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Key Points:
- Archived records exist for hundreds of stream and rain gauges
- Cuvette wetlands may be dominated by rainfall instead of fluvial water exchange
- The "tropical rainbelt" may be changing in response to global warming, as evidenced in Congo discharge records

Supporting Information:
- French Translation

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Opportunities for hydrologic research in the Congo Basin

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Abstract We review the published results on the Congo Basin hydrology and summarize the historic and ongoing research. Annual rainfall is ~1900 mm/yr along an east-west trend across the basin, decreasing northward and southward to ~1100 mm/yr. Historic studies using lysimeters, pans, and models suggest that the annual potential evapotranspiration varies little across the basin at 1100 to 1200 mm/yr. Over the past century, river discharge data have been collected at hundreds of stream gauges with historic and recent data at 96 locations now publicly available. Congo River discharge at Kinshasa-Brazzaville experienced an increase of 21% during the 1960–1970 decade in comparison to most other decades. Satellite altimetry measurements of high and low flows show that water levels in the "Cuvette Centrale" wetland are 0.5 m to 3.0 m higher in elevation than the immediately adjacent Congo River levels. Wetland water depths are shallow at about a meter and there does not appear to be many sizable channels across the "Cuvette"; thus, wetland flows are diffusive. Cuvette waters alone are estimated to emit about 0.5 Pg CH_4 and CO_2 equivalents/yr, an amount that is significant compared to global carbon evasions. Using these results, we suggest seven hypotheses that focus on the source of the Cuvette waters and how these leave the wetland, on the river discharge generated by historic rainfall, on the connection between climate change and the rainfall-runoff generated by the migrating "tropical rainbelt," on deforestation and hydroelectric power generation, and on the amount of carbon emitted from Congo waters.

1. Introduction

Earth science research in the Congo Basin represents an opportunity for scientific discovery, as the Congo is one of the least studied major river basins on Earth. Keys to such discoveries include the acquisition of new measurements, reworking of existing data, and conducting research in geographic locations that are not as well understood as other areas [*Oliver*, 1991]. Or, in the case of the Congo, keys also include rehabilitating the network of hydrometric stations and strengthening physiochemical laboratories. Perhaps foremost amongst these is the notion that there are aspects of a science that are not understood in either a specific time (e.g., geologic time, historic, or present) or at a geographic location, or that there are gaps in knowledge when considering a global view of the scientific field. As discussed throughout this paper, the Congo Basin is the embodiment of these discovery ideals.

Our primary focus is on the hydrology and hydrodynamics of the waters in the Congo Basin. Given that peer-reviewed science papers represent a state of knowledge, we compared the publication counts for Congo related papers to those of the Amazon (Table 1). This comparison is appropriate because both basins lie within the humid tropics, constitute the world's two largest river water flows, and have an abundance of tropical forests and wetlands. Note that the data presented in Table 1 are not meant as a complete analysis of all hydrological publications; rather the purpose is to illustrate the relative comparison between the two basins. As such, our contemporary understanding of the Congo Basin and its hydrology is about an order of magnitude less than that of the Amazon. This is ironic, given that four decades ago, *Marlier* [1973] stated that in comparison to the Congo Basin, "we know less about the physical characteristics of the Amazon."

Table 1. Numbers of Peer-Reviewed Papers in Selected Hydrology or in Selected Earth Science Journals[a]

Journal Name	Congo	Amazon
Geophysical Research Letters	4	34
Hydrological Processes	3	50
Hydrology and Earth Systems Sciences	0	9
International Journal of Remote Sensing	3	18
Journal of Geophysical Research	9	71
Journal of Hydrology	7	42
Nature	1	14
Remote Sensing of Environment	2	17
Science	0	4
Water Resources Research	4	40
Totals	33	299

[a]Searches conducted December 2013 for all previous dates available in a given journal's online database. Search criteria were for the words "Congo," "Zaire," or "Amazon" in the titles or in the abstracts (Congo and Zaire numbers are combined in the Congo column). Resulting papers were further investigated for having significant discussion on hydrology, climate, or biogeochemistry of the particular basin. Table is representative, not comprehensive of all papers.

Despite these low relative numbers of publications, there is a foundation of hydrologic research and measurements upon which to build opportunities for discovery (see sections 2 and 3). Historically, there have been more than 400 stream gauges operating throughout the Congo Basin at various times during the first half of the 1900s (Figure 1a) [e.g., *Croneborg*, 2013; M. A. Trigg, personal communication, 2013]. Some of the data from these gauges are available via the Global Runoff Data Center [*Global Runoff Data Center* (*GRDC*), 2014], whereas others are available from HYBAM [*HYBAM*, 2015]. For example, we have downloaded from the Global Runoff Data Center (GRDC) and used discharge data from 96 gauges (21 with data after the year 2000). In the past two decades, satellites have provided measurements of rainfall, changes in total storage, water surface elevation, and flooded areas all throughout the entire basin (see section 2).

The main goal of this paper is to provide a basis for new hydrologic research in the Congo Basin and thus allow a better understanding of the potential for climate change to impact hydraulics and related hydrologic applications. We first describe the basic geography, geology, and history of the basin in as much as these relate to hydrology. In section 2, we focus on the measurements and modeling results of the basin's hydrology and hydrodynamics. Because tropical hydrology plays an important role in the carbon cycle, we briefly review carbon biogeochemical focused studies in section 3. With the expectation that most researchers have more knowledge of the Amazon Basin, comparisons of the Amazon and Congo Basins in section 4 help to further build a foundation for Congo research. All of this information is used in section 5 to describe potential research hypotheses that could lead to important hydrologic discoveries. In the conclusions, we suggest several actions that would be helpful toward addressing the hypotheses.

1.1. Geography of the Congo Basin

Reported sizes of the basin range from about 3.6 M km^2 to 4.1 M km^2 [e.g., *Kazadi and Kaoru*, 1996; *Crowley et al*., 2006; *Marlier*, 1973]. However, the methods used to derive these areas are often not described. We used the 90 m SRTM DEM (Shuttle Radar Topography Mission digital elevation model) [*Farr et al*., 2007] and an equal-area projection with the WGS84 ellipsoid to derive topographic downslope directions and to link together flow directions and hence the river network (Figures 1–3, see *Lehner et al*., 2008 for details of similar methods; see also maps of *Dieulin et al*. [2006] and *Dieulin* [2007] and data from *Système d'Informations Environnementales sur les Ressources en Eau et leur Modélisation* (*SIEREM*), 2015 and *Boyer et al*. [2006]). Our measured basin area of 3,687,000 km^2 (Figure 2) compares well with the value of 3,705,000 km^2 from the 15 arcsecond HydroSheds Basin Boundaries [*Lehner et al*., 2008]. Differences between the area that we derive and the values of others are perhaps attributable to inclusion of Lake Tanganyika and its drainage area in our measured areas or that some researchers use only the area above Kinshasa-Brazzaville. The Lukuga River drains Lake Tanganyika and flows to the Lualaba River, which is the main upstream reach of the Congo River (Figure 1b). In the recent, historic, and geologic pasts, the lake has intermittently drained into the Congo Basin [*Beadle*, 1981]; thus, we also measured the drainage area upstream of the lake outlet and find the sub-basin and lake to be 236,300 km^2. Other sub-basin areas are noted in Figure 2. In our analysis, the Congo Basin area above Kinshasa-Brazzaville is 3,617,200 km^2.

1.2. Geology of the Congo Basin

The Congo Basin sediments consist of about 8 km of Paleozoic marine formations and 1 km of overlying Mesozoic-Cenozoic lacustrine rocks [*Daly et al*., 1992; *Giresse*, 2005]. Prior to the rifting of the African and

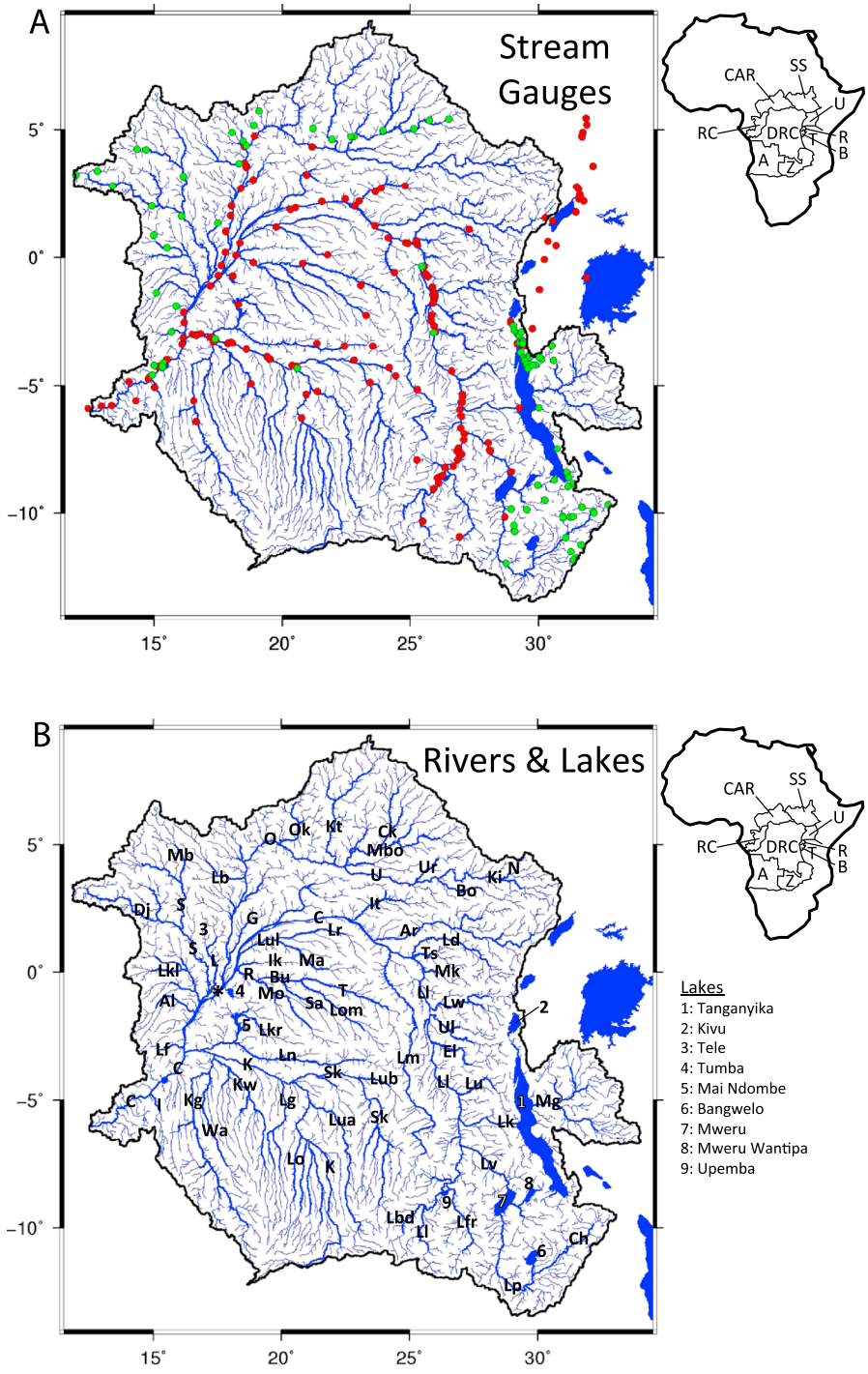


Figure 1. (a) Stream gauges in the Congo Basin. Green dots indicate locations of 96 stream gauges with data available from the *GRDC* [2014]. Red dots indicate locations of 164 stream gauges based on *Devroey* [1951]; and thus, these gauges were operational before 1951. Countries are DRC, Democratic Republic of the Congo; RC, Republic of the Congo; CAR, Central African Republic; SS, South Sudan; U, Uganda; R, Rwanda; B, Burundi; T, Tanzania; Z, Zambia; and A, Angola. (b) Congo Basin rivers and lakes. Asterisk at 17.54°E, 0.74°S is the location of the satellite altimetry data in Figure 9. See Figure 1a for country identifications. Rivers are Al, Alima; Ar, Aruwimi; Bo, Bomokandi; Bu, Busira; Ch, Chambeshi; Ck, Chinko; C, Congo; Dj, Dja; El, Elila; G, Giri; Ik, Ikelemba; I, Inkisi; It, Itimbiri; K, Kasai; Ki, Kibali; Kg, Kwango; Kt, Kotto; Kw, Kwilu; Lf, Lefini; Lkl, Likouala; L, Likouala aux Herbes; Ld, Lindi; Lg, Loange; Lb, Lobaye; Lkr, Lokoro; Lm, Lomami; Lom, Lomela; Lr, Lopori; Lo, Lovua; Lw, Lowa; Ll, Lualaba; Lu, Luama; Lp, Luapula; Lub, Lubefu; Lbd, Lubudi; Lfr, Lufira; Ln, Lukenie; Lk, Lukuga; Lul, Lulonga; Lua, Lulua; Lv, Luvua; Mk, Maiko; Mg, Malagarasi; Ma, Maringa; Mbo, Mbomou; Mb, Membere; Mo, Momboyo; N, Nzoro; Ok, Ouaka; O, Oubangui; R, Ruki; Sa, Salonga; S, Sangha; Sk, Sankuru; Ts, Tshopo; T, Tshuapa; U, Uele; Ul, Ulindi; Ur, Uere; and Wa, Wamba.

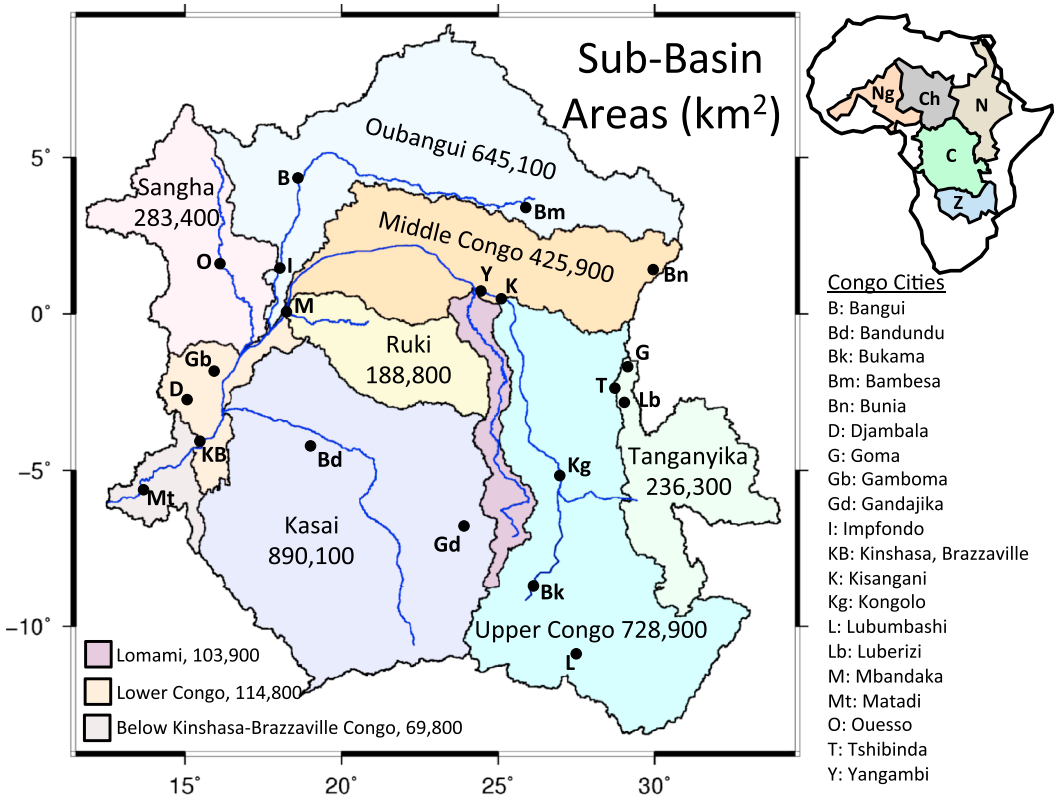


Figure 2. Congo sub-basins and their areas. Areas are given in square kilometers. See section 1.1 for methods used to extract river networks and related basin areas. Major river basins surrounding the Congo Basin are C, Congo; Ch, Chad; N, Nile; Ng, Niger; and Z, Zambezi.

