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HYDROLOGICAL ANALYSIS AND IMPACTS OF LAND USE AND OCCUPATION IN THE VERDE RIVER BASIN/MG: EVALUATION FROM THE GR4J MODEL

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ABSTRACT
The Rio Verde watershed, with an area of 6,891 km², is influenced by geological and climatic characteristics. Knowledge of the flow regime of the Rio Verde basin, located in the South/Southwest of Minas Gerais, is essential for agriculture, energy generation and drinking water supply. Data were collected from fluviometric and rainfall stations, highlighting the importance of integrating land use and hydrological behavior for more accurate hydrological forecasts. The GR4J hydrological model can be used to evaluate the rainfall-flow ratio in order to characterize and establish a variation about the water regime of a basin. The calibration of the model, carried out between 1989 and 1992, resulted in an NSE of 0.51, indicating a moderate ability to replicate the hydrological behavior, although with difficulties in capturing flow peaks. In the validation, from 1993 to 1994, the performance improved, with an NSE of 0.68 and a KGE of 0.84, demonstrating greater accuracy in the flow patterns. The analysis of land use in the 90's revealed the predominance of pastures, occupying about 29.8% of the area in 1991, which may have increased the surface runoff.

Keywords: Hydrological Modeling. Flow. Surface runoff.

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Revista ARACÊ
ISSN: 2358-2472

INTRODUCTION

Flow forecasting is one of the main challenges related to the integrated knowledge of climatology and hydrology. Advance knowledge of the flow of a watershed is most commonly used for flood forecasting, for predicting moisture in arable soil, for predicting the water levels of a navigable river, and for knowledge of water availability in the water supply for irrigation and electricity production (TUCCI et al. 2002).

Hydrological models can be considered as a tool developed to represent the behavior of the river basin, predict future conditions and/or simulate hypothetical situations in order to evaluate impacts of changes. Hydrological simulation is limited by the physical heterogeneity of the basin and the processes involved, which has greatly contributed to the development of many models (OLIVEIRA, 2003). These, however, differ from each other depending on the objectives to be achieved, the data they use and the priorities that are established in the representation of physical processes.

With the development of technologies regarding the study of watershed flow, several hydrological models were developed, such as the SMAP (SILVA et al, 2001), TOPMODEL (BEVEN AND KIRKBY, 1979), ARNO (TODINI, 1996) and AÇUMOD (PASSERAT DE SELANS et al, 2000) models.

The GR4J conceptual model (Perrin et al., 2003) developed in France is representative due to its implementation in different countries in Europe, Australia, Brazil and Russia, presenting promising results in regions with varied climatic, geological, pedological and vegetation cover characteristics (OUDIN et al., 2010; PONCELET et al., 2017; PAGANO et al., 2010; NETO et al., 2021; AYZEL et al., 2019). Another advantage of this model is the dependence on a few parameters and the use of two input data, which are: the series of average precipitation of the basin and potential evapotranspiration. Such advantages were extremely important for the choice of the application of the GR4J model in the present study.

The study area consists of the Rio Verde Hydrographic Basin, an extensive basin in the south of the state of Minas Gerais. The basin has an area of approximately 6,800 km², covering 31 municipalities and 600 thousand people. The basin is of extreme social and economic importance for the region, being used for human supply, recreation, animal watering, fishing and irrigation. Considering the multiple uses of the waters of the Rio Verde hydrographic basin, it is necessary to understand the flow in the rivers and their variations.

Revista ARACÊ
ISSN: 2358-2472

RESULTS AND DISCUSSION

In the calibration, the minimum flow was 5,814m³/h, the average flow was 27,610m³/h and the maximum was 533,040. The average daily minimum temperature was 14°C and the average maximum temperature was 27°C.

CALIBRATION

The calibration of the GR4J model, performed from 12/01/1989 to 12/01/1992 (FIGURE 1) showed varied performance in the efficiency indexes. The NSE (Nash-Sutcliffe Efficiency) reached 0.51, indicating a moderate ability of the model to replicate the hydrological behavior of the basin. This value, although acceptable, suggests that the model does not perfectly reproduce the flow peaks, which is corroborated by the graphical visualization, where the simulation (orange line) fails to adequately capture the magnitude of extreme events. The NSE version for the flow with square root was 0.63, indicating that the model better simulates the medium and low flows, showing a smoothing of the deviations observed in the high flows.

