



HAL
open science

The Hydrology of the Congo Basin

Raphael M Tshimanga, Mark A Trigg, Michel Bechtold, Venkataramana Sridhar, Philippe Négrel, Benjamin Kitambo, Gode Bola, Catherine Awidi Mushi, Kechnit Djamel, Guy Moukandi, et al.

► To cite this version:

Raphael M Tshimanga, Mark A Trigg, Michel Bechtold, Venkataramana Sridhar, Philippe Négrel, et al.. The Hydrology of the Congo Basin. Inogwabini, BI.; Sonke, B.; Koutika, LS.; White, L.J. Resilience and Sustainability in the Congo Basin, Springer Nature Switzerland, pp.1 - 41, 2026, 978-3-032-02023-9. <10.1007/978-3-032-02023-9_5-1>. <hal-05566958>

HAL Id: hal-05566958

<https://brgm.hal.science/hal-05566958v1>

Submitted on 25 Mar 2026

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License



The Hydrology of the Congo Basin

Raphael M. Tshimanga, Mark A. Trigg, Michel Bechtold, Venkataramana Sridhar, Phillip Negrel, Benjamin Kitambo, Gode Bola, Catherine Awidi Mushi, Kechnit Djamel, Guy Moukandi, Cyriaque Nguimalet, Sebastian Apers, Adrien Paris, Sly Wongchuig, Ayan Santos Fleischmann, Fabrice Papa, and Paul Bates

Contents

Introduction	3
Dominant Features of the Hydrology of the Congo Basin and Connectivity	5
Congo River Catchment and Its Evolution	5
Large River Channels Morphology	7
Headwater Catchments	9
Wetlands, Peatlands, and Lakes	10
Groundwater	11
Measurements, Remote Sensing, Modeling, and Decision Support System	12
In Situ Measurements	12
Remote Sensing	18
Evaluation of Hydrologic Model Applications in the Congo Basin	19

R. M. Tshimanga (✉) · G. Bola · K. Djamel

Congo Basin Water Resources Research Center (CRREBaC) & the Regional School of Water (ERE), University of Kinshasa (UNIKIN), Kinshasa, Democratic Republic of the Congo

M. A. Trigg

School of Civil Engineering, University of Leeds, Leeds, UK

M. Bechtold

Department of Earth and Environmental Sciences, KU Leuven, Belgium

V. Sridhar

Department of Biological Systems Engineering, Virginia Polytechnic Institute and State University Blacksburg, Virginia, USA

P. Negrel

BRGM, Orléans, France

B. Kitambo

Congo Basin Water Resources Research Center (CRREBaC) & the Regional School of Water (ERE), University of Kinshasa (UNIKIN), Kinshasa, Democratic Republic of the Congo

Institute of Geodesy, University of Stuttgart, Stuttgart, Germany

Department of Geology, Faculty of Sciences, University of Lubumbashi (UNILU), Lubumbashi, Democratic Republic of the Congo

© The Author(s) 2026

B.-I. Inogwabini et al. (eds.), *Resilience and Sustainability in the Congo Basin*,
https://doi.org/10.1007/978-3-032-02023-9_5-1

Understanding Hydrological Processes and Functions in the Congo Basin	20
Rainfall Input	21
Forest Canopy Interception and Evaporative Losses	22
Evapotranspiration and Surface Air Temperature	23
Storage	23
River Discharge and Flow Variability	24
Wetland, Peatland, and Lake Dynamics and Functions	25
Biogeochemical Processes	29
Supply and Demand of Water Resources	31
Dynamical Evolution of the Hydrology of the Congo Basin	32
Synthesis, Gaps, and Challenges	33
References	36

Abstract

The chapter provides a comprehensive review of the hydrology of the Congo River Basin (CRB), emphasizing its physical features, current data and models, hydrological processes, environmental pressures, and the evolving scientific understanding. Water resources of the CRB support vital ecosystem and societal services that include agriculture, fisheries, hydropower, navigation, water supply, biodiversity conservation, and maintenance of vulnerable ecosystems such as peatlands and flooded forests that are crucial for carbon storage and climate resilience. The CRB hydrology is shaped by its diverse physiographical and geomorphological features, linked through a complex river network encompassing wetlands, lakes, and groundwater systems. Connectivity between headwaters, the Cuvette Centrale, and major tributaries (Kasai, Lualaba, Oubangui, and Sangha) plays a central regulatory role. Our current understanding of these processes remains very limited, which restricts our ability to implement policies for water security and address the impacts of change on physical systems

C. A. Mushi

Department of Civil and Environmental Engineering, Ardh University, Dar es Salaam, Tanzania

G. Moukandi

LMEI/CUSI/ENSP, Marien N'gouabi University, Brazzaville, Congo

C. Nguimalet

Département de Géographie, Faculté des Lettres et Sciences Humaines, Bangui, République Centrafricaine

S. Apers

Soil Service of Belgium (BDB), Willem de Croylaan, Leuven, Belgium

A. Paris

Hydro Matters, 1 chemin de la Pousaraque, Le Faget, France

S. Wongchuig · F. Papa

Université de Toulouse, LEGOS, CNES/CNRS/IRD/UT, Toulouse, France

A. S. Fleischmann

Mamirauá Institute for Sustainable Development, Tefé, Brazil

P. Bates

School of Geographical Sciences, University of Bristol, Bristol, UK

and society. Increasing pressures from deforestation, mining, land use, and climate change threaten hydrological stability, livelihoods, and ecosystem resilience. Heightened vulnerability to hydro-climatic extremes, such as floods, droughts, and landslides, and biological risks like Ebola outbreaks raises concerns of an approaching hydro-ecological tipping point. The chapter calls for urgent investment in monitoring networks, remote sensing, data integration, and predictive modeling to support sustainable water resources management and development. **Fifteen major hydrological research challenges are identified**, underscoring the need for robust scientific investment. Beyond the CRB, findings will enhance global understanding of tropical forest hydrology and reinforce the basin's critical role in the Earth System.

Keywords

Congo River Basin · Hydrological processes · Environmental pressures · Data and models · Scientific challenges

Introduction

The contemporary history of the Congo River Basin (CRB) that we know to date includes the expedition of Henry Morton Stanley in early 1875 for the exploration of the great Congo River (Stanley 1890; Baker 1894; Wack 1905). It also includes the role of the Congo River in the transaction of goods between Arabs and the inhabitants of the Congo Basin in the nineteenth century, the slave trade, and the colonialism by western powers. The history is also shaped by early migrations of peoples who colonized the river banks of the basin (Vansina 1990; Tshimanga 2009). In February 1885, the General Act of the Berlin Conference provided the status of the Congo Basin in terms of its geographical extent, but also the freedom for trade and shipping across the Congo River to its mouth in the Atlantic Ocean and the ban on the slave trade. “This basin is bounded by the watersheds (or mountain ridges) of the adjacent basins, namely, in particular, those of the Niari, the Ogowé, the Chari, and the Nile, on the north; by the eastern watershed line of the affluents of Lake Tanganyika on the east; and by the watersheds of the basins of the Zambesi and the Logé on the south. It therefore comprises all the regions watered by the Congo and its affluents, including Lake Tanganyika, with its eastern tributaries.”

The Congo River rises from the tributaries of the Lualaba and Lufira Rivers, in the southeast of the Katanga in the Democratic Republic of Congo (DRC), and flows 4700 km before emptying its average annual flow rate of about 41,000 m³/s into the Atlantic Ocean, covering a drainage area of 3.7 million km². The riparian countries of the CRB include DRC (62%), Central African Republic (11%), Angola (8%), Republic of Congo (7%), Zambia (5%), Tanzania (4%), Burundi, and Rwanda (0.49%). The tropical forest of the Congo Basin extends to the northwestern part of the topographic hydrographic boundary of the CRB, encompassing six riparian countries: Cameroon, Central African Republic, DRC, Gabon, Guinea Equatorial,

and the Republic of the Congo. This review focuses on the topographic hydrographic boundary of the CRB.

Historically, the Congo River served as the artery of colonial economic networks, enabling the export of minerals, timber, rubber, and other goods. Hydrological studies of the Congo Basin evolved largely to support these economic needs, particularly ensuring safe navigation for exports and assessing rainfall variability critical to agriculture.

A landmark in hydrological monitoring was the establishment of the Kinshasa gauging station in 1903 (4.30°S, 15.31°E), followed by over 400 flow gauges, 150 climate stations, and 1000 rainfall gauges between 1903 and the 1960s (Tshimanga 2022). This network provided robust hydrological data. However, after independence in the 1960s, monitoring networks declined due to limited state capacity and shifting political priorities. The implication is that there is a good coverage of hydrological records for the period before 1960, which are not sufficient to represent the current conditions of environmental changes in the basin.

The challenge of data quality necessary to foster adequate understanding of the hydrological functioning of the CRB and enable predictive capacities prompted large-scale experiments to collect new field data (Borges et al. 2019; Tshimanga 2022; Bates et al. 2023) and application of new robust approaches for hydrological predictions in the basin or validation of satellite missions (Als Dorf et al. 2016; Papa et al. 2022). There have also been efforts toward the use of global datasets, including global climate (both reanalysis and satellite-based) and physical basin properties datasets as well as satellite altimetry for prediction of water level and discharge (Kitambo et al. 2022; Paris et al. 2022). However, there are several challenges for performing such studies, including the uncertainty in modeling approaches and satellite estimates (Washington et al. 2013) and the lack of adequate in situ data to validate satellite-based information. Jointly, they pose difficulties to develop locally relevant predictive approaches that can effectively support water resources development in the basin.

The hydrology of the Congo Basin remains poorly understood, limiting effective water resource management and forecasting of environmental change impacts. Meanwhile, the basin faces escalating pressures from pollution (mining, industry, plastics, urban waste), river fragmentation, and deforestation, disrupting hydrological regimes and degrading aquatic habitats. Recent years have seen more frequent and intense extreme hydro-climatic events, including floods and landslides, signaling major shifts in basin dynamics (Tshimanga et al. 2016; Bola et al. 2022a). Research highlights a growing trend of hydrological drought in the Cuvette Centrale, threatening biodiversity and the survival of sensitive ecosystems like peatlands and permanently inundated forests, with profound ecological and socio-economic consequences Ndehedehe et al. (2022).

All these extreme events and the emergence of infectious diseases (Ebola, monkey pox) translate a disruption in the functioning of the Congo Basin ecosystem. What are the causes? Are we close to a tipping point in the Congo Basin? Demands for water resources are expected to increase from the other drought-plagued countries of Africa, which need the availability of information to establish sustainable

water resources management strategies. As human pressures grow, these ecosystems are at risk, and all the potential economic and environmental benefits they provide, including fluvial navigation and the blue economy, hydropower and renewable clean energy, agriculture for food security, and maintenance of endemic species and vulnerable ecosystems such as peatlands (Trigg and Tshimanga 2020).

There are major challenges for hydrological research and water resources management in the CRB (Alsdorf et al. 2016; Tshimanga 2022), which necessitate urgent attention in terms of investment for new data collection with experimental field work, remote sensing, and robust process based and predictive models, including artificial intelligence. This chapter provides a review of what we know to date on the hydrology of the CRB, current and future impacts, and it identifies possible knowledge gaps to inform future investment for hydrological science research and water resources management strategies in the Congo Basin and the region of central Africa.

Dominant Features of the Hydrology of the Congo Basin and Connectivity

Congo River Catchment and Its Evolution

The CRB is located within 10°N, 12°E to 14°S, 34°E (Fig. 1) and shares its drainage divides with other large river and lake basins of Africa, including the Zambezi basin in the south, the Nile basin in the east, and the Lake Chad basin (through the Chari River) in the north, all of which drain in opposite directions, thus emphasizing the complexity of regional drainage patterns. The extent of the Congo Basin tropical forest encompasses a number of other watersheds that include Kouilou-Niari, Ogoué, and Sanaga and drain their water into the Atlantic Ocean. Within the CRB itself, there is no single classical mode of drainage pattern which emphasizes the heterogeneous nature of the underlying geology. The CRB is approximately circular, ringed by topographic highs, also called “Swells” (Kadima et al. 2011) or “Rises” (Runge 2008), with a large central depression, an internal drainage basin known as the *Cuvette Centrale* (Bwangoy et al. 2010). These topographic highs include the Atlantic Rise on the western ridge of the basin, the Asante Rise on the northern ridge, the Mitumba Mountains on the eastern ridge, and the Lunda Rise (Shaba and Angola swells) in the southern ridge. The main rivers generated from the Atlantic Rise are known as the Sangha, Likouala Mossaka, Likouala Aux Herbes, Kouyou, Alima, Lefini, Nkeni, Foulakari, Mponzo, Luozi, and Inkisi. The Asante Rise encompasses the streams that drain the CRB starting from its drainage divides with the Chari (Lake Chad) and Nile Basins to the main trunk of the Congo River. This drainage unit is known as the Oubangui basin, the name of the main stream that connects all the upstream north-eastern tributaries to the main trunk of the Congo River (Nguimalet 2022). The Mitumba Mountains mark a clear drainage divide between the Congo and the Nile basins and constitute the source of the main rivers that provide substantial flow contributions to the Congo River at Kisangani and the lower

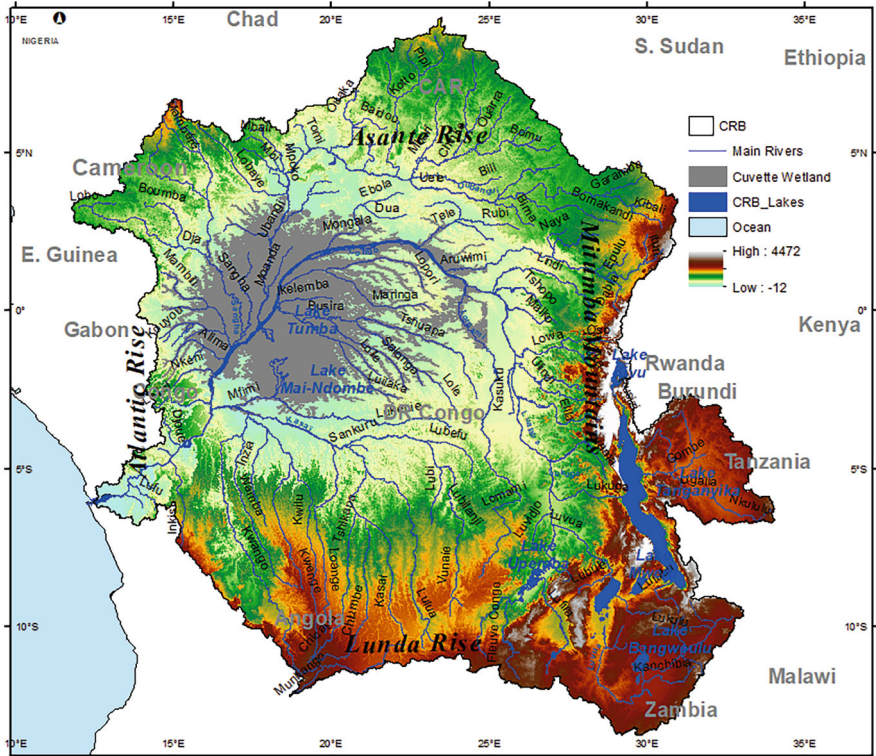


Fig. 1 Physiographic setting of the Congo River Basin

part of Lualaba. The southern rim of the CRB is flanked by the Lunda Rise, which is shaped by the Angolan highlands in the south-west and the Shaba, or north Zambian swell in the south-east. The main rivers of the southern CRB, notably the Kasai and Lualaba Rivers, rise in the highlands of the Angolan and Shaba Swells (Lunda Rise), respectively.

