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Estimating the influence of land-use on hydrological parameters of the peatlands of the Itimbiri River Basin, north-eastern Congo Basin

[Estimation de l'Influence d'Occupation du Sol sur les Paramètres Hydrologiques de la Zone à Tourbière du Bassin versant de La Rivière Itimbiri dans la Partie Nord -Est du Bassin Du Congo]

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Abstract

This study aims to develop a hydrological model for the Itimbiri River Basin to assess available water resources and support decision-making for effective and sustainable water resource management. Historical climatic and hydrological data were utilized using the soil moisture method integrated into the WEAP hydrological model. The modeling results are satisfactory, with performance indicators such as an NSE of 0.65, an R^2 of 0.75, SqrtNSE,0,71 and a PBIAS of -2%, demonstrating the model's ability to accurately replicate the basin's hydrological regimes. The study provides a comprehensive approach to sustainable water resource management and emphasizes the need to establish a dense and reliable hydro-climatic monitoring network to ensure regular and rigorous tracking of water resources in the Itimbiri River Basin.

Keywords: Land use, Hydrological parameters, peatland, WEAP Modelling, Itimbiri Basin.

Résumé

Cette étude vise à établir un modèle hydrologique pour le bassin versant de la rivière Itimbiri afin d'évaluer les ressources en eau disponibles et d'appuyer la prise de décision pour une gestion efficace et durable de ces ressources. Les données climatiques et hydrologiques historiques ont été exploitées en utilisant la méthode d'humidité du sol intégrée dans le modèle hydrologique WEAP. Les résultats de la modélisation sont satisfaisants, avec des indicateurs de performance tels qu'un NSE de 0,65, un R^2 de 0,75, SqrtNSE, 0,71 et un PBIAS de -2 %, témoignant d'une bonne capacité du modèle à reproduire les régimes hydrologiques du bassin. L'étude propose une approche intégrée pour la préservation durable des ressources en eau et souligne la nécessité de mettre en place un réseau hydro-climatique dense et performant afin d'assurer un suivi régulier et rigoureux des ressources en eau dans le bassin de la rivière Itimbiri.

Mots-clés: Modélisation hydrologique, Ressources en eau, Modèle WEAP et Bassin d'Itimbiri.

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1. Introduction

The catchment area of the Itimbiri river, located in the north-east of the Democratic Republic of Congo, is an essential hydrological resource for local communities and the surrounding ecosystems (Omassombo, 2011). This basin, characterised by physiographic and climatic diversity, presents major challenges in terms of water resource management, particularly in the face of climate and water change, the result of conflicts linked to the migration of Mbororo herders from Sahelian countries (Tshimanga et al., 2022). The latter, in search of water for their herds, exert additional pressure on water resources, exacerbating conflicts of use and management challenges.

In addition, the presence of peatland forests in certain sub-units of the Itimbiri catchment is an essential ecological factor. These wetlands play a vital role in balancing the climate and regulating hydrological flows (Bwangoy, 2010). Their preservation is strategic for maintaining ecosystem functions and strengthening resilience in the face of climate change (Dargie et al., 2017).

However, water resource management in the Itimbiri river basin faces a number of challenges. The availability of hydro-climatic data remains limited due to the lack of ground measurement stations, which complicates the accurate estimation of flows and the planning of management strategies. In addition, the effects of climate change are increasing the uncertainties associated with hydrological regimes.

In this context, it is becoming imperative to use reliable hydrological modelling tools to gain a better understanding of the dynamics of water resources and to strengthen adaptation strategies. The work of Tshimanga et al. (2011) has highlighted the need for rigorous calibration of hydrological models, given the high variability of climatic and physiographic conditions. However, few studies have focused specifically on the Itimbiri river basin, leaving a gap in the scientific literature and a lack of understanding of the hydrological dynamics of this region.

