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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, using WEAP model

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Abstract

This research examines the degradation of peatlands caused by climate change, which disrupts their capacity to store water and carbon, potentially leading to increased greenhouse gas emissions. The objective is to create a hydrological model for the Itimbiri River Basin, establishing links between land uses and hydrological parameters. The model demonstrates satisfactory results, with NSE indices ranging from 0.63 to 0.71, R^2 from 0.7 to 0.76, and PBIAS from -3.1% to 9.3%. Thus, the study provides a comprehensive approach for the sustainable preservation of water resources and peatland ecosystems.

Keywords: Land use, Hydrological parameters, Peatlands ('tourbiere' in French), WEAP Modelling, Itimbiri Basin

Estimation de l'influence de l'utilisation des terres sur les paramètres hydrologiques des tourbières du bassin de la rivière Itimbiri, au nord-est du bassin du Congo, à l'aide du modèle WEAP

Résumé

Cette recherche examine la dégradation des tourbières causée par le changement climatique, qui perturbe leur capacité à stocker l'eau et le carbone, ce qui pourrait entraîner une augmentation des émissions de gaz à effet de serre. L'objectif est de créer un modèle hydrologique pour le bassin de la rivière Itimbiri, établissant des liens entre l'utilisation des terres et les paramètres hydrologiques. Le modèle présente des résultats satisfaisants, avec des indices NSE compris entre 0,63 et 0,71, un R^2 compris entre 0,7 et 0,76 et un PBIAS compris entre -3,1 % et 9,3 %. Ainsi, l'étude propose une approche globale pour la préservation durable des ressources en eau et des écosystèmes de tourbières.

Mots clés : Utilisation des terres, paramètres hydrologiques, tourbières, modélisation WEAP, bassin d'Itimbiri.

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1.Introduction

The Water Evaluation And Planning tool (WEAP) is a model featuring hydrological processes and the impact of land-use on hydrological parameters. This methodological tool has been recently adopted to develop an approach for assessing the dynamics of peatland areas. This approach has been essential for developing an integrated watershed management strategy for peatlands, allowing for the design of sustainable management practices for their water resources and ecosystems, particularly concerning evapotranspiration and the maintenance of water levels (Beighley, 2011; Chishugi & Alemaw, 2009).

Land use is a key factor influencing the hydrological parameters of sensitive ecosystems, especially peatland areas. These ecosystems play a crucial role in water and carbon storage, thereby contributing to climate regulation and biodiversity preservation. However, they are particularly vulnerable to changes in land use and the impacts of climate change (Angessa et al., 2021). As wetland ecosystems, peatlands are essential for regulating hydrological cycles. They act as sponges, absorbing and storing water, which helps maintain water levels in surrounding rivers and aquifers. However, changes in land use, such as drainage for agriculture or urbanization, disrupt this hydrological balance, leading to a decrease in water storage capacity and an increase in greenhouse gas emissions (Baghdadli, 2014; Dargie, 2017).

This study aims to estimate the influence of land use on the hydrological parameters of the peatlands located within the Itimbiri River Basin, establishing quantitative links between different land uses and the hydrological parameters of this area. These hydrological, ecological, and land use aspects have provided a comprehensive understanding of the functioning of the Itimbiri River Basin, with results that can be applied to other basins (Angessa and Aloysius, 2021, Tshimanga, R. M., & Hughes. (2012).).

By analyzing the interactions between different forms of land use and hydrological responses, we hope to provide crucial information for the sustainable management of water resources and the conservation of the peatlands in this watershed. The results of this research will contribute to a better understanding of the hydrological dynamics in the Itimbiri River Basin and to the development of adaptation strategies in response to the challenges posed by climate change and anthropogenic pressures.

2. Materials and Methods

2.1. Study area

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 and Tshopo Provinces, and to the west by the Equateur and Sud-Ubangi provinces (OSFAC, 2023).

The Itimbiri River Basin is located in the northeastern part of the Congo Basin, and is experiencing a degradation of its peatlands due to urbanization, agriculture, and other anthropogenic activities has significant consequences for local hydrology (Tshimanga, 2012; UNEP, 2011). The Itimbiri River Basin is primarily composed of the Rubi River, which flows through the territories of Poko, Bambesa, Buta, and Aketi, where it converges with the Tele River and the Likati River to form the Itimbiri River. The Itimbiri River discharges into the Congo River approximately 15 km from Bumba (Omasombo, 2011; 2014; Molua, 2015).

The map below shows the location of the Itimbiri River Basin.

