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Key Points:
- A semidistributed hydrological model is presented for the Congo Basin
- The model adequately simulates the dominant processes of the basin hydrology
- The paper addresses some of the challenges of prediction in the Congo Basin

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Basin-scale performance of a semidistributed rainfall-runoff model for hydrological predictions and water resources assessment of large rivers: The Congo River

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Abstract Gaps in hydrological information of the Congo Basin increase uncertainties in understanding hydroclimatic processes in the basin, and consequently the risks associated with decision making for major water resources development plans. There is also uncertainty about the predictions of future climate and land use change. These challenges make it essential to explore possible approaches to close the information gaps. Some of the gaps can be filled using hydrological simulation models, which if they prove practical, can be established with available data, but generate sufficiently reliable information for management purposes. This paper discusses the results of applying a semidistributed rainfall-runoff model which was established for the whole Congo Basin, using the available historical data, with an ultimate goal of understanding processes of runoff generation as well as assessing the impacts of future climate and land use changes on water resources availability, including options for water resources development in the basin. Issues of water resources assessment in the basin, approaches used to address them and some directions for future research are discussed. It is noted that the hydrological model applied in this study for the Congo Basin is able to capture the timing and magnitude of high and low flows satisfactorily, irrespective of the subbasins are located in headwater areas, downstream areas or at the outlets of regions strongly affected by wetlands and lakes. There remain a number of opportunities to improve the methods used for water resources assessment within the basin.

1. Introduction

Water resources planning and management within large river basins of Africa is an important issue, but there is almost always insufficient observed information over appropriate temporal and spatial scales to formulate decision making strategies and therefore modeling approaches have to be investigated. However, the success of models is similarly constrained by the limitations of the observed information. The focus in the past has been on streamflow magnitudes and their variability in time and space; however, more recently, the importance of accurately quantifying related hydrological processes and state variables such as soil moisture, evapotranspiration processes, groundwater recharge, storage, and discharge (to rivers) has been emphasized [*Gupta et al*., 2008]. Reducing model uncertainties relies on a sound understanding of the processes, application of appropriate models and the acquisition of data to support the application of models [*Fenicia et al*., 2008]. This was the quest for the IAHS science decade (2002–2012) on Predictions in Ungauged Basins [PUB: *Sivapalan et al*., 2003; *Blöschl et al*., 2013; *Hrachowitz et al*., 2013], as well as the new decade (2012–2022) with the focus on hydrological change and society [Panta Rhei: *Montanari et al*., 2013].

The lack of adequate data to support hydrological predictions, the remoteness and large size of the basin, the complexity of natural processes, as well as population growth and land use change represent serious constraints to water resources assessment and sustainable management in the Congo River Basin. The water resources management needs in the basin include the quantification of current and future supplies and demands that include the impacts of future changes associated with climate and land use. These management needs must be supported by an adequate understanding of the hydrological dynamics of the basin, including spatial and temporal variability and the way in which the basin responds to different climate and land use conditions.

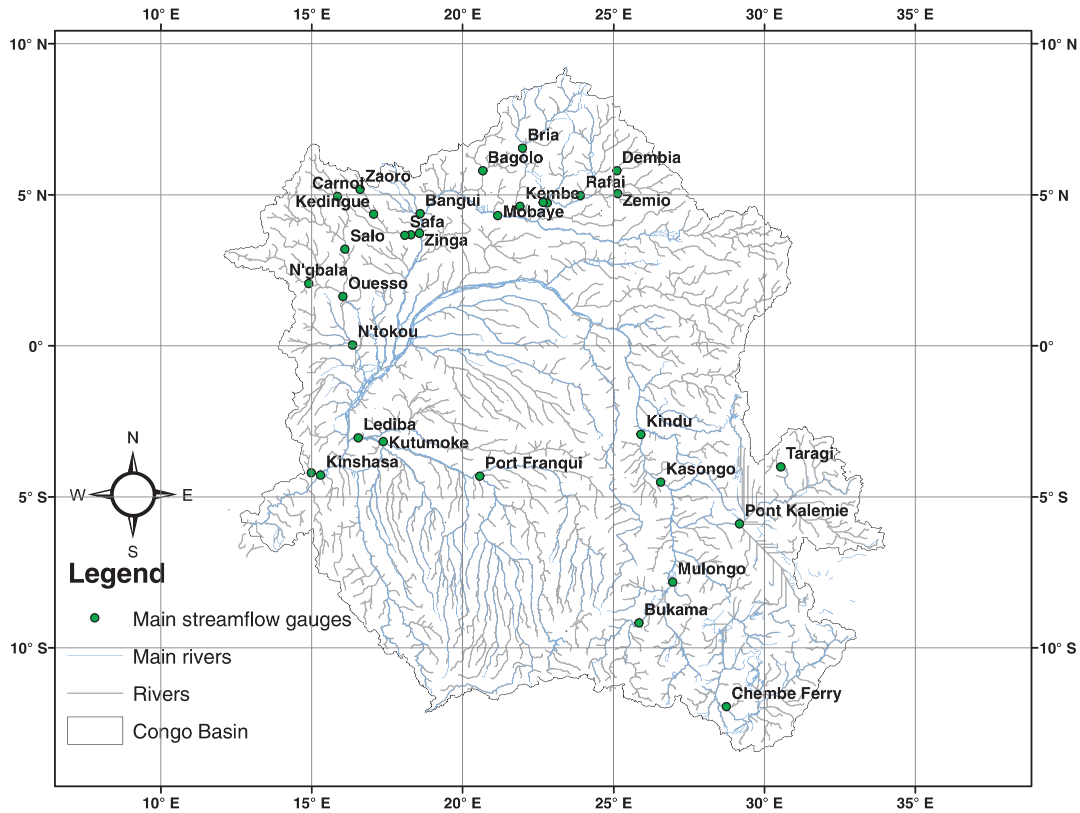

Figure 1. Physical layout of the Congo Basin showing the main streamflow gauges and the river lines (temporal and spatial characteristics of the available streamflow gauging sites are given in Table 3).

The complexity and difficulties of modeling the Congo Basin (Figure 1) are partly due to scale issues [*Blöschl and Sivapalan*, 1995] associated with the large geographic area covered by the basin ($\sim$3.7 $\times$ 10^6 km^2) and partly due to the sparse sources of information on physical basin properties, climate drivers, and observed hydrological response. The central part of the basin has low slopes, but many of the headwaters have steeper topography [*Runge*, 2008], from which flow the four main tributaries (Oubangui River in the north east, Sangha River in the north west, Kasai River in the south west, and Lualaba River in the south east) that meet in the central basin and constitute the main stream of the Congo River. Within the upper parts of the Lualaba River are Lake Tanganyika and several quite large wetlands that are expected to affect downstream flow regimes. The channels in the central part of the basin are, understandably, very large and flanked by floodplains which are inundated during high water periods [*Hughes and Hughes*, 1987]. Land cover varies from dense forest in the central parts to a mosaic of vegetation types including variable density woodlands and shrubland. Similarly, soils and geology are variable throughout the basin, while the information about their hydrological characteristics is only available at a coarse spatial resolution.

The variability in rainfall reflects the dependence of the climate on the many external and regional factors which act on atmospheric-ocean interactions and the monsoonal processes [*Balas et al*., 2007; *Farnsworth et al*., 2011]. The northern and southern parts of the basin have different wet seasons. The wet season in the northern subbasins coincides with the dry season in the southern subbasins. The overall result of the large scale of the basin and the likely diversity of climate and physical properties is that a hydrological model will have to represent (either implicitly or explicitly) a different range of processes than will be encountered in small to moderate sized basins upon which a great deal of our modeling experience is based and upon which many models are tested and validated.

Emerging evidence suggests that climate and land use change pose substantial threats to water resources availability in the Congo Basin [*Hoare*, 2007]. Increasingly, reports of forest logging, mining, and human settlements are affecting the patterns of natural variability of the basin hydrology. *Ladel et al*. [2008] pointed to a

