

Article

Sustainability Under Deforestation and Climate Variability in Tropical Savannas: Water Yield in the Urucuia River Basin, Brazil

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Abstract

By 2023, deforestation in the Cerrado biome surpassed 50% of its original area, primarily due to the conversion of native vegetation to pasture and agricultural land. In addition to anthropogenic pressure, climate change has intensified hydrological stress by reducing precipitation and decreasing river flows, thereby threatening water security, quality, and availability in that biome. The Annual Water Yield (AWY) model from the InVEST platform provides a tool to assess ecosystem services by estimating the balance between precipitation and evapotranspiration (ET). In this study, we applied the AWY model to the Urucuia River Basin, analyzing water yield trends from 1991 to 2020. We evaluated climate variables, land use dynamics, and river discharge data and validated the model validation using observed stream flow data. Although the model exhibited low performance in simulating observed streamflow (NSE = −0.14), scenario analyses under reduced precipitation and increased evapotranspiration (ET) revealed consistent water yield responses to climatic variability, supporting the model's heuristic value for assessing the relative impacts of land use and climate change. The effects of deforestation on estimated water yield were limited, as land use changes resulted in only moderate shifts in basin-wide ET. This was primarily due to the offsetting effects of land conversion: while the replacement of savannas with pasture reduced ET, the expansion of agricultural areas increased it, leading to a net balancing effect. Nevertheless, other ecosystem services—such as water quality, soil erosion, and hydrological regulation—may have been affected, threatening long-term regional sustainability. Trend analysis showed a significant decline in river discharge, likely driven by the expansion of irrigated agriculture, particularly center pivot systems, despite the absence of significant trends in precipitation or ET.

Keywords: Cerrado biome; sustainable land use; water resource management; climate changes; deforestation



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1. Introduction

The Brazilian Cerrado biome is a global biodiversity hotspot [1,2], encompassing 24% of Brazil's national territory [3], which has been subjected to intensive deforestation in recent decades, primarily driven by the conversion of native vegetation into pasture and agricultural lands and recurrent wildfires [2,4]. The remaining native vegetation is unevenly distributed in that biome, with large vegetation remnants mostly found in the northeastern region of the biome, while the southern region had been heavily deforested [5]. Furthermore, many of those native vegetation remains have been fragmented and located within protected areas or unsuitable areas for mechanized agriculture, resulting in a biased spatial representation of the landscapes that have been protected [6].

Vegetation in the Cerrado biome forms a structural gradient, ranging from open savanna to dense forest formations [7]. Recent research emphasizes that variations in vegetation structure, more than species composition, are key to understanding ecosystem functioning across the biome [8]. Structural attributes such as canopy height, leaf area, and root depth modulate ecological processes, particularly evapotranspiration, infiltration, and water retention [9,10]. Consequently, changes in vegetation cover, whether driven by land use or climate changes, have significant potential to affect hydrological dynamics [11].

Over the past decades, land use change in the Cerrado biome has advanced predominantly toward the MATOPIBA region—an area comprising the states of Maranhão, Tocantins, Piauí, and Bahia—recognized as Brazil's current agricultural frontier [12–15]. The accelerated conversion of native vegetation into croplands and pastures has further intensified the biome's ecological vulnerability. In 2023, the Cerrado recorded the highest deforestation rate in Brazil, with over one million hectares of native vegetation lost in a single year [15].

The limited extent of protected areas exacerbates this scenario. Only 8.6% of the Cerrado is currently protected, with just 3.1% under strict protection and the remainder designated for sustainable use [16]. Furthermore, 40% of the remaining native vegetation in the Cerrado biome is still legally suitable for deforestation [4].

Depending on the type of land use that replaces the native vegetation, evapotranspiration may either increase or decrease depending on the vegetative characteristics that influence this hydrological process. As a result, this can lead to either an increase or a decrease in water availability [17]. For example, ref. [18] observed that forest disturbances and climate variability significantly affected streamflow in the Willow River watershed, British Columbia, Canada, often in opposite ways. Forest disturbances caused by partial logging increased average streamflow, whereas climate variability contributed to its decrease.

Similarly, ref. [19] observed that while forest disturbances increased annual streamflow, baseflow, and surface runoff, climate variability had the opposite effect. However, climate variability had a greater impact than forest disturbances in the Upper Similkameen River Watershed, an international watershed located in Canada and the United States. Meanwhile, ref. [20] found that the effects of watershed disturbances on streamflow varied with seasonal changes, particularly during the spring and summer. In their study, forest disturbances helped offset the effects of climate change on summer streamflow.

In addition to land use change, global climate change has strongly impacted on the Cerrado biome. Estimates indicate that the Cerrado has become hotter and drier over the past decades, with a noticeable decline in precipitation levels [21,22]. Based on the principles of the water balance, these changes are expected to significantly affect water resource availability in the biome, as reduced precipitation combined with increased evapotranspiration naturally leads to lower river flows [17,23]. Indeed, estimates indicate that this phenomenon is widespread across most river basins in the Cerrado [24].

Land use, forest disturbances, and associated management practices are a fundamental component of water resource management. The integration between water resource management and land use planning is acknowledged in the National Water Resources Policy, which establishes watersheds as management units [25]. Thus, hydrological modeling at the watershed scale, incorporating different land use and climate change scenarios, can support more concrete planning actions for land and water resource management, as well as adaptation strategies to climate change and drought events [19,26].

The InVEST Annual Water Yield (AWY) model from the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) tool, developed by the Natural Capital Project at Stanford University [27], has been widely applied across diverse landscapes to estimate ecosystem service provision related to water resources. Applications include forested watersheds in China [28], semi-arid regions in Ethiopia [29], and United Kingdom basins [30]. While relatively simple, the model provides scalable estimates of water balance and hydrological service distribution, making it suitable for analyses under land use and climate change scenarios [27].

In this study, we aimed to evaluate how water yield in the Urucuia River Basin has responded to land use changes and climate variability over the period from 1991 to 2020. In the Urucuia River Basin, located in the state of Minas Gerais within the Cerrado biome, historical deforestation has followed similar patterns over recent decades, particularly in the northern region [12,31].

The following research questions were addressed: (i) How has water yield in the Urucuia River Basin evolved over the past three decades under observed land use and climate changes? (ii) To what extent do land use changes influence water yield compared to climate variability in this specific basin? (iii) How sensitive is the InVEST Annual Water Yield model in detecting hydrological responses to the combined pressures of land use transitions and climatic fluctuations?

To answer these questions, the InVEST Annual Water Yield model was applied to analyze water yield dynamics in the Urucuia River Basin, integrating historical land use transitions, climatic variability, and hydrological modeling to assess impacts on water-related ecosystem services. Additionally, the model's response was tested under different land use and climate variation scenarios, and complementary analyses related to water resources were conducted.

2. Materials and Methods

2.1. Study Area

The study area comprises the Urucuia River Basin, a major tributary of the São Francisco River, also referred to as the Middle São Francisco (Figure 1). Based on Strahler's classification, the Urucuia River is classified as a sixth-order stream [32], contributing approximately 10% of the total discharge and 18% of the sediment load to the São Francisco River. The basin spans an area of approximately 25,000 km², accounting for about 10% of the total area of the São Francisco River Basin [33].