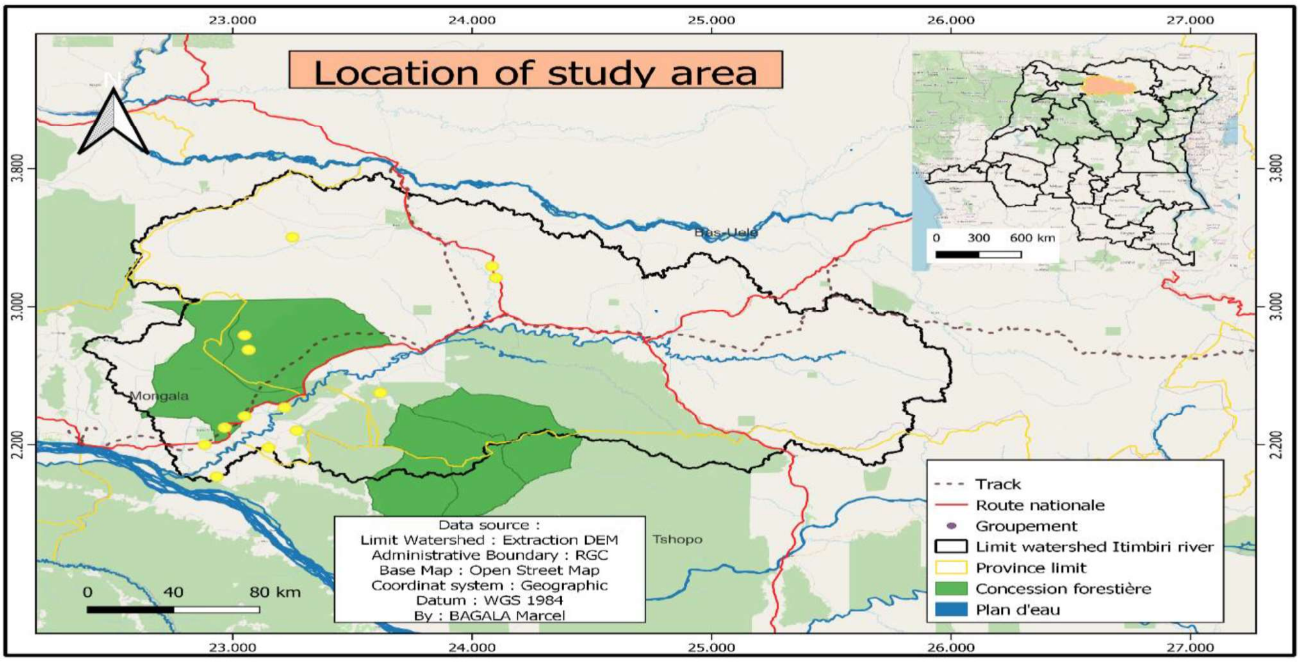


Figure 1: Location of the study area

During the Belgian colonial period, the Itimbiri basin was the site of expansion by concessionary companies such as Abir and Anversoise, which exploited rubber, ivory, and other regional resources (Geheugen Collectief, 2021). This frequently negatively impacted local communities, leading to exploitation and coerced labor.

After independence in 1960, the province continued to play an important economic role, particularly through timber extraction along the Itimbiri and its tributaries. However, the lack of oversight and reinvestment has led to environmental degradation and social conflicts. Today, the Itimbiri basin is subject to initiatives aimed at more sustainable natural resource management, involving local communities. Nevertheless, significant obstacles remain regarding economic development, environmental preservation, and social stability in this remote region of the DRC (Geheugen Collectief, 2021).

2.2. Data collected

The data utilized at this stage includes hydrometeorological measurements, such as monthly time series of flow, precipitation, and temperature, collected from the relevant authorities in the Democratic Republic of Congo and the region. Additionally, data from other sources, including the 0.5-degree spatial resolution climate data grid from the Climate Research Unit (CRU) (Harris et al., 2020; University of East Anglia Climatic Research Unit et al., 2021), has been incorporated.

2.3. Data analysis

This research employs the WEAP model to support sustainable management of water resources in the Itimbiri River catchment. WEAP integrates various water cycle components, addressing surface and groundwater needs across sectors like agriculture and industry (Pouget et al., 2021). It simulates scenarios related to water demand, management policies, and climate change, assessing sustainability at the basin level (Kuchement, 1971; Beven, 1989; Spence et al., 2004; Kampf et al., 2007). The model aids in decision-making for water allocation and infrastructure planning while enabling local stakeholders to improve their skills in integrated water management (Pouget et al., 2021).

2.3.1. Hydro-climatic data for hydrological simulation

The data used includes hydrometeorological measurements, such as monthly series of flow, rainfall, and temperature, collected from the relevant authorities in the Democratic Republic of the Congo. Additional data, such as that from the Climate Research Unit (CRU) with a spatial resolution of 0.5 degrees, have also been integrated. Hydrometric data from an in-situ station at Aketi were used in the WEAP model for the entire Itimbiri basin, as this station is the only one available in the region to cover the 32 sub-basins. Climatic data were extracted for the Itimbiri basin, subdivided into 32 sub-units, with the aim of extracting the average data series for the period 1957-1977. A table summarizes the data used in the research.

2.3.2 Development of the hydrological model

If a suitable link is established between a sub-basin node and a groundwater node, and the empirical water balance equation is determined, deep percolation in a sub-basin can be transferred to a surface water body as baseflow or directly to groundwater storage (SEI, 2016; Stockholm Environment Institute, 2016; Stockholm Environment Institute (SEI), 2015). The resulting empirical water balance (Equation 1) and the conceptual scheme of the soil moisture method (Figure 2) are therefore as follows.