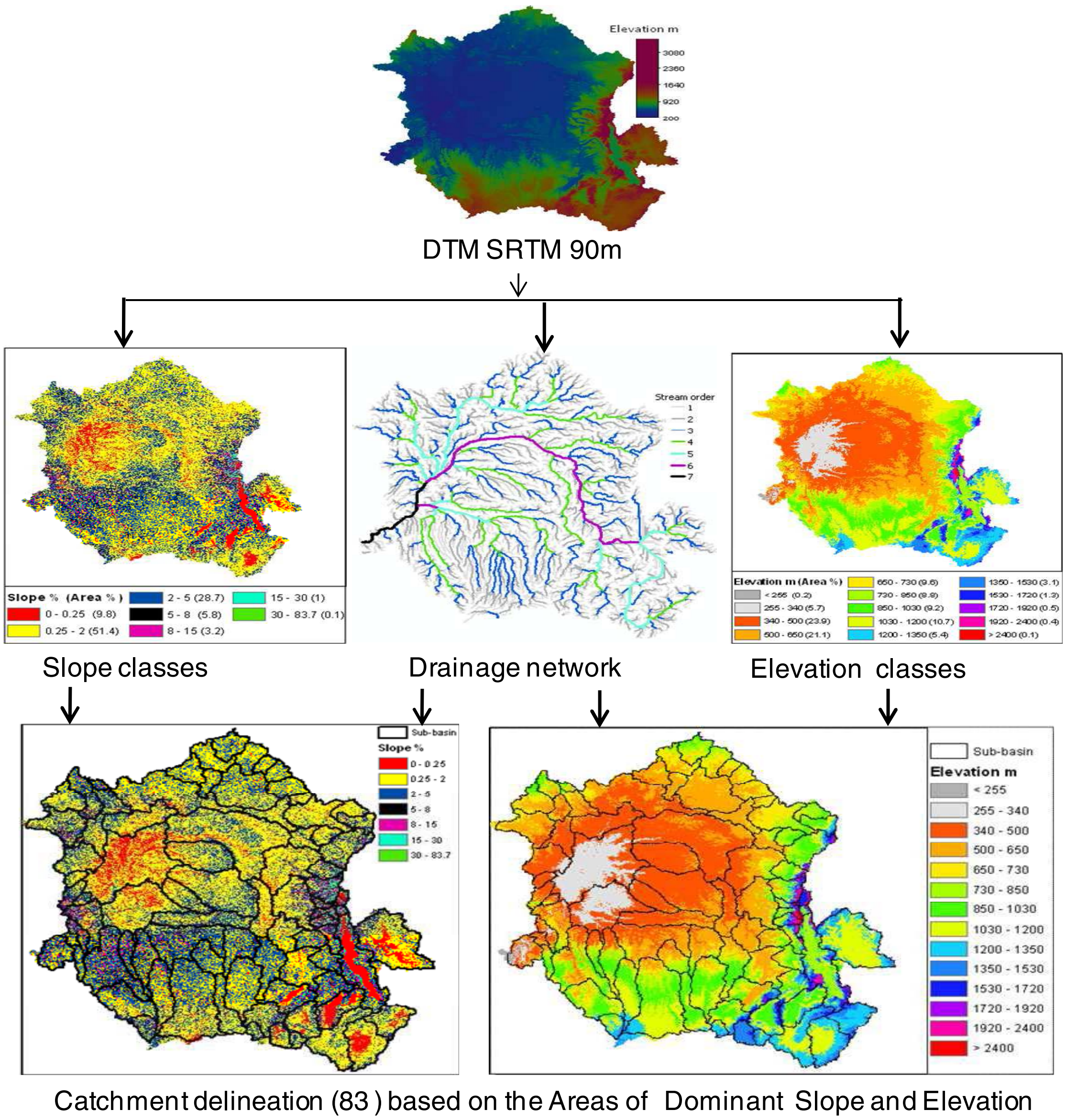

Figure 2. Spatial characteristics and modeling units (subbasins) of the Congo Basin based on the SRTM data set.

decrease in the river flow of about 18% in the Oubangui River, a major tributary of the Congo Basin. This decrease has reportedly affected navigation along the tributary, resulting in increased days of noneconomic navigation when the water height is less than 0.9 m. Therefore, it is important that not only the natural hydrological processes have to be understood but also the potential alterations due to anthropogenic activities and climate change and the vulnerability of the basin water resources to multiple drivers and pressures.

Previous papers highlighted many of the problems with the application of hydrological models as well as the need to develop appropriate analysis approaches that can improve the understanding of the hydrology and water resources systems in the Congo Basin [*Ducharne et al*., 2003; *Shem and Dickinson*, 2006; *Chishugi and Alemaw*, 2009; *Tshimanga et al*., 2011a, 2011b]. This paper presents a study that was designed to establish a semidistributed hydrological model and to assess its performance for water resources assessment in the Congo River Basin. The paper presents the status of the available data in the Congo Basin (section 2), the approaches used to establish a semidistributed model (section 3), the performance of the model at the basin-scale using the available data (section 4), and the future direction for hydrological research in the basin (section 5).

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Table 1. Main Components of Hydrological Processes and the Parameters Designed to Represent Them in the GW-PITMAN Model

Main Model Components	Model Parameters	Description	Units
Surface Processes			
Precipitation	RDF	A rainfall distribution factor	
Impervious area	AI	Impervious fraction of subbasin	%
Potential ET	PEVAP	Annual subbasin evaporation	mm
Interception	PI1 and PI2	Interception storage for two vegetation types	mm
	AFOR	Proportion of the basin area covered by the second veg type	%
	FF	The ratio of forest/grassland potential evapotranspiration	
Actual ET	R	Evaporation-moisture storage relationship parameter	
Catchment Absorption	ZMIN, ZAVE, ZMAX	Min, average, and max catchment absorption rate	mm month^{-1}
Subsurface Processes			
Soil moisture store	ST	Maximum moisture storage capacity	mm
Soil moisture runoff	FT	Runoff from moisture storage-runoff equation	mm month^{-1}
	POW	Power of moisture storage-GW recharge equation	
Groundwater recharge	GW	Maximum groundwater recharge at full capacity (ST)	mm month^{-1}
	GPOW	Power of moisture storage-GW recharge equation	
	SL	Soil moisture threshold below which no GW recharge occurs	mm
Groundwater store and discharge	T	Groundwater transmissivity	m^2 d^{-1}
	S	Groundwater storativity	
	DDENS	Drainage density	km km^{-2}
	Slope	Initial groundwater gradient	%
	RWL	Rest water level	m
	RSF	Riparian strip factor	%
Flow Routing and Water Use			
Channel routing	CL	Channel routing coefficient	Months
	TL	Lag of surface and soil moisture runoff	Months
	TLGmax	Channel losses	Months
Abstraction and return flow	Airr, IWR, IrrAreaDmd, NirrDmd, EffRf		Multiple
Reservoir parameters	DAREA, MAXDAM, A, B		Multiple

2. Modeling Data

Water resources assessment in the Congo Basin has been challenged for a long time by a lack of data [*Shem and Dickinson*, 2006] and the first step in this study was therefore an appraisal of appropriate data sources and the development of a database that could be used to establish a primary understanding of the basin processes [*Tshimanga*, 2012] and to support the application of models. Given the general lack of local data sources, the majority of the information used was based on data sets available at the global scale:

1. The NASA Space Shuttle Radar Topography Mission data (SRTM, 3 arc sec or approximately 90 m, http://srtm.csi.cgiar.org/).

2. The global land cover map [GLOBCOVER, *Bontemps et al.*, 2011].

3. A global Leaf Area Index derived from field measurements [*Scurlock et al.*, 2001].

4. The Harmonized World Soil Database Version 1.1 [*Nachtergaele et al.*, 2010].

5. The Soil and Terrain Database and the World Inventory of Soil Emission Potentials (ISRIC-WISE soil type version1).

6. The soil depth data from the global data set on soil particle sizes [*Webb et al.*, 1991].

7. The hydrogeological properties of Africa [*Seguin*, 2005].

8. The global groundwater recharge database of *Döll and Flörke* [2005].

The main hydrometeorological data inputs for the modeling study encompass the global rainfall database from the Climate Research Unit [CRU TS v2.1: *Mitchell and Jones*, 2005] and evaporation demand data [*Griesser et al.*, 2006]. The sources of streamflow data include the Global Discharge Data Centre [GRDC: *Fekete et al.*, 1999], the Office National de Recherche et du Developpement [ONRD: *Lempicka*, 1971], and Hydrosciences Montpellier—Système d'Informations Environnementales (SIEREM, http://hydrosciences.fr/sierem). Streamflow data for the Congo Basin are also provided by the Observatoire de Recherche en Environnement (www.ore-hybam.org). While it would be very useful to quantify the uncertainties associated with the input climate data, this is very difficult to achieve given the lack of alternative data sets.

