New Measurements of Water Dynamics and Sediment Transport along the Middle Reach of the Congo River and the Kasai Tributary

Raphael M. Tshimanga[1], Mark A. Trigg[2], Jeff Neal[3], Preksides Ndomba[4], Denis A. Hughes[5], Andrew B. Carr[2], Pierre M. Kabuya[1,2], Gode B. Bola[1], Catherine A. Mushi[4], Jules T. Beya[1], Felly K. Ngandu[1], Gabriel M. Mokango[6], Felix. Mtalo[4], and Paul Bates[3]

[1]*Congo Basin Water Resources Research Center – CRREBaC & Department of Natural Resources Management, University of Kinshasa, DR Congo,*
[2]*School of Civil Engineering, University of Leeds, UK.*
[3]*School of georgraphical sciences, Bristol Uiversity, UK,*
[4]*Department of Water Resources Engineering, Dar es Salaam University, Tanzania,*
[5]*Institute for Water Research, Rhodes University, South Africa,*
[6]*Regie des Voies Fluviales – RVF, Kinshasa, DR Congo*

ABSTRACT

The Congo River provides potential for socio-economic growth at the regional scale, but with limited information on the river dynamics it is difficult for basin countries to benefit from this potential, and to invest in the development of water resources. In recent years, the number of hazards related to navigation and flooding has sharply increased, resulting in high loss of human lives as well as economic losses. Associated problems of river management in the Congo also include inefficiency in hydropower production, an increase in rate of river sedimentation and land use changes. Accurate information is needed to support adequate management strategies such as prediction of navigation water levels and sediment movement, and assessment of environmental impacts and engineering implications of water resources infrastructure. Modelling approaches and space observations have been used to understand the Congo River dynamics, but their effective application has proved difficult due to a lack of ground-based observational data for validation. Recent developments in data capture with acoustic Doppler technologies have considerably improved measurements of river dynamics. As well measuring river discharge, they also allow the analysis of the multiple hydrodynamic features occurring in fluvial systems. This paper presents the results of field measurement campaigns carried out in the middle reach of the Congo River and the Kasai tributary using state of the art measurement technology (ADCP, Sonar, GNSS) for investigation of large rivers. The measurements relate to river flow at multiple transects, river bathymetry, static and continuous water surface elevation, and targeted sediment sampling along the river. The paper provides a descriptive summary of the measurement results, a discussion on the application and performance of the equipment used in the Congo River, and lessons for future use of this equipment for measurements of large rivers in a data scarce environment such as the Congo Basin.

Keywords: Accoustic Doppler technolgy, Hydrodynamics, Discharge, Field measurment, Large rivers, River bathymetry, Sediment transport, Water surface elevation.

1. Introduction

The value of observations from experimental research and field data has been recognized and implicitly accepted in the development of the qualitative understanding of water resources systems and the dominant processes of the river dynamics (Clark et al., 2011). Building this understanding remains a challenge in large river basins such as the Congo, where experimental research is hindered by problems related to scales, costs, expertise, complexity of natural processes and the remoteness of the basin. These issues partly contributed to this complex hydro-system to remain largely understudied. In addition, governments of the countries of the Congo River Basin (CRB) did not prioritize assessment of water resources, partly due to a relatively low pressure of water scarcity, but also because of a widely spread belief that abundant water resources do not require management. However, the current context of global environmental change and the pressing needs for water resources management that include the quantification of current and future supplies and demands under non stationary conditions has rung a bell for scientific investigations to enable prediction and improve water resources management practices in the CRB (Tshimanga et al., 2020, this issue). The advent of the Integrated Water Resources Management concept also laid down a foundation for the implementation of many regional River Basin Organizations, which have been instrumental to increase awareness about water resources management and development in the CRB. Despite the current increased level of awareness about water resources issues in the basin, scientific knowledge gap remains critical, and a great deal of effort is required to advance scientific knowledge and avail adequate information at the appropriate scales of prediction and management. With limited information on Congo River dynamics, it is difficult to realize the optimal benefit of the Congo River's potential, and equally difficult to invest for the development of water resources (Trigg &Tshimanga, 2020).

Trigg et al. (2020, this issue) report a population number of 100 million (2015 estimates) in the CRB, including the nine riparian countries, out of which 83 million live within 50 km of a major river, and 33 million within 50 km of a navigable river. Due to difficulty of maintaining road infrastructure, the majority of the population relies on river navigation for the exchange of goods and services. In recent years, the number of hazards related to river navigation and floods has sharply increased, resulting in high loss of lives as well as economic losses (Tshimanga et al., 2016). Statistics on river navigation report a death toll of about 2,000 persons per year, due to river accidents and incidents (CICOS, 2012). Associated problems of river management in the CRB also include inefficiency in hydropower production, an increase in rate of river sedimentation and land use changes. Accurate information is needed to provide adequate management strategies such as prediction of navigation water levels and sediment movement, and assessment of the environmental impacts and engineering implications of water resources infrastructure. Alsdorf et al. (2016) points to a number of hypotheses for research and discovery in the Congo Basin, and for which direct river measurements such as flow distribution, water surface slopes, river bathymetry and connectivity with floodplains will be relevant. Trigg and Tshimanga (2020) advocate that the use of easily accessible global datasets and models is essential for science research in the region, given the vast scale of the basin and the data availability challenges. Several modelling approaches as well as experiments from space observation have been developed to understand Congo River dynamics, but their effective application has proven difficult due to a lack of observational ground-based data that could be used in the validation process. Recent developments in data capture with the evolution of the acoustic Doppler technologies have considerably improved measurements of river dynamics. The current use of the acoustic Doppler technologies such as Acoustic Doppler Current Profilers (ADCPs) is not only limited to the assessment of river discharge, but also the analysis of the multiple hydrodynamic features occurring in fluvial systems (Tomas et al., 2016). While these relatively new technologies provide an unprecedented opportunity for detailed quantification of fluvial processes in large rivers, their application to the Congo River has been limited due to the reasons mentioned above (Jason et al., 2009). This paper presents the results of field measurement campaigns carried out in the middle reach of the Congo River and the Kasai tributary as part of the Congo River Hydraulics and Morphology (CRuHM) project (see Trigg et al., 2020 for details). The project campaigns used state of the art technology (ADCP, Sonar, GNSS) for the investigation of large rivers. The paper discusses the performance of the application of this equipment in the Congo River and also provides lessons for future use of this equipment for large scale measurement of large rivers in data scarce environments such as the CRB. The data produced in this study are available on request at the Congo Basin Water Resources Research Center (CRREBaC, www.crrebac.org).

2. Study reach and reconnaissance survey

A general description of the main course of the Congo River includes an upper reach that starts from the Katanga Plateaus until the Boyoma Falls at Kisangani, where the basin area covers about 960,000 km^2. This is followed by the middle reach that encompasses the region between the cities of Kisangani and Kinshasa, providing a cumulative basin area of about 3.6 M km^2. Finally, there is the lower reach that extends to the outlet of the Congo River, the Atlantic Ocean, making a cumulative basin area of 3.7 M km^2. Figure 1 illustrates the main hydrographic features of the CRB. The river that starts its main course from the Katanga plateaus runs over a distance of 4,700 km before discharging its average annual flow rate of about 41, 000 m^3 s^{-1} into the Atlantic Ocean. From Katanga, the river marks its course by first taking the direction towards north, then west and south, thus forming an arc that crosses the Equator twice as it traverses a vast swampy basin of the *Cuvette Centrale*, a shallow depression along the Equator in the CRB.

The upper course of the Congo River is also known as the Lualaba River where it crosses swampy areas and rapids until it reaches the Boyoma Falls at Kisangani, where the River takes its name of Congo. Through its middle course from Boyoma Falls to Malebo Pool at Kinshasa, the river drops only 115 m over 1740 km as it crosses the *Cuvette Centrale* (Hughes & Hughes, 1992). This depression results in a river that is multi-channeled, up to 10 km wide, and only between 5 and 10 m deep for much of the reach (Trigg &Tshimanga, 2020). The river system throughout the *Cuvette Centrale* is characterized by large wetlands and floodplains that hold rich endemic aquatic and terrestrial biodiversity. The water course in this area has many of the characteristics of a lacustrine environment, many of the islands are partially or fully inundated at periods of high water. Behind the river bank levees, permanent and periodically inundated swamp forests extend for distances of up to 35 km on either side of the rivers on continuous alluvial tracts (Campbel, 2005). The most extensive peatland complex in the tropics that store carbon, known to be equivalent to the carbon stored in the entirety of above-ground rainforest biomass, has been recently been discovered in the forests of the *Cuvette Centrale* (Dargie et al., 2017). In addition, the forest hydrology of the *Cuvette Centrale* plays a key role in sustaining the continental air moisture circulation (Spracklen et al., 2012).

The major tributaries that join the Congo River in its middle course, from upstream to downstream, are known as the Lindji, Awuruwimi, Lomami, Lulonga, Ruki, Oubangi, Sangha, Alima, and Kasai Rivers. The Oubangui joins the Congo River opposite Lake Tumba, almost on the Equator, where swamps are most extensive. From Tshumbiri (255 km from Kinshasa) the river course enters a 220 km stretch known as the *Chenal*. In this section, the channel is confined to low hills and narrow channels, and is 900-1,600 m wide with depths up to some 40 m. In this section the flow velocities are higher than those observed from the upstream part of the main stem. A circular riverine water body, the Malebo Pool, marks the end of the *Chenal* before the Congo River enters its lower part downstream of Kinshasa. Only two streamflow monitoring stations are operational along the middle reach of the Congo River: the Kisangani and Kinshasa/Brazzaville stations. Due to the difficulty of maintaining road infrastructure in this tropical environment, these river reaches provide the main navigation corridors for the transport of goods and exchange of services between the countries of the Congo Basin, but also, they have been used since the colonial era for international trade.