The aim of this study is to model the hydrological dynamics and assess the components of the water balance in the Itimbiri river catchment using the Water Evaluation and Planning (WEAP) model. The main objective is to establish a hydrological model in order to accurately simulate flow regimes, estimate the main components of the water balance (precipitation, evapotranspiration, infiltration, surface runoff and groundwater recharge), with a view to developing recommendations for optimised management of hydrological resources in the Itimbiri river catchment..

2. Materials and Methods

2.1. Study area

Figures 1, below show this investigation took place in the Bumba territory in the Mongala province of the Democratic Republic of Congo. The Mongala province is part of the new provinces that emerged from the former Equateur province. It covers a geographical area of 56,252 km². It is bounded: to the north by the Nord-Ubangi province, to the south by the Tshuapa and Equateur provinces; to the east by the Bas-Uele, Nord Oubangui and Tshopo provinces, and to the west by the Equateur and Sud-Ubangi provinces (OSFAC, 2023). Below is the map showing the location of the Itimbiri River water she.

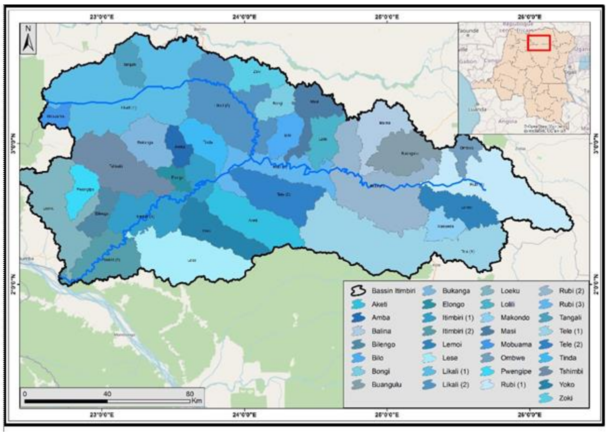

Figure 1. Location of the Study Area

2.2. Data collection

Gridded climate data from the CRU (Climatic Research Unit) source at 0.5-degree resolution, including precipitation as well as maximum, minimum and mean temperatures Harris et al. (2020), were used in the WEAP model. In situ hydrological data, in particular flows observed at the Aketi hydrometric station over the period 1951-1977, were also incorporated. In addition, spatial attributes, including the boundaries of 32 hydrological sub-units and the hydrographical network, taken from CRREBaC's CBCIS hydrological information system (www.crrebac.org), were used to configure the model.

2.2.1. *Development of the hydrological model*

Several models have been explored for modelling the water balance in the Congo Basin (Tshimanga, 2022). However, this study chose the WEAP model for its conceptual simplicity and its ability to represent the overall functioning of the water cycle at the scale of a catchment, based on climatic variables such as precipitation (P), temperature (T) and potential evapotranspiration (ETP). WEAP offers particular flexibility in the management of interactions between surface resources and groundwater. When a suitable link is established between a sub-basin and a groundwater reservoir, and an empirical water balance equation is defined, deep percolation can be transferred either to a surface water body in the form of base flow, or directly to groundwater storage (SEI, 2015; SEI, 2016). This approach makes it possible to integrate the complex dynamics of the hydrological cycle in a coherent manner, facilitating a better assessment of water flows in the basin under study. The empirical water balance adopted and the conceptual scheme based on the soil moisture method (figure 2) form the basis of this modelling.