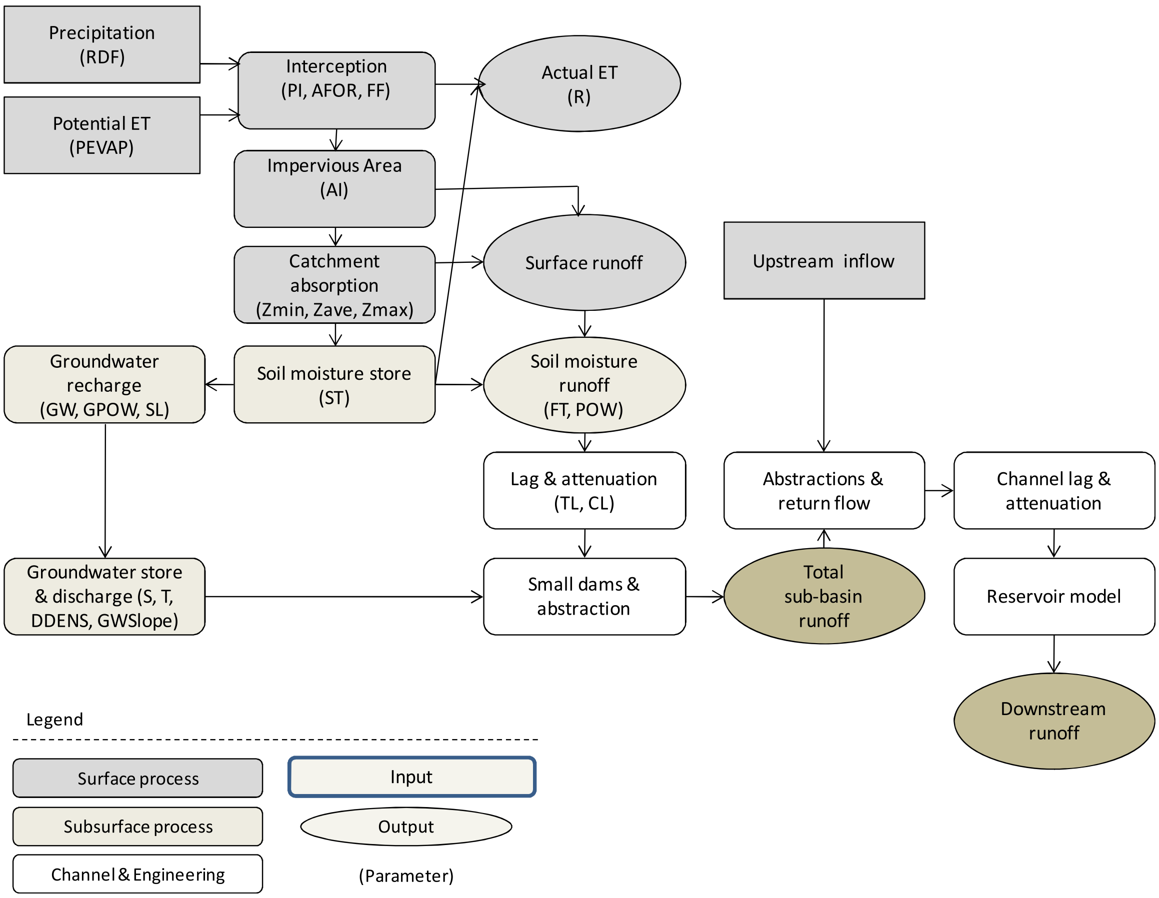


Figure 3. Flow diagram of the GW-PITMAN model showing the main model components and their relevant parameters [*Kapangaziwiri*, 2010].

3. Modeling Approaches

3.1. Sub-basin Delineation

Two main attributes of terrain morphology, elevation and slope, are valuable for understanding the processes of catchment hydrology [*Jarvis et al*., 2004]. The SRTM data set was used to delineate the subbasin units based on overlaying slope classes, elevation classes, and the basin drainage network and delineating the dominant features of elevation and slopes. This approach was meant to avoid an excessive number of modeling units for which the estimation of parameters may not be easy for such a large basin [*Wagener et al*., 2004], but also to provide a basis for evaluation of similar information about some functional characteristics of the landscape processes such as elevation-area and slope-area relationships. These relationships and their derivatives can be used to explain many lithologic and hydroclimatic conditions of the catchment hydrological functioning [*Weiss*, 2001; *Jarvis et al*., 2004; *Clark et al*., 2011; *McMillan et al*., 2011].

Figure 2 shows the 83 subbasin units which resulted from this analysis, while 16 additional subbasins were added based on the location of the main streamflow gauging sites, which resulted in a total number of 99 subbasins delineated for the whole Congo Basin. The elevation classes representing the dominant elevation areas were derived from a frequency distribution of the elevation-area relationship. Slope classification criteria proposed by different authors [*van Engelen et al*., 2006; *Neitsch*, 2009; *Nachtergaele et al*., 2010] were used to derive a unique slope map with seven classes for the Congo Basin.

3.2. PITMAN Rainfall-Runoff Model

To accommodate the variety of physical basin characteristics and the expected spatial variation in hydrological response required the identification of an appropriate model structure that would include an adequate

Table 2. Parameters and Algorithms Used for the Wetland Submodel

Parameters	Description
MaxWA (km^2)	The maximum wetland land area that is permanently or periodically inundated and accounts for local runoff entering directly into the wetland
RWV (m^3 $\times$ 10^6)	Residual wetland storage volume below which there are no return flows to the river channel
IWV (m^3 $\times$ 10^6)	Initial wetland storage volume at the start of the simulation
AVC (m^{-1})	Constant in the WA = AVC $\times$ WV^{AVP} relationship, where WA (m^2) and WV (m^3) are the current wetland area (limited to MaxWA) and volume, respectively
AVP (N/A)	Power in the WA = AVC $\times$ WV^{AVP} relationship
QCap (m^3 $\times$ 10^6)	Channel capacity below which there is no spill from the channel to the wetland
QSF (N/A)	Channel spill factor in SPILL = QSF $\times$ (Q $-$ QCAP), where Q is the upstream flow and SPILL is the volume added to wetland storage
RFC (N/A)	Return flow constant in the RFF = RFC $\times$ (WV/RWV)^{RFP} relationship. RFF is a fraction limited to a maximum of 0.95 and the return flow volume is calculated from RFLOW = RFF $\times$ (WV $-$ RWV)
RFP (N/A)	Return flow power in the RFF = RFC $\times$ (WV/RWV)^{RFP} relationship
EVAP (mm)	Annual evaporation from the wetland (distributed into monthly values using a table of calendar month percentages)
ABS (m^3 $\times$ 10^6)	Annual water abstractions from the wetland (distributed into monthly values using a table of calendar month percentages)

conceptual representation of relevant processes and storages such as interception, soil moisture, groundwater, wetlands, and lakes as well as attenuation in large channel systems. Based on these requirements, a perceived need for regional consistency in modeling approaches and because of its demonstrated applicability to many different hydroclimatic regions of Africa [*Pitman*, 1973; *Hardy et al.*, 1989; *Hughes*, 1997; D. Mazvimavi, Estimation of flow characteristics of ungauged catchments, unpublished PhD thesis, Wageningen University and International Institute for Geo-Information and Earth Observation, ITC, Enschede, Netherlands, 2003; *Mwelwa*, 2004; *Kapangaziwiri*, 2008] and outside Africa (M. S. Abulohom, Calibration of a mathematical model for generating monthly river flows from meteorological data for a selected catchment, unpublished MSc thesis, CEWRE, UET, Lahore, 1997), the PITMAN monthly rainfall-runoff model was chosen for hydrological modeling of the Congo Basin. The model allows various possible runoff generation mechanisms to be explored [*Hughes*, 2013]. The original model [*Pitman*, 1973] has been modified to account for the continued challenges of water resources management in Africa and in this study the semidistributed GW-PITMAN model was used [*Hughes*, 2004; *Hughes et al.*, 2006; *Hughes*, 2013]. Table 1 lists the parameters of this version of the model and the structure is illustrated in Figure 3. A brief description of the model is provided below, while further details can be found in the above-mentioned publications.

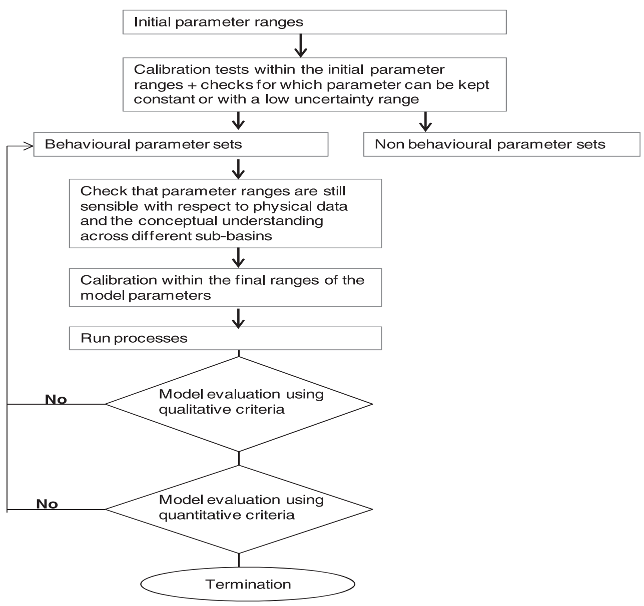


Figure 4. Procedures used for the GW-PITMAN model parameters estimation calibration in the Congo Basin.

The GW-PITMAN model is a conceptual type, semidistributed hydrological model, consisting of storages (interception, soil moisture, and groundwater) linked by functions designed to represent the main hydrological processes at the subbasin scale such as infiltration, excess flow, saturation excess flow, direct overland flow, and groundwater flow [*Hughes et al.*, 2006]. The model accounts for the proportion of rainfall intercepted by the vegetation canopy that does not contribute to streamflow using an interception storage capacity parameter (PI) and the total rainfall. Two parameters (PI1 and PI2) are used to represent two dominant vegetation types and seasonal variations are allowed for.