South American continents at about 120 Ma [*Nürnberg and Müller*, 1991], the western margin of the present-day Congo Basin was located well within Gondwana and thus the Congo River may have experienced eastward directed flow instead of its present-day westward flow [*Stankiewicz and de Wit*, 2006]. Since rifting, the basin has experienced significant periods of internal drainage and shorter periods when waters were discharged to the Atlantic [*Goudie*, 2005]. *Goudie* [2005] summarizes that stream capture of the Congo River by a small coastal river may have occurred sometime in the past 30 Myr and that the river was fully linked to the Atlantic sometime during the Miocene. Supportive of this stream capture theory, downstream of Kinshasa-Brazzaville both *Oberg et al.* [2009] and *Stanley* [1885] measured mainstem Congo depths in excess of 100 m and that the channel bottom topography changes significantly in short stretches (see section 2.4). This led *Oberg et al.* [2009] to suggest that this downstream reach of the Congo River is more like a high-gradient mountain stream rather than the mouth of a major global river.

Among the more intriguing geologic issues is that the basin topography is above 300 m, yet lies atop the Congo craton (cratons are multibillion years old, tectonically inactive, crystalline rocks that form the core of continents, Figure 3). For example, from the river source to the Stanley Pool (also known as Malebo Pool) is about 4200 km flow distance with elevations mostly between 1000 m and 300 m. However, from the Pool to the Atlantic Ocean, the flow distance is about 500 km with a sharp 300 m change in elevation, as marked by unnavigable cataracts. Large rivers draining other cratons, such as the Mississippi River lying over the North American craton (known as Laurentia) or the Amazon River over the Amazonia craton, are at lower elevations and lack similar cataracts. For example, the confluence of the Mississippi and Ohio Rivers at Cairo Illinois is about 90 m in elevation, whereas the confluence of the Solimoes and Negro Rivers at Manaus Amazonas is about 20 m. To account for this higher topography, it has been suggested that the Congo craton is associated with a deep lithospheric mass [*Downey and Gurnis*, 2009] or is associated with buoyancy forces in the mantle [*Moucha and Forte*, 2011]. Despite these proposed dynamics, the 9 km thickness of sedimentary layers within the Congo Basin has not experienced any significant deformation, i.e., the thrust faults that produce structural

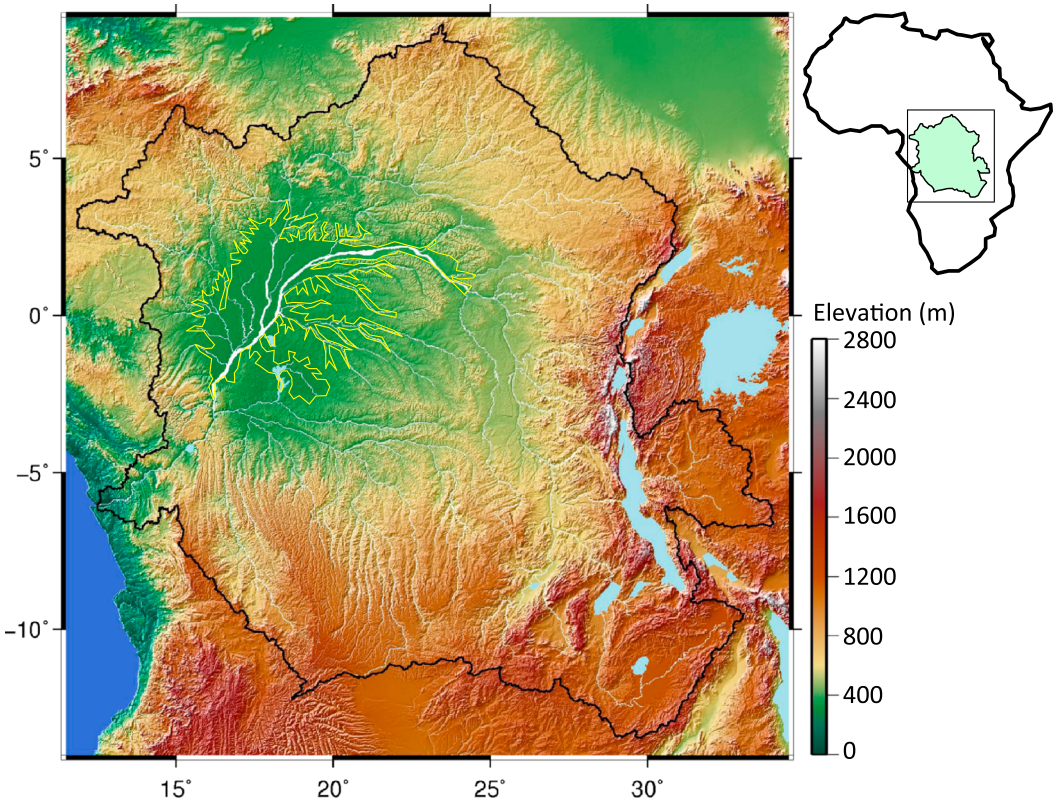


Figure 3. Congo Basin topography and location of Cuvette Centrale wetlands. Topography is from SRTM [*Farr et al.*, 2007], and location of Cuvette Centrale wetlands (yellow polygon) is generalized from *Bwangoy et al.* [2010].

highs within the basin have meter-scale throw [*Daly et al.*, 1992] as opposed to the mountain building thrust faults of the Himalaya and Andean orogenies with kilometer-scale motions.

1.3. Users of Water and Related Resources

Industrial activity, as well as small-scale and, in some places, illegal operations such as open-pit artisanal mines and logging, continues to grow in the Congo [*Koenig*, 2008]. For example, the multibillion dollar Kibali gold mine, which is a legal joint venture between three corporations and operated by Randgold and started in 2009, has already installed a 20 megawatt (MW) hydropower plant on the Nzoro River (N in Figure 1) and anticipates installing three more hydro facilities by 2016 [*RandGold*, 2012, 2013]. The U.S. Energy Information Agency [*Energy Information Agency*, 2014] indicates in their analysis brief that the Republic of the Congo (often called "Congo Brazzaville") is generating hydroelectricity at three plants but is only realizing 4% of their hydroelectric potential of nearly 4000 MW. The "Grand Inga Dam" is the follow on to the Inga I and Inga II dams, both located on the mainstem Congo downstream of Kinshasa-Brazzaville. This enormous project will cost $80 billion and will have twice the installed electricity generating capacity as the Three Gorges Dam [*Wachter*, 2007]. In March 2014, the World Bank continued its funding of the Inga projects by approving a $70 million "technical assistance project" to further prepare for this vast hydroelectric power capability at the Inga Dam location [*World Bank*, 2014]. In general, the hydroelectric potential of the Congo is significant compared to the few operating dams throughout the Congo, e.g., Inga I and Inga II, the Imboulou Dam on the Léfini River, the Mobaye Dam in the Oubangui Basin, and the Nzoro facility noted above.

In addition to these industrial users, the river networks present thousands of kilometers of navigable waterways and an opportunity for interbasin water transfer. The navigable portions change according to the drafts of the boats and seasonality of each river's hydrograph. Due to the poor quality or complete lack of roads and related infrastructure, navigation represents a better option for the supply of goods and services and of

regional trade. The continued decreasing water levels in Lake Chad, to the northwest of Bangui, have drawn the attention of commissioners and engineers. They have proposed that a dam and reservoir at Palambo, 65 km upstream of Bangui, on the Oubangui River could enable some water to be transferred via pumping over the basin divide and gravity flow in a new canal that would connect to the Chari River [*Salman and Momha*, 2009; *Lake Chad Basin Commission*, 2016]. Clearly, hydrology and hydrodynamics are important to all such operations.

1.4. A Brief History of Congo Hydrological Measurements

In the early 1900s, the Congo Basin was divided between Belgium and France. Belgium ruled the area generally to the south of the mainstem Congo containing the left bank tributaries and present-day Democratic Republic of the Congo (DRC), whereas France ruled the area to the north of the mainstem Congo containing the right bank tributaries and present-day Republic of the Congo (RoC) and Central African Republic (CAR). The hydrological networks in the Congo Basin were created during this colonial era, such that discharge and precipitation measurements were recorded during the first half of the 1900s in many Congo Basin locations. In fact, stage and hence discharge measurements have been recorded daily since 1902 on the Congo River at Kinshasa-Brazzaville (see section 2.3). While many records are available from the 1930s through the 1950s, these measurements were not always continuously recorded such that temporal gaps exist or measurements were made for a brief time period. Because of poor funding or because the overseeing hydrological agency no longer exists, few recent stations have records longer than a decade. Fortunately, there are agencies that have kept records such as the National Navigation Service, *Groupement d'Interet Economique Service Commun d'Entretien des Voies Navigables de la Republique du Congo et la Republique Centraafricaine* (*GIE-SCEVN*) [2015], and the collaboration of IRD with the Ministère de la Recherche Scientifique, Congo to form the DGRST (Délégation Générale à la Recherche Scientifique et Technologique). The archives of the *GRDC* [2014] are also available. The colonial geographic division of the Congo has more or less continued since the 1960s independence such that many hydrologic research reports are archived in French institutes, e.g., the Institut de Recherche pour le Développement (IRD, which before 1998 was the Office de la Recherche Scientifique et Technique Outre-Mer, ORSTOM) or in Belgian institutes, e.g., the Royal Academy for Overseas Sciences or the Royal Museum for Central Africa. Studies including many doctoral theses, various papers, and gray literature on the hydrology of the left bank sub-basins were and continue to be conducted by universities of the DRC often in partnership with universities and Belgian institutions, while those on the right bank are mainly between universities in the RoC and CAR often in partnership with universities and French institutions in line with earlier work initiated by ORSTOM during the 1940s.

As a specific example of the type of work that has gone on in the Congo Basin, stage measurements at the Kinshasa-Brazzaville stream gauge have been recorded since 1902 by the Régie des Voies Fluviales at the Kinshasa station on the left bank (DRC) and are available until 1983 in the *Mateba 22 report* [1984] and from the Global Runoff Data Center (GRDC, see section 2.3). These left bank data have been used to extend the water stage data series from the Brazzaville station on the right bank back to 1902 [*Olivry et al*., 1989]. In fact, for the Brazzaville station, measurements of water stage have been carried out since 1947, first by ORSTOM and then by *GIE-SCEVN* [2015]. Stage discharge rating curves were developed by ORSTOM for the Maluku Trechot gauging station 30 km upstream using traditional gauging with current meters. An inventory of existing monthly data series can be found on the Système d'Informations Environnementales sur les Ressources en Eau et leur Modélisation (SIEREM) website [2015; *Boyer et al*., 2006] with links to the original data from various Congo national services. Recent daily hydrometric data for the Brazzaville gauging station are available from the Environmental Research Observatory *HYBAM* [2015] starting in 2005 and continuing until today in near real time, thanks to the collaboration of the GIE-SCEVN agency of Brazzaville. This station also provides monthly biogeochemical measurements, which are freely available via the collaboration of the DGRST with Université Marien Ngouabi in Brazzaville.

2. Hydrologic Measurements and Related Models

Describing the water balance of a basin or sub-basin is often a starting point for understanding its hydrology. The standard equation is generalized as

$$\Delta S = P - E - Q \tag{1}$$

where ΔS is the change in water storage over some given time period; P and E are the amounts of precipitation

Table 2a. Basic Water Balance Values From Various Authors[a]

Reference	Notes	Location	Years	Amount (mm)
Samba et al. [2008]	Gauge[b]	Impfondo	1950–1998	1757
Samba et al. [2008]	Gauge[b]	Gamboma	1950–1998	1717
Samba et al. [2008]	Gauge[b]	Djambala	1950–1998	2028
Samba et al. [2008]	Gauge[b]	Brazzaville	1950–1998	1394
Kazadi and Kaoru [1996]	Gauge[b]	Bunia	1960–1992	1540
Kazadi and Kaoru [1996]	Gauge[b]	Mbandaka	1960–1992	1780
Kazadi and Kaoru [1996]	Gauge[b]	Goma	1960–1992	1135
Kazadi and Kaoru [1996]	Gauge[b]	Bandundu	1960–1992	1540
Kazadi and Kaoru [1996]	Gauge[b]	Kinshasa	1960–1992	1422
Kazadi and Kaoru [1996]	Gauge[b]	Matadi	1960–1992	991
Kazadi and Kaoru [1996]	Gauge[b]	Lubumbashi	1960–1992	1174
Bultot and Griffiths [1972]	Gauge[b]	Yangambi	1930–1959	1828
Bultot and Griffiths [1972]	Gauge[b]	Bambesa	1930–1959	1781
Bultot and Griffiths [1972]	Gauge[b]	Kinshasa	1930–1959	1375
Bultot and Griffiths [1972]	Gauge[b]	Gandajika	1930–1959	1395
Bultot and Griffiths [1972]	Gauge[b]	Lubumbashi	1930–1959	1244
Bultot and Griffiths [1972]	Gauge[b]	Tshibinda	1930–1959	1833
Brutsaert [1965]	Gauge[b]	Luberizi	1957	934
Riou [1984]	Gauge[c]	Bangui	pre-1984	1600
Beighley et al. [2011]	TRMM[d]	Oubangui Basin	1998–2011	1227
Beighley et al. [2011]	PERSIANN[e]	Oubangui Basin	2000–2011	2876
Beighley et al. [2011]	CMORPH[f]	Oubangui Basin	2002–2011	2484
Beighley et al. [2011]	TRMM[d]	Kasai Basin	1998–2011	1372
Beighley et al. [2011]	PERSIANN[e]	Kasai Basin	2000–2011	2540
Beighley et al. [2011]	CMORPH[f]	Kasai Basin	2002–2011	2403
Beighley et al. [2011]	TRMM[d]	Congo Upstream	1998–2011	1498
Beighley et al. [2011]	PERSIANN[e]	Congo Upstream	2000–2011	3484
Beighley et al. [2011]	CMORPH[f]	Congo Upstream	2002–2011	3014

[a]Annual precipitation values are given in millimeters and are averaged over the years listed.
[b]Monthly data presented from in situ rain gauges.
[c]Monthly data presented in graphical form.
[d]Satellite-based TRMM data at 0.25° resolution.
[e]Satellite-based PERSIANN data at 0.25° resolution.
[f]Satellite-based CMORPH data at 0.25° resolution.

and evaporation during that same time (*E* includes evapotranspiration in this generalization); and Q is net outflow from the basin, which is often considered the summed river discharge during the given time but can also include groundwater fluxes. The following subsections describe our understanding of each of these values. Table 2a provides a summary of each value. This table does not include all values from all publications, rather it is representative of various time periods and geographic locations.