Twelve municipalities are located within the boundaries of the Urucuia River Basin, although four of them have their administrative centers situated outside its limits (Figure 1). By 2010, its population was 94,408, with 59.3% living in urban areas, with Buritis and Arinos emerging as the primary urban centers. Although Unaí is the most populous municipality in the region, its administrative center lies outside the basin [34].

Located within the Brazilian Cerrado biome, the Urucuia River basin is characterized by a tropical savanna climate (Aw according to the Köppen–Geiger classification) with distinct wet and dry seasons [35]. Climatological normals from the INMET stations indicate annual precipitation between 1000 and 1300 mm and average annual temperatures

ranging from 23 to 25 °C. The predominant soils include Latosols, Neosols, Argisols, and Cambisols [36], with elevations varying from 444 to 1076 m above sea level and average slopes between 2.59% and 8.54% [36].

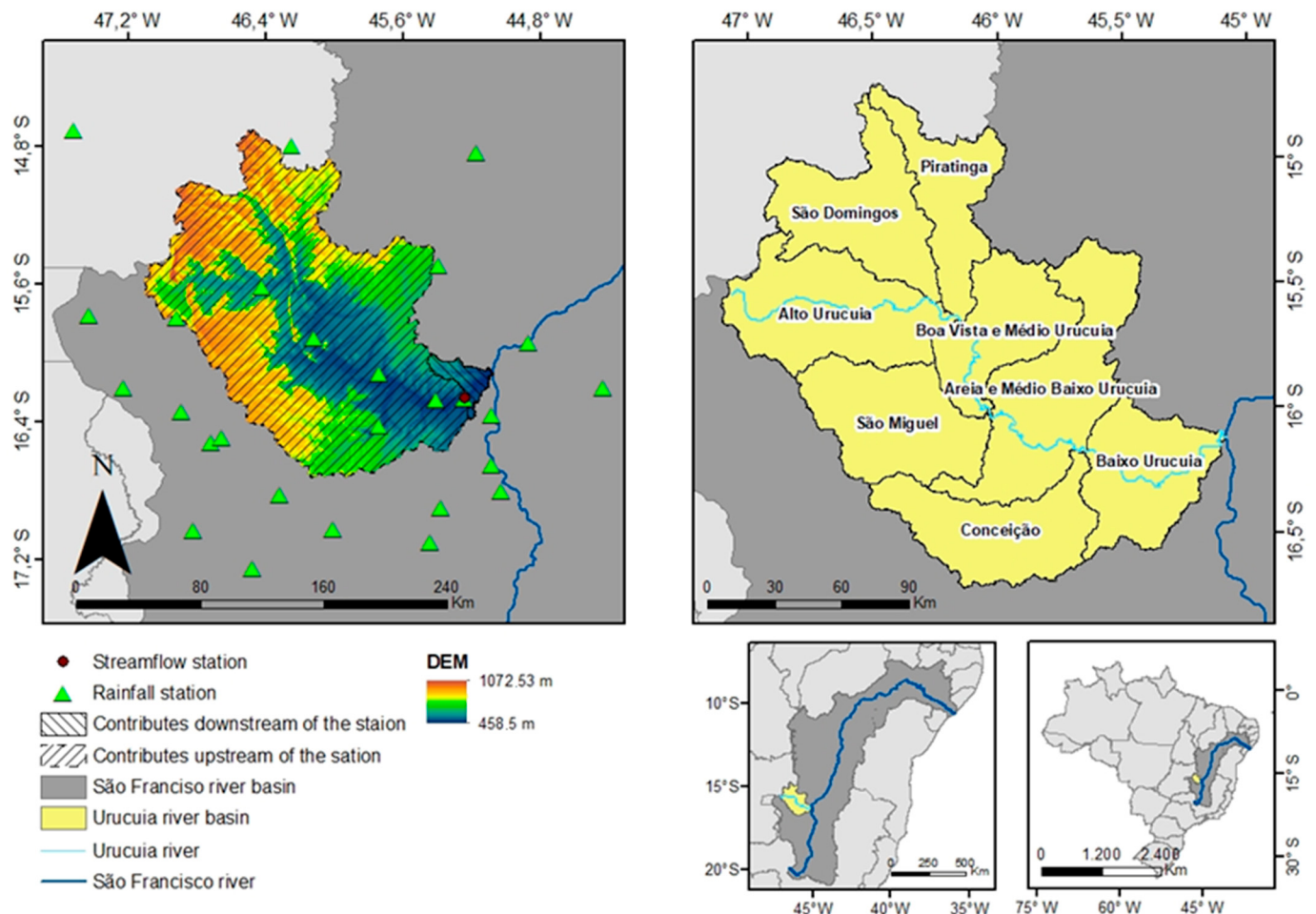


Figure 1. Spatial location of the Urucuia River Basin (URB) within the São Francisco River Basin, along with meteorological stations from the Brazilian National Institute of Meteorology (INMET).

Land use and land cover (LULC) within the basin are characterized by agricultural and livestock activities alongside remnants of native vegetation. Agricultural and pasture lands covered approximately 41% of the Urucuia basin by 2022. Forest and savanna formations cover about 43%, while non-forest natural formations account for around 15%. The primary crops cultivated include soybeans, corn, beans, sorghum, and sugarcane, with smaller areas with permanent crops [4,37].

2.2. Data Acquisition and Pre-Processing

Precipitation data were collected from 27 rain gauge stations managed by the Brazilian National Water Agency (ANA), accessed via the HIDROWEB platform [38]. These stations are distributed within and around the Urucuia River Basin. To fill precipitation data gaps, we initially used reanalysis datasets from ANA. Where these were unavailable, we applied a regional weighted interpolation approach using data from the nearest neighboring weather stations. The gap-filling method yielded a Nash–Sutcliffe Efficiency of 0.86, indicating high reliability. Additionally, when reanalysis was insufficient, multiple imputation techniques such as linear regression models and climatological averages were applied, following the methodology recommended by [39].

Reference evapotranspiration (ET_0) data were acquired from the NASA/POWER platform, which offers broad spatial and temporal coverage. ET_0 was calculated using the Penman–Monteith method based on variables provided by NASA/POWER, yielding a Nash–Sutcliffe efficiency of 0.79 compared to available ground observations. Annual ET_0 values were spatialized across the basin through ordinary kriging interpolation.

Soil physical properties, specifically the Root Restricting Layer Depth (RRD) and Plant Available Water Content (PAWC), were derived from the ISRIC database, a global repository endorsed by the InVEST model documentation. RRD was defined as the depth to bedrock, acknowledging uncertainties in determining actual root depth across heterogeneous landscapes.

Land use and land cover (LULC) data were sourced from the MapBiomas Project, Collection 7 [40], which provides annual land use and land cover maps for the entire country of Brazil, derived from satellite imagery. The data were reclassified to meet the model's requirements, including the assignment of biophysical parameters such as crop coefficients (K_c), root depth, and vegetation presence. Table 1 summarizes the root depth and K_c values assigned to each LULC class, adapted from [29,41–44].