The Congo River's unique arc-shaped course is a result of the basin's ancient geological and tectonic history, combined with its location across the Equator. This distinctive path is largely influenced by the Congo Craton, an ancient, stable continental crust in central Africa, which creates a bowl-shaped depression (the Cuvette Centrale) that directs the river in a sweeping arc across the region (Flugel 2014). This unusual course allows the river to cross the Equator twice, leading to its bimodal flood pattern and relatively stable year-round discharge with relatively small amplitude range for such a large river (Kitambo et al. 2022). The Congo's path also contributes to its extensive drainage network, which includes many large tributaries from both north and south of the Equator. This complex network results in consistent water flow, as the alternating wet and dry seasons in different parts of the basin integrate into the main channel to provide a continuous source of water to the river

throughout the year. Further west, the Congo passes through regions with varied topographies, including the Malebo Pool (formerly Stanley Pool), a wide, lake-like section where Kinshasa and Brazzaville sit on opposing banks (Kechnit et al. 2024). As the river approaches the Atlantic, it descends rapidly through the Livingstone Falls, a series of rapids that present a dramatic drop in elevation at the of its journey from the interior of Central Africa to the coast, where the river has no delta and instead carves a canyon into the sea floor (Talling et al. 2022).

Two main theories explain the Congo River's geomorphology and flow direction (Tshimanga 2012). The first posits a southeastward flow into the Indian Ocean during the Late Cretaceous–Paleogene, redirected by East African highlands uplift in the Oligocene/Eocene (Stankiewicz and de Wit 2006). Marine deposits in southeastern valleys support this, though some argue they reflect northern marine intrusions (Giresse 2005). Alternatively, Giresse suggests initial northward drainage via the Chari Basin into Lake Chad. Despite differing views, both theories agree the basin was once landlocked or a deep-sea fan, with current Atlantic drainage being recent, shaped by long-term channel modifications (Runge 2008).

Large River Channels Morphology

The Congo River ranks second largest in the world after the Amazon, and first in the African continent, in terms of discharge and drainage area. Meanwhile, within the CRB itself, there are tributaries of second and third order which surpass all other African major rivers in terms of their area and discharge. Table 1 shows some comparative characteristics for the major river basins of Africa.

The hydrographic network of the CRB features a complex geomorphology that is vital for understanding ecosystems' distribution. The Congo River's course is characterized by significant hydrographic features, including expansive lakes, floodplains, wetlands, peatlands, and islands. Tshimanga et al. (2022a) identify three major reaches of the Congo River's course. The upper reach begins at the Katanga Plateaus and flows north to Boyoma Falls at Kisangani. This segment, known as the Lualaba, is followed by the middle reach, which extends approximately 1740 km from the city of Kisangani to the city of Kinshasa. The middle reach ends at the Pool Malebo, a significant fluvial-lacustrine system (Kichnit et al. 2024a) before the Congo River advances downstream toward the Atlantic Ocean (see Fig. 2). There are major tributaries, including Kasai River in the southern hemisphere, and Oubangui and Sangha Rivers in the northern hemisphere that join the Congo River in its middle course. The influx of water from these tributaries influences flow dynamics, leading to variations in river velocity and sediment transport patterns. This interaction fosters diverse habitats that support a wide range of aquatic species, enhancing the overall biodiversity of the Congo River system. Understanding the interactions of these tributaries is crucial for effective management and conservation strategies, particularly in the face of environmental changes and human activities.

The hydrodynamics of the Congo River are shaped by bathymetry and morphology, with stark contrasts between the Chenal and multithreaded reaches. The Chenal

Table 1 Major river basins of Africa and their drainage area and discharge characteristics

No.	River Basin	Drainage area (*1000 km ²)	Discharge (m ³ /s)
1	Congo	3700	41,000
1.1	<i>Kasai</i>	900	11,020
1.2	<i>Lualaba</i>	970	8940
1.3	<i>Oubangui</i>	604	5320
1.4	<i>Sangha</i>	220	2570
2	Niger	2300	5589
3	Zambezi	1330	3500
4	Nile	3400	2830
5	Chari	600	1059
6	Senegal	337	650
7	Okavango	721.258	475
8	Orange	973	365
9	Limpopo	413	170

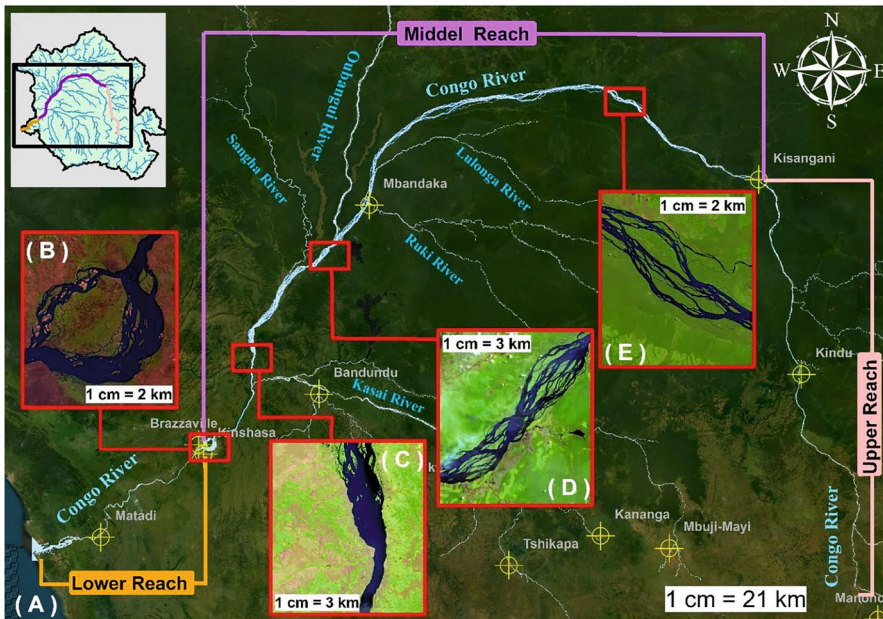


Fig. 2 Overview of the Congo River Reaches, including (a) various reaches, (b) Pool Malebo, (c) the Chenal reach at Tshumbiri, and multithreaded reaches in (d) Lukolela and (e) Bumba. (River course from Landsat 8_9. Source: <https://earthexplorer.usgs.gov/>)

reach, with greater depths, supports higher velocities due to reduced friction and better hydraulic efficiency. In contrast, the multithreaded reaches between Kisangani and Kinshasa feature numerous islands that split the channel, disrupting flow and

causing turbulence and sediment deposition. As only 20% of the middle reach maintains a single channel (Alsdorf et al. 2016), flow velocities are markedly lower. These dynamics critically influence sediment transport and ecological processes, highlighting the strong link between river morphology and hydrodynamic behavior.

Headwater Catchments

The CRB is structured around four dominant headwater catchments, namely, the Oubangui (Northeast), Sangha (Northwest), Kasai (Southwest), and Lualaba (Southeast), with the Plateaux Batékés extending the Cuvette Centrale in the west (Moukandi N’kaya et al. 2022). These upstream units are large, varying from 212,400 km² (Sangha) to 961,648 km² (Lualaba), drain steep topographies, and form the Congo River’s major tributaries (Fig. 3). A catchment classification system is required in this area to help synthesize our understanding of the interaction between climate variability, catchment characteristics (e.g., vegetation, soils, topography), and the resulting hydrological responses (Sivakumar et al. 2015).

Tshimanga et al. (2022b) developed a framework delineating 1740 catchment units, based on topography (199), socio-economic and anthropogenic factors (204),

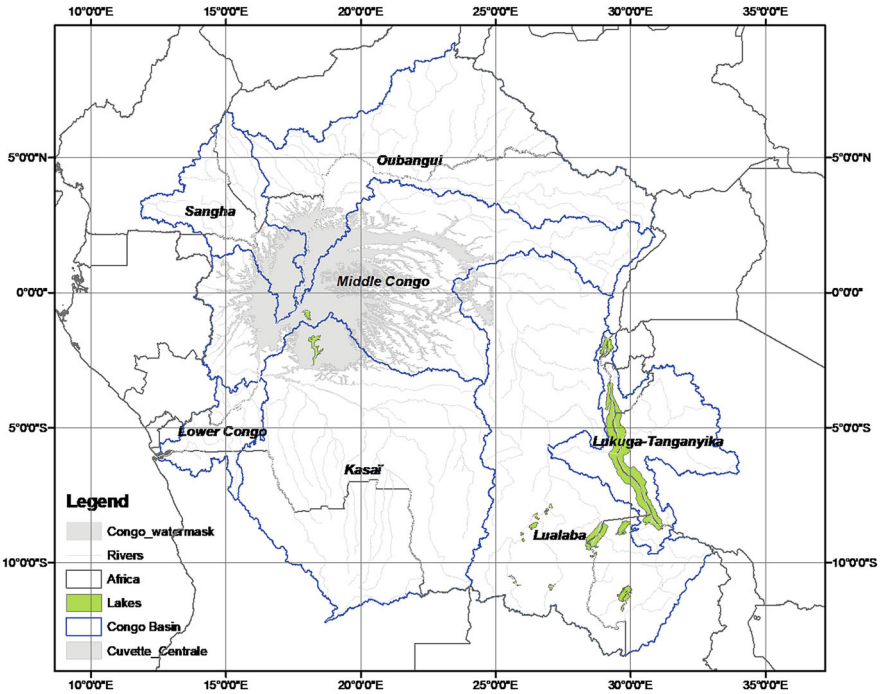


Fig. 3 Major drainage units and headwater catchments of the CRB

and traditional hydrological nomenclature (1337). These units provide standardized descriptors of physical and socio-environmental attributes. This framework underpins the Congo Basin Catchment Information System (CB-CIS, www.cbicis.info), offering 128 attributes across seven management themes: governance, climate, physiography, hydrology, risks, water uses, and external linkages. CB-CIS enhances data availability and scalability, supporting integrated water resource management, policy decisions, and transboundary cooperation.

Wetlands, Peatlands, and Lakes

The CRB hosts several wetlands, peatlands, and natural lakes of global significance, including various Ramsar sites (wetlands of international importance; see section “Wetland, Peatland, and Lake Dynamics and Functions” for details). These water

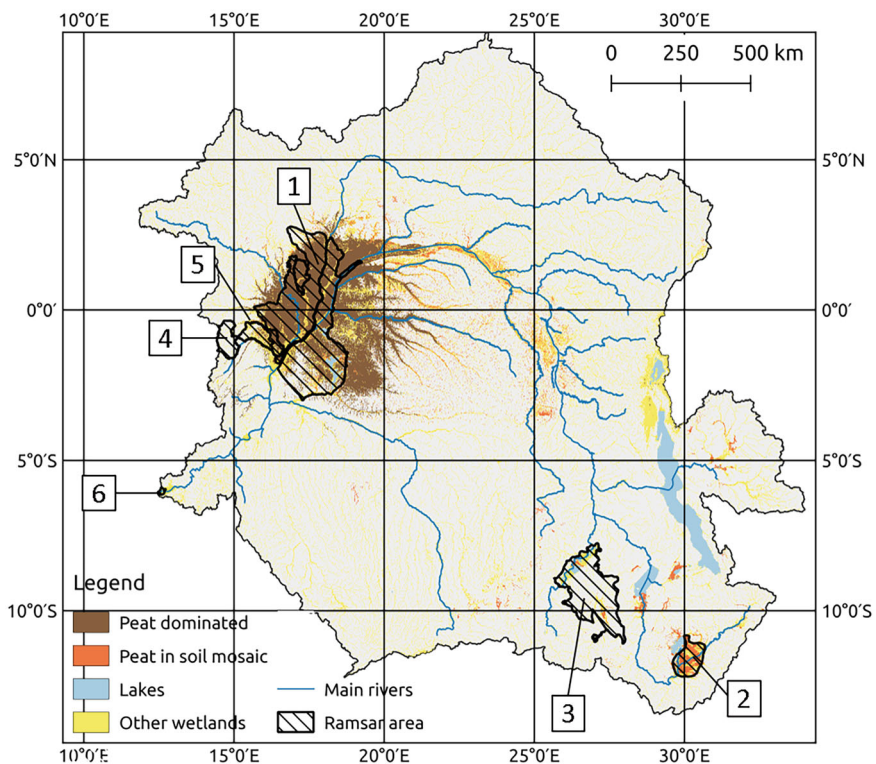


Fig. 4 Distribution of wetlands, including peatlands, with areas declared as Ramsar sites (1) flooded Cuvette Centrale; (2) Bangweulu Wetlands; (3) Basin de la Lufira; (4) Leketi-Mbama; (5) Tchikapika-Owando; (6) Parc national des Mangroves). (Data sources: Global Peatland Map 2.0, Ramsar sites (<https://rsis.ramsar.org>), Global Lakes and Wetlands Database, Cuvette Centrale peat distribution from Crezee et al. (2022))

bodies are predominantly distributed across the south-eastern rim of the basin, in the Lualaba drainage system; in the central part of the basin characterized by the Cuvette Centrale; and in the coastal region of the basin with a large extent of mangroves (Hughes and Hughes 1987; Bwangoy et al. 2011; Hughes et al. 2013; Kabuya et al. 2020; Dargie et al. 2017; CRREBaC 2022). Figure 4 shows the geographical distribution of what we know to date in terms of wetlands, peatlands, and natural lakes of the Congo Basin. It should be stressed that there is quite a good number of water bodies of great relevance in terms of the storage volume and aquatic ecosystem services in the Congo Basin, but which remain unclassified due to a lack of adequate studies (Tshimanga et al. 2022b).

Groundwater

The CRB holds significant groundwater resources (Tourian et al. 2023), distributed in four major hydrogeological units, which influence significantly the spatial variability in groundwater storage anomalies (GWSA) (Kitambo et al., 2025). These include the unconsolidated sedimentary aquifer composed of coarse alluvial sediments reaching up to 120 m thick, the cretaceous consolidated sedimentary intergranular aquifer consisting mainly of semi-continuous sandy loam and soft sandstone, the consolidated sedimentary one dominated by fracture flow composed mainly of sandstone and calcareous rocks, and the Precambrian basement aquifer often consisting of basalt and granite (UNEP 2011; Africa Groundwater Atlas 2019).

Currently, little is known and understood about the characteristics (i.e., the size of the aquifers, recharge rates, or interactions between groundwater and surface water), the spatiotemporal variability of groundwater resources, and the way they link to climate variations within the basin, leading to a significant gap in the scientific knowledge of the Congo Basin's groundwater resources. Despite the recent advances in characterizing groundwater storage anomaly changes (Crowley et al. (2006), Richey et al. (2015), Becker et al. (2018), Tourian et al. (2023),, Mouakoumbat et al. (2022)), its knowledge at the large scale is still inadequate. A recent study performed by the Congo Basin Water Research Center (CRREBaC) and its international partners (i.e., Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, University of Stuttgart) helped to characterize the dynamics of groundwater storage at the basin and subbasin scales (Kitambo et al., 2025). The study revealed that GWSA consists of 24%, 42%, 42%, 29%, 16%, and 19% of the total water storage anomaly from GRACE satellite, respectively, in Sangha, Oubangui, Kasai, Middle Congo, Lower Congo, and Lualaba subbasins (Fig. 5) (Kitambo et al. 2025). This work enhanced our understanding of groundwater dynamics in the basin through Earth Observation and field integration. A groundwater storage database using GRACE, remote sensing, and monitoring networks are vital to assess climate impacts, understand groundwater-surface water interactions, identify recharge zones, and strengthen integrated resource management.