2.1. Precipitation

Both in situ and satellite-based precipitation data are available for the Congo Basin (Table 2a). For example, monthly rainfall data for many locations throughout the African continent are available from SIEREM [*SIEREM*, 2015; *Boyer et al*., 2006], which includes metadata on several thousand rain gauges throughout Africa and from 958 within the Congo Basin. The past century of raw data from these sources has been used to generate a gridded monthly rainfall database for the years 1940–1999 [*Rouché et al*., 2010]. Raw data are not publicly available from the SIEREM website but can be requested from the National Services (contact information is given in the website). Metadata regarding river discharge, evaporation, temperature, atmospheric pressure, wind speed, relative humidity, water level, sunshine duration, and saturation vapor pressure are available from the SIEREM web pages. The contemporary gauge-based data are sparsely distributed, with the right bank tributaries of the Congo mainstem better reported than others, especially in comparison to those tributaries of the left bank. In contrast, the satellite data are well distributed but not well validated.

All data show the well-known migration of rainfall across the basin with the main seasonal peak in precipitation falling around December–March in the basin areas well south of the equator and falling around

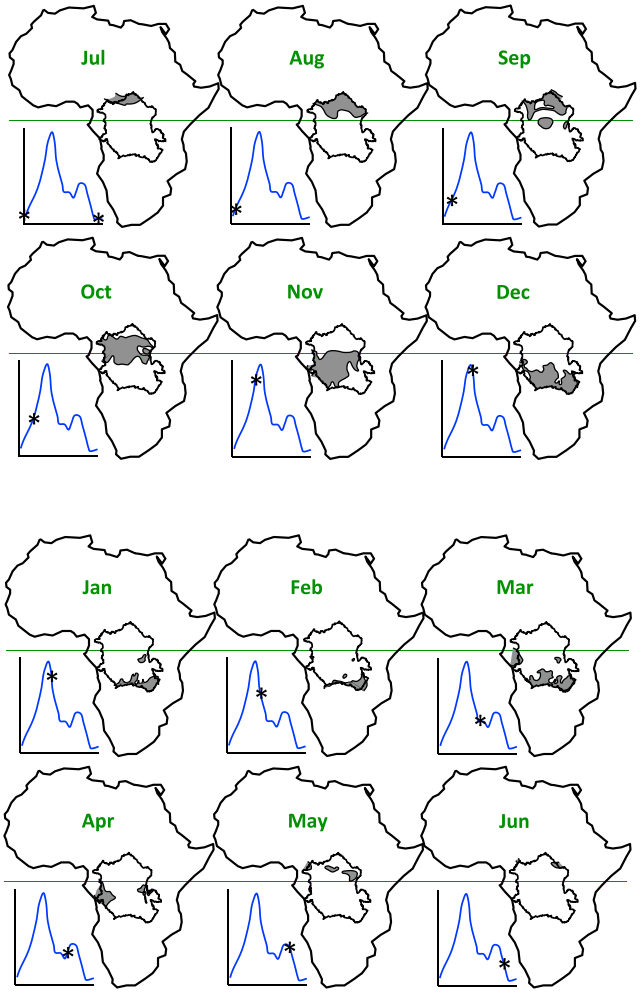


Figure 4. Locations of large rainfall amounts in the Congo Basin and discharge time series approximated from the Kinshasa-Brazzaville gauging stations. Grey polygons are the 200 mm contour copied from *Bultot* [1971]. This contour indicates a geographic location for large rainfall amounts during a given month. The hydrograph is a simple representation of Congo River discharge based on the century of streamflow measurements at Kinshasa-Brazzaville. Asterisks mark the given month on the hydrograph. Note that discharge for the given month originated from precipitation that fell between 15 days and 2 months prior and with locations more distant from Kinshasa-Brazzaville taking more flow time (see section 2.3). The green line marks the equator. As of September 2014, copyright permission for *Bultot* [1971] rainfall has been granted by the L'Institut National pour l'Etude et la Recherche Agronomique in the DRC.

July–October for the regions north of the equator (Figure 4) [e.g., *Bultot*, 1971; *Kazadi and Kaoru*, 1996; *Mahé*, 1995; *Mahé et al*., 2012]. Those locations nearest the equator show two peaks each year, with a lesser peak during March–May and a greater peak during September–November. Historically and until somewhat recently, the north-south movement of rainfall across the Congo Basin has been assigned to the seasonal migration of the Intertropical Convergence Zone (ITCZ). This previous viewpoint held that the ITCZ enhanced local convection thus delivering the migrating rainfall patterns with ITCZ movement. However, meteorologists are currently challenging this view by demonstrating that the rainfall patterns may be due to mesoscale convective systems bounded by the seasonally migrating Northern and Southern Africa Easterly Jets and enhanced by orography, i.e., the bowl like topography of the Congo Basin [*Jackson et al*., 2009] (see Figure 3). Because we focus on precipitation, rather than the atmospheric drivers of the ITCZ and of Africa's jets, throughout this manuscript we have adopted the "tropical rainbelt" terminology of *Nicholson* [2009] to designate the seasonal movement of precipitation across the basin.

Bultot [1971] provides maps of monthly-averaged and mean-annual precipitation based on "500 reference stations" that are well distributed across the basin and which collected rainfall data from 1930 to 1959 (Figures 4 and 5). His basin-wide analysis is the most spatially comprehensive effort from the decades before 1960. Small *XY* plots with monthly and annually averaged rainfall totals are given for 22 locations. Eleven of these 22 are repeated in tabular form in *Bultot and Griffiths* [1972]—a reference that is perhaps more easily attained. He estimates the basin-wide annual-average rainfall at 1527 mm [*Bultot*, 1971, Figure 43]. Annual-average rainfalls for seven sub-basins are also provided. Bultot's data are a valuable historic marker as these provide annual-average rainfalls for seven sub-basins. The historical significance of these Bultot maps is important for helping to dispel ideas that hydrological measurements do not exist in the Congo and, moreover, for ensuring that studies focused on long-term hydrological or climatological change have sufficient data.

Mahé et al. [2012] provide an important and historic to contemporary source of precipitation data. Their rainfall map covers all of Africa and is composed of about 6000 rain gauge stations from 1940 to 1999. It is

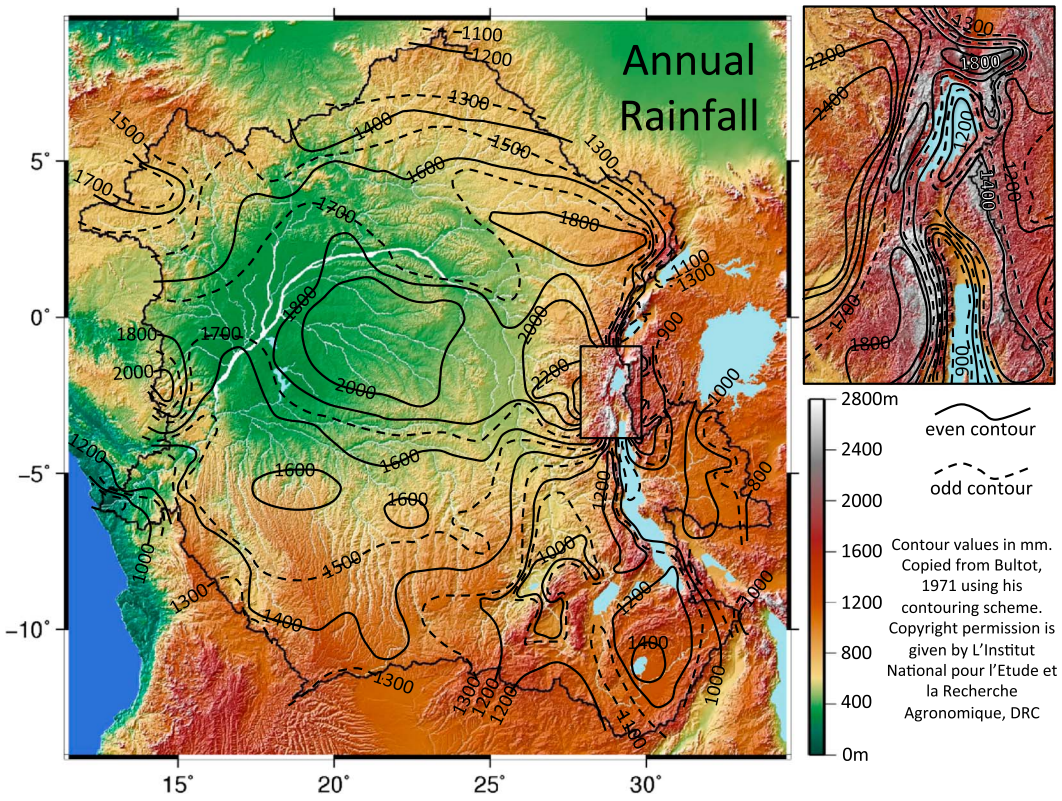


Figure 5. Congo Basin annually averaged rainfall overlain on topography. Contours copied from *Bultot* [1971]. Topography is the same as Figure 3. As of September 2014, copyright permission for *Bultot* [1971] rainfall has been granted by the L'Institut National pour l'Etude et la Recherche Agronomique in the DRC.

an annual average of this entire 60 year period at a half-degree spatial resolution. While the Congo mainstem right bank sub-basins are well represented in this map, there are also dozens of rain gauging stations from the left bank sub-basins. *Mahé* [1995] finds an interannual average of about 1560 mm over the period 1951–1989, from 251 stations that cover the entire basin. The interannual variability ranges from a high of 1610 mm during the wettest decade 1961–1970 to a low of 1515 mm during the driest decade of 1981–1989. Due to lack of measurements and available data since the 1990s over the area, it is only recently that new work has been performed on a rainfall gridded data set for the Congo basin [e.g., *Tshitenge Mbuebue et al*., 2015]. *Tshitenge Mbuebue et al*. [2015] showed three major shifts (around 1960, 1970, and 1983) in the signal (i.e., the stationarities) of the rainfall in the Congo, Kasai, and Oubangui Basins, which affected the 2–4 year, 4–8 year, and the 8–16 year bands. Wavelet coherence confirms a weak relationship between the rainfall of the Congo basin and the long-term forcing sea surface temperature (SST) of the Pacific and tropical Atlantic. The rainfall decrease after the 1970s is less apparent in the east and southeast portions of the basin, than in the north and western portions, and is more influenced by the Atlantic monsoon flow than by the Indian and South African air masses.

Samba et al. [2008] present a detailed analysis of in situ measured rainfall in the northern basin. They focused on 13 precipitation gauges in the Republic of the Congo with data from 1950 to 1998. They report annual rainfall amounts from four stations located within the Basin (Table 2a). Average monthly variations for these stations are, unfortunately, not reported in raw numbers, which would be useful for water balance studies, but are instead presented in a figure as normalized anomalies. In the five decades of observations at Gamboma, Djambala, and Brazzaville, the July dry season is more pronounced than the March or November wet seasons. Using Mann-Kendall tests, *Samba et al*. [2008] show that rainfall deficits begin in 1986 for Impfondo with a 13% decline, begin in 1979 for Gamboma with a 9% decline, and begin in 1980 for Djambala with a 6% decline, whereas no significant multidecadal trend exists at Brazzaville. These deficits extend to the end of the data in 1998.

Kazadi and Kaoru [1996] present a detailed analysis of in situ measured rainfall from seven gauges located in the Democratic Republic of the Congo (DRC, Table 2a). Four of these gauges are located on or very near the mainstem Congo River, two are on the flanks of the east Africa rift system, and the seventh is in Lubumbashi, located near the southernmost basin divide. Essentially, none are located well within the sub-basins whose rivers drain the southern portions of the Congo Basin. Data extend from 1960 to 1992 and show declines of 10% to 40% in precipitation for five of the seven gauges (percentages are in comparison to the three-decade averages). Two stations with the largest declines are located at the easternmost and southernmost edges of the basin, whereas modest declines or even gains are noted at the other five gauges. The number of rainy days declined by as little as 1 day to as much as 73 days (a rainy day is defined as having more than 0.1 mm of rainfall measured at a given station). Interestingly, *Kazadi and Kaoru* [1996] report that the Kinshasa gauge showed an increase in precipitation from 1960 to 1990 by 239 mm, compared to their long-term annual average of 1422 mm (i.e., 17% increase). *Samba et al*. [2008] report essentially the same long-term annual average at Brazzaville, which is located across the Congo River from Kinshasa, but they do not find any multidecadal changes in precipitation. The reason for this discrepancy is not clear, especially given that the two gauges have nearly the same multidecadal annual mean values.

Both *Samba et al*. [2008] and *Laraque et al*. [1998a] present gauge-based monthly rainfall data at Ouesso, presumably from the same gauge. The *Samba et al*. data are from 1950 to 1998 and are presented graphically as normalized anomalies, whereas the *Laraque et al*. data are from 1985 to 1994 and are presented graphically as raw values. *Laraque et al*. show that October has about 30 mm less rainfall than their September, whereas *Samba et al*. suggest that these two months have the same rainfall. *Laraque et al*. show that November has 20 mm less rainfall than their June, whereas *Samba et al*. suggest that November has a greater rainfall than June. The reason for these greater October and November values in *Samba et al*. is not clear, given that they suggest that September-October-November at Ouesso have no multidecadal trends, whereas they do indicate from other gauges that the region around Ouesso has experienced a decline in precipitation of 10% to 20% during 1980s and 1990s (as compared to the data from the 1950s).