Table 1. Root depth and K_c values for land use and land cover class.

LULC	Root Depth (mm)	K_c
Forest	8000	0.8
Savanna	6000	0.7
Native grassland	1500	0.5
Wetland	1000	1
Rocky outcrops	100	0.2
Silviculture	7000	1
Pasture	1000	0.45
Agriculture	2000	0.8
Mosaico	2000	0.6
Urban area	100	0.4
Water	1	1
Other non-vegetated areas	1	0.2

Note: Root depth and K_c values were adapted from [41]. Sources: [29,41–44].

The basin boundaries were defined based on metadata from the National Water and Sanitation Agency (ANA). The Z parameter, representing rainfall seasonality, was calculated as proposed by [45], by dividing the number of annual rainfall events (days with precipitation > 0.1 mm) by five. This parameter was computed annually based on ANA's precipitation records.

The pre-processed datasets, summarized in Table 2, were formatted according to the requirements of the InVEST AWY model.

2.3. Annual Water Yield Model (InVEST)

The estimation of water yield in the Urucuia River Basin was performed using the Annual Water Yield (AWY) model, part of the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) suite developed by the Natural Capital Project at Stanford University. This model estimates the annual water yield per pixel by calculating the difference between annual precipitation and actual evapotranspiration (AET), considering land cover characteristics, reference evapotranspiration (ET_0), and soil properties, especially the Root Restricting Depth (RRD) and the Plant Available Water Content (PAWC) [27].

Table 2. Input data for AWY model.

Input	Source	File Format
Precipitation	ANA	Raster
Reference evapotranspiration	NASA/POWER	Raster
RRD	ISRIC	Raster
PAWC	ISRIC	Raster
Land use and land cover	MAPBIOMAS	Raster
River basin shape	ANA	Shapefile
Kc (crop coefficient)	Literature review	CSV
Root depth	Literature review	CSV
Z (N/5)	ANA	One value per year

A core assumption of the AWY model is that all water not lost through evapotranspiration contributes to water yield, either via surface runoff or subsurface flow. However, the model does not explicitly differentiate between these pathways nor account for anthropogenic water withdrawals, such as irrigation [27], which is a relevant limitation in regions like the Urucuia Basin where irrigated agriculture is expanding.

The model is applied to a water balance equation to estimate annual water yield (Y) per pixel:

$$Y = \left(1 - \frac{AET}{P}\right) \cdot P$$

where: Y is the annual water yield (mm), AET is actual evapotranspiration (mm), and P is annual precipitation (mm).

The estimation of AET varies depending on whether the land cover is vegetated. For vegetated land, the Budyko curve, adapted for the model, was applied as follows [45]:

$$\frac{AET}{P} = 1 + \frac{PET}{P} - \left(1 + \left(\frac{PET}{P}\right)^\omega\right)^{\frac{1}{\omega}}$$

where PET = potential evapotranspiration (mm) and ω = controlling parameter of the Budyko curve.

Potential evapotranspiration is derived by multiplying the reference evapotranspiration by a crop coefficient (Kc) [41]:

$$PET = k_c \cdot ETO$$

where ETO = reference evapotranspiration (mm).

The ω parameter is estimated as [46]

$$\omega = Z \cdot \frac{AWC}{P} + 1.25$$

where Z is the seasonality factor and AWC is the Available Water Content. The AWC is calculated by multiplying the PAWC by the minimum between the root depth and the Root Restricting Layer depth.

The Z parameter plays a critical role in representing rainfall seasonality but remains uncertain. Two methods for estimating Z are suggested in the literature: calibration against streamflow data or computing the number of rainfall events per year divided by five [46]. In this study, the latter approach was adopted, using ANA's precipitation records to count days with rainfall greater than 0.1 mm.

All input data required by the model, including precipitation, ET_0 , soil attributes, LULC, crop coefficients, root depths, and the Z parameter, were previously presented in

Section 2.2. This structured approach ensured that the spatial and temporal dynamics of the basin were appropriately represented across the 30-year analysis period from 1991 to 2020.

2.4. Water Yield Validation

The validation of the Annual Water Yield (AWY) model outputs was conducted by comparing the simulated water yield with observed streamflow data from the Urucuia River Basin. The discharge records were obtained from station ID#43980002, managed by the Brazilian National Water Agency, which is the monitoring station closest to the basin's outlet. As the station is not located exactly at the river's mouth, the modeled basin boundary was adjusted to correspond to the drainage area upstream of this monitoring point.

The AWY model generates water yield in millimeters per year for each pixel. To enable direct comparison with observed streamflow data, these values were converted into volumetric discharge (cubic meters per second). The conversion was performed following the methodology adapted from [27], using the equation

$$QT_{sim} = \left(\frac{0.001 \cdot AWY \cdot A}{T} \right)$$

where QT_{sim} is the simulated streamflow (m^3/s), AWY is the annual water yield (mm), A is the drainage area (m^2), and T is the number of seconds in a year.

Model validation covered the same time span as the simulations, from 1991 to 2020. Three statistical metrics were employed to evaluate model performance: the coefficient of determination (R^2), percent bias (PBIAS), and the Nash–Sutcliffe Efficiency (NSE).

The coefficient of determination (R^2) quantifies the proportion of variance in the observed data explained by the model estimates, ranging from 0 to 1, with higher values indicating stronger correlations [47].

Percent bias (PBIAS) assesses the average tendency of the model to overestimate or underestimate observations, where a value of zero denotes perfect agreement, positive values indicate underestimation, and negative values suggest overestimation [48]. The Nash–Sutcliffe Efficiency (NSE), here also referred to as the Coefficient of Efficiency (CE), evaluates the predictive power of the model relative to the observed mean, with values closer to 1 indicating better model performance, whereas negative values imply poor predictive capacity [49].

The criteria for interpreting these performance metrics follow the classification proposed by [47], summarized in Table 3.

Table 3. Performance evaluation under different estimators.

Performance	R^2	PBIAS	CE
Very good	$0.7 < R^2 \leq 1$	$PBIAS < \pm 10$	$0.75 < NS \leq 1$
Good	$0.6 < R^2 \leq 0.7$	$\pm 10 \leq PBIAS < \pm 15$	$0.65 < NS \leq 0.75$
Moderate	$0.5 < R^2 \leq 0.6$	$\pm 15 \leq PBIAS < \pm 25$	$0.5 < NS \leq 0.65$
Unsatisfactory	$R^2 \leq 0.5$	$PBIAS \geq \pm 25$	$NS \leq 0.5$

This validation framework ensured a comprehensive assessment of the AWY model's capacity to replicate hydrological patterns in the Urucuia River Basin over three decades.

2.5. Testing for Trends

To complement the qualitative evaluation of the AWY model results and to investigate the potential influence of climate variability and land use change on water yield trends in the Urucuia River Basin, statistical analyses were conducted using established methods for trend detection in environmental time series. The Mann–Kendall test was applied

to identify the presence of monotonic trends, while the magnitude of these trends was quantified using Sen's slope estimator, as proposed by [50].

