknowledge the work of Trip Jennings and his crew of kayakers (see www.epicocity.com) who volunteered to collect river depth data for this research. Lastly, we especially acknowledge Jim Rogers, of Teledyne RD Instruments, who arranged for the loan of a 300 kHz ADCP which proved so essential to our data collection.

REFERENCES

Dinehart, R.L., and Burau, J.R. (2005) “Repeated surveys by acoustic Doppler current profiler for flow and sediment dynamics in a tidal river” *J. Hydrol.*, v. 314, 21 p.

Oberg, K.A., Morlock, S.E., and Caldwell, W.S. (2005) “Quality-assurance plan for discharge measurements using acoustic Doppler current profilers.” *U.S. Geological Survey Scientific Investigations Rep.* 2005–5183, 35 p.

Robert, M. (1946) “Le Congo Physique”. 3 ed., H. Vaillant-Carmanne, S.A., Impr. de L'Academie, Liege (France).

Runge, J. (2008). “The Congo River, Central Africa.” *Large Rivers: Geomorphology and Management*, A. Gupta, ed., Wiley, Somerset, NJ, 293-309.

Szupiany, R. N., Amsler, M. L., Parsons, D. R., and Best, J. L., (2009) “Morphology, flow structure, and suspended bed sediment transport at two large braid bar confluences.” *Water Resour. Res.*, in press.