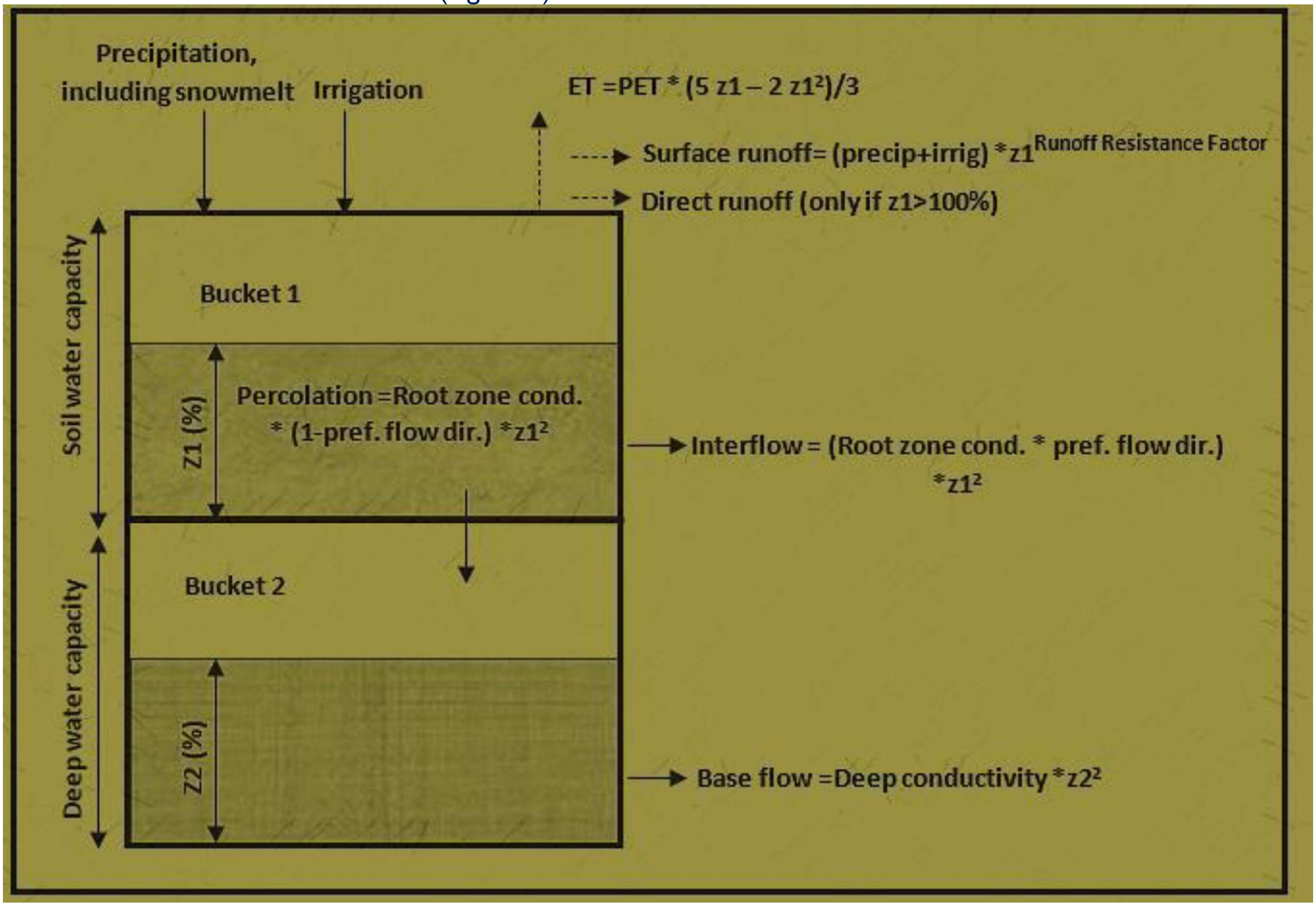


Figure 2. Conceptual framework and equations incorporated in the soil moisture model (adapted after Sieber et al., 2011)

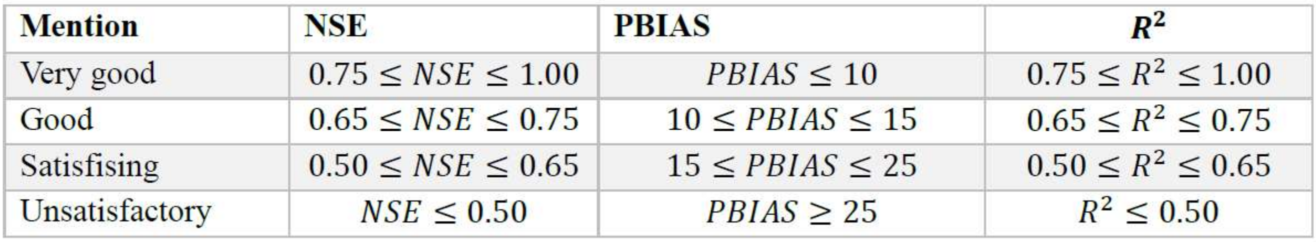
2.3.3 Calibration of hydrological modelling with WEAP

The iterative calibration procedure is employed to develop a WEAP model that accurately represents the hydrological functioning of the Itimbiri River catchment, a crucial step for analyzing water management scenarios (Pouget et al., 2021). Hydrometric data from relevant stations were utilized to calibrate the model, aiming to establish a set of parameters that characterize the hydrological behavior of the Congo Basin. A manual trial-and-error method was applied to align simulated flows with observed flows. The soil moisture method in WEAP incorporates seven parameters related to soil type and land use, including the cultivation coefficient (Kc), the capacity of the upper soil layer (CCS), and the capacity of the lower soil layer.

2.4. Statistical analysis and assessment of model performance

This study focuses on the statistical analyses related to the performance criteria of hydrological models. These analyses can be straightforward, such as the ratio of simulated to observed water volumes, or involve more complex statistical methods for standardizing comparisons between simulation results and observations. Key performance criteria, including those established by Nash and Sutcliffe (1970), Beven and Binley (1992), Franchini et al. (1996), and Siebert (1999), are detailed. There is no universal criterion for evaluating model performance; however, it is advisable to compare calculated flows with observed flows. Model quality, robustness, and reliability are interpreted based on Miossec (2004). Model sensitivity is assessed using various hydrological criteria, including the Nash criterion, correlation coefficient R, coefficient of determination R^2, mean square error (NSE), and root mean square error (RMSE), which are summarized in Table 1.

Table 1. Statistical performance criteria



Mention	NSE	PBIAS	R^2
Very good	$0.75 \leq NSE \leq 1.00$	$PBIAS \leq 10$	$0.75 \leq R^2 \leq 1.00$
Good	$0.65 \leq NSE \leq 0.75$	$10 \leq PBIAS \leq 15$	$0.65 \leq R^2 \leq 0.75$
Satisfising	$0.50 \leq NSE \leq 0.65$	$15 \leq PBIAS \leq 25$	$0.50 \leq R^2 \leq 0.65$
Unsatisfactory	$NSE \leq 0.50$	$PBIAS \geq 25$	$R^2 \leq 0.50$

Source: Semsar (1999)

3. Results and Discussion

3.1. Setting up the hydrological model

The conclusions of this chapter are based on the hydrological modelling of the entire Itimbiri basin across the 32 sub-basins. The land use parameters for calibrating the model are estimated, the hydrological simulations in time series and in percentage of passage time are presented, as well as the statistical tests to validate the hydrological model.

3.2 Calibration of the hydrological model

The results of the calibration procedure, along with the boundary values of estimated parameters for each sub-basin, are essential for accurately adjusting parameters to ensure the reliability of hydrological simulations. This manual adjustment, conducted on a monthly scale using a trial-and-error method, covered the period from 1951 to 1977 based on data from the Aketi station. Key land use criteria, including crop coefficient (Kc), deep layer capacity (CCI in mm), surface layer capacity (CCS in mm), surface conductivity (CS in mm/month), preferred flow direction (DPE), and leaf area index (IF), are detailed for the 32 sub-basins of Itimbiri.

