Velocity Mapping in the Lower Congo River: A First Look at the Unique Bathymetry and Hydrodynamics of Bulu Reach, West Central Africa

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ABSTRACT: The lower Congo River is one of the deepest, most powerful, and most biologically diverse stretches of river on Earth. The river's 270 m decent from Malebo Pool though the gorges of the Crystal Mountains to the Atlantic Ocean (498 km downstream) is riddled with rapids, cataracts, and deep pools. Much of the lower Congo is a mystery from a hydraulics perspective. However, this stretch of the river is a hotbed for biologists who are documenting evolution in action within the diverse, but isolated, fish populations. Biologists theorize that isolation of fish populations within the lower Congo is due to barriers presented by flow structure and bathymetry. To investigate this theory, scientists from the U.S. Geological Survey and American Museum of Natural History teamed up with an expedition crew from National Geographic in 2008 to map flow velocity and bathymetry within target reaches in the lower Congo River using acoustic Doppler current profilers (ADCPs) and echo sounders. Simultaneous biological and water quality sampling was also completed. This paper presents some preliminary results from this expedition, specifically with regard to the velocity structure and bathymetry. Results show that the flow in the bedrock controlled Bulu reach of the lower Congo is highly energetic. Turbulent and secondary flow structures can span the full depth of flow (up to 165 m), while coherent bank-to-bank cross-channel flow structures are absent. Regions of flow separation near the banks are isolated from one another and from the opposite bank by high shear, high velocity zones with depth-averaged flow velocities that can exceed 4 m/s.

1 INTRODUCTION

From the Great Rift Valley in the east to the Atlantic Ocean in the west, the Congo River drains approximately 3,822,000 km^2 of equatorial Africa. The upper Congo connects large areas of lowland forests with headwaters that encircle all of central Africa (Figure 1). The lower Congo comprises a series of 66 falls and rapids formed as the river drops approximately 270 m in the 498 km run to the Atlantic Ocean (Runge 2007). The lower Congo was formed in a single, highly energetic geomorphic event that breached the watershed divide at Malebo Pool (see Figure 1), thus draining the Pliocene Congo Lake in central Africa to the Atlantic Ocean (Runge 2007). The lower Congo carries the huge volume of water collected throughout its interior basin through a series of gorges where the gradient is more similar to a mountain headwater stream. The steep slope combined with the river's large average annual discharge—roughly five times that of the Mississippi—has led to a powerful river that traverses some of Earth's largest cataracts, falls, plunge pools, and river depths.

A major taxonomic collection effort, led by the American Museum of Natural History (AMNH), has brought to light over 300 species of fish in the lower Congo River, 30% of which are found nowhere else on the planet (Stiassny, M., AMNH, pers. comm.). In addition to being Earth's second largest river basin, the Congo is one of the most biologically diverse river systems. The great diversity of fishes in the lower Congo is believed to be a result of its unique geology and geomorphology. Many fish species have specialized adaptations such as extended snouts for burrowing into sediment or flattened bodies that allow water to flow with minimal resistance. These morphologic features allow fishes to exploit the river-bottom environment. Molecular data have also shown that morphologically similar fishes are genetically distinct (Schelly, R., AMNH, pers. comm.). Genetic dissimilarity implies long-term separation of populations of fishes, and the most obvious mechanism for separating fishes within the Congo is the power of the river itself. On north and south banks, for example, populations within the genus *Teleogramma* are clearly separable on the basis of mitochondrial DNA. While they subsist within hundreds of meters of one another, populations have not interbred due to the presence of a massive set of rapids, just below Malebo Pool, that prevent movement of fishes across the channel. Many species' distributions are also restricted to longitudinal (i.e., streamwise) portions of the lower Congo River with unique geomorphic settings. Some species are found only in the steep upper section. Others are only evident within the navigable mid-section, and a third set is only found within the torrential lower section. Biologists have been intrigued by the possibility that the barrier presented by the Congo to terrestrial species has also shaped evolution within the river.

Of particular interest to biologists is *Lamprologus lethops*, a blind, depigmented cichlid fish species that has only been found in the "Bulu" reach of the lower Congo (Figure 2). Specimens of this species have been found only dead or nearly dead. The characteristics of the fish combined with observations of gas bubbles under the skin of a dead fish found by fishermen suggest this fish lives at great depths (Stiassny, M., AMNH, pers. comm.). Biologists believe that the found fish may have been subject to rapid ascent through the water column from the benthic zone by turbulent upwelling, therefore causing death due to rapid decompression. Because *Lamprologus lethops* has never been found outside of this reach, biologists speculate that flow and channel bathymetry present barriers to migration of this species.

