Investigating the role of the Cuvette Centrale in the hydrology of the Congo

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Abstract

The increasing pressure on wetland resources continues to threaten the role wetlands play in maintaining the ecological balance of watersheds. The Cuvette Centrale of the Congo is the greatest intertropical peatland in the world. To fully understand its role in water resources and ecological services linked to the quality of water and life in the basin, we first need to quantify its role in the hydrological dynamics. To achieve this aim, we used the Soil and Water Assessment Tool model (SWAT)-modified for tropical environments-in combination with monthly discharge data. We analyzed water fluxes entering and flowing out of the Cuvette Centrale of the Congo River Basin on a monthly time scale for the 2000-2012 period. The model was calibrated, validated, and compared with discharge from gauging stations and surface water elevation from radar altimetry. Results showed that upland runoff from the Congo River was the highest contributor to the Cuvette Centrale (33 percent) followed closely by efficient precipitation inside the Cuvette Centrale (31 percent) with right bank and left bank tributaries contributing 25 percent and 11 percent respectively. We simulated monthly mean interannual inflows of approximately 34,150 m 3 s-1 (88 billion m 3) with the main flood peaking in November (45,310 m 3 s-1) and total outflows averaging around 39,860 m 3 s-1 (100 billion m 3) peaking at 52,430 m 3 s-1 in December for the simulation period. We subsequently estimated a negative monthly mean interannual variation of storage in the Cuvette Centrale wetlands in the order of 5,700 m 3 s-1 suggesting that the Cuvette Centrale supplies the river during low water periods. This highlights the important regulatory function of the Cuvette Centrale and the need for protection of groundwater resources in order to maintain wetland water quantities and quality.

Investigating the role of the Cuvette Centrale in the hydrology of the Congo River Basin

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Abstract

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1. INTRODUCTION

Wetlands are an important component of the global ecosystem. It has been pointed out that the wetlands of the world are on a steady decline (Papa et al., 2010; Ramsar Convention on Wetlands, 2018) and this is more worrying considering the ecosystem services they provide (Bwangoy et al., 2013; Davidson, 2014; Keddy et al., 2009; Sauvage et al., 2018). Alluvial wetlands control several physical, chemical, and biological processes (Borges et al., 2015; Bouillon et al., 2014). They can be connected to the river and influence water, sediment and nutrient balances by playing a role in the hydrological dynamics (Weng et al., 2003), in carbon sources or sinks (Peyrard et al., 2008) or in nitrate removal by denitrification (Bernard-Jannin et al., 2017; Fabre et al., 2020; Guilhen et al., 2020; Jung et al., 2010; Kim et al., 2017; Papa et al., 2010; Sun et al., 2016). Fluctuations in wetland water volumes are very important in estimating hydrological and biogeochemical functioning of wetlands as the timing and duration of flood pulses affect fauna and flora, which depend on them directly (Forsberg et al., 1993).

After the Amazon basin, the Congo River Basin (CRB) contains the second-largest continuous rainforest on the planet with a covering of 1.8 million km² (Haensler et al., 2013). At the heart of the basin is the “Cuvette Centrale”, a vast forested wetland depression occupying close to half of the watershed with a strong influence over the hydrology and the biogeochemical characteristics of the rivers that cross it (Laraque et al., 1998a, 2009). Alsdorf et al. (2016) summarized the hydrologic studies carried out over the wetland areas of the basin, noting the challenges associated with hydrologic measurements in this part of the CRB. These challenges are a result of the peculiar characteristics which include ill-defined shorelines and the dense forest canopy, which obscure most of the inundated areas. Nevertheless, different approaches have continued to be used to study the wetlands of the (CRB). Traditional or direct methods of hydrological measurements in the Congo basin wetlands are difficult. This is due mostly to the largely ungauged nature of the catchment, the briefness, inconsistency, and unreliability of observable data where they exist, and the accessibility limitations of the physical environment (Munzimi et al., 2017; Runge, 2007; Alsdorf et al., 2016). For these reasons, and to better understand the wetland hydrology, it has become imperative to seek alternative indirect means of measurement. One of these alternative solutions is to combine modeling approaches with the use of satellite remote sensing techniques, which have largely become the only options for in situ data in remote areas (Papa et al., 2010).

Altimeters have been recognized as a special tool for measurement of hydrological dynamics in data-scarce regions, with the major drawbacks being its spatial resolution. This is because altimeters are mostly limited by their repeat cycles causing virtual stations to be located far apart (Kugler et al., 2019; Rosenqvist & Birkett, 2002). Kim et al. (2017) generated multi-temporal water level maps over parts of the Congo main-stem based on the relationship between the Environmental Satellite (ENVISAT) altimetry-derived river level changes, the Phased Array type L-band Synthetic Aperture Radar (PALSAR) and Scanning Interferometric Synthetic Aperture Radar (ScanSAR) backscattering coefficient changes. They were able to classify the CRB into permanent open water, forest, macrophytes, and herbaceous plants. Tourian et al. (2016) employed a method using a multi-satellite approach over the Po river (the largest river in Italy), by which all virtual stations of several satellite altimetry missions were connected hydraulically and statistically. This enabled them to densify water level time series at any given location along the river, thus dealing with problems related to the spatial resolution of altimeters. They validated the transferability of their methodology in the CRB. Their densified time series correlated well with Insitu data in the Congo, Mississippi, and the Danube rivers. Yuan et al. (2017) applied the Interferometric Synthetic Aperture Radar (InSAR) and ENVISAT altimetry to generate long term water storage time series over the floodplains of the CRB for the period 2002-2011. They calculated a difference in water volume storage of approximately 4 km^3 between wet and dry years of 2002 and 2005, respectively. They concluded that their floodplain water storages were in overall agreement with the seasonal variations of Total Water Storage (TWS) and precipitation.

Kim et al. (2019) experimented with a machine learning technique to estimate discharge using stage heights from the Envisat altimetry data obtained from 2002 to 2010. By using a combination of several rating curves established at different points over the CRB, they were able to produce better discharge estimates. Although this process still depends on in situ data, it holds promise for filling in missing data. Combining the Global Inundation Extent from Multi-Satellites (GIEMS) dataset, (Prigent et al., 2007) with ENVISAT altimetry water level measurements, Becker et al. (2018) were able to estimate surface water extent of floodplains, lakes, rivers, and wetlands of the CRB. They found the annual variation in surface water storage in the CRB to be around 80 km^3 or approximately 6 percent of annual water volume that the Congo River exports to the Atlantic Ocean.

Hydrological models have been deployed with varying degrees of success in the CRB. Modeling in this basin poses several challenges due to the sheer size and heterogeneity of the watershed, as well as the attenuation effects of the Cuvette Centrale (Alsdorf et al., 2016). Chishugi and Alemaw (2009) parameterized the Hybrid Atmospheric and Terrestrial Water Balance model for purposes of computing water resource availability. They simulated soil moisture and runoff of the basin and were able to distinguish two main climatic regions based on the Evapotranspiration ratio. They did this even though their model was not calibrated but only parameterized using global datasets. Tshimanga et al. (2011) calibrated the Pitman-GW model, a conceptual semi-distributed hydrological model, reproducing observed hydrological responses adequately. Significant variations in model parameters were put down to the complex nature of the basin or inadequate model structure. The complexity in hydrological processes in parts of the basin questions the representativeness of these model parameters to the hydrological response. Similarly, Tshimanga & Hughes (2014) used the semi-distributed Pitman model to determine key hydrological processes within the basin and found that it captured the magnitude of high and low flows in the majority of the subbasins within the catchment. The model was not able to satisfactorily capture the runoff response of the central basin and flows downstream of lakes and wetland areas, thereby highlighting the importance of groundwater and channel routing parameters. Recently, Paris et al. (this volume) used a combination of remote sensing datasets and hydrologic-hydrodynamic modeling at the basin scale and on a daily basis to infer hydrologic state all over the basin in near-real-time.

Beighley et al. (2011) calibrated the hillslope river routing model in a bid to test the impact of satellite-derived precipitation datasets on streamflow. Three precipitation datasets were tested: The Tropical Rainfall Monitoring Mission (TRMM), the Climate Prediction Centre Morphing Technique Product (CMORPH), and the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIAN). They found that four parameters: maximum soil moisture deficit, horizontal subsurface conductivity, hillslope surface roughness, and channel roughness were the most sensitive. The tests showed that the TRMM estimates agree more with historical data compared to CMORPH and PERSIAN as it matched observed data more closely. They also showed that satellite rainfall showed discrepancies in equatorial regions of the basin. Others analyzed climate change scenarios in the CRB with different predictions for hydrologic variables (Alloysius et al., 2016; Tshimanga and Hughes, 2012).

The Commission Internationale du Bassin Congo – Oubangui - Sangha (CICOS) published in 2016 a report (BRLi, 2016), which included water balance studies of the CRB. Using the hydrological model Mike Hydro Basin (MHB), they estimated -an average variation in storage in the Cuvette Centrale of approximately 1.3 billion m^3 of water for the period 1951-2012. More recently, Munzimi et al. (2019), using the Geospatial Streamflow Model (GeoSFM) semi-distributed hydrological model, achieved acceptable modeling by applying a basin and subbasin “ensemble calibration” approach with a selection of appropriate model routines and parameters to slow the flow of water across the basin. They were also able to capture the flow, seasonality and timing at all locations calibrated with their model.

It is evident that within the last two decades, there have been remarkable advances in the approaches used to study the hydrology of the CRB. However, it is also clear that there remains a lot to be done to fully comprehend the hydrological functioning of the ungauged central portion of the Congo basin. By reason of its location in both hemispheres, the Congo basin experiences two periods of high water and two periods of low water. The two floods are the greater September-October-November (SON) floods influenced by the southern tributaries and a lesser one in March-April-May (MAM) controlled by the equatorial regions. Two low water levels then punctuate these two floods, one in February-March, corresponding to the dry season of the northern part and the other in July-August at the time of the southern dry season. The Cuvette Centrale is uniquely positioned to receive flow from the different tributaries that cross this great basin at different times of the hydrological year. Most of the modeling studies did not consider the spatio-temporal variations in the tributaries that contribute to the Cuvette Centrale and provide little to no distinction on the Cuvette Centrale hydrology based on timescale and seasons. We build on an approach initiated by the BRLi and complementary work done by Moukandi N'kaya et al. (this volume), to estimate the change in storage of the Central Basin, by the first upstream-downstream hydrological balance obtained from calibration and validation of in situ data. Using a mass balance approach, we estimated the fluxes of water feeding into the Cuvette Centrale from eleven tributaries located both on the right and left banks of the Congo River and on the outer fringes of the wetland before they become fully influenced by the wetlands. Afterward, we compared these fluxes with the measured output at the basin outlet in Brazzaville/Kinshasa in order to observe the impact of the Cuvette Centrale on these flows. Knowing the importance of evapotranspiration using this approach, we use a modified Soil and Water Assessment Tool (SWAT) model fitted with a module to better estimate the amounts of water that are removed from the Cuvette Centrale. This will also aid in identifying the source of Cuvette Centrale waters in line with the theories proposed by Alsdorf et al. (2016) concerning the source and emptying of Cuvette Centrale waters. Therefore, the main objective is to enhance our knowledge of the hydrological functioning of the Cuvette Centrale and the limitations of using a distributed hydrological model.