Table 3. Temporal and Spatial Characteristics of the Available Streamflow Gauging Sites in the Congo Basin

Station ID	Lat.	Long.	Station and River Names	Drainage Area km^2	Drainage Area %basin	Period of Records	Months	% Missing	Source
1	5.17	16.62	Zaoro, Lobaye	5880	0.16	1958–1960	21	0.0	SIEREM
2	5.78	25.13	Dembia, Ouarra	19,590	0.54	1953–1975	269	19.3	GRDC
3	4.73	22.68	Loungouba, Mbari	22,153	0.61	1967–1973	80	20.0	GRDC
4	5.03	25.15	Zemio, Mbomou	26,454	0.73	1952–1975	281	41.3	GRDC
5	3.65	18.10	Safa, Lobaye	30,503	0.84	1953–1975	272	11.4	SIEREM
6	3.67	18.30	M'bata, Lobaye	31,037	0.86	1950–1975	302	3.3	GRDC
7	5.78	20.68	Bambari, Ouaka	28,333	0.78	1952–1975	282	21.3	GRDC
8	4.97	23.92	Rafai, Chinko	51,959	1.43	1952–1973	249	16.1	GRDC
9	6.53	22.00	Bria, Kotto	58,898	1.62	1959–1975	204	10.8	SIEREM
10	4.60	21.92	Kembe, Kotto	75,994	2.10	1953–1965	156	0.0	GRDC
11	4.72	22.82	Bangassou, Mbomou	117,644	3.24	1952–1956	57	5.3	GRDC
12	4.30	21.18	Mobaye, Oubangui	389,856	10.75	1939–1960	260	5.0	GRDC
13	4.37	18.61	Bangui, Oubangui	492,405	13.58	1940–2000	61	0.0	GRDC
14	3.72	18.58	Zinga, Oubangui	524,497	14.47	1952–1975	282	16.0	SIEREM
15	4.35	17.07	Kedingue, Lobaye	14,259	0.39	1957–1975	218	17.9	GRDC
16	4.93	15.87	Carnot, Membere	18,098	0.50	1953–1971	227	22.5	SIEREM
17	2.05	14.92	N'Gbala, Dja	38,600	1.06	1968–1978	131	13.0	SIEREM
18	1.62	16.05	Ouesso, Sangha	143,314	3.95	1948–1983	432	0.0	GRDC
19	3.18	16.12	Salo, Sangha	69,544	1.92	1953–1994	492	35.0	GRDC
20	−4.33	20.58	Port Franqui, Kasai	234,770	6.48	1932–1959	336	0.0	GRDC
21	−3.18	17.38	KutuMoke, Kasai	732,838	20.21	1932–1959	336	0.0	GRDC
22	−3.06	16.56	Lediba, Kwa	876,632	24.18	1950–1959	120	0.0	ONRD
23	−4.02	30.56	Taragi, Malagarasi	8792	0.24	1971–1979	108	5.6	GRDC
24	−9.19	25.86	Bukama, Lualaba	61975	1.71	1950–1959	120	0.0	ONRD
25	−11.97	28.76	Chembe Ferry, Lualaba	119,259	3.29	1957–1981	300	0.0	GRDC
26	−7.84	26.98	Mulongo, Lualaba	158,099	4.36	1950–1959	120	0.0	ONRD
27	−5.91	29.19	Pont Kalemie, Lukuga	231,635	6.39	1957–1959	31	6.5	ONRD
28	−4.53	26.58	Kasongo, Lualaba	751,806	20.74	1950–1959	120	0.0	ONRD
29	−2.95	25.93	Kindu, Lualaba	789,234	21.77	1933–1959	324	0.0	GRDC
30	−4.30	15.31	Kinshasa, Congo	3,570,566	98.48	1969–1984	192	0.0	GRDC

Surface runoff simulations are based on the monthly rainfall and a triangular distribution defined by the parameters ZMIN, ZAVE, and ZMAX assumed to represent the spatial distribution of catchment absorption capacity. Surface runoff can also be generated from impervious areas (AI) and the exceedence of the maximum soil moisture store (ST mm). The soil moisture water balance includes components of evaporative loss, interflow runoff, and recharge to groundwater. Both interflow runoff (QI mm month^{-1}) and groundwater recharge (GWR mm month^{-1}) simulations are based on nonlinear power functions of the relative soil moisture storage (S/ST). The functions are defined by maximum values (FT and GW mm month^{-1}) when S is equal to ST, thresholds of S (SL mm) below which no recharge occurs and power parameters (POW and GPOW):

$$QI = FT \times (S/ST)^{POW} \tag{1}$$

$$GWR = GW \times ((S-SL)/(ST-SL))^{GPOW} \tag{2}$$

The model assumes a linear relationship between the ratio of actual evaporation to the potential evapotranspiration (PE) and the relative level of the soil moisture store (S/ST) and parameter R ($0 < R < 1$) determines the slope of the relationship. The groundwater recharge is routed through a simple groundwater function that accounts for discharge to streamflow, riparian losses to evapotranspiration, and discharge to downstream catchments [*Hughes et al*., 2006]. The function is based on parameters [*Hughes*, 2004] that define the geometry, storage, and drainage characteristics of the groundwater store and include effective Drainage Density (DDENS), Transmissivity (T m^2 d^{-1}), Storativity (S), Regional Groundwater Slope (RGWS), Riparian Strip Factor (RSF, % of catchment area), and the Rest Water Level (RWL).

Following a number of trial manual calibration runs it was concluded that the model could be successfully applied to the Congo Basin. However, part of this initial evaluation, as well as parallel studies in the Okavango and Zambezi River basins, identified the need to include a wetland/natural lake submodel for some parts of the basin [*Tshimanga et al*., 2011a] and the details of these developments are presented in *Hughes et al*. [2013]. Table 2 lists the wetland model parameters that are designed to account for exchanges

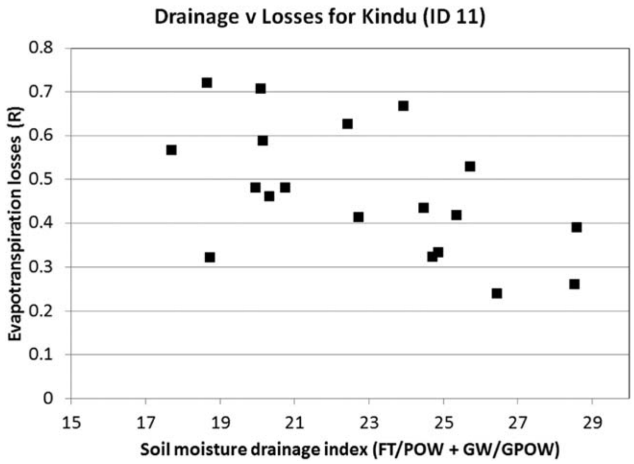


Figure 5. Relationship between an index of total drainage from the soil moisture store and the main evapotranspiration parameter (R) for the Kindu station based on the 20 best ensembles.

between rivers and lakes or wetlands. While the submodel may appear to be overparameterized, it was found to be difficult to simplify the approach and still retain the representation of important exchange processes between river channels and wetland storage. Some of the parameters can be quantified from measured physical properties of the wetland (from Earth Observation data for example), while others have to be calibrated in some way. For typical wetland situations where a river channel meanders through an area of low topography, the model assumes that water will spill onto the wetland once the channel capacity has been exceeded. The spill fraction (QSF) would be expected to be between 0 and 1. The rate of return (RWV, RFC, and RFP) will be highly dependent on the 3-D geometry of the wetland relative to the channel. For natural lakes, the QCap parameter will be 0 and the spill factor (QSF) will always be 1 to ensure that all inflows contribute to lake storage. Return flows to the downstream channel will depend on the size of the lake outlet channel.

3.3. Model Setup and Calibration Procedures

The GW-PITMAN model was established for the 99 subbasins within the Congo Basin, using the Spatial Time Series Information Modeling software [SPATSIM: *Hughes and Forsyth*, 2006]. Figure 4 shows the procedures used for the model parameter estimation and calibration. Two software versions of the model are available within SPATSIM. The first runs the model once with a single parameter set and is used with manual calibration. The second is an uncertainty version based on inputs of uniform parameter distributions defined by minimum and maximum values for each subbasin and Monte Carlo sampling to generate 10,000 ensembles of simulated streamflows. This version of the model allows for the input of observed data (where it exists) and generates several objective function values for each ensemble [*Hughes*, 2013]. The ensemble outputs can also be subjected to sensitivity analysis [*Kapangaziwiri et al*., 2012] to assist in the identification of which parameters to focus on during manual calibration.

The uncertainty version was used to establish the most sensitive parameters for the gauged subbasins and to identify the behavioral ensemble outputs and further constrain the parameter ranges during the subsequent manual calibration (Figure 4). The main reason for relying on manual calibration was related to the known equifinality in the model [*Hughes*, 2013] and the desire to get the right outputs for the right reasons [*Kirchner*, 2006]. It was found to be more straightforward to explore and account for the equifinality during a manual calibration process.

A total of 30 gauging sites (Table 3) with flow records falling within the period 1931–2000 were used for model calibration, although the length of the records vary from one station to another. The flow records of the gauging sites with relatively long time series (more than 20 years) were split to account for both calibration and validation periods, while the total period was used in other cases to ensure that sufficient data are included in the calibration set to represent variability.

3.4. Model Performance Criteria

The criteria used in this study to assess the model performance for the Congo Basin are both quantitative and qualitative. The qualitative criteria include the visual assessment of hydrographs, seasonal distributions of mean flow and flow duration curve plots to compare simulated and observed flows. The quantitative criteria include a range of objective functions that are typically used in hydrological modeling studies.