Considering that hydrological and climatic time series often exhibit serial correlation, which can affect the results of trend analyses, the Trend-Free Pre-Whitening (TFPW) procedure was applied prior to the application of the Mann–Kendall test. This methodology, developed by [51], removes the effect of autocorrelation, ensuring that the trend detection remains reliable and statistically sound.

The trend analyses encompassed the primary input variables of the AWY model, including annual precipitation, reference evapotranspiration (ET_0), and the extent of native vegetation cover. In addition, the model outputs, such as potential evapotranspiration (PET), actual evapotranspiration (AET), and annual water yield, were analyzed to provide a comprehensive understanding of the hydrological processes and their responses to environmental changes. The observed annual mean streamflow recorded at the Urucuia River monitoring station (ANA station ID#43980002) was also included in the analysis to compare observed and modeled trends.

All statistical procedures were performed in the R Version 4.3.3 programming environment, utilizing appropriate packages for trend detection and analysis of time series data. This analytical framework ensured a robust and comprehensive assessment of long-term changes in the basin's hydrology over the thirty-year study period.

3. Results and Discussion

3.1. Model Performance Assessment

The performance of the Annual Water Yield (AWY) model in simulating streamflow in the Urucuia River Basin was assessed using three statistical metrics. The AWY model showed moderate performance according to the coefficient of determination ($R^2 = 0.64$) and percent bias (PBIAS = -11.11), whereas the Nash–Sutcliffe efficiency (NSE = -0.14) indicated unsatisfactory performance [49].

A comparison between estimated and observed streamflow data from 1991 to 2020, using a linear regression model, indicates that the estimates derived from the AWY model explain 71% of the variance in observed streamflow, as indicated by the coefficient of determination ($R^2 = 0.71$; Figure 2).

Although the model showed low performance in simulating observed streamflow (NSE = -0.14), scenario analyses under reduced precipitation and increased evapotranspiration (ET) revealed consistent water yield responses to climatic variability, supporting the model's heuristic value for assessing the relative impacts of land use and climate change.

3.2. Sensitivity to Climate Inputs

Scenario simulations revealed a pronounced sensitivity of water yield to variations in precipitation and evapotranspiration (ET_0). Higher precipitation combined with lower ET_0 resulted in increased water yield and higher estimated streamflow (Figure 3), while the opposite conditions led to substantial reductions. These findings are consistent with previous studies, which emphasize that the AWY model is primarily driven by climatic inputs, particularly precipitation and evapotranspiration rates [46].

This climatic sensitivity is inherent to the model's structure, in which water yield is directly calculated as the difference between precipitation and actual evapotranspiration. As a result, climate change projections indicating reduced precipitation and increased evapotranspiration in the Cerrado biome [52,53] suggest a potential decline in water yield, thereby diminishing the provision of ecosystem services in the region.

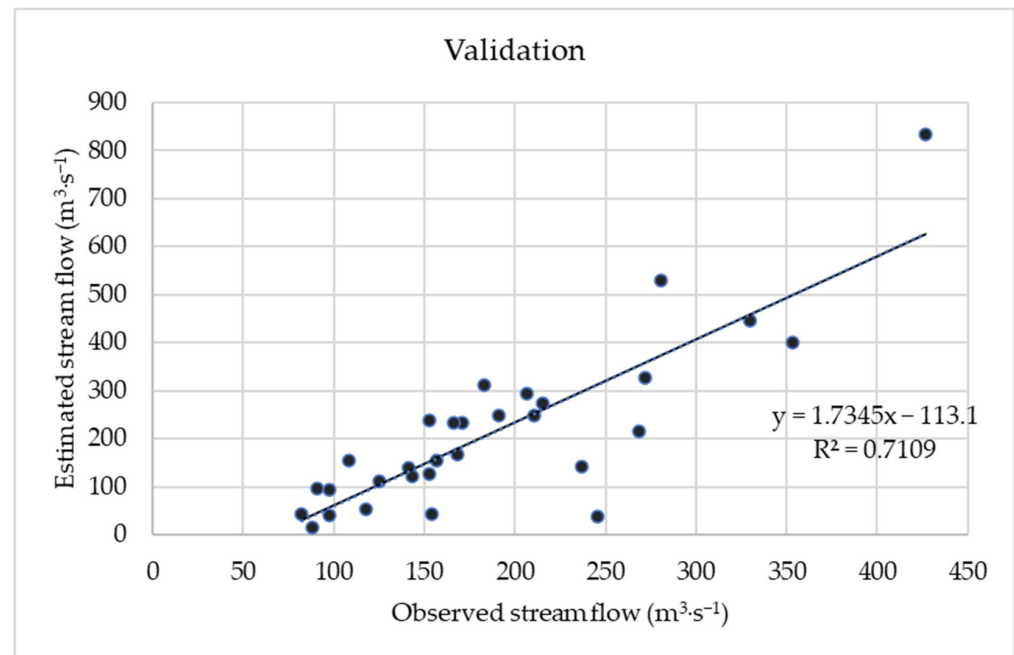


Figure 2. Estimated and observed streamflow data from 1991 to 2020 in the Urucuia River Basin. Source: from streamflow dataset [38].

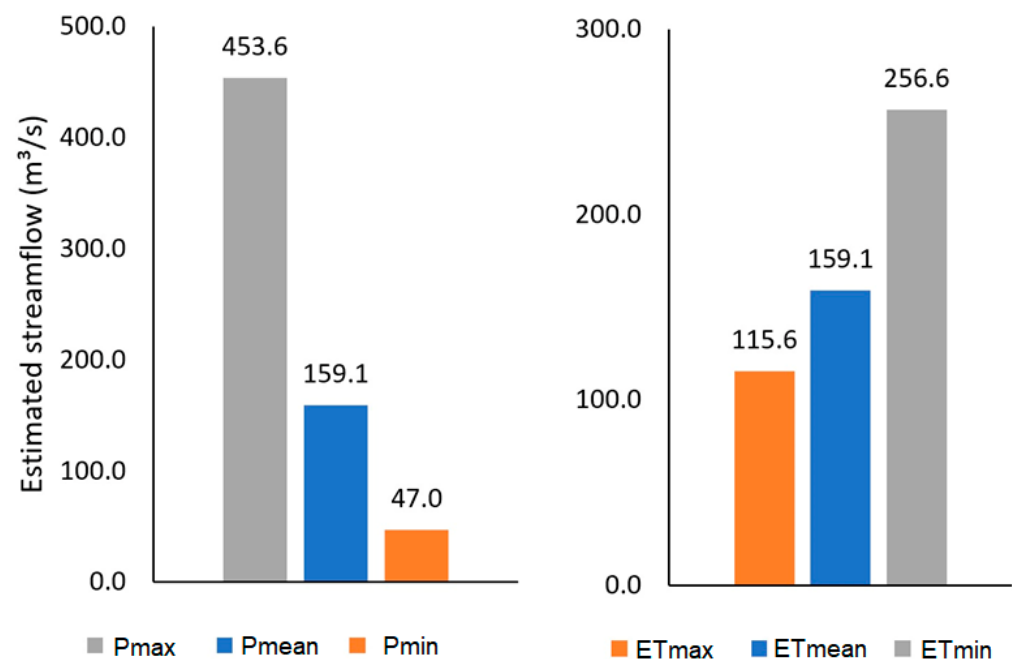


Figure 3. Estimated streamflow under different climatic scenarios in the Urucuia River Basin, varying precipitation and reference evapotranspiration, where Pmax, mean, min = maximum, mean, minimum precipitation and ETmax, mean, min = maximum, mean, and minimum evapotranspiration (ET_0).