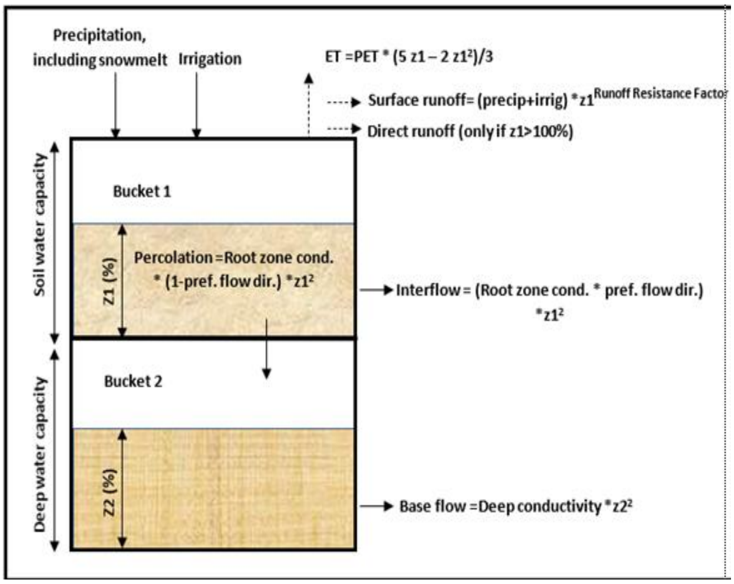

Figure 2. Conceptual framework and equations integrated into the soil moisture model (adapted from Sieber et al., 2011).

2.3. Data analysis

2.3.1. Hydrological modelling with WEAP

Figures 3, below show the soil moisture method in WEAP is used for this study, incorporating seven parameters related to soil type and land use. The parameters involved are Crop Coefficient, Kc (-); Deep Layer Capacity, CCI (mm); Surface Layer Capacity, CCS (mm); Superficial Conductivity, CS (mm/month); Deep Conductivity, CP (mm/month); Preferred Direction of Flow, DPE (-); Initial Upper Soil Storage, Z1 (%); Initial Deep Soil Storage, Z2 (%); Leaf Area Itdex, IF (-).

The iterative calibration procedure was used to adapt the parameters precisely in order to guarantee the accuracy and reliability of the hydrological simulations. This manual modification was carried out on a monthly scale, using a trial-and-error method for all periods of data available at the Aketi station.

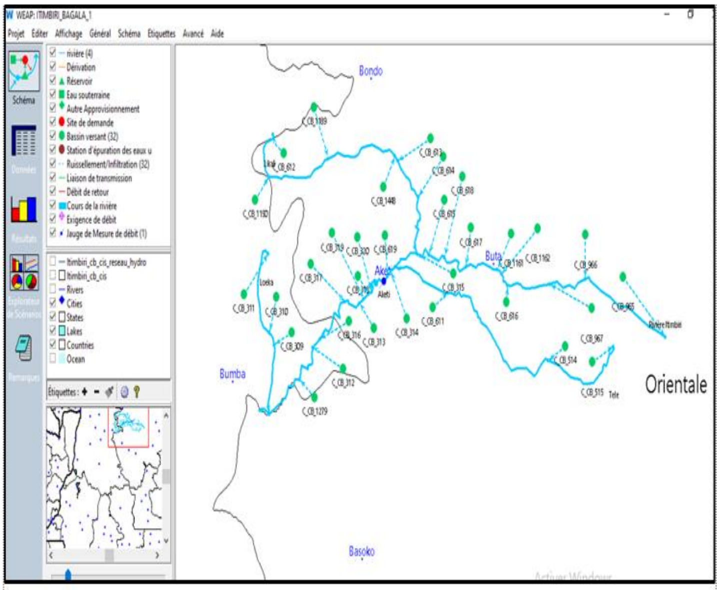

Figure 3. WEAP interface and its different parts

2.3.2. Evaluation of model performance

The main statistical analyses used are based on the performance criteria of a hydrological model. They can be simple (ratio of simulated and observed volumes of water) or generally based on statistical methods designed to standardise the comparison between simulation or forecast results and observations. The performance of the model is assessed using criteria including the Nash-Suttclif efficiency coefficient (NSE), the coefficient of determination (R2) and the percentage bias (PBIAS) and the efficiency coefficient, in particular SqrtNSE (square root of the Nash-Sutcliffe efficiency). These criteria are described in table II below.