The KGE index (Kling-Gupta Efficiency) presented a value of 0.55, which signals a reasonable performance, balancing correlation, bias and flow variability. By applying the square root of the flows, the KGE improved to 0.69, reinforcing the conclusion that the model has greater accuracy at more moderate flows, while showing difficulties in flood events. The graph corroborates these results, with the simulations approaching the observations (Qobs) for most of the period, but diverging mainly during the extreme peaks.

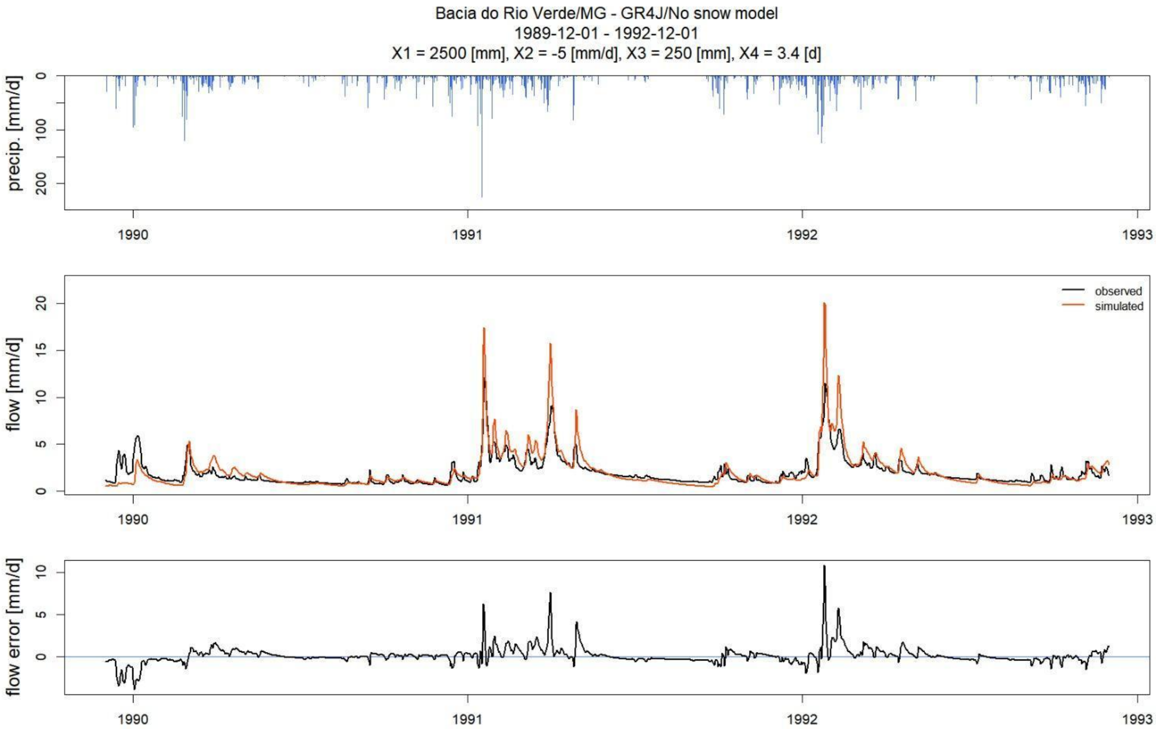
The bias of 1.07 points to a slight overestimation of the simulated flows compared to the observed ones, suggesting that the model tends to predict more flow than recorded, especially at peak times. These results are common in conceptual models such as GR4J, which simplify hydrological processes and may have limitations in modeling extreme events. Visual analysis of the graph also indicates that the model is effective at capturing the seasonal pattern of flows, but needs additional adjustments to improve the simulation of extremes.

The NSE of 0.51 and the KGE of 0.55 presented are in line with results reported by Andrade et al. (2022) in the hydrological modeling of the Piranhas-Açu river basin, where the NSE ranged from 0.42 to 0.68, depending on the period and calibration conditions. In the case of this study, difficulties were also observed in flow peaks, attributed to intrinsic limitations of GR4J in representing extreme events (ANDRADE et al., 2022).