Laraque et al. [2001] used four statistical tests to analyze rainfall from the right bank sub-basins whose rivers drain the northern and western portions of the Congo Basin. They found that all of the sub-basins experienced a decrease in rainfall when comparing the first years to the last years of the data, i.e., from 1951 to 1993. For example, the Oubangui basin experienced a 3.2% decrease in rainfall when comparing 1951–1960 to 1961–1999, whereas the entire Congo Basin experienced a decreased rainfall of 4.5%. While the authors report that 160 rain gauging stations are available throughout the entire Congo Basin, their focus was on that data from the right bank tributaries which contain the only gauges with daily data, continuous over decades. Similarly, *Mahé et al*. [2001] analyzed rainfall data from 891 gauges across west and central Africa and suggest that for the Congo Basin any rainfall trend from 1951 to 1989 is minimal and that there are no discontinuities. Unfortunately, they were not allowed to present the raw precipitation values; fortunately, all of these data have been used to create the new monthly rainfall gridded data set over the period 1940–1999 that is available from the SIEREM website.

Satellite-based rainfall data are available from the well-known Tropical Rainfall Measuring Mission (TRMM) [*Kummerow et al*., 1998] as well as from the Climate Prediction Center Morphing technique (CMORPH) [*Joyce et al*., 2004] and from the Precipitation Estimation from Remote Sensing Information using Artificial Neural Network methodology (PERSIANN) [*Hsu et al*., 1997]. Using the Hillslope River Routing model, *Beighley et al*. [2011] compared the precipitation values from these three satellite-based methods and found that CMORPH and PERSIANN often provide significantly more rainfall compared to TRMM (Table 2a). For example, they separated the basin into nine different Pfafstetter units (similar to sub-basins) and found that for the unit comparable to the Oubangui Basin mean-annual rainfall was 1227 mm in the TRMM data, whereas it was 2484 mm and 2876 mm in the CMORPH and PERSIANN data sets, respectively. For comparison, *Bultot* [1971] estimated the mean-annual rainfall for the Oubangui Basin at 1534 mm, while *Mahé* [1995] found 1529 mm during 1951–1989. *Beighley et al*. [2011] also compared the rainfall generated runoff from the satellite-based data sets to in situ gauge estimates of river discharge in four different sized sub-basins (sizes ranged from 34 K km^2 to the entire basin): results suggested that TRMM rainfall, compared to CMORPH and PERSIANN, yielded discharge that more closely matched gauged river values.

Table 2b. Basic Water Balance Values From Various Authors[a]

Reference	Notes	Location	Years	Amount (mm)	Amount (mm)
				PET	AET
Bultot and Griffiths [1972]	PET AET[b]	Yangambi	1930–1959	1095	1091
Bultot and Griffiths [1972]	PET AET[b]	Bambesa	1930–1959	1217	1176
Bultot and Griffiths [1972]	PET AET[b]	Kinshasa	1930–1959	1110	970
Bultot and Griffiths [1972]	PET AET[b]	Gandajika	1930–1959	1211	1108
Bultot and Griffiths [1972]	PET AET[b]	Lubumbashi	1930–1959	1161	836
Bultot and Griffiths [1972]	PET AET[b]	Tshibinda	1930–1959	971	962
				ET	E
Brutsaert [1965]	ET E[c]	Luberizi	1957	1623	2459
				PET	
Riou [1984]	PET[d]	Bangui	1966–1971	1239	
Riou [1984]	PET[d]	Brazzaville	1968–1971	1071	

[a]Annual evaporation and evapotranspiration values are given in millimeters and are averaged over the years listed. The usage of potential and actual follows the original, quoted authors nomenclature. PET, potential evapotranspiration.
[b]Potential ET, PET, calculated from energy balance methods; Actual Evapotranspiration, AET, calculated from Thornthwaite's method.
[c]In situ lysimeter was used to measure ET; an in situ pan was used to measure *E*.
[d]In situ pans and in situ lysimeters were used to measure potential ET.

McCollum et al. [2000] determined that the differences between rain gauge and satellite-based measurements of rainfall were not a result of the sparse distribution of rain gauges, rather were a result of cloud physics. They found that satellite estimates of rainfall from the Global Precipitation Climatology Project [e.g., *Xie et al*., 2003] provide too great of rainfall compared to values from in situ gauges, which they ascribed to the presence of aerosols and the heights of cloud bases. They noted that aerosols result in small drop sizes, which combined with high cloud bases yield a rainfall that evaporates before reaching the ground and hence an overestimate by satellite methods compared to gauges. The bases of convective clouds that form under dry air conditions, such as those of central equatorial Africa, are generally higher than bases of clouds forming in moist air environments, such as those of South America. Thus, they find that central Africa yields an anomalously high satellite-based estimate of rainfall when compared to gauges, whereas the satellite estimates for South America are more correct.

In summary, based on the studies that address multidecadal in situ measurements of rainfall, there is not a clear agreement that precipitation has significantly declined from 1960 to 1990 across the entire basin. Some authors report declines in some areas, notably at the west and north basin boundaries, whereas others suggest essentially no substantial change for the entire basin. Perhaps, the most striking result of this review of published in situ precipitation data is the lack of contemporary measurements from sub-basins draining the south and flowing into the left bank of the mainstem Congo River. This lack of southern basin in situ values places some limitations on validating satellite-based rainfall products. Although *Bultot* [1971] is a reference that is difficult to obtain, the maps (e.g., Figures 4 and 5) demonstrate that important precipitation data are available for the entire Congo Basin from the decades before 1960, and this is confirmed by the recent map of rainfall for Africa by *Mahé et al*. [2012] which was drawn on the basis of a new 1940–1999 monthly rainfall gridded data set.

2.2. Evapotranspiration and Temperature

Compared to precipitation, less information is published regarding evapotranspiration and temperature. Note that in this section, we use the same "potential" and "actual" nomenclature as the cited authors. Like precipitation, *Bultot* [1972] provides basin-wide maps of monthly and annually averaged temperatures "based on 229 reference stations" for the years 1950 to 1959. Reading the maps, it appears that the annual average daily maximum, mean, and minimum temperatures for most of the Congo Basin are 30°C to 31°C, 23°C to 25°C, and 18°C to 20°C, respectively. *Bultot and Griffiths* [1972] (Table 2b) estimate ET over *Paspalum notatum* and state that "the annual potential evapotranspiration does not differ greatly from one region to the next (from about 1,100 to a little over 1,200 mm) …." Furthermore, using Thornthwaite's water balance method, they indicate that the actual ET in the wet season is usually equal to the potential ET, whereas in the dry season the actual ET is less than the potential ET. The actual ET does vary from region to region across the basin from "a little more than 800 mm in Katanga to a little less than 1200 mm in

Uele" (Katanga is a region in the southernmost Lualaba Basin, and the Uele region occupies the eastern portion of the Oubangui Basin). For the entire Congo Basin, the actual ET "generally measures between 75% and 85% of the annual precipitation."

Nicholson et al. [1997] found similar ET results. They combined in their climatonomy model 60 years of rainfall from 1400 gauging stations distributed across Africa with other input variables that described soils and vegetation. Outputs included ET, runoff, and soil moisture. Across the Congo Basin, they find annually averaged ET peaking at about 1500 mm/yr, decreasing northward and southward to less than 1000 mm/yr. As a quality check on their model, they find annually averaged runoff varying from 200 mm/yr to 500 mm/yr. Assuming a midrange value of 350 mm/yr for the entire Congo Basin and using our measurement for the basin area above Kinshasa-Brazzaville yield an annual-average discharge of 40,100 m^3/s. This is well aligned with measured discharge values at the river gauge in Kinshasa-Brazzaville (see section 2.3).

Brutsaert [1965] studied the Ruzizi valley located in the easternmost portion of the Congo Basin. The valley connects Lake Kivu to the north with Lake Tanganyika to the south and is part of the African rift valley system. He measured daily evaporation using a pan method and measured evapotranspiration using a lysimeter (Table 2b). Both *E* and ET more than doubled during 1957 with smallest values in February and largest in September. Potential evaporation from Penman's and Thornthwaite's estimation methods yielded lower seasonal variability than measured *E* given the low variability in temperature. *Riou* [1984] presented results from a 10 year study along a corridor from Chad in the north to Bangui and Brazzaville in the south. He used pan and lysimeter methods (Table 2b). Measured potential ET at Bangui and at Brazzaville was greatest in March–April and least in July, with the maximum to minimum differences being much smaller than those of the Ruzizi valley. Note that Brutsaert's ET values from the African rift system are greater than those of Riou from the northwestern portions of the Congo Basin.

In addition to analyzing rainfall data (see section 2.1), *Samba et al*. [2008] also examined temperature data at the same locations. They report that average temperatures at Brazzaville range from 22°C to 26°C. Based on their analysis of data within the northern portions of the Congo Basin, the annual-average temperatures from the 1990s compared to the 1950s have increased by 0.4°C to 1.0°C (depending on station location). Similarly, *Kazadi and Kaoru* [1996] also found a small range in temperature when comparing the cold and warm months: generally a range of about 2°C for stations within the Congo Basin and about a 4°C to 6°C range for stations near the western and southern basin divides. Based on their analysis of stations within the DRC, they also find increasing temperatures from 1960 to 1990 with increases of 0.60°C/30 yr to 1.62°C/30 yr. For comparison, the 1957 temperatures in the Ruzizi valley study of *Brutsaert* [1965] ranged from 21°C to 24°C with a 12 month average of 22.6°C, whereas *Kazadi and Kaoru* [1996] found that Goma, located north of the Ruzizi valley, had a 30 year average of 18.9°C.

Kazadi and Kaoru [1996] also investigated the temperature data for periodicities. Using Fourier band-pass filtering and cross correlation with the Southern Oscillation Index (SOI), they found that filtered temperatures from four of the stations had a −0.5 to −0.6 correlation with the SOI. They suggested that anomalously warm conditions over the Congo are more likely to be observed 2 to 8 months after El Nino has started over the Pacific.

2.3. River Discharge

Before 1960, there were more than 400 stream gauges throughout the Congo Basin, whereas today there are only about 10 operating stations [e.g., *Croneborg*, 2013] (note that not all of these stations are available via the GRDC). Two stations with amongst the longest, continuous records of discharge are at Brazzaville-Kinshasa and at Bangui. Congo River discharge data from the Kinshasa station in the DRC are available from the GRDC, with daily data extending from 1903 to 2010, and similarly available from the GRDC are daily discharge values on the Oubangui River at the Bangui station from 1935 to 2007 (Figure 6). Data from 1941 to 2015 for the Brazzaville station are available from the hydrological services of GRSEN Groupe de Recherche en Sciences Exactes et Naturelles and Service Commun d'Entretien des Voies Navigables. The Kinshasa-Brazzaville gauges provide an estimate of discharge for just over 98% of the Congo Basin area (see areas in section 1.1 and in Figure 2 and see historical description of the combined Kinshasa-Brazzaville gauges in section 1.4). In all, the GRDC has discharge data from 96 stations within the Congo Basin and with the majority having more than 10 years of data (Table 3).

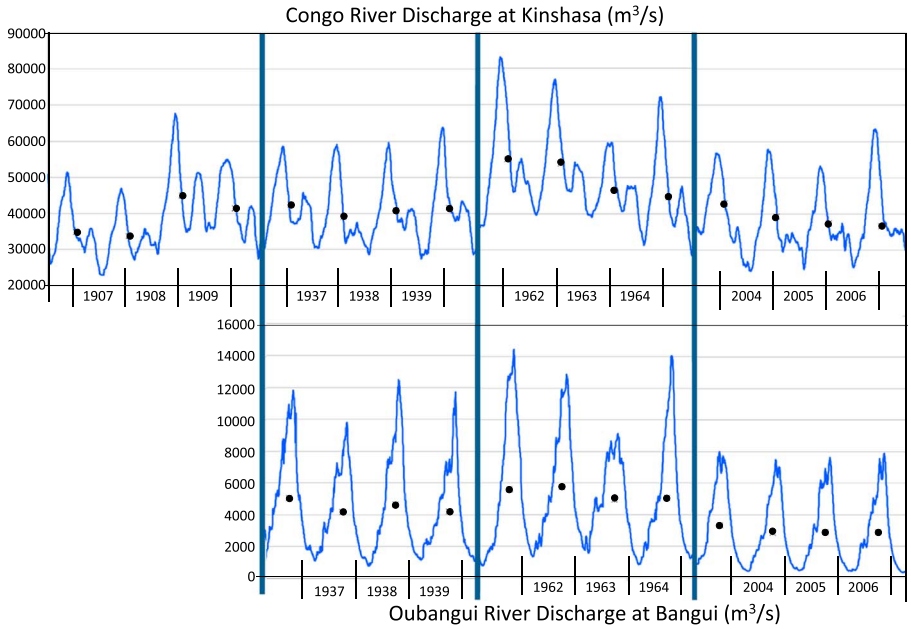


Figure 6. Congo River discharge at Kinshasa and Oubangui River discharge at Bangui. Data are provided by *GRDC* [2014]. Dots are the average of daily discharge values for a given water year. We use low flows as the water year delineator; thus, the Congo River water year at Kinshasa starts in early August and ends in late July. Oubangui River water year starts in early April and ends in late March. Calendar years are noted on *X* axis.

The present-day mainstem Congo River discharges an annual flow of 40,662 m^3/s (Table 2c). Our mean discharge value is a straightforward average of the *GRDC* [2014] daily streamflow values from 2001 to 2010 reported from the Kinshasa-Brazzaville gauge. This most recent decade of river flow agrees with the value of 40,612 m^3/s of *Laraque et al.* [2013a] who calculated their average from a century of data from 1902 to 2010. This is interesting because, as described below, the Congo discharge has varied considerably between 1960 and about 1995 and is only now returning to its long-term average. Monthly gauge data from about 1950 to 1994 and daily gauge data from 1987 to 1994 for 11 stream gauge stations on tributaries of the mainstem Congo right bank are provided by *Laraque and Maziezoula* [1995]. This document and its references provide technical details of

Table 2c. Basic Water Balance Values From Various Authors[a]

Reference	Notes	Location	Years	Amount (m^3/s)
This Paper	Average[b]	KB[h]	2000–2010	40,662
This Paper	Average[b]	KB	4–13 July 2008	32,015
This Paper	Average[c]	KB	Aprils, 1903–1907	35,082
This Paper	Minimum[d]	KB	2 April 1907	29,270
This Paper	Maximum[e]	KB	24 April 1904	42,140
Oberg et al. [2009]	ADCP[f]	Luozi	4 July 2008	35,800
Stanley [1885]	In situ[g]	Kinshasa	April 1882	40,687
Laraque et al. [2001]	Average[b]	KB	1936–1993	40,300
Laraque et al. [2001]	Average[b]	KB	1902–1959	39,600
Laraque et al. [2001]	Average[b]	KB	1960–1970	48,000
Laraque et al. [2001]	Average[b]	KB	1971–1981	41,400
Laraque et al. [2001]	Average[b]	KB	1982–1993	37,500
Laraque et al. [2013a]	Average[b]	KB	1903–2010	40,600

[a] Discharge values are given in m^3/s and are averaged over the given time period.
[b] Average of daily data on the Congo River for the given time period, i.e., over a few days to several years.
[c] Average of daily data on the Congo River for 30 days in each April from 1903 to 1907.
[d] Minimum of the daily data on the Congo River during 30 April days for 1903–1907.
[e] Maximum of the daily data on the Congo River during 30 April days for 1903–1907.
[f] ADCP measurements collected from kayaks at nine locations below Kinshasa.
[g] Plumb line used to measure depth; velocity was estimated.
[h] KB indicates the gauges at Kinshasa and Brazzaville.