The following equations express each statistical parameter respectively:

$$R^2 = \frac{(\Sigma[x_i - \bar{x}][y_i - \bar{y}])^2}{\Sigma(x_i - \bar{x})^2 \, \Sigma(y_i - \bar{y})^2} \quad \text{Eq. (1)}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(x_i - y_i)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad \text{Eq. (2)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}} \quad \text{Eq. (3)}$$

$$PBIAS = \frac{\sum_{i=1}^{n}(x_i - y_i) * 100}{\sum_{i=1}^{n}(x_i)} \quad \text{Eq. (4)}$$

Where Xi, Yi; X‾, Y‾; and n denote the ith measured monthly flow data, the ith simulated monthly flow data, the mean of the measured monthly flow data, the mean of the simulated monthly flow data and the total number of observation data, respectively. Moriasi et al (2007) describe the PBIAS (%) as an error index that evaluates the average deviation of the volume of simulated mean monthly flows from the observed data. In this study, model performance was considered to be within ±5%.

The efficiency coefficient, in particular SqrtNSE (square root of the Nash-Sutcliffe efficiency), is a key indicator in the evaluation of hydrological models using WEAP. It quantifies the model's ability to reproduce observed variations in flow or other hydrological variables. The choice of this coefficient depends on the purpose of the modelling and the characteristics of the data (Tshimanga et al., 2011a; Tshimanga, 2012). The formula for the efficiency coefficient, in particular SqrtNSE (square root of the Nash-Sutcliffe efficiency), is given by:

$$\text{SqrtNSE} = 1 - \frac{\sum_{t=1}^{N}(Q\,o\,b\,s,t - Q\,mod\,,t)2}{(Q\,o\,b\,s,t - \bar{Q}\,ob\,s\,)2} \quad \text{Eq. (5)}$$

Where:

Q o b s, t = observed flow at time

Q mod, t= modelled flow at time

Q‾o b s = mean of observed flows

N = number of observations

Table I. Performance of the hydrological model

Mention	NSE &(SqrtNSE)	PBIAS	R^2
Very good	$0.75 \leq NSE \leq 1.00$	$PBIAS \leq 10$	$0.75 \leq R^2 \leq 1.00$
Good	$0.65 \leq NSE \leq 0.75$	$10 \leq PBIAS \leq 15$	$0.65 \leq R^2 \leq 0.75$
Satisfactory	$0.50 \leq NSE \leq 0.65$	$15 \leq PBIAS \leq 25$	$0.50 \leq R^2 \leq 0.65$
Unsatisfactory	$NSE \leq 0.50$	$PBIAS \geq 25$	$R^2 \leq 0.50$

Source : (Semsar, 1995).

3. Resultats

3.1. Hydrological model

3.1.1. Estimation of Calibration Parameters

Table II shows the values of land use parameters estimated after calibration of the WEAP model in the Itimbiri river catchment. The result demonstrates the importance of precision in the adjustments to guarantee a reliable hydrological simulation. Land use parameters such as cultural coefficient (Kc), deep layer capacity, CCI (mm), surface layer capacity, CCS (mm), surface conductivity, CS (mm/month), preferred direction of flow, DPE (-) and leaf area index, IF (-) for the 32 Itimbiri sub-basins show relative homogeneity in vegetation distribution, moderate water retention, moderate soil permeability, hydrological stability and moderate plant density.

Table II. Parameters estimated after calibration of the WEAP model

Variables	Critèrion	Default value	Parameters estimated by sub-basin		
			Maximals	Minimals	Averages
Cultivation coefficient, Kc (-)	≥ 0	1	1.25	0.4	0.8
Deep layer capacitance, CCI (mm)	≥ 0	1000	2500	300	2650
Surface layer capacitance, CCS (mm)	≥ 0	100	1800	200	1000
Superficial conductivity, CS (mm/month)	≥ 0.1	20	59	20	39.5
Deep Conductivity, CP (mm/month)	≥ 0.1	20	30	11	20.5
Preferred Direction of Runoff, DPE (-)	0 – 1	0.15	0.9	0.5	0.7
Initial Top Soil Storage, Z1 (%)	0 - 100	30	0.2	0.6	0.4
Initial Deep Soil Storage, Z2 (%)	0 - 100	30	65	30	47.5
Leaf Area Index, IF (-)	0 - 100	2	100	30	65