Revista ARACÊ
ISSN: 2358-2472

In the study by Astorayme et al. (2015), in the Chillón River basin in Peru, higher SES values were reported, close to 0.75, which can be explained by the semi-distributed approach adopted, which improves the spatial representation of hydrological variables, demonstrating the importance of the initial configuration of the model. In Andrade (2024), when analyzing basins in the Brazilian Northeast, a bias similar to his work was found, indicating overestimation trends that corroborate the need to adjust the parameters for different climates and physiographic characteristics.

Figure 1: Calibration of the GR4J model in the Rio Verde sub-basin/MG from 1989 to 1992.



Source: The authors.

VALIDATION

The validation of the GR4J model, carried out from 06/01/1993 to 06/01/1994 (FIGURE 2), presents significantly better results than those obtained in calibration. The NSE (Nash-Sutcliffe Efficiency) of 0.68 demonstrates that the model now more effectively reproduces the flow patterns, which is visible in the graph, where the simulated (Qsim) and observed (Qobs) lines are quite close, except for some minor variations in the flow peaks. The NSE applied to the square root of the flows also presents a slightly lower value, 0.61, indicating that the model maintains a good capacity to represent both average and low flows.

Revista ARACÊ
ISSN: 2358-2472

The KGE (Kling-Gupta Efficiency) index reached 0.84, representing a substantial improvement over calibration (KGE of 0.55), which suggests that the model now more accurately captures the correlation, bias and variability of flow rates. This can be visually corroborated by the proximity between the simulation and observation lines throughout almost the entire validation period. The KGE value for the square root of the flows was 0.78, which reinforces the model's improvement in predicting average flows.

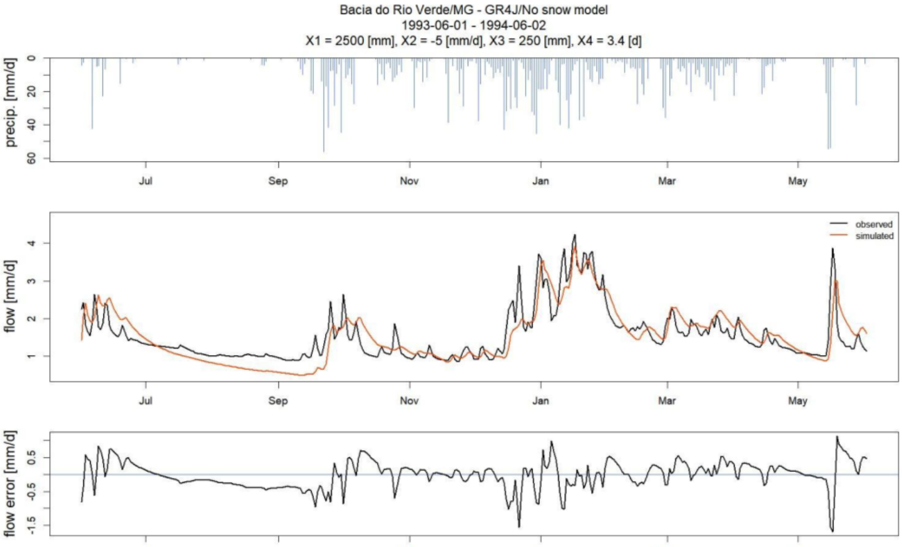
Finally, the bias of 0.99 indicates that the model is practically without a tendency to overestimate or underestimate, which is a significant improvement over the bias of 1.07 observed in calibration. This convergence between the simulated and observed flows shows that the adjustments made to the model during calibration resulted in better performance in the validation phase, especially in terms of accuracy in flows and lower error in flood events.

In the work by Andrade et al. (2022), it was also observed that, after adjustments in calibration, efficiency indices such as NSE and KGE showed significant improvements during validation, with NSE values ranging from 0.60 to 0.72, close to the value of 0.68 found in the present study. The reduction in bias (from 1.07 to 0.99) and the increase in KGE to 0.84 in validation highlight a more balanced performance of the model, similar to the results of Andrade (2024), who found KGE values between 0.80 and 0.86 when validating GR4J in northeastern basins, highlighting its effectiveness in seasonal simulation of flows.

In the study by Astorayme et al. (2015), using the model in different climatic conditions in the Chillón River basin, similar results in the validation showed an improvement in the indices with appropriate adjustments, reinforcing that the validation phase benefits from a detailed calibration. Thus, the validation carried out reinforces the robustness of GR4J by capturing hydrological patterns and reducing discrepancies in peak events, although its limitations are still noted in some extreme events.