3.3. Effects of Land Use and Land Cover Change

In contrast to the climatic variables, land use and land cover (LULC) changes between 1991 and 2020 had a more nuanced impact on water yield. The MapBiomas data indicates a reduction in native vegetation cover from 67.4% in 1991 to 53.5% in 2020, mainly due to the conversion of savanna formations into pasture [40]. Despite this significant land cover transformation, when precipitation and ET_0 were held constant, the modeled streamflow remained relatively stable (Figure 4).

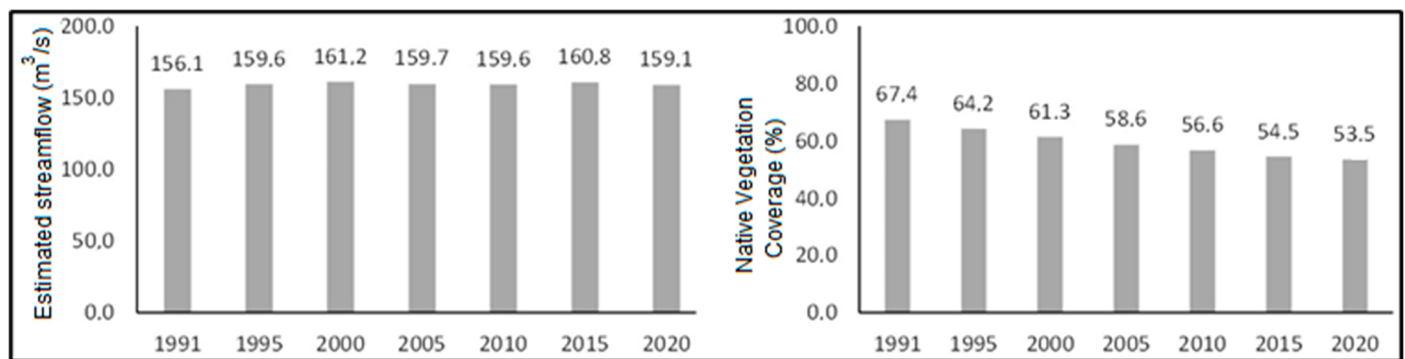


Figure 4. Estimated streamflow in the Urucuia River Basin in response to land use and land cover changes from 1991 to 2020.

This result can be explained by the characteristics of the LULC changes observed in the study region. The replacement of native vegetation by pasture generally reduces the evapotranspiration potential of the landscape, as pastures often exhibit lower crop coefficients (K_c) compared to savanna formations [41,43]. However, in some cases, transitions from mosaics of land uses to agriculture or from pasture to agriculture may increase K_c and, consequently, the evapotranspiration rate. Figure 5 summarizes the most frequent LULC transitions in the study period and the associated changes in K_c values.

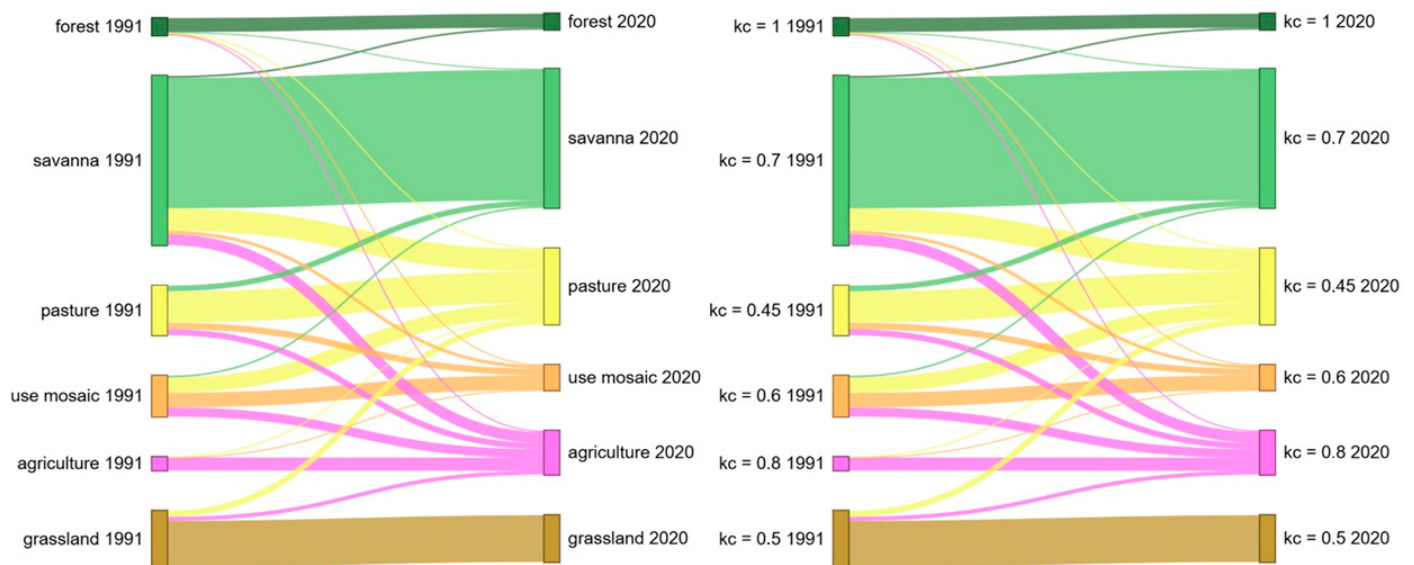


Figure 5. Main land use and land cover changes and associated crop coefficient (K_c) changes in the Urucuia River Basin occurred between 1991 and 2020. Source: from land use dataset [4].

Even with these transformations, the overall K_c value for the basin underwent minimal variation. This relative constancy contributed to balanced actual evapotranspiration levels, which in turn resulted in limited variation in the modeled water yield. Similar findings have been reported in other studies, where the impact of LULC changes on water yield depends on the types of conversions and their associated evapotranspiration potential [29,54].

Our results demonstrated that precipitation and evapotranspiration were the primary controlling factors of water yield in the Urucuia River Basin. This finding is consistent with previous studies on the hydrology of the Cerrado biome, which have identified a persistent decline in precipitation and a rise in temperature across the region, both of which directly influence hydrological processes [21,22]. Ref. [22] reported that between 1961 and 2019, maximum temperatures increased by 2.2 to 4.0 °C and minimum temperatures by 2.4 to 2.8 °C, followed by a significant increase in the vapor pressure deficit and an approximate

15% reduction in relative humidity. These climatic changes have critical effects on the dry season, particularly by reducing night cooling, which diminishes dew formation, an important moisture source for Cerrado species. Such alterations threaten both ecosystems' functioning and the regional water balance.