Source : (Authors, 2025)

3.2. Hydrological simulations in the Itimbiri basin

The figures 4, 5 and 6 below show the simulations obtained after calibration of the model in the Itimbiri river catchment at the Aketi station for the period 1951 to 1977. Overall, the forecasts stand out with an NSE of 0.65 and a coefficient of determination (R2) of 0.66. Despite a moderate underestimate (-2% of PBIAS), the monthly averages of the time series flows show an NSE of 0.93 and a coefficient of determination (R2) of 0.96

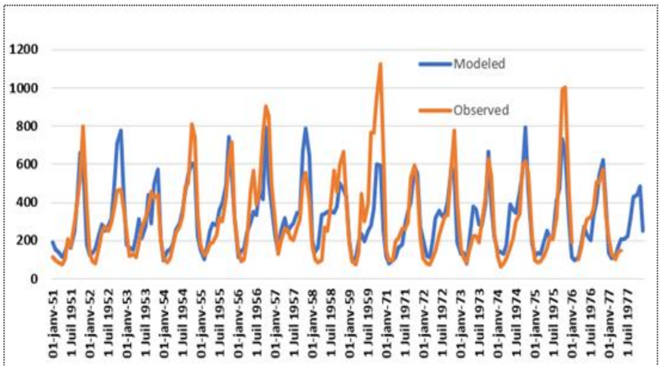

Figure 4. Hydrological simulations at the Aketi station (Authors, 2025)

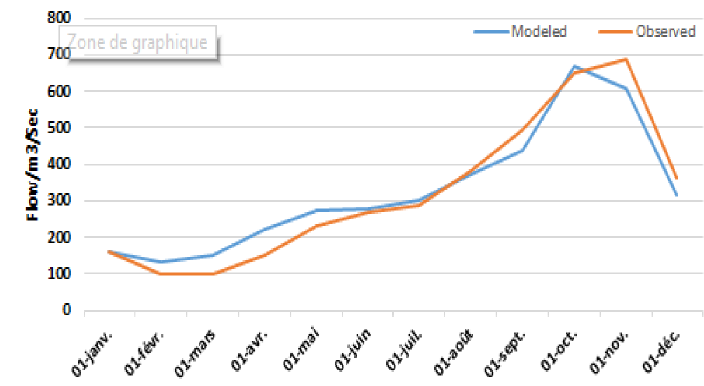

Figure 5. Long-term monthly averages at the Aketi station (Authors, 2025)

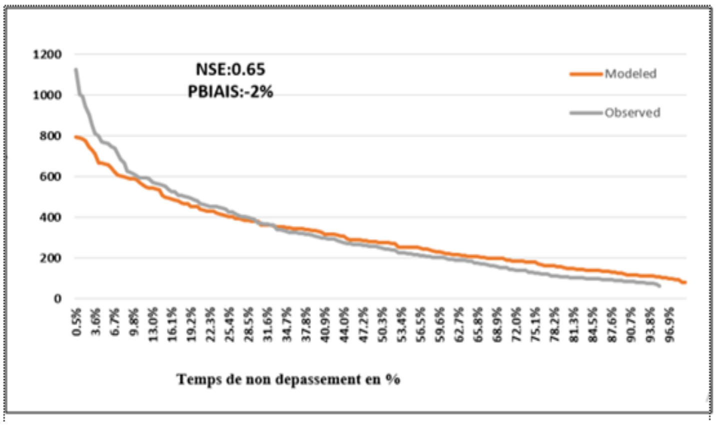

Figure 6. Unclassified flow curvein % (Authors, 2025)

3.3. Performance evaluation

Table III shows the average statistics for the hydrological model performance indicators for the Itimbiri basin as a whole. The validation of the model aims to assess the reliability of the calibrated land-use parameters at various periods, with varying environmental conditions (Abera Abdi et al., 2021; Datok, et al., 2022). The search for a common period to calibrate and validate the model in all the hydrological units available in the gauging station was complicated by the absence of hydrometric stations in the hydrographical network of the Itimbiri basin. Historical data available at the Aketi gauging site were therefore used (Tshimanga et al., 2011).