Specifically, we intend to:

(i) Simulate and assess water flows entering the Cuvette Centrale using modeling tools.
(ii) Analyze the impacts of the Cuvette Centrale on streamflow and the water balance components in the catchment at the basin outlet.

These objectives will be met by combining modeling, gauging station data, and satellite data observations in order to represent the hydrological system within the Cuvette Centrale adequately.

2. MATERIALS AND METHODS

2.1. Study site

In Africa, the Congo River is the second longest river after the Nile at 4,700 km, and first in terms of discharge and basin size - 40,500 $m^3 s^{-1}$ and 3.7 x 10^6 km^2 respectively - second only to the Amazon globally. The Congo River forms a broad curve that crosses the equator twice. Its basin extends between the parallels 9°N and 14°S and the meridians 11°E and 34°E, with its form, relief, geology, climate, as well as its vegetal cover, structured concentrically around the Cuvette Centrale; - a central depression already described by Laraque et al. (2009, 2013b) (Figure 1). The twin stations of Brazzaville/Kinshasa controls 98 percent of its total area. The Brazzaville/Kinshasa gauge station (Figure 2a) is located approximately 400 km upstream to its oceanic outlet, and the hydrologic input along this last reach is close to 1,000 $m^3 s^{-1}$. The Cuvette Centrale lies at the heart of this basin (see Figure 2b) within longitudes 16° to 20° E and latitudes 2°30' N to 2° S (Davies & Gasse, 1987). It is a vast Cenozoic depression consisting of clayey and sandy fluvial quaternary alluvial deposits measuring 700 km from North to South (Laraque et al., 1998a). In periods of high water, the Cuvette Centrale extends from Ouesso on the Sangha River to Impfondo on the Ubangi River on its right bank (Figure 2a). The Likouala aux Herbes is the emblematic flooded basin of the Cuvette Centrale during high flow (Laraque et al., 1998a, 1998b). It also comprises the central portions of the basin, including the Tumba-Ngiri and Mai Ndombe wetlands and lakes on its left bank, the areas of which are 65,695 km^2 (O'Loughlin, 2013).

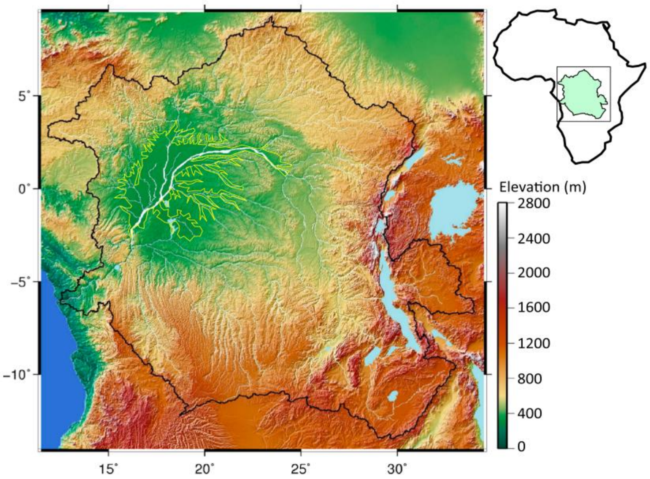

Figure 1. Shuttle radar topography mission (SRTM) digital elevation model (Farr et al.,2007) of the topography of the Congo River basin showing the area of the Cuvette Centrale within the yellow polygon as generalized by Bwangoy et al. (2010) (adapted from Alsdorf et al., 2016).

The physiography, climate, and vegetation of the CRB are generally centered and extend around the Cuvette Centrale . The Cuvette Centrale has an equatorial climate with mean rainfall between 1,800 mm yr^{-1} and 2,200 mm yr^{-1} falling throughout the year (Bultot, 1971). The mean annual temperatures are 25° C (Bernard, 1945) with evapotranspiration at 1,050 mm yr^{-1} (Bultot, 1971). Bwangoy et al. (2010) using remote sensing delineated an area of 360,000 km^2 as the maximum inundated area of wetlands within 5°N to 6° S and 13°E to 26°E. The CICOS project, based on the work of various authors (Becker et al., 2014; Bwangoy et al., 2010; Lee et al., 2011), used an approach proposed by Betbeder et al. (2014) to identify four inundation zones (Figure 2b) in the central basin; (a) forests inundated for short periods and low amplitudes at the northern fringes of the Cuvette Centrale and west of the Ubangi river (b) a permanently inundated swamp forest that encloses the lower Sangha and south of the Likouala aux Herbes rivers (c) a mosaic of flooded and dry areas north of lake Mai Ndombe (d) another mosaic of flooded and the dry regions south-east of lake Mai Ndombe. This is in addition to other seasonally inundated forests at the edges of watercourses.

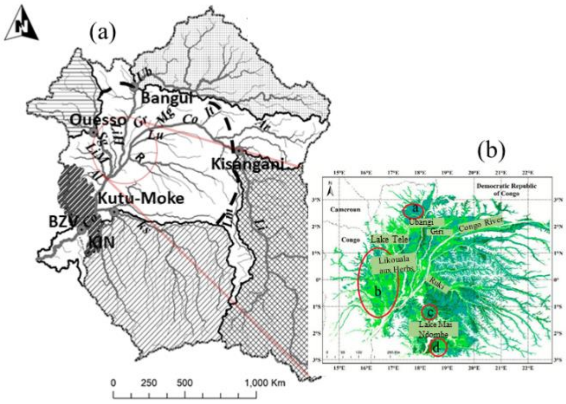

Figure 2. (a) Outline map of the Congo River basin showing the four main drainage units and major rivers. Also shown are in situ gauging stations where flow records were obtained, they are Sangha at Ouesso, Ubangi at Bangui, Lualaba at Kisangani, Kasai at Kutu-Moke and Congo at Brazzaville/Kinshasa (BZV/KIN). Rivers are Al, Alima; Ar, Aruwimi; Co, Congo; Gr, Giri; It, Itimbiri; Ks, Kasai; LiM, Likouala Mossaka; LiH, Likouala aux Herbes; Lm, Lomami; Lu, Lulonga; Ll, Lualaba; Mg, Mongala; Ob, Ubangi; R, Ruki; Sg, Sangha. The black dashed line encircles the central basin sensu lato while the area shaded with thick diagonal lines is that of the Batékés Platéaux (adapted from Moukandi N'kaya et al. this volume) and (b) Cuvette Centrale showing the Ubangi, Giri, Congo, and Ruki Rivers adjacent to seasonally and permanently inundated areas. Also shown are the locations of Lake Mai Ndombe, within non-flooded forests, and Lake Tele north of the Likouala aux Herbes River (adapted and generalized from Betbeder et al. (2014) and BRLi, (2016).

The Cuvette Centrale has a complex hydrological system due to the number of tributaries and swamps that are linked to it. The slopes of the middle reach of the Congo River are as low as 2cm.km^{-1} and run through the Cuvette Centrale (Laraque, 1998a) but steepens to 8 cm.km^{-1} at the outlet of the Cuvette Centrale (Carr et al., 2019). Several rivers join the main stem at the middle reach, notably the Mongala, Giri, Ubangi, and Sangha rivers on the northern bank and the Lulunga, Ikelemba, Kasai, and Ruki rivers on the southern bank. The Ubangi is the second largest tributary of the Congo River and the main one on the right bank. In contrast, the Kasai River, which is the main tributary of the Congo River on the left bank, does not feed into the Cuvette Centrale directly. The lowest point of the Cuvette Centrale occurs at the confluence where the Congo meets with the Ubangi, Likouala aux Herbes, Sangha, and Likouala Mossaka (Laraque et al., 1998a). The Cuvette Centrale is bounded to the South by the sandstone aquifers of the Batekes group of rivers, which serve an important buffering role on the hydrological cycle well described by Laraque et al. (1998b). Importantly too, the Cuvette Centrale hosts the single largest peatland complex known in the tropics (Dargie et al., 2017).

2.2. Model selection

The SWAT model is a physically-based, semi-distributed hydrologic model that has been used extensively to predict the impact of land management practices on water, sediment, and agricultural chemical transport (Arnold et al., 1998, 2012). Moreover, SWAT can provide continuous simulations for dissolved and particulate elements in large and complex catchments with varying weather, soils, and management conditions over long periods (Arnold et al., 1998). Due to the size and spatial heterogeneities associated with the Congo basin, it was important to choose a model that will consider a majority of the relevant hydrological processes like infiltration, interception, soil moisture, groundwater components as well as attenuation effects of wetlands, ponds, and artificial reservoirs. SWAT has demonstrated its applicability in several regions of the world (Malagó et al., 2017; Zhang et al., 2013) in Africa (Van Griensven et al., 2012) and in the Congo basin (Aloysius et al., 2017). Also, the easy accessibility of basic GIS data that are required as SWAT inputs and the availability of a reliable developer support increases its appeal even in data-scarce areas (Van Griensven et al., 2012; Gasman et al., 2010). This is in stark contrast to models like the Systéme Hydrologique Européen (MIKE SHE), which requires extensive model data and physical parameters that may not be available all the time. It also makes the model difficult to set up, coupled with the fact that users are unable to modify the code (Devi et al., 2015). Easton et al. (2010) used the SWAT model to determine runoff and erosion in the Blue Nile basin to find out the respective sources. They found out that only minimal direct calibration is required to obtain good hydrologic predictions. Borah and Bera (2004) have made a comparison between SWAT, Hydrological Simulation Program-Fortran (HSPF) and the Dynamic Watershed Simulation Model (DWSM) models and found 17 applications of SWAT in North America. They concluded that it could be applied for continuous simulations of water flow, sediments, and nutrient transport. Furthermore, SWAT has been successfully used for water quantities (Schuol & Abbaspour, 2007), climate change studies (Aloysius and Saiers, 2016), and water quality (Gassman et al., 2007) assessments for a wide range of scales and environmental conditions.