3.3. Hydrological simulations

The results of hydrological simulations in the Itimbiri basin are presented using the Aketi station and the curves of monthly averages of time series flows classified in percentage of time of non-exceedance of seven (7) land use parameters, including plant coefficient (KC), deep layer capacity, CCI (mm), superficial soil layer capacity (CCS), superficial soil conductivity (CS), preferred direction of flow (DPE), and leaf area index (IF) calibrated and validated in the 32 hydrological sub-units.

3.3.1. Hydrological simulations with crop coefficient Kc (-)

Figure 5 below presents the results illustrating the situation of thirty-two (32) hydrological sub-units of the Itimbiri river basin.

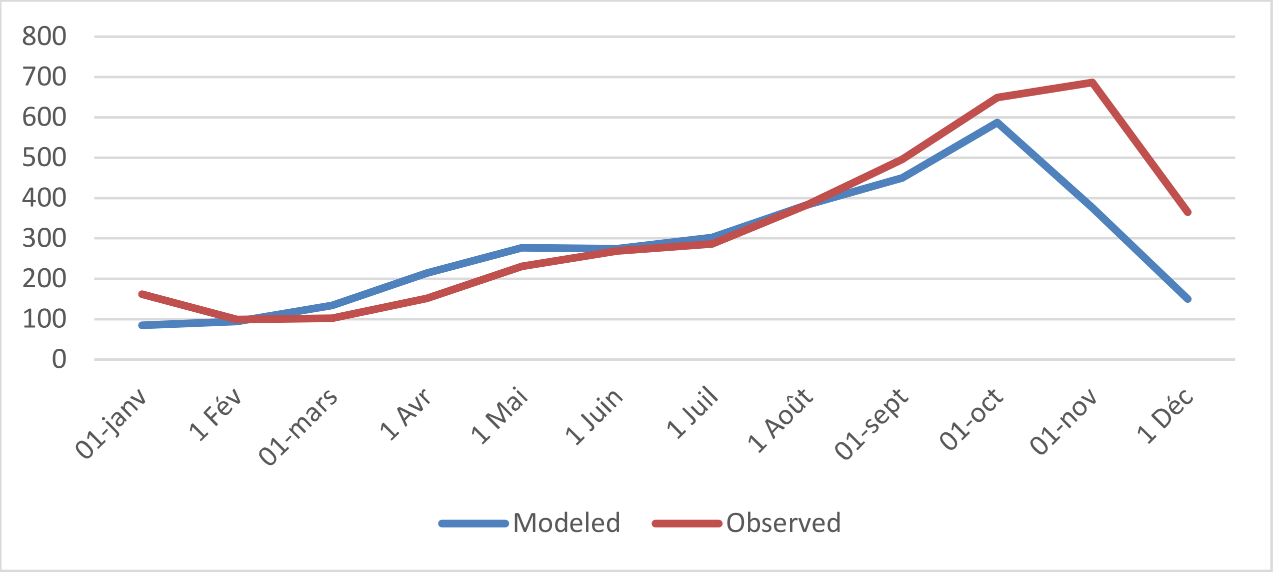


Figure 5. Hydrological simulations with crop coefficient Kc (-)

The cultural coefficient Kc (-) is present, resulting in an NSE of 0.71 and an R² of 0.73. Although the model's performance is justified by an underestimate (-3.3% of PBIAIS), this demonstrates a significant match and the model's ability to explain the observed variance, even though the simulated flows are underestimated compared with the observed flows due to the low-water period. The crop coefficient (KC) found estimates crop evapotranspiration (ETc) and influences the environmental characteristics of the peatland ecosystem, including species, variety, and growth cycle (Allen et al., 1998), canopy height (Doorenbos & Pruitt, 1977), planting density, and soil cover (Katerji & Hoorn, 1992), while its environmental factors include climate (temperature, humidity, wind, radiation) (Allen et al., 1998), soil characteristics (texture, moisture, salinity) (Doorenbos & Kassam, 1979), and management methods (irrigation, fertilisation, tillage) (Allen et al., 1998), which contribute to the hydrological process in the Itimbiri river catchment.

3.3.2. Hydrological simulations with deep layer capacity (DLC)

The evaluation of hydrological model performance indicates significant results for each land use parameter is shown in Figure 6.