The present study consists of field measurements carried out along the middle reach of the Congo River, between the cities of Kinshasa and Kisangani, over a distance of 1,734 km. The measurements were also extended to some important adjacent tributaries along the Congo River main stem to assess their immediate contribution to flow in the main channel. The Kutumuke site in the Kasai tributary was also surveyed for continuous monitoring of flows and sediments. Figure 2 shows the course of the Congo River between Kinshasa and Kisangani and the sites where measurments were carried out. From 2017 to 2019, multiple fieldwork campaigns were carried out in the middle reach of the Congo River and some of its tributaries, mostly between June and August, which matches the low flow season. These fieldwork campaigns where achieved under the CRuHM project, a research and capacity building initiative funded under the Royal Society -DFID Africa capacity building facility. The types of measurements carried out included river channel cross sectional velocity distribution and discharge measurements, river bathymetry, continuous water surface elevation over time and static water surface elevations at specific locations. Two main phases were essential for these measurements, the first took place between July to August 2017 and covered the main stem of the Congo River between Kinshasa and Mbandaka (700 km), and the Kasai tributary at Kutumuke site; the second phase involved fieldwork measurements over 1734 km between Kisangani and Kinshasa from July to August 2019. The fieldwork campaigns were carried out by researchers from the Universities of Kinshasa in the Democratic Republic of Congo, Dar es Salaam in Tanzania, Rhodes in South African, and Bristol and Leeds in the United Kingdom. Based on a Memorandum of Understating between the Congo Basin Water Resources Research Center (CRREBaC) of the University of Kinshasa and the Congo River Navigation Authority (RVF), expertise from both organizations were utilized during the fieldwork campaigns.

3. Materials and Methods

Recent developments in the measurement of river dynamics involve application of acoustic Doppler technologies necessary to analyze the entirety of hydrodynamic features occurring in fluvial systems. Some of these instruments have been acquired under the CRuHM initiative and used for the field measurements. Measurement technologies used include:

- An Acoustic Doppler Current Profiler (ADCP, Teledyne RiverRay, 600 kHz) which is a device designed to calculate the hydraulic characteristics of rivers using the Doppler effect of acoustic waves scattered back from particles within the water column;
- A Global Navigation Satellite System (GNSS-Trimble, R10) used to take the elevations of water bodies needed to calculate hydraulic gradients and approximate flood levels using the convergence of a required number of satellites;
- A Garmin echosounder (GT22) used to determine the depths and shapes of the riverbed based on the acoustic wave principle;
- Automatic Water Level Recorders (Heron pressure loggers) that were installed at specific sections to collect water level variations continuously, at hourly intervals;
- Automatic sediment sampler (ISCO) installed at Kutumuke, on the Kasai tributary.

3.1 ADCP measurement

Hydrodynamic characteristics such as wetted perimeter, hydraulic depths, velocity distribution and discharges are relevant for studies involving the design and planning of hydraulic structures, sediment transport, habitat restoration, and for supporting numerical simulations. ADCP has the ability to measure a number of these hydrodynamic characteristics accurately with high resolution (cm scale). Besides the depth and velocity components, additional data inherent to the acoustic measuring method can be analyzed, such as the backscatter intensity and velocity standard deviation, suspended sediment transport analysis, and turbulence quantities (Tomas et al., 2018). ADCP measurements in this study were carried using the latest ADCP RiverRay, acquired under the CRuHM initiative. The RiverRay transducer uses a frequency of 600 kHz, has a blank zone of 16 cm, minimum depth cell size of 10 cm, and maximum profiling depth of 60 m. The ADCP measurements followed the moving boat procedure (TRDI, 2017), therefore a manned boat equipped with an outboard motor, was used for ADCP surveys. The advancement in the field of the acoustic Doppler technology has also called for a push on the development of data processing and analysis tools that are made open source domain. In this study, we used WinRiver II software (TRDI, 2017) to calibrate and run in real time the ADCP RiverRay 600 kHz during data collection and for data processing. The ADCP was mounted on one side of the boat and for most of time coupled with sonar attached on the other side of the boat. It is a standard procedure for the sonar to be utilized alongside the ADCP device during discharge measurements. The river channel transects recorded by each device were verified as being the same and thus provided some assurance that each device was working correctly. Figure 3 shows an excerpt of one of the longest ADCP transects carried out (3 km) with the WinRiver II software. The real time ADCP recording based on the WinRiver interface also allows evaluation of uncertainties during measurements, e.g. heading, pitch, roll, lost and bad ensembles, ship track and directional bias, beam intensity profile in the water column, and boat-water speed ratio. Transects were carried out for 29 cross sections along the middle reach of Congo River between 2017 and 2019 (Table 1). The measurements targeted both single and multi-thread channel styles in the middle reach of the Congo River. Measurements at multi-thread channels involved cross sections at each of the channel segments to record the river characteristics across the whole width of the channel style (Figure 4). In many cases, boat speed slightly above the water speed was considered to have negligible influence on the measurements.

Due to larger cross section widths, most of which extended over 1 km, repeat measurements were limited to two transects per cross section. However, some more transects were recommended at locations where high variance was observed between two transects. Standard procedures for ADCP measurement with moving boat require that the operator strikes a balance of the ratio boat speed-water speed, while maintaining a straight line of the ship track for measurement. While all the necessary effort was made to stick to this procedure, it should be mentioned here that the task was not that easy given flow current that could drift the boat downstream (distorting the ship track alignment) , the large section to be surveyed and the wind effect over the large channels. In many cases, boat speed slightly above the water speed was considered to have negligible influence on the measurement and was often required to maintain as close to perpendicular track as possible.

3.2 Water surface elevation

Precise measurement of elevation is not straightforward in the CRB due to the absence of cellular networks and sparsity of benchmark elevation references in the region. Fortunately, specialist surveying technologies for data-sparse applications such as Precise Point Positioning (PPP) are now widely practicable. The PPP technology used in the field campaign processes measurements from a single surveying instrument, using detailed physical models and corrections, and precise GNSS orbit and clock products computed beforehand (e.g. Samper & Merino, 2013). Importantly, PPP differs from other precise-positioning approaches like Real Time Kinematic (RTK) in that no reference stations are needed in the vicinity of the user; rather it obtains all its correction information from either the internet or a dedicated satellite. A GNSS - Trimble R10 instrument was purchased under the CRuHM initiative and used in the field campaigns, which minimizes convergence timescales to approximately 30 – 60 minutes by receiving positional information from multiple global navigation satellite systems (GNSS). The instrument was complemented with the Trimble CenterPoint RTX correction service, which provides the instrument with correction information from a dedicated satellite, enabling processed results to be obtained in the field. Thus, there is no requirement for an internet connection in order to obtain results, which is crucial for fieldwork in the Congo Basin.

Trimble (2019) reports that the RTX CenterPoint correction service has a vertical accuracy of 5 cm Root Mean Square Error (RMSE). This represents a significant improvement on the accuracy of existing satellite altimetry derived WSE datasets such as Envisat, which has a reported accuracy for large rivers of 28 cm (Frappart et al., 2006). The GNSS instrument can therefore provide WSE measurements with unprecedented accuracy. A useful comparison can be made here with NASA's planned Surface Water and Ocean Topography (SWOT) mission science requirements: accurate WSS slope measurement is one of the key aims of the SWOT mission, and is required to do so with an accuracy of 1.7cm/km over a 10km long river reach (Biancamaria et al., 2016; Desai, 2018). In comparison, a pair of WSEs 10 km apart measured with the RMSE of 5cm utilized in this field campaign produces a measured WSS with a RMSE equal to the sum of the WSE measurement errors divided by the reach length, which computes to 1 cm/km. To measure WSE along the middle reach of the Congo, the GNSS instrument was deployed at designated shoreline locations. The instrument was set up to converge on a tripod directly over water if access permitted, otherwise it was set up to converge on land then transferred to a detail pole which was positioned over water. Where possible, flood levels were also measured from wrack marks and with advice from local communities. Measurement precision was checked by measuring the elevation of an historic benchmark structure multiple times over a three-day period, which gave a standard deviation of 3.4 cm. Additional checks were carried out by taking multiple measurements at each measurement location and computing their standard deviations, which were no greater than 6.4 cm.

In addition to measuring WSE at shorelines, whilst of the fieldwork boat, efforts were made to acquire additional measurements on the boat whilst navigating, in order to reduce the number of boat stopping points required, and increase the spatial density of the WSE measurements. This entailed setting up the GNSS instrument attached to the boat to operate in a continuous measurement mode whereby it measures elevation at set distance intervals. In 2017, we tried collection of a continuous water surface profile using the Trimble GNSS set up on the roof of the boat, these efforts were mostly unsuccessful because the pitching and rolling movements of the boat were too severe and caused the instrument to lose its convergence. Ultimately, only one 50 km long reach was successfully measured in this way.

In 2019, we repeated the procedure, but in this case using a large barge which provided much more stability to the GNSS instrument set up. The procedure was very successful, although whether this was due to a firmware update the Trimble had this year or the more stable barge platform, this should be investigated. WSE data were therefore collected continuously at intervals of every 50m for most of the middle reach of the Congo River between Kisangani and Kinshasa in 2019. Figure 5 shows the use of GNSS-Trimble instrument for both static and continuous measurements.

3.3 River bathymetry

River depth measurements were made using two Garmin GT22 single beam sonar echo sounders that provided a spatial coverage density of approximately 2 m distance interval between measurements. Each of the sonar devices comprises a transducer and a display. The transducers were fixed to the sides of the boats via metal brackets, away from any turbulence associated with the engines that were located at the rear of the boats. One sonar was installed on the main boat and measured depth whenever the boat was travelling. The main boat followed the established navigation route, and in accordance with the rules set out by the captain, did not deviate from this route. Therefore, the resulting sonar measurement track generally follows the stream-wise direction, covers only one channel thread, and does not provide cross sectional coverage, but does represent well the navigation channel. The other sonar was installed on the canoe (small power boat) and used at designated locations to survey cross sections and more detailed bathymetry. Specifically, it was used to survey a series of channel threads along a designated high-resolution study reach (chainage 480 – 550 km) and was also deployed during all ADCP measurements to verify the sonar and ADCP depth measurements were in agreement. The sonars were validated by comparison of all crossover points where depth was measured twice within 5m horizontally, which gave a standard deviation of 0.34 m or 8%. All sonar measurements of depth were converted to bed elevation values by subtracting them from local WSEs that were derived by linearly interpolating the GNSS WSE measurements. The primary purpose of the sonar was to obtain river bathymetry, but the live imagery recorded by the device provided a second dataset that captures morphological processes such as the flow of bed load sediment and the geometry of dune systems.