2.2.1. Modified parameters for the tropics

The SWAT hydrological model was originally developed for temperate regions. The main limitation in its use in tropical areas is related to the simulation of tropical vegetation. SWAT applies dormancy to terminate growing seasons while in the tropics, the wet and dry seasons can only be represented by defining heat unit-specific “plant” and “kill” operations, which are fixed for every year of simulation (Strauch & Volk, 2013). The plant growth component of SWAT is based on the radiation use efficiency approach with empirical parameters. Plant growth can be inhibited by temperature, water, nitrogen, and phosphorus stress. Plant development is based on daily accumulated heat unit values. The heat unit states the stage of plant development. It varies from 0 to 1, 0 indicating the sowing time and 1 the optimal moment for the plant to be harvested. By modifying the plant growth module, an alternative approach was presented in which annual growing cycles were initiated based on changes in soil moisture. A soil moisture threshold was set that automatically triggers new growing seasons for perennial crops during the transition from the wet to the dry seasons. Furthermore, a logistic leaf area decline function was defined that enabled a user to set a minimum leaf area index (LAI). Further details on the procedure can be found in Strauch and Volk (2013).

2.2.2. Water Balance

The SWAT system is coupled with a geographical information system (GIS) engine that integrates various spatial environmental data, including soil, land cover, climate and topographical features (Arnold et al.,1998). Evapotranspiration can be estimated using either the Penman-Monteith, Priestly-Taylor, or Hargreaves methods. SWAT simulates the hydrology of a catchment in two ways; the land phase and the routing phase. The land phase describes the loading of water, nutrients, and pollutants into the main channel in each subbasin. In contrast, the routing phase is the movement of these substances through the channel watershed network to the outlet of the basin. The simulation of the hydrologic cycle by SWAT is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i-1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

where SW_t is the final soil water content (mm water), SW_o is the initial soil water content in day i (mm water), t is the time (days), R_{day} is the amount of precipitation in day i (mm water), Q_{surf} is the amount of surface runoff in day i (mm water), E_a is the amount of evapotranspiration in day i (mm water), W_{seep} is the amount of water entering the vadose zone from the soil profile in day i (mm water), and Q_{gw} is the amount of return flow in day i (mm water).

In SWAT, each HRU is a closed system with no transfer of water between HRUs. Instead the processes in the land phase are simulated within individual HRUs and cumulatively summed to calculate the overall water balance (Neitsch et al., 2012). The water balance in the aquifer was simulated in SWAT using the linear reservoir method to simulate the groundwater flow. This method assumes that the groundwater storage and base flow have a linear relationship. Water in the unsaturated zone is either stored as soil moisture or percolates using a storage routing technique based on the saturated hydraulic conductivity and field capacity of the soil profile. A kinematic storage model (Sloan et al., 1984) simulates lateral flow accounting for variation in conductivity, slope, and water content. As water percolates below this unsaturated zone, it reaches the shallow aquifer. These processes can be controlled by setting threshold values in the respective groundwater parameters to regulate the movement of water within these storages. Further equations relating to other hydrological components can be found in the SWAT theoretical documentation (Neitch et al., 2011).

2.2.3. Input Data

The primary input data used for the model were freely available data, which included the 90 m resolution Shuttle Radar Topography Mission (SRTM) topography data from the Consortium for Spatial Information (CGIAR-CSI). This resolution was chosen considering the size of the watershed. The land use map was extracted from the Global Land Cover Characterization (GLCC) database and used to estimate vegetation, anthropogenic influences, and water bodies in the watershed area. Values of minimum and maximum temperature for the period 1979-2014 were obtained from the Climate Forecast Reanalysis System (CFRS). The Tropical Rainfall Monitoring Mission (TRMM) precipitation products for the period 1998-2015 were used while the model simulated all other climate variables. Digital soil data for the study was extracted from the harmonized digital soil map of the world (HWSD v1.1) produced by the Food and Agriculture Organization of the United Nations (FAO). This soil database provides data for 16,000 different soil mapping units of two layers containing 30 cm and 30 - 100 cm depth). The Global Wetland Database (GLWD) provided information on swamps and lakes, while the source of in situ gauge observations for the five hydrological stations used for model calibration was from the SO-HYBAM and BRLi report. Table 1 below gives further details of these inputs.

The period for the current study (2000 to 2012), is chosen due to the common period of availability of contemporary meteorological records for all the five stations under consideration. In addition, (Moukandi N'kaya et al., this volume; Tshitenge Mbuebue et al., 2015), showed that the trends/breaks or shifts in rainfall could be found in runoff, with a ten-year time lag in some of the major subbasins. Furthermore, the observed flow records at the Brazzaville/Kinshasa gauging station is almost equal to the hundred-year interannual modulus of discharge (Laraque et al., 2001, 2013a; BRLi, 2016).

Table 1. SWAT data inputs and observations datasets

Data Type	Period	Resolution	Source
Digital Elevation Model (DEM)		90 m	Consortium for spatial information (https://cgiarcsi.community/data/srtm-90m-digital-elevation-database)
Soil		1 km	Harmonized World Soil Database v 1.1 (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/index.html?sb=1)
Land use		1 km	Global Land Cover 2000 database (http://forobs.jrc.ec.europa.eu/products/glc2000/products.php)
TRMM (TMPA) 3B42 V.7 Daily product	1998-2015	0.25°	Multi-satellite precipitation analysis (Https://pmm.nasa.gov/data-access/downloads/trmm#) Huffman et al. (2007)
Meteorological data	1979 – 2014	~38 km	Climate Forecast System Reanalysis (CFSR) Model (http://rda.ucar.edu/pub/cfsr.html&http://globalweather.tamu.edu/) Dile and Srinivasan (2014); Fuka et al., (2013)
River discharge	2000 – 2012	Daily	SO-HYBAM (http://www.so-hybam.org/); BRLi (2016)
Supporting data			
Water productivity	2009 – 2018	250m	FAO (https://wapor.apps.fao.org/catalog/WAPOR_2/1)
Global Wetlands database	1992-2000	30x30 second	Lehner and Döll (2004) (https://www.worldwildlife.org/publications)
Geology	2012	0.5°	Global lithological database (Hartmann and Moosdorf, 2012).

2.2.4. Model setup

The preprocessing of the SWAT model was performed within ESRI ArcGIS 10.4 using the ArcSWAT interface (www.esri.com). The basin was delineated based on the dominant land use, soil and slope classes taking into cognizance the size and spatial heterogeneities of the basin allocating one Hydrologic Response Unit (HRU) per subbasin resulting in 272 subbasins and HRUs with 20 land use classes and 14 soil classes (Figure 3). The period of simulation was from 1998 to 2012, comprising calibration (2000-2006), validation (2006-2012), and a two-year warm-up period (1998-2000) to allow the model to simulate the hydrological cycle properly. Lakes and wetlands in the upper parts of the Lualaba watershed, which affect the river discharge substantially, were also integrated into the model. Specifically, they were placed in subbasins 201, 230, and 238. These subbasins receive flow from Lakes Tanganyika, Upemba, and Mweru, respectively (see Figure 3d). We also parameterized the reservoirs based on available information and assuming that no management system was in place (Table 2)

Table 2. Areas and volumes defined for reservoirs in the SWAT model

Lake name	Subbasin	Surface area (km^2)	Storage Volume (km^3)
Tanganyika	201	32,900	19,000
Upemba	230	550	1.3
Mweru	238	5,000	38

The water balance was simulated, and the evapotranspiration calculated using the Penman-Monteith method. The Penman-Monteith method also gave better estimates of evapotranspiration when used with the Strauch modified module (section 2.2.1). Minimum and maximum temperature, wind speed, relative humidity, and solar radiation were other meteorological data used in combination with the Penman-Monteith. Surface runoff was simulated using a modification of the soil conservation service Curve Number (CN) method. The runoff from each subbasin was routed through the river network to the main basin outlet using the variable storage method. Further theory and details of hydrological processes integrated into the SWAT model are given by (Arnold et al., 1998; Neitsch et al., 2011) and are also available online in the SWAT documentation (http://swatmodel.tamu.edu/; Neittsch et al ., 2012).

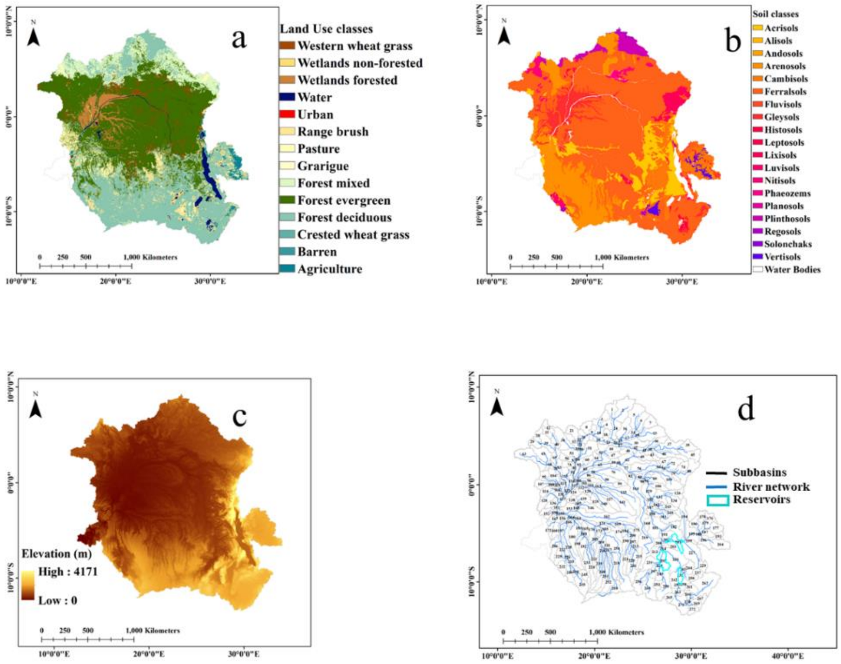

Figure 3. Main SWAT inputs showing; (a) Land Uses (b) Soil classes (c) Digital Elevation map and (d) Delineated subbasins of the watershed with locations of Reservoirs as implemented in ArcSWAT.

2.2.5. Model Calibration

The model was calibrated using monthly discharge data from five stations located on major tributaries of the Congo River. Two of the stations are located on the northern side of the basin (Ubangi at Bangui and Sangha at Ouesso). In contrast, two are located on the southern side (Lualaba at Kisangani and Kasai at Kutu-Moke), and the fifth station is located at the Brazzaville/Kinshasa gauging station that controls 98 percent of the entire catchment. The stations are evenly distributed and represent (within practical limits) the heterogeneity of the basin. The common period of calibration for the stations was taken as the years 2000 to 2012 coinciding with the availability of Satellite meteorological data and gauge station observations.