Table 3. Numbers of Stream Gauges Available via the *GRDC* [2014][a]

Year Range	Number of Gauges With Data
pre-1940	7
1940–1950	10
1950–1960	24
1960–1970	27
1970–1980	78
1980–1990	82
1990–2000	47
2000–2010	21
2010–current	1
Years of Data	**Number of Gauges**
>50	3
41–50	11
31–40	12
21–30	15
11–20	25
1–10	30

[a]The top portion indicates how many gauges have discharge data available for the indicated decade. The bottom portion indicates the numbers of gauges having the noted number of years of discharge data, e.g., three gauges have more than 50 years of discharge available. See Figure 1a for locations of these 96 stream gauges.

the 1987 to 1994 Program of Study of the Intertropical Geosphere Operation Great Basin Fluvial (PEGI/GBF) monitored by ORSTOM and the Congolese General Directorate for Scientific Research (DGRST).

Rating curves for the Kinshasa station have not been updated since the 1960s (M. A. Trigg, personal communication during his visit to Kinshasa, 2013). The rating curve for the Maluku Trechot station, located 30 km upstream of Kinshasa-Brazzaville, was not updated during the three decades of 1980 to 2010. Recently, however, a series of acoustic Doppler current profiler (ADCP) measurements were started in June 2010 by the ORE-Hybam program and are now continued by the Congo-Hydrological Cycle Observing System (HYCOS) program on the Maluku Trechot and Brazzaville-Kinshasa reach of the Congo mainstem (HYCOS is the Hydrological Cycle Observing System of the World Meteorological Organization, WMO). Maluku Trechot is located just upstream of the Stanley Pool, whereas Kinshasa-Brazzaville is just downstream of the pool. The pool is a wide channel reach of about 25 km width and 35 km length, characterized by numerous sand bars, which emerge during low flows. *Laraque* [2010] presents the first ADCP discharge measurements of this reach and suggests that there has been little change in the channel.

Oberg et al. [2009] and *Stanley* [1885] each provide one-time estimates of discharge. In 4–13 July 2008, *Oberg et al*. [2009] used kayaks and pirogues equipped with differential GPS, ADCP, and echo sounders to measure channel depths and water velocities. Their discharge estimate of 35,800 m^3/s at Luozi (DRC) compares well with 32,015 m^3/s, which is the 10 day average from 4 to 13 July 2008 at the Kinshasa gauge (Table 2c) and agrees with the values from the Brazzaville station. Their measurements are collected at nine locations between ~130 km and ~200 km downstream of Kinshasa. In these distances, a few tributaries contribute to the mainstem flow and thus their larger discharge value is expected. Moreover, they note that discharge tended to decrease between 9 and 13 July, which is also in agreement with a decrease at the Kinshasa gauge. In April of 1882, *Stanley* [1885] collected depth soundings and measured the width of the Congo mainstem just above the Stanley Pool. He estimated the flow velocity at "three and half knots per hour" (i.e., 1.80 m/s) to calculate a discharge of 1,436,850 ft^3/s (i.e., 40,687 m^3/s). Two decades later, the Kinshasa gauge values from just the 30 days of each of the five Aprils from 1903 to 1907 range from 29,270 m^3/s to 42,140 m^3/s (Table 2c, Figure 6 shows values from mid-1906 to mid-1910). These two comparisons provide a sense of the quality of the Kinshasa-Brazzaville gauge discharge values at opposite ends of its century of history.

Laraque et al. [2001] analyzed daily discharge data at the main hydrological stations of eight right bank tributaries of the Congo mainstem between 1950 and 1993 and at Brazzaville, from 1902 to 1993, and found four periods of statistically significant discharge segments: for Brazzaville 1902–1959 is considered the background discharge value (annually averaged value of 39,600 m^3/s), whereas, in comparison to this background, 1960–1970 saw a 21% increase, 1971–1981 had a 4.5% increase, and 1982–1993 saw a decrease of −5.3% in discharge (Table 2c). They analyzed the records from nine stream gauges located in tributaries draining the northern sub-basins of the Congo and found similar segments of increased discharge during 1960–1970 followed by decreased discharge in the two decades that followed (see Figure 6 for examples of Oubangui River discharge). *Orange et al*. [1997] showed that some of the discharge decrease in the Oubangui River resulted from a decrease in groundwater storage, due to the long lasting rainfall shortage since the 1970s in the northernmost part of the Congo Basin. *Mahé et al*. [2013] reviewed the Congo River

discharge from Brazzaville and also noted similar decadal shifts, with a more recent return to normal flows (i.e., since 1995) [*Laraque et al*., 2013a], but also indicated that there is no long-term trend over the past century. In their plot of ~100 years of annually average discharge, the Congo River experienced its greatest discharge in the 1960s, the only years in which the annual average exceeded 50,000 m^3/s. Annual-average low flows appear to be about 30,000 m^3/s and high flows about 55,000 m^3/s, hence a near doubling in discharge from low to high.

Runge and Nguimalet [2005] analyzed flood frequencies using Oubangui River discharge hydrographs at Bangui for 73 years between 1911 and 1999. They determined that floods with a 2 year return period have magnitudes of about 9800 m^3/s, whereas the 100 year flood should have a magnitude of 15,800 m^3/s: a value that compares well with the largest flood on record, in October of 1916 at 16,000 m^3/s. Similar to *Laraque et al*. [2001], *Wesselink et al*. [1996] and *Runge and Nguimalet* [2005] find that maximum discharge values decreased after the 1960s and remained low until the 1990s (e.g., Figure 6).

The large size of the Congo Basin spread beneath the migrating tropical rainbelt and its seasonally migrating rainfall (see section 2.1) produces flood waves on the various tributaries that have differing timings of water pulses delivered to the downstream Congo mainstem. *Bricquet* [1995] estimated the time that it takes for water masses to leave their originating basin until arrival at Brazzaville: it takes 2 months for the water mass to move from the confluence of the Lualaba and Elila Rivers (see Figure 1b) to Brazzaville; it takes 1 month for transport from the confluence of the Kotto and Oubangui Rivers; and it takes about 15 days from the confluence of the Loange and Kasai Rivers. *Bricquet* [1995] separates the Congo Basin into 10 different zones (essentially sub-basins) and provides timings of flood waves and water amounts seasonally contributing to the total outflow from the entire basin. Some zones contribute 0.5 $L/s/km^2$ (outlet of Lake Tanganyika) and others as much as 20 or even 35 $L/s/km^2$ (zones containing the Batékés plateau).

In Figure 6, we note that the dual-peaked nature of the Congo River discharge at Kinshasa might be changing over time. In the early 1900s, the April–May peaks appear more pronounced compared to the April–May peaks of the 2000s. For example, compare the amplitudes of the April–May 1907 peak to the preceding peak of December 1906. The difference is about 16,000 m^3/s. Other differences in the 1900s of Figure 6 are the same or less. Yet differences in the 2000s are generally greater than 20,000 m^3/s. Others, such as *Olivry et al*. [1995] and *Tsalefac et al*. [2015], also note a decrease in the Spring flood of Central Africa (i.e., the smaller peak that occurs in April–May). We return to this idea in sections 5.3 and 5.4.

2.4. River Channel Measurements

River channel measurements include water stage, channel depth, channel width, and slope of the water surface or slope of the along-stream bathymetry. Few in situ measurements of stage are in the published literature. Stage is not included in the 96 Congo GRDC gauges. *Runge and Nguimalet* [2005] reported a few maximum stage values for the associated maximum flood discharges (see their Table 7). *O'Loughlin et al*. [2013] coalesced decades of stage values from three gauges located in Kinshasa, Mbandaka, and Kisangani and determined that water levels on the mainstem Congo River, on average, vary between low and high stage by about 3.5 m, 2.5 m, and 2.5 m, respectively. The average stage range reported by *Betbeder et al*. [2013] for the Congo River at Mbandaka is also 2.5 m, based on in situ gauge data. *Harwood* [2012] canoed nearly the entire Congo River and reported that houses on the riverbanks in mid-Congo reaches were built on ~2 m stilts, thus accommodating the stage range (personal email communication with D. Alsdorf). *Rosenqvist and Birkett* [2002] investigated 32 stream gauges distributed throughout the Congo Basin with data for the years between ~1900 and ~1950. They present a table indicating the maximum minus minimum stage range: the greatest range on the mainstem Congo is found at Kisangani with 6.40 m, whereas the greatest range of all 32 stations is at Bangui with 9.22 m on the Oubangui River.

Satellite-based measurements of stage from radar and lidar altimetry are available throughout the Congo Basin. *Lee et al*. [2011, 2014] used Envisat altimeter measurements from 2002 to 2009 and found that the mainstem Congo River levels ranged about 2 m to 3 m seasonally. *Rosenqvist and Birkett* [2002] used Topex/Poseidon radar altimeter measurements from 1996 and found the same 2 m to 3 m seasonal variations in stage on the mainstem Congo, but they also noted a 5.5 m range in stage on the Oubangui River near its confluence with the Giri River. *O'Loughlin et al*. [2013] investigated water stage on the mainstem Congo River between Kinshasa, at the downstream end of their study reach, and Kisangani at the upstream end. They used Ice, Cloud, and land Elevation Satellite (ICESat) measurements, all referenced to a common Earth centric

datum and located all along the entire study reach, to show that water level elevations are about 360 m at Kisangani and about 275 m at Kinshasa.

Becker et al. [2014] present a large data set of radar altimetry-based water levels for the entire Congo Basin. Their data are from 2003 to 2009, and after culling through 140 virtual stations, they found 99 continuous time series mostly from the Congo, Oubangui, Uele, Kasai, and Lukenie Rivers with fewer measurements on other smaller rivers. Based on a least squares statistical method (K means clustering), they grouped the time series into nine geographical and temporal zones, each with its own statistically unique hydrograph. These nine zones correspond in time and space reasonably well with the 10 of *Bricquet* [1995] (see section 2.3). *Becker et al*. [2014] show that the range in water stages between low and high levels is about 2 m for the Kasai, Tshuapa, Lukenie, and upper Uele rivers; about 3 m for the Lualaba, Congo, and lower Uele rivers; and over 4 m for the Oubangui River.

Channel depths for all rivers throughout the Congo Basin are not well published. For most of its course, the mainstem Congo is likely shallow which is perhaps unexpected given its massive discharge. Between Bukama and Kongolo, where the upper Congo River is known as the Lualaba River, the channel depth is no longer maintained and hence not able to support 40 tonnes boats (*Runge* [2007] who references *Wiese* [1980]). This implies shallow depths of say less than a few meters. Between Kongolo and Kisangani, the Lualaba River is marked by a number of cataracts and narrows, perhaps the most well known being the Boyoma Falls (formerly the Stanley Falls, located at Kisangani). This section is navigable only by small boats (e.g., canoes), and, given the tectonic and geologic controls, the depths in the section are likely complex, varying with width. Between Kisangani and Kinshasa-Brazzaville the Congo mainstem is navigable by 800 tonnes vessels (*Runge* [2007] who references *Wiese* [1980]). Around the confluence with the Kasai River, the Congo mainstem is located in a region known as "the channel" where depths are 23 m to 30 m [*Marlier*, 1973]. For comparison, *Stanley* [1885] measured the Congo channel cross section in April 1882 just above the Stanley Pool and reported depths that average 11 m to 12 m. *Marlier* [1973] suggests that depths throughout the navigable portions of the Congo rarely exceed 15 m (with the exception of the channel), and at low water the mainstem depths are often less than 2.5 m.

However, from Kinshasa-Brazzaville to its mouth on the Atlantic coast of Africa, the Congo River drops 277 m in just 498 km [*Runge*, 2007]. Based on our stream network and SRTM elevations, the drop is 263 m in 511 km (Figures 1–3). Most of this path has cataracts followed by pools having depths of ~100 m, and in one location between 130 km and 200 km downstream of Kinshasa the channel depth is greater than 220 m, likely making this reach of the Congo the deepest river in the world [*Oberg et al*., 2009]. Indeed, *Stanley* [1885] measured such extreme depths finding that the Congo River just above Matadi (DRC, see Figure 7) "… must be a depth of ninety fathoms of water at this spot. We discovered two facts in connection with this: viz., that there was a strong undercurrent of water flowing up stream in this bend, while the surface water flowed downward, and that the bottom, deep as it was, was covered with great rocks, which could only be caused by a yet greater depth midstream and below, which prevented the deposit of alluvium there." Note that 90 fathoms is 540 ft or 165 m deep.

Channel depths of Congo tributaries are less known. *Runge and Nguimalet* [2005] show cross sections of the Oubangui River at Bangui, demonstrating that the tributary at Bangui is, on average, 2 m to 3 m deep. However, upstream of Bangui the river is marked by rapids and is otherwise too shallow for the large boats that travel downstream to Kinshasa-Brazzaville [*Runge and Nguimalet*, 2005]. Bathymetric maps of the Kasai River, at a location just upstream of its confluence with the Kwango River, indicate depths of 3 m to 4 m in a wider, multithreaded portion, and 10 m to 12 m in a narrow, single-channel section of 400 m width (M. A. Trigg, personal communication, 2013). Fortunately, some bathymetric surveys of the Congo River right bank tributaries are occasionally made by the Brazzaville service waterways [*GIE-SCEVN*, 2015].

Recently, *O'Loughlin et al*. [2013] conducted an extensive study on channel widths and the number of islands in the middle reach of the Congo River, i.e., between Kisangani and Kinshasa-Brazzaville. This reach is best described as multithreaded and marked by just one channel for only 20% of the reach. Summing all channels for a given cross section to produce an effective width, the water surface varies from 512 m to just over 13 km wide. They note five locations where the river narrows to one channel, causing a restriction on flows and hence backwater conditions.

O'Loughlin et al. [2013] also measured the slope of the mainstem Congo water surface. They collected ICESat measurements from 2003 to 2009, focusing on those from March, June, and November time periods, corresponding to the falling limb, low flow, and rising limb of the annual flood wave, respectively. They find that



Figure 7. Suspension bridge over the Congo River at Matadi, DRC. View is looking downstream. In this reach and upstream of here, extreme depths of over 100 m have been measured, see section 2.4. Photo: R.G.M. Spencer.

there is no statistically significant variation in water surface slope over time for any given location; however, there are changes in slope geographically. For the upper half of their study reach, they find that the slope is generally 6 cm/km or greater throughout the passage of the flood wave. From about Mbandaka to downstream, the slope is less than 6 cm/km.

2.5. Lake and Wetland Areas, Depths, Stages, and Storage Volumes

While satellite-based mapping of wetland areas is routine for some regions of the world, the challenges in the Congo Basin are amplified because water shorelines are diffuse and much of the inundated area is under a dense canopy, notably in the "Cuvette Centrale" (one of the world's largest swamp forests, see Figure 8).