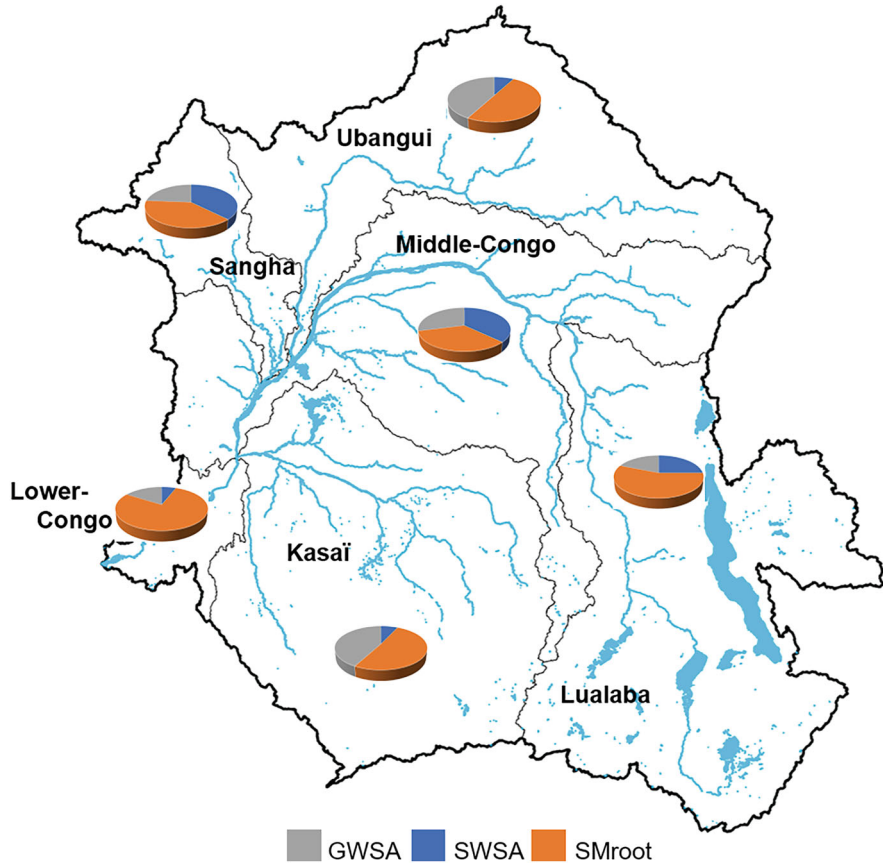


Fig. 5 Contribution (%) from surface water storage anomaly (SWSA), root zone soil moisture (SMroot), and groundwater storage anomaly (GWSA) reservoirs to Total Water Storage Changes from GRACE for each subbasin in the CRB

Measurements, Remote Sensing, Modeling, and Decision Support System

In Situ Measurements

Since the 1960s, many riparian countries of the CRB have been marked by a drastic decline in the hydro-meteorological stations, so that, within the CRB, no more than 15 gauging in situ stations are considered operational today (Tshimanga 2022). Figure 6 shows the quality and distribution of the existing streamflow monitoring gauges in the Congo Basin that spans 3.7 million km². Comparatively, this is critically far beyond the hydrometric monitoring network of the United Kingdom, which encompasses more than 1400 gauges over 230,000 km² of the surface area.

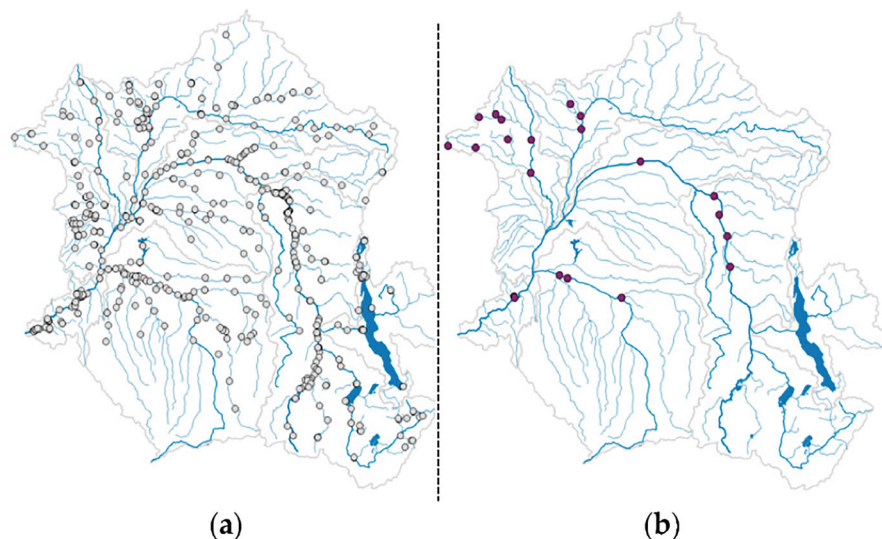


Fig. 6 Decline in the hydrological monitoring stations of the Congo Basin, (a) before 1960s and (b) current situation

Also, as a comparison, the Brazilian portion of the Amazon River Basin currently has around 60 operational river gauges (Moreira et al. 2023). At present, and still in the absence of any real National Hydrological Service, it is the river navigation services of the Congo and CAR (GIE-SCEVN—Groupement d’Intérêt Economique—Service Commun d’Entretien des Voies Navigables) and then the DRC (Regie des Voies Fluviales) that have inherited part of the data from the former hydrometric networks.

During the last decade, scientists endeavored a number of meso- and large-scale field experiments aiming at enhancing the quality and availability of in situ data (Borges et al. 2019; Tshimanga et al. 2022a; Bates et al. 2023). One of these initiatives is the Congo River users Hydraulics and Morphology—CRuHM project (2016–2022, Bates et al. 2023), which focused on carrying out several cross sectional ADCP measurements over the main navigable reach of the Congo Basin (1700 km long), between the towns of Kisangani and Kinshasa, as well as the lower reach of the Kasai River from the town of Bandundu to its outlet in the Congo River (Fig. 7).

ADCP Measurement

The first ADCP measurements in the Congo River were carried out in July 2008 (Oberg et al. 2009). RVF and GIE-SCEVN initiated other numerous ADCP measurements, which remain unpublished. Between 2017 and 2019, the CRuHM project conducted ADCP measurements over 29 cross sections along the middle reach of Congo River (Tshimanga et al. 2022a). The measurements targeted both single and multi-thread channel styles in the middle reach of the Congo River (Fig. 8).

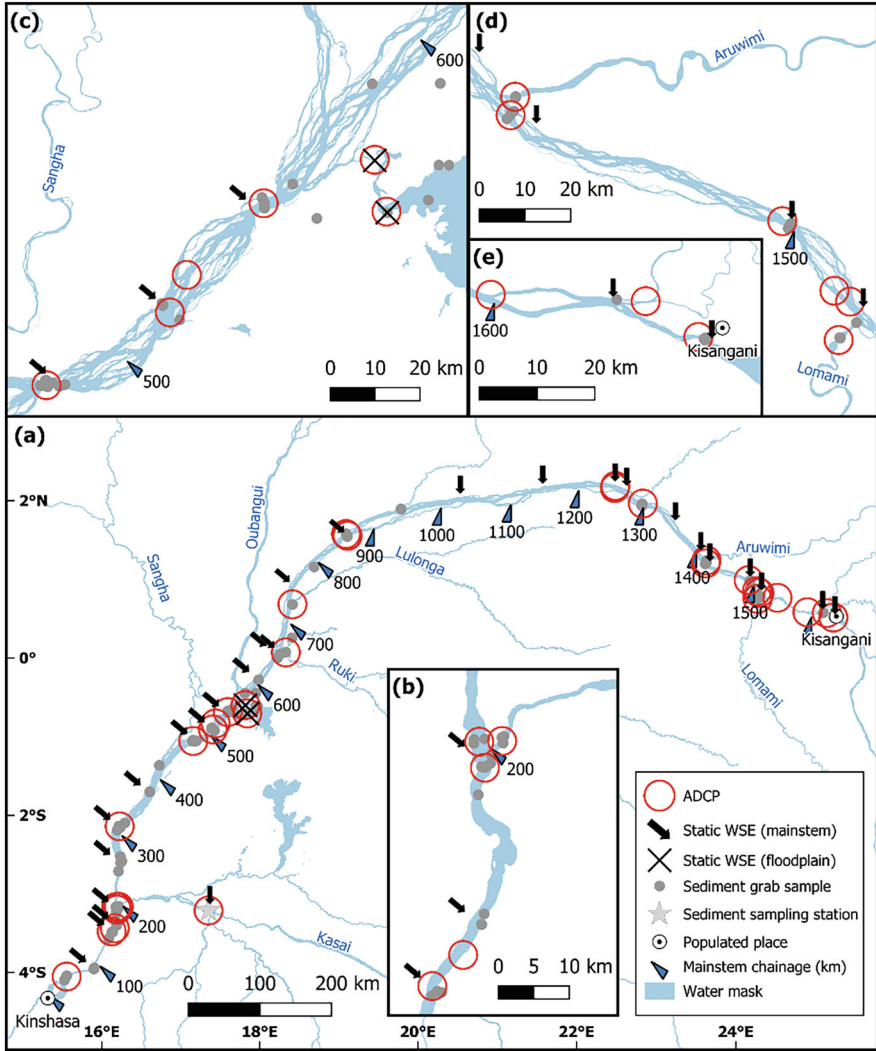


Fig. 7 Study reach and locations of measurements (Chainage calculated from the navigation path used with the CRuHM boat)

Water Surface Elevation and River Bathymetry

Measuring elevation in the Congo River Basin (CRB) is challenging due to sparse benchmarks and limited cellular networks. To address this, the CRuHM team used Precise Point Positioning (PPP) with GNSS equipment in 2019, collecting continuous Water Surface Elevation (WSE) data every 50 m along the Congo River between Kisangani and Kinshasa (Fig. 9). This dataset is indispensable for the determination of the longitudinal profile and the hydraulic gradient, which are important characteristics in the optimal use of a river. Taking into account the longitudinal profile, this

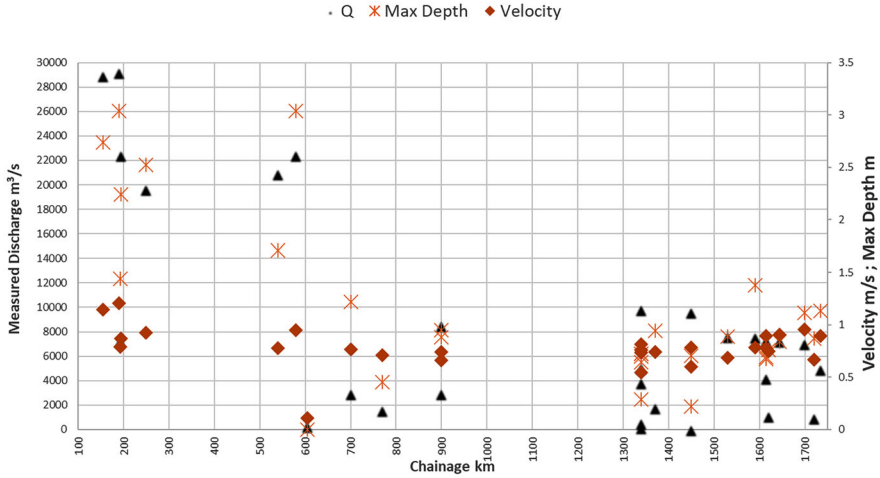


Fig. 8 Measured discharge, channel hydraulic depth, and velocity for 29 cross sections along the Congo River main stem (max depth values divided by 10 to fit the scale) (Tshimanga et al. 2022a)

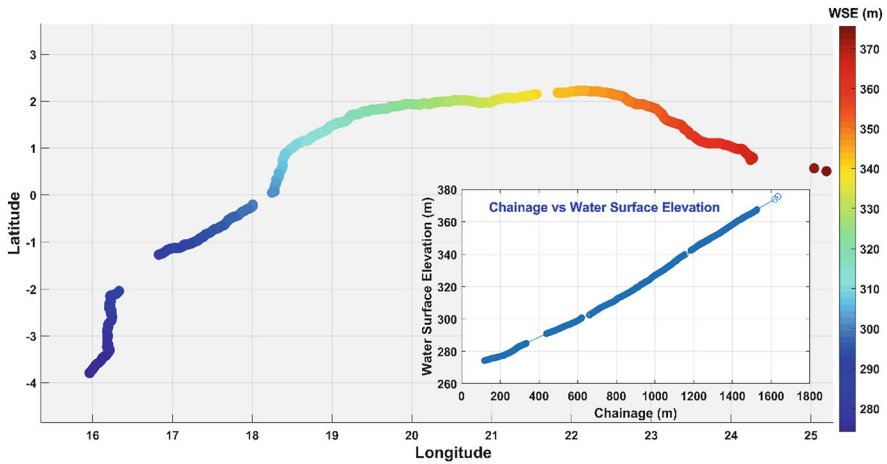


Fig. 9 Continuous water surface elevation measurements along the middle reach of the Congo River using GNSS (Tshimanga et al. 2022a)

allows the identification of locations with similar hydro-sedimentary characteristics. Through a longitudinal profile, slope variations can be observed that can indirectly provide information on past climates, structural controls, eroding and deposition sections, sediment transport capacity, and upstream-downstream flow dynamics.

Figure 9 illustrates the WSE data along the studied river reach and its relationship with chainage (distance along the river). The longitudinal profile of WSE reveals a clear and consistent increase in water levels from the upstream to the downstream end of the reach. This systematic downstream rise in WSE is attributed to the river’s slope and flow characteristics, which influence the longitudinal variation in water

surface elevation. Analysis of the data highlights a significant range in WSE within the studied river reach, with maximum values reaching approximately 370 m and minimum values around 270 m. This variation is a critical parameter for establishing accurate boundary conditions in hydraulic models and informing effective water resource management decisions.

Several initiatives have been undertaken to measure the bathymetry of the middle reach of the Congo River, as highlighted in studies by Alsdorf et al. (2016), Carr et al. (2019), and Tshimanga et al. (2022a). While earlier measurements did not comprehensively cover the entire reach, data from the PANAV project has effectively encompassed the middle reach, particularly the Chenal reach, which extends from 50 km to 250 km along the river. In this segment, data were collected at 100-meter intervals between each cross-section, providing a detailed understanding of the river's depth and topography, which is crucial for navigation and environmental management. In contrast, the multithreaded reach, extending from 250 km to 1600 km, presents unique challenges that require a different measurement strategy. Here, data collection occurred at 1-km intervals due to the river's complex geomorphology, characterized by numerous islands and extensive cross-sectional areas. These geological features complicate the maintenance of consistent measurement intervals, thereby impacting the precision and reliability of the bathymetric data.

Figure 10 shows the map of the interpolated bathymetry for the main channel of the Congo River and its singularities (Ketchnit 2024). The in situ dataset for a 1740 km stretch of the river consists of cross sections spaced at 1 km intervals.

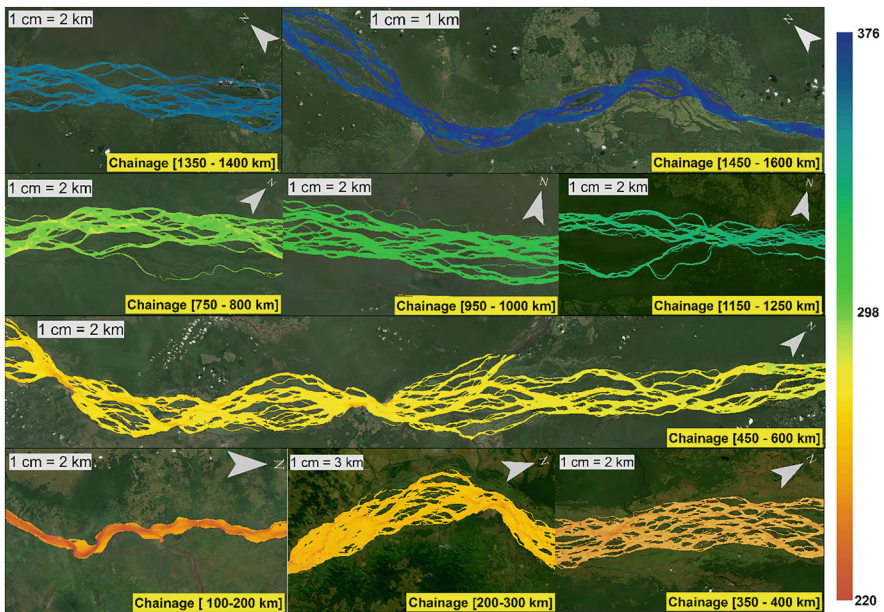


Fig. 10 Interpolated bathymetry along the middle reach of the Congo River

Overall, the WSE and bathymetry measurements taken along the middle reach of the Congo River between 2017 and 2019 have revealed that the variability in water surface slope is greater than previously thought. Such variability is important for characterizing the hydraulic behavior of river reaches (Montazem et al. 2019). The variability appears to be the result of changes in bathymetry, especially as the Congo River enters the *Chenal* and is joined by the Kasai tributary. Initially, the water surface slope becomes relatively steep (8 cm/km) as it approaches the entrance to the *Chenal*.