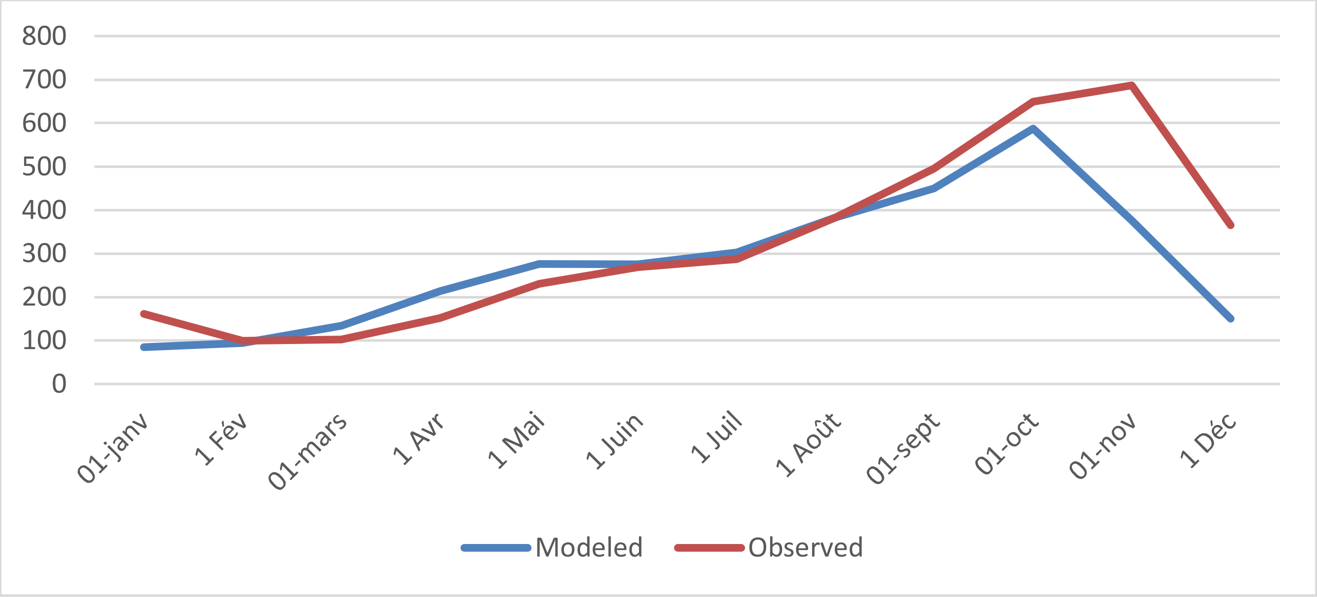


Figure 6. Hydrological simulations with deep layer capacity (CCl)

Specifically, the capacity of the deep layer (CCI) shows high efficiency, with an NSE of 0.63 and an R² of 0.74, reflecting a strong correlation between model simulations and observations. The PBIAS of -9.3% suggests a slight tendency to overestimate forecasts, highlighting the hydric behavior of agricultural soils and their capacity to store water at depth. This deep-water reserve is vital for crop resilience to water stress, influenced by various soil and environmental factors, including soil texture (Rawls et al., 1982), profile depth and continuity (Håkansson & Lipiec, 2000), and organic matter content (Saxton & Rawls, 2006), as well as climate conditions (Allen et al., 1998) and topography (Bohne, 2005).

3.3.3. Hydrological simulations with surface layer capacity (SLC)

Figure 7 below shows the hydrological simulations in time series of the capacity of the surface layer (CCS) and the curve of the classified flows obtained in the situation of thirty-two (32) hydrological sub-units of the Itimbiri river basin.

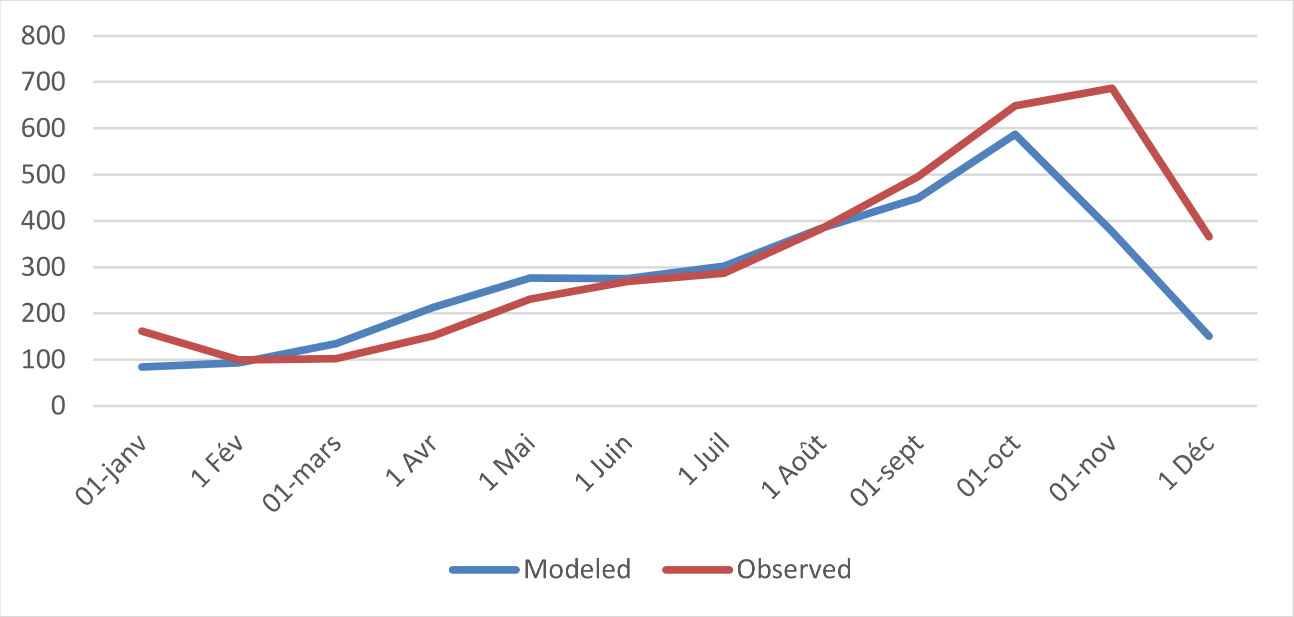


Figure 7: Hydrological simulations with deep layer capacity (CCI)

The forecasts were very effective, with an NSE of 0.71 and an R2 of 0.74. However, the presence of a slight systematic underestimation of the forecasts is highlighted by the PBIAS of -3.1%. These results indicate a reasonable match between forecasts and observations, although simulated flows may be slightly lower than the actual observed flows. Water stored in the surface root zone plays an essential role in crop water supply, particularly at the start of the cycle in the Itimbiri catchment.

3.3.4. Hydrological simulations with Superficial Conductivity (SC)

Figure 8 below shows the results for thirty-two (32) hydrological subunits in the Itimbiri river basin. Superficial conductivity (CS) is present, resulting in an NSE of 0.69 and an R2 of 0.73. And a Percentage Bias (PBIAS) of -3.3%, demonstrating a significant correspondence and a capacity of the model to explain the variance, despite a slight systematic underestimation.