Despite its geologic, geomorphic, biologic, and economic significance, the lower Congo River's hydrologic characteristics have been little studied. The objectives of this research are to characterize the hydraulic behavior of the river and to elucidate geomorphic and hydraulic features that have shaped the patterns of freshwater fish biodiversity observed in the lower Congo River. This paper presents some preliminary results from a survey of the Bulu reach of the lower Congo River in July 2008.

2 STUDY SITE

This paper focuses on a reach of the lower Congo River known as "Bulu" (Figure 2). Although field work on the lower Congo River in the summer of 2008 involved data collection in a number of other reaches of the lower Congo River, the reach near Bulu was a primary focus due to the biodiversity present in this reach. Bulu is made up of two bends in the river in the west-central portion of the Democratic Republic of the Congo (Figure 2). The outside of the first bend is flanked by a large bar or bar-like feature and the second bend drops into a large, deep pool before exiting through a narrow constriction (see Figures 3 and 4). A series of three rapids link the two bends. Upstream from the Bulu reach, near Luozi, the Congo River is wider (2.2 km) and shallower (25 m or less), uncharacteristic of much of the lower Congo. The bed in the Bulu reach is believed to be primarily bedrock (Pre-Cambrian quartzites and schists), though substantial alluvial deposits are found in sections of the lower Congo. Discharge for the survey period was relatively constant at about 36,000 m^3/s at Luozi (Oberg et al. 2009), significantly lower than the annual mean discharge for the lower Congo at Kinshasa of 46,200 m^3/s (Runge 2007).

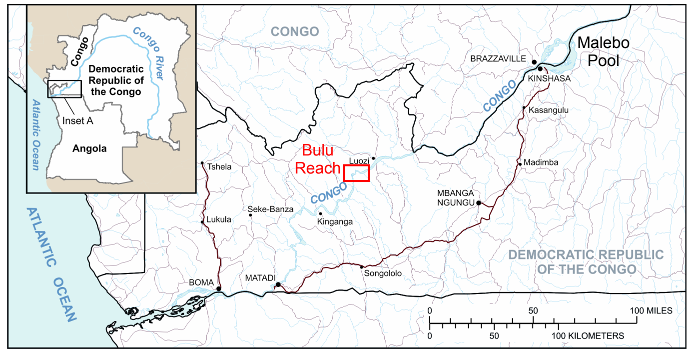

Figure 1. The lower Congo River, west central Africa. Red box denotes the Bulu study area.

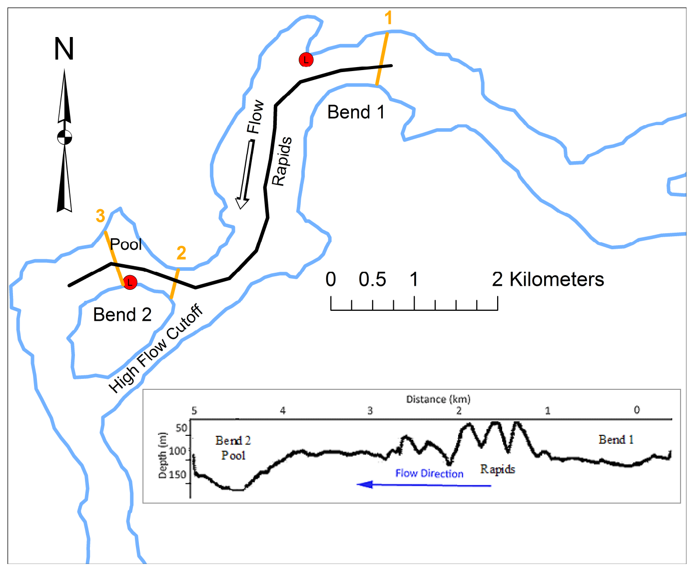

Figure 2. Bulu reach of the lower Congo River. Channel profile (along black line in main figure) shown in inset. Red dots show locations of *Lamprologus lethops* samples and orange lines show locations of selected cross sections.

3 METHODS

3.1 *Resources*

The remote locations of the survey sites and the lack of navigable water in the lower Congo required the use of local boats and operators for the survey. The primary water craft used for the mapping was a traditional 'pirogue' created from a single hollowed-out log outfitted with a 15 horse-power outboard motor. Although different from typical survey crafts, the pirogue is proven in the swift water of the lower Congo and the locals operating the boats had intimate knowledge of the rapidly varying flows making these crafts suitable (though not ideal) for the survey. However, the swift and often turbulent flow combined with limited communication with the boat operators (they spoke little to no English), made it difficult to remain on course for repeated transects. Instrumentation was provided primarily by the U.S. Geological Survey (USGS) as well as by Teledyne RDI (TRDI). Electronic instrumentation and batteries were charged via collapsible solar panels (and vehicles when possible).