The observed reduction in native vegetation in our study area reflects the broader historical trend of land use change in the Cerrado. The agricultural frontier, especially in the MATOPIBA region, has advanced by systematically replacing savanna and forest formations with pastures and croplands [12–14]. In 2023, the Cerrado was once again the most deforested biome in Brazil, with over one million hectares of native vegetation cleared [40]. As noted by [15] da Conceição Bispo et al. (2023), this loss has been concentrated in areas that still harbored significant native vegetation, intensifying both ecological and hydrological vulnerabilities.

Our findings indicated relative stability in water yield despite land use changes. However, the existing literature shows that the impacts of vegetation replacement on evapotranspiration are highly dependent on the characteristics of the new land cover [17,41]. In the Urucuia River Basin, the dominant conversion from savanna formations to pastures, which generally have lower crop coefficients (K_c), tends to reduce the evapotranspiration potential. Other transitions, such as from pasture to agriculture, can increase K_c and enhance evapotranspiration, as evidenced in other regions [29,55]. These observations confirm that the specific nature of land cover changes is a critical determinant of their hydrological impact.

An additional concern is the limited scope of formal conservation efforts in the Cerrado biome. Ref. [16] observed that only 8.6% of the Cerrado is currently protected by conservation units, with just 3.1% under strict environmental protection. Furthermore, approximately 40% of the remaining native vegetation is still legally subject to deforestation under current Brazilian legislation [2]. This scenario is particularly alarming in Minas Gerais, where the Urucuia River Basin is located, since the northern region of the state experienced peak deforestation during the 1990s and early 2000s [12,31].

It is important to interpret our findings within the framework of Brazil's National Water Resources Policy, which establishes the watershed as the fundamental unit for planning and management [25]. Hydrological models such as InVEST, when applied alongside scenarios of land use and climate change, offer valuable insights for informing conservation strategies and adaptive management. This approach is increasingly necessary given the intensification of extreme climate events and the escalating anthropogenic pressure on water resources [26].

4. Conclusions

This study assessed the dynamics of water yield in the Urucuia River Basin over the period from 1991 to 2020, considering the combined effects of land use changes and climate variability. Using the InVEST Annual Water Yield model, we investigated how these environmental drivers influence hydrological processes in a region that is both ecologically and hydrologically strategic within the Brazilian Cerrado.

Our first research question addressed the historical evolution of water yield in the basin. The results demonstrated that, despite significant reductions in native vegetation and advances in agricultural land use, water yield remained relatively stable over the past three decades. This apparent stability was primarily driven by climatic factors, particularly the variations in precipitation and reference evapotranspiration, which showed a stronger influence on hydrological outputs than land use changes alone.

Regarding the second question, this study found that climate variability exerts a more decisive influence on water yield compared to land use transitions in the Urucuia

River Basin. Precipitation and evapotranspiration dynamics were the dominant factors controlling the availability of water resources, confirming patterns reported in other studies of the Cerrado biome. Although land use changes modified the vegetation cover and associated crop coefficients, their net effect on water yield was attenuated due to the compensatory nature of the land transitions observed, such as the replacement of savanna formations with pastures of lower evapotranspiration potential.

In response to the third question, the InVEST Annual Water Yield model demonstrated adequate sensitivity in detecting the hydrological responses to climate variability. However, the model presented limitations in capturing the effects of land use changes, particularly in regions with complex agricultural dynamics and irrigation practices. The model's structure, which does not account for subsurface flows or consumptive water use, limits its precision in contexts where groundwater dynamics and irrigation play significant roles.

Overall, this study highlights the importance of considering climate as the main driver of hydrological services in the Cerrado, while recognizing that land use changes can amplify or mitigate these effects depending on the nature of the transformations. The findings reinforce the need for more comprehensive models that integrate surface and subsurface hydrology, land use practices, and climate projections to improve water resource planning and management in the region, offering valuable guidance for sustainable land and water management. Ultimately, this study contributes to improving sustainable development goals by supporting a policy definition that balances economic growth with the conservation of crucial ecosystem services, ensuring long-term regional sustainability and the resilience of water-dependent local communities in the Cerrado biome.

Future research should focus on refining input datasets, incorporating consumptive water use explicitly, and enhancing model calibration and validation with observed hydrological data. Such advancements are essential to support public policies aimed at balancing agricultural production with the conservation of water-related ecosystem services in the Cerrado.