The performance of the model at the Aketi hydrometric station is evaluated with NSE of 0.65, SqrtNSE of 0.71 R2 of 0.75 and (PBIAS) -2%. From the above, the model is very good.

Table III. Performance of the hydrological model

	Mention	NSE	(SqrtNSE)	PBIAS (%)	R2
Calibration (1951-1977)	Good	**0.65**	**0.71**	**−2**	**0.75**
Long-term monthly average (1951-1977)	Very good	**0.95**	**0.93**	**-2.1**	**0.97**

Source: (Authors, 2025)

3.4. Evaluation of the components of the hydrological balance

Table IV shows the long-term monthly breakdown of the components of the hydrological balance for the Itimbiri river catchment as a whole for the calibration period (P: rainfall, DHS: decrease in soil moisture, ETP: evapotranspiration, AHS: increase in soil moisture, R: surface runoff; EI: intermediate runoff, and EB: base runoff).

Table IV. Monthly distribution of water balance components in mm

	P	DHS	ETP	AHS	EI	R	EB
Jan	36.8	110.7	-135.8	0.0	-5.1	-4.0	-2.4
Feb	68.0	50.0	-109.2	0.0	-2.5	-4.1	-2.1
Mar	127.3	9.6	-115.9	-10.5	-2.2	-6.4	-1.9
Apr	166.1	1.7	-116.4	-36.5	-3.2	-10.1	-1.7
May	183.9	1.1	-125.9	-39.2	-4.0	-14.5	-1.5
Jun	145.6	6.3	-122.1	-10.9	-4.5	-13.1	-1.3
Jul	156.1	3.7	-127.2	-12.1	-4.7	-14.7	-1.2
Aug	188.2	1.5	-137.1	-26.7	-5.1	-19.7	-1.1
Sep	192.3	3.6	-144.0	-22.3	-5.7	-22.9	-1.1
Oct	224.0	0.0	-53.2	-125.3	-4.4	-40.1	-1.2
Nov	133.1	0.3	-55.4	-37.2	-5.8	-33.3	-1.8
Dec	59.8	125.0	-161.5	0.0	-8.7	-12.5	-2.0
Somme	1681.3	313.3	-1403.6	-320.7	-55.9	-195.4	-19.2
Moyenne	140.1	26.1	-117.0	-26.7	-4.7	-16.3	-1.6
Pourcentage (%)	47.2	8.8	39.4	9.0	1.6	5.5	0.5

Source: (Authors, 2025)

4. Discussion

4.1 Discussion of the results of the Estimation of Calibration Parameters

a) Discussion of Results Regarding the Itimbiri River Peatland Area Structured Around Different Land Use Parameters (Kc, CCI, CCS, CS, CP, DPE, and IF) and Insights from Scientific Literature

Cultural Coefficient (Kc) The results show a Kc ranging from 0.4 to 1.25 in table II, with an average of 0.8. According to Hans Joosten (2021), this coefficient is crucial for estimating evapotranspiration in peatlands, where values can reach 1.4 to 1.6 due to the proximity of the water table. The observed values suggest that the area may experience periods of water stress, which could influence plant growth and, consequently, the seasonal variability of Kc, as highlighted by Lafleur et al. (2005). The presence of environmental stresses, such as intermittent droughts, may also reduce this coefficient, in line with observations by (Dimitrov et al., 2011).