3.4 Automatic water level loggers

Water Lever Loggers (WLL) are automatic devices that record real time water level variation at a specific location via pressure changes. Data recorded from these devices may assist in developing hydrodynamic models necessary to understand one of the major domains of hydrological complexity that involves interaction between river channels and wetlands in the CRB (Kabuya et al., 2020). The installation of the WLL was carried out in several steps, including site identification, construction of concrete structures and installation of the sensors. The latter requires determination of datum point, height below the datum point, and determination of WLL installation parameters. The main parameters include depth from the river bed to the bottom of the housing pipe, depth from the bottom of the housing pipe to the transducer, depth from the tip of the transducer to the top of the pipe , height of the pipe, initial installation water level height above the tip of the transducer, initial flow depth from the bottom of the housing pipe to the surface of water, and elevation of the top of the pipe. The main characteristics related to the site identification include a suitable site that is able to contain flow during low and high flows, visibility of the site to public to avoid vandalism, presence of a stable structure to which the water level logger housing pipe is attached (such structures can be a steel stake on river bedrock stabilized with concrete, a timber construction on river bedrock stabilized with concrete or we can take advantage of trees that have grown up on rocky river banks, or existing shipping structure adjacent to the river). During the first campaign of the fieldwork in 2017, a number of wooden structures were implemented along the Congo main stem to house the WLL devices. However, it came to be understood that many of these wooden structures faced damages from navigation traffic and strong currents during high flows along the main channel. It was then resolved during the successive fieldwork campaigns to replace the wood by concrete structures with the ability to resist traffic and strong flow current. Figure 6 and Table 2 show the design and configuration types for a WLL installed in the N'Sele River near the city Kinshasa. A datum point is a fixed known point that is used in the setting up process of a water level logger. We assigned an elevation value to this point using the GNSS and laser distance measuring instrument (Disto). GNSS provides the elevation of a particular point (temporary benchmark) and this information has been projected through the Disto to the point that we used as our datum point, which in this process is the top of the water level logger housing pipe. The height below the datum point is a measured value from the zero point of a water logger to the datum point used. This information is useful as it helps in the conversion process of the measured water height into water elevation. During the installation process, the height of water above the tip of the logger is important information that we measured *in situ* as it helps to validate the data recorded by the logger. This information is collected during the installation of a water level logger (for calibration) and every time the data are downloaded (for validation). The water level device provides a range of recording time steps, and in this the installation we used an hourly time step to record water level variation. Table 3 shows the location of the WLL implemented in the CRB.

3.5 Sediment sampling

Common practices of land use change in the CRB induce the generation of huge volumes of sediment into the river networks, with significant implications on water quality, river navigation routes, operation of hydraulic infrastructure, and aquatic habitats. The component of sediment measurement in this study involved sampling of suspended sediment, bedload, and soil sampling on the stream banks and floodplains at multiple locations of interest along the middle reach. The measurements also involved implementation of a site for continuous sediment sampling using an Integrated Sediment Sampling-ISCO at Kutumuke in Kasai (Mushi et al. 2020, this issue). This paper only reports on the suspended sediment sampling carried out along the middle channel of the Congo River during August 2019, while the other measurement of sediments including bedload, coring and soil profiles that were carried out along the middle channel and the Kasai tributary in 2017 are reported in Mushi et al. (2018) and Mushi et al. (2020, this issue). The initial sediment sampling plan was set to collect sediments at different depths of the water column using Van Dorn sampler and the sediment pump equipment. However, the implementation of this initial plan was challenged with unsuccessful field operation of the above-mentioned devices (strong currents and lost parts), which could therefore not be used as planned. This meant that it was only possible to take surface samples (arm length depth). While not ideal, they still provide a useful measurement, especially as we took them at multiple sites across each section. Three 600 ml sample bottles were filled for each location and depth. This was to allow plenty of sample volume for laboratory processing at the University of Kinshasa. Overall, 51 samples were collected along the route (Table 4). The laboratory analysis consisted of the determination of total suspended sediment (TSS) and the organic matter (OM), both obtained according to the procedures described in ''Standards Methods for Examination of Water and Waste Water" (APHA et al., 1992). According to Ndomba (2012), the total suspended load is obtained by the product of the mean concentration and the flow rate obtained in a given section. This method was used to express the total suspended matter passing through a section at a given time, as well as the organic matter obtained from the analysis of the same sample. The sediment yield is calculated by estimating the amount of mg per liter of both suspended sediment and organic matter contained in a water column sample, representative of the section. After preparation, the sample is poured into a funnel, then filtered by means of an air pump through a filter paper previously weighed on a precision balance of three digits after the decimal point and placed in a funnel fixed on a volumetric container. In this study, each filter paper was provided with the pores of 65 micro-meters. After filtration, the filter paper was placed in an oven at a temperature of 105° C for 24 hours. After leaving the oven, the paper is kept in a desiccator and then weighed again after filtration. The weight in excess of that which was initially weighed before heating is that of the total suspended sediment (TSS) and the formula used to make computation was:

$$\mathrm{TSS} = \frac{(P2 - P1) * 1000000}{Vol}$$

Where:

- TSS: Total suspended sediment
- P1(g): the weight of dry filter paper
- P2(g): the weight of filter paper + residue after filtering and evaporating at (105°)
- Vol(ml): volume of sample used to filter

Similarly, for organic matter (OM), a precise volume of water samples is poured into a porcelain crucible that has been duly weighed. The crucible is then placed in the oven heated to 105 ° C for 24 hours, after leaving the oven, the crucible is weighed again and then placed in an oven and heated to 550 ° C for 20 minutes and then cooled and weighed for a final time. The formula for the calculation of OM was as follow:

$$OM = \frac{P2 - P3 * 1000000}{Vol}$$

Where:

- P1(g) : weight of crucible before poured a volume of sample
- P2(g) : weight of crucible with residue after ignition at 105°
- P3(g) : weight of crucible with residue after ignition at 505° in oven
- Vol(ml): volume of sample poured in the crucible

4. Results and Discussion

In summary, the results of the fieldwork campaigns undertaken along the main stem of the Congo River and some of its adjacent tributaries consisted of the following:

- Discharge measurements, including river channel cross sectional velocity profiles using an ADCP;
- Single point WSE from GNSS Receivers at regular intervals along the Congo River;
- Continuous WSE while travelling using the GNSS Receiver setup on the barge;
- River channel bathymetry using sonar;
- Suspended sediment samples;
- Continuous water level variation at specific locations using water level loggers;
- Accounts from interviews with river users.

The following sections provide a descriptive analysis of the data collected for the various measurements. The Velocity Mapping Toolbox (VTM), a Matlab-based software, was used to process and analyze data recorded from the field collected using the ADCP (Parsons et al., 2013). Flow maps of primary and secondary velocities from one or more transects at a site can be generated using the VMT. In the VMT, backscatter and secondary velocity data can be integrated on the same plot, allowing the visualization of apparent sediment transport.

4.1 Hydraulic characteristics and flow distribution along the main river channel of the Congo Basin during the low flow season

Figure 7 shows velocity magnitude and depth-averaged velocity for the cross sections located at the confluence of the Kasai-Congo Rivers and in the *Chenal*. Figures 8 and 9 provide the results for selected measured primary variables at 29 locations (cross-sections) along the river channel collected using the ADCP. These variables include total discharge, average velocity, maximum channel hydraulic depth, and river width. Secondary data incorporated in the ADCP measurements include velocity and flow directions, and geometric characteristics of the section that are important to develop hydrodynamic models necessary for many river operations and scientific investigations.

Overall, the discharge measured along the Congo River main stem is consistent with its cumulative flow regime from upstream to downstream. The higher discharge further downstream in the *Chenal* of the Congo River results from the Kasai tributary, which provides about 1/3 of flow contribution to the Congo River during low flows (7,323 m^3s^{-1} , XS 26 at chainage 193 km / 22,442 m^3s^{-1}, XS 27 at chainage 195 km). At this period of measurement, the Kasai River is at its low flow season, and it is understood that this contribution of the Kasai River to the main channel is huge during high flow seasons. The significant increase in the flow along the Congo River course in the middle channel is also observed from Gombe (XS 23, chainage 580 km), which is principally due to the contribution from the Oubangui River, a main tributary that drains the northern catchments that experiences wet season conditions during July and August. It should be stressed here that in contrast to the trend of flow increase from up to downstream along the main channel, ADCP measurements undertaken at three locations including Gombe (XS 23, chainage 580 km, Q 22,473 m^3s^{-1}), Klock-Pointe (XS 24, chainage 540 km, 20,955 m^3s^{-1}) and Lukolela (XS 25, chainage 250 km, Q 19,666 m^3s^{-1}) show a striking difference. The measurement XS 25 was taken on 08th August, and is considered consistent with the flow distribution in this part of the channel reach, given inflow from a northern tributary of Lufini. The measurements XS 24 and XS 23 were taken on 09th and 13th August respectively, which indicates there could have been a change in upstream flow conditions due to rainfall input in the upper catchments. Unfortunately, discharge and rainfall records from upstream have not been made available to assess the influence of upstream inflow to our measurements. The region from Kisangani up to chainage 1,340 km (Bumba) shows no significant increase in flow, 5,000 m^3s^{-1} to 9,885 $m^3s^{-1)}$, which is due to an absence of major tributaries in this reach. Higher velocities and depths have been measured in the reach downstream XS 23, from chainage 580 km; this reach also provides higher wetted sections than the upstream reaches.

Due to bed load materials and sediment transport characteristics and the season of the year, moving bed conditions should be checked for in a river, as they have implications for discharge accuracy from ADCP measurements. It is therefore a standard procedure to carry out a Moving Bed Test (MBT) before any attempts to carry out ADCP measurements. In this study, ADCP MBTs were carried out at different sites using stationary methods. The results of the MBTs revealed no moving bed conditions throughout the main channel, whereas some sites in the tributaries showed moving bed conditions, at least for the period of measurements in August 2019. Table 5 shows the results of MBT results for the site in the Ruki River.

4.2 Flow dynamics along the Congo River -Lake Tumba channel

Lake Tumba is a water body located in the central part of the Congo Basin, south of the Equator, and is connected to the main stem of the Congo River through a channel 25 km long (Figure 10). In July 2017, the fieldwork campaign team attempted to install a water level logger at the outlet of the channel near the city of Irebu (chainage 605 km). Our experience showed that during the time of the fieldwork, in August 2017, the Congo River was discharging into Lake Tumba through the channel. A note in the 1911 Encyclopedia Britannica relates the occurrence of this phenomenon to flood season.