3.4.1. Percent Bias of the Mean Monthly Flows (PBIAS, %)

PBIAS is an error index that measures the percentage deviation of the simulated mean monthly flow volume from the observed mean flow [*Moriasi et al*., 2007]. Different authors have recommended

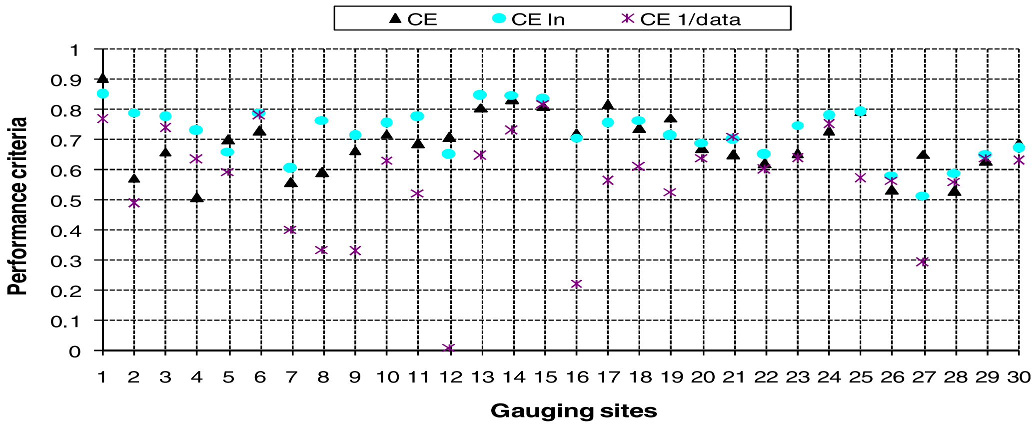


Figure 6. Nash-Sutcliffe coefficient of efficiency values for untransformed and transformed data for all Congo River gauging sites.

different values for acceptable model calibrations and a relatively low bias of ±5% has been used in this study.

3.4.2. Nash-Sutcliffe Coefficient of Efficiency (CE)

CE is a normalized dimensionless measure of model efficiency that determines the relative magnitude of the residual variance compared to the measured variance [*Nash and Sutcliffe*, 1970]. The CE value ranges between $-\infty$ and 1, and values of greater than 0.5 have been considered acceptable in this study.

In this study, the two objective functions are calculated for both untransformed (PBIAS and CE) data and natural logarithm transformed values (PBIAS ln and CE ln), to ensure that both high and low flow components of the simulations are effectively evaluated. The CE values are also computed using an inverse transformation (CE 1/data) which further emphasizes the fit to low flows.

4. Basin-Scale Model Performance

4.1. Sensitivity and Uncertainty Analysis Results

Initial runs of the uncertainty version of the model with quite wide ranges for almost all of the parameters (including the areal extent of forest) confirmed the high degree of equifinality in the model structure. The range of behavioral parameters based on the better simulations (using the objective functions already referred to) were not very different to the range for the total 10,000 ensembles. However, most of the uncertainty analysis results suggested high values for ST and ZMAX (high storage and low surface runoff potential) and there are some clear indications of parameter combinations that are more behavioral than others, including FT/POW and GW/GPOW, as well as the sum of these two ratios as an indication of overall

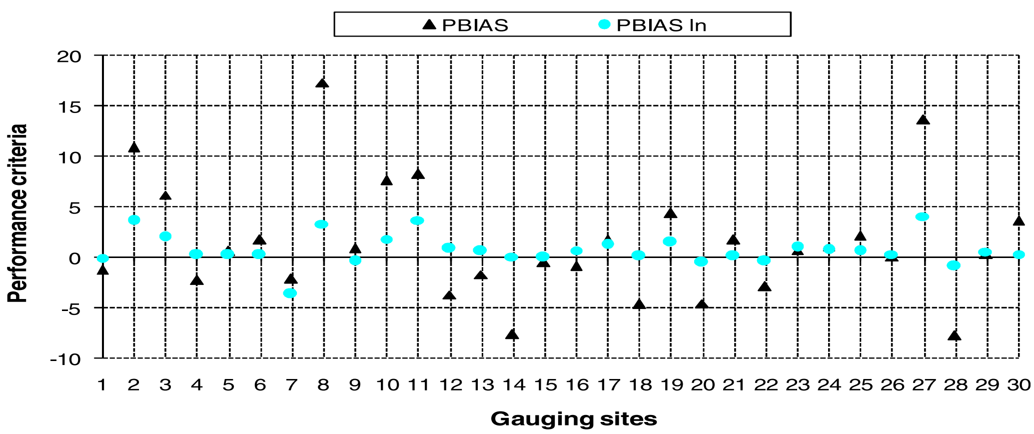


Figure 7. Bias statistics for the gauged subbasins of the Congo Basin (the target range was between −5 and 5%).

Table 4. Model Performance During Validation

Station ID	CE (Q)	CE (ln Q)	CE (1/data)	%Diff (Q)	%Diff (ln Q)
2	0.54	0.75	0.77	7.47	4.20
6	0.83	0.84	0.39	0.82	1.10
13	0.76	0.89	0.83	−8.89	−0.23
18	0.79	0.76	0.66	7.56	1.06
19	0.49	0.76	0.64	9.15	2.15
20	0.48	0.61	0.63	0.92	0.02
21	0.59	0.59	0.49	6.89	0.95

low flow drainage response. For example, the original range of the sum of these ratios for the Kindu station (ID 29) was between 4 and 60, while the best 20 ensembles reduced the range to between 19 and 28. Figure 5 illustrates that it is also possible to identify relationships between this index of drainage and the main evapotranspiration parameter (R). Similar conclusions were reached by *Hughes* [2013] who illustrated an approach to limiting the model parameter space for a small South African catchment. This study emphasized the value of additional information such as estimates of mean annual groundwater recharge values to help constrain the values of GW and GPOW.

For the Congo study, it was therefore considered necessary to fix some of the parameter values and concentrate on some of those that determine the overall volumetric response of streamflow to rainfall. The parameters forming the focus of the subsequent manual calibrations were ZMIN, ZAVE, ZMAX, ST, FT, GW, POW, and GPOW that determine the volumes of surface runoff, interflow and groundwater contributions to streamflow. The fixed parameter values were based on the available basin property data and previous experience of the application of the model in the southern Africa region [*Hughes*, 1997; *Mwelwa*, 2004; *Hughes et al.*, 2006; *Hughes*, 2013] and further details about the use of the physical property data in the Congo can be found in *Tshimanga* [2012] and *Tshimanga et al.* [2011b].

4.2. Model Performance Results

Figures 6 and 7 illustrate the overall performance results with regard to the objective functions used in this study. In general terms, the model efficiency for the majority of the gauging stations range from 0.5 to 0.9, regardless of whether untransformed or ln-transformed data are used. The inverse transformation gives generally poorer results (Figure 6). In most cases, it was possible to constrain the percentage bias in mean monthly flows to within ±5% for the calibration period, while there are some sites where the bias is beyond ±10%. Table 4 presents the objective function values for the sites where the observed record length was considered long enough to split the data into calibration and validation periods. The efficiency objective functions (CE, CE ln, and CE 1/data) are not very different to the calibration results, while the % bias values are generally worse but remain within the range of ±10%.

Figures 8–13 illustrate the model performance using a monthly streamflow hydrographs and flow duration curves for a selection of sites within the whole basin, using the full time series (calibration and validation periods) in each case. The model is able to capture the timing and magnitude of high and low flows

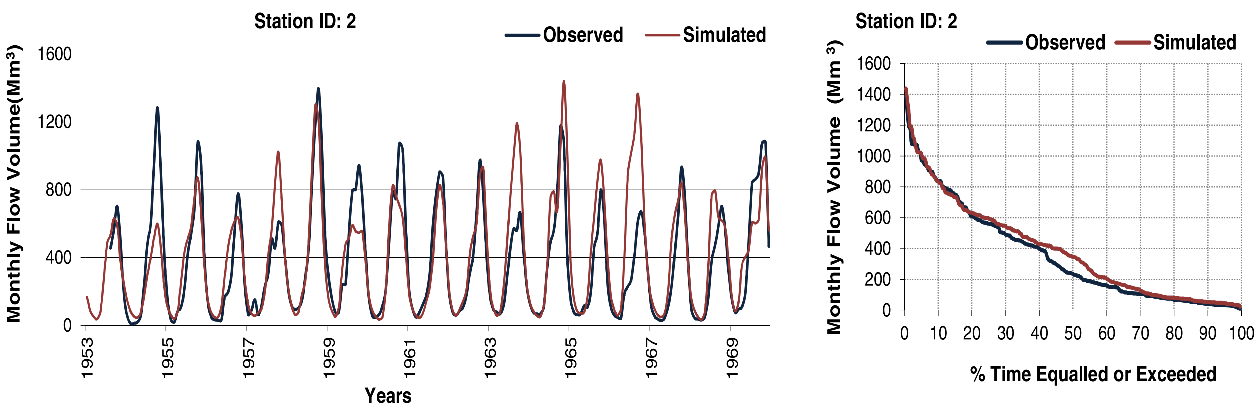


Figure 8. Observed and simulated monthly flows for Dembia gauging site in the Oubangui drainage area.