Sediments and Carbon

Coynel et al. (2005) published the results of 6-year experiment, including TSS, particulate organic carbon (POC), and dissolved organic carbon (DOC), for the main stem of the Congo River near Brazzaville-Kinshasa station, and the Oubangui, Mpoko, and Ngoko-Sangha tributaries, where they noted a clockwise hysteresis pattern in relation to river discharge. The results obtained in this study are in the same order of magnitude, most specifically for TSS, although it is currently difficult with instantaneous samples taken over one low flow season to derive variability and establish a comprehensive pattern.

Alsford et al. (2016) and Richey et al. (2022) provide a comparative summary of the river discharge-controlled carbon fluxes in the Congo and Amazon basins. They identified that Congo River has an exceptionally low TSS yield, which however has a high POC content and ranks fifth in terms of annual POC flux to the oceans. With respect to DOC, the Congo River is a major global exporter with a total flux estimated at between 11.5 and 12.4 Tg C/yr. 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.

During 2019, the research team under the CRuHM project conducted a number of samplings together with ADCP cross sectional measurement (Tshimanga et al. 2022a). These data encompass total suspended sediment (TSS) and organic matter (OM) for the sections with ADCP measured discharge (MD). The results are representative of the low flow season during the month of August 2019 along the main channel of the Congo River between Kisangani and Kinshasa.

Basically, these observations, while highlighting the role of these major tropical river basins of the world in the dynamic of aquatic carbon fluxes, also lead to many hypotheses that should be investigated through a combined approach that include field measurements, laboratory analyses, and modeling to establish the geographic distributions and magnitude of the riverine carbon fluxes. To date, there is little knowledge of the spatial distribution of these fluxes across the hydrographic continuum of the Congo Basin, including wetlands and lakes, headwater catchments, and their small streams that currently undergo major land use changes. Furthermore, there is a lack of information on how the change in hydrological regime, including rainfall, streamflow, and sediment loads influences these dynamics.

Remote Sensing

A number of satellite-based products necessary for assessing basin-wide water balance or improving hydrological predictions are now available at the global scale, encompassing the region of the CRB (Papa et al. 2022). These products have been used in many studies such as temporal changes in river water levels derived from radar imagery (Rosenqvist and Birkett 2002), seasonal and long-term trends of terrestrial water storage from Gravity Recovery and Climate Experiment (GRACE, Crowley et al. 2006), and temporal changes in water surface elevations and connectivity between the mainstem and floodplain channels evaluated from space-borne radar (Jung et al. 2010). Satellite altimetry has been used to infer hydrologic variables and evaluate water sources and sinks along wetlands using multiple remote sensing measurements such as GRACE, satellite radar altimetry, GPCP, JERS-1, SRTM, and MODIS (Lee et al. 2011; Becker et al. 2014; Kim et al. 2019; Carr et al. 2019). Landsat imagery has been used to characterize the hydraulics of the middle reach of the Congo River (O'Loughlin et al. 2013), and hydrologic modeling of the CRB has used various sources of satellite derived rainfall as input (Paris et al. 2022; Wongchuig et al. 2023). While the benefits of these satellite-based products are of no doubt, it is important however to recognize the difficulty of validation and associated uncertainties in some large areas of the CRB where there is a complete lack of ground-based historical observations (Washington et al. 2013).

Current efforts to leverage the use of these products and take into account uncertainty have led to the validation of a quite good coverage of satellite derived products, including ~2300 surface water level virtual stations, covering the period 1995 to 2020 and spatially distributed across the Congo Basin, with a total number of 323 VSs (Virtual Stations) from ERS-2; 364 and 342 VSs for ENV and ENV2 (new orbit of ENVISAT since late 2010), respectively; 146 and 98 VSs for Jason 2 and Jason 3, respectively; 358 VSs for SRL; 354 VSs for Sentinel 3A; and 326 VSs for Sentinel 3B. Figure 11 shows the map of the existing virtual stations with long-term time series of water level.

The current knowledge based on the use of these products reveals a persistent trend of drought over the central part of the Congo Basin, the distribution of the water availability throughout the basin, the quantification of the TDWS, and the spatial and temporal dynamics of the extent of episodic and seasonal inundation, wetlands, rivers, lakes, reservoirs, and floodplains (Kitambo et al. 2022; Kitambo et al. 2023; Wongchuig et al. 2023; Kechnit et al. 2024). However, the scientific community is still uncertain about the causes of the observed changes and how they would evolve in the future. Observed ground data are required to constrain predictive models to help improve our understanding of the processes, impacts, and causal relationships.

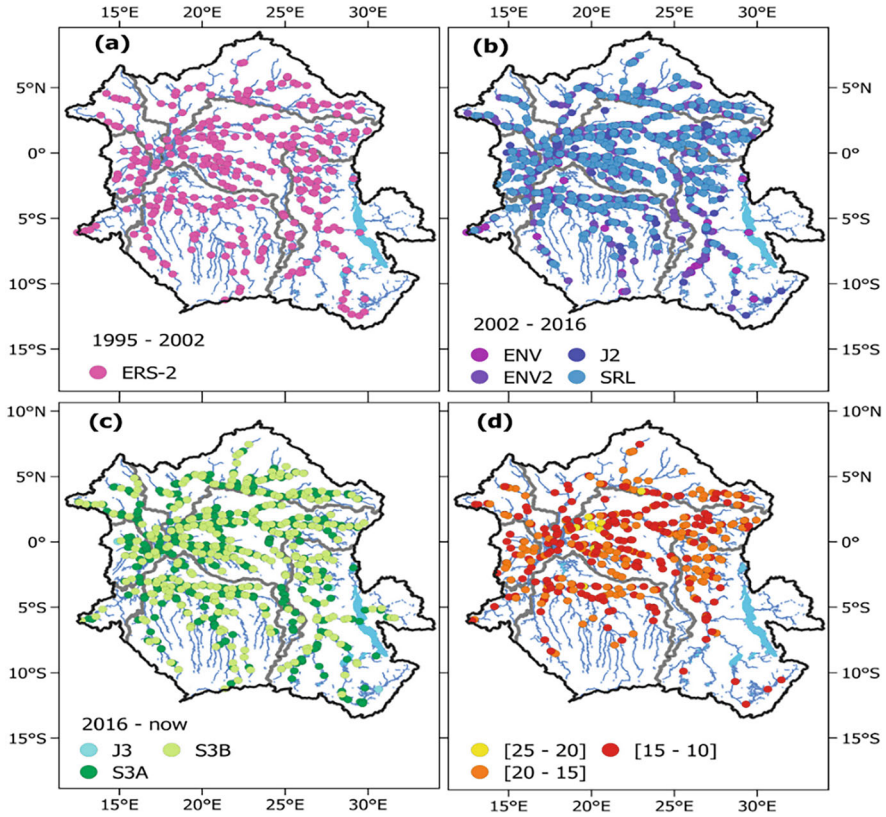


Fig. 11 Locations of ~2311 Virtual Stations (VSs) from multi-satellite missions validated by Kitambo et al. (2022)

Evaluation of Hydrologic Model Applications in the Congo Basin

The advent of hydrological modeling in the Congo Basin is relatively recent, given the need to address the many challenges of water resources management in the basin. In a review of two decades of hydrological modeling in the Congo Basin, Tshimanga (2022) showed that there has been a great deal of efforts from the past modeling studies to address both data issues and process understanding and to establish models that represent the basin’s hydrologic processes. The analysis also shows that there are still numerous issues and uncertainties that should attract the attention of future modeling studies—*right modeling for the right reason*. Modeling in the Congo Basin has evolved to encompass rainfall-runoff, hydrodynamic, and water allocation models. However, development has often focused on testing model viability rather than meeting operational needs of basin stakeholders. Key modeling systems include the following:

- Hydrologic Modeling System (HMS)—Source-to-sink approach for flow routing at continental scale. Applied to both the Congo and Nile Basins, but only Nile Basin gauging sites were used for validation (Asante 2000).
- River-Transfer Hydrologic Model (RiTHM)—Rainfall-runoff model applied to 11 major world basins, including the Congo. Successful elsewhere, but Congo calibration yielded a negative Nash Efficiency due to systematic overestimation of flows (Ducharne et al. 2003).
- PITMAN-GW—Semi-distributed rainfall-runoff model for the entire Congo Basin (99–403 sub-basins). Incorporation of storages (canopy, wetlands, lakes) and improved routing enhanced performance, calibrated with 31 gauging stations (Tshimanga et al. 2011; Hughes et al. 2013). Used for climate change impact studies, and informed WEAP, MIKE-HYDROBASIN, and later Lisflood-FP wetland parameterization (Kabuya et al. 2020).
- LISFLOOD-FP—4 km resolution hydraulic model combining in situ and modeled flows. Provided insights into Congo River discharge seasonality, flood-plain interactions, and flood wave propagation (O’Loughlin et al. 2020).
- SWAT—Daily rainfall-runoff model for the whole basin, calibrated with 20 gauging sites. Successfully assessed water availability, climate change scenarios, and uncertainty from sparse hydrometric networks (Aloysius and Saiers 2017; Sridhar et al. 2022).
- Hillslope River Routing (HRR)—Daily model calibrated with four sites to simulate total water storage, validated against GRACE-derived storage changes (Beighley et al. 2011).
- Geospatial Streamflow Model (GeoSFM)—Daily rainfall-runoff model using satellite rainfall estimates. Initial results prompted model/data refinements, improving performance (Munzimi et al. 2019).
- Large Basins Model (MGB)—Hydrologic-hydrodynamic model calibrated with in situ and remote sensing data, with improved lake representation and assimilation of discharge/water level observations (Paris et al. 2022).

These modeling efforts are significant but still face structural and operational limitations. Many models are not directly usable by water managers due to lack of stakeholder integration and data input constraints. The absence of a catchment classification system has further limited model transferability and generalization (Tshimanga et al. 2022b).

Understanding Hydrological Processes and Functions in the Congo Basin

The processes that take place at the Congo Basin scale are under the influence of many internal and external factors of the climate dynamics, land use and land cover, soil types, and the geology of the terrain. Figure 12 provides a schematic of our conceptual formulation of these processes. They include surface and sub-surface response to rainfall at the small scale but also include storage and attenuation effects

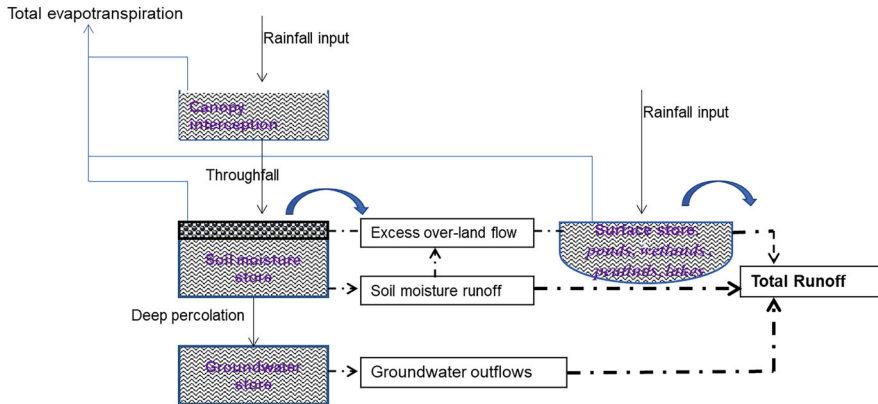


Fig. 12 Conceptual dominant hydrologic processes for the CRB

of wetlands, floodplains, natural lakes, and the channel systems of large rivers. An adequate conceptual representation of storages such as forest canopy interception, soil moisture, groundwater, lakes, and wetlands as well as space-time variations in quantities such as interflow, soil moisture flow, recharge, runoff, transmission losses, and evaporation would be a true representation of the hydrologic behavior of the CRB hydro-system.

Rainfall Input

Chapter ► [“Climate of the Congo Basin”](#) of this book provides a comprehensive review of rainfall process over the Congo Basin. Mean Annual Precipitation over the Congo Basin is estimated to 1700 mm. Overall, there are three dominant modes of annual rainfall recycling over the Congo Basin (Worden et al. 2021):

- Transport of moisture flux from the Atlantic Ocean into the Congo Basin, which plays a critical role in determining the climate variability of the region throughout the year (Pokam et al. 2012).
- Transport of moisture flux from the Indian Ocean into the Congo Basin (Dyer et al. 2017).
- A significant part of rainfall recycling in the Congo Basin is vegetation-sourced, which accounts for up to 52% of the annual rainfall from local evapotranspiration (Smith et al. 2023). This process has been identified as a key modulator of the Congo Basin water recycling, suggesting that the Congo rainforest could be an important source of moisture for initiating the rainy season.

During the wet season, higher evapotranspiration rates are typically observed, which significantly contribute to local rainfall patterns and sustain the forest’s hydrological cycle. In the dry season, reduced evapotranspiration levels result in a

lower recycling rate, making the region more dependent on external moisture sources, such as the Atlantic and Indian Oceans. Part of the amount of the moisture recycled over the Congo Basin is transported to other regions of Africa, contributing to rainwater supply to those regions. This has huge implications for livelihood of about 100 million of rural famers who depend direct on red-fed agriculture in the Congo Basin and a further 300 million of rural famers from the Sahel region and Ethiopian highlands who benefit from rainfall through atmospheric moisture recycling from the Congo Basin forests (Barimalala et al. 2023).

Analysis of historical ensemble precipitation data for the Congo Basin rainforest region shows a decreasing precipitation trend with about -90 mm per decade and an increasing dryness index of about 0.05 per decade (Wongchuig et al. 2025). This has also affected the trend in river flow. However, we are currently uncertain to whether this trend is induced by deforestation or change in the ocean sourced moisture flux to the Congo Basin. Deforestation in the Congo Basin affects not only the mean rainfall in the basin and neighboring countries, but also the spatial distribution and the temporal characteristics of the rain, such as the onset, cessation, and length of the rainy seasons. These have crucial implications in the agricultural sectors. The projected overall Congo Basin forest loss between 2015 and 2100 is estimated to induce a rainfall decline of 8% to 10% in the basin itself. The deforestation will also have large effects on neighboring regions as a result to its impact on rainfall patterns, which despite large uncertainties is believed to be potentially substantial. The indirect effect of deforestation on agriculture through the effect on rainfall is likely to be large, as there is a strong dependency on rain-fed agriculture in Africa.

Forest Canopy Interception and Evaporative Losses

The tropical rainforest of the Congo Basin plays a key role in the hydrological cycle of the basin and the African continent. This role includes local rainfall recycling, but also regional moisture recycling, which further ensure rainfall supply to as far as the Sahel and Ethiopian highlands region. It is unfortunate that this role remains poorly understood to date, which undermines conservation efforts as well as promotion of the ecosystem services. It is understood that the massive forest canopy of the Congo Basin constitutes a major atmospheric storage that intercepts a significant amount of rainfall, which then undergo direct evaporative losses to the atmosphere without reaching the ground. Variability in land cover composition for the basin implies variability in surface canopy which will also affect the variability in rainfall interception storage across the basin. The type and structure of the forest canopy determine the amount of rain water that is captured and subsequently released to the atmosphere. Associated with the types of vegetation cover are litter depths and types, rooting depth, and densities, all of which have effects on the water balance and runoff generation mechanisms (Chappell et al. 2008). Some studies in the basin have been able to use proxy data to model the interception loss through forest canopy (Tshimanga and Hughes 2014). Adequate quantification of these processes could help understand the impact of the loss of forest canopy, through deforestation, on

river runoff and flooding, soil erosion, and sediment transport. Similarly, the forest cover plays a significant role in the infiltration processes, which remains understudied in the Congo Basin. In light of the heightened pressure from land use change in the basin, the findings of these studies are particularly pertinent.