Accounts from interviews with local residents confirmed the change of flow direction in the channel due to seasonal variation. *From June to September, water flows from the Congo main stem into Lake Tumba, whereas the reverse situation of water flowing from the Lake to the Congo River is observed from October up to February.* The same interview accounts mentioned a situation of stationary flow conditions within the channel around May and April.

Surprisingly, during the fieldwork visit to the site in August 2019, the research team was able to observe a reverse situation of flow leaving the lake towards the Congo River main stem. Unfortunately, weather conditions and insufficient logistics did not permit additional measurements to be carried out at the site during the last visit. Meanwhile, ADCP measurements were carried out at one site in the channel on 12th August 2017, at Bompombo village (17.8088 E, -0.6012 S) where we recorded at total discharge of 283.6 m^3s^{-1}, maximum water depth of 14.5 m, the channel width of 304 m, the wetted area of 2,292 m^2, and a very low mean flow velocity of 0.11 m/s. Analysis of the velocity profile and channel geometry at the Bompombo site is given in Figure 11, which shows a similar pattern of velocity magnitude throughout the hydraulic depth.

4.3 Water surface elevation and bathymetry measurement

Measurements of Water Surface Elevation at different points of a watercourse can be used to determine the longitudinal profile and the hydraulic gradient, which are important characteristics in the optimal use of a river. Taking into account the longitudinal profile, this allows identification of locations with similar hydro-sedimentary characteristics. Through a longitudinal profile, slope variations can be observed that can indirectly provide information on past climates, structural controls, eroding and deposition sections, sediment transport capacity, and upstream-downstream flow dynamics. Figure 12 shows a raster map of WSE recorded along the Congo main stem, between Kisangani and Kunzulu city near Kinshasa. The measurement took place from 31 July to 26 August 2019, and 25,088 continuous points of WSE were recorded at an interval of 50 m. Bad weather conditions interrupted measurement at chainages 661 km to 546 km, and 440 km to 334 km. In Figure 13 we show the water surface profile drawn from the WSE measurement at an interval 5 km. WSE and sonar measurement were also taken in July-August 2017 over a distance of 700 km between Kinshasa and Mbandaka, and are presented in Carr et al. (2019).

Overall, the WSE and bathymetry measurements taken along the middle reach of the Congo River between 2017 and 2019 have revealed that the variability in water surface slope is greater than previously thought. Such variability is important for characterizing the hydraulic behavior of river reaches (Garambois et al., 2016; Montazem et al., 2019). The variability appears to be the result of changes in bathymetry, especially as the Congo River enters the C*henal* and is joined by the Kasai tributary. Initially, the water surface slope becomes relatively steep (8 cm/km) as it approaches the entrance to the *Chenal*. Along the *Chenal*, the water surface slope then gradually reduces to 2 cm/km at the Kasai confluence. The continuous WSE measurements obtained at the *Chenal* entrance provide more details of the water surface slope curvature at this location, and show that water surface slope locally steepens to a maximum of 12cm/km. Within the multichannel reach (between 300 and 650 km), the static WSE measurements show the water surface slope to be highly regular (5–6 cm/km). This regularity is maintained through Chainage 480–610 km, where there are four WSE measurements, and the river includes significant morphological features including two major width constrictions and the Oubangui confluence. This suggests that these morphological features do not cause backwater conditions during low flows.

Within the multichannel reach surveyed (between 300 and 650 km), the stream-wise bathymetry measurements reveal that the bed slope is relatively constant and almost parallel to the WSE at the 50-km scale, indicating close to uniform flow conditions. Mean river depths also remain relatively constant at 7 – 8 m, including through the confluences with the Oubangui and Sangha. It should be noted that the stream-wise depth measurements do not indicate the hydraulic mean depth of the channel. Rather, they sample river depth along the established navigation route, which is known to follow the deeper channel threads in order to minimize the risk of vessels grounding. Hydraulic mean channel depths through the reach were obtained only at four ADCP transect locations. Three of these cross sections were obtained at locations where the channel is narrow and single thread and are therefore atypical of the morphology throughout the reach. Mean depth for each of these cross sections was measured as 7.2 m at chainage 315 km, 11.7 m at chainage 485 km, and 11.8 m at chainage 550 km. By comparison, the cross section at chainage 515 km is at a 5 km wide section of channel that is typical of the morphology through the reach, and showed a mean depth of 5 m. This indicates that at the width constrictions, the channel has adjusted to varying degrees in order to maintain morphological equilibrium. Through the *Chenal*, the 50 km scale bed slope produced by the stream wise bathymetry measurements is variable and consistently differs from the water surface slope. In the 50 km reach upstream of the Kasai confluence, the bed slope is 19 cm/km, before flattening out and eventually becoming negative in the 50km reach upstream of the Malebo Pool. Hydraulic mean channel depth is 13 m upstream of the Kasai confluence, and shows no increase immediately downstream, but does increase to 17 m over a distance of 50 km.

4.4 Sediment distribution

Table 6 shows the results of TSS and OM for the sections with ADCP measured discharge (MD). The results are representative of low flow season during the month of August 2019 along the main channel of the Congo River between Kisangani and Kinshasa. Coynel et al. (2005) published the results of six-year experiment, including total suspended sediment (TSS), particulate organic carbon (POC), and dissolved organic carbon (DOC), for the main stem of the Congo River near Brazzaville-Kinshasa station, and the Oubangui, Mpoko, and Ngoko-Sangha tributaries, where they noted a clockwise hysteresis pattern in relation to river discharge. The results obtained in this study are in the same order of magnitude, most specifically for TSS, although it is currently difficult with instantaneous samples taken over one low flow season to derive variability and establish a comprehensive pattern.

5. Conclusion, lessons learned and perspectives for future measurements

Field work measurements of the Congo River have always been a challenge due to issues of scale, the remoteness of the basin and the complexity of fluvial processes, thus limiting access to information necessary to develop strategies for major water resources planning and development in the riparian countries. The field campaigns carried out in this study has provided insights into the usefulness of the acoustic Doppler technology for large scale studies in the Congo River, thus providing much needed data such as river discharge, bathymetry, velocity distribution, WSE and patterns of geomorphological features. These data are of much benefit to the development of new predictive tools and validation of other remotely sensed products such as the satellite altimetry data that need in-situ water level validation. In general, discharge is measured using the velocity-area method. Acoustic technologies utilize the same velocity-area approach but measure the velocity in the entire profile in hundreds or even thousands of bins. The resulting issues relate to the accurate determination of the boat position (boat velocity, direction, orientation, etc.) relative to the bottom or some other reference. The GNSS RTX live correction works very well in the Congo Basin, provided there is a clear view of the sky available on the river. Recreational grade sonars ('Fish finder') also performed well. Garmin ClearVu functionality has value – and captures geomorphological processes such as dune formation. There is a lot to be learned from the depositional patterns on the islands about sediment sources and process and that future field work should consider coring. The collection of data from the reported fieldwork represents a valuable river dataset for many hydro-geomorphological and other studies, and will form a valuable baseline for future measurements (available on request from CRREBaC). The fieldwork carried out in this study targeted measurements along the middle reach of the Congo River during low flow season. It is also important to envisage measurements during high flow seasons that will provide a clear understanding of the river channel connectivity with floodplains. The tributaries that discharge flow to the main stem of the Congo River are, in fact, as large as the other world's large rivers such as the Mekong and Mississippi Rivers. They play a critical role in sustaining water resources services for socio-economic development. In the same time, these tributaries undergo pressure from land use change, with major implications on river sedimentation, water quality, and hydro-geomorphological changes. It is also important to extend measurements to these tributaries. During the fieldwork campaigns, interviews with the Congo River users revealed a number of issues that require formulation of new policies to address river basin planning for economic growth and sustainable development. Some of these issues are reported in Trigg et al. (2020, this issue). The data generated in this study will start to be explored in view of addressing the challenge of water resources management in the Congo Basin.

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Table 1 ADCP cross sections and locations (X, Y in Degrees Decimal Minutes; * tributaries; [a] RVF measurements)

XS	Location	Chainage km RVF	Y	X	Date [D/M/Y]
1	Kisangani	1734	0°30.294900 N	25°11.451100 E	28/7/2019
2	Lindi Tributary*,[a]	1720	0° 33.728920 N	25° 6.034548 E	1/6/2019
3	Ile Berta [a]	1699	0° 34.362031 N	24° 51.561618 E	16/6/2019
4	Yangambi [a]	1644	0° 45.289383 N	24° 29.206488 E	17/6/2019
5	Lomami Tributary*	1620	0°45.939000 N	24°15.693600 E	1/8/2019
6	Isangi 5km ds	1615	0°49.20000 N	24°15.693000 E	2/8/2019
7	Isangi - left channel	1614	0°49.50000 N	24°14.70000 E	2/8/2019
8	Lileko	1590	0°58.467900 N	24°8.864700 E	3/8/2019
9	Lokutu	1530	1°11.971300 N	23°36.072900 E	4/8/2019
10	Basoko /Arumimi Trib*	1370	1°13.348800 N	23°36.268400 E	4/8/2019
11	Mombongo-Main channel	1450	1°55.195600 N	22°47.719000 E	5/8/2019
12	Mombongo-Right island	1450	1°54.802200 N	22°47.910000 E	5/8/2019
13	Bumba Island 1	1340	2° 9.719400 N	22° 27762400 E	7/8/2019
14	Bumba Island 2	1340	2° 9.588100 N	22° 27.135800 E	7/8/2019
15	Bumba Island 3	1340	2° 9.588100 N	22° 27.135800 E	7/8/2019
16	Bumba Island 4	1340	2° 9.588100 N	22° 27.135800 E	7/8/2019
17	Bumba	1340	2° 9.588100 N	22° 27.135800 E	7/8/2019
18	Makanza_island 1	900	1°33.706800 N	19°5.493700 E	12/8/2019
19	Makanza_island 2	900	1°33.706800 N	19°5.493700 E	12/8/2019
20	Lulonga *	770	0°40.751100 N	18°24.227700 E	13/8/2019
21	Ruki *	700	0°3.836500 N	18°19.142500 E	16/8/2019
22	Bopombo Lake Tumba *	605	0°35.966537 S	17° 48.534389 E	12/8/2017
23	Gombe	580	0°41.545167 S	17°35.184343 E	13/8/2017
24	Klok Pointe	540	0°54.228652 S	17°23.522715 E	10/8/2017
25	Lukolela	250	1°3.034631 S	17° 8.943566 E	9/8/2017
26	Kasai Tributary*	193	3°9.897924 S	16°12.601848 E	3/8/2017
27	Ferme Lenga-Lenga	195	3°10.180492 S	16°10.655582 E	3/8/2017
28	Aval Kwamouth	190	3°11.761204 S	16°11.620400 E	3/8/2017
29	Kunzulu	155	3°28.577531 S	16°7.063207 E	30/7/2017