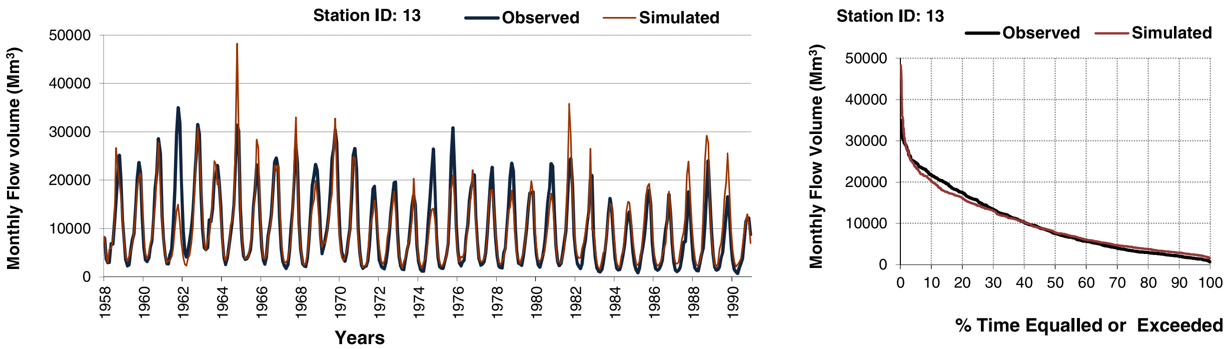


Figure 9. Observed and simulated monthly flows for the most downstream gauging site (Bangui) in the Oubangui drainage area.

satisfactorily, irrespective of the subbasins are located in headwater areas, downstream areas or at the outlets of regions strongly affected by wetlands and lakes (Figure 12). Figure 12 also illustrates that the inclusion of the wetland function has a substantial effect on the overall simulation results, the main impact being the reduction of wet season flows through evapotranspiration losses. Based on the graphical comparisons (rather than the objective functions), the worst overall simulation is at the basin outlet, where the pattern of low flows is not captured very well (Figure 13). Part of this problem is related to the need to use the channel routing parameter (CL in Table 1) to allow for attenuation in the main channel and partly because large parts of the central part of the basin are not gauged. There are therefore no observed data available to calibrate the runoff response of these parts of the basin, nor to establish progressive attenuation effects in a downstream direction.

Some drainage areas such as the lower Oubangui, Sangha, and Kasai show a relatively high degree of consistency in the calibrated parameter values, suggesting some degree of homogeneity in hydrological processes for these areas. There is, however, a large variation in the calibrated parameters across some of the subbasins, which may reflect heterogeneity in hydrological processes, but could also be the result of the calibration process coupled with the high degree of equifinality contained within the model structure. These parameter variations are particularly marked in the Lualaba drainage systems where the process of calibrating the runoff generation components of the model is affected by the presence of lakes and wetlands and the need to calibrate the wetland subcomponent, further adding to the equifinality. The simulations for headwater subbasins (stations 23 and 24 in Figures 6 and 7) in the Lualaba River area are generally better than those downstream that are impacted by lakes and wetlands (stations 25, 26, 27, and 29 in Figures 6 and 7). The storage capacity of these water bodies is massive (e.g., Lake Tanganyika) and greatly alters the downstream flow regimes. During the early phases of modeling, prior to the inclusion of the wetland function [*Hughes et al.*, 2013] the only way to obtain vaguely satisfactory simulations was to change the parameters to unrealistic values to compensate for an inadequate model structure. Although, this increases the

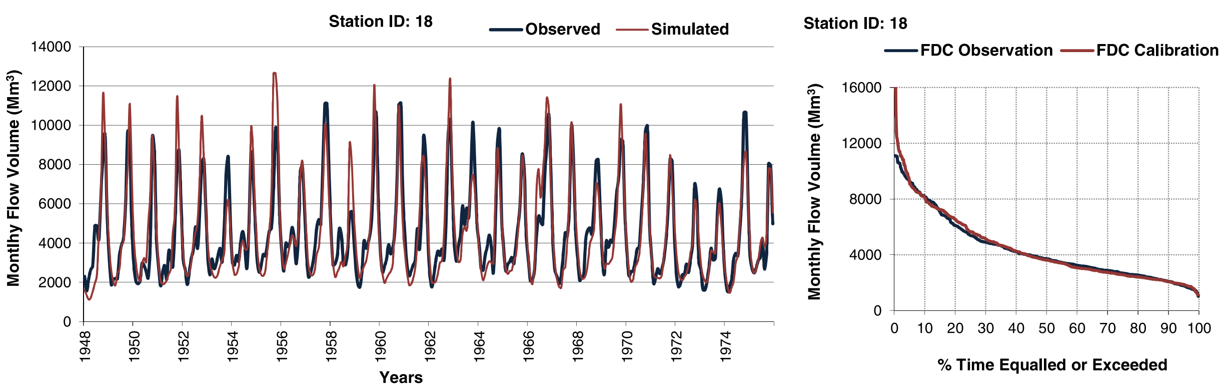
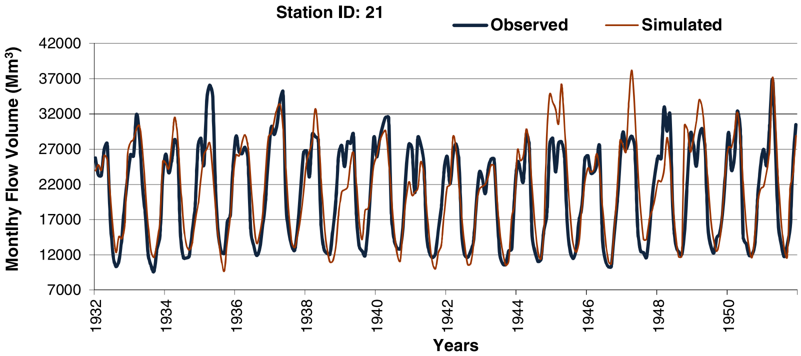


Figure 10. Observed and simulated monthly flows for the most downstream gauging site (Ouesso) of the Sangha drainage area.



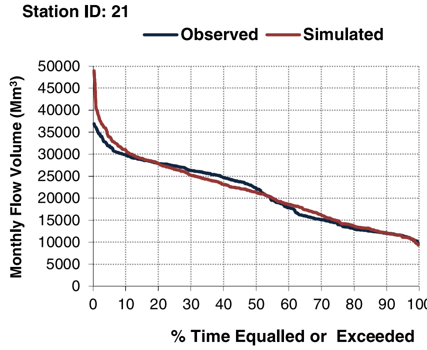


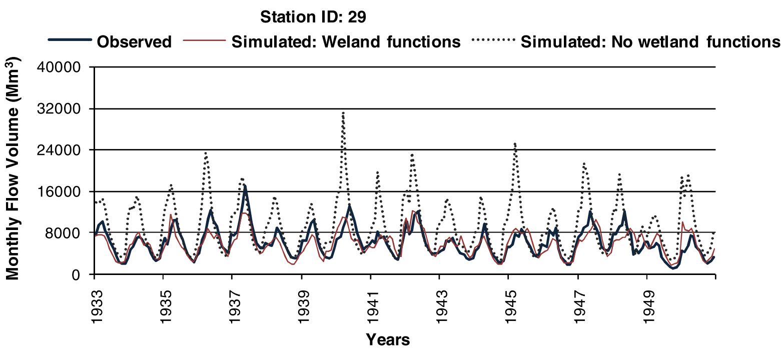
Figure 11. Observed and simulated monthly flows for the most downstream gauging site (KutoMoke) of the Kasai drainage area.

model parameter space and equifinality, it allows the parameters for the other parts of the model to be more consistent with those used for the other parts of the basin and achieves overall better simulations (Figure 12).

The central basin receives flows from the four main upstream drainage systems and includes a number of additional tributary rivers. The complexity in hydrological processes increases from upstream and is further exacerbated by the ungauged nature of the central basin, and therefore it is difficult to be confident that the parameter values obtained in this study for the central part of the basin are the adequate representations of the hydrological response. The calibration exercise at this site highlighted the importance of the channel routing (CL) and groundwater recharge (GW) parameters. However, a number of questions remain about the adequate definition of the model parameters for the central basin and Figure 13 illustrates that interannual variations in the low flows at the Kinshasa gauging site (30) could not be captured very well. The implication is that more information is required about the hydrological response, and specifically the attenuation characteristics of the main channel to improve the total basin simulations.

5. Discussion and Conclusions

Modeling large river basins involves challenges associated with data scarcity and the complexity of natural processes at different scales, all of which increase predictive uncertainties. These complexities are not only associated with the main runoff processes and the water balance of the subbasins, but also with the processes involved in routing upstream streamflow through wetlands, lakes, and large river channels (and their floodplains during high flows). As with all modeling studies in the post-PUB era, quantifying the major sources of uncertainties in simulations of hydrological response should be considered to be best practice [*Montanari et al.*, 2013; *Blöschl et al.*, 2013; *Hrachowitz et al.*, 2013] and is clearly a prerequisite for reducing uncertainty. This section discusses the main uncertainty issues that arose from the GW-PITMAN model application in the Congo Basin.



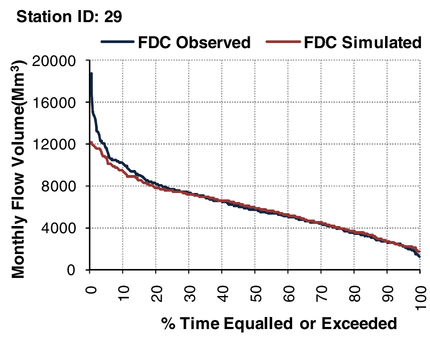


Figure 12. Observed and simulated monthly flows for the most downstream gauging site (Kindu) of the Lualaba drainage area.