Evapotranspiration and Surface Air Temperature

There are relatively fewer studies that address Evapotranspiration (ET) and Surface Air Temperature in the Congo Basin, compared to precipitation (Alsdorf et al. 2016; Tshimanga 2022). An analysis based on 229 reference stations for the years 1950 to 1959 shows 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 1972). The actual ET varies from region to region, from “a little more than 800 mm in Katanga to a little less than 1,200 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.” Potential evapotranspiration (PET) peaks at about 1500 mm/yr near the equator, with lower values further north and south (Nicholson et al. 1997).

Storage

Storage here refers to surface water stores such as lakes, wetlands and peatlands, and the subsurface stores in soil and groundwater. Our current understanding of these processes in the CRB is limited due to experimental challenges related to the measurement of these processes. However, the advent of satellite derived products such as total water storage variations from GRACE and inundation extent are enabling these measurements.

For instance, using satellite data, Tourian et al. (2023) show that currently the Congo Basin’s Total Drainable Water Storage (TDWS) lies within a range of 476 km³ to 502 km³, unevenly distributed throughout the region, with 63% being stored in the southernmost sub-basins, Kasai (220–228 km³) and Lualaba (109–169 km³), while the northern sub-basins contribute only 173 ± 8 km³. The Kasai sub-basin has the highest capacity, storing 220 ± 4 km³ or about 43% of the total drainable water of the Congo Basin. Sangha, Oubangui, and Middle Congo contain in total 173 ± 8 km³, equivalent to 63% of the Kasai sub-basin. The Middle Congo, with its Cuvette Centrale, stores 90 ± 6 km³ of TDWS, only 40% of the Kasai estimates. Such a difference is expected, as both Kasai and Middle Congo receive similar annual precipitation, but the latter is a shallow watershed with much larger discharge (498 ± 20 mm/yr) and evapotranspiration. The Lualaba sub-basin accounts for approximately 21% of the basin TDWS with 109 ± 4 km³ (sum of its subbasins North, South and Lukuga), but most of the storage (61%) is concentrated in the Lualaba-South (67 ± 2 km³). Over the Lualaba-Lukuga the TDWS is

$20 \pm 1 \text{ km}^3$, for which the storage of Lake Tanganyika was subtracted from Total Water Storage Anomaly (TWSA).

Tourian et al. (2023) emphasize that the water amount of $476 \pm 10 \text{ km}^3$ TDWS of the Congo Basin corresponds to $133 \pm 3 \text{ mm}$ of equivalent drainable water height, i.e., the level at which the discharge reaches zero. This means that when the Congo reaches its minimum drainable storage in August— 40 mm (137 km^3), the basin could still be drained by about 339 km^3 ($476 - 137 \text{ km}^3$). Conversely, when both the water storage and the discharge reach their maximum in December, the basin holds a water volume of 613 km^3 .

Comparing the estimates over the Congo and Amazon basins, a ratio of about 25% between Congo's TDWS $476 \pm 10 \text{ km}^3$ to Amazon's TDWS $1766 \pm 47 \text{ km}^3$ is obtained. This is roughly equivalent to the ratio estimated between their mean annual discharge to the ocean (Congo $40,000 \text{ m}^3/\text{s}$, Amazon $209,000 \text{ m}^3/\text{s}$) and the ratio between the amplitude of their water storage anomaly (Congo 40 mm , Amazon 170 mm) as well as the ratio between their recharge (P-ET), e.g., Congo $300 \text{ mm}/\text{yr}$ and Amazon $1100 \text{ mm}/\text{yr}$. Other attempts to characterize the surface water storage of the Congo Basin include the studies by Lee et al. (2011); Yuan et al. (2017); Becker et al. (2018); and Kitambo et al. (2023).

River Discharge and Flow Variability

The Congo River is distinguished by its exceptional discharge characteristics, with an average annual flow rate of approximately $41,000 \text{ m}^3/\text{s}$ recorded at the Brazzaville-Kinshasa hydrological stations (Tshimanga et al. 2022a; Moukandi N'kaya et al. (2022)). The river, situated at the equator, displays a weakly contrasting equatorial flow regime, exhibiting low seasonal discharge variability. The ratio between the highest monthly mean discharge of $75,500 \text{ m}^3/\text{s}$ and the lowest of $23,000 \text{ m}^3/\text{s}$ is only 3.3, indicating a relatively stable seasonal flow pattern. According to Laraque et al. (2020), Paris et al. (2022), the hydrological year starts in August and features two high-flow periods (October–January and April–May) alternating with two low-flow periods (February–March and June–September) (Fig. 13). A spatial analysis of discharge variability across the Congo River Basin reveals that local and regional factors exert a significant influence on the hydrological regime. For instance, discharge and rainfall patterns at specific locations such as Bangui, Ouesso, and Kisangani exhibit considerable variation, suggesting that discharge characteristics are not uniform throughout the basin (Bola et al. 2022b). Significant variations in river discharge have been observed over the years. Between 1960 and 1995, fluctuations were noted, with the river only recently returning to its long-term average. For Kinshasa/Brazzaville station, discharge increased by 21% between 1960 and 1970, 4.5% from 1971 to 1981, followed by a 5.3% decrease from 1982 to 1993, compared to the 1902–1959 average.

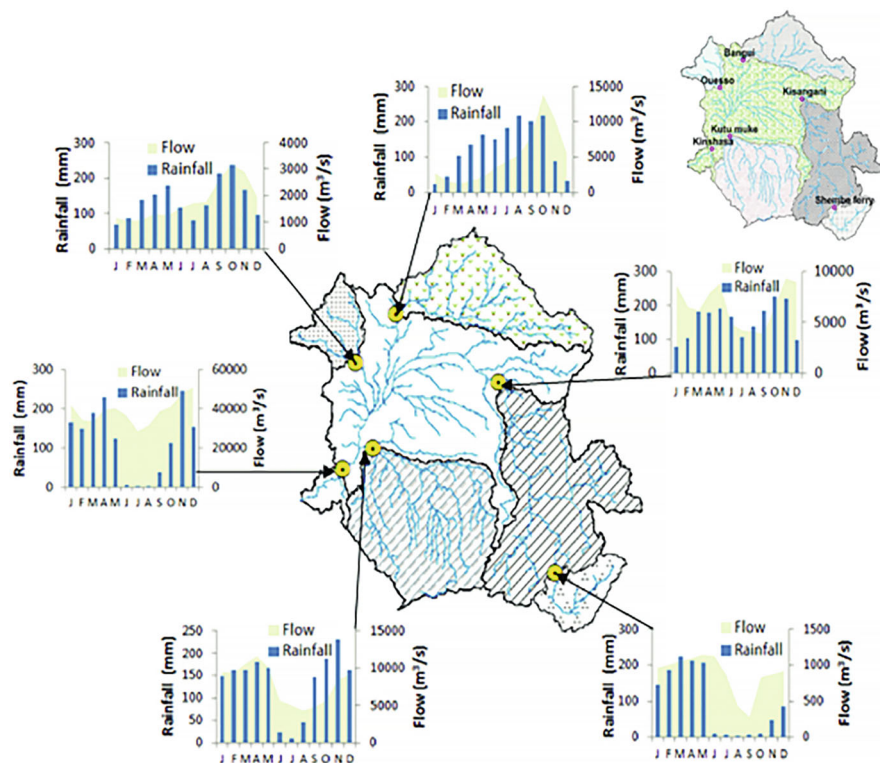


Fig. 13 Rainfall-runoff relationship in specific stations of the Congo Basin (Bola et al. 2022b)

Wetland, Peatland, and Lake Dynamics and Functions

A combination of available in situ measurements, hydrological modeling, and satellite observations is used to gain insights into these dynamics. A mass balance analysis by Yuan et al. (2022) estimated that river-wetland exchange accounts for less than 20% of the wetland inflow, while hydrological modeling by Datok et al. (2022) suggested a 69% contribution of the Congo River (33%) and tributaries (25% RoC and 11% DRC) to the wetland inflow, with remaining water input coming from precipitation. Georgiou et al. (2023) mapped the spatial distribution of the main water source for a subregion of the Cuvette Centrale. They found that 27.5% of the wetlands in the subregion received river or groundwater input. O’Loughlin et al. (2020) found that more than 16% of the river channel network actively exchanges water with wetlands and identified river-wetland exchange as a crucial feature in the propagation of Congo River flood waves. Interfluves co-occur with floodplains along the Likouala-Mossaka and Sangha Rivers, and floodplains are also found next to the Congo River, east/upriver along the left bank tributaries, and north and east of Lac Mai-Ndombe (Biddulph et al. 2021).

The dominant feature of the Bangweulu system is the seasonal flooding regime, which influences every aspect of the local environment and economy. By January each year, vast areas of the Bangweulu floodplains are inundated from local rainfall and runoff. Peak water levels occur in March when the inflow from the Chambeshi and other rivers draining the surrounding catchment spills across the seasonally flooded plains (6800 km²) and into the permanent deepwater swamps (5000 km²). Waters recede slowly during the dry season, reaching their lowest level in October/November, leaving only the central basin permanently under water. The mean annual outflow to the Luapula River is about 440 m³/s. The extent of the floodwater inundation and the rate with which it rises and recedes varies from year to year. The climate is divided into three distinct seasons: a cool dry season from April to August, a hot dry season from August to October, and a warm wet season from November to April (Chundu et al. 2024). The wetland is fed by 17 major rivers from a catchment area of 190,000 km² but is only drained by one river, the Luapula River (Kamweneshe et al. 2003).

The wetlands associated with the Lufira River create extensive floodplains, papyrus, and other marshes, especially in the Upemba National Park region. The Lufira rises in the Shaba plateau south of Likasi. The river was dammed in 1926 at Mwadingusha near Likasi to form Lake Tshangalele, a reservoir for a hydroelectric generator supplying power for copper smelting. It flows northward through the Bia Mountains for about 500 km, joining the Lualaba in Lake Kisale. Its discharge at Kapolowe has been measured since 1920 (Devroey 1951, 1952). It is therefore fairly accurately known. Maximum discharge (between 150 and 250 m³/s) coincides with flooding in the second half of the rainy season (February, March, or April). The minimum (between 7 and 2.5 m³/s) occurs toward the end of November, i.e., after the start of the rainy season. The first rains serve mainly to provide the soil with moisture equivalent to field capacity. The heavy storms of November and December cause only minor, short-lived flooding. The peaks in the diagram represent a runoff of less than 1% of the water that fell. In the basin, only steep slopes with thinner weathering mantle are likely to favor runoff or hypodermic flow. In December, the latter rises, heralding the outcropping of the aquifer in the Dembos, flared-bottomed valleys with no organized linear flow. From January to April, the centimeter-thick sheet of runoff that appears in these valleys and sometimes lasts for several days after a period of heavy rain provides a significant proportion—around 40%—of the river's flow (Alexandre 1977). The Lufira basin is a wetland of worldwide importance, as the edapho-climatic factors prevailing in the area provide good conditions for the formation of various ecosystems and the development of a varied herbaceous and shrub flora. This ensures the maintenance of biological diversity, with the presence of numerous endemic species.

Lake Tanganyika partially drains into the Lukuga River at Kalemie and further feeds the Lualaba basin. This discharge contributes to 18% of the total annual water loss of the lake, while its water balance is mainly governed by evaporation, corresponding to 82% of its total annual water loss. Similarly, Lake Bangweulu and its surrounding wetlands ultimately discharge into the Luapula River, Lake

Mai-Ndombe and its wetlands contribute to the Fimi River, and Lake Mweru with its surrounding wetlands are drained by the Luvua River.

Leketi-Mbama is a unique inland wetland with a diverse mix of habitats including lakes, marshes, and floodplains. The main hydrological function of the Leketi-Bama zone is groundwater recharge: it retains around 35% of the direct rainfall over the region. The Kouyou is the main river feeding the area, receiving water from several tributaries including the Okeli Ambori stream and flowing into the Likouala Mossaka at Loboko village.

The Tchicapika-Owando is mainly made up of the Kouyou and Alima rivers, whose tributaries are the Lavouma and Diéle, respectively. The Kouyou flows into the Likouala-Mossaka, which in turn flows into the Congo River. The Alima flows directly into the Congo River. During high-water periods, all these rivers are connected in some places to floodplains and swampy forests. Floods are regular and of fairly long duration. Variations in river discharge regulate the intensity and duration of exchanges between the various geographical elements of the river-alluvial plain system. When the water level rises, water invades part of the alluvial plain, establishing connections and enabling exchanges with the minor bed. Conversely, when water levels fall, certain areas of the alluvial plain become isolated from the riverbed. Oscillations in the hydrological regime have an impact on the amplitude, duration, and frequency of floods. Whatever the period of high or low water, they exert a greater or lesser influence on the productivity of hydro systems (Fig. 14).

Most wetlands in the Congo Basin significantly contribute to dampening the flood risks downstream through many functions (Hooijer et al. 2005; Dommain et al. 2010; Acreman and Holden 2013; Gao et al. 2016; Crump et al. 2017). The Cuvette Centrale significantly extends the travel time of water from different regions of the Congo Basin before it reaches Kinshasa and Brazzaville and partly explains the long residence times of 2 months for the flow to move from the confluence of the Lualaba and Elila Rivers to Brazzaville, 1 month from the confluence of the Kotto and Oubangui Rivers, and approximately 15 days from the confluence of the Loange and Kasai Rivers (Sridhar et al. 2022). Besides taking up water, the Cuvette Centrale acts as a natural reservoir that traps sediment from upstream rivers thus reducing the amount of suspended particles flowing downstream. Reduced uptake of sediments would lead to a rise of the riverbed and impact flooding dynamics in downstream areas.

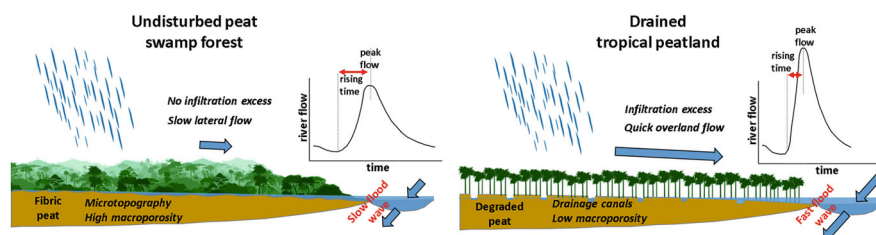


Fig. 14 Schematic illustrating the buffering role of peatlands during rainy periods and high river stages, highlighting how human disturbance amplifies downstream flood risks

In the Cuvette Centrale, peat formation began at least 19,600 calibrated years before present (cal yr BP; taken as AD 1950; Garcin et al. 2022; Hawthorne et al. 2023), but mostly from about 10,500 cal yr BP (Dargie et al. 2017), coinciding with more humid conditions at the beginning of the Holocene (Schefuß et al. 2005). Peat accumulation is a good proxy for hydrological stability, as organic material will only accumulate under relatively stable hydrology (Dargie et al. 2017). Studies of Cuvette Centrale peat show that shifts in the hydrology have led to periods of peat accumulation, where the hydrology has been conducive, as well as hiatuses of that growth (Garcin et al. 2022).