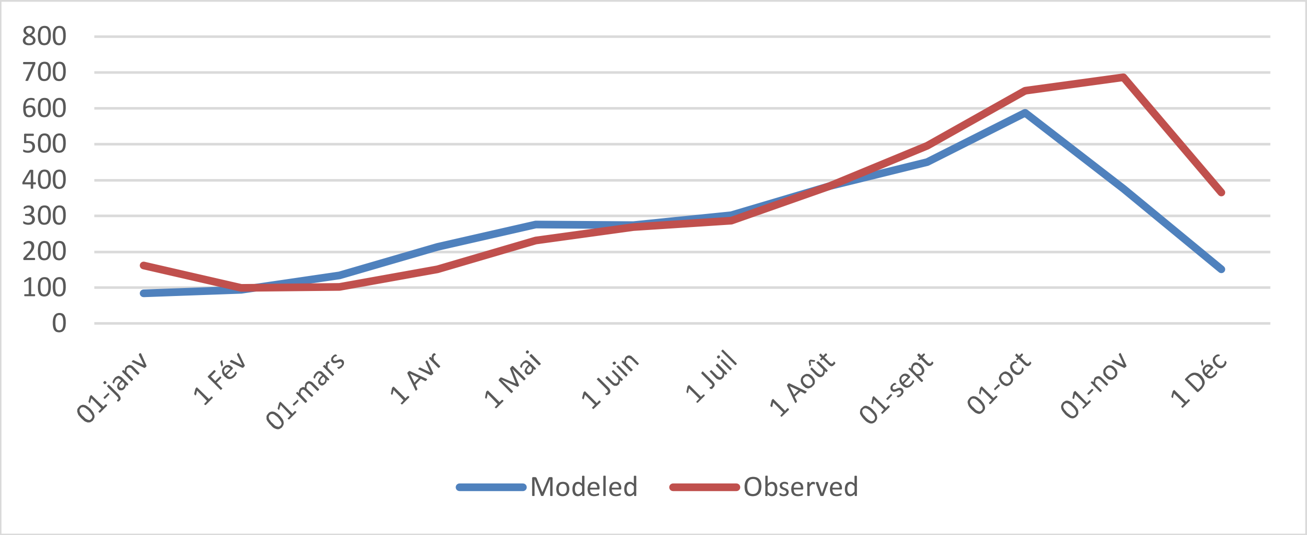


Figure 8: Hydrological simulations with Superficial Conductivity (SC)

Surface conductivity refers to the soil's capacity to evacuate water in the surface layer, usually in the first 30 to 50 centimetres. The role of this physical characteristic of the soil is crucial in water transfer mechanisms such as infiltration, runoff and evaporation, which are influenced by several characteristics of the soil and environmental conditions, as highlighted by the previous coefficients (Rawls et al., 1998).

3.3.5. Hydrological simulations with deep conductivity (CP)

Figure 9 below shows the results for thirty-two (32) hydrological subunits in the Itimbiri river basin. Deep conductivity (CP) is present, resulting in an NSE of 0.71 and an R2 of 0.75. And a Percentage Bias (PBIAS) of -3.5%, demonstrating a significant match and the model's ability to explain the variance, despite a slight systematic underestimation. The situation shows how the soil's capacity to evacuate water in the deep layers of the profile and the recharge of groundwater are characterised by this physical property (Mualem, 1976).

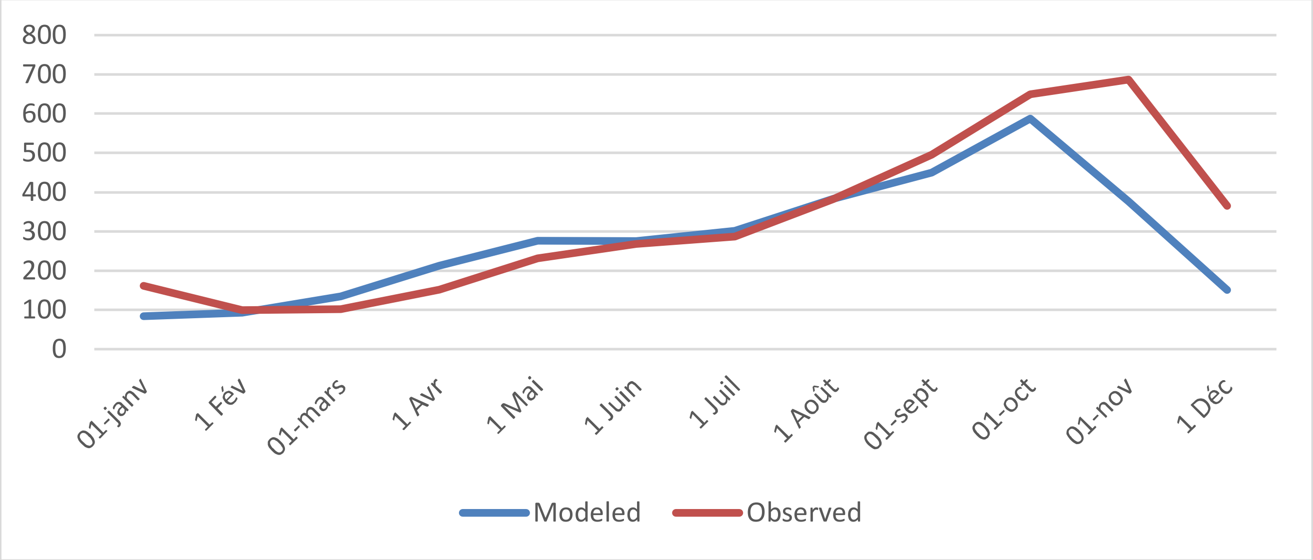


Figure 9. Hydrological simulations with deep conductivity (CP)

3.3.6. Hydrological simulations with Preferred Flow Direction (PFD)

The evaluation of hydrological model performance reveals significant results for each land use parameter. Specifically, the land use parameter related to the preferred direction of flow (DPE) demonstrates very high efficiency, with an NSE of 0.69 and an R² of 0.75, indicating a strong correlation between model simulations and observations. The PBIAS value of -3.5% suggests a slight tendency toward systematic overestimation of forecasts. The preferred direction of flow (PDF) refers to the tendency of water to flow preferentially in certain directions rather than uniformly. Understanding this soil characteristic is crucial for comprehending the mechanisms of runoff, infiltration, and water circulation in the soil profile (Hendrickx & Flury, 2001). The preferred direction of flow in the soil is influenced by various factors such as soil texture (including clay content, silt and sand) (Hendrickx & Flury, 2001).