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References

1. Myers, N.; Mittermeier, R.A.; Mittermeier, C.G.; da Fonseca, G.A.B.; Kent, J. Biodiversity hotspots for conservation priorities. *Nature* **2000**, *403*, 853–858. [CrossRef]
2. Strassburg, B.B.N.; Brooks, T.; Feltran-Barbieri, R.; Iribarrem, A.; Crouzeilles, R.; Loyola, R.; Latawiec, A.E.; Oliveira Filho, F.J.B.; De Scaramuzza, C.A.M.; Scarano, F.R.; et al. Moment of Truth for the Cerrado Hotspot. *Nat. Ecol. Evol.* **2017**, *1*, 0099. Available online: <https://www.nature.com/articles/s41559-017-0099> (accessed on 15 July 2025). [CrossRef]
3. Sano, E.E.; Rosa, R.; Brito, J.L.S.; Ferreira, L.G. Mapeamento de Cobertura Vegetal do Bioma Cerrado: Estratégias e Resultados. 2007. Available online: <https://www.sidalc.net/search/Record/dig-infoteca-e-doc-570887> (accessed on 15 July 2025).
4. MAPBIOMAS. RAD2024: Relatório Anual do Desmatamento no Brasil 2023. São Paulo, Brasil, 2024. 154p. Available online: <https://alerta.mapbiomas.org/relatorio/> (accessed on 14 July 2025).
5. de Carvalho, F.M.V.; Ferreira, L.G.; Lobo, F.C.; Diniz-Filho, J.A.F.; Bini, L.M. Padrões de Autocorrelação Espacial de Índices de Vegetação MODIS No Bioma Cerrado. *Rev. Árvore* **2008**, *32*, 279–290. [CrossRef]
6. Carvalho, F.M.V.; De Marco, P.; Ferreira, L.G. The Cerrado Into-Pieces: Habitat Fragmentation as a Function of Landscape Use in the Savannas of Central Brazil. *Biol. Conserv.* **2009**, *142*, 1392–1403. [CrossRef]
7. De Castro, E.A.; Kauffman, J.B. Ecosystem structure in the Brazilian Cerrado: A vegetation gradient of aboveground biomass, root mass and consumption by fire. *J. Trop. Ecol.* **1998**, *14*, 263–283. [CrossRef]
8. Klink, C.A.; Sato, M.N.; Cordeiro, G.G.; Ramos, M.I.M. The role of vegetation on the dynamics of water and fire in the Cerrado ecosystems: Implications for management and conservation. *Plants* **2020**, *9*, 1803. [CrossRef] [PubMed]
9. Da Rocha, H.R.; Manzi, A.O.; Cabral, O.M.; Miller, S.D.; Goulden, M.L.; Saleska, S.R.; R-Coupe, N.; Wofsy, S.C.; Borma, L.S.; Artaxo, P.; et al. Patterns of water and heat flux across a biome gradient from tropical forest to savanna in Brazil. *J. Geophys. Res. Biogeosci.* **2009**, *114*, 1–8. [CrossRef]
10. Oliveira, R.S.; Bezerra, L.; Davidson, E.A.; Pinto, F.; Klink, C.A.; Nepstad, D.C.; Moreira, A. Deep root function in soil water dynamics in cerrado savannas of central Brazil. *Funct. Ecol.* **2005**, *19*, 574–581. [CrossRef]
11. Anache, J.A.; Wendland, E.; Rosalem, L.M.; Youlton, C.; Oliveira, P.T. Hydrological trade-offs due to different land covers and land uses in the Brazilian Cerrado. *Hydrol. Earth Syst. Sci.* **2019**, *23*, 1263–1279. [CrossRef]
12. Parente, L.; Nogueira, S.; Baumann, L.; Almeida, C.; Maurano, L.; Affonso, A.G.; Ferreira, L. Quality Assessment of the PRODES Cerrado Deforestation Data. *Remote Sens. Appl.* **2021**, *21*, 100444. [CrossRef]
13. Pires, M.O. ‘Cerrado’, Old and New Agricultural Frontiers. *Braz. Political Sci. Rev.* **2020**, *14*, e004. [CrossRef]
14. Trigueiro, W.R.; Nabout, J.C.; Tessarolo, G. Uncovering the Spatial Variability of Recent Deforestation Drivers in the Brazilian Cerrado. *J. Environ. Manag.* **2020**, *275*, 111243. [CrossRef]
15. da Conceição Bispo, P.; Picoli, M.C.A.; Marimon, B.S.; Marimon Junior, B.H.; Peres, C.A.; Menor, I.O.; Silva, D.E.; de Figueiredo Machado, F.; Alencar, A.A.C.; de Almeida, C.A.; et al. Overlooking Vegetation Loss Outside Forests Imperils the Brazilian Cerrado and Other Non-Forest Biomes. *Nat. Ecol. Evol.* **2023**, *8*, 12–13. [CrossRef]
16. Santos, S.A.; Cherem, L.F.S. Estrutura Espacial e Temporal Das Unidades de Conservação No Cerrado: Heterogeneidade Combinada em prol da Conservação. *Soc. Nat.* **2022**, *35*, e65504. [CrossRef]
17. Fenicia, F.; McDonnell, J.J. Modeling Streamflow Variability at the Regional Scale: (1) Perceptual Model Development through Signature Analysis. *J. Hydrol.* **2022**, *605*, 127287. [CrossRef]
18. Wei, X.; Zhang, M. Quantifying streamflow change caused by forest disturbance at a large spatial scale: A single watershed study. *Water Resour. Res.* **2010**, *46*, 1–15. [CrossRef]
19. Li, Q.; Wei, X.; Zhang, M.; Liu, W.; Giles-Hansen, K.; Wang, Y. The cumulative effects of forest disturbance and climate variability on streamflow components in a large forest-dominated watershed. *J. Hydrol.* **2018**, *557*, 448–459. [CrossRef]
20. Aryal, Y.; Zhu, J. Effect of watershed disturbance on seasonal hydrological drought: An improved double mass curve (IDMC) technique. *J. Hydrol.* **2020**, *585*, 124746. [CrossRef]
21. Campos, J.d.O.; Chaves, H.M.L. Tendências e Variabilidades Nas Séries Históricas de Precipitação Mensal e Anual No Bioma Cerrado No Período 1977–2010. *Rev. Bras. Meteorol.* **2020**, *35*, 157–169. [CrossRef]