3.2 *Instrumentation*

Water velocity and bathymetry data were collected using an acoustic Doppler current profiler (ADCP) in tandem with a Trimble[1] Ag132 differential GPS receiver (with Omnistar subscription) and a 200 kHz Lowrance LCX-15MT digital echo sounder. TRDI's software package WinRiver was used for data acquisition and integration of the data streams with position information from the DGPS.

Three different ADCPs were used during this expedition, a 300 kHz TRDI Workhorse ADCP and 600 and 1200 kHz TRDI Rio Grande ADCPs. However, due to the large depths, the 300 kHz unit was used almost exclusively for the data discussed in this paper. The ADCPs were mounted in an Ocean Science trimiran tethered boat and towed along-side the manned boat. The DGPS unit was located directly above the ADCP unit. The depth sounder was mounted to the side of the manned boat opposite the ADCP. Water mode 1 with bin sizes between 1 m and 2 m was used to collect the data presented in this paper.

3.3 *Survey Approach*

Data were collected in accordance with USGS protocol for discharge measurements and velocity surveys when possible (Oberg et al. 2005; Dinehart and Burau 2005). However, deviations from this protocol were required in order to map a relatively large reach in the given time with the resources available. Repeated transects at the same cross section were rare (as opposed to USGS protocol of at least four transects for a discharge measurement or the recommended six transects for a velocity survey). Instead, most transects were spread over the length of the reach to allow for a more detailed map of flow evolution and bathymetry. In some reaches, continuous acquisition, "zig-zag" survey lines through the reach were used to allow for more complete coverage in the allotted time. Several longitudinal transects were also collected. All transect locations were predetermined to provide data in reaches of biological interest. No moving bed tests were performed. A compass calibration was performed prior to all measurements, and analysis of the discharge measurements suggests some compass errors (Oberg et al. 2009). Provided no strong magnetic anomalies exist at the site, these compass errors may produce a slight shift (±4 to 7 degrees) in observed velocity direction for an entire transect.

3.4 *Data Processing*

Data were reviewed in TRDI's WinRiver II and output as ASCII text files after preprocessing. Preprocessing included subsectioning the "zig-zag" surveys into single transects and general data review. Care was taken during subsectioning to select relatively straight segments (based on ship track) to provide better data for mapping. The data were referenced to GPS (VTG) and no correction was made for deviations from a model-derived magnetic variation.

The ASCII output files were loaded into a MATLAB-based software package called Velocity Mapping Tool (VMT) for further processing and data visualization. VMT was recently developed by the USGS utilizing the methodology and scripts of Parsons et al. (2007) for averaging and computation of secondary flows from multiple transects. VMT allows users to generate flow maps of primary and secondary velocities from one or more transects at a site. In addition, reach-scale circulation can be studied by visualizing plan view depth-averaged (or layer-averaged) velocities for large number of transects. Secondary velocities are computed with (or without) a zero net cross-stream discharge criterion (Lane et al. 2000). VMT also allows backscatter and secondary velocity data to be integrated on the same plot, allowing the visualization of apparent sediment transport. Bathymetric data in the form of heading-, pitch-, and roll-corrected individual beam depths data can also be visualized and exported using VMT.

While VMT allows multiple transects to be averaged at a site resulting in a single representative mean cross section and velocity distribution, the highly variable flows in the lower Congo, the rugged bathymetry, and the lack of precise boat control demanded that (in most cases) each transect be analyzed individually in order to capture the variability in the flow structure and bed. This technique preserves (i.e. does not average out) the turbulent structures in each cross section and through comparison of multiple cross sections in the same general area, one can identify persistent secondary flow structures. Transects were only averaged if subsequent transects showed persistent features. Velocity data for each transect were gridded to 1 m in the horizontal and the bin spacing in the vertical (typically 1 to 2 m depending on the ADCP used and configuration modes) along a line representing the best fit to the boat path. Missing data were not interpolated but may be filled during averaging of multiple transects. A moving average filter is applied when plotting velocity vectors using a user defined window size (typically 3-4 horizontal grid cells) and vertical exaggeration was set to 2 for the figures in this paper.

Bathymetry data from all four beams of the ADCP were analyzed using VMT. Data were corrected for beam angle, pitch, roll, and heading and were written to an ASCII file. This data file was used to create a Triangular Irregular Network (TIN) using the ArcGIS Spatial Analysis Toolbox. A boundary file representing the approximate location of the shoreline digitized from a Digital Elevation Model (DEM) was integrated into the TIN. Depths have not been converted to bed elevations as water surface elevation data are not available. Echo sounder data were not used to generate this TIN (only ADCP data).