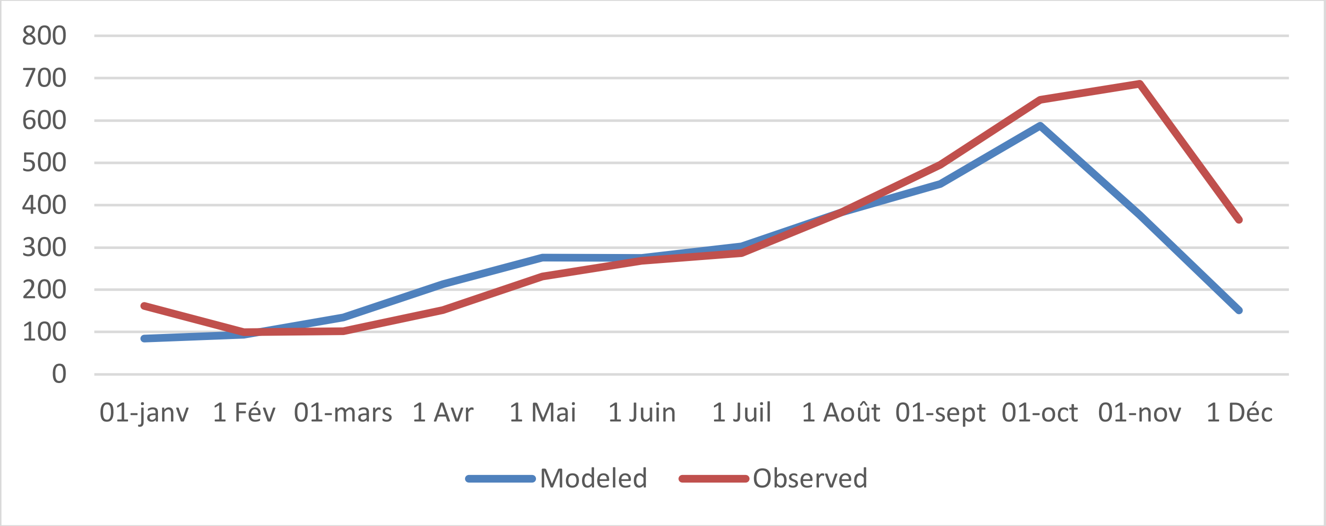


Figure10. Hydrological simulations with Preferred Direction of Flow (PDF)

3.3.7. Hydrological simulations with Leaf Area Index (LAI)

Figure 11 below shows the results for thirty-two (32) hydrological subunits in the Itimbiri river basin. The leaf area index (LAI) shows an NSE of 0.71 and an R2 of 0.76. And a Percentage Bias (PBIAS) of -3.1%, demonstrating a significant match and the model's ability to explain the variance, despite a slight systematic underestimation, which represents the leaf area per unit of soil surface in the Itimbiri basin for estimating plant productivity, solar radiation interception, evapotranspiration, etc. (Monteith, 1973).

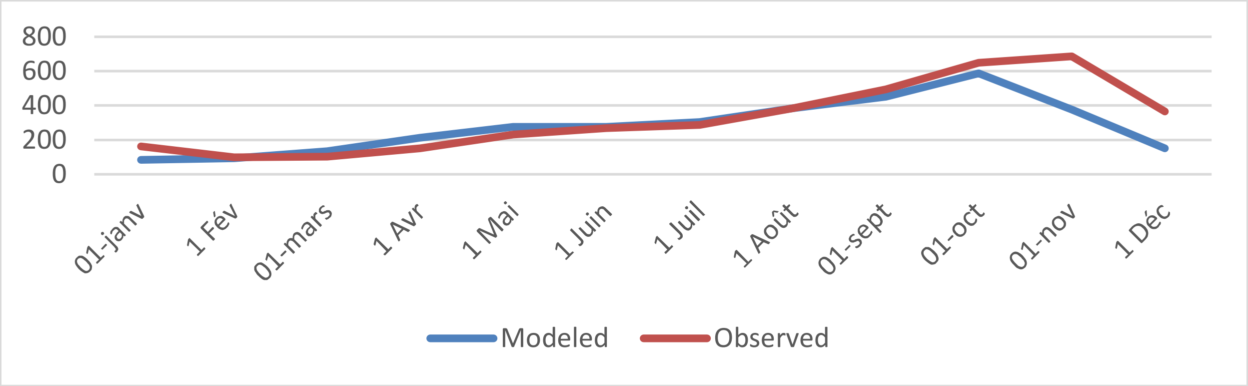
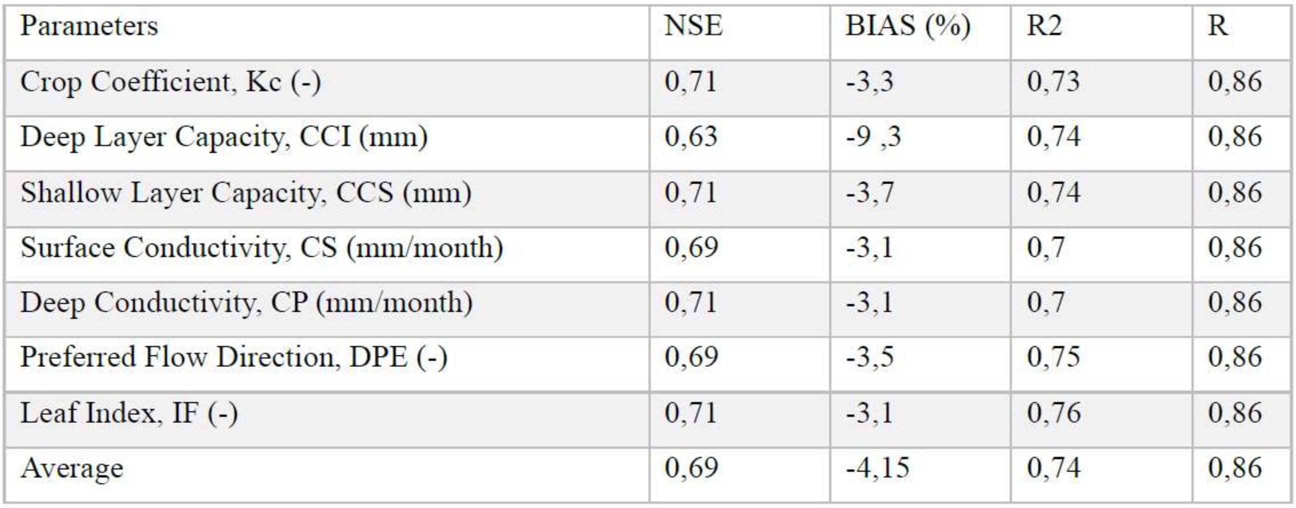