Table 2 Technical specifications of the water level loggers and staff gauge at N'sele site

Specifications	**WLL**	**Baro-logger**	**Staff gauge**
Serial number	14388	11567	
Job number	11567	11567	
Height above tip of logger (m)	1.52		
Bench mark elevation (m)	BM1=275.117; BM2= 282.128		
Datum Point	TOP		TOSG
Elevation of the Datum (m)	275.556		277.036
Elevation of the H_o (m)	274.036		274.036
Water Height above the tip of the logger at the launching (cm)	29.5		

Date and time of launching	29-Aug-2018/16 hr 13’		
Sampling interval	Hourly	Hourly	Daily

Table 3 Location and structure types of the WLL implemented in the CRB (O: Operational, NO: Non Operational)

Site	Location	Long	Lat	Date installed	Structure type	Current Status
1	Kunzulu, Congo River	16.1290	-3.4781	08/2017	Wood	NO
2	Bolobo, Congo River	16.2244	-2.1526	08/2017	Wood	NO
3	Lukolela, Congo River	17.1877	-1.0544	08/2017	Wood	NO
4	Bopombo, Lake Tumba	17.8088	-0.6012	08/2017	Wood	NO
5	Mbandaka, Congo River	18.2888	0.0707	08/2017	Wood	NO
6	Kutumuke, Kasai River	17.3428	-3.2043	09/2017	Wood	O
7	N'Djili River, Kinshasa	15.3662	-4.3881	09/2017	Wood	O
8	N'sele River, Kinshasa	15.6252	-4.4561	08/2018	Concrete	O
9	Maluku, Congo River	15.59	-4.2119	08/2018	Concrete	NO
10	Kisangani, Congo River	25.1938	0.5046	07/2019	Concrete	O
11	Bumba, Congo River	22.4375	2.18151	08/2019	Concrete	O
12	Bantoyi, Ruki River	18.3981	0.2581	08/2018	Concrete	O

Table 4 Location and site characteristics of the sediment samples

S/ID	Location	River	Date	Longitude	Latitude
S1	Kisangani	Congo	28-07-19	25.1938	0.5047
S2	Kisangani	Congo	30-07-19	25.1919	0.5031
S3	Kisangani	Congo	30-07-19	25.1913	0.5029
S4	Kisangani	Congo	30-07-19	25.1928	0.5011
S5	Kisangani	Congo	30-07-19	25.1930	0.5008
S6	Kisangani	Lindji	31-07-19	25.0554	0.5648
S7	Isangi	Congo	1/8/2019	24.2415	0.7454
S8	Isangi	Lomami 1.5km	1/8/2019	24.2427	0.7443
S9	Isangi	Lomami-Congo	3/8/2019	24.2431	0.7454
S10	Isangi	Lomami 5km	3/8/2019	24.2746	0.7750
S11	Lileko	Congo	3/8/2019	24.1465	0.9728
S12	Lileko	Congo	3/8/2019	24.1442	0.9692
S13	Lileko	Congo	4/8/2019	24.1416	0.9648
S14	Lileko	Congo	4/8/2019	24.1405	0.9622
S15	Lokutu	Congo	4/8/2019	23.5865	1.1817
S16	Lokutu	Congo	4/8/2019	23.5922	1.1882
S17	Lokutu	Congo	4/8/2019	23.5956	1.1929
S18	Lokutu	Congo	4/8/2019	23.6000	1.1969
S19	Basoko	Aruwimi	5/8/2019	23.6038	1.2259
S20	Basoko	Aruwimi	5/8/2019	23.6039	1.2239
S21	Mombongo 2	Congo	5/8/2019	22.7916	1.9247
S22	Mombongo 2	Congo	5/8/2019	22.7940	1.9310
S23	Mombongo 2	Congo	5/8/2019	22.7983	1.9362
S24	Mombongo 2	Congo	11/8/2019	22.8026	1.9415
S25	Mombongo Branche	Congo	12/8/2019	22.7986	1.9136
S26	Mongala Tributary	Mongala	12/8/2019	19.7717	1.8882
S27	Makanza	Congo	12/8/2019	19.0944	1.5400
S28	Makanza	Congo	12/8/2019	19.0901	1.5592
S29	Makanza	Congo	12/8/2019	19.0808	1.5704
S30	Makanza	Congo	13-08-19	19.0791	1.5750
S31	anabranch	Congo	13-08-19	18.6762	1.1564
S32	Lulonga	Lulonga Tributary	16-08-19	18.4020	0.6794
S33	Lulonga	Lulonga Tributary	20-08-19	18.3997	0.6796
S34	Bantoyi	Ruki	21-08-19	18.3972	0.2581
S35	NGombe	Congo	21-08-19	17.6928	-0.7183
S36	Lake Tumba1	Canal Congo-Tumba	21-08-19	17.9403	-0.4456
S37	Lake Tumba2	Canal Congo-Tumba	21-08-19	17.9375	-0.6106
S38	Irebu	Congo	23-08-19	17.9164	-0.6811
S39	Bompombo	Canal Congo-Tumba	23-08-19	17.9581	-0.6108
S40	Lokolela 1	Congo	23-08-19	17.1628	-1.0505

Table 4 ctd Location and site characteristics of the sediment samples

S/ID	Location	River	Date	Longitude	Latitude
S41	Lokolela 2	Congo	24-08-19	17.1380	-1.0567
S42	Constriction	Congo	24-08-19	17.1407	-1.0565
S43	Bolobo 1	Congo	24-08-19	16.2858	-2.0983
S44	Bolobo 2	Congo	24-08-19	16.1906	-2.1887
S45	Tchumbiri 1	Congo	25-08-19	16.2329	-2.6028
S46	Tchumbiri 2	Congo	25-08-19	16.2064	-2.7116
S47	Kwamouth 1	Congo	25-08-19	16.1897	-3.1983
S48	Kwamouth 2	Congo	26-08-19	16.1796	-3.2343
S49	Mayi Ndombe	Congo	26-08-19	16.0837	-3.5710
S50	Entree Pool 1	Congo	27-08-20	15.5240	-4.0962
S51	Entree Pool 2	Congo	27-08-21	15.5544	-4.0421

Table 5 Results of the MBT carried out in the Ruki River

Distance Upstream:	0.265 [m]
Duration:	622.480 [s]
Moving Bed Velocity:	0.000 [m/s]
Moving Bed Direction:	157.930 [degrees]
Water Velocity:	0.444 [m/s]
Depth:	3.129 [m]
Percent Bad BT:	0.000 [percent]
Potential MB Error:	0.096 [percent]
Mean Near Bed Velocity:	0.341 [m/s]
Measured Discharge	2999 [m3/s]
MBT Corrected Discharge	3002 [m3/s]

Table 6 Total Suspended solids (TSS) and organic matter (OM) results

			ADCP*MD	TSS	OM	TSS*MD	OM*MD
S-ID	**Location**	**Date**	**m^3*s^{-1}**	**(mg*l-1)**		**$mg*m^{-3}*s^{-1}$**	
S1	Kisangani, Congo River	28-07-19	5,000	40	50	$2*10^8$	$2.5*10^8$
S6	Lindji River	31-07-19	1,113	40	40	$2.2*10^7$	$4.5*10^7$
S7	Isangi, Congo River	01-08-19	7,365	23	40	$6.7*10^7$	$3.7*10^8$
S8	Isangi, Lomami River	01-08-19	1,142	34	50	$6.8*10^6$	$4.6*10^7$
S11	Lileko, Congo River	03-08-19	7,626	9	50	$1.5*10^8$	$1.5*10^8$
S15	Lukutu, Congo River	04-08-19	7,666	6	40	$2.1*10^8$	$2.3*10^8$
S19	Basoko, Aruwimi River	05-08-19	1,830	27	20	$8.6*10^7$	$3.7*10^7$
S32	Lulonga River	16-08-19	1,642	27	30	$1.2*10^7$	$3.3*10^7$
S34	Bantoyi, Ruki River	21-08-19	2,697	23	10	$2*10^7$	$8.1*10^7$
S35	Gombe, Congo River	21-08-19	18,853	13	20	$3.8*10^8$	$1.9*10^8$
S40	Lukolela, Congo River	23-08-19	19,949	33	10	$2*10^8$	$4*10^8$
S43	Bolobo, Congo River	24-08-19	22,419	13	20	$3.8*10^8$	$2.2*10^8$
S45	Tchumbiri, Congo River	25-08-19	23,612	13	10	$2.7*10^8$	$7*10^8$
S48	Kwamouth, Congo River	26-08-19	26,417	28	20	$5.3*10^8$	$2.6*10^8$
S51	Entrée Pool, Congo River	27-08-20	31,211	23	20	$5.3*10^8$	$1.2*10^9$

New Measurements of Water Dynamics and Sediment Transport along the Middle Reach of the Congo River and the Kasai Tributary

Raphael M. Tshimanga[1], Mark A. Trigg[2], Jeff Neal[3], Preksides Ndomba[4], Denis A. Hughes[5], Andrew B. Carr[2], Pierre M. Kabuya[1,2], Gode B. Bola[1], Catherine A. Mushi[4], Jules T. Beya[1], Felly K. Ngandu[1], Gabriel M. Mokango[6], Felix. Mtalo[4], and Paul Bates[3]

[1]*Congo Basin Water Resources Research Center – CRREBaC & Department of Natural Resources Management, University of Kinshasa, DR Congo,*
[2]*School of Civil Engineering, University of Leeds, UK.*
[3]*School of georgraphical sciences, Bristol Uiversity, UK,*
[4]*Department of Water Resources Engineering, Dar es Salaam University, Tanzania,*
[5]*Institute for Water Research, Rhodes University, South Africa,*
[6]*Regie des Voies Fluviales – RVF, Kinshasa, DR Congo*