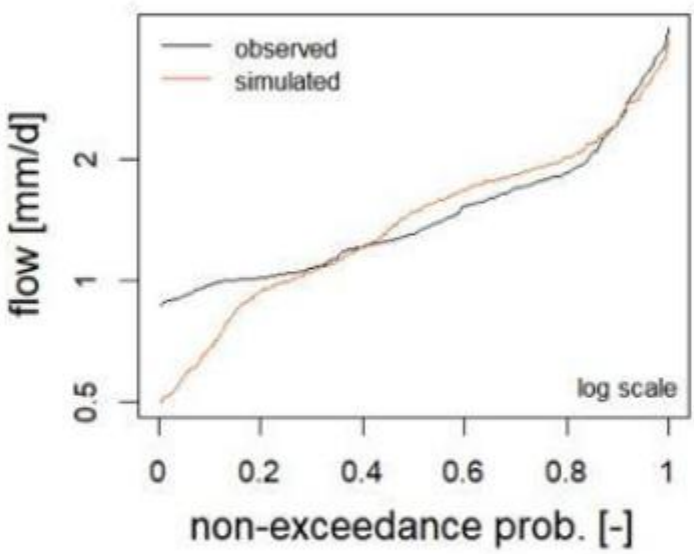
Revista ARACÊ
ISSN: 2358-2472

Figure 2: Validation of the GR4J model in the Rio Verde sub-basin/MG from 1993 to 1994.



Source: The authors.

Figure 3: Permanence curve of the flow in the basin studied in the period from 1993 to 1994.



Source: The authors.

GR4J MODEL PARAMETERS

During the calibration and validation process of the GR4J model, the parameters X1, X2, X3 and X4 played a crucial role in the simulation of the flows observed in the Rio Verde basin/MG. Parameter X1, referring to the production storage capacity, was set at 2,500 mm in both calibration and validation. This high value indicates a large water storage capacity in the soil, which is consistent with regions where infiltration and underground storage are prevalent. The high production storage capacity reflects the importance of groundwater reserves in controlling surface runoff in periods of intense rainfall and prolonged droughts, smoothing the flow peaks observed in the graph.

The X2 parameter, which corresponds to the exchange coefficient between river basins, was adjusted to -5 mm/day in both phases, indicating a constant loss of water to neighboring basins or groundwater. This negative value suggests that there is a flow of water leaving the basin, which may be related to geological features that allow percolation or drainage to adjacent regions. This water transfer helps to reduce the volume of runoff and may explain the underestimations observed during flow peaks, as the model loses a part of the volume that should remain in the basin.

The X3, which represents the routing storage capacity, was kept at 250 mm. This value controls the storage capacity in the transfer zone of the runoff to the main river. An intermediate routing capacity such as this suggests that the response time between precipitation and flow in rivers is not immediate, allowing for gradual drainage. This explains the smoothing of the flow peaks and the fact that the model manages to capture well the recession phases of rainy events, but still presents small divergences in the highest peaks.

The X4, which refers to the time constant of the unit hydrograph, was set at 3.4 days in the two stages. This average value indicates a moderate response time of the basin to precipitation events. That is, runoff reaches its peak approximately 3.4 days after the rainfall event, which corresponds well to the behavior observed in the graph, where responses to heavy rainfall occur with some delay, smoothing the runoff curve and reducing instantaneous flow variability.

These calibration and validation values reflect a basin with large storage capacity, moderate response time, and significant interaction with adjacent water systems. The minimal variations in peak flow can be attributed to the need for more refined adjustments, especially in the X2 parameter, to improve the representation of inter-basin exchanges.

LAND USE AND OCCUPATION

The analysis of land use and occupation data (FIGURE 4) in the Rio Verde basin shows that, during the calibration (1991-1992) and validation (1993-1994) periods of the GR4J model, pasture was the predominant use class, occupying approximately 29.8% of the total area in 1991 and marginally varying to 29.5% in 1994 (TABLE 1). This predominance of pasture has direct implications for the hydrological behavior of the basin,

Revista ARACÊ
ISSN: 2358-2472

since pasture areas, due to their lower infiltration capacity compared to forests, promote greater surface runoff. This may explain the flow peaks observed during the most intense rainfall events, reflected in the calibration and validation results, where the rapid response of the basin indicated a low water holding capacity.