The heterogeneous hydrology of the Congo Basin peatlands could indicate that various processes have initiated peat development at distinct times (Biddulph et al. 2021). A drying period between 5000 and 2000 yr bp implies a regional drop in the water table, causing peat decomposition, including some of that was already accumulated. There was no evidence of human impacts on the forest in that period. After 2000 yr bp, conditions stabilized and peat accumulation resumed. The authors conclude this may show that the stability of the carbon stocks in the peatlands may be sensitive to a climatic drought threshold (Garcin et al. 2022). Whenever the self-regulating hydrology of peatlands is disturbed by external factors such as artificial drainage, land use change, and climate change, their ecosystem functions and services are often lost. Future exploration of unexposed, remote peatland areas might strongly impact the peatland hydrology in the Cuvette Centrale (Dargie et al. 2019). The Congolese rainforest is relatively dry compared to tropical forests in Southeast Asia and Central and South America, receiving approximately 35–40% less precipitation (1700 mm yr^{-1} ; Samba and Nganga 2012) than its Amazonian counterpart (Guan et al. 2015; Alsdorf et al. 2016). The limited precipitation and its bimodal pattern (Longandjo et al. 2024) make the Congolese rainforest and its peatlands water-limited during dry seasons and highly vulnerable to drought intensification or changes in the rainfall pattern (Jiang et al. 2019). Drought pressure poses a major threat to the peatlands of the central Congo Basin (Loisel et al. 2021), potentially leading to carbon emissions via oxidation or fires. Ongoing climate warming will likely increase drought severity, while possible intensification of El Niño could further prolong droughts (Rifai et al. 2019). Garcin et al. (2022) used paleo records from peat cores in the Cuvette Centrale and identified a long period (between 5000 and 2000 cal yr BP) of dry conditions, i.e., the “Ghost interval.” Their research showed that environmental change could lead to a regional drop in peatland water levels with decreased peat accumulation or even peat decomposition, which might be a precedent of the impact of current and future drought pressure on these peatlands.

Most of the progress in our understanding of these historical conditions before traditional measurements has therefore been made by paleoenvironmental studies. We also see evidence of these significant changes in the hydrology from studies of Congo sediment in the Atlantic. A high aridity period during the last glacial maximum, an increase in precipitation and high river discharges from 15,200 yr BP, and around 9000–8000 cal ka BP, rainforest vegetation inhibited soil erosion and therefore sediment discharge (Marret et al. 2008).

While much remains to be done in this research area, including understanding how far back peat accumulation started, what we can take away is that changes in the hydrological regime can cause significant changes in the basin, such as loss of peat, and these can last thousands of years and potentially link to important carbon climate feedback mechanisms. The point here is that there have been significant changes in the magnitude and timing of the hydrology cycle induced by climate and vegetation changes in the past, showing that it may actually change substantially in the future if we perturb the current context.

Biogeochemical Processes

Borges et al. (2019) carried out field measurements across the lowland part of the Congo River network to describe the spatial variations in fluvial dissolved carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) concentrations. Field measurements across the lowland regions of the Congo River network revealed a pronounced oversaturation of surface waters with carbon dioxide (CO₂) and methane (CH₄) relative to atmospheric equilibrium. Greenhouse gas dynamics in Congo Basin rivers showed extreme variability. CO₂ partial pressures (1087–22,899 ppm) and CH₄ concentrations (22–71,428 nmol/L) far exceeded equilibrium values (~400 ppm and ~2 nmol/L, respectively), while N₂O varied less. Spatial variability, driven by stream size, stream order, and floodplain interactions, dominated over seasonal or diurnal changes. Larger streams had lower CO₂/CH₄ and higher oxygen. Rivers draining the Cuvette Centrale exhibited highest greenhouse gas levels, linked to flooded forests and wetland inputs. Elevated DOC (1.8–67.8 mg/L) and oxygen undersaturation (0.3–122.8%) highlighted strong organic matter decomposition.

In the Congo Basin, major and trace elements and Sr isotope ratios were investigated at the Pool Malebo for the 1989 and 2010 hydrological cycles (see for details Négrel 1993; Négrel and Dupré 1995; Henchiri et al. 2016). Additionally, the main tributaries were also investigated (Oubangui, Kasai, Sangha, Likouala, and Lefini).

Figures 15 and 16 present the fluctuations of the ⁸⁷Sr/⁸⁶Sr ratios and the discharge in the dissolved load obtained for the Congo River for the 1989 and 2010 surveys. Both figures showed that the ⁸⁷Sr/⁸⁶Sr ratios are highest during low flow and decrease with increasing discharge. This type of relationship can be interpreted as a mixing with two signatures (Grosbois et al. 2000; Négrel et al. 2003).

The ⁸⁷Sr/⁸⁶Sr isotope ratios exhibited strong seasonal patterns, peaking during low-flow periods and declining with increasing discharge. This inverse relationship suggested a dual-source mixing model, where Sr inputs during low flow likely derived from rock weathering and terrestrial sources, while during high flow, dilution from precipitation or other tributary inputs dominated (Fig. 17).

Further insight was gained from the relationship between Sr and sodium (Na) concentrations. A clear positive correlation existed between Na and Sr across seasons, with lowest concentrations during low water periods. Tributaries such as the Kasai, Oubangui, and main Congo River channel displayed higher Na-Sr contents, while dilute, DOC-rich tributaries draining the central depression (e.g., Sangha,

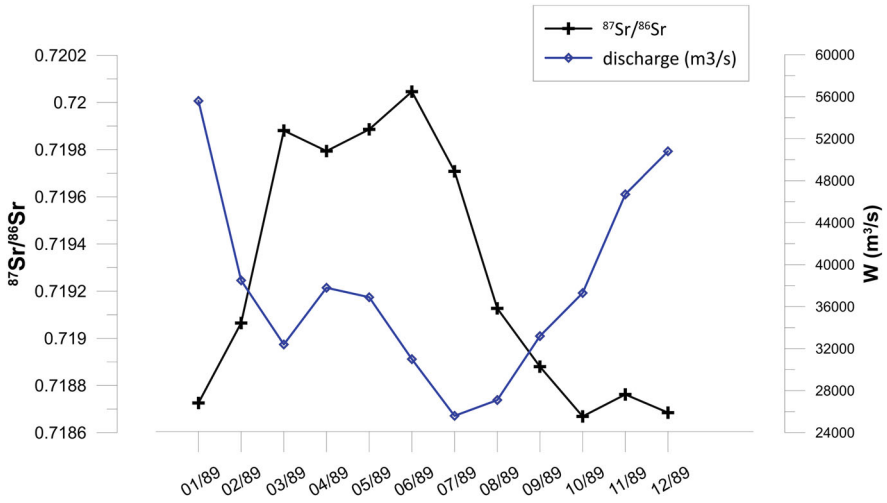


Fig. 15 Mean monthly discharge of the Congo River at the Brazzaville station (W in m^3/s) and $^{87}\text{Sr}/^{86}\text{Sr}$ values for the samples collected each month at the Brazzaville station (Négrel and Dupré 1995)

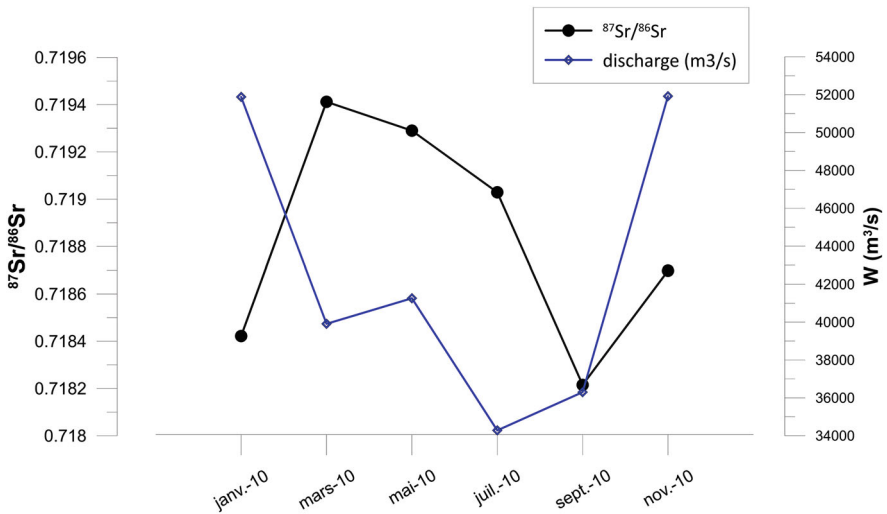


Fig. 16 Mean discharge of the Congo River at the Kinshasa station (W in m^3/s) and $^{87}\text{Sr}/^{86}\text{Sr}$ values for the samples collected every 2 months at the Kinshasa station (Henchiri et al. 2016)

Likouala, Alima) exhibited much lower values. The Lefini River, draining the Batékés plateaus, also showed very low Na-Sr signatures, consistent with its geologic setting.

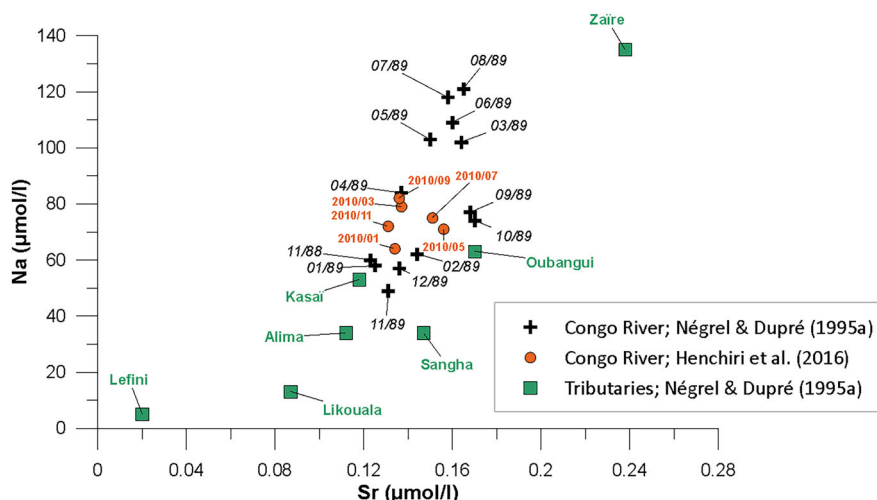


Fig. 17 Plot of Na versus Sr contents for the samples of the Congo River, collected each month at the Brazzaville station (Négrel and Dupré 1995), every 2 months at the Kinshasa station (Henchiri et al. 2016) and for the tributaries (Oubangui, Zaïre, Kasai, Sangha, Likouala, and Lefini; Négrel 1992)

The biogeochemical processes in the Congo River Basin are controlled by a complex interplay of lateral carbon inputs, organic matter decomposition, stream size, floodplain dynamics, and geological substrate. CO_2 and CH_4 emissions are sustained primarily by allochthonous carbon sources, especially from wetlands. Meanwhile, Sr isotopes and elemental ratios offer deep insights into hydrological and geochemical mixing, helping to trace the influence of both surface water and groundwater across varying spatial and temporal scales. These findings underscore the importance of integrating biogeochemical, hydrological, and isotopic approaches to understand carbon cycling and water movement in tropical river systems like the Congo.

Supply and Demand of Water Resources

The Congo Basin's main water uses are urban/municipal supply, agriculture, hydro-power, navigation, and biodiversity maintenance. The population of roughly 120 million (70% in rural areas) depends heavily on rainfed, slash-and-burn farming, a key driver of deforestation. Expanding irrigation could promote sedentary agriculture, curb forest loss, boost productivity, stabilize incomes, and mitigate rainfall variability impacts.

Hydropower potential is estimated at 100,000 MW, yet installed capacity is just 2700 MW. Electrification is low, with only 9% of the population having access. Major future projects—such as Grand Inga (40,000 MW) and Inga III (4320 MW)—

could transform regional energy supply, reduce reliance on wood fuel, and cut deforestation pressure.

The basin also has around 25,000 km of navigable waterways, but navigation is hindered by infrastructure deficits. Strategic investments in ports, terminals, and dredging could lower transport costs, facilitate trade, and connect landlocked countries to global markets. Enhanced navigation would stimulate industry, attract investment, and foster political and economic integration. Additionally, improved access could support ecotourism, generating income and jobs while promoting conservation.

The Congo Basin's water resources hold transformative potential for regional development. Realizing this will require coordinated investment in water supply, irrigation, hydropower, and navigation infrastructure, alongside sustainable management to balance economic growth with environmental protection in the face of climate change.

Dynamical Evolution of the Hydrology of the Congo Basin

Like all large river basins, large-scale geological processes have shaped the Congo Basin over geological epochs. However, the changes that this basin has been exposed to have resulted in a basin like no other currently on the planet. This intracontinental sag basin has resulted in a remarkable deposit of up to one billion years of sediments (Delvaux et al. 2021). It is important to understand these shaping influences as they explain much of the core hydrological systems of what we see today, while also highlighting the long-term non-stationary aspect of the basin's dynamic hydrology. The legacy of these geological changes is evident in the basin's current hydrological systems. The interplay between tectonic stability and climate-induced fluctuations has shaped the region's deep river channels (below Malebo Pool), its vast wetlands, and rich alluvial plains, making the Congo River remarkably stable in terms of discharge.

On very short timescales of the last 100 years or so, the system does appear to be relatively stable (Laraque et al. 2020). For example, a study of the planform of the main river channel and islands conducted by Trigg et al. (2022) using a comparison of recent satellite images and historical navigation maps shows that the main river is relatively stable and only appears to change slowly over the period assessed. However, there was an indication in this study that either a recent reduction in hydrology inputs or increase in sediment inputs were driving a slow accumulation of sediment in the main channel.

While on recent human timescales there appears to be relative stability in the hydrological systems of the Congo, this can be deceptive, as large systems can change, albeit relatively slowly and are actually always changing. Studies of hydrology variables at climate and river stations across the Congo Basin reveal that, set in this stable context, we observe both gradual changes such as increases in temperature (Samba et al. 2008) and discontinuities in runoff variables during particular historical periods in the last 100 years (Laraque et al. 2020). This indicates the main flood

regime is not stationary (Bola et al. 2022a) and extremes such as floods have very real impacts on the local populations (Bola et al. 2022b), as many millions live near and rely on the Congo for their livelihood and economic transport (Trigg et al. 2022). This can be worsened in the future as climate change impact show increasing trend in flood regime. The climatic and environmental shifts over the past tens of thousands of years have also contributed to the unique hydrology of the Congo Basin, influencing everything from river discharge to biodiversity. Understanding these deeper historical changes is essential for predicting how future climatic and anthropogenic changes may impact the basin.

Given the focus on “influencing equitable resource sharing and maintaining the Congo Basin’s ecological role,” it is important to understand the current drivers of hydrological change in the Congo Basin. The drivers constitute interconnected demands for water, energy, and food resources, and these competing demands drive changes across the basin’s hydrology. The three major drivers are hydropower and large water infrastructure development, deforestation and land use change, and mining.

These trends highlight the urgency of integrated and sustainable resource management in the CRB. While much of the current deforestation remains artisanal, experiences from other basins show that unchecked development can lead to profound hydrological consequences. Understanding ecological thresholds and enforcing land use limits will be critical to safeguarding the basin’s environmental services and the livelihoods that depend on them.

Synthesis, Gaps, and Challenges

The time scale of this review spans from 1903 to the present. This is because we lack measurements prior to this year which marks the start of the hydrological monitoring in the Congo Basin. It is also unfortunate that indigenous knowledge about the hydrology in the Congo Basin is not documented prior to this period (Tshimanga 2009).

There is no doubt that there have been enormous efforts deployed during this time period to collect in situ data and use various empirical analyses and numerical models to establish an understanding of the basin’s hydrologic variability and changes. The difficulty of acquiring spatial and temporal in situ data of sufficient quality prompted the use of earth observation datasets. However, quality in situ data are still required to validate data obtained from remote sensing. Many hydrology studies have been variously challenged by problems related to lack of appropriate data, as well as the lack of a thorough understanding of climate-hydrology processes. There has also been a lack of integration of this understanding in models and therefore, lack of integrated and critical model assessment. There is a lack of a quantitative understanding of the spatial heterogeneity and dynamics of different components of the hydrology of the Congo Basin, which inhibits the advancement of innovative approaches and their applications in water resources management, climate modeling, and ecosystem vulnerability studies. For example, it is currently

unknown how changes to the wetland hydrology and energy balance might alter the local climate across the basin and beyond through teleconnections (White et al. 2021). It is assumed that by stabilizing the regional hydrological cycle, wetland forests may reduce extreme variations in rainfall, which can otherwise lead to severe floods. A stronger scientific understanding of the land-atmosphere coupling over the vast wetland area of the Cuvette Centrale would give these wetlands a new value that goes beyond already known critical services such as local carbon storage and biodiversity. To advance in these fields, there is an urgent need to address the scarcity of in situ measurements of hydrological variables and to exploit the wealth of historical and newly available satellite observations.