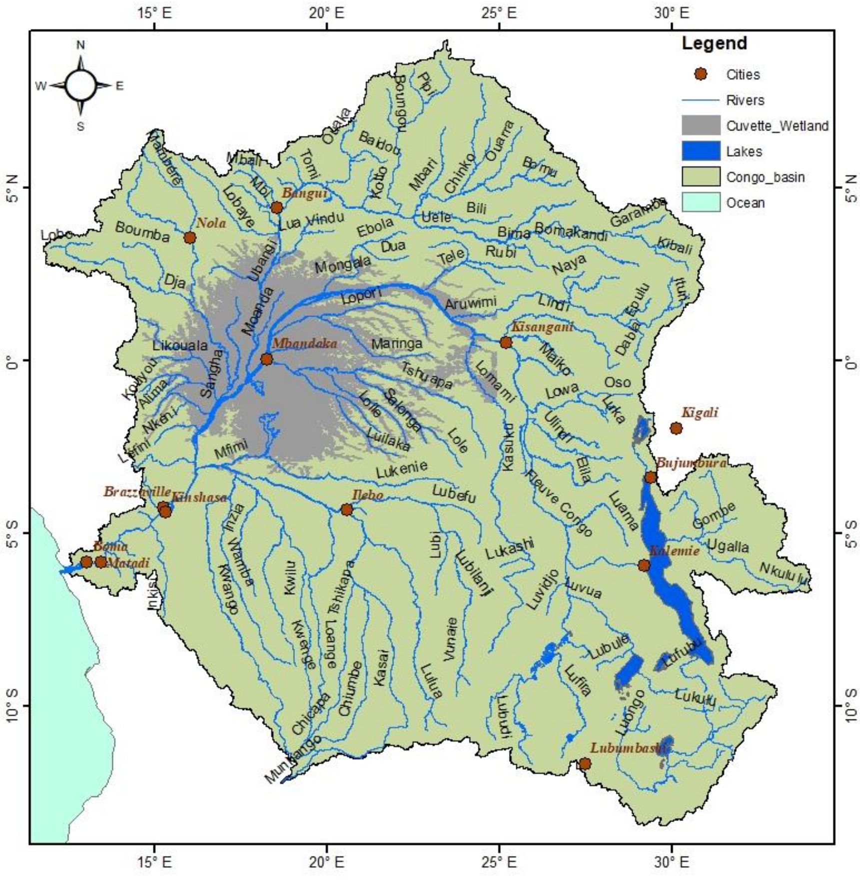

Figure 2 Main hydrographic features of the CRB

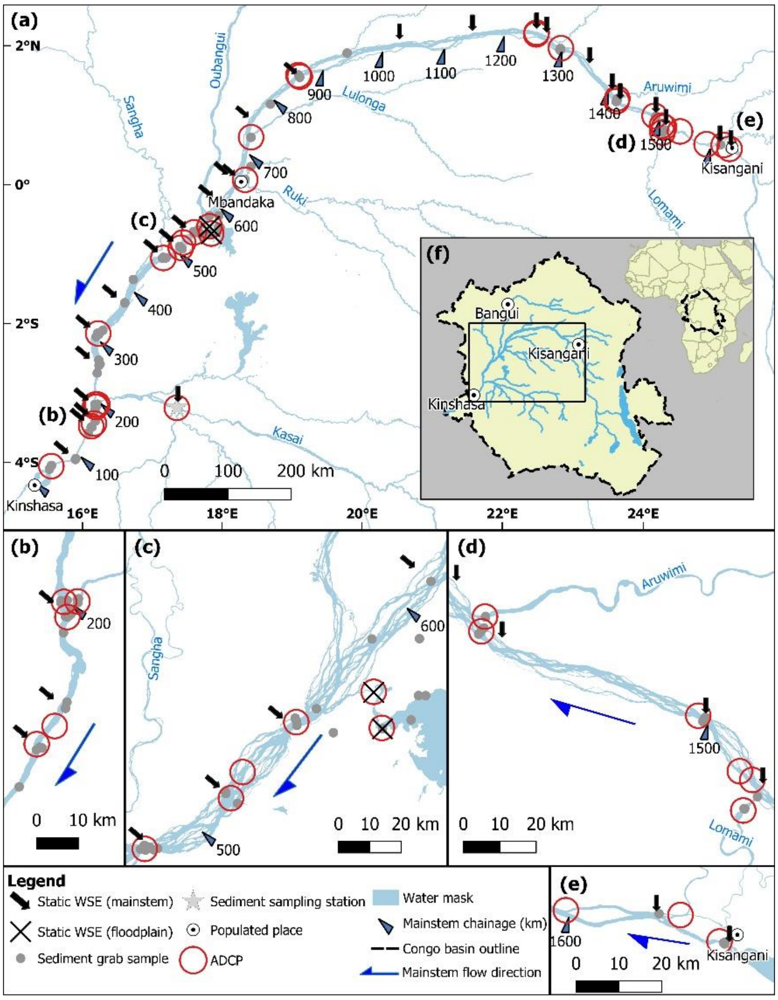

Figure 2 Study reach and locations of measurements (Chainage calculated from the navigation path used with the boat) as shown from panel (a). Panels (b), (c), (d) and (e) correspond to a zoom from panel (a).

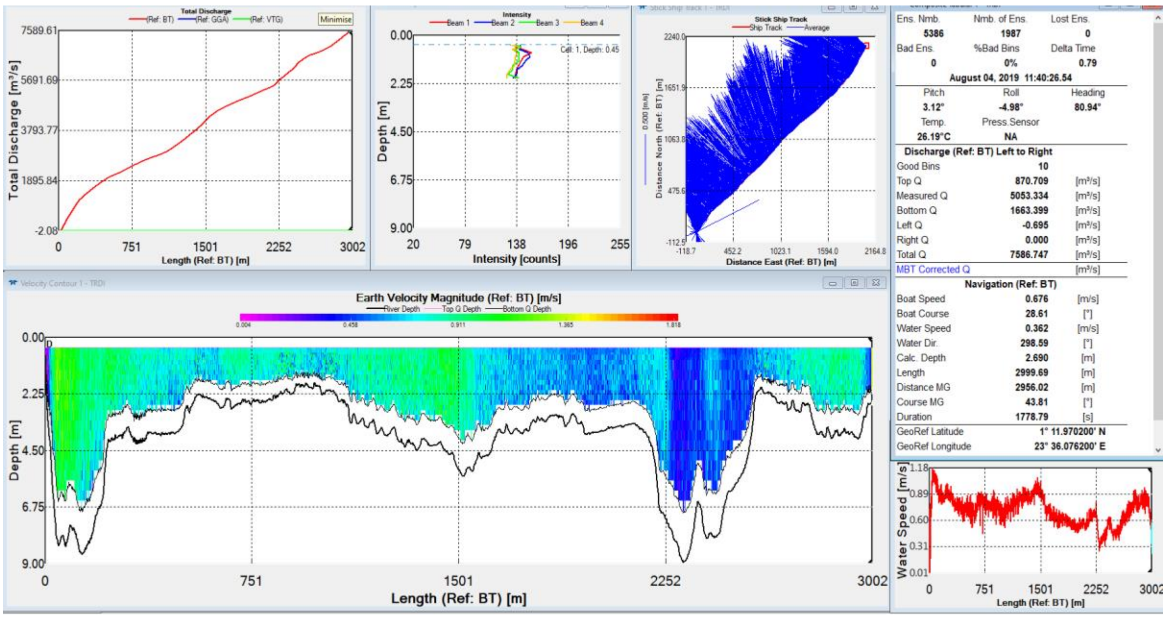

Figure 3 Real time ADCP Transect (3 km river width) recorded using WinRiver II at Lukutu

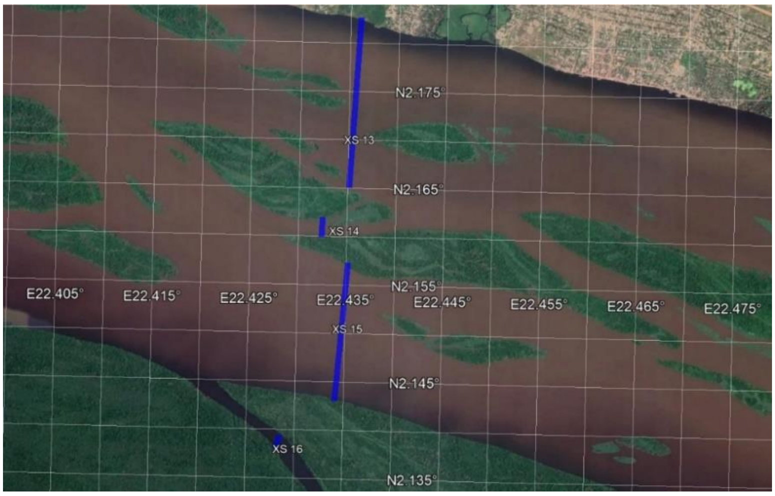

Figure 4 Google image of ADCP measurements involving a multi-thread channel

Figure 5 GNSS-Trimble set up for continuous (left) and static (right) WSE recording

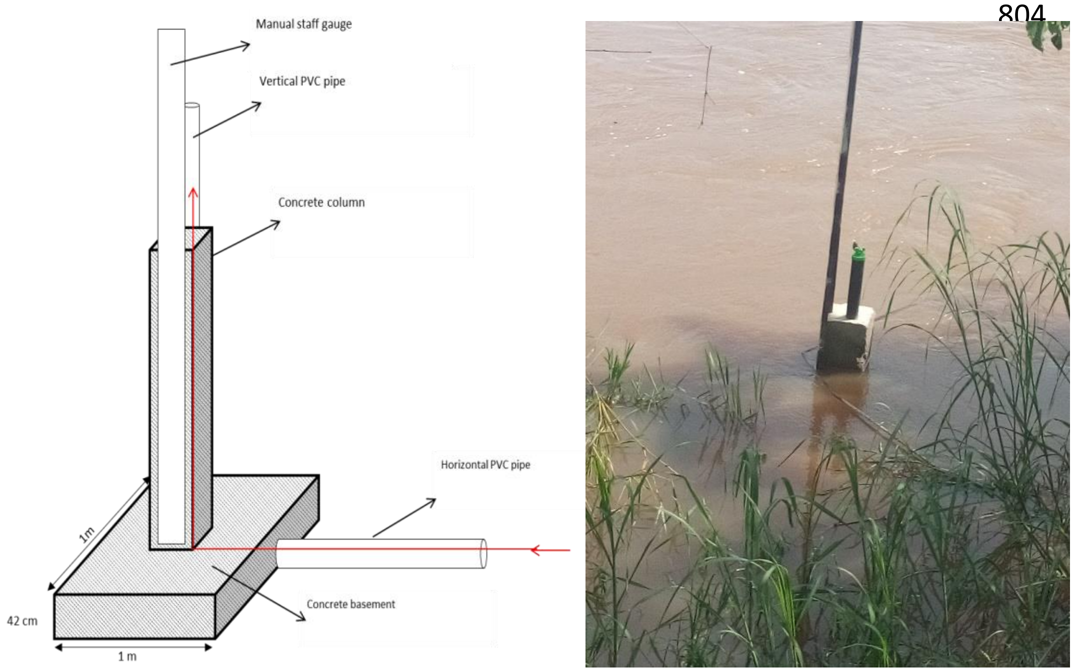

Figure 6 Design of a concrete housing structure of the WLL (N'sele tributary)

