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HYDROLOGICAL MODELING IN URBANIZED BASINS: THE IMPACT OF LAND USE CHANGE USING THE CN METHOD

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ABSTRACT

Changes in land use and land cover, especially in urbanized areas, have significantly impacted the hydrological regime of river basins, intensifying surface runoff and peak flows. In this context, this study sought to investigate the impacts of these changes in the sub-basins of the Fojo and Perdizes streams, in Campos do Jordão, SP, answering the question: how do changes in land use and land cover impact the hydrological regime of the sub-basins, and how can the CN (Curve Number) method be applied to estimate these impacts? The objective was to stimulate water resilience through the application of the CN method, associated with the use of geoprocessing tools, to estimate design flows in different scenarios. The results revealed that, between 2002 and 2022, forest areas decreased by 6% in the Perdizes sub-basin and 18% in the Fojo sub-basin, with a corresponding increase in urbanized areas and land use mosaics. This transformation increased peak flows, especially at high return times (50 and 100 years), with maximum values of 18 m³/s in the Fojo stream and 7 m³/s in the Perdizes stream in 2022. In addition, a reduction in the concentration time was observed, indicating faster and more intense runoff, especially in the Fojo sub-basin due to the greater slope and contribution area. The

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results demonstrate the hydrological impacts of anthropogenic pressures and highlight the need for sustainable management strategies, reinforcing the importance of public policies to mitigate the effects of changes in land use and promote water resilience in the region.

Keywords: Surface Runoff. Peak Flow. Geoprocessing. Urbanization.

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INTRODUCTION

As units of analysis, river basins play a central role in understanding the interactions between hydrological processes and anthropogenic pressures, and are fundamental for environmental planning and sustainable development (Ferreira et al., 2023a). However, changes in land use and occupation significantly alter the hydrological regime, impacting patterns of runoff, erosion, and sedimentation in basins (Fan et al., 2013). According to Santos et al. (2012), such transformations compromise the hydrological cycle and the quality of water resources, especially in urban and peri-urban areas, where disorderly growth intensifies impacts, requiring sustainable management and water resilience strategies. In Brazil, the Integrated Water Resources Management System (SIGRHI) organizes hydrological monitoring and planning. However, the scarcity of continuous data requires the use of estimation methods, such as the Curve Number (CN) model, which calculates runoff based on land use and land cover, soil type, and hydrological conditions (Soulis, 2021). Today, the integration of this method with hydrological tools, such as the Soil and Water Assessment Tool (SWAT), Storm Water Management Model (SWMM), and Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS), allows for more accurate and detailed analyses, facilitating local calibration (Machado et al., 2003; Fenglei et al., 2013). In this context, the Capivari River basin, located in Campos do Jordão, in the Metropolitan Region of Vale do Paraíba and Litoral Norte (RMVPLN), stands out as a relevant object for the study of the CN method due to its water importance and the anthropogenic pressures to which it is subjected. Its sub-basins of the Perdizes and Fojo streams are essential for supplying the local population, making the area particularly sensitive to changes in land use and cover. These changes intensify the challenges of the hydrological regime, highlighting the need for studies that support environmental and water management policies (Santos et al., 2012).

Given this, the question is: how do changes in land use and cover impact the hydrological regime of urbanized sub-basins, and how can the CN method be applied to estimate surface runoff and support sustainable management strategies?

This study investigates the impacts of these changes by applying the CN method and using geoprocessing tools to estimate design flows. The results aim to support sustainable water management, in line with the Sustainable Development Goals (SDGs) of the 2030 Agenda, especially SDG 6, which deals with efficient water management, and SDG 11, which seeks to promote resilient cities and communities. In this sense, the study