The model was calibrated using an iterative (trial and error) method of testing different parameter values and selecting the best parameter sets. These parameter sets are selected based on performance criteria that evaluate simulation results against observation data (Werth et al., 2009). The model was manually calibrated, while parameterization of the model was carefully done by adjusting influential parameters, especially those that are driving forces. Maximum canopy storage (CANMX) was adjusted based on information from the food and agricultural organization (FAO) water productivity (WAPOR) database, while others were adjusted based on local knowledge, e.g. aquifer percolation coefficient (RCHG_DP) and exempted from further calibration (Whittaker et al., 2010; Pagliero et al., 2014). Also, the calibration was regionalized according to the characteristics of the subbasins where in situ data is collected. For instance, revaporation coefficient (GWREVAP) was calibrated based on land use in one region and based on soils in another. The main parameters that were calibrated were the groundwater parameters that have a strong effect on the water retention and transfer between the soil and aquifer as well as the parameters with influence on runoff, infiltration and evapotranspiration.

2.2.6. Model Assessment

Previous studies in the basin and other global data sets and literature were used to obtain a proper understanding of dominant processes occurring in the basin. Quantitative and qualitative means of assessment were used to evaluate the model performance. For the former, the Nash Sutcliffe efficiency (NSE), the coefficient of determination (R^2), percentage bias (PBIAS) and the Kling-Gupta Efficiency (KGE) were used (Moriasi et al., 2015; Gupta et al., 2009) while the graphical visual assessment was used for a qualitative assessment.

2.2.7. Change in Storage

A mass balance approach was used to estimate the water balance in the Cuvette Centrale. The change in storage is the difference between the inputs and outputs into and out of the Cuvette Centrale and can be represented as:

$$\Delta S = P + Q_i - ET - Q_{out}$$

Where S is the change in annual storage, P is the Efficient precipitation over the Cuvette Centrale, Q_i represents the River inflows, ET is Evapotranspiration over the Cuvette Centrale, and Q_{out} represents River outflows in the basin outlet downstream of the Cuvette Centrale after the confluence with the Kasai tributary.

Therefore, with respect to Figure 4:

$$\Delta S = P + Q_{1+}Q_{2+\ldots}Q_{11} - ET - (Q_0 - Q_{12})$$

Where Q_0 is the discharge at Brazzaville/Kinshasa gauging station in the main stream and Q_{12} discharge from the Kutu-Moke gauging station (Kasai tributary).

Subbasin outlets were defined during the watershed delineation phase of the project. Outlets were chosen on tributaries that feed into the Cuvette Centrale (see Figure 4).

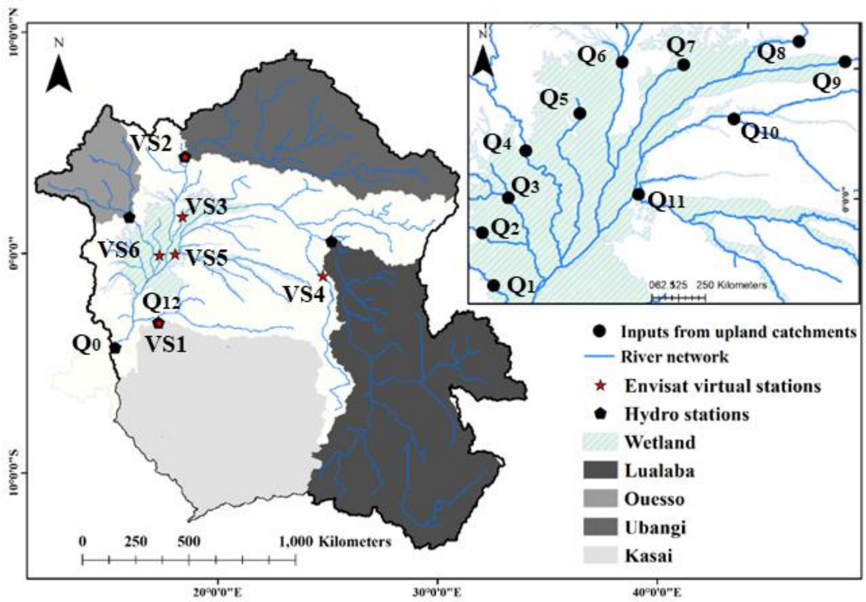

Figure 4. Close up map of the Cuvette Centrale in the CRB wetlands showing points of inflow (Q1, Q2…Q11) and outflow (Q0-Q12) used in calculating the wetland water balance. Also shown are locations of Envisat virtual stations (VS1-VS6) used in validating the model.

2.3. Envisat Altimetry

The Environmental Satellite (ENVISAT) was a mission by the European Space Agency launched in March 2002 and ended in April 2012. It had a repeat cycle of 35 days and established virtual stations everywhere its ground tracks intersected a river tributary. From this database, we were able to validate our model with over 20 virtual stations both within and outside the Cuvette Centrale, and we present six of such stations in this paper. We used water surface elevation (WSE) time series from the Theia Hydroweb database (available at http://hydroweb.theia-land.fr/) as a means of validating our model results (Data processing procedures can be found in Santos da Silva et al. (2010)). The ICE 1 algorithm was used for processing. Various corrections were applied, including geophysical and environmental corrections. Height values are corrected for biases specific of each mission/processing algorithm and then converted into orthometric height by removal of the Earth Gravitational Model (EGM) 2008 geoidal undulation. The accuracy of altimetry derived water levels over inland water bodies is estimated to range between 10 and 40–50 cm on rivers (Becker et al., 2018). The raw ENVISAT data are freely available at the Centre for Topographic studies of the Oceans and Hydrosphere (CTOH, http://ctoh.legos.obs-mip.fr/) in along-track Geophysical Data Records (GDRs) format. It is worth noting that this dataset was extensively validated in the CRB by Paris et al. (this volume). Surface water elevation from satellite altimetry was found to provide accurate information on large rivers and even on smaller streams.

3. Results and Discussion

3.1. Performance of the model

Calibration was done at a monthly time step at the outlet of the four main drainage units that comprise the basin and at the basin outlet. Regional calibration of our model was important to conserve the peculiar physical characteristics of each drainage basin so as to reflect the heterogeneity of the entire basin. The model was able to accurately capture the seasonality of the different subbasins, adequately reflecting the dry and wet seasons as well as years of high and low discharge. Generally, the model was able to reproduce the timing of floods and recessions as well as the general shape of the hydrograph, giving a good representation of the discharge components in each subbasin. The calibration of the Congo basin highlighted the ability of the SWAT model to separate evaporation and runoff from precipitation at the annual time scale (see the following section). For this study, we used the performance evaluation criteria recommended by Moriasi et al. (2007, 2015) in Table 3, which was based on a meta-analysis of peer-reviewed literature of widely used watershed models, including the SWAT model to assess our model performance in discharge evaluation. In addition, the KGE statistic was used (see section 2.2.6). For the calibration period, our ranges of NSE were from 0.16 to 0.81, R^2 from 0.59 to 0.83, PBIAS from -2.11 to 14.52, RSR from 0.43 to 0.99 and KGE from 0.23 to 0.9 while for the validation period NSE was from 0.08 to 0.66, R^2 from 0.39 to 0.78, PBIAS from -4.10 to 8.19, RSR from 0.58 to 0.75 and KGE from 0.31 to 0.78 (Table 4). Less acceptable results occurred at the Congo basin outlet and Lualaba subbasins for reasons discussed in the following sections.

Table 3. Performance evaluation criteria, as suggested by Moriasi et al. (2007, 2015).

Measure	Monthly Performance Evaluation Ranges			
	Very good	Good	Satisfactory	Not satisfactory
R^2	$R^2 > 0.85$	$0.75 < R^2 \leq 0.85$	$0.60 < R^2 \leq 0.75$	$R^2 \leq 0.60$
NSE	NSE > 0.80	0.70 < NSE ≤ 0.80	0.50 < NSE ≤ 0.70	NSE ≤ 0.50
PBIAS	PBIAS < ±5	±5 ≤ PBIAS < ±10	±10 ≤ PBIAS < ±15	PBIAS ≥ ±15
RSR	0.00 < RSR < 0.50	0.50 < RSR < 0.60	0.60 < RSR < 0.70	RSR > 0.70

Table 4. Results of the Performance evaluation statistics used in calibration

	Criteria	Ubangi/Bangui	Sangha/Ouesso	Kasai/Kutu-Moke	Lualaba/Kisangani	*BRZ/KIN outlet
Calibration	NSE	0.81	0.67	0.63	*0.02*	*0.16*
	R^2	0.83	0.71	0.76	*0.49*	0.59
	PBIAS	4.01	8.37	-2.11	7.84	14.52
	RSR	0.43	0.57	0.61	0.99	0.92
	KGE	0.90	0.80	0.48	0.23	0.71
Validation	NSE	0.66	0.59	0.59	*0.08*	0.44
	R^2	0.67	0.65	0.78	0.39	0.54
	PBIAS	-0.86	-1.30	-4.66	-8.19	4.10
	RSR	0.58	0.64	0.64	0.96	0.75
	KGE	0.74	0.78	0.31	0.58	0.73

*Brazzaville/Kinshasa

Nonetheless, our results compared favorably with other applications in similarly sized catchments; for instance, Lu et al. (2019) ran the SWAT model in the Yangtze river basin using CFSR meteorological data and obtained values for streamflow of R^2 and NSE greater than 0.7 in both calibration and validation periods. Gassman et al. (2014) also in an evaluation of 22 large catchments in different continents modeled with SWAT, noted only four studies with R^2 and NSE greater than or equal to 0.9 for both calibration and validation periods on a monthly time scale. Also, Malago et al. (2017) obtained monthly PBIAS values with a magnitude of not more than 25 for 70 percent and 60 percent of gauging stations for both calibration and validation periods, respectively, for their SWAT model in the Danube basin.

Aloysius et al. (2017) also ran the SWAT model in the CRB using historical data for the 1950-2008 period. Their watershed was delineated into 1575 subbasins, which were further divided into at least 5 HRUs per subbasin. They included sixteen lakes in their model to regulate the hydrological fluxes applying a power-law relationship. Despite these differences with our model, they had similar Nash-Sutcliff efficiency values for the Bangui, Brazzaville /Kinshasa, Kisangani, Kutumoke, and Ouesso, stations of 0.86, 0.34, 0.04, 0.77 and 0.64 respectively for a similar range of parameters used to calibrate the model (see supplement to Aloysius & Seirs, 2017).