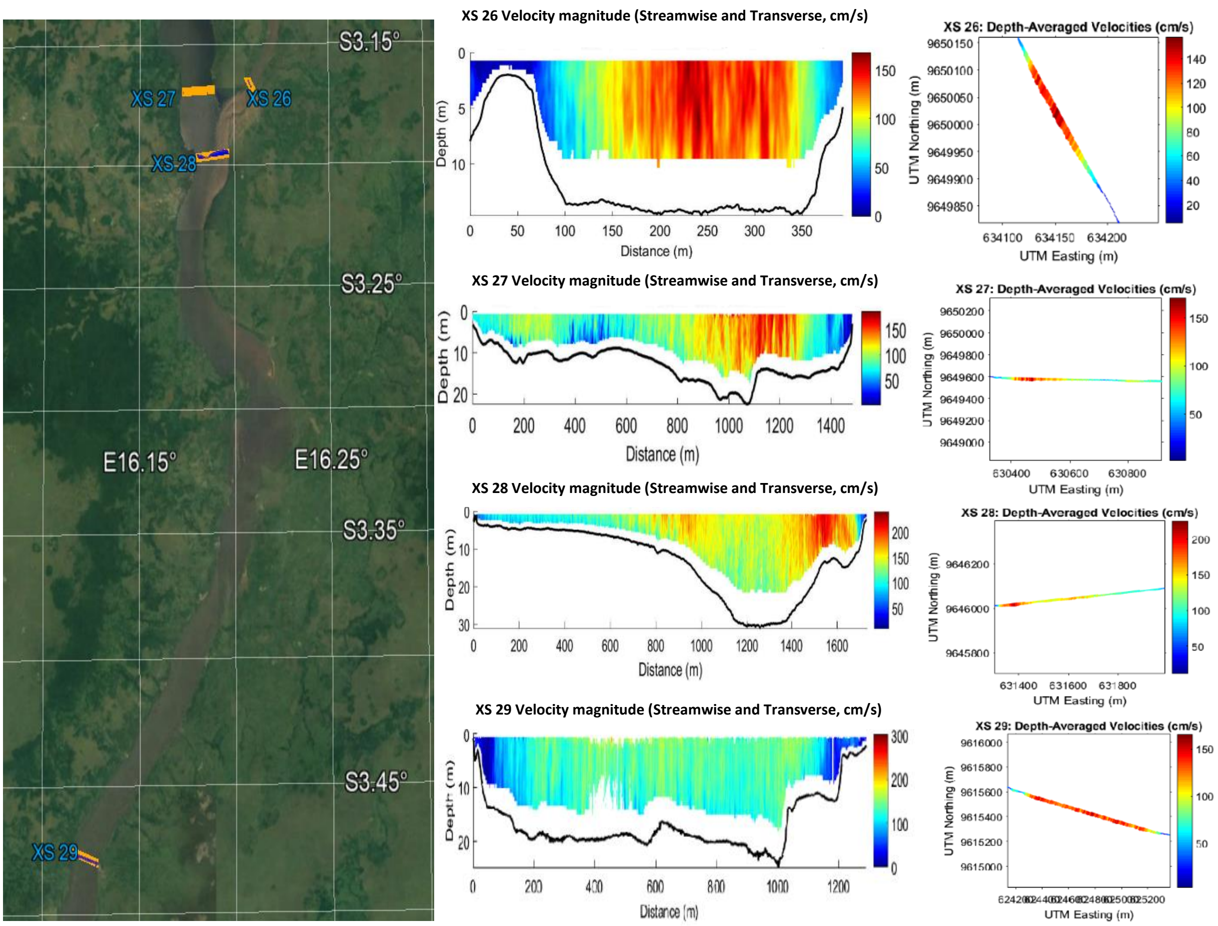

Figure 7 Depth averaged velocity and velocity magnitudes (cm/s) for four cross sections located in the google map, in the Kasai River and the *Chenal*

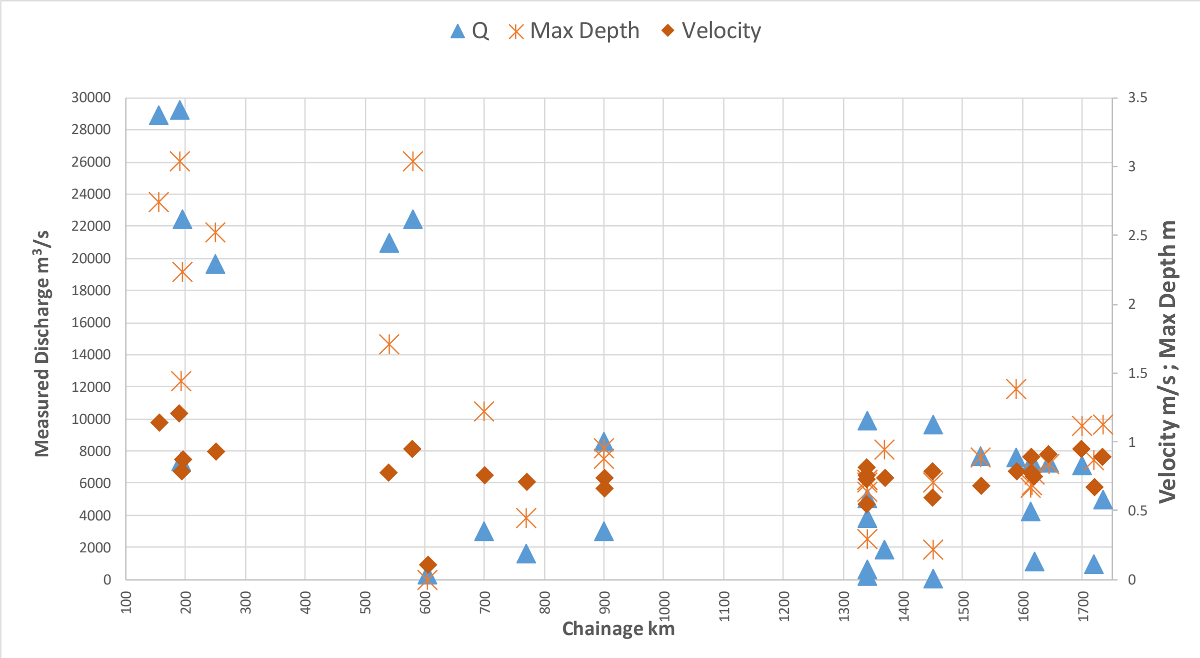

Figure 8 Measured discharge, channel hydraulic depth and velocity for 29 cross sections along the Congo River main stem (Max Depth values divided by 10 to fit the scale)

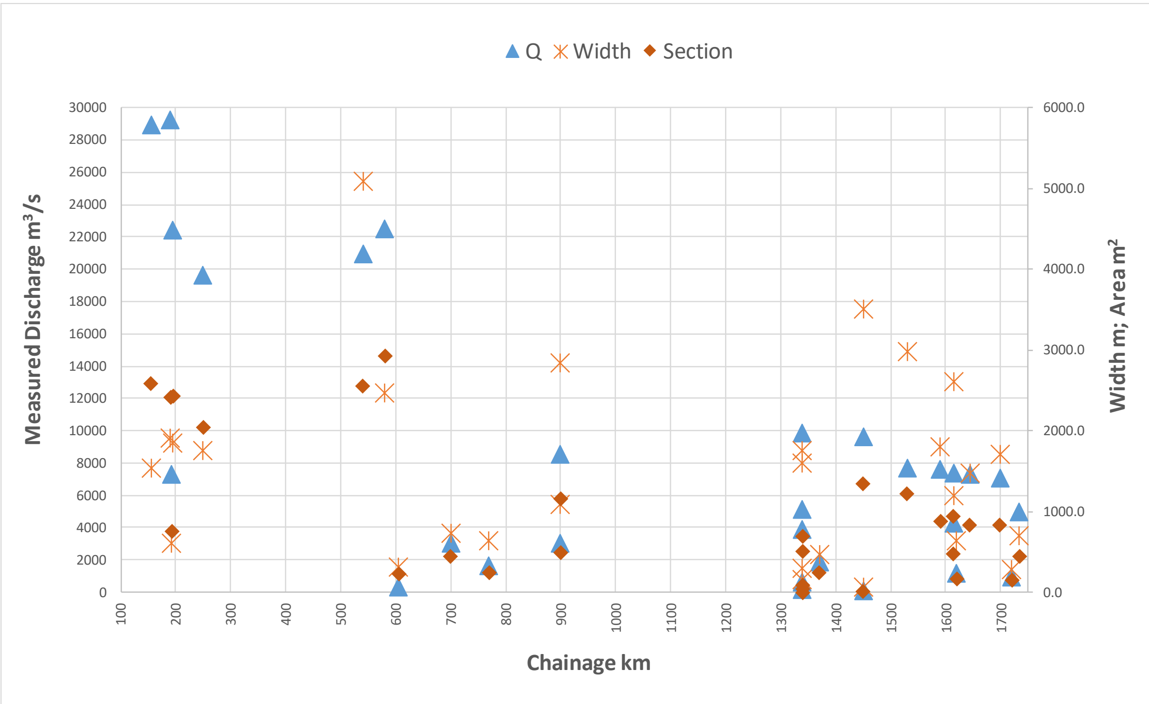

Figure 9 Measured discharge, channel width, and wetted area for 29 cross sections along the Congo River main stem (Area values divided by 10 to fit the scale)