In contrast, forest formations remained stable at around 13.4% throughout the period, contributing in a limited way to the moderation of runoff. The presence of forest vegetation generally increases the infiltration capacity, slows the runoff and stabilizes the water regime of the basin. However, the low proportion of forest cover in the basin may have reduced the ability to dampen runoff peaks, influencing the performance of the model, which showed rapid hydrological responses in both periods.

Another relevant factor is the mosaic of uses, which increased from 3.5% in 1991 to 4.2% in 1994. This class reflects a diversified landscape, with fragments of agricultural areas and natural vegetation, which can generate spatial variability in the runoff. Mixed-use areas can make it difficult to predict runoff due to the heterogeneity of infiltration and runoff conditions, influencing both calibration and model validation.

In addition, the urbanized area, although small, changing from 0.22% in 1991 to 0.30% in 1994, still contributes to soil impermeabilization, which can intensify localized and rapid runoff during precipitation events. This increase in waterproofing can have a punctual but significant effect on the increase in surface runoff in specific regions of the basin.

Coffee cultivation, which decreased from 2.34% in 1991 to 1.98% in 1994, and other perennial and temporary crops had small variations, indicating a slight decrease in the most intensive agricultural areas. These changes may have moderate impacts on runoff, since temporary crops have lower water holding capacity compared to perennial crops, contributing to variations in the runoff regime observed during calibration and validation periods.

Thus, the association between changes in land use and occupation and hydrological results reflects the importance of considering land management in hydrological simulations. The high proportion of grassland, combined with limited forest cover, plays a crucial role in the rapid response of the basin during precipitation events, while urbanized areas and the mosaic of uses generate additional variability. These factors significantly influence the performance of the GR4J model in the calibration and validation periods, highlighting the need for an integrated analysis between land use and hydrological behavior to improve the accuracy of the forecasts.

Revista ARACÊ
ISSN: 2358-2472

The analysis of land use and occupation in the Rio Verde basin points to direct implications on hydrological behavior, corroborating findings of similar studies. For example, Andrade et al. (2022) highlighted the influence of pasture areas on the increase in surface runoff in semi-arid basins, where lower infiltration capacity reduces water retention and intensifies flow peaks. These results are congruent with the predominance of pasture in the Rio Verde basin, which occupied about 29% of the territory, contributing to rapid responses during heavy rainfall events. In addition, studies such as that of Andrade (2024) show the importance of forest formations in moderating the water regime, attributing to forests a greater capacity for infiltration and attenuation of extreme flows. In the Rio Verde basin, the limited proportion of forest cover (13.4%) partially contributes to dampen runoff peaks, but not on a sufficient scale to balance the predominance of more intensive uses, such as pastures and urbanized areas.

Urbanized areas, although small, play a significant role in soil sealing, an effect also observed by Astorayme et al. (2015) in the Chillón River basin, where increased urbanization has generated more intense localized runoff. In the case of Rio Verde, urban growth from 0.22% to 0.30% between 1991 and 1994 probably intensified point flows, affecting the ability of the GR4J model to capture complex flow patterns. On the other hand, the mosaic of uses and perennial crops, whose variations were small, generate spatial heterogeneity in the runoff, in line with the results of studies such as those by Andrade (2024), which indicate additional challenges in hydrological modeling in diversified landscapes.

This work contributes to the understanding of the relationship between land use and hydrological responses, reinforcing the need to consider occupation characteristics in the calibration of hydrological models such as GR4J. The analyses carried out highlight the importance of integrated land management to improve hydrological forecasting, providing subsidies for sustainable land use policies and water resources management.

Table 1: Table of land use and occupation in area (Km) and percentage of the study region.