Deep Layer Capacity (CCI) The CCI varies from 300 mm to 2650 mm, with an average of 1000 mm. This wide range is consistent with studies by Price and Whitehead (2001), which report that CCI values in peatlands can be significant. High storage capacity is essential for regulating discharge and maintaining soil moisture, as emphasized by Norberg (2018). Variability can be attributed to the depth of the peat and its degree of decomposition, in accordance with findings by Lafleur et al. (2005).

Surface Layer Capacity (CCS) CCS values, ranging from 200 mm to 1000 mm, are relatively low compared to expectations in wet environments. According to Holden. (2005), the composition of peat, rich in organic matter, should provide high water retention capacity. The results suggest that surface conditions may be less favorable, possibly due to erosion or inappropriate management practices, which could reduce CCS compared to expected values in healthy peatlands.

Surface Conductivity (CS) With CS values between 20 and 59 mm/month and an average of 39.5 mm/month, these results indicate variability consistent with observations by Baird et al. (2008). Anisotropy theory suggests that conductivity may be higher horizontally, which could explain the variations observed in this context. The effects of peat decomposition and microtopography, as noted by Whittington & Price (2006), may also influence these values.

Deep Conductivity (CP) CP values range from 11 to 30 mm/month, with an average of 20.5 mm/month. This reflects moderate drainage capacity and aligns with the work of Holden & Burt (2003), which indicates that CP is affected by the saturation level of the peat. A high CP could indicate advanced decomposition, as suggested by Clymo & Hayward. (1982), highlighting the importance of proper management to maintain peatland health.

Preferred Flow Direction (DPE) The DPE ranges from 0.15 to 0.9, with an average of 0.5, indicating anisotropy in water flows, confirming the findings of Holden (2009). Microtopography and soil structures influence this direction, and climatic events can lead to temporary modifications of the DPE, as noted by Baird & Gaffney. (2000). Understanding the DPE is essential for modeling nutrient and water transport.

Leaf Index (IF) IF values range from 30 to 100, with an average of 65. This variability, linked to microtopography and floristic diversity, is consistent with observations by Belyea & Clymo (2001). An increase in IF is often associated with higher evapotranspiration, underscoring the importance of IF in modeling water balances, as suggested by Bubier et al. (1998).

b) Discussion of Results Regarding Manual Calibration Approach (Hydrological Simulation)

The variations observed in the parameters between the different sub-basins (table I and III) reflect the diversity of physiographic and climatic conditions in the basin (Tshimanga et al., 2022). This heterogeneity demonstrates the need for precise parameter adjustment to obtain reliable hydrological simulations.

In this study, the manual trial-and-error calibration approach was guided by prior knowledge of the environment, acquired through field investigations and analysis of land-use maps of the basin. Although the calibration values obtained do not always perfectly reflect the reality of the physiography and soil types of the basin, they have enabled satisfactory calibration and coherent simulations to be obtained. These results constitute a solid, but perfectible, basis for future studies. The integration of additional data from field measurement campaigns could refine these parameters and further strengthen the robustness of the hydrological simulations.

These results also raise questions about the implications for the development of calibration methods in the Congo Basin in general and in the Itimbiri Basin in particular. This basin presents challenges linked to the scarcity of hydrological data and the complexity of its ecosystems, particularly the vast areas of forest and peatland. The manual approach used, although effective, reveals the limitations of a method dependent on the user's experience. Future studies in the Itimbiri basin should address the calibration approach, which incorporates automated optimization algorithms and uncertainty estimation (Kabuya et al., 2022; Tshimanga et al., 2011). Coupled with data from satellite observation, these methods would make it possible to improve model accuracy while reducing the uncertainties associated with modelling the components of the hydrological process.

4.2. Discussion of the results of hydrological simulations in the Itimbiri basin

The hydrological simulations carried out in the Itimbiri basin, as illustrated in Figures 4, 5 and 6, show interesting results after calibration of the model at the Aketi station. The Nash-Sutcliffe coefficient (NSE) of 0.65 and the coefficient of determination (R^2) of 0.66 indicate that the model has an acceptable performance for simulating flows, in line with the standards established in the literature (Munzimi et al., 2019). These values suggest that the model is capable of reproducing observed hydrological trends, although there is still room for improvement.