Figure 11. Hydrological simulations with Indice foliaire (IF)

3.4. Performance evaluation and model validation

Table 2 below shows the statistics for the hydrological model performance indicators for the Itimbiri basin as a whole. The aim of model validation is to assess the reliability of the calibrated land-use parameters at various periods, with varying environmental conditions (Dos Santos et al., 2022; Nicholson et al., 2019). The search for a common period to calibrate and validate the model in all the hydrological units available in the gauging station was complicated due to missing data. Thus, historical data available at the Aketi gauging site were used to confirm (Tshimanga et al., 2011). High-flow errors are better studied by the Nash-Sutcliffe criterion. Model performance for all land use parameters of 32 hydrological subunits is evaluated with mean NSE 0.69, R2 0.74, R 0.86, and (PBIAS) -4.15%.

Table 2. Validation of the hydrological model of the Itimbiri basin using Land use parameters



Parameters	NSE	BIAS (%)	R2	R
Crop Coefficient, Kc (-)	0,71	-3,3	0,73	0,86
Deep Layer Capacity, CCI (mm)	0,63	-9 ,3	0,74	0,86
Shallow Layer Capacity, CCS (mm)	0,71	-3,7	0,74	0,86
Surface Conductivity, CS (mm/month)	0,69	-3,1	0,7	0,86
Deep Conductivity, CP (mm/month)	0,71	-3,1	0,7	0,86
Preferred Flow Direction, DPE (-)	0,69	-3,5	0,75	0,86
Leaf Index, IF (-)	0,71	-3,1	0,76	0,86
Average	0,69	-4,15	0,74	0,86

Source: Authors (2024)

3.5. Discussion of Results

This study highlights the importance of land use parameters in the hydrological functioning of the Itimbiri River Basin. Previous research, such as that by Beighley et al. (2011), demonstrates that land use changes, including deforestation and agricultural expansion, significantly impact hydrological regimes. Kabuya et al. (2017) found that converting forests to agricultural land decreases water storage capacity and infiltration, affecting river base flows. The observed performance differences among parameters underscore the influence of topographical and environmental factors, with soil texture playing a critical role in infiltration capacity (Rawls et al., 1998). Allen et al. (1998) emphasize the necessity of accurately estimating the crop coefficient (Kc) for effective irrigation management, as Kc variations are influenced by environmental and crop characteristics. Breda (2003) addressed the Leaf Area Index (LAI) and its variability, noting that vegetation cover heterogeneity can introduce measurement uncertainties, which Jonckheere et al. (2004) also highlight. Furthermore, the results indicate that climate change exacerbates the effects of deforestation and urbanization, supported by Chishugi and Alemaw (2009), who found that forest conversion leads to lower groundwater levels. Recognizing the role of forests in regulating flows and recharging aquifers is vital for ecosystem preservation, as noted by Laraque et al. (2001). Finally, the recommendations by Munzimi et al. (2019) for future research emphasize improving input data quality and model calibration, advocating for process-based hydrological models to better understand the impacts of land use and climate change on the vulnerable peatland ecosystems of the Itimbiri River Basin. Overall, this study enhances the understanding of hydrological dynamics amid environmental change and underscores the need for a comprehensive approach to water resource management in this critical area.

Evaluates the model's performance for each land use parameter across the 32 hydrological sub-units, revealing that these parameters evolved in line with indicators such as NSE, R, and PBIAS. These indicators measure the concordance between simulated and observed flows, with NSE ranging from 0.63 to 0.71, R^2 from 0.7 to

0.76, and PBIAS from -3.1% to 9.3%. Variations in model performance across parameters can be attributed to topographical, environmental, and hydrological factors. Moreover, the conversion of forests to agricultural areas and urban development has resulted in decreased groundwater levels and reduced base flows, while climate change adversely affects peatland wetlands, which are crucial for regulating the water cycle and carbon storage in the Congo Basin.

The significance of these peatlands for maintaining the biosphere highlights the necessity of a detailed management policy to prevent ecosystem degradation, which provides essential services to local communities and humanity. This research establishes quantitative links between various land use forms and key hydrological parameters in the Itimbiri River Basin's peatland area. The findings indicate that land use changes, particularly deforestation and agricultural expansion, significantly influence the region's hydrology, emphasizing the vital role of forest areas in regulating flows and recharging aquifers that sustain peatlands.

Conclusion and Recommendations

A hydrological model was developed to quantify the relationships between land uses and hydrological parameters, enhancing understanding of land use impacts on peatland wetlands in the Itimbiri River Basin. The WEAP model performed satisfactorily but required adjustments for each sub-basin due to soil and environmental variations. The study highlights the need to protect forest areas, particularly peatlands, and proposes sustainable agricultural practices, wetland restoration initiatives, and integration of findings into water resource management strategies at the Congo Basin level. Future research should explore land use and hydrology links in other peatland regions and assess climate change scenarios against the model's results.

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Compliance with ethical rules

The authors declare no conflict of interest. Field research did not involve any threat to any community or protected species. No informal or legal organization played a key role in the design of the study, the collection and analysis of data so as to decide on the final outcome of the study. The decision to prepare the manuscript and publish it was solely taken by the authors.

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