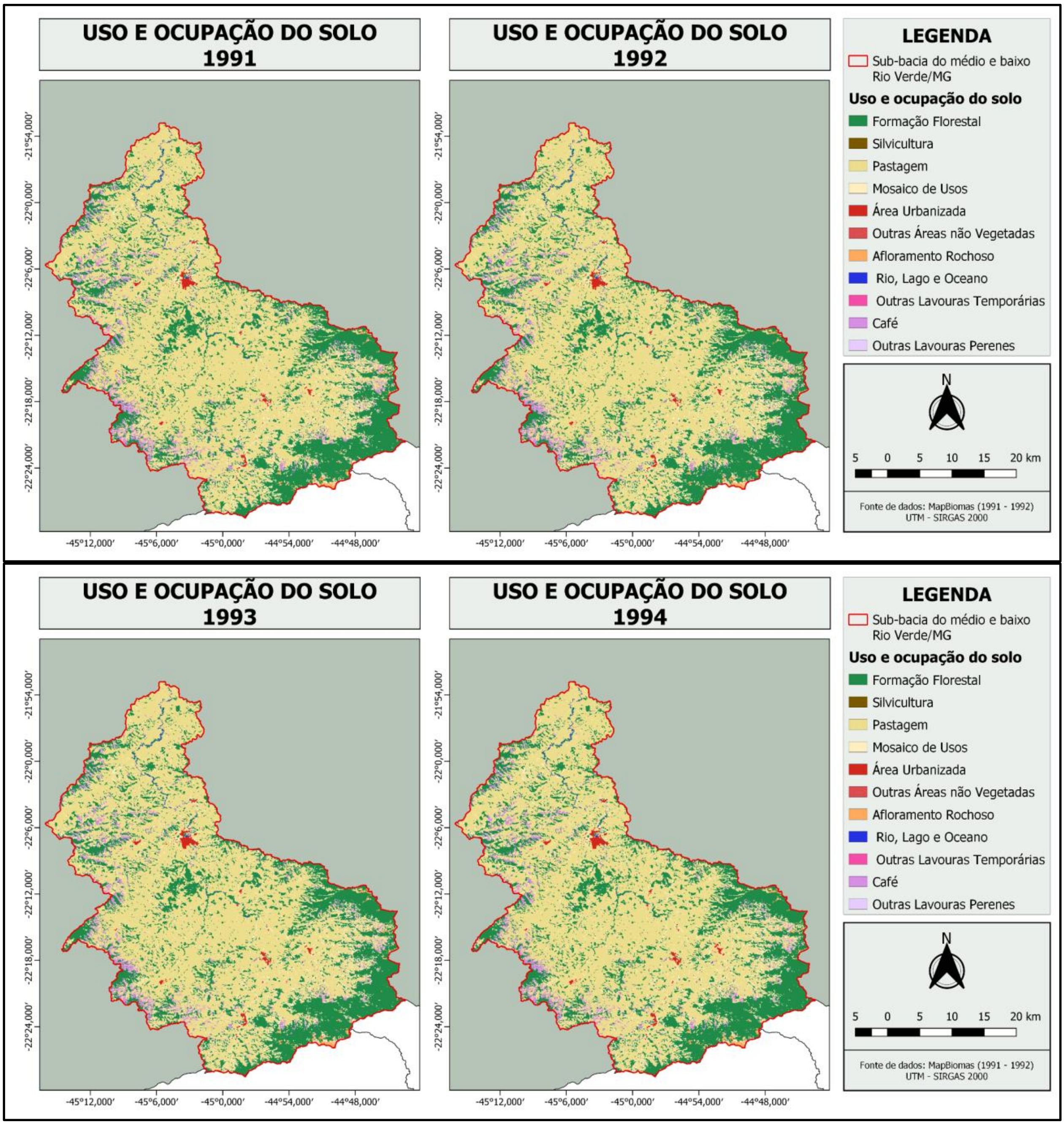
Land use and occupation	1991		1992		1993		1994	
	MILES	%	MILES	%	MILES	%	MILES	%
Forestry Training	496.13983	13.4491%	495.69811	13.4360%	494.45200	13.4002%	496.42967	13.4531%
Silviculture	0.29265	0.0079%	0.25611	0.0069%	0.17404	0.0047%	0.18811	0.0051%
Pasture	1100.60319	29.8165%	1103.91043	29.9115%	1099.90192	29.7971%	1086.75250	29.4482%