Table 5. Parameters used to calibrate the model for the simulation period

Parameters	Default value	Description	Calibrated range
Groundwater parameters:			
ALPHA_BF	0.048	Base flow alpha factor (days).	0.002-0.016
GWQMN	1,000	Threshold depth of water in the shallow aquifer for return flow to occur (mm).	500-1,000
GW_REVAP	0.12	Groundwater “revap” coefficient	0.02-0.12
REVAPMN	750	Threshold depth of water in the shallow aquifer for “revap” to occur (mm).	0.002
GW_DELAY	31	Groundwater delay time (days).	31
RCHRG_DP	0.05	Deep aquifer recharge	0
HRU parameters:			
CANMX	0	Maximum canopy storage (mm)	50-250
Reach parameters:			
CH_N2	0.014	Manning’s “n” value for the main channel	0.014-0.06
Subbasin parameters:			
CH_N1	0.014	Manning’s “n” value for tributary channels	0.014-0.06

Table 5 reveals the parameters used to establish the model. They were as much as possible allowed to retain their physical meaning with the deviation from default values minimized in order to achieve realistic simulation. Six out of the nine parameter values presented in Table 5, were groundwater parameters controlling the occurrence, movement, and losses of water from the system, underlining their importance. This was also noted by Van Griensven et al. (2012) while reviewing SWAT applications in upper Nile basin countries where they identified 19 out of 29 parameters that affect hydrological processes and suggested that high values of deep aquifer recharge parameter (RCHRG_DP) were unrealistic in large basins.

3.1.1. ENVISAT Altimetry

To further validate the applicability of our model in the basin, we made a qualitative comparison between WSE variations from altimetry from 2002 to 2010 and our simulated streamflow. Paris et al. (this volume), extensively validated the WSE dataset used over the Congo basin. Graphs of the satellite altimetry WSE time series compared with modeled discharges for six locations along rivers of different widths (see Table 6) are shown in Figure 5. Two of the virtual stations (VS1, VS2) share the same SWAT subbasins where *in situ* gauge stations are located (Kutu-Moke and Bangui, respectively); hence comparisons with observed data were possible. In VS1, two signals from the SWAT model failed to follow the Envisat and observed discharge. This is in contrast to VS2, where the dynamics of the flow components are produced well. This is a reflection of the good calibration at the Bangui station and the less well-reproduced simulation at the Kutu-Moke station and further points to the applicability of altimetry in assessing hydrological model output. Concerning the seasonal observations at the northern and southern drainage units, there is good agreement in peak discharge months, as seen in VS1, VS4 (March/April) and VS2, VS3, and VS6 (October/November) which are representative of both the northern and southern hemispheres respectively. VS5 located on the mainstem Congo River exhibits a second lesser peak characteristic of the flow regimes recorded at the Brazzaville/Kinshasa station. A further look at VS3 is necessary. Indeed, at this VS, the Pearson correlation coefficient was only 0.3, compared to more than 0.6 on the other VSs (Table 6). This decrease in fit between SWE and discharge is noteworthy, and it is due to an error in the precipitation inputs resulting in two peaks of discharge during the low-flow period in 2007 and 2008. These peaks are higher than the peak monthly discharges found in the rest of the study period. Altimetry readings confirm that these two peaks never occurred on this ungauged river during the study period. This particular station highlights the applicability of water stage elevation in validating precipitation products. Satellite-derived precipitation products have been shown to overestimate precipitation due to cloud microphysical processes and moisture distribution in the environment (McCollum et al., 2000). TRMM precipitation products have been known to overestimate high rainfall events and show marked variability in equatorial regions (Beighly et al., 2011; Bharti and Singh, 2015; McCollum et al., 2000; Nicholson et al., 2003). Anomalies could also be caused by errors in sampling arising from sparse gauge network and rainfall amount data or natural variations like El Nino (Huffman,1997; Iada et al., 2010; Morrissey et al., 1995). A slight temporal shift between stage and discharge is observed in VS4 particularly in 2006; this is a typical behavior of heteroscedasticity in the H-Q relationship due to backwater from the Congo River (see evidence of backwater effect in stage-discharge rating curve from altimetry in Paris et al. (2016)). VS5 is located on the Congo River main stem, upstream the confluences with the Ubangi and the Kasaï Rivers. VS5 is located in equatorial regions of the CRB, and it has been shown by Beighly et al. (2011), that Envisat showed inconsistency in variation with streamflow at this region. The comparison with altimetry corroborates what was already discussed, that the upper reach calibration is uncertain due to the lack of data; nevertheless, the good calibration of the Ubangi and Kasaï basins leads to a good fit at Brazzaville/Kinshasa. The WSE, as used in this study, confirms that radar altimetry can capture both small and large rivers and can be used where in situ data is scarce. Overall, the Envisat stage measurements give some confidence that the simulated discharge is able to represent the hydrology of the Congo River Basin adequately.

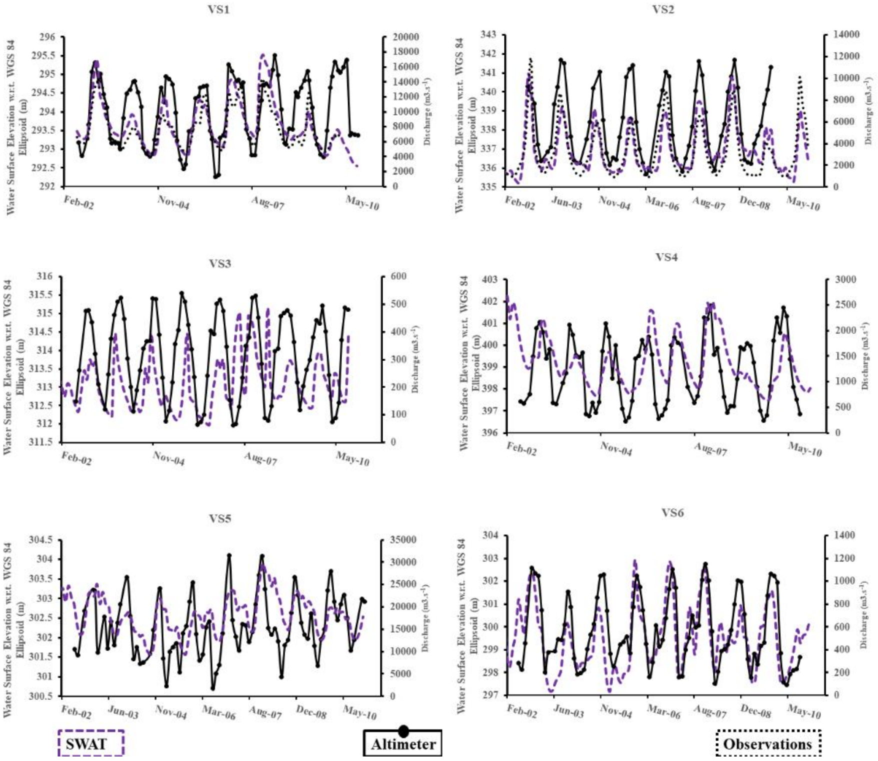

Figure 5. Envisat stage measurements compared with simulated and observed discharge (VS1 and VS2) and with simulated discharge (VS3-VS6) at six locations in the Congo basin. Refer to Figure 4 for locations of the VSs.

Table 6. Characteristics of ENVISAT altimetry stations used in this study**.** Temporal coverage period: 2002 to 2010

Virtual station Name	Virtual station number	River	Latitude	Longitude	Distance from river mouth (km)	River width (m)	Pearsons correlation coefficient
ENV_930_01	VS1	Kasai	−3.22	17.386	61	1,987	0.61
ENV_343_01	VS2	Ubangi	4.351	18.576	599	1,205	0.76
ENV_887_01	VS3	Giri	1.635	18.454	255	70	0.30
ENV_543_01	VS4	Lomami	−1.083	24.8	398	269	0.66
ENV_429_01	VS5	Congo	−0.072	18.112	1,154	4,461	0.61
ENV_973_01	VS6	Likoula aux Herbes	-0.123	17.404	178	126	0.68

3.2. Basin Wide Water Balance

Using the TRMM precipitation data set as input over the entire basin area upstream of the Brazzaville/Kinshasa gauging station, the model returned an annual average precipitation amount of 1,510 mm yr^{-1} with higher rainfall in the central part of the basin (Figure 6a). Evapotranspiration is returned as 1,058.3 mm yr^{-1}, which translates to about 70 percent of total annual precipitation. In the same way, the central part of the basin presents higher evapotranspiration. The lakes zone in the upper parts of the Lualaba River returned high evapotranspiration rates in accordance with the work of Chishugi and Alemaw (2009). Finally, soil moisture returned various rates along the watershed with an average interannual content of 196 mm yr^{-1}. Potential evapotranspiration was returned as 1,665.5 mm yr^{-1} for our simulation period. With regards to infiltration and streamflow, 452.7 mm $yr^{-1}$of annual precipitation percolated to the shallow aquifer, of which 219.49 mm yr^{-1} returned to make the greatest contribution to streamflow. Lateral runoff and surface runoff contributed 14.84 mm $yr^{-1}$and 131.35 mm yr^{-1} to streamflow, respectively (Table 7).

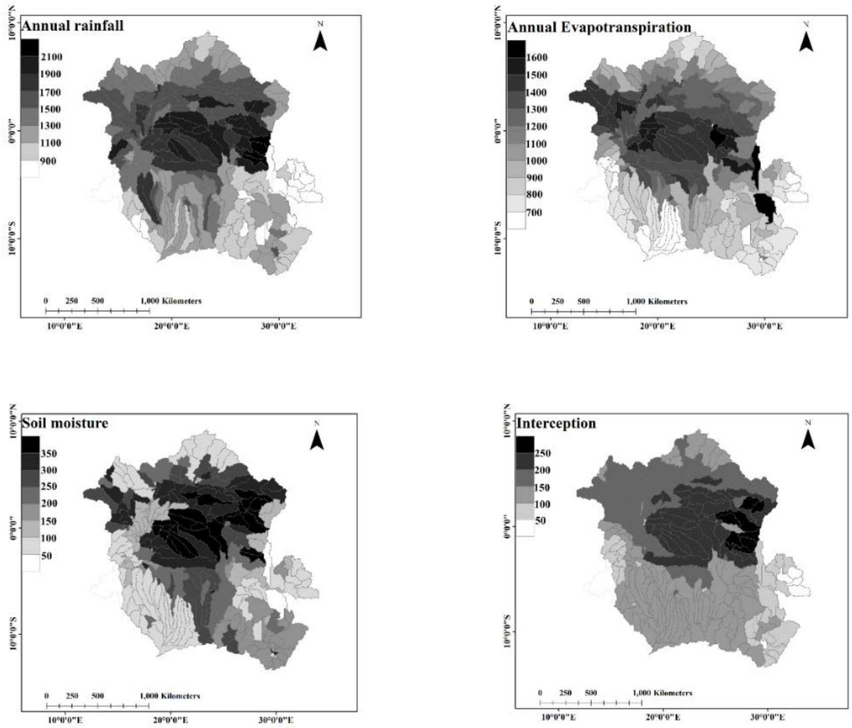

Figure 6. Maps of mean annual Rainfall, Interception, Evapotranspiration and Soil moisture for the simulation period 2000-2012.Validated against Chishugi and Alemew (2009).