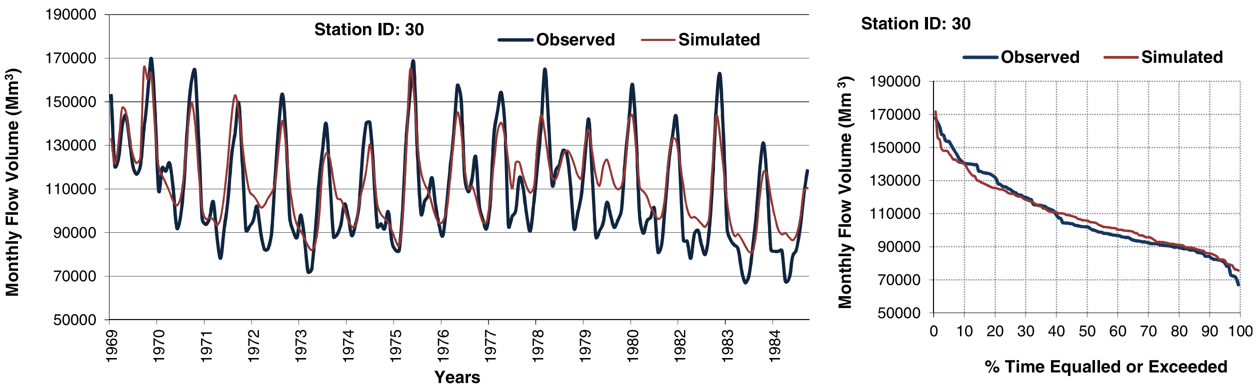


Figure 13. Observed and simulated monthly flows for the most downstream gauging site (Kinshasa) of the total Congo Basin.

5.1. Uncertainty in Input Data and Correct Interpretation of the Available Data

Uncertainties in model simulations have multiple sources, including errors of input data, which are exacerbated by incorrect interpretation of the data, particularly those data that are not primarily prepared for hydrological use. This type of uncertainty is unavoidable, given discrepancies in various global data sets of earth observations. These discrepancies result from differences in scale or resolution, classification methodology, training, and ground reference data, the type of satellite sensors used and errors due to georeferencing. The paucity of rainfall gauges in the Congo Basin means that few observed records are used in the construction and validation of global data sets, contributing to potential errors and input uncertainties. *Tshimanga* [2012] used two different data sets to demonstrate the importance of rainfall uncertainty in the basin and the need for improved rainfall estimates. Some of the global data sets on basin physical properties showed inconsistencies in the information provided and the need for care if these data are to be used for parameter estimation. An example is the use of global data sets that include soil depth and possibility that low values would lead to low storage parameters and excessive runoff during high rainfall months [*Tshimanga et al*., 2011b; *Tshimanga*, 2012].The streamflow data used in this study do not include technical information such as water heights and rating curves to permit the analysis of measurement errors and the related model calibration uncertainties. This is an aspect of input data uncertainty that should attract future attention by the various data distribution centers.

5.2. Spatial Discretization and Scale of the Modeling Units

One possible approach to reduce model parameter uncertainty is to reduce the spatial scale of modeling and therefore the spatial variability in physical basin properties and expected hydrological response. However, the value of a reduced spatial scale is reliant upon the availability of physical basin property data at an appropriate resolution. Part of the problem is attributed to the coarse resolution of global data sets used to estimate the parameter values and the correctness of the interpretation of the data sets which are frequently not prepared for direct use in hydrological modeling [*Tshimanga*, 2012]. This problem occurs regardless of whether the basin property data are used directly for parameter estimation [*Kapangaziwiri*, 2008], or whether they are used to guide a parameter regionalization approach after calibration at gauged sites.

5.3. Model Structural and Parameter Uncertainties

This study emphasized uncertainties in some of the parameters, such as the channel routing parameter (CL). Initially, it was assumed that CL would only be important in downstream subbasins, where channel storage and attenuation effects might be expected to be important even at the monthly time scale. However, sensitivity analyses [*Tshimanga*, 2012] suggested that parameter may also play a role in some of the headwater subbasins (sites 2 and 4, for example). However, it is also possible that the attenuation effect is associated with other processes that the model is not designed to cater for. This issue needs to be further explored to identify physiographic conditions under which monthly scale attenuation effects can be physically justified. *Hughes and Hughes* [1987] point to the existence of extensive floodplains adjacent to the rivers in the central basin, while *Bwangoy et al*. [2010] suggested that an area of about 359,556 km^2 is occupied by channel margin wetlands in the central basin. This study contributed to the development of a new wetland function [*Hughes et al*., 2013] but it was only used in the upper parts of the Lualaba River (including Lake Tanganyika), while CL is used for attenuation effects in the central basin. The question remains whether there is sufficient information to establish the wetland function in the central basin and whether this could contribute to improved downstream simulations. Given the differences in the physical characteristics of the various drainage units of the Congo Basin, it is not unreasonable to expect that these differences would be translated into model parameter value differences across the subbasins. However, it is also difficult to separate out these effects from the inherent equifinality [*Beven*, 2001] of the model structure and parameter space, regardless of the method of calibration used. The next steps in the application of the model to the Congo basin should therefore be the use of reliable and appropriate physical basin characteristics to constrain the parameters, reduce uncertainty and obtain more physically realistic parameter sets [*Kirchner*, 2006].

In general terms, the objective functions and graphical evidence support the conclusion that the hydrological model applied in this study should prove to be adequate for simulating the necessary hydrological information for water resources management and planning at the basin scale. This includes headwater subbasins, sites located downstream of the main drainage areas and the wetland/lake dominated subbasins in the south eastern parts of the Congo Basin. The study suggests that the focus area for model improvement should be the largely ungauged central parts of the basin. In this complex and data scarce area, appropriate modeling approaches are needed to assess various water resources planning and management strategies. While, uncertainty issues have been considered throughout this study, no attempts are made in this paper to present uncertainty bounds around the simulations. The authors consider that this needs to be done in the future, but should be based on a comprehensive assessment of the input hydroclimate data, the model results, the existing (manually calibrated) parameter sets and the available subbasin physical property data. One of the objectives should be to reduce the uncertainty in the spatial differences in parameter sets that are partly linked to model equifinality. These more detailed uncertainty assessments should also account for some of the model structure issues that have been identified, and specifically the explicit inclusion of wetland processes. They should also account for the future water resources management needs in the basin that might include accounting for changing land use patterns, as well as changing climate patterns. It will be important to quantify how reliable the model can be expected to be under such future, potentially, nonstationary environments.

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References

Balas, N., E. S. Nicholson, and D. Klotter (2007), The relationship of rainfall variability in West Central Africa to sea-surface temperature fluctuations, *Int. J. Climatol.*, *27*, 1335–1349.

Beven, K. J. (2001), *Rainfall-Runoff Modeling: The Primer*, John Wiley, Chichester, U. K.

Blöschl, G., and M. Sivapalan (1995), Scale issues in hydrological modeling: A review, *Hydrol. Processes*, *9*, 251–290.

Blöschl, G., M. Sivapalan, T. Wagener, A. Viglione, and H. Savenije (Eds.) (2013), *Runoff Prediction in Ungauged Basins. Synthesis Across Processes, Places and Scales*, Cambridge Univ. Press.

Bontemps, S., P. Defourny, E. van Bogaert, O. Arino, V. Kalogirou, and J. Ramos (2011), *GLOBCOVER 2009 Products Description and Validation Report*, Université catholique de Louvain (UCL) & European Space Agency (ESA), Belgium, Version 2.2, 53 pp., hdl:10013/epic.39884.d016.

Bwangoy, J. R. B., C. M. Hansen, P. D. Roy, D. G. Grandiand, and O. C. Justice (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.

Chishugi, B. J., and B. F. Alemaw (2009), The hydrology of the Congo River basin: A GIS-based hydrological water balance model. World environmental and water resources congress 2009: Great Rivers, *ASCE Conf. Proc.*, pp. 1–16, doi:10.1061/41036(342)593.

Clark, M. P., H. K. McMillan, G. B. D. Collins, D. Kavetski, and R. A. Woods (2011), Hydrological field data from a modeller's perspective. Part 2: Process-based evaluation of model hypotheses, *Hydrol. Processes*, *25*, 523–543.

Döll, P., and M. Flörke (2005), Global-scale estimation of diffuse groundwater recharge, *Frankfurt Hydrol. Pap. 3*, Inst. of Phys. Geogr., Frankfurt Univ., Frankfurt am Main, Germany.

Ducharne, A., C. Golaz, E. Leblois, K. Laval, J. Polcher, E. Ledouxand, and G. Marsily (2003), Development of a high resolution runoff routing model, calibration and application to assess runoff from the LMD GCM, *J. Hydrol.*, *280*, 1–4.

Farnsworth, A., E. White, C. J. R. Williams, E. Black, and D. R. Kniveton (2011), Understanding the large scale driving mechanisms of rainfall variability over Central Africa, in *African Climate and Climate Change: Physical, Social and Political Perspectives*, edited by C. J. R. Williams and D. R. Kniveton, 212 pp., Springer, Dordrecht, Netherlands.