4 RESULTS

4.1 *Channel Bathymetry*

The Bulu reach of the lower Congo is one of the deepest documented sections of river in the world. Within this reach, the channel flows through two 180 degree bends linked by a short, straight section (Figure 2). The channel is highly constricted in places and undergoes rapid changes in direction in response to the variable bedrock bathymetry. Entering the first bend at Bulu, the channel aspect ratio (width divided by mean depth) is 13.3 and becomes even smaller (approx. 5.2) toward the apex of the first bend as the channel width decreases and the maximum depth increases to approximately 120 m (see Figure 3). A large bar-like feature at the outside of the bend constricts the flow at the apex. At the apex of the bend, a deep pool exists which shallows in the downstream direction before reaching a series of three rapids in the exit to the bend.

Entering the second bend, the flow bends sharply northwest creating an area of flow separation formed by a high-flow cutoff on the left bank. The channel is narrow (aspect ratio 5.11) and steep (bed slope 8.5%) here as it falls into a circular pool that is 160 m deep (Figure 4). The TIN shown in Figure 4 was created from approximately 26,000 soundings from ADCP beam depths collected during 67 transects. As the river exits the pool near the apex of the bend, it shallows slightly (to 140 m deep) and constricts to 300 m wide.

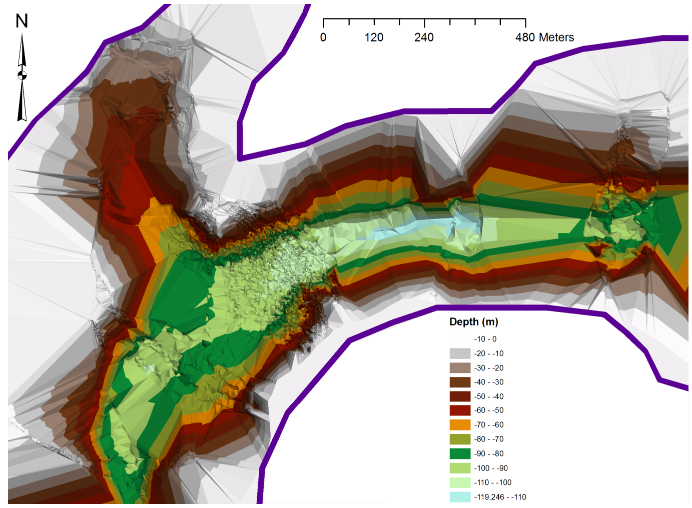

Figure 3. Bathymetry of bend 1 in the lower Congo River at Bulu, July 2008.

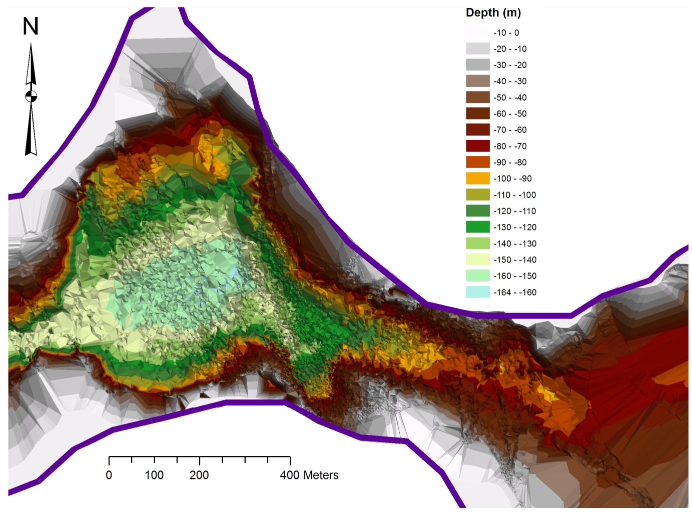

Figure 4. Bathymetry of pool in the lower Congo River at bend 2 near Bulu, July 2008.

4.2 *Hydrodynamics*

Entering the first bend at Bulu, the flow is uniformly distributed across the channel with depth-averaged flow velocities near 2.5 m/s and high velocity gradients near the banks (Figure 5). The hydrodynamics are dominated by a large primary velocity core (primary velocity is defined by the direction of dominant discharge and zero net cross-stream discharge; see Lane et al. 2000) centered in the channel throughout the bend. Depth-averaged flow velocities exceed 4 m/s for individual profiles in cross section 1 (Figures 5 and 6) as the flow converges nearing the apex of the bend.

Approximately 1 km before the apex of the bend, flow separation on the inside of the bend is well-defined and persists throughout the bend, sometimes occupying as much as 40% of the channel width (Figure 5). Examination of individual transects and depth-averaged velocities shows a zone of flow separation at the inside of the bend, which is bounded by a shear layer with high velocity gradients, large vortices and turbulent structures, and significant recirculation with upstream velocities that can exceed 2 m/s (Figure 6). Within the primary velocity core and recirculation zone, the secondary flow velocities near the bed can exceed 2 m/s and vertical velocities can reach 1 m/s.