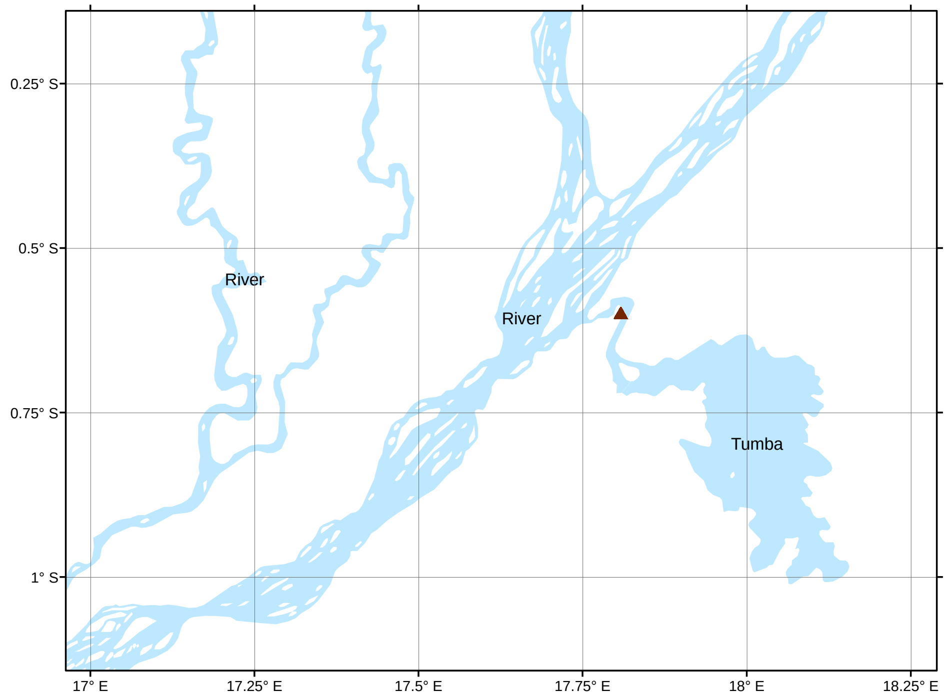

Figure 10 Location of Lake Tumba, red triangle dot represent the WLL and ADCP measurement site

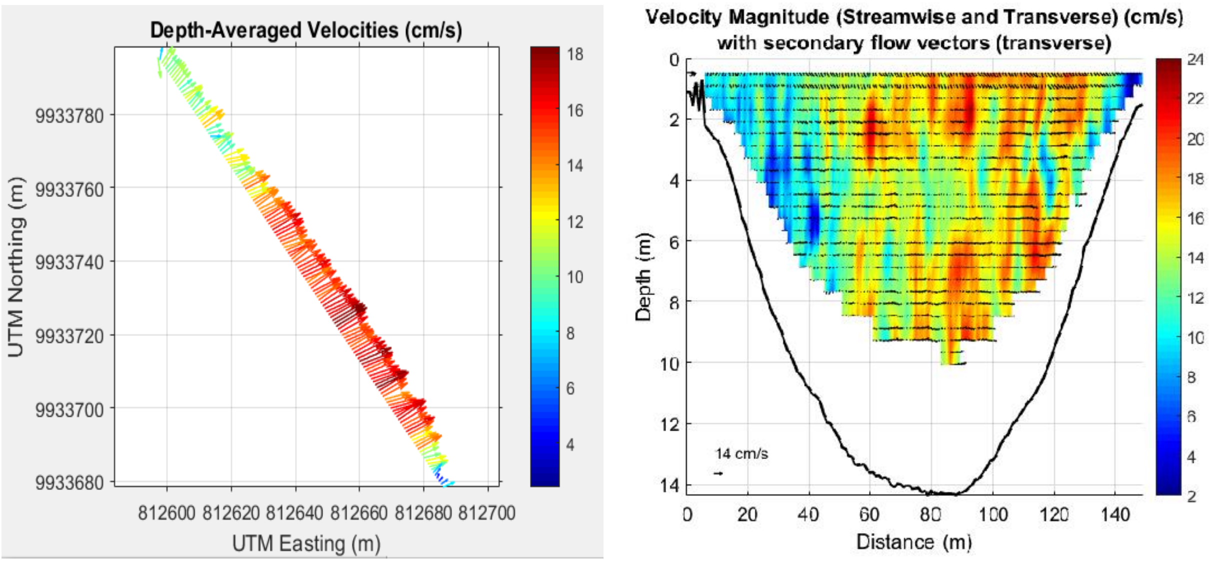

Figure 11 Hydraulic characteristics of Lake Tumba -Congo River channel, at Bompombo

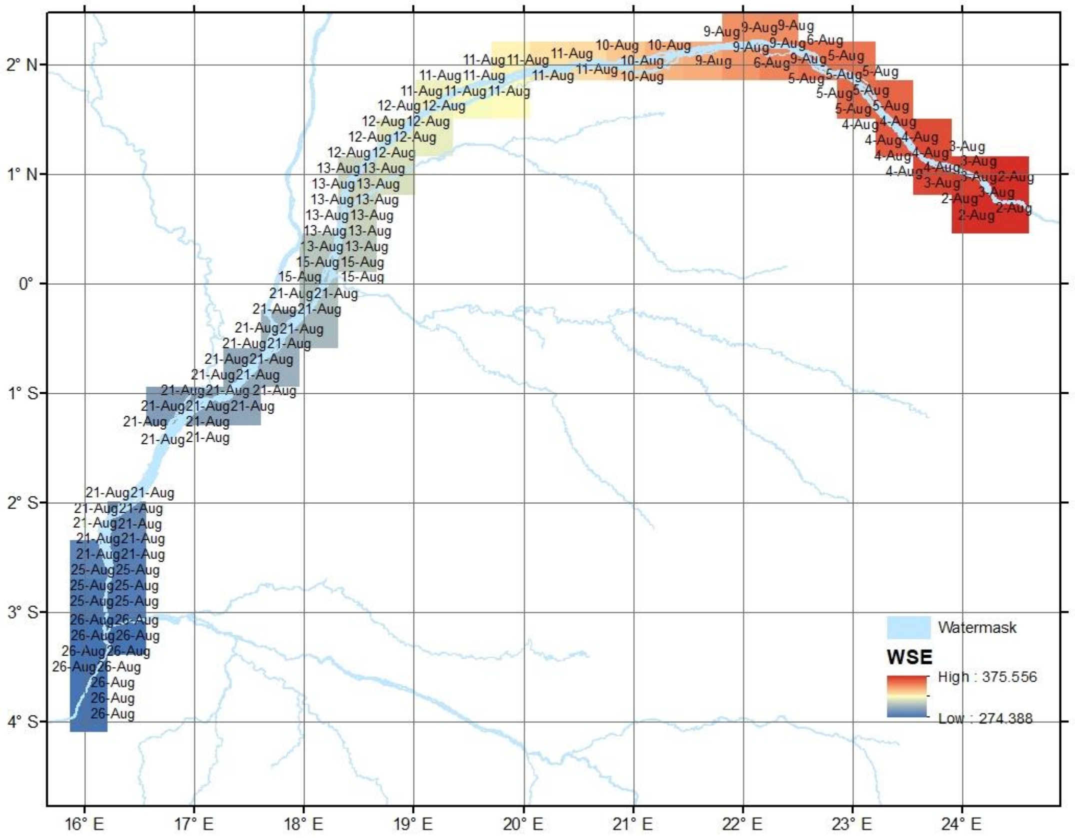

Figure 12 Raster map representing 25,088 continuous points of WSE recorded along the Congo main stem at 50 m interval (measurements made from 2nd to 26th August 2019)

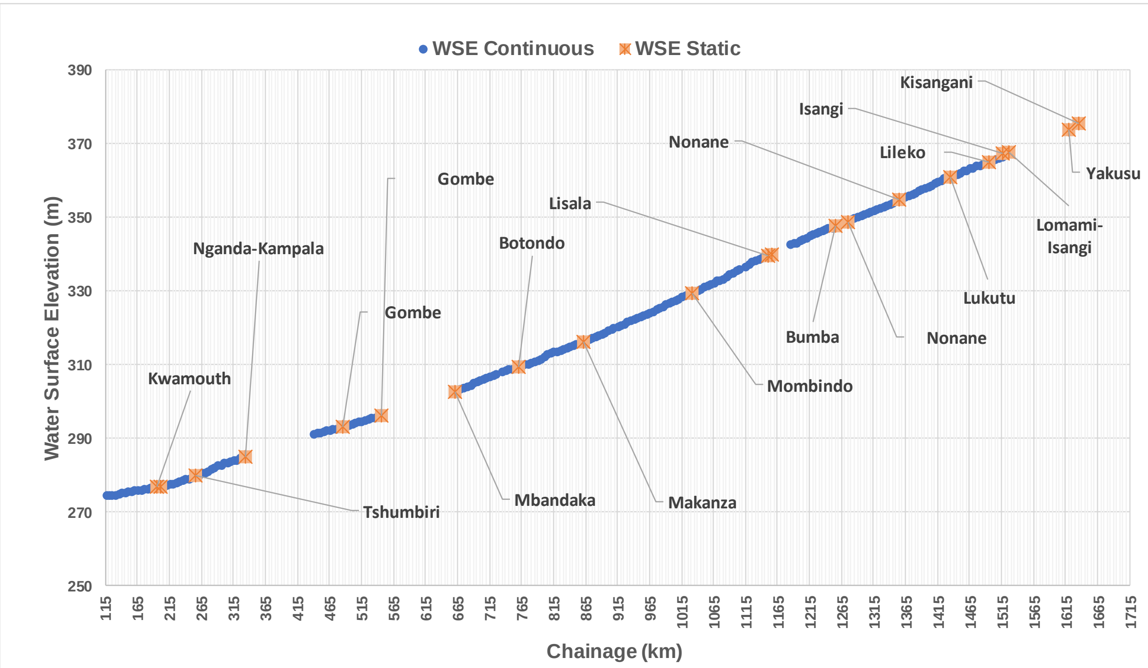

Figure 13 Water surface profile drawn from the WSE measurement at an interval 5 km