Table 7. Annual water balance components for the simulation period 2000-2012 at the outlet of the basin (Brazzaville/Kinshasa gauging station).

Water balance components	Values (mm yr^{-1})
Precipitation	1,510.7
Actual evapotranspiration	1,058.3
Potential evapotranspiration	1,665.5
Surface runoff	131.35
Lateral flow	14.84
Baseflow	219.49
Deep aquifer recharge	0

3.3. Hydrological responses in the main tributaries

The Ubangi from its confluence at Mbomou –Uélé to the city of Bangui is 546 km long (Nguimalet and Orange, 2019) and drains the streams originating from the North of the basin with the outlet of the drainage unit located about 600 km downstream of the Bangui gauging station. The monthly averaged interannual discharge simulated at this station was 3,085 $m^3 s^{-1}$ compared to the average observed values of 3,125 $m^3 s^{-1}$ for the 2000 to 2012 period (Table 8). The overall performance of the model at this outlet was satisfactory to very good for both the calibration and validation period for most of the performance criteria. The values for the NSE, R^2, PBIAS, RSR and KGE are 0.81, 0.83, 4.01, 0.43, 0.90 and 0.66, 0.67, -0.86, 0.58, 0.74 for both the calibration and validation periods respectively. The reduced efficiency of 0.66 and negative bias for the validation period results from the overprediction of low and high flows in the drier years of 2009 and 2010 (Figure 7a). The relatively low contribution of lateral flow to streamflow corroborates the ferruginous nature of soil characteristics described in the Ubangi basin (Runge & Nguimalet, 2005). The simulation gave a very good representation of the magnitude of high and low flows, mimicking the unimodal rainfall pattern observed from gauge records and reflecting the responsiveness of the Ubangi's flow to the rainfall dynamics of its catchment area (Nguimalet et al., 2019). It also indicates that most of the processes occurring in the watershed were being simulated. The simulation at the Ubangi was aided by the fact that hydrological observations for the northern subbasins of the CRB are relatively long and of good quality, thus guaranteeing the reliability of results (BRLi, 2016). Generally, the shape of the hydrograph and the statistical model performance indicate a satisfactory to very good performance of the SWAT model for the simulation period.

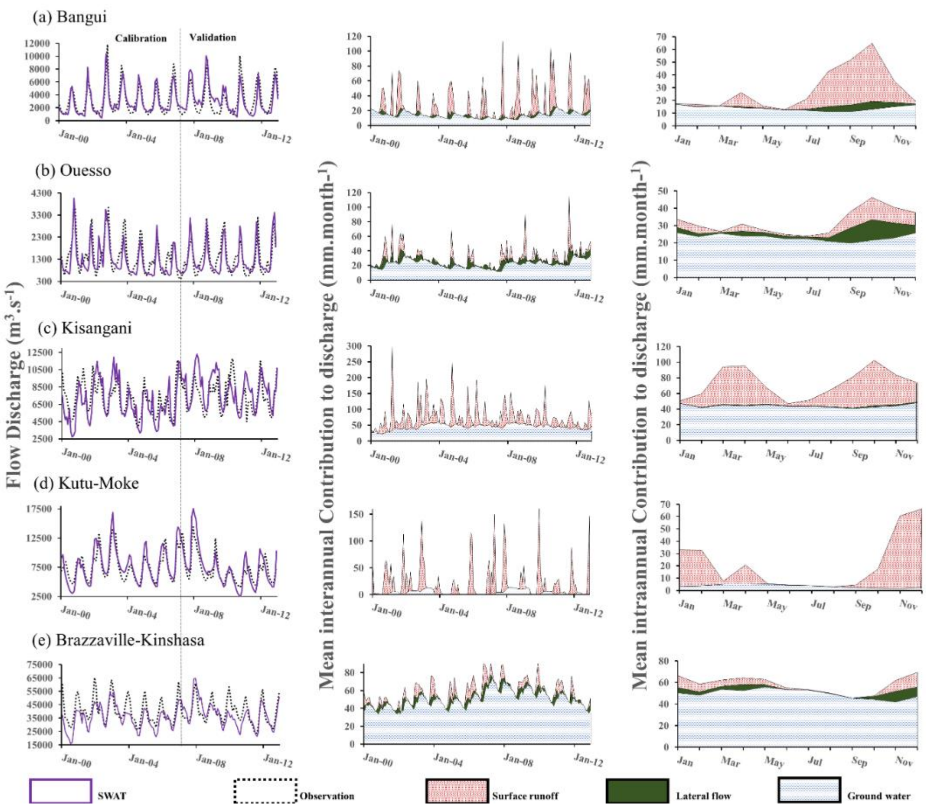

Figure 7. Hydrograph showing the observed and simulated discharge for the calibration (2000-2012) and validation (2007-2012) period indicated by the broken line. Also shown are the different contributions of surface, lateral and groundwater flow for the same period. a-e correspond to the Bangui, Ouesso, Kisangani, Kutu-Moke and Brazzaville/Kinshasa gauging sites respectively.

Table 8. Comparison of historical flow with current simulation

Drainage basin	Station	Drainage area km^2	Interannual flow m^3.s^{-1}	Specific discharge L s^{-1} km^{-2}	Interannual flow (sim)* m^3 s^{-1}	Interannual flow (obs)* m^3 s^{-1}	Specific discharge* L s^{-1} km^{-2}
Lualaba	Kisangani	974,138	7,640[1]	7.8	7,323	7,264	7.5
Kasaï	Kutu-Moke	750,032	8,070[2]	10.7	7,621	7,365	10.1
Sangha	Ouesso	159,480	1,550[3]	9.7	1,282	1,386	8.03
Ubangi	Bangui	494,088	3,660[4]	7.4	3,085	2,931	6.2
Congo	*Bzv/Kin	3,659,897	40,500[5]	11.1	36,361	39,963	9.9

Periods: [1]: 1951 to 2012; [2]: 1940 to 2012; [3]: 1948 to 2017 ; [4]: 1936 to 2017; [5]: 1903 to 2017. (Data adapted from Moukandi N'kaya et al. (this volume)
*current simulation period (2000-2012); obs=observed flow; sim=simulated flow, Bzv/Kin=Brazzaville /Kinshasa

Like the Ubangi, the modeled discharge at the Sangha station was able to follow the observed hydrograph. It also gave good to satisfactory results for both the calibration and validation periods. Some peaks were overestimated by the model, notably in October 2007 and June 2007. Nonetheless, the model was able to show the steadiness of groundwater flow and the relatively abundant contribution of lateral flow compared to other subbasins (Figure 7b). However, it was not able to adequately represent a series of minor floods that characterizes the flow series in July and August. Of the five sites calibrated, the Sangha basin has the lowest discharge simulated of 1,282 m^3 s^{-1} against an observed discharge of 1,415 m^3 s^{-1} for the period under consideration. It is evident that there are losses here that the model cannot account for. This is illustrated by the huge deficit in simulated flow. Similarly, Munzimi et al. (2019) reported a residual (under-estimate) bias at this station for their subbasin model. They obtained a simulated mean flow of 859 m^3.s^{-1} compared to an observed mean flow of 1,258 m^3.s^{-1} for a similar period to our study. The proximity to floodplains, the inability to capture the minor floods, and the non-integration of wetland processes in both models may account for the reduced response dynamics in this station. This result further illustrates the need for more reliable and improved wetland models in order to reduce biases associated with discharge estimates.

The Lualaba drainage subbasin was very complicated to model owing to the presence of many lakes and swamps, including the Tanganyika lake. The Kisangani gauging station is located downstream of these water bodies, and thus it was necessary to integrate reservoirs in our model that will account for attenuation of excess flows. Sub-standard performances were recorded in the Lualaba subbasin for the NSE statistic, which is sensitive to high peaks (Legates et al., 1999). In the Lualaba subbasin, peaks were overestimated in all the years of the validation period (2007-2012) while there was an over and underestimation of peaks in the calibration period (2000-2006) (Figure 7c). We hypothesize that this may be due to the TRMM precipitation products used. For instance, Beighly et al. (2011) showed that TRMM overestimates rainfall in specific periods while Nicholson et al. (2003) highlighted discrepancies in the product compared to gauge observations. The sharp precipitation gradients in the southeastern and adjoining eastern parts of the basin (Tshimanga, 2012) may also be a contributory factor. Nicholson et al. (2019) validated precipitation datasets over the Congo basin western and eastern peripheries. They noted that station density in recent years (1998 to 2010) compared to earlier years (1983 to 1994) was much lower and hence contribute to lower performance of precipitation products. However, the modeled discharge of 7,323 m^3 s^{-1} compared favorably with the observed discharge of 7,264 m^3 s^{-1} for the simulation period with a difference of less than 1 percent. The discrepancies between the objective functions and the good agreement between the modeled and observed discharge can be explained by the PBIAS. It measures the average tendency of the simulated data to be larger or smaller than the measured ones (Gupta et al., 1999). This will explain the close simulation of the magnitude of the discharge. Nonetheless, the modeling here should be taken with caution and weighed based on the objectives to be achieved.

The Kasai subbasin drains the southeastern portions of the Congo basin. Figure 7d shows the simulation results obtained at the Kutu-Moke gauging station that drains the Kasai, the Kwango, and the Kwilo rivers. The model simulated the streamflow components of the Kasai overestimating some peak years (2004, 2006, 2007, 2008, 2011, 2012) and underestimating recessive periods (2000, 2010, 2012), thereby suggesting that more calibration with appropriate model parameters may be possible. The performance evaluation criteria ranged from satisfactory to very good with the regular flows of the Kasai hydrology well simulated. Like the Lualaba basin, we were able to simulate an interannual monthly discharge within 3 percent of the observed value of 7,365 $m^3 s^{-1}$.

The Brazzaville/Kinshasa gauging station of the CRB receives flow from most of the tributaries that flow into the Cuvette Centrale as well as the Kasai, Plateaux Batekés Rivers and other tributaries downstream of the Cuvette Centrale. The underprediction of low and peak flows influenced the NSE, which is sensitive to extreme flows. Nevertheless, we captured well the timing of flood events, the bimodal pattern of rainfall over the basin, wet and dry years, and the regularity of groundwater flow over the simulation period (Figure 7e). The relatively high difference between our modeled discharge of 36,360 $m^3 s^{-1}$ to 39,960 $m^3 s^{-1}$ of observed discharge, showing a difference of 9 percent, could be attributed to the attenuation effects of the Cuvette Centrale wetlands. We would need more information about the physical basin characteristics that slow the flow of water in the Cuvette Centrale as well as more information on the hydrological dynamics here in order to improve the simulation. Since we have reliable observed discharge flow records at this site, our results will not be affected.