Secondary flow structures appear to be persistent. Upstream from the apex of bend 1, secondary flow structures generally consist of a clockwise cell within the recirculation on the left (inside) bank and one or more cells on the right (outside) bank (Figure 6). These cells flank the primary velocity core

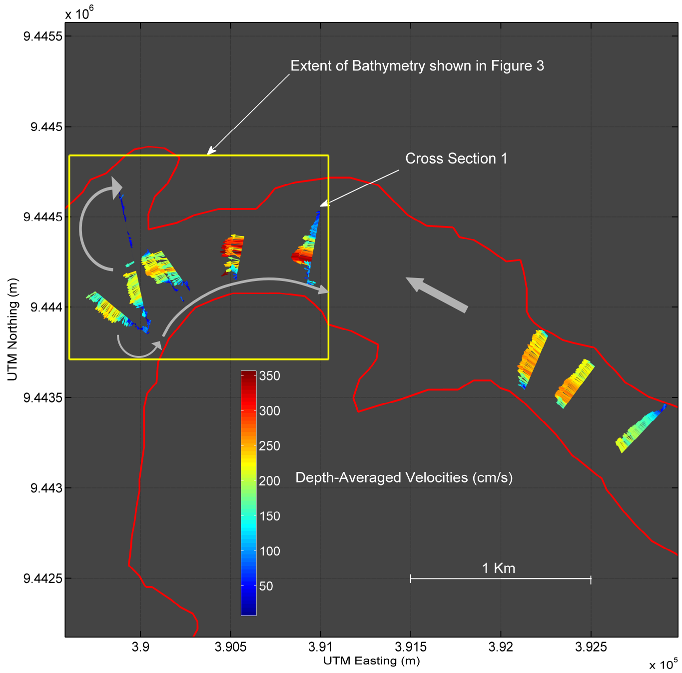

Figure 5. Depth-averaged flow velocity in the lower Congo River bend 2 near Bulu.

which is descending in the water column in response to the increasing channel depth, creating downwelling on its flanks. Downstream from the bend apex, the flow diverges due to a sudden channel expansion, with the shear layer on the inside of the bend denoting the boundary between the diverging cells. A second large zone of recirculation is formed in the lee of the bar-like feature on the outside of the bend just past the apex.

As the flow enters bend 2 at Bulu, the flow rapidly accelerates as it turns northwest and plunges approximately 100 m into a deep pool (Figure 7). Depth-averaged flow velocities can exceed 4 m/s within the second bend; however, the depth-

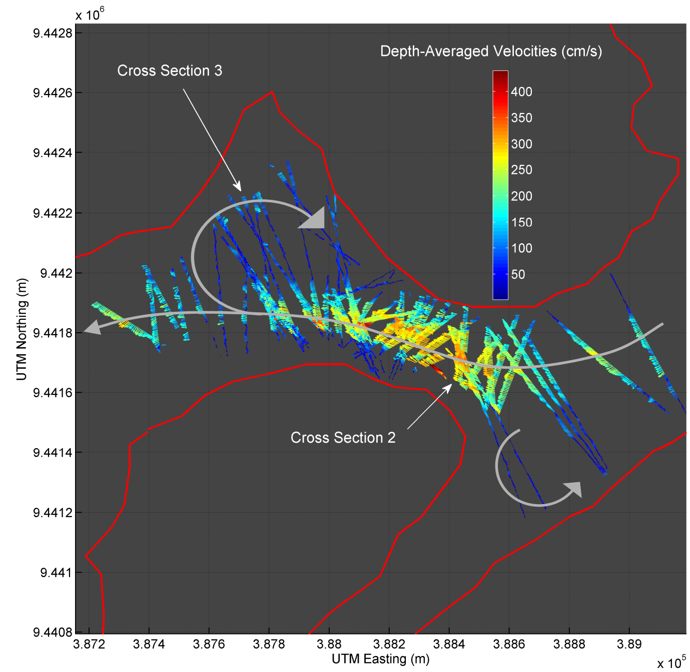

Figure 7. Depth-averaged velocities for selected transects in bend 2 of the lower Congo River near Bulu.

averaged flow velocity is generally around 3 m/s entering bend 2. Within the pool, the depth-averaged flow velocity decreases considerably. It is important to note that within the pool, high velocity cores exist with velocities that can exceed 5 m/s at depths of 100 m or more as the primary velocity core plunges into the pool. This results in layer-averaged flow velocities below 100 m depth that typically exceed 1.5 m/s and can be as high as 4.5 m/s.