Revista ARACÊ
ISSN: 2358-2472

Mosaic of Uses	129.924 13	3.5204%	134.3 9040	3.6427 %	143.67 387	3.8945 %	154.28 518	4.1816 %
Urbanized Area	8.23567	0.2231%	8.497 75	0.2303 %	10.211 06	0.2767 %	11.082 47	0.3003 %
Other non-vegetated areas	0.22906	0.0062%	0.234 86	0.0064 %	0.2365 3	0.0064 %	0.2207 4	0.0060 %
Rocky outcrop	7.79270	0.2111%	7.780 23	0.2108 %	7.7446 0	0.2098 %	7.7354 9	0.2096 %
River, Lake & Ocean	4.16593	0.1129%	4.230 62	0.1146 %	4.1235 4	0.1117 %	4.0205 6	0.1090 %
Other Temporary Crops	0.21409	0.0058%	0.241 40	0.0065 %	0.2712 0	0.0073 %	0.3060 5	0.0083 %
Coffee	86.4515 9	2.3439%	78.79 566	2.1359 %	73.255 12	1.9842 %	72.988 32	1.9777 %
Other Perennial Crops	0.71619	0.0194%	0.729 46	0.0198 %	0.7211 7	0.0195 %	0.7559 5	0.0205 %

Revista ARACÊ
ISSN: 2358-2472

Figure 4: Thematic maps on land use and occupation in the study area in the years 1991, 1992, 1993 and 1994.



Source: The authors.

MATERIALS AND METHODS

FIELD OF STUDY

The Rio Verde has its source in the border region between the municipalities of Passa Quatro and Itanhandu, on the western slope of the Serra da Mantiqueira, at an altitude of approximately 2,600 meters, near the border between the states of Minas Gerais, São Paulo and Rio de Janeiro. From its source, the river heads west, running along the slope of the mountain until it flows into the Furnas dam, located on the border of the municipalities of Elói Mendes and Três Pontas, reaching an altitude of about 800 meters. During its course, the Verde River receives several significant tributaries, such as the Passa Quatro River, Carmo River, Lambari River, São Bento River, Aterrado River, Palmela River, Caeté River, Capivari River, Baependi River, Peixe River, in addition to the Pouso Alto and Espera streams (IGAM, 2010). The Rio Verde hydrographic basin (Figure 5) is entirely located in the state of Minas Gerais, between the parallels 210 20' to 220 30', south latitude, and 440 40' to 450 40', west longitude, covering an area of 6,891 km² and bathing 31 municipalities in the south/southwest mesoregion of the state (IGAM, 2010). According to the 2022 IBGE census, approximately 618,544 inhabitants live in the area of this basin. The natural vegetation cover is composed of fields, savannahs, paths and remnants of semideciduous seasonal forest. However, silviculture, especially eucalyptus planting, has substantially modified this vegetation (TESE, 2008). The relief is characterized by asymmetrical ridges, escarpments, colluvial ramps, "hill seas", convex hills, steep slopes and embedded valleys, typical of the geomorphology of the Serra da Mantiqueira (BEATO et al., 1999). Geologically, the region is predominantly composed of Precambrian rocks of the Amparo, Andrelândia, Paraisópolis, Varginha and São João Del Rei complexes, with the presence of quartzites in various formations and an extensive granite-gneiss complex. The Quaternary formations, composed of alluvial sedimentary deposits and undifferentiated covers, occupy smaller areas of the basin.

The climate in the area is characterized as mesothermal, with moderate temperatures and high humidity, with three months of drought. The average annual temperature varies between 18 and 19 °C, corresponding mainly to the Cwa climatic type, although in the headwater areas, it is possible to observe typical Cwb climate conditions. The upper portion of the Rio Verde is located near the municipality of São Lourenço, in a region dominated by steep slopes and shallow soils. The lower course of the river, in the region of Varginha, is located at altitudes ranging between 900 and 1,000 meters (IGAM, 2010).

Revista ARACÊ
ISSN: 2358-2472

Figure 5: Map of the location of the study area.

Source: The authors.

DATA

Flow data from the fluviometric station of Conceição do Rio Verde, Minas Gerais (code 61460000), located in the Rio Verde basin, covering the period from 1933 to 2023, were used. The georeferencing information was obtained from the Spatial Data Infrastructure of the State System of Environment and Water Resources (IDE-Sisema, 2023). Additionally, data from fluviometric and rainfall stations provided by the National Water Agency (ANA, 2019) were used, as well as climate data from the National Institute of Meteorology (INMET, 2022). For the analysis of temperature and evaporation, data from the meteorological station of São Lourenço/MG were considered, as well as rainfall information from 10 stations located in the study area, all with historical series of more than 20 years.