3.4. Cuvette Centrale Water Balance

To account for all waters that contribute to the central basin, we estimated the total inputs by integrating the precipitation that falls directly on the Cuvette Centrale. This was done by integrating the SWAT subbasins which fall under our wetland area as defined by the Global Wetland Database shape with the streamflow inputs from drainage catchments upstream and around the Cuvette Centrale (Table 9). Points that coincide with historical gauge stations, as documented by Laraque et al. (1995), were used where possible. For the 2000 to 2012 period of our study, we estimated a monthly mean of 34,160 $m^3 s^{-1}$ of water entering the Cuvette Centrale. Considering only flow, we simulated a monthly mean inflow of 24,250 $m^3 s^{-1}$ coming in from the eight tributaries of the right bank (Mongala, Giri, Ubangi, Likouala aux Herbes, Sangha, Likouala Mossaka, Kouyou, Alima), the Congo river at Lisala and two tributaries of the left bank (Lulonga and Ruki). These tributaries have a combined contributing area of 2,191,066 km^2. We were able to capture the seasonality of the flows with a first flood peaking in November and a second lesser one in April. The Congo at Lisala contributes 33 percent of the total inputs, with precipitation almost equaling it at 31 percent. The largest tributary on the right bank – the Ubangi, contributes 16 percent of the total while the left bank tributaries provide 11 percent (Figure 8).

Table 9. Average monthly interannual simulated inflows and outflows in the Cuvette Centrale from contributing tributaries expressed as flow ($m^3 s^{-1}$) for the 2000-2012 period.

	Inputs													**Outputs**		
	Alima at Tchikapika (Q1)	Kouyou at Linnegue (Q2)	Likouala Mossaka at Makoua (Q3)	Sangha at Ouesso (Q4)	Likouala aux Herbes at Epena (Q5)	Ubangi at Bangui (Q6)	Giri (Q7)	Mongala (Q8)	Congo (Lisala) (Q9)	Lulonga (Q10)	Ruki (Q11)	PPT	Total Inputs	Congo-Kasai (Q0-12)	ETP	Total outputs
Aug	411	147	173	1,047	58	4,206	35	347	8,602	927	1,983	8,224	26,160	25,035	7,289	32,323
Sep	395	140	171	1,850	177	8,641	132	533	8,549	1,028	2,127	12,871	36,614	30,503	6,974	37,477
Oct	446	160	261	2,970	222	9,464	134	880	11,053	1,270	2,732	14,757	44,351	36,563	5,704	42,267
Nov	491	205	442	2,419	172	7,717	95	867	14,350	1,599	3,680	13,278	45,314	44,068	4,147	48,215
Dec	520	216	445	1,447	121	4,619	70	639	15,522	1,470	4,069	8,599	37,738	48,603	3,822	52,426
Jan	526	210	403	1,119	116	3,401	56	470	15,055	1,430	3,760	6,541	33,087	42,473	3,505	45,978
Feb	570	201	352	1,015	106	3,047	51	415	15,115	1,320	3,505	8,250	33,948	31,805	5,622	37,427
Mar	551	187	276	869	75	2,512	44	363	13,029	1,129	2,918	10,642	32,595	26,556	11,429	37,985
Apr	532	201	347	1,076	136	2,860	82	446	14,001	1,324	3,261	11,549	35,815	26,518	8,751	35,270
May	504	180	273	932	74	2,552	43	398	12,692	1,206	2,849	10,364	32,066	27,809	10,203	38,012
Jun	474	173	223	838	65	2,222	53	352	13,256	1,101	2,502	7,435	28,692	26,673	10,254	36,926
Jul	439	157	191	796	62	2,164	37	339	9,798	968	2,191	6,337	23,477	24,580	9,430	34,010
Mean flow	488	181	296	1,365	115	4,450	69	504	12,585	1,231	2,965	9,904	34,155	32,599	7,261	39,860

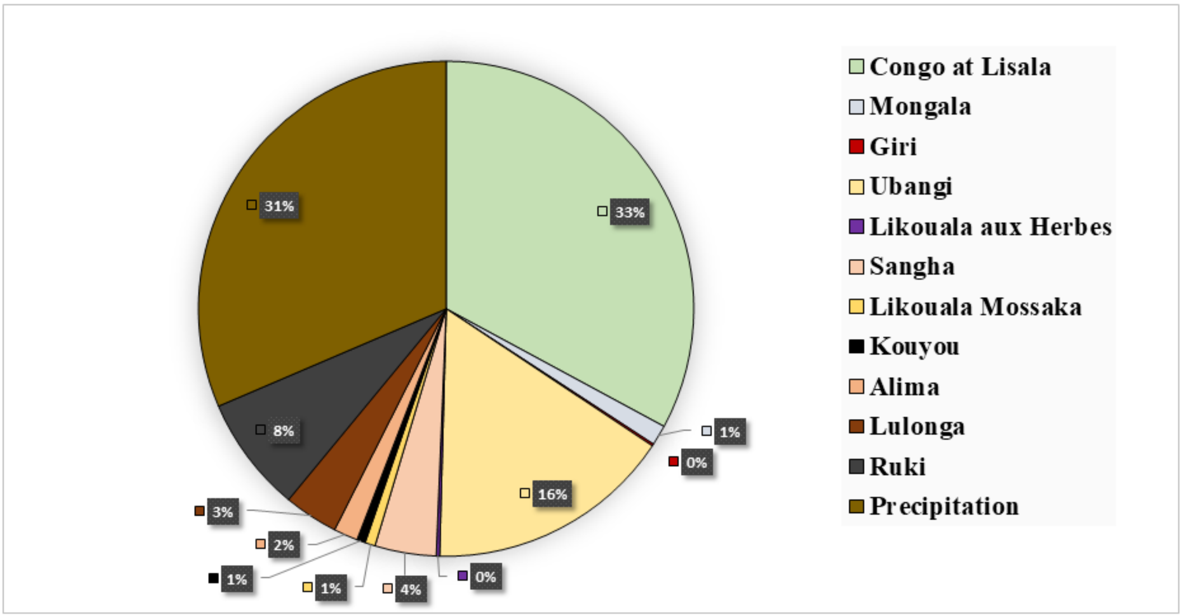

Figure 8. Pie chart showing the annual mean contribution of Cuvette Centrale tributaries and efficient precipitation for the period 2000-2012.

By subtracting the flow recorded at the Kutu-Moke gauging station from the flow recorded at the Brazzaville/Kinshasa gauging station, we could estimate with a high degree of certainty, considering the reliability of the gauge records at this site, the flows at the exit of the cuvette wetlands. In the same manner, in which we estimated the total inputs, we were able to estimate the total outputs by also integrating the uptake from evapotranspiration from the subbasins that comprise the Cuvette Centrale (Table 9). By assuming losses as negligible, we estimated a monthly mean output from the Cuvette Centrale of 39,860 $m^3 s^{-1}$ or 32,600 $m^3 s^{-1}$ when we take evapotranspiration into account. A graphical representation of the flows (Figure 9) also shows we simulated one main flood in December with two relatively lower floods peaking in March and May.

We compared our results with the work of Moukandi et al. (this volume), which is the first attempt to reconstitute the balance of the Cuvette Centrale. Their work was based on deductions from a study of the in situ hydrological chronicles of the major drainage features of the Congo basin. Figure 9 shows similarities with their reconstruction, notably the peak in flows in December and January and the second flood in May with a dome-shaped peak attributable to the April-May floods from the Kasai. The small floods of July-August associated with the Sangha are not decipherable due to the relatively small size of discharge. In any case, their analysis suggested that from 1971 to 2017, these floods were replaced by a Plateau. Similarly, the flows in the Ubangi contribute to the floods that begin to rise in September and recede around February, as illustrated in Figure 9. The Ubangi, with the lowest calculated specific discharge of the tributaries studied, and the most Northern of the studied basins is the most sensitive to hydroclimatic deterioration and the most fragile in the basin (Laraque et al., 2013b; Nguimalet, 2017; Nguimalet and Orange, 2013, 2019). These deficiencies from the Ubangi are augmented by the Flows from the Lualaba and Kasai Rivers and are regulated by the Cuvette Centrale.

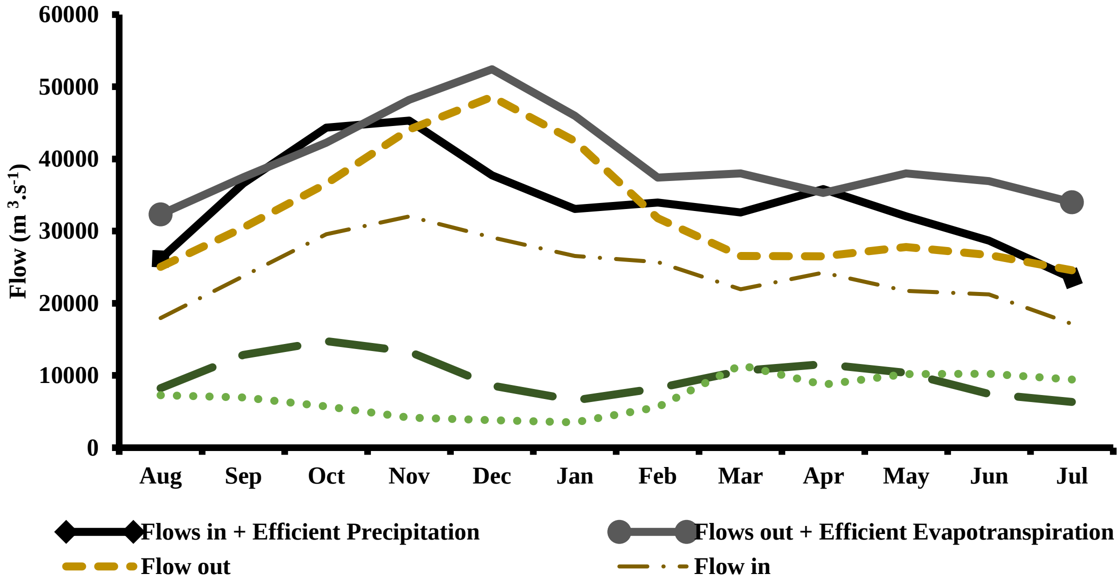

Figure 9. Average monthly interannual hydrograph of flows in and out, Precipitation falling and evapotranspiration removed directly from the Cuvettte Centrale in the 2000-2012 simulation period.