Plunging flow in bend 2 generates flow separation on both banks and secondary flow cells that drive upwelling on the banks and downwelling at the shear layer (Figure 8). The secondary flows can be sufficient at the banks for sediment suspension.

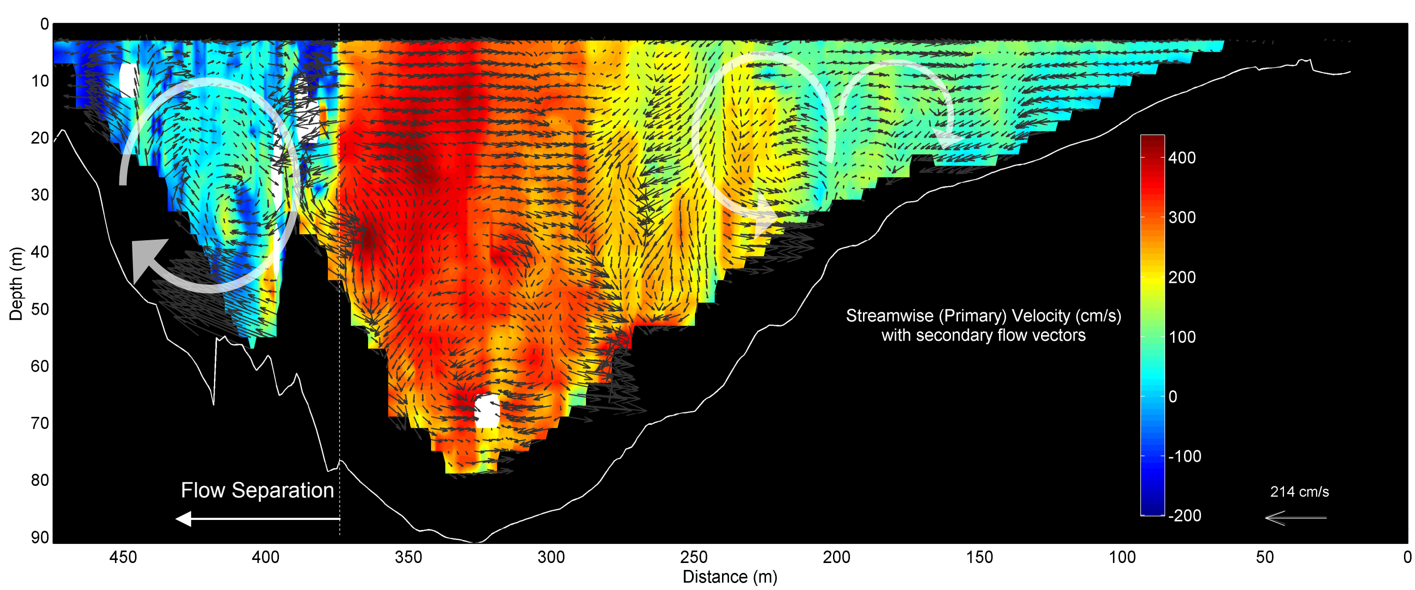

Figure 6. Primary and secondary velocities for cross section 1 in bend 1 in the Bulu reach of the lower Congo River. Primary velocities are shown as a color contour, secondary velocities (including the vertical component) are shown as flow vectors. The flow field is an average of three repeated transects looking downstream. Missing data due often to intense turbulence is denoted by white interior cells and black edge cells. Side-lobe interference limits the data acquisition close to the bed (6% of the depth of the shallowest beam). The white line denotes the channel bed.

Figure 8 shows a significant increase in acoustic backscatter (associated with suspended sediment) that is highly correlated with secondary flow vectors. Within the pool, maximum secondary velocities exceeded 3 m/s and maximum vertical velocities exceeded 1 m/s. The pool displays coherent structures that can span the full 160 m depth (Figure 9). Large, persistent cells of upwelling and downwelling coexist with turbulence and vertical jets that rapidly transport water between the benthic zone and the surface (Figure 9). Depth-averaged vertical velocities exceed 75 cm/s as plunging flow from the southeast corner of the pool is met with upwelling flow in the northwest corner of the pool as the water rapidly ascends in response to the change in the bathymetry at the walls of the pool (Figure 10). In general, downwelling occurs within the center of the channel with upwelling near the banks.