The delimitation of the watershed area and the selection of stations with appropriate data series were carried out using the QGIS software (QGIS.org, 2024). Subsequently, precipitation, evapotranspiration, and flow data were processed using the R software (R Development Core Team, 2024), allowing the conversion and filling of gaps in the time series.

HYDROLOGICAL MODELING WITH THE GR4J MODEL

GR4J (Modèle du Génie Rural à 4 paramètres Journalier) is a daily precipitation-runoff hydrological model widely used for watershed flow simulation. This model operates with four main parameters: X1, which corresponds to the maximum production storage capacity in millimeters; X2, related to the groundwater exchange coefficient; X3, which represents the maximum storage capacity of one day in the transfer reservoir in millimeters; and X4, which defines the base time of the unit hydrograph (Perrin et al., 2003; de Andrade et al., 2022). The GR4J belongs to the category of water balance models, being designed to capture soil dynamics and its interaction with precipitation and evapotranspiration.

The model uses precipitation (P) and potential evapotranspiration (E) as daily inputs, both expressed in millimeters. Its structure is composed of two main reservoirs, which simulate the processes of storage of liquid precipitation, percolation and infiltration in the soil. These reservoirs allow GR4J to effectively capture the hydrological behavior of the basin, considering the complex interactions between the surface and the subsurface (de Andrade et al., 2022; Astorayme et al., 2015).

CALIBRATION AND VALIDATION

The property of the hydrological model GR4J was performed using the AirGR (Coron et al., 2018) in the R programming environment (R Development Core Team, 2024). The mobility process based on the method proposed by Michel (1991), in which the Nash- Sutcliffe (NSE) as an objective function. The NSE measures the accuracy of the simulations in relation to the observed data, with values ranging from -∞ to 1, with 1 being the ideal score (Schönfelder et al., 2017).

In addition to the NSE, other performance indicators were used to validate the model, including the mean square error (RMSE), the percentage (Pbias), the Pearson demonstration coefficient (r), and the Kling-Gupta index (KGE). The RMSE provides a measure of the average magnitude of errors in the flow estimates, while the Pbias evaluates the trend of the simulations, decreases if the model tends to underestimate or overestimate the observed values. Pearson's transparency coefficient (r) quantifies the linear relationship between simulated and observed flows, ranging between -1 and 1, with 1 representing a perfect representation. The KGE, in turn, combines the demonstration coefficient, bias and variability, being a comprehensive metric of model performance (Kling et al., 2012).

The model considers processes such as percolation and infiltration in the soil, using two reservoirs to store precipitated water. The net amount, when higher than evapotranspiration, is stored in the production reservoir, whereas, under evapotranspiration conditions predominantly, the model adjusts evaporation based on the level of moisture in the soil (Perrin et al., 2003). Direct flow and restricted percolation for the volume of water

Revista ARACÊ
ISSN: 2358-2472

that reaches the routing reservoir, the latter being responsible for the simulation of delayed and fast flows, which are treated by unit hydrographs with variable base times, according to the X3 and X4 configurations (Nayak et al., 2021).

At the end of the verification process, the model was validated based on historical flow data, using performance metrics to ensure that the simulations satisfactorily represent the hydrological conditions of the scientific basin.

MAP BIOMES

For this study, data from MapBiomas for the years 1991 to 1994 were used, accessed directly from the MapBiomas Collection 8.0 platform portal (MapBiomas, 2023), which provides annual maps of land cover and use for the entire Brazilian territory. The images corresponding to each year were processed and analyzed using the QGIS software (QGIS.org, 2024). The focus was on the evaluation of the dynamics of land use and land cover in the Rio Verde basin, Minas Gerais, with emphasis on changes in native vegetation and agricultural areas.

The relevance of this approach lies in the fact that changes in land use directly impact hydrological processes in watersheds, affecting factors such as surface runoff, infiltration and aquifer recharge, as demonstrated by studies such as those by Vieira et al. (2020) and Oliveira et al. (2018). Associating MapBiomas data with hydrological analysis allowed us to identify correlations between land use dynamics and flow and water quality patterns in the Rio Verde basin. This methodology broadens the understanding of the impacts of anthropogenic activities on water sustainability and provides subsidies for the integrated management of water resources (Oliveira *et al*., 2018).

Revista ARACÊ
ISSN: 2358-2472

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