Figure 8. Vegetation and waters of the Cuvette Centrale. Photo: R.G.M. Spencer.

The bimodal hydrograph of the mainstem Congo also complicates the construction of basin-wide mosaics of satellite data where some images might be flooded while others in the same mosaic are relatively dry [e.g., *Rosenqvist and Birkett*, 2002].

Arguably, the efforts of several teams to assess the Japanese Earth Resources Satellite-1 synthetic aperture radar (JERS-1 SAR) data represent the first basin-wide studies to provide high-resolution, seasonal mapping of inundated areas [e.g., *Rosenqvist and Birkett*, 2002; *De Grandi et al*., 2000] (JERS-1 SAR is the first Japanese Earth Resources satellite which used synthetic aperture radar to map the world in an effort called the Global Rain Forest Mapping project or GRFM). To overcome the limitations from using one satellite system, *Bwangoy et al*. [2010] used the SRTM DEM, the GRFM mosaics, and Landsat data in a decision tree classification method to delineate wetlands throughout the center of the Congo Basin. They validated their classification using over 6000 measurements collected in five field sites and found that wetlands occupy 359,556 km^2 in their study region (5°N to 6°S and 13°E to 26°E). *Betbeder et al*. [2013] used the Moderate Resolution Imaging Spectroradiometer Enhanced Vegetation Index to identify forest types; they used ICESat to measure canopy heights and used PALSAR scenes from different flooding times to map inundation extents (PALSAR is the Phased Array type L band SAR, a follow on to JERS-1). They identified four different types of forest, three of them in which a canopy height could be discerned. Two of these were flooded and had canopy heights of 20 m and 30 m. *Lee et al*. [2014] compared backscatter coefficients in 15 PALSAR ScanSAR scenes from one 350 km × 350 km frame location with those of Envisat radar altimetry and also included water surface elevations from the altimetry, in order to classify inundated areas in the radar imagery. They found that from 2007 to 2011 in the radar frame over the Cuvette Centrale, high water flooded forest areas covered about 17,700 km^2 to 29,400 km^2 (these were in December), whereas the low water areas were varied from 7600 km^2 to 3400 km^2 (these were in March). Note that the *Lee et al*. [2014] study area is a fraction of the size of the *Bwangoy et al*. [2010] study area, hence smaller numbers for the flooded areas.

Water depths and stages in the wetland areas are rarely reported in the peer-reviewed literature. *Laraque et al*. [1998a] measured depths of 3 m in Lake Tele from the northwestern Cuvette Centrale and noted mud marks on trees indicating an annual range in level of about 1 m. They quote three references from 1959 to 1961 indicating that Lake Tumba is 3 m to 8 m deep and Lake Mai-Ndombe is 3 m deep, both with annual fluctuations in levels of 2 m to 4 m. *Marlier* [1973] reports the same Lake Tumba depths. *Laraque et al*. [1998a] also indicate that the "Likouala aux Herbes River, its entire watershed (like that of the whole of the Congolese 'Cuvette') is crisscrossed with natural or man-made channels that link it to the adjoining hydrographic basins. These channels are narrow (2 to 3 m wide), sometimes more than 2 m deep and often encumbered with snags, when they are not completely obstructed by the 'grassy corks'."

The narrow sizes of the channels perhaps explain why they are not evident in the visible band and SAR satellite imagery reported by *Jung et al*. [2010]. The satellite data have spatial resolutions of several tens of meters. At the scales of the satellite data, wetland flows through the Cuvette are diffuse, lacking well-defined boundaries [*Jung et al*., 2010]. In *Laraque et al*. [2009] they explain that water hydraulic gradients in this area are less than 2 cm/km with flows of 1 to 2 km/h (0.28 to 0.56 m/s). Regarding the Likouala aux Herbes basin in the center of the Cuvette Centrale, *Laraque et al*. [1998b] state that "beyond the choking edges of narrow channels, the spreading waters probably mix with the alluvial water table, which appears in many places. The totality slips at imperceptible speed downstream in a laminar manner. One could then qualify all of it as a 'fluvial table'."

Using Envisat radar altimetry, *Lee et al*. [2011, 2014] investigated wetland water level fluctuations at five locations along the mainstem Congo River and within the Cuvette Centrale (e.g., Figure 9). From 2002 to 2009, they found that wetland stage variations from dry to wet seasons were subtle at only about 0.5 m to 1.0 m (blue line, Figure 9). Because they referenced all measurements to a common Earth centric datum, their measurements are suitable for absolute elevation comparisons between the wetlands and the adjacent mainstem Congo River. Interestingly, they found that water levels on the mainstem around the Cuvette Centrale are consistently lower than water levels in adjacent wetlands (less by 0.5 m to 3.0 m, compare elevations of blue line to red line in Figure 9).

Like the depths, wetland storage volumes are also not well known. *Lee et al*. [2011, 2014] combined their satellite-based measurements of variations in wetland areas and stages to estimate 2007–2010 annual storage changes between 21 km^3 and 31 km^3 (their study does not include the entire Cuvette Centrale).

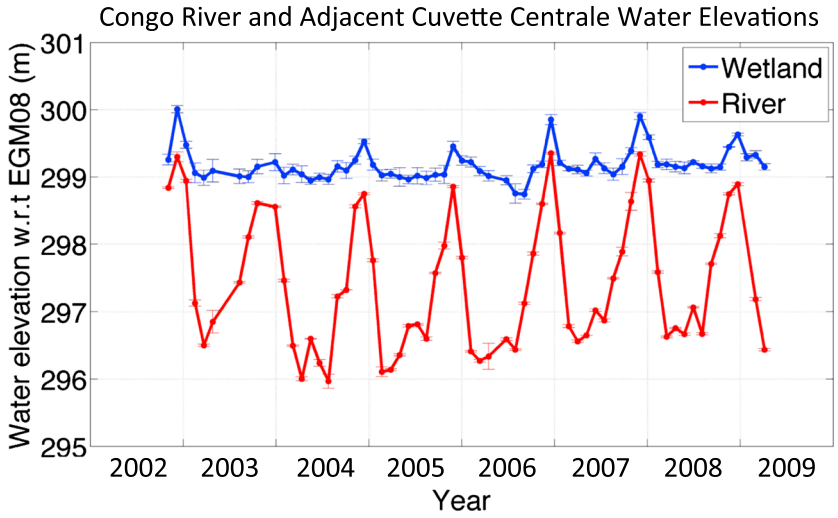


Figure 9. Water surface elevations for the Congo River and immediately adjacent wetlands of the Cuvette Centrale at 17.54°E, 0.74°S. Elevations are from the EnviSat radar altimeter, pass number 973. Elevations are with respect to the EGM08 geoid model.

These compared well with their storage change estimates collected from the Gravity Recovery and Climate Experiment (GRACE) satellites, which, because these use gravity methods, are entirely independent of the ground conditions and hence of the imaging and altimetry methods. Building on their remote sensing approach, *Lee et al.* [2015] generated water depth maps over the Cuvette Centrale by combining imaging and altimetry methods in a linear regression model. They validated their mapped depth changes with interferometric SAR measurements of water level changes. Over their section of the swamp, they report water volumes of $11.3 \pm 2.0\,km^3$ for December 2006, $10.3 \pm 2.3\,km^3$ for December 2007, and $9.3 \pm 1.8\,km^3$ for December 2008.

In addition to the vast wetland systems, the basin contains several large, permanent open water lakes, including the world's second largest by volume and depth (Lake Tanganyika) which alone holds approximately 17% of the world's fresh water [*Coulter*, 1991] and ranks second in Africa for fish production [*Dobiesz and Hecky*, 2011]. Additional lakes each with a surface area of more than $1000\,km^2$ (Mweru, Kivu, Bangweulu, Mai-Ndombe, and Chishi) provide a cumulative open water area of approximately $45{,}500\,km^2$ and storage volume of $19{,}500\,km^3$. Lake Tanganyika alone has shown a storage range of approximately $100\,km^3$ during the 1950s and 1960s with year-to-year variability of 10–30 km^3 [*Bergonzini*, 1998]. A series of studies [*O'Reilly et al.*, 2003; *Verburg et al.*, 2003; *Verschuren*, 2003] have linked climate change to Lake Tanganyika warming and decreases in fishery productivity. *Tierney et al.* [2010] used sediment core data to suggest that the recent warming trend exceeds natural variability for the previous 1500 years. Understanding the current and future water budget for these lakes is especially important to fully capture the further impacts of climate change on lake dynamics and fishery production.

While the references are difficult to obtain, it is important to realize that both historic and recent work have addressed waters in Congo lakes and wetlands. For example, *Salumu et al.* [2011] used local topography, channel widths, SRTM measurements, and HydoSHEDS to quantify the spatial distributions and seasonal changes in water levels in the Stanley Pool (SRTM is the Shuttle Radar Topography Mission and HydroSHEDS is the Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales). Historic works such as *Devroey* [1939] and *Burgis and Symoens* [1987] also provide additional information about central African wetlands and shallow lakes.

2.6. Groundwater

Compared to surface water, groundwater is less understood given the paucity of peer-reviewed literature that discusses the Congo Basin water table. According to a United Nations Environment Programme (*UNEP*) [2011] report, groundwater formations beneath the Cuvette Centrale and southern Oubangui Basin

are spatially continuous, recharged via rainfall or from surface waters, and have high potential for water supply.

Wesselink et al. [1996] studied rainfall and runoff of the Oubangui Basin from the 1910s to the 1990s and found a distinct decrease in basin river flows starting in 1971, commensurate with a decrease in rainfall. However, the impacts of these drought conditions across the basin were not uniform. They suggested, based on river flow rates, that groundwater recharge was negligible in the northern and dryer portion of the Oubangui Basin (1000 mm/yr of rainfall), whereas recharge was continuing in the southern and wetter portion of the basin (1700 mm/yr of rainfall). Similarly, others link the drought since 1971 (until at least the publication date) to Oubangui Basin river base flows noting that minimum values in annual hydrographs decreased by 60%, suggesting a possible lowering in the groundwater table [*Orange et al*., 1997]. On the Sangha River, *Bricquet et al*. [1997] find that low flows during the 1980s were half of those from the 1970s and attributed this decrease to groundwater losses resulting from persistent drought. Outside of the Congo, *Mahé* [2009] found decreased rainfalls in western Africa since 1970 and linked these to decreases in the water table and hence to decreases in river base flow in the upper Niger River. But, in the upper Volta River, which also experienced decreased rainfall, the runoff increased as a result of land use changes.

Beneath the Batékés Plateau, located in the highlands to the north of Kinshasa-Brazzaville and to the southwest of the Oubangui Basin, lies a spatially semicontinuous aquifer that is recharged by rainfall and supplies water to rivers during low flows [*UNEP*, 2011; *Laraque et al*., 1998b, 2001]. Underlying most of the remainder of the basin and surrounding the Cuvette Centrale are sandstone and calcareous formations having rapid recharge and low to moderate potential for water supply [*UNEP*, 2011]. Nongovernment organizations (NGOs) could be a source of information given that some are drilling water table wells in villages. For example, D. Alsdorf spoke with an NGO working in the northernmost Congo Basin and they indicated that, because of the limitations of the pump, they stop drilling at 50 m. This results in about one third of the thousands of drilled wells being dry to at least 50 m deep. In summary, there is a lack of information on fundamental recharge processes at local and basin scales and how these could be affected by future changes of climate and land use. Improved understanding of surface water-groundwater interaction mechanisms is required for basin-wide planning.

2.7. Model-Based Studies

Sections 2.1–2.6 focused on measurements, whereas here in section 2.7 the focus is on identifying hydrologic results from model-based studies. These studies range from global models that provide general indications regarding the Congo Basin [e.g., *Syed et al*., 2009] to basin specific models that detail rainfall and water resource issues (e.g., *Beighley et al*. [2011] already reviewed in section 2.1 [*Tshimanga and Hughes*, 2011; *Tshimanga et al*., 2012; *Tshimanga and Hughes*, 2014]).

Syed et al. [2009] solved equation (1) for Q in an effort to estimate global discharge from the continents to the oceans. Essentially, they used GRACE data from 2003 to 2006 to estimate terrestrial water storage changes (ΔS), globally, and used precipitation and evapotranspiration (P-E) in global reanalysis products created by NCEP-NCAR and by ECMWF (National Centers for Environmental Protection-National Center for Atmospheric Research and the European Centre for Medium-Range Forecasts). Of the eight large basins in their study, the Congo yielded the least correlative results when comparing gauge-based discharge to their model-based discharge (correlation was only 0.56). Differences approached 100 km^3 in an average October.

Tshimanga and Hughes [2011], *Tshimanga et al*. [2012], and *Tshimanga and Hughes* [2014] assessed the performance of their semidistributed rainfall-runoff model, which was driven by a number of inputs from global data sets, e.g., topography, vegetation, soils, etc., and its outputs were compared mainly to river discharge. They constructed 99 sub-basins based on classifications of elevation, topographic slope, and the stream network. Using 30 stream gauges with data ranging from 1932 to 2000, they suggest that across all catchment classes the model compares well to these in situ measurements. The challenges they find in modeling the Congo Basin hydrology include phenomenon such as the south-to-north large changes in seasonal rainfall, the varying geologic lithologies and resultant soil types, and differing vegetation types and thus varying ET. For example, many of the observed data that are available for the Congo Basin are at the outlets of large sub-basins where it is difficult to interpret the hydrological response characteristics because of the large scale of the basins and because of a multiplicity of interacting processes. These processes not only include surface and subsurface response to rainfall

at the small scale but also include storage and attenuation effects of wetlands, floodplains, natural lakes, and the channel systems of large rivers. These all make it difficult to establish appropriate model parameters. *Hughes et al.* [2014] recognized this difficulty during the development of a wetland model for the areas of Lake Tanganyika, Lake Upemba, and the Bangweulu Swamps. They concluded that the dynamics of the interchange of water between wetlands and river channels can be complex and different depending on their physical configuration and that remote sensing has the potential to contribute to this understanding.

3. Carbon Fluxes

The Congo River has an exceptionally low total suspended sediment (TSS) yield (8.2–9.4 t/km^2/yr); however, Congo TSS has a high particulate organic carbon (POC) content and ranks fifth in terms of annual POC flux to the oceans at approximately 2 Tg/yr [*Mariotti et al.*, 1991; *Coynel et al.*, 2005; *Spencer et al.*, 2012; *Laraque et al.*, 2013b; *Seyler et al.*, 2006]. The POC yield (0.5 g C/m^2/yr) of the Congo is low in relation to other major tropical rivers (e.g., the Amazon and Orinoco Rivers are 1 and 1.5 g C/m^2/yr, respectively) but is greater than reported for the major Eurasian Arctic Rivers (e.g., the Lena, Ob', and Yenisei range from 0.1 to 0.2 g C/m^2/yr). With respect to dissolved organic carbon (DOC) the Congo River is a major global exporter with a total flux estimated at between 11.5 and 12.4 Tg C/yr [*Seyler et al.*, 2006; *Coynel et al.*, 2005]. This is equivalent to the DOC loads of the three largest Arctic Rivers combined (the Yenisei, Lena, and Ob') or greater than 6 times that of the Mississippi [*Raymond et al.*, 2007; *Spencer et al.*, 2013]. Combining the DOC and POC loads, the Congo River exports 14.4 Tg C/yr of organic carbon to the Atlantic Ocean and is the second major exporter of terrestrial organic carbon on Earth after the Amazon. Conversely, due to low denudation rates the Congo has relatively low inorganic carbon export resulting in the Congo River exporting about 7 times more organic carbon than inorganic carbon [*Gaillardet et al.*, 1999; *Spencer et al.*, 2014; *Wang et al.*, 2013].