It is important to note the moderate underestimation of flows, with a PBIAS of -2% and -3.2% in the time series. Such underestimation could be attributed to factors such as uncertainties in the input climate data (CRU) or simplifications in the representations of hydrological processes (Tshimanga et al., 2011).

The monthly mean flows, with an NSE of 0.93 and an R^2 of 0.96, demonstrate the model's excellent ability to explain the variance in observed flows. These results are encouraging and suggest that the model can be used for reliable hydrological forecasts, which are an important aspect of water resource management in the current context of climate change (Aloysius et al., 2017).

4.3. Discussion of the hydrological balance results

The hydrological balance of the Itimbiri river catchment shows a dynamic characterized by a predominance of outflow components over inflows. Average annual rainfall of 1,681.3 mm is the main source of water input, while potential evapotranspiration (PET), at 1,403.6 mm, represents a major loss, accounting for 39.4% of the overall balance. This evapotranspiration, typical of tropical regions, confirms the climatic variability exerted on water resources, limiting soil moisture and runoff. The low intermediate and base flows reflect the reduced capacity of aquifers to sustainably supply water courses, probably due to a geology that does not favour infiltration. This dynamic is therefore a significant indicator of the hydrological vulnerability of the Itimbiri catchment to climatic and anthropogenic pressures.

The waves of migration linked to the arrival of Mbororo herders in the north-eastern part of the DRC and the climatic challenges demonstrate the importance of water resource management strategies in the Itimbiri catchment (Tshimanga et al., 2022). Under these conditions, the conservation of peatland sub-basins, which are essential for hydrological regulation, can help to strengthen resilience in the face of climate and migration challenges. But it is also recommended that a dense hydro-climatic monitoring system be set up in this basin to ensure sustainable and effective management of water resources.

5. Conclusion

This study has enabled the hydrological dynamics of the Itimbiri catchment to be explored and better understood. The variations observed between sub-catchments show the extent to which physiographic and climatic conditions influence hydrological behaviour. Thanks to manual calibration guided by a good knowledge of the terrain and land-use maps, the simulations produced acceptable results, with satisfactory performance on observed flows. The hydrological balance revealed a strong predominance of evapotranspiration, limiting base flows, which means that the basin is hydrologically vulnerable. These findings demonstrate the need to implement appropriate strategies for the sustainable management of water resources in a context of climate change and anthropogenic pressures.

Recommendations

The study highlights the need to protect forest areas, particularly peatlands, and proposes sustainable agricultural practices as well as the development of a dense hydro-climatic monitoring network to facilitate continuous monitoring of critical hydrological variables.

It also recommends incorporating the results into water resource management strategies for the Congo Basin. Future research should examine the links between land use and hydrology in other peatland regions and assess climate change scenarios in relation to the model results.

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Conflicts of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interes.

Compliance with ethical rules

The authors declare that they have no conflicts of interest. The field research posed no threat to communities or protected species. No informal or legal organisation played a key role in the design of the study, the collection and analysis of the data, or in deciding on the final outcome of the study. The decision to prepare the manuscript and publish it was taken solely by the authors.

Author Contributions

A. B.M: Designed and drafted the manuscript, collected and analyzed the data.

M.T. R: Supervised the study and validated the final version.

L.N.C: Co-supervised the study, participated in statistical analysis, and co-validated the final version.

N.N.L: Contributed to data integration, WEAP model calibration, and hydrological model validation.

K K N: Participated in the installation of WEAP software and watershed characterization. NMP: Participated in the selection of the peatland area, interpretation of results, and manuscript review.

A. L. Y: Participated in monitoring result analyses in the context of climate change.

K.E.S: Participated in data collection in the peatland area.

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