Having looked at the past and present of the current basin hydrology dynamics, what does the future hold? Recent hydrological studies of multimodel regional climate downscaling suggest future changes in river flow ranging from -31.8% to $+9.2\%$ under RCP4.5 and -42.5% to $+55.5\%$ under RCP8.5 scenarios. In the upstream reaches, these changes are more pronounced. Discharge is also shown to decline in the basin's center and south while increasing in the southeast and northwest (Karam et al. 2023).

In the context of ongoing climate change, the CRB is geopolitically at the center of many proposed solutions due to its perceived abundance of water (Inogwabini 2020). However, across the basin, challenges such as overfishing and lack of transboundary management plans complicate this water resources management expectations. Thus, although the basin is commonly perceived as having a relatively low anthropogenic influence compared to other large river basins, this is unlikely to continue in the future as development pressures increase and humanity looks at climate change adaptation.

The future hydrology of the Congo Basin is expected to undergo significant changes due to climate change, with varying impacts across different regions of the basin. Increased temperatures and variable precipitation patterns will likely lead to changes in runoff, river flow, and the frequency of hydrological extremes such as droughts. The complexity and uncertainty in climate model projections highlight the need for comprehensive and adaptive water management strategies to mitigate the potential adverse effects on agriculture, hydropower, and water availability for human and ecological systems (Tshimanga and Hughes 2014).

While much progress has been made in the last few decades in beginning to understand the hydrological systems in the CRB and how the core of this system functions, nonetheless there is much we are still trying to explain. There are many hazards posed by changes in the future for the Congo Basin that may detrimentally affect its biodiversity and ecosystem services for humanity locally and at planetary scale. How these changes, which are inevitably coming, will affect the dynamics of the Congo Basin is still poorly understood. We urgently need to gain this understanding in order to manage as best as we can how changes manifest in the system. This will provide evidence-based decision-making to preserve and indeed, if possible, enhance the value of this unique and precious systems for local populations as well as globally. This can be exemplified by the need to improve the knowledge of surface-groundwater links. The regulating role of the aquifer is highlighted by the

contrast between the low seasonal variations of the river flow rates in the Cuvette Centrale despite the significant seasonal variability of rainfall in this part of the basin. This should be extended to other parts of the basin, in close relation with the study of wetlands.

The data scarcity problem needs to be addressed through the support of data rescue efforts, i.e., the digitization of colonial and post-colonial archives (mainly weather station and stream gauge data), as well as the expansion of the currently established monitoring network for surface waters and wetland groundwater levels as well as energy and carbon fluxes through eddy covariance towers. Together with satellite data, the new measurement data can be upscaled and combined with hydrological models to derive realistic replicates of the water cycle over the wetland in the Congo Basin that could be used in scenario modeling to present the impact of disturbance to regional and global stakeholders.

This review helps articulate a number of major challenges of hydrological research in the Congo Basin in terms of process understanding and critical information gaps, which require major scientific investment. Specifically, future work should address the following:

1. Local and external factors (atmospheric-ocean interactions and the monsoonal processes) that influence variability in rainfall
2. Influence of global warming on rainfall pattern and water storage and their seasonal distributions, and implications for rainfed agriculture-food security, hydropower, and ecosystems services
3. Forest hydrology: forest canopy interception and evapotranspiration dynamics
4. Local and regional moisture recycling and the impact of deforestation
5. The spatial distribution of permanently and seasonally inundated forests, interaction between rivers and wetland/peatland hydrology and their connectivity
6. Human disturbance in logging and oil palm concessions and local and remote impact on wetland/peatland hydrology and carbon stocks
7. Large-scale deforestation, mining and impacts of river flows, water quality, and biodiversity
8. Deforestation, evapotranspiration losses and impacts on runoff, groundwater recharge, and river base flows
9. Land cover change, land degradation, sediment yield, and changes in aquatic habitats
10. Floodplains and sediment dynamics
11. Hydro-climatic variability, trends, and environmental risks including extreme floods and droughts
12. Water pollution (plastic, industries, and mining)
13. River diversion, impoundment, and fragmentation of water resources/ecosystem services
14. Current and future water use patterns
15. Regional water stress, migrations, and conflicts

The results of such studies will not only be relevant to the Congo River Basin but will also yield important science insights that are widely applicable across other tropical forest regions and which will transform our understanding of the role of the Congo Basin as a critical element in the global Earth System. While the challenges for hydrologic science are enormous, so are the potential rewards, and the Congo Basin is currently one of the most exciting frontiers in hydrological science.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

References

- Acreman M, Holden J (2013) How wetlands affect floods. *Wetlands* 33(5):773–786. <https://doi.org/10.1007/s13157-013-0473-2>
- Africa Groundwater Atlas (2019) Africa Groundwater Atlas. British Geological Survey. <https://www.bgs.ac.uk/geology-projects/africa-groundwater-atlas/>
- Alexandre J (1977) Hydrologie des bassins du Congo et du Zaïre
- Aloysius NR, Saiers JE (2017) Simulated responses of the Congo River Basin hydrology to climate change. *Clim Chang* 141(3):533–546. <https://doi.org/10.1007/s10584-017-1904-x>
- Alsdorf D, Beighley E, Laraque A, Lee H, Tshimanga R, O’Loughlin F, Mahé G, Dinga B, Moukandi G, Spencer R (2016) Opportunities for hydrologic research in the Congo Basin. *Rev Geophys* 54(2):378–409. <https://doi.org/10.1002/2016RG000517>
- Asante KO (2000) Approaches to continental scale river flow routing. PhD thesis, University of Texas at Austin. <https://repositories.lib.utexas.edu/handle/2152/6800>
- Baker SW (1894) *The Albert N’yanza*. Macmillan, London
- Barimalala R et al (2023) Moisture recycling from the Congo Basin and implications for African rainfall. *Clim Dyn*. [In press/preprint]
- Bates PD, Tshimanga RM, Trigg MA, Carr A, Mushi CA, Kabuya PM, Bola G, Neal J, Ndomba P, Mtalo F, Hughes D (2023) Creating sustainable capacity for river science in the Congo Basin through the CRuHM project. *Interface Focus* 14(4). <https://doi.org/10.1098/rsfs.2023.0079>
- Becker M et al (2018) Satellite-based estimates of surface water dynamics in the Congo River Basin. *Int J Appl Earth Obs Geoinf* 66:196–209. <https://doi.org/10.1016/j.jag.2017.11.015>
- Beighley RE et al (2011) Simulated water storage changes in the Congo Basin and comparison with GRACE satellite observations. *J Hydrol* 404(1–2):141–154. <https://doi.org/10.1016/j.jhydrol.2011.04.037>
- Biddulph S, Baird AJ, Swindles GT, Lawson IT (2021) Wetland dynamics in the Cuvette Centrale, Congo Basin. *Environ Res Lett* 16(7):074022. <https://doi.org/10.1088/1748-9326/ac0d9d>
- Bola GB et al (2022a) Multi-return periods, flood hazards, and risk assessment in the Congo River Basin. In: *Congo Basin hydrology, climate, and biogeochemistry: a foundation for the future*. AGU/Wiley, pp 519–540. <https://doi.org/10.1002/9781119657002.ch27>
- Bola GB et al (2022b) Understanding flood seasonality and flood regime shift in the Congo River Basin. *Hydrol Sci J* 67(10):1496–1515. <https://doi.org/10.1080/02626667.2022.2083966>
- Borges AV et al (2019) Variations in dissolved greenhouse gases (CO₂, CH₄, N₂O) in the Congo River network overwhelmingly driven by fluvial-wetland connectivity. *Biogeosciences* 16:3801–3834. <https://doi.org/10.5194/bg-16-3801-2019>
- Bultot F (1972) *Atlas climatique du bassin congolais*. Troisième Partie, Température et Humidité de l’air, Rosée, Température du Sol. I.N.E.A.C, Brussels
- Bwagoy JRB, Hansen MC, Roy DP, Grandi GD, Justice CO (2010) Wetland mapping in the Congo Basin using optical and radar remotely sensed data and derived topographical indices. *Remote Sens Environ* 114(1):73–86. <https://doi.org/10.1016/j.rse.2009.08.004>

- Carr AB, Trigg MA, Tshimanga RM, Borman DJ, Smith MW (2019) Greater water surface variability revealed by new Congo River field data: implications for satellite altimetry measurements of large rivers. *Geophys Res Lett* 46(14):8093–8101. <https://doi.org/10.1029/2019GL083720>
- Chundu ML, Banda K, Lyoba C, Tembo G, Sichingabula HM, and Nyambe IA (2024) “Modeling land use/land cover changes using quad hybrid machine learning model in Bangweulu wetland and surrounding areas, Zambia”. en. In: *Environmental Challenges* 14:100866. <https://doi.org/10.1016/j.envc.2024.100866>
- Crump J, Avagyan A, Baker E, Barthelmes A, Velarde C, Dargie G, Guth M, Hergoualc’h K, Johnson L, Joosten H (2017) *Smoke on water: countering global threats from peatland loss and degradation—a rapid response assessment*. Backup Publisher: UN Environment
- Dargie GC, Lewis SL, Lawson IT, Mitchard ETA, Page SE, Bocko YE, Ifo SA (2017) Age, extent and carbon storage of the central Congo Basin peatland complex. *Nat* 542:86–90. <https://doi.org/10.1038/nature21048>
- Dargie GC, Lawson IT, Rayden TJ, Miles L, Mitchard ETA, Page SE, Bocko YE, Ifo SA, Lewis SL (2019) “Congo Basin peatlands: threats and conservation priorities”. In: *Mitigation and Adaptation Strategies for Global Change* 24.4. Publisher: Springer, pp. 669–686. <https://doi.org/10.1007/s11027-017-9774-8>
- Datok P, Fabre C, Sauvage S, N’kaya GDM, Paris A, Santos VD, Laraque A, Sánchez-Pérez J-M (2022). Investigating the role of the cuvette centrale in the hydrology of the congo river basin. In: *congo basin hydrology, climate, and biogeochemistry: A Foundation for the Future*. Publisher: Wiley Online Library, pp. 247–273. <https://doi.org/10.1002/9781119657002.ch14>
- Delvaux D, Maddaloni F, Tesauro M, Braitenberg C (2021) The congo basin: Stratigraphy and subsurface structure defined by regional seismic reflection, refraction and well data. *Glob Planet Change* 198:103407. <https://doi.org/10.1016/J.GLOPLACHA.2020.103407>
- Devroey E-J (1951) *Carte des Eaux Superficielles*, Institut Royal Colonial Belge, Commission Centrale de l’Atlas General du Congo. In: *Fond dressé par le Service Cartographique du Ministère des Colonies*. Institut Géographique Militaire, Bruxelles Index No. 340.1
- Devroey E-J (1952) *Annuaire hydrologique du Congo belge et du Ruanda-Urundi*. In: *Mémoires de la classe des sciences techniques, (IRCB)*. T. VIII , f. 5: 208 (in-8°)
- Dommain R, Couwenberg J, Joosten H (2010) Hydrological self-regulation of domed peatlands in south-east Asia and consequences for conservation and restoration. In: *Mires & Peat* 6. <https://doi.org/10.19189/001c.128357>
- Ducharme A, Golaz C, Leblois E, Laval K, Polcher J, Ledoux E, Marsily G (2003) Development of a high resolution runoff routing model, calibration and application to assess runoff from the LMD GCM. *J. Hydrol* 280:1–4
- Dyer ELE, Jones DBA, Nusbaumer J, Li H, Collins O, Vettoretti G, Noone D (2017) Congo basin precipitation: assessing seasonality, regional interactions, and sources of moisture. *J Geophys Res Atmos* 122:6882–6898. <https://doi.org/10.1002/2016JD026240>
- Flugel TJ (2014) The evolution of the Congo-Kalahari Watershed: African mega-geomorphology. <https://open.uct.ac.za/handle/11427/8695>
- Gao J, Holden J, Kirkby M (2016) The impact of land-cover change on flood peaks in peatland basins. In: *water resources research* 52.5. Publisher: Wiley Online Library, pp. 3477–3492. <https://doi.org/10.1002/2015wr017667>
- Garcin Y, Schefuß E, Dargie GC, Hawthorne D, Lawson IT, Sebag D, Biddulph B Crezee YE Bocko S A Ifo (2022) Hydroclimatic vulnerability of peat carbon in the central Congo Basin. In: *Nature*. Publisher: Nature Publishing Group UK London, pp. 1–6. <https://doi.org/10.1038/s41586-022-05389-3>
- Georgiou S, Mitchard ET, Crezee B, Dargie GC, Young DM, Jovani-Sancho AJ, Kitambo B, Papa F, Bocko YE, Bola P (2023) Mapping Water Levels across a Region of the Cuvette Centrale Peatland Complex. In: *Remote Sensing* 15.12. Publisher: MDPI, p. 3099. <https://doi.org/10.3390/rs15123099>
- Grosbois C, Négrel Ph, Fouillac C, Grimaud D (2000) Dissolved load of the loire river: Chemical and isotopic characterization. *Chem Geol* 170:179–201

- Guan K, Pan M, Li H, Wolf A, Wu J, Medvigy D, Caylor KK, Sheffield J, Wood EF, Malhi Y (2015) Photosynthetic seasonality of global tropical forests constrained by hydroclimate. In: *Nature Geoscience* 8.4. Publisher: Nature Publishing Group, pp. 284–289. <https://doi.org/10.1038/ngeo2382>
- Hawthorne D, Lawson IT, Dargie GC, Bocko YE, Ifo SA, Garcin Y, Schefuß E, Hiles W, Jovani-Sancho J, Tyrrell G (2023) Genesis and development of an interfluvial peatland in the central Congo Basin since the Late Pleistocene. In: *Quaternary Science Reviews* 305. Publisher: Elsevier, p. 107992. <https://doi.org/10.1016/j.quascirev.2023.107992>
- Henchiri S, Allègre CJ, Nègre P, Dupré B (2016) Strontium isotope systematics in the Congo River Basin: a tracer of continental weathering. *Appl Geochem* 75:90–103. <https://doi.org/10.1016/j.apgeochem.2016.09.003>
- Hooijer A, Silvius M, Wösten H, Page S (2005) Peat-CO₂, assessment of CO₂ emissions from drained peatlands in SE Asia and options for mitigation, Delft Hydraulics Report Q3943 (2006). [Applied here for Congo peatland hydrological stability references]
- Hughes DA, Tshimanga RM, Tanner J (2013) Simulating wetland impacts on streamflow in Southern Africa using a monthly hydrological model. *Hydrol Process* 27(12):185–196. <https://doi.org/10.1002/hyp.9725>
- Inogwabini B-I (2020) The changing water cycle: Freshwater the Congo, *WIREs Water*, 7:e1410. <https://doi.org/10.1002/wat2.1410>
- Jiang Y, Zhou CJ, Tucker A, Raghavendra W, Hua YY, Liu J, Joiner (2019) Widespread increase of boreal summer dry season length over the Congo rainforest. In: *Nature Climate Change* 9.8. Publisher: Nature Publishing Group, pp. 617–622. <https://doi.org/10.1038/s41558-019-0512-y>
- Jung HC, Alsdorf D, Shum CK, Duan J (2010) Large-scale characterisation of Congo floodplain inundation using satellite radar altimetry. *Remote Sens Environ* 114(4):611–619. <https://doi.org/10.1016/j.rse.2009.10.015>
- Kabuya PM, Hughes DA, Tshimanga RM, Trigg MA, Bates PD (2020) Establishing uncertainty ranges of hydrologic indices across climate and physiographic regions of the Congo River Basin. *J Hydrol Region Stud* 30:100710. <https://doi.org/10.1016/j.ejrh.2020.100710>
- Kadima E, Delvaux D, Sebagenzi SN, Tack L, Kabeya M (2011) Structure and geological history of the Congo Basin: an integrated interpretation of gravity, magnetic and reflection seismic data. *Basin Res* 23(5):499–527. <https://doi.org/10.1111/j.1365-2117.2011.00500.x>
- Kamweneshe B, Beilfuss R, McCann K, Zyambo P (2003) opulation and distribution of wattled cranes, shoebills, and other large waterbirds in the Bangweulu Swamps, Zambia. In: Working paper #5 Zambia Crane and Wetland Conservation Project, International Crane Foundation
- Karam S, Zango SB, Seidou O, Perera D, Nagabhatla N, Tshimanga RM (2023) Impacts of climate change on hydrological regimes in the congo river basin. *Sustainability* 2023, 15(7):6066. <https://doi.org/10.3390/su15076066>
- Kechnit D, Tshimanga RM, Ammari A, Trigg MA (2024) Assessing uncertainties of a remote sensing-based discharge reflectance model for applications to large rivers of the Congo Basin. *Hydrol Sci J*. <https://doi.org/10.1080/02626667.2024.2378486>
- Kechnit D, Tshimanga RM, Ammari A, Trigg MA, Carr AB, Bahmanpouri F, ... Moramarco T (2024) Bathymetry and discharge estimation in large and data-scarce rivers using an entropy-based approach. *Hydrol Sci J* 69(15):2109–2123. <https://doi.org/10.1080/02626667.2024.2402933>
- Kim J et al (2019) Remote sensing hydrology of African basins: applications for monitoring Congo Basin water resources. *Water* 11(9):1805. <https://doi.org/10.3390/w11091805>
- Kitambo B, Papa F, Paris A, Tshimanga RM et al (2022) A combined use of in situ and satellite-derived observations to characterize surface hydrology and its variability in the Congo River Basin. *Hydrol Earth Syst Sci* 26(7):1857–1882. <https://doi.org/10.5194/hess-26-1857-2022>
- Kitambo BM, Papa F, Paris A, Tshimanga RM, Frappart F, Calmant S, Omid Elmi, Ayan Santos Fleischmann, Melanie Becker, Mohammad J, Tourian, Rômulo A. Jucá Oliveira, and Sly Wongchuig (2023) A long-term monthly surface water storage dataset for the Congo basin from 1992 to 2015. <https://doi.org/10.5194/essd-15-2957-2023>
- Kitambo BM, Wongchuig S, Tshimanga RM, Paris A, Blazquez A, Moreira D, Frappart F, Fleischmann AS, Kileshye J-MO, Tourian MJ, Papa F (2025) Hydrogeological control of