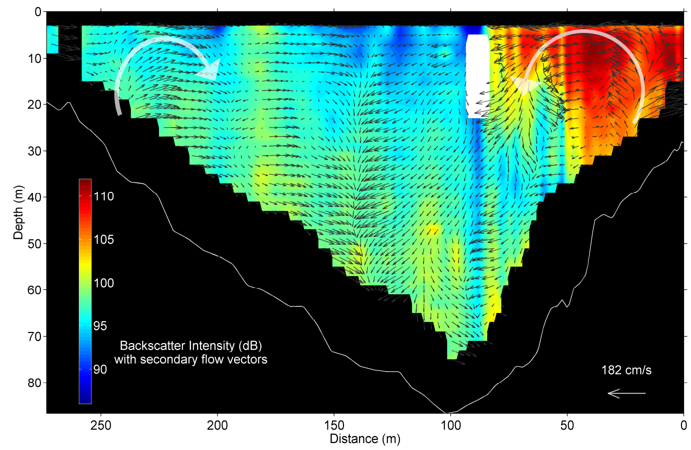

Figure 8. Acoustic backscatter and secondary velocities for cross section 2 in bend 2 in the Bulu reach of the lower Congo River. Acoustic backscatter is shown as a color contour, secondary velocities as flow vectors.

5 CONCLUSIONS

The lower Congo drainage basin and channel morphology are controlled by the uplift of the Pre-Cambrian Crystal Mountains. The Bulu reach, with its two distinct bends and narrow constrictions, is a prime example of the tortuous route this massive river must take in its final dash for the Atlantic Ocean.

The highly dynamic flow and extreme depths of the Bulu reach of the lower Congo River generate an array of flow regimes and environments for aquatic species. Regions of low flow velocity created by flow separation near the banks throughout these