An analysis of the variation in the water balance (Table 10) shows that within the simulation period, the balance is in surplus only at the peak of the rainy seasons (October and April). During all other periods (November to March and May to September), the balance is in deficit, implying that at these times, the storage held in groundwater and flooded areas supply the Congo River. Figure 10 shows the trend in water balance over the 2000-2012 period showing a high deficit in the year 2000 and a gradual restoration of balance to equilibrium in 2012. This coincides with the well-documented deficits in precipitation recorded in the Congo basin from the years 1983-2003 (Nguimalet et al., 2019). In addition, an analysis of the Ubangi River at Bangui showed below-average discharge since the year 2000 (Nguimalet et al., 2013). It also suggests that the regulatory role of the Cuvette Centrale during this hydrological cycle has been seriously challenged. Figure 11 shows monthly averages of water balance components in the Cuvette Centrale. Lateral flow is almost nonexistent, while groundwater flow maintains constant levels all year round with no discernible peaks or lows. Surface runoff reflects the bimodal pattern of rainfall in the basin while the total yield increases in October through to December with a peak in November. The total water yield also reflects the bimodal rainfall pattern with increased surges in April. Evapotranspiration and potential evapotranspiration peak in March and July respectively, differing by up to 100 mm in July, signifying longer periods of dryness. The precipitation reflects the seasonal dynamics associated with the basin by a larger flood in October and a lesser one in April. The importance of groundwater in the CRB is particularly highlighted in the Sangha basin and at the Brazzaville/Kinshasa station, where groundwater levels remain consistent throughout the simulation period varying only minimally even during wet and dry years in the Sangha subbasin. Lateral flow is also more pronounced in the Sangha basin compared to any other subbasin. These characteristics of the Sangha basin fit the description of a “fluvial table or shallow aquifer” of low hydraulic gradients (2 $cm.km^{-1}$) ascribed to the Likouala aux Herbes basin by Laraque et al. (1998b). This is not surprising as the Ouesso station borders the Cuvette Centrale and is proximate to the Likouala aux Herbes basin, where the depth to the groundwater table is likely closer to the surface. In contrast, there is a minimal contribution of lateral flow at the Brazzaville/Kinshasa outlet with groundwater levels varying relatively more, especially in the year 2008. This coincides with high discharge recorded in the Lualaba river at Kisangani and Kasai river at Kutu-Moke in the same year, suggesting an increased contribution from these two southern tributaries. Overall, the groundwater flow of the Congo basin simulated at the basin outlet demonstrated the regulatory effect of the central basin as it receives contributions of various amounts at different seasons of the year, highlighting the obvious linkages between the upland catchments and the wetland system of the Cuvette Centrale. This is very important considering the deficit being experienced by the Northern tributaries of the CRB (Laraque et al., 2013; Nguimalet 2013, 2017, 2019) as well as future landuse and water diversion plans that will have an impact on this system.

Table 10. Average monthly interannual change in storage expressed as flow ($m^3 s^{-1}$) for the 2000-2012 period.

	Total inputs	Total outputs	Change in storage
Aug	26,160	32,323	-6,163
Sept	36,614	37,477	-863
Oct	44,351	42,267	2,084
Nov	45,314	48,215	-2,901
Dec	37,738	52,426	-14,688
Jan	33,087	45,978	-12,891
Feb	33,948	37,427	-3,479
Mar	32,595	37,985	-5,390
Apr	35,815	35,270	545
May	32 066	38,012	-5,946
Jun	28,692	36,926	-8,234
Jul	23,477	34,010	-10,533
Mean	34,155	39,860	-5,705

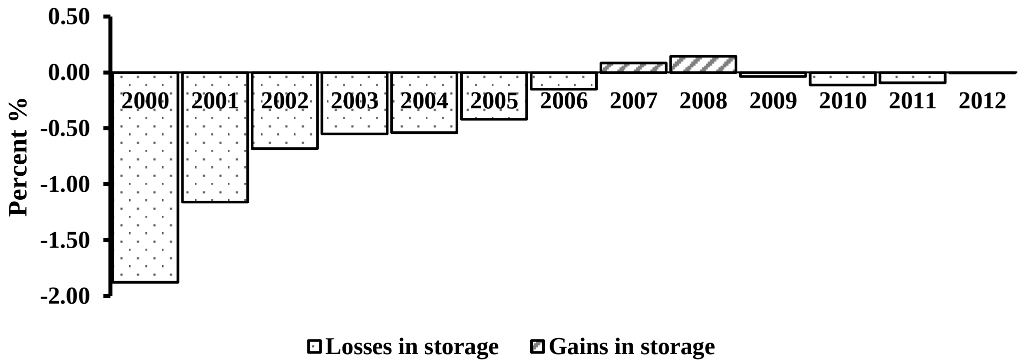

Figure 10. Relative interannual change in storage within the Cuvette Centrale for the 2000-2012 period.

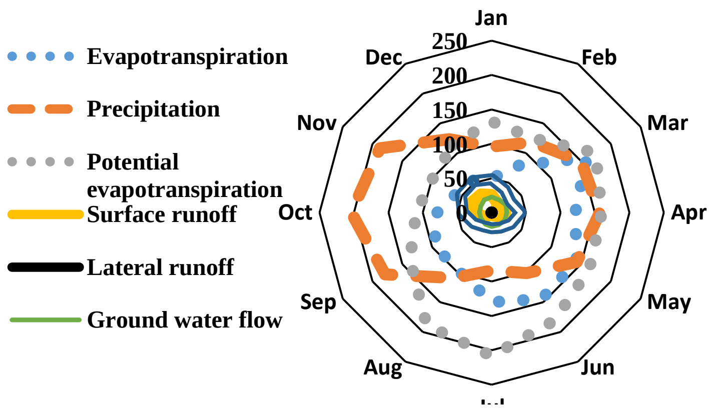

Figure 11. Monthly averages of water balance components (in millimeters) within the Cuvette Centrale for the 2000-2012 simulation period.

To conclude this section, it is noteworthy to acknowledge that there is an unavoidable uncertainty in input data. Rainfall data tests in Africa and elsewhere have revealed this (Strauch et al., 2012; Tshimanga et al., 2012). Rainfall input uncertainty will, therefore, result in uncertainty in runoff and evapotranspiration as well. The FAO soil data used in this study was primarily prepared for agricultural use, with soil depths not exceeding 100 m. Areas with deeper soils will, therefore, have lower storage capacity resulting in over simulation of peak flows (Tshimanga et al., 2014). The simulations in the subbasins impacted by large lakes and wetlands expose the uncertainties in model structural responses as a result of the over-simplification of assumptions. There are also the unknown parameters of the central basin and the unknown effects of other variables that the model cannot account for.The work of Sun et al.(2016) on surface and ground-water mixing with the SWAT model on the floodplains of the Garonne River is encouraging and can be modified for larger catchments. Therefore,we have no doubt, that by integrating flood plains in our model, we will have much more improved simulations as reflected in those tributaries not impacted by the Cuvette Centrale.

4. Conclusion

Using a combination of in situ derived discharge data, satellite precipitation data, and freely available geodatasets, the Congo River basin has been modeled to reflect the spatial and temporal variations in streamflow and its associated components. We have shown that not only does the Cuvette Centrale perform a regulatory role on a seasonal scale between high and low water periods, but also between yearly hydrological cycles. The regional approach to calibration took into account the influence of the Cuvette Centrale and its attenuation effects on downstream flows. This is the first study using the SWAT model that attempts to account for the inflows and outflows of water in the Cuvette Centrale. The importance of groundwater in the basin is further highlighted with a majority of the important parameters used to calibrate the model being groundwater parameters. Groundwater levels in the Cuvette Centrale remain constant and steady all year round and supply the river in times of water deficit. The regulatory effect of the Cuvette Centrale is emphasized by the fact that contributions of different amounts and times from different tributaries feed the Cuvette Centrale. Yet, it is able to balance these inputs and even achieve states of equilibrium at certain peak periods.

Furthermore, the hydrological simulation conducted with the SWAT model in our study, emphasized the need to explicitly account for wetland processes in the model. The complex interactions between hydrological processes in the basin with respect to the vegetation, soils, climate, and basin physiography add to the challenges of modeling the CRB. An ideal model should be capable of routing flows through wetland depressions in addition to routing overland, channel, and subsurface flow (McKillop et al., 1999). Additionally, a model should be able to realistically simulate the river-wetland exchange dynamics (Hughes et al., 2014). Future improvements of the model will need to consider a very high-resolution digital elevation model that can capture wetland depressions accurately, and thus estimate with high confidence the flow hydrograph at the outlet of the basin. The spatial variability of the parameters within the various subbasins in our model indicates the extent to which the model represents the hydrological processes. Further testing of the spatial and temporal variability of the basin with appropriate basin parameters and inputs of different resolutions, will be an interesting study (Reggiani et al., 1998). This will also aid in identifying the main factors that limit model performance-whether inappropriate model structure or inaccurate parameter values (Melsen et al., 2016). In addition, future efforts will be made to develop wetland modules that are compatible with the main model, (e.g. Hughes et al., 2014) and can be used in the assessment of a wide variety of ecological functions (Fabre et al., 2020; Guilhen et al., 2020).

Throughout the discussion, we have referred to the inherent uncertainties associated with our model. There remains insufficient information to estimate the parameters in the Cuvette Centrale. Validation of model results on the field will go a long way in constraining the wetland parameters and supplying information on basin physiographic conditions, which can improve the model. There is also a need to establish more gauge networks for improved observations. Concerted efforts should also be made to harmonize regional datasets in order to reduce input uncertainties. Furthermore, local researchers should be encouraged through increased funding to make their research more visible and accessible to the global community.

The central Congo basin hosts internationally important sites, including the lake Tumba and Mai-Ndombe lakes, parks, and game reserves. While the Cuvette is strongly dependent on upstream year-round surface and groundwater contributions, changes to the wetland hydrology can have negative impacts on the ecology of the wetland as a habitat for fauna and flora. With the ever-increasing demands on natural resources and the collision of various interests within the catchment, there is the need for a harmonization of these interests through sustainable management of Congo basin wetland resources. The objective functions and flow dynamics recreated in tributaries not impacted by the Cuvette Centrale confirm that the SWAT model applied in this study is capable of being used; after taking into account the uncertainties, for the assessment of water resources as well as in experimental studies associated with the hydro-ecological functioning of the basin. The results from this study with the SWAT model demonstrated an appropriate level of performance in estimating the seasonal pattern of water volume fluctuations in the Cuvette Centrale. Given the relative stability of Congo River hydrology as well as the relatively pristine state of the Congo wetlands, models like this one can be used as a baseline for assessing future changes in wetland hydrology. Estimates from streamflow components can also be used to examine eco hydrological relationships in wetlands and the effect of land use on natural wetland features as well as to gauge the sensitivity of wetland communities to hydrological changes.

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