22. Hofmann, G.S.; Cardoso, M.F.; Alves, R.J.V.; Weber, E.J.; Barbosa, A.A.; de Toledo, P.M.; Pontual, F.B.; Salles, L.d.O.; Hasenack, H.; Cordeiro, J.L.P.; et al. The Brazilian Cerrado Is Becoming Hotter and Drier. *Glob. Change Biol.* **2021**, *27*, 4060–4073. [CrossRef] [PubMed]
23. Siqueira, P.P.; Oliveira, P.T.S.; Bressiani, D.; Meira Neto, A.A.; Rodrigues, D.B.B. Effects of Climate and Land Cover Changes on Water Availability in a Brazilian Cerrado Basin. *J. Hydrol. Reg. Stud.* **2021**, *37*, 100931. [CrossRef]
24. Salmona, Y.B.; Matricardi, E.A.T.; Skole, D.L.; Silva, J.F.A.; Coelho Filho, O.d.A.; Pedlowski, M.A.; Sampaio, J.M.; Castrillón, L.C.R.; Brandão, R.A.; da Silva, A.L.; et al. A Worrying Future for River Flows in the Brazilian Cerrado Provoked by Land Use and Climate Changes. *Sustainability* **2023**, *15*, 4251. [CrossRef]
25. BRASIL. Lei N° 9.433, de 8 de Janeiro de 1997. Institui a Política Nacional de Recursos Hídricos, Cria o Sistema Nacional de Gerenciamento de Recursos Hídricos, Regulamenta o Inciso XIX Do Art. 21 Da Constituição Federal, e Altera o Art. 1o Da Lei No 8.001, de 13 de Março de 1990, Que Modificou a Lei No 7.990, de 28 de Dezembro de 1989. Available online: https://www.planalto.gov.br/ccivil_03/leis/19433.htm (accessed on 14 July 2025).
26. Bendito, B.P.C.; Chaves, H.M.L.; Scariot, A. Erosion and Sedimentation Processes in a Semi-Arid Basin of the Brazilian Savanna under Different Land Use, Climate Change, and Conservation Scenarios. *Water* **2023**, *15*, 563. [CrossRef]
27. Sharp, R.; Chaplin-Kramer, R.; Wood, S.; Guerry, A.; Tallis, H.; Ricketts, T.; Nelson, E.; Ennaanay, D.; Wolny, S.; Olwero, N.; et al. *InVEST User's Guide*; The Natural Capital Project, Stanford University: Stanford, CA, USA; University of Minnesota: Minneapolis, MN, USA; The Nature Conservancy: Arlington, VA, USA; World Wildlife Fund: Washington, DC, USA, 2018. [CrossRef]
28. Yu, Y.; Sun, X.; Wang, J.; Zhang, J. Using InVEST to Evaluate Water Yield Services in Shangri-La, Northwestern Yunnan, China. *PeerJ* **2022**, *10*, e12804. [CrossRef]
29. Aneseyee, A.B.; Soromessa, T.; Elias, E.; Noszczyk, T.; Feyisa, G.L. Evaluation of Water Provision Ecosystem Services Associated with Land Use/Cover and Climate Variability in the Winike Watershed, Omo Gibe Basin of Ethiopia. *Environ. Manag.* **2022**, *69*, 367–383. [CrossRef] [PubMed]
30. Redhead, J.W.; Stratford, C.; Sharps, K.; Jones, L.; Ziv, G.; Clarke, D.; Oliver, T.H.; Bullock, J.M. Empirical Validation of the InVEST Water Yield Ecosystem Service Model at a National Scale. *Sci. Total Environ.* **2016**, *569–570*, 1418–1426. [CrossRef]
31. Espírito-Santo, M.M.; Leite, M.E.; Silva, J.O.; Barbosa, R.S.; Rocha, A.M.; Anaya, F.C.; Dupin, M.G.V. Understanding Patterns of Land-Cover Change in the Brazilian Cerrado from 2000 to 2015. *Philos. Trans. R. Soc. B Biol. Sci.* **2016**, *371*, 20150435. [CrossRef]
32. de Oliveira Filho, E.R. Revitalização por barragem na Bacia Hidrográfica do Rio Urucuia. HUMBOLDT 1, No. 1. 2020. Available online: <https://www.e-publicacoes.uerj.br/humboldt/article/view/52457> (accessed on 14 July 2025).
33. ANA—National Water and Sanitation Agency. Projeto de Gerenciamento Integrado. Plano Decenal de Recursos Hídricos da Bacia Hidrográfica do Rio São Francisco—Pbhsf. 2004. Available online: https://cdn.agenciapexvivo.org.br/media/2020/01/Sintese_Resumo_Exec.-PLAN-DECENAL.pdf (accessed on 14 July 2025).
34. IGAM—Minas Gerais Water Management Institute. Plano Diretor de Recursos Hídricos da Bacia Hidrográfica do Rio Urucuia—SF8: Relatório Final Volume I B Diagnóstico da Bacia Hidrográfica SF8. 2014. Available online: <http://repositorioigam.meioambiente.mg.gov.br/handle/123456789/679> (accessed on 14 July 2025).
35. Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; de Moraes Gonçalves, J.L.; Sparovek, G. Köppen's Climate Classification Map for Brazil. *Meteorol. Z.* **2013**, *22*, 711–728. [CrossRef] [PubMed]
36. Mata, C.L.; de Carvalho Júnior, O.A.; De Carvalho, A.P.F.; Gomes, R.A.T.; Martins, É.d.S.; Guimarães, R.F. Avaliação Multitemporal Da Susceptibilidade Erosiva Na Bacia Do Rio Urucuia (Mg) Por Meio Da Equação Universal de Perda de Solos. *Rev. Bras. Geomorfol.* **2007**, *8*, 2. [CrossRef]
37. IBGE—Brazilian Institute of Geography and Statistic. Censo Agrícola—2017. Available online: <https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/21814-2017-censo-agropecuario.html> (accessed on 14 July 2025).
38. ANA—National Water and Sanitation Agency. HIDROWEB v3.3.8361.0 Platform. 2025. Available online: <https://www.snirh.gov.br/hidroweb/apresentacao> (accessed on 14 July 2025).
39. Xavier, A.C.; King, C.W.; Scanlon, B.R. Daily gridded meteorological variables in Brazil (1980–2013). *Int. J. Climatol.* **2016**, *36*, 2644–2659. [CrossRef]
40. Projeto MapBiomass—Coleção 7.0 da Série Anual de Mapas de Cobertura e Uso da Terra do Brasil. Available online: <https://brasil.mapbiomas.org/map/colecao-7/> (accessed on 12 May 2025).
41. Allen, R.G. Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements. *FAO Irrig. Drainage* **1998**, *56*, 60–64.
42. Schenk, H.J.; Jackson, R.B. Rooting Depths, Lateral Root Spreads and below-Ground/above-Ground Allometries of Plants in Water-Limited Ecosystems. *J. Ecol.* **2002**, *90*, 480–494. [CrossRef]
43. Saad, S.I. Modelagem e Valoração Dos Serviços Ambientais Hidrológicos Na Recuperação Da Vegetação No Ribeirão Dsa Posses, Extrema, MG. Ph.D. Thesis, Universidade de São Paulo, São Paulo, Brasil, 2015.
44. He, J.; Zhao, Y.; Wen, C. Spatiotemporal Variation and Driving Factors of Water Supply Services in the Three Gorges Reservoir Area of China Based on Supply-Demand Balance. *Water* **2022**, *14*, 2271. [CrossRef]
45. Ning, T.; Li, Z.; Liu, W. Vegetation dynamics and climate seasonality jointly control the interannual catchment water balance in the Loess Plateau under the Budyko framework. *Hydrol. Earth Syst. Sci.* **2017**, *21*, 1515–1526. [CrossRef]

46. Donohue, R.J.; Roderick, M.L.; McVicar, T.R. Roots, Storms and Soil Pores: Incorporating Key Ecohydrological Processes into Budyko's Hydrological Model. *J. Hydrol.* **2012**, *436–437*, 35–50. [[CrossRef](#)]
47. Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Trans. ASABE* **2007**, *50*, 885–900. [[CrossRef](#)]
48. Gupta, H.V.; Sorooshian, S.; Yapo, P.O. Status of Automatic Calibration for Hydrologic Models: Comparison with Multilevel Expert Calibration. *J. Hydrol. Eng.* **1999**, *4*, 135–143. [[CrossRef](#)]
49. Nash, J.E.; Sutcliffe, J.V. River Flow Forecasting through Conceptual Models Part I—A Discussion of Principles. *J. Hydrol.* **1970**, *10*, 282–290. [[CrossRef](#)]
50. Sen, P.K. Estimates of the Regression Coefficient Based on Kendall's Tau. *J. Am. Stat. Assoc.* **1968**, *63*, 1379. [[CrossRef](#)]
51. Yue, S.; Wang, C.Y. Applicability of prewhitening to eliminate the influence of serial correlation on the Mann–Kendall test. *Water Resour. Res.* **2002**, *38*, 4-1-4-7. [[CrossRef](#)]
52. Feng, M.; Liu, P.; Guo, S.; Gui, Z.; Zhang, X.; Zhang, W.; Xiong, L. Identifying changing patterns of reservoir operating rules under various inflow alteration scenarios. *Adv. Water Resour.* **2017**, *104*, 23–36. [[CrossRef](#)]
53. Marengo, J.A.; Cunha, A.P.M.A.; Nobre, C.A.; Ribeiro Neto, G.G.; Magalhães, A.R.; Torres, R.R.; Sampaio, G.; Alexandre, F.; Alves, L.M.; Cuartas, L.A.; et al. Assessing drought in the drylands of northeast Brazil under regional warming exceeding 4 °C. *Nat. Hazards* **2020**, *103*, 2589–2611. [[CrossRef](#)]
54. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2021—The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2023. [[CrossRef](#)]
55. Zhang, M.; Liu, N.; Harper, R.; Li, Q.; Liu, K.; Wei, X.; Ning, D.; Hou, Y.; Liu, S. A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. *J. Hydrol.* **2017**, *546*, 44–59. [[CrossRef](#)]

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