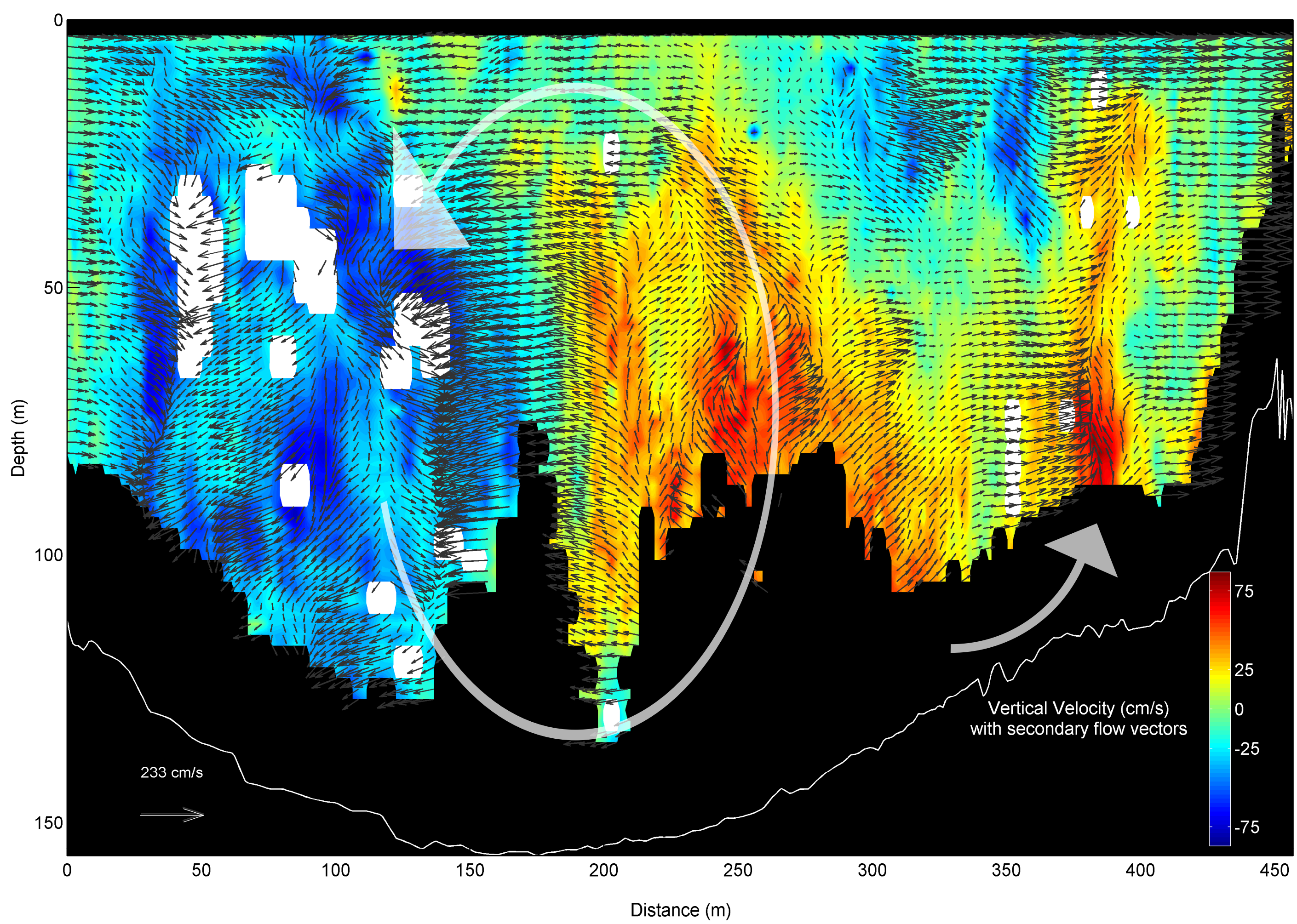

Figure 9. Vertical and secondary velocities for cross section 3 in bend 2 in the Bulu reach of the lower Congo River. Vertical velocities are shown as a color contour, secondary velocities as flow vectors. Missing data due often to intense turbulence is denoted by white interior cells and black edge cells. Side-lobe interference limits the data acquisition close to the bed (6% of the depth of the shallowest beam). The white line denotes the channel bed.

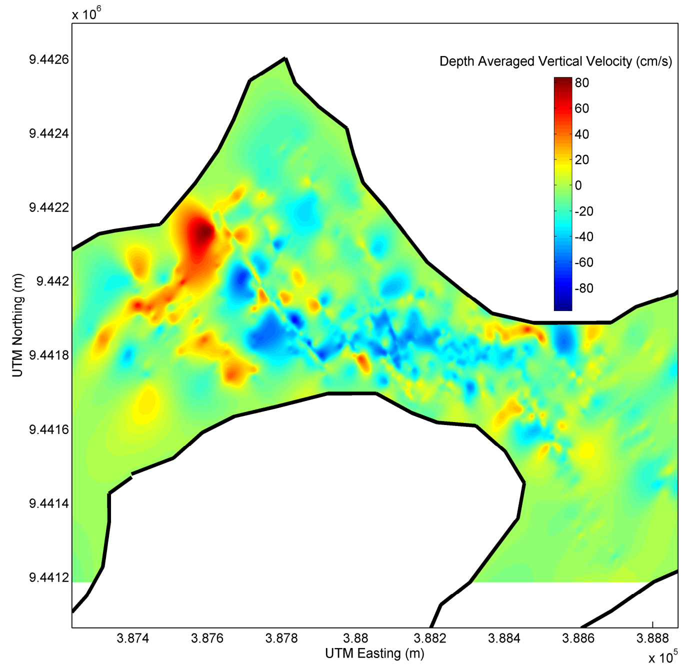

Figure 10. Depth-averaged vertical velocity for bend 2 of the Bulu reach of the lower Congo River.

bends are isolated from the opposite bank and from other recirculation zones on the same bank by swift moving water. Away from the bends, the swift downstream flow occupies almost the entire cross section of the river channel and pinches off the recirculation zones. Species unable to navigate high velocity currents (> 2 m/s) may be unable to leave these recirculation zones. Unlike single thread alluvial rivers that may display bank-to-bank cross-channel secondary circulation cells in bends, the Bulu reach of the lower Congo River shows no evidence of coherent circulation structures that span the channel width. Instead, the discrete cells are formed on either side of the primary velocity core limiting bank-to-bank transport.

The near-bed environment seems to present little shelter for organisms as the primary velocity core appears to extend close to the bed and near-bed turbulence can be high (given by the lack of correlation resulting in missing ADCP data). Within the pool at bend 2, velocity maxima for a cross section often occur nearer to the bed than the surface. In addition to very strong primary (streamwise) velocities, organisms in this reach have to cope with continuous turbulent and secondary flow cells that can rapidly transfer water (and sediment) from the bed to the surface. Fortunately, the large downwelling structures, vortices and continuous turbulence present in both bends should be capable of transporting oxygen-rich surface water and organic matter to the benthic zone, thus sustaining bottom-dwelling species.

This paper presents a first look at the Bulu reach of the lower Congo River. If possible, future work will involve a more rigorous analysis of the data including (where possible) a layer-by-layer analysis of the velocity field (rather than depth-averaged), quantification of the intensity and spatial distribution of turbulence, computation of bed shear stress, and recomputation and analysis of secondary flows using the Rozovskii method (see Lane et al. 2000). In order to allow for a more accurate and complete velocity mapping survey, future field work on the lower Congo should: 1) perform repeated transects at every cross section, 2) maintain boat position along a planned line and minimize lateral deviation off the line, 3) mount the ADCP to the manned boat allowing for deeper draft to minimize missing data due to air entrainment under the transducers in turbulent water, and 4) make (if possible) stationary measurements at a site to capture the temporal variability of the flow.

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