Fekete, B. M., J. C. Vorosmarty, and W. Grabs (1999), Global, composite runoff fields based on observed river discharge and simulated water balances, *GRDC Rep. 22*, Global Runoff Data Cent., Koblenz, Germany.

Fenicia, F., H. H. G. Savenije, and H. C. Winsemius (2008), Moving from model calibration towards process understanding, *Phys. Chem. Earth*, *33*(17), 1057–1060.

Griesser, J., R. Gommesand, and M. Bernardi (2006), New LocClim—The Local Climate Estimator of FAO, *Geophys. Res. Abstr., 8*, 08305, SRef-ID: 1607-7962/gra/EGU06-A-08305.

Gupta, H. V., T. Wagenerand, and Y. Liu (2008), Reconciling theory with observations: Elements of a diagnostic approach to model evaluation, *Hydrol. Processes*, *22*, 3802–3813.

Hardy, S., G. Dugdale, R. J. Milford, and V. J. Sutcliffe (1989), The use of satellite derived rainfall estimates as inputs to flow prediction in the River Senegal, in *New Directions for Surface Water Modeling*, edited by M. L. Kavvas, pp. 23–30, *Proceedings of the Baltimore Symposium, IAHS Publ. 181*.

Hoare, A. L. (2007), *Clouds on the Horizon: The Congo Basin's Forests and Climate Change*, The Rainforest Found., London. [Available at http://www.rainforestfoundationuk.org.]
Hrachowitz, M., et al. (2013), A decade of Predictions in Ungauged Basins (PUB)—A review, *Hydrol. Sci. J.*, *58*(6), 1198–1255.
Hughes, D. A. (1997), Southern African FRIEND—The application of rainfall-runoff models in the SADC region, *Rep. 235/1/97*, Water Res. Comm., Pretoria.
Hughes, D. A. (2004), Incorporating ground water recharge and discharge functions into an existing monthly rainfall-runoff model, *Hydrol. Sci. J.*, *49*(2), 297–311.
Hughes, D. A. (2013), A review of 40 years of hydrological science and practice in southern Africa using the Pitman rainfall-runoff model, *J. Hydrol.*, *501*, 111–124.
Hughes, D. A., and D. A. Forsyth (2006), A generic database and spatial interface for the application of hydrological and water resource models, *Comput. Geosci.*, *32*, 1389–1402.
Hughes, R. H., and J. S. Hughes (1987), *A Directory of African Wetlands: Zaire*, Samara House, Tresaith, Wales. [Available at http://www.iwmi.cgiar.org/wetlands/pdf/Africa/Region4.zaire.]
Hughes, D. A., L. Andersson, J. Wilk, and H. H. G. Savenije (2006), Regional calibration of the Pitman model for the Okavango River, *J. Hydrol.*, *331*, 30–42.
Hughes, D. A., R. M. Tshimanga, S. Tirivarombo, and J. Tanner (2013), Simulating wetland impacts on stream flow in southern Africa using a monthly hydrological model, *Hydrol. Processes*, *28*(4), 1775–1786. doi:10.1002/hyp.9725.
Jarvis, A., J. Rubiano, A. Nelson, A. Farrow, and M. Mulligan (2004), Practical use of SRTM data in the tropics: Comparisons with digital elevation models generated from cartographic data, *Working Doc. 198*, 32 pp., International Centre for Tropical Agriculture (CIAT), Cali, Colombia.
Kapangaziwiri, E. (2008), Revised parameter estimation methods for the Pitman monthly rainfall-runoff model, *Water SA*, *32*(2), 183–191.
Kapangaziwiri, E. (2010), Regional application of the pitman monthly rainfall-runoff model in southern Africa incorporating uncertainty. PhD thesis, Rhodes University, Grahamstown, South Africa. [Available at http://eprints.ru.ac.za/1777/.]
Kapangaziwiri, E., D. A. Hughes, and T. Wagener (2012),Constraining uncertainty in hydrological predictions for ungauged basins in southern Africa, *Hydrol. Sci. J.*, *57*(5), 1000–1019.
Kirchner, J. W. (2006), Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology, *Water Resour. Res.*, *42*, W03S04, doi:10.1029/2005WR004362.
Ladel, J., P. Nguinda, A. Pandi, C. K. Tanania, L. B. Tondo, G. Sambo, N. Tellro-Wai, E. A. Buluku, and M. Hoepffner (2008), Integrated Water Resources Management in the Congo Basin based on the development of Earth Observation monitoring systems in the framework of the AMESD Programme in Central Africa, paper presented at 13th World Water Congress, Montpellier, France, 1–4 Sept.
Lempicka, M. (1971), Bilan hydrique du basin du fleuve Zaïre. I : Ecoulement du bassin 1950–1959, Office National de la Recherche et du Développement, Kinshasa, 147 pp.
McMillan, H. K., M. P. Clark, B. W. Bowden, M. Duncan, and R. A. Woods (2011), Hydrological field data from a modeler's perspective. Part 1: Diagnostic tests for model structure, *Hydrol. Processes*, *25*, 511–522.
Mitchell, T. D., and P. D. Jones (2005), An improved method of constructing a database of monthly climate observations and associated high-resolution grids, *Int. J. Climatol.*, *25*, 693–712.
Montanari, A., et al. (2013), ''Panta Rhei—Everything Flows'': Change in hydrology and society—The IAHS Scientific Decade 2013–2022, *Hydrol. Sci. J.*, *58*(6), 1256–1275.
Moriasi, D. N., G. J. Arnold, W. M. van Liew, L. R. Bingner, D. R. Harmel, and L. T. Veith (2007), Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, *Trans. ASABE*, *50*, 885–900.
Mwelwa, E. M. (2004), The application of a monthly time step Pitman rainfall-runoff model to the Kafue river basin of Zambia, MSc thesis, Rhodes Univ., Grahamstown, S. Afr. [Available at http://eprints.ru.ac.za/173/.]
Nachtergaele, A. F., et al. (2010), Harmonized world soil database, in *Proceedings of the 19th World Congress of Soil Science, Soil Solutions for a Changing World*, edited by R. J. Gilkes and N. Prakongkep, pp. 34–37, 1–6 Aug., Int. Union of Soil Sci., Brisbane, Australia (Published on DVD).
Nash, J. E., and J. Sutcliffe (1970), River flow forecasting through conceptual models part A. Discussion of principles, *J. Hydrol.*, *10*, 282–290.
Neitsch, L., S. Arnlod, G. J. Kiniry, and R. J. Williams (2009), Soil and Water Assessment Tools Theoretical Documentation, Grassland, soil and water research laboratory, agriculture research service, Tex.
Pitman, W. V. (1973), A mathematical model for generating river flows from meteorological data in South Africa, *Hydrol. Res. Unit, Rep. 2/73*, Univ. of the Witwatersrand, Johannesburg, South Africa.
Runge, J. (2008), The Congo River, Central Africa, in *Large Rivers: Geomorphology and Management*, edited by A. Gupta, John Wiley, London.
Scurlock, J. M., G. P. Asnerand, and S. T. Gower (2001), Worldwide historical estimates and bibliography of leaf area index, 1932–2000, *ORNL Tech. Memo. TM-2001/268*, Oak Ridge Natl. Lab., Oak Ridge, Tenn.
Seguin, J. J. (2005), *Projet Reseau SIG-Afrique, Carte hydrogeologique de l'Afrique a l'echelle du 1/10 M*, BRGM/RP-54404-FR.
Shem, O. W., and R. E. Dickinson (2006), How the Congo basin deforestation and the equatorial monsoonal circulation influences the regional hydrological cycle, paper presented at the 86th Annual American Meteorological Society Meeting, Atlanta, Ga. [Available at http://www.ametsoc.org/.]
Sivapalan, M., et al. (2003), IAHS Decade on Prediction in Ungauged Basins (PUB), shaping an exciting future for the hydrological sciences, *Hydrol. Sci. J.*, *48*(6), 857–880.
Tshimanga, R. M. (2012), Hydrological uncertainty analysis and scenario-based streamflow modelling for the Congo River Basin, PhD thesis, Rhodes Univ., South Africa. [Available at http://eprints.ru.ac.za/2937/.]
Tshimanga, R. M., D. A. Hughes, and E. Kapangaziwiri (2011a), Initial calibration of the Pitman rainfall-runoff model for the Congo River Basin, *Phys. Chem. Earth*, *36*, 14–15.
Tshimanga, R. M., D. A. Hughes, and E. Kapangaziwiri (2011b), Understanding hydrological processes and estimating model parameter values in large basins: The case of the Congo River Basin, *IAHS Publ.*, *345*, 17–22.
van Engelen, V. W. P., N. H. Batjes, J. A. Dijkshoorn, and J. R. M. Huting (2005), *Harmonized Global Soil Resources database, Final Report), 2005/06, ISRIC, World Soil Information, Wageningen*.
Wagener, T., H. S. Wheater, and H. V. Gupta (2004), *Rainfall-Runoff Modelling in Gauged and Ungauged Catchments*, 332 pp., Imp. Coll. Press, London.
Webb, R. S., C. E. Rosenzweigand, and E. R. Levine (1991), A global data set of soil particle size properties, *NASA Tech. Memo. 4286*, NASA Goddard Inst. for Space Stud., N. Y.
Weiss, A. (2001), Topographic position and landforms analysis, poster presented at ESRI User conference, San Diego, Calif.