The outgassing of carbon from water surfaces and directly into the atmosphere is now recognized as an important component in the global carbon balance [e.g., *Raymond et al.*, 2013]. Tropical wetlands are key contributors to the carbon cycle given their vast water surfaces and abundant carbon supplies [e.g., *Melack*, 2016]. Despite the massive size of the Congo Basin, few studies have measured carbon evasion in its rivers and wetlands.

Tathy et al. [1992] were perhaps the first to measure methane (CH_4) fluxes in the Congo wetlands. They collected samples in February and October 1988 (dry and wet seasons, respectively) from field locations in the wetlands west and north of the Oubangui and Congo Rivers. An airborne campaign was also conducted in December 1987. Results suggest that flooded soils (i.e., water depths of 10 to 40 cm) emit CH_4 at an average rate of 4.59×10^{12} molecules/cm^2/s, whereas dry soils uptake CH_4 at rates 2 orders of magnitude smaller. While not the focus of their study, they report that carbon dioxide (CO_2) emission rates from flooded soils are 1.54×10^{14} molecules/cm^2/s, whereas dry soils also emit at 1.11×10^{14} molecules/cm^2/s. Based on their value of 10^5 km^2 of wetland area, they estimate an overall CH_4 emission of 1.6 to 3.2 Tg/yr (CH_4) (which we convert to 1.2 to 2.4 Tg C/yr).

More recent studies, however, have examined CH_4 in a wide range of fluvial environments in the Congo Basin and report concentrations ranging across 3 orders of magnitude from 22 to 71,430 nmol/L [*Borges et al.*, 2015a]. Sampling stations were located mostly along the mainstem Congo between Kinshasa and Kisangani with additional stations along the Kasai River and smaller tributaries. Congo pCO_2 values measured by *Borges et al.* [2015a] ranged from 1090 to 22,900 ppm. *Borges et al.* [2015b] estimated the flux of CH_4 and CO_2 from the Cuvette Centrale to be 0.48 ± 0.08 PgCO_2 equivalents/yr, and this is likely a conservative estimate, as it does not include the ebullition of CH_4.

Wang et al. [2013] focused on just the Congo mainstem river waters located at Kinshasa-Brazzaville and collected monthly samples from December 2010 to December 2011. The focus of their paper was on the overall inorganic carbon content of the river waters: they did not measure CO_2 evasion, rather they calculated it from measured pH and dissolved inorganic carbon (DIC). To calculate their CO_2 fluxes, they used a one-dimensional flux model. Because of the lack of Congo River gas transfer velocities (k), they used an Amazon River k value. Resulting partial pressure CO_2 (pCO_2) values correlate positively with river discharge from a low of 2018 μatm to a high of 6853 μatm.

Mann et al. [2014] estimated surface water pCO_2 in a range of streams and rivers within the Congo Basin encompassing savannah, forest, and swamp dominated systems. Surface water pCO_2 in savannah and tropical forest dominated watersheds ranged from 2600 to 11,922 μatm, and swamp regions exhibited extremely

high pCO_2 values (10,598–15,802 μatm), similar to the findings of *Borges et al*. [2015b]. To estimate CO_2 flux from water to the atmosphere, *Mann et al*. [2014] utilized published gas transfer velocities (k) and derived areal outgassing rates ranging from 312 mmol $CO_2/m^2/d$ to 1429 mmol $CO_2/m^2/d$ depending on the dominant watershed land cover type. Overall surface water pCO_2 values from this study, excluding swamp waters in the Congo Basin, compare well to reported values from the Amazon Basin [*Richey et al*., 2002]. The high pCO_2 values from Congo Basin swamp waters reported by *Mann et al*. [2014] and by *Borges et al*. [2015a, 2015b] are far greater than those reported for global wetlands (2900 uatm [*Aufdenkampe et al*., 2011]) and emphasize the potentially important role of vast swamps like the Cuvette Centrale in regional and even global carbon budgets, and the need to better assess seasonal inundation dynamics in this region.

4. Comparisons of the Congo and Amazon Basins

The relatively greater amount of published Amazon Basin research compared to that of the Congo Basin (Table 1) highlights the need for future studies to address this major, relatively pristine basin as well as studies to better assess differences between these two globally important tropical ecosystems. We first compare basic components of basin-wide water balances, next we consider differences in local hydrodynamics, and we end with a comment on carbon evasion.

4.1. Basin-Wide Water Balance Comparisons

Rainfall along the mainstem Amazon River decreases from 3.06 m/yr in the west to about 2.31 m/yr in the east ([*Alsdorf et al*., 2010]—utilizing the Global Precipitation Climatology Project data of *Xie et al*. [2003] with a basin-wide average of 2.13 m/yr [*Costa and Foley*, 1998]—utilizing a combination of in situ gauges and satellite products). The annual rainfall maps of *Bultot* [1971] and *Mahé et al*. [2012] (see section 2.1, Figure 5) show a ~1900 mm ridge trending east-west across the middle of the basin with values decreasing northward and southward to lows of about 1100 mm. *Bultot* [1971] indicates that the annual-average rainfall for the Congo Basin above Kinshasa is 1.53 m (see his Figure 43, 1527 mm/yr). Thus, there is almost a 40% greater amount of rain in the Amazon compared to the Congo (i.e., for any given location). Based on an analysis of model and atmospheric water balance studies, with time spans of 1 to 30 years, *Costa and Foley* [1998] report values of Amazon ET ranging from 3.1 mm/d to 4.6 mm/d with an average of 3.62 mm/d (i.e., 1.1 m/yr to 1.7 m/yr and 1.32 m/yr, respectively). *Bultot* [1971] estimates basin-wide ET across the Congo above Kinshasa at 1.20 m/yr (see his Figure 43, 1196 mm/yr). Thus, the Amazon ET is only 10% greater than that of the Congo, but the percent of precipitation that is evapotranspired back to the atmosphere is greater for the Congo at 78% compared to 62% for the Amazon. These P and ET values demonstrate why the annually averaged Amazon River discharge is about 5 times greater than that of the Congo River despite the basin areas differing by less than 2 times (i.e., 206,000 m^3/s [*Callède et al*., 2010] versus 40,700 m^3/s; 6 M km^2 versus 3.7 M km^2).

4.2. Hydrodynamic Comparisons

Perhaps, the most obvious hydrodynamic difference between the Amazon and Congo Basins is the flood waves: the Amazon mainstem has one major flood peak per year whereas the Congo mainstem has one major and one minor peak per year (these refer to downstream basin locations, whereas upstream locations have more complex flood waves). The mainstem channels are different with the Amazon largely marked by a single thread and an occasional island, whereas much of the Congo mainstem is significantly multithreaded [*O'Loughlin et al*., 2013]. The annual Amazon flood wave causes backwater conditions on its tributaries [*Meade et al*., 1991], whereas narrowing of the Congo to single channels at a few restrictions causes its backwater conditions [*O'Loughlin et al*., 2013]. At 20 m to 80 m deep [*LeFavour and Alsdorf*, 2005; *Trigg et al*., 2009; *Marlier*, 1973], the mainstem Amazon channel is deeper than the Congo mainstem everywhere above Kinshasa (section 2.4). From Kinshasa to the mouth, however, the Congo channel is often deeper than 100 m (section 2.4) with whirlpools, high surface waves, and deep waters flowing up-gradient [e.g., *Stanley*, 1885].

Less understood, but still important hydrodynamic differences exist in the wetlands of these two major rivers. Along the mainstem Amazon River, the water elevations in the river and the immediately adjacent floodplain are equivalent, with the rise and fall of the annual flood pulse producing nearly the same water level changes in both the river channel and in the immediately adjacent floodplain areas [*Lee et al*., 2011]. Thus, the river and floodplain are exchanging water throughout the passage of the flood wave [*Alsdorf et al*., 2010]. In

contrast, it appears that water levels in the Congo mainstem, as it passes through the Cuvette Centrale wetlands, are consistently lower in elevation than the immediately adjacent wetland waters. Here water level changes in the wetlands are small compared to changes in river levels (see section 2.5). Furthermore, the mainstem Amazon floodplain contains large numbers of interconnected channels that mark boundaries to water flows, resulting in complex hydraulics with spatially varying changes in water levels during filling and draining [e.g., *Alsdorf et al*., 2007; *Rudorff et al*., 2014; *Bonnet et al*., 2005; *Martinez and Le Toan*, 2007]. In contrast, the Cuvette Centrale wetlands do not have similar sized channels and the water flow is diffuse, lacking similar boundaries and lacking complex water level variations [*Jung et al*., 2010]. More work is needed before these few Congo measurements can be more broadly ascribed (see sections 5.1 and 5.2).

Storage changes in the mainstem Amazon floodplain are a function of both water levels and inundated area, whereas in the Congo Cuvette the function appears to be governed more so by fluctuations in flooded areas than by changes in water levels. For example, *Alsdorf et al*. [2010] measured flooded areas in six 330 km by 330 km regions along the Amazon mainstem and found low water areas of about 4000 km^2 to 16,000 km^2 and found high water areas of 10,000 km^2 to 30,000 km^2, i.e., a 2 times to 4 times increase. *Lee et al*. [2014] studied a 350 km by 350 km region of the Congo Cuvette and found a similar increase in area from low to high water (see section 2.5). However, changes in wetland water levels range about 5 m to 10 m in the Amazon floodplain compared to only 0.5 m to 1 m in the Cuvette Centrale [*Alsdorf et al*., 2010; *Lee et al*., 2011]. This difference in water level fluctuations is suggestive of differing wetland hydrodynamics. Riverine supplies and thus deeper floodplain waters dominate the mainstem Amazon floodplain, whereas the shallow Congo Cuvette wetlands may not be fluvially supplied and instead might be dominated by precipitation falling directly on the wetland surface. In sections 5.1 and 5.2, we return to this issue.

4.3. Carbon Evasion Comparisons

In the Amazon, *Richey et al*. [2002] combined 1800 measurements of partial pressures of CO_2 (pCO_2) with satellite-based measurements of water surface areas to map the spatial and temporal variations in outgassed CO_2. They suggested that Amazon waters evaded 0.5 Gt of carbon per year (470 Tg C/yr) with pCO_2 values ranging from ~3000 μatm to over 44,000 μatm, depending on water body type and season. They also find that greater CO_2 outgassing is naturally positively correlated with increased water depths during the seasonal hydrograph. Recently, *Melack* [2016] reviewed measurements of CO_2 evasion from the Amazon basin and concluded that the combination of improved estimates of gas exchange coefficients and the areal extent of the variety of habitats result in larger fluxes than those estimated basin wide by *Richey et al*. [2002] by 3 to 4 times. *Melack* [2016] summarized Amazon methane evasion studies to suggest a basin-wide flux of 22 Tg C/yr of methane.

Comparing these Amazon carbon values with the few published Congo measurements (section 3) suggests that the Congo may emit a similar or greater amount of carbon per given area than the Amazon. For example, *Borges et al*. [2015a] note that their CH_4 concentrations in the Congo mainstem and in its large and small tributaries are higher than in similarly sized rivers in the Amazon. However, their pCO_2 values for the same river-type comparisons showed similar or slightly lower values for the Congo compared to the Amazon. Solely from the Cuvette Centrale, *Borges et al*. [2015b] estimate the flux of CH_4 and CO_2 at 480 ± 80 $TgCO_2$ equivalents/yr, without including the ebullition of CH_4. These values are similar to those reported by *Melack* [2016] for the Amazon Basin (see paragraph above). However, the Congo Basin is smaller than the Amazon (3.6 M versus 6 M km^2) and may have a smaller wetland fraction. We estimate wetland areas at around 11% of the Congo Basin drainage upstream of Kinshasa-Brazzaville. We note that *Bwangoy et al*. [2010] measured wetland areas in the Cuvette Centrale at 359,556 km^2 (see section 2.5), which is 10% of the basin area upstream of Kinshasa-Brazzaville. Additional wetlands such as those around Lake Bangweulu, Lake Upemba, and Lake Mweru-Wantipa (Figure 1) as well as other wetlands throughout the basin may occupy an additional 40,000 km^2 (while this is a reasonable estimate, remote sensing studies of the entire basin are required). *Melack and Hess* [2010] estimated that 17% of the Amazon Basin below 500 m elevation is subject to flooding (this percentage is limited by the 100 m resolution of the spaceborne imagery used in the study, thus it does not include small rivers and associated riparian zones). Thus, while the two basins might have similar carbon fluxes, the smaller size and smaller fractional water area of the Congo suggests that it has a larger carbon emission per unit area compared to the Amazon. Clearly, these numbers are extrapolations from limited data sets, but they highlight the potential importance of the Congo Basin with respect to regional and global carbon dynamics and the urgent need for future studies to refine these estimates.

5. Research Hypotheses That Lead to Discoveries

Hypothesis testing is a key part of the foundation of science. A properly designed hypothesis leads to a research discovery, whether the hypothesis is proven true or false. In contrast, a research question is usually only valuable if it is affirmed, i.e., negative results are not always encouraging. The following hypotheses and related tests were developed based on the measurements and models reviewed in sections 2, 3, and 4.

5.1. The Water in the Cuvette Centrale Is Supplied Mostly by Rainfall

If this hypothesis is true, then carbon is produced within the wetland and sedimentation is minimal. A previous geochemical study suggests this may be true as between the well-studied site at Bangui (Central African Republic) and the Oubangui River's (second largest tributary) confluence with the Congo mainstem, the tributary passes through the Cuvette Centrale and its characteristics are known to change as TSS export rates decrease slightly and DOC concentrations increase dramatically [*Laraque et al*., 2009]; however, no water balance was conducted. This would mean that the impact on the water supply to the Cuvette from mining, electric power generation, or water diversion schemes would be minimal. If false, then the supply is mostly from fluvial sources that bring their own carbon, nutrients, and sediment. This would imply the existence of diffuse overbank flows and related deposits from rivers adjacent to the Cuvette or specific up-gradient pathways connecting upstream rivers to the Cuvette. Human alterations of fluvial processes could then also impact the wetland.