- groundwater variations in the Congo River Basin revealed by GRACE water storage change decomposition. *J Hydrol Reg Stud* 62:102810. <https://doi.org/10.1016/J.EJRH.2025.102810>
- Laraque A, N'kaya GDM, Orange D, Tshimanga R et al (2020) Recent budget of hydroclimatology and hydrosedimentology of the Congo River in Central Africa. *Water* 12(9):2613. <https://doi.org/10.3390/w12092613>
- Lee H, Beighley RE, Alsdorf D, Chul H, Shum CK, Duan J, Guo J, Yamazaki D, Andreadis K (2011) Remote Sensing of Environment Characterization of terrestrial water dynamics in the Congo Basin using GRACE and satellite radar altimetry, *Remote Sens Environ* 115:3530–3538. <https://doi.org/10.1016/j.rse.2011.08.015>
- Loisel J, Gallego-Sala AV, Amesbury MJ, Magnan G, Anshari GD, Beilman W, Benavides JC, Blewett J, Camill P, Charman (2021) Expert assessment of future vulnerability of the global peatland carbon sink. In: *Nature climate change* 11.1. Publisher: Nature Publishing Group, pp. 70–77. <https://doi.org/10.1038/s41558-020-00944-0>
- Longandjo GN et al (2024) Rainfall seasonality and variability in the Congo Basin. *Clim Dyn*. <https://doi.org/10.1007/s00382-024-06985-4>
- Marret F, Scourse J, Kennedy H, Ufkes E, Jansen JHF (2008) Marine production in the Congo-influenced SE Atlantic over the past 30,000 years: a novel dinoflagellate-cyst based transfer function approach. *Mar Micropaleontol* 68(1–2):198–222. <https://doi.org/10.1016/j.marmicro.2008.01.004>
- Montazem A et al (2019) Hydraulic variability in the Congo Basin: a model-based analysis. *J Hydrol* 578:124086. <https://doi.org/10.1016/j.jhydrol.2019.124086>
- Mouakoumbat NJL et al (2022) Hydrogeological characterization and approach to a conceptual model of the aquifer of the Cuvette Basin, Republic of Congo. *Int J Geosci* 13(11):997–1023. <https://doi.org/10.4236/ijg.2022.1311051>
- Moukandi N'kaya G, Alsdorf D, Tshimanga RM, Laraque A (2022) Hydrology of the Oubangui Basin: challenges and opportunities Wiley-AGU. <https://doi.org/10.1002/9781119657002.ch18>
- Munzimi Y, Linard C, Tatem AJ (2019) Geospatial hydrologic modeling in the Congo Basin: a spatial database approach. *Environ Model Softw* 114:130–142. <https://doi.org/10.1016/j.envsoft.2019.01.013>
- Ndehedehe CE, Ferreira VG, Getirana A (2022) Trends in drought and water storage variability in the Congo Basin. *Sci Total Environ* 806(2):150946. <https://doi.org/10.1016/j.scitotenv.2021.150946>
- Négrel P (1992) Strontium isotope systematics in rivers: a method for studying continental weathering. *Chem Geol* 95(3–4):283–292. [https://doi.org/10.1016/0009-2541\(92\)90063-O](https://doi.org/10.1016/0009-2541(92)90063-O)
- Négrel P (1993) Strontium isotope systematics of the Congo River Basin. *J Hydrol* 151(1–4):71–100. [https://doi.org/10.1016/0022-1694\(93\)90222-E](https://doi.org/10.1016/0022-1694(93)90222-E)
- Négrel Ph, Dupré B (1995) Temporal variations of strontium isotopic ratios of the Oubangui river basin: Implications for the sources of material. *Colloques et Séminaires de l'ORSTOM, Grands Bassins Fluviaux, Olivry & Boulègue (eds.)*, 181–198
- Négrel Ph, Petelet-Giraud E, Barbier J, Gauthier E (2003) Surface water-groundwater interactions in an alluvial plain: Chemical and isotopic systematics. *J Hydrol* 277:248–277
- Nguimalet CR (2022) Hydrology of the Oubangui River: past discharge trends and future challenges. *Hydrol Sci J* 67(4):623–636. <https://doi.org/10.1080/02626667.2022.2032907>
- O'Loughlin F et al (2020) High-resolution remote sensing and hydraulic modelling of flood dynamics in the Congo Basin. *Remote Sens Environ* 239:111662. <https://doi.org/10.1016/j.rse.2019.111662>
- Papa F, Crétaux JF, Grippa M, Robert E, Trigg M, Tshimanga RM, Kitambo B, Paris A, Carr A, Fleischmann AS, de Fleury M, Gbetkom PG, Calmettes B, Calmant S (2023) Water resources in Africa under global change: monitoring surface waters from space. *Surv Geophys* 44(1):43–93. <https://doi.org/10.1007/s10712-022-09700-9>. Epub 2022 Apr 20. PMID: 35462853; PMCID: PMC9019293
- Paris A et al (2022) Monitoring hydrological variables from remote sensing and modelling in the Congo River Basin. Wiley-AGU. <https://doi.org/10.1002/9781119657002.ch18>

- Pokam WM, Djotang LT, Mkankam FK (2012) Moisture transport into The Congo Basin: mechanisms and climatic implications. *Clim Dyn* 38(5–6):1045–1060. <https://doi.org/10.1007/s00382-011-1050-5>
- Richey AS, Thomas BF, Lo MH, Reager JT, Famiglietti JS, Voss K, Swenson S, Rodell M (2015) Quantifying renewable groundwater stress with GRACE. *Water Resour Res* 51(7):5217–5239. <https://doi.org/10.1002/2015WR017349>
- Richey JE, Melack JM, Borges AV (2022) Carbon fluxes in the Congo and Amazon river systems: comparative hydrology and biogeochemistry. *Glob Biogeochem Cycles* 36(5):e2021GB007145. <https://doi.org/10.1029/2021GB007145>
- Rifai SW, Hales K, Frolking S (2019) El Niño events and drought in the Congo Basin: a tree-ring perspective. *Geophys Res Lett* 46(11):6024–6033. <https://doi.org/10.1029/2019GL082441>
- Rosenqvist A, Birkett C (2002) Large-scale monitoring of wetlands and floodplains in the Congo Basin using satellites. *Int J Remote Sens* 23(12):2415–2436. <https://doi.org/10.1080/01431160110075815>
- Runge J (2008) The Congo River, Central Africa. In: Gupta A (ed) *Large rivers: geomorphology and management*. Wiley-Blackwell, Chichester, pp 293–309. <https://doi.org/10.1002/9780470723722.ch14>
- Samba G, Nganga D, Mpounza M (2008) Rainfall and temperature variations over Congo-Brazzaville between 1950 and 1998. *Theor Appl Climatol* 91(1–4):85–97. <https://doi.org/10.1007/s00704-007-0298-0>
- Samba G, Nganga (2012) Rainfall variability in Congo-Brazzaville: 1932–2007. In: *International Journal of Climatology* 32.6. Publisher: Wiley Online Library, pp. 854–873. <https://doi.org/10.1002/joc.2311>
- Scheffé E, Schouten S, Schneider RR (2005) Climatic controls on central African hydrology during the past 20,000 years. In: *Nature* 437.7061. Publisher: Nature Publishing Group UK London, pp. 1003–1006. <https://doi.org/10.1038/nature03945>
- Smith A, Washington R, James R, Rowell DP (2023) Rainfall recycling by Congo forests: insights from isotope tracers. *Clim Dyn*. <https://doi.org/10.1007/s00382-023-06781-5>
- Sridhar V, Kang H, Ali GB, Bola GB, Tshimanga RM, Lakshmi V (2022) Water budgets and droughts under current and future conditions in the Congo River Basin. Wiley-AGU. <https://doi.org/10.1002/9781119657002.ch23>
- Stankiewicz J, de Wit MJ (2006) A proposed drainage evolution model for Central Africa – did the Congo flow east? *J Afr Earth Sci* 44(1):75–84. <https://doi.org/10.1016/j.jafrearsci.2005.11.010>
- Stanley HM (1890) *In Darkest Africa*. Sampson Low, Marston, Searle & Rivington, London
- Tourian MJ, Papa F, Elmi O, Sneeuw N, Kitambo B, Tshimanga RM, Paris A, Calmant S (2023) Current availability and distribution of Congo Basin’s freshwater resources. *Commun Earth Environ* 4(1):1–13. <https://doi.org/10.1038/s43247-023-00836-z>
- Trigg MA, Tshimanga RM (2020) Capacity building in the Congo Basin: rich resources requiring sustainable development. *One Earth* 2(2):148–151. <https://doi.org/10.1016/j.oneear.2020.02.008>
- Trigg MA, Tshimanga RM, Carr AB, Neal J, Bates PD (2022) Putting river users at the heart of hydraulics and morphology research in the Congo Basin. Wiley-AGU. <https://doi.org/10.1002/9781119657002.ch21>
- Tshimanga RM (2009) Traditional systems of water and water resources management along the Upper Congo River. In: Tvedt T, Coopey R (eds) *Water, culture and identity: comparing past and present traditions in the Nile Basin Region*. BRIC Press, Bergen, pp 253–272. ISBN 978-82-7453-080-5
- Tshimanga RM (2012) Hydrological uncertainty analysis and streamflow modelling in the Congo Basin. *Hydrol Sci J* 57(5):985–1002. <https://doi.org/10.1080/02626667.2012.695061>
- Tshimanga RM (2022) Two decades of hydrologic modeling and predictions in the Congo River Basin: progress and prospect for future investigations. Wiley-AGU. <https://doi.org/10.1002/9781119657002.ch12>
- Tshimanga RM et al (2011) Initial calibration of a semi-distributed rainfall–runoff model for the Congo River Basin. *Phys Chem Earth* 36(14–15):761–768. <https://doi.org/10.1016/j.pce.2011.07.062>

- Tshimanga RM et al (2022a) New measurements of water dynamics and sediment transport along the middle reach of the Congo River and the Kasai Tributary. Wiley-AGU. <https://doi.org/10.1002/9781119657002.ch23>
- Tshimanga RM et al (2022b) Towards a framework of catchment classification for hydrologic predictions and water resources management in the ungauged basin of the Congo River. In: Tshimanga RM, N'kaya GDM, Alsdorf D (eds) Congo Basin hydrology, climate, and biogeochemistry: a foundation for the future. Wiley-AGU, pp 497–518. <https://doi.org/10.1002/9781119657002.ch24>
- Vansina J (1990) Paths in the rainforests: toward a history of political tradition in equatorial Africa. University of Wisconsin Press, Madison
- Wack J (1905) Voyages au Congo. Librairie Hachette, Paris
- Washington R, James R, Pearce H, Pokam WM, Moufouma-Okia W (2013) Uncertainty in satellite and climate data for Central Africa. *Nat Clim Chang* 3(9):759–762. <https://doi.org/10.1038/nclimate1905>
- White LJT, Bazaiba Masudi E, Doret Ndongo J, Matondo R, Soudan-Nonault A, Ngomanda A, Ifo SA, Ewango CEN, Sonké B, Lewis SL (2021) Congo Basin rainforest—invest US\$150 million in science. *Nature* 598:411–414. <https://www.nature.com/articles/d41586-021-02818-7>
- Wongchuig S, Kitambo B, Papa F, Paris A, Fleischmann A, Gal L, Boucharel J, Paiva R, Oliveira R, Tshimanga RM, Calmant S (2023) Improved modeling of Congo's hydrology for floods and droughts analysis and ENSO teleconnections. *J Hydrol. Regional Studies*. 50:101563. <https://doi.org/10.1016/j.ejrh.2023.101563>
- Wongchuig Sly, Papa Fabrice, Fleischmann, Ayan Santos, Sierra, Juan Pablo, Boucharel, Julien, Espinoza, Jhan Carlo, Kitambo, Benjamin, Oliveira, Rômulo Jucá, Paris, Adrien, Paiva, Rodrigo, Casas, Pauline, Tshimanga, Raphael (2025) Recent significant drying in Central Congo Basin linked to weakened Walker circulation and warmer Atlantic. *npj Clim Atmos Sci* 8, 344(2025). <https://doi.org/10.1038/s41612-025-01225-3>
- Worden J, Bowman K, Kulawik S, Frankenberg C (2021) Moisture recycling in the Congo Basin revealed from satellite isotopic observations. *Nat Geosci* 14(10):709–715. <https://doi.org/10.1038/s41561-021-00810-3>
- Yuan J, Dong W, Chen Y, Tian X (2017) Hydrological modeling of wetland–river exchanges in the Congo Basin. *J Hydrol* 553:505–520. <https://doi.org/10.1016/j.jhydrol.2017.08.054>
- Yuan T, Lee H, Jung CH, Aierken A, Beighley E, Alsdorf DE, Tshimanga RM, Kim D (2017) Absolute water storages in the Congo River floodplains from integration of InSAR and satellite radar altimetry. *Remote Sens Environ* 201:57–72. <https://doi.org/10.1016/j.rse.2017.09.003>
- Yuan T, Lee H, Beighley RE, Jung HC, Tshimanga RM (2022) Sources and Sinks of Water of the Cuvette Centrale Wetlands Using Multiple Remote Sensing Measurements and a Hydrologic Model. In: Congo Basin Hydrology, Climate, and Biogeochemistry: A Foundation for the Future. Publisher: Wiley Online Library, pp. 237–245. <https://doi.org/10.1002/9781119657002.ch13>

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