This hypothesis can be tested by measuring water surface elevations throughout the Cuvette and comparing these to immediately adjacent river levels. Locations with higher wetland levels cannot receive water from the adjacent river, thus eliminating diffuse overbank flows as a water source, local to that specific point. Proof of a false result could be achieved by high-resolution spatial mapping of the various potential pathways of water flow. If there are sufficient numbers and sizes of flow channels to convey the amount of water required to seasonally fill the Cuvette wetlands, then the hypothesis is false. Ideally, this hypothesis would be tested by comparing rainfall measurements located directly in the Cuvette to the changes in stored water volumes. ET confounds this approach by removing unmeasured amounts of water. In hypothesis 5.2, we suggest a test using water and energy balance modeling. It is important to note that if rainfalls and water level fluctuations are well timed, where rainfall events lead to increases in water levels that occur before an upstream flood wave could deliver the water, then the hypothesis is true. High temporal resolution measurements would be required for such a test.

5.2. The Water Empties From the Cuvette Centrale Mostly by ET

If this hypothesis is true, then there is little water from the wetland supplied to the adjacent rivers; and thus, the river sediments, nutrients, and carbon are not altered by the wetlands. It remains possible for the wetland to receive water from an up-gradient river but to empty mostly by ET; and thus, the wetland receives sediment, nutrients, and carbon but supplies none. If this hypothesis is false, then the Cuvette is altering the biogeochemistry of down-gradient rivers.

The methods of testing this hypothesis are similar to those of hypothesis 5.1. Measurements of water levels in the wetlands and the immediately adjacent rivers would demonstrate the local hydraulic gradient. If the gradient throughout the entire water year is consistently downslope from the wetland to the river, then it is possible that the wetland empties via surface water paths and thus the hypothesis is false. For such a false result, spatial mapping would need to demonstrate that the size of the surface flow pathways was large enough to accommodate the expected water volume emptied from the Cuvette wetlands. Water and energy balance modeling should be able to provide upper and lower bounds on the volume of water that is removed by ET. For example, if modeling demonstrated that ET could remove 80% of one season of wetland storage change, then surface pathways should be evident to remove the remaining 20%. This approach assumes a long-term wetland ΔS of zero and that groundwater is not sufficiently fast enough to remove the 20%.

5.3. Despite Known Variations in the Discharges of the Congo and Oubangui Rivers, Previous Rainfall Amounts Have Varied Comparatively Less Across the Basin

If this hypothesis is true, then either plant physiology or subsurface lithologies account for the differences between rainfall and the expected river runoff. For example, *Matsuyama et al*. [1994] used stream and precipitation gauge measurements combined with vapor flux convergence data from ECMWF and with

normalized difference vegetation index (NDVI) mappings to find that seasonal variations in the basin water balance are largely related to characteristics of the deciduous forest located in the southern half of the basin and that NDVI and ET are in-phase with seasonal precipitation over the evergreen forests of the northern half of the basin. Regarding lithologies, *Laraque et al*. [1998b] found that there is little seasonal variation in the discharges of rivers that drain the Batékés plateau despite monthly rainfall variations ranging from greater than 250 mm to less than 50 mm (i.e., rivers that drain the highland areas around Brazzaville of Figure 3 and located in the "Lower Congo Basin" of Figure 2). *Laraque et al*. [1998b] indicate that a 200 m to 400 m thick sandstone aquifer underlies the plateau and that river flows are "highly diluted clear waters, relatively rich in dissolved silica" and thus suggest that the aquifer regulates the plateau river discharges leaving them independent of rainfalls. These examples imply that rainfall-runoff ratios may vary significantly throughout the Congo Basin. *Nguimalet and Orange* [2015] suggests that rainfall-runoff ratios over the Oubangui Basin do not vary in time. They studied rainfall data from 1935 to 2015 over the basin and found a 5% decrease in rainfall after 1970 and that Oubangui River discharge during this same period has also remained lower than its long-term average with a most recent decline of 22% since 1983. If this hypothesis is false, then important rainfall variations have occurred in the past but have gone unmeasured in key regions of the basin.

A multistep approach is perhaps required to test this hypothesis. First, basin-wide water and energy balance modeling parameterized with the most up to date vegetation and soil maps should demonstrate the bounds on the water volumes governed by ET, plants, root zones, and aquifers. In the next step, locations where the model results have significant errors resulting from inadequate measurements should be targeted for field studies such as evaporative pans, flux tower measurements, water levels, stream discharges, etc. Future steps involve model and subsequent measurement refinements until errors are reduced and the hypothesis is reasonably tested.

5.4. Because of Its Location Beneath the Tropical Rainbelt, the Congo Basin Will Experience Significant Changes in Both Rainfall Amounts and Geographic Locations From Climate Change

If this hypothesis is true, then hydroelectric, transportation, and other water users will need systems designed to meet these multidecadal fluctuations. Not only are water users potentially impacted, but so too are ecosystems that are reliant on regular seasonal water pulses. If this hypothesis is false, then planning can be based on today's water volumes and fluxes while ecosystem functioning remains little changed. The tropical rainbelt annually moves back and forth across the equator based on the positioning of Africa's atmospheric easterly waves [*Jackson et al*., 2009; *Nicholson*, 2009]. These waves have multiannual teleconnections with sea surface temperatures and associated surface pressures [*Nicholson*, 2000, 2009; *Todd and Washington*, 2004]. Interannual positioning is further governed by the presence or absence of the Africa Westerly Jet: a northward displacement of this jet brings rain further north for multiannual periods [*Nicholson*, 2009]. Because of these teleconnections with ocean temperatures, the question arises about the impacts that global warming will have. For example, *Ceppi et al*. [2013] indicate that global warming could warm the Northern Hemisphere more than the Southern, potentially resulting in a geographic shift in the ITCZ (as noted previously, while the ITCZ is not the driver of Congo's rainfall, it is an example of a large-scale atmospheric phenomenon influenced by temperatures) [*Ceppi et al*., 2013]. Given that the left bank (southern) tributaries have annual flood pulses in March–April and the right bank (northern) tributaries have theirs in October–November, a geographic shift in the tropical rainbelt could modify this geographic distribution with perhaps wetter sub-basins and greater flood pulses in the north and dryer sub-basins and lower flood pulses in the south.

Changes in river discharge, which might be indicative of a shifting tropical rainbelt, have been found in some river basins west and northwest of the Congo [*Mahé et al*., 1990, 2013; *Mahé and Citeau*, 1993; *Citeau et al*., 1988; *Olivry et al*., 1995; *Bricquet et al*., 1997; *Liénou et al*., 2008]. They show that (1) the spring flood wave (i.e., February to May) decreased after 1970 and remained low throughout the 1980s, whereas the fall flood wave (i.e., September to December) was unchanged, and (2) the annual sharp April–May increase in rainfall before the 1970s was not as evident during the decreased rainfall periods after the 1970s. They suggest that in January through June of the dry years in the decades of the 1970s and 1980s that the ITCZ does not migrate as far south as it does in wetter years; and thus, river discharges during the spring are modified by ITCZ migration timing and geographic distribution (note that here we use the authors' ITCZ nomenclature).

Testing this hypothesis will require the combining of global climate, atmospheric, and land-atmosphere models with Congo Basin hydrological models. If the output from climate and atmospheric models detailing

the positioning and rainfall amounts from the tropical rainbelt is not sufficiently definitive to answer this hypothesis, then hydrological models, operated in a Monte Carlo fashion with feedback and forcings from coupled land-atmosphere models, may provide probabilities that are still useful for water resource management. Perhaps, the modeling could provide early indicators of hydrological response to shifts in the tropical rainbelt, which might be useful when investigating historic rainfall and river discharge data for any potential changes that have already occurred. In fact, such targeted field campaigns may be useful for improving our understanding of rainfall processes by measuring both the precipitation and the atmospheric transport of water vapor [e.g., *Washington et al*., 2013]. Additionally, combining these hydrologic and atmospheric studies with multitemporal vegetation greenness research may help to understand which basin areas are experiencing long-term changes in precipitation and hence in hydrology [e.g., *Zhou et al*., 2014].

5.5. Deforestation of 30% of the Headwater Sub-Basins Will Significantly Increase Headwater Flows and Hence Increase Downstream Discharges

If this hypothesis is true, then annual flood pulses in Congo Basin tributaries will increase in magnitude resulting in possible ecological changes such as modifications of fisheries habitats. If this hypothesis is false, then the loss of canopy and presumably its replacement by smaller vegetation does not impact the local water balance sufficiently to alter fluvial processes. This hypothesis is based on the concept that deforestation decreases the amount of ET resulting in more of a given amount of rainfall becoming runoff, compared to the case of no deforestation [e.g., *Coe et al*., 2009, 2011]. The 30% area value is chosen because currently around 30% of central Africa's forests are under logging concessions [*Laporte et al*., 2007] but could instead be a sliding scale or tied to a set of economic and demographic drivers. For example, drivers of Congo deforestation include slash-and-burn clearing for agriculture, unregulated logging, and the collection of wood for fuel [*Koenig*, 2008]. These have become evident in the central and eastern portions of the basin since 1990 [*Mayaux et al*., 2013]. Therefore, to test this hypothesis, stream discharge data collected from these regions before the advent of deforestation can be compared to discharge data collected recently. Assuming that local deforestation is the major driver of local hydrologic change during this time interval, gauge data might show recent increases in discharge and thus prove the hypothesis. This approach likely will require long-term gauge data from nearby, undisturbed basins in order to ensure that hydrological changes are specific to deforestation. If isolating the deforestation signal proves not to be this straightforward, e.g., *Liénou et al*. [2008], then hydrological modeling, first developed for deforestation studies in other tropical forests, will be needed.

5.6. Future Hydroelectric Power Generation Will Not Impact Waters Flowing in Rivers

If this hypothesis is true, then any environmental impacts from hydroelectric generation will not result from changes in river discharge. If this hypothesis is false, then the societal improvements from having electrical power should be balanced against the challenges from having artificially changing river water flows and hence related changes in the channel depths. Past and present hydroelectric facilities in the Congo Basin are usually located at cataracts, where run-of-the-river methods with no pondage are often used to turn turbines (e.g., RandGold's efforts on the Nzoro River), rather than using methods that impound water and create an artificial pressure head with periodic storage releases. There are potentially two methods of testing this hypothesis; one uses measurements and the other relies on modeling. River discharge data collected before and after the installation of a hydroelectric facility might demonstrate that river flows have not been altered in terms of amplitude or timing; and thus, the hypothesis would be proven true (at least for that facility and perhaps for similar styles of installations). More generally, hydrologic models with reservoir and run-of-the-river hydraulics could be used to demonstrate the potential for impacts.

5.7. The Annual-Average Amount of CO_2 and CH_4 Evasion From All Congo Basin Waters Is More Than 480 Tg C/yr, i.e., More Than a Value Comparable to That of the Amazon per Unit Area

If this hypothesis is true, then the Congo Basin plays a central role in global carbon dynamics, despite being less understood than the Amazon Basin. For example, *Raymond et al*. [2013] estimate the global carbon evasion rate from rivers, lakes, and reservoirs (but not from wetlands) at 2.1 Pg C/yr. The *Borges et al*. [2015b] estimate of flux of CH_4 and CO_2 at 480 ± 80 $TgCO_2$ equivalents/yr from the Cuvette Centrale highlights the importance of the Congo Basin in the global carbon cycle (i.e., Congo wetlands alone could add significantly to the Raymond et al. value). If this hypothesis is false, then the Congo Basin can perhaps be understood by



Figure 10. Archives of historic hydrologic data including river stage measurements and discharge estimates. This set of archives is located in Kinshasa, DRC. For photos of other archives, see *UNEP* [2011]. Photo: M.A. Trigg.

extrapolation of evasion studies from other tropical basins. To test this hypothesis will require multiseasonal field campaigns designed to measure the amounts of CO_2 and CH_4 evading from the various types of water surfaces in the Congo, including the mainstem river, major tributaries, headwaters, and the wetlands as well as direct measurements of gas transfer velocities within the Congo Basin.

6. Conclusions and Actions

Ideally, new scientific discoveries will result from addressing these and other hypotheses related to Congo Basin hydrology. For example, researchers studying the hydrology, hydrodynamics, and carbon emissions of the Cuvette Centrale wetlands using the hypotheses may discover that these vast wetlands function rather different from those of the Amazon and its floodplain (i.e., the Amazon mainstem, not its tributaries). Because the Amazon floodplain, with its annual flood wave and fluvial-wetland exchange, is considered a key example of the flood pulse paradigm [e.g., *Junk et al.*, 1989], discoveries that differentiate the Congo from the Amazon could lead to the Congo being considered a new paradigm for other tropical wetlands. Such paradigms incorporate the hydrologic sciences with related fields of research such as ecology, biology, geology, and biogeochemistry. As another example, the spring flood changes over rivers of central Africa, e.g., the Ogooue River, combined with decreased rainfall after the 1970s, suggest that central Africa hosts important climate changes. However, the connections of these changes beyond the Congo Basin to other tropical latitudes and indeed to the Sahel are not well known. Studies that address the hypotheses may discover the connections between atmospheric phenomenon (e.g., continental scale atmospheric jets), river discharge, and climate and thus stretch our understanding of climate change beyond that of just the Congo Basin to all of Africa.

To realize these discoveries will take an active community, funding, and access to both archival data and the acquisition of new data in key locations throughout the Congo Basin. One small team of researchers cannot address all of these hypotheses. A few teams have provided important results, but the vast size of the basin, its varying geomorphology and plant cover, and the annual movement of the tropical rainbelt have limited the extrapolation of these findings. Many teams are needed, with international collaborations and the regular sharing of data and results. Such approaches will enable the resolution of discrepancies such as those of the multidecadal rainfall trends noted in section 2.1 where some authors note long-term trends and others do not. Moreover, gaps in our understanding of hydrological processes and their controls can be overcome by taking the following actions: (1) further build the international collaborations of hydrologic researchers to include those from other countries in addition to France, Belgium, the DRC, and the RoC; (2) broaden funding to include not only federal agencies but also foundations, industry, and international groups; and (3) develop and maintain an open-access online database of hydrologic measurements and model results,

including the historic measurements from the colonial era (Figure 10) through to today's in situ, airborne, and satellite-based measurement programs.

The completion of these actions will take considerable time, probably a decade or more. But now is the time to start. It is important that hydrologic scientists everywhere understand that there are ongoing research efforts in the Congo Basin, e.g., the United Nations Cap-Net initiative, *CB-Hydronet* [2014], and the Commission Internationale du Bassin Congo-Oubangui-Sangha [*CICOS*, *Commission Internationale du Bassin Congo-Oubangui-Sangha*, 2015] which were started in 1999 and are an ongoing effort of six Congo Basin countries to promote inland navigation and to integrate water resources management. Thus, the pervasive notion that the Congo is a "Heart of Darkness" [*Conrad*, 1902] is erroneous. Indeed, The Economist recently recognized that science in Africa generally is "on the rise" [*Economist*, 2014]. Nevertheless, overcoming the challenges of the previous decades is not straightforward and will require a concerted effort by the global scientific community.

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