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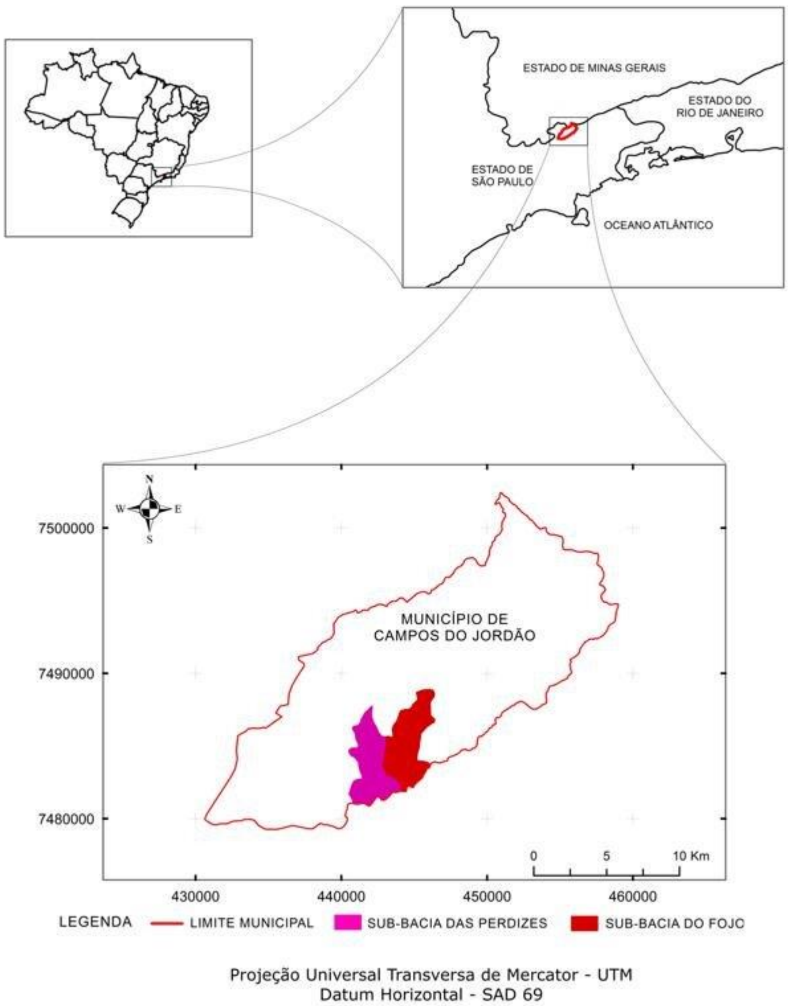
aims to strengthen water resilience, allowing hydrological systems to respond to anthropogenic pressures while contributing to environmental balance through sustainable management strategies.

MATERIAL AND METHODS

CHARACTERIZATION OF THE STUDY AREA

This study covers the hydrographic sub-basins of the Perdizes and Fojo streams, which flow into the Sapucaí-guaçu River, in the central region of the municipality of Campos do Jordão, SP (Figure 1). Situated at an average altitude of 1,600 meters, the municipality is part of the Metropolitan Region of Vale do Paraíba and Litoral Norte and has a population of 47,983 inhabitants. (IBGE, 2024).

Figure 1. Location of the sub-basins under study, about the municipality of Campos de Jordão, SP. In purple: Perdizes; In red: Fojo.



Source. Santos *et. al*. (2011).

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Campos do Jordão is one of the seven municipalities in São Paulo that are part of the Serra da Mantiqueira Environmental Protection Area (APA). The topography of the municipality is predominantly rugged, with approximately 85% of undulating regions, 10% of mountain slopes, and 5% of steep areas. The central area of the city is located in a narrow valley, with an average width of 500 meters, while points in the surrounding area reach altitudes of over 2,000 meters (São Paulo, 2010). Urban occupation is predominantly developed in the flat portion of this valley, coinciding with the mouth of the two sub-basins under study.

The Perdizes stream basin, located in the northeastern portion of the municipality of Campos do Jordão, is characterized by an area with strongly undulating and rugged relief, typical of the mountainous region of Serra da Mantiqueira. The basin is predominantly forested, although it has suffered losses over the years due to urban expansion and occupation by areas with a mosaic of uses. The area near the mouth of the stream, in the Capivari neighborhood, has seen significant growth in urban infrastructure, especially with the expansion of the hotel and service network.

The Fojo stream basin, in turn, has similar characteristics in terms of relief. In the early 2000s, forest cover was predominant, but from 2010 onwards there was a more significant loss compared to the Perdizes basin, reflecting greater anthropic pressure. The Fojo basin has also seen the expansion of urbanized areas and a mosaic of uses, particularly in regions with lower slopes, which contributes to increased surface runoff and associated risks, such as erosion and flooding. These changes highlight the need for continuous monitoring and management strategies aimed at water resilience and environmental conservation. Both sub-basins are paired and, as important tributaries of the Capivari River, play a fundamental role in the drainage of the region and the local water supply.

PROCEDURES FOR ESTIMATING SURFACE RUNOFF AND GENERATION OF THE HYDRO GRAM

The characterization of land use and cover of the Fojo and Perdizes river sub-basins was carried out for the years 2002 and 2022, using the QGIS software. The data were obtained from MapBiomas (version 9.0), a project that provides land use and cover maps

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in Brazil and South America based on satellite images from the Landsat series, covering the period between 1985 and 2022, with a spatial resolution of 30 meters.

A relevant parameter in the applied model is the time of concentration (Tc), which represents the time required for the runoff to travel from the furthest point of the basin to the outlet. Tc was estimated using the California Culvert Practice (California, 1944), expressed by Equation (1):

$$T_c = 57\,x\,(\frac{L^3}{\sqrt{I_{eq}}})^{0,385} \quad (1)$$

where: Tc = Time of concentration (minutes); Ieq = Equivalent slope of the thalweg (m/km); L = Length of the thalweg (km). In this study, the length of the thalweg was subdivided into sections, and the calculation considered the individual slope of each segment.

The maximum precipitation for return times of 10, 25, 50, and 100 years were estimated from Equation (2), proposed by Martinez Junior and Magni(1999):

$$I\,(t,T) = 19{,}153(t+15)^{-0{,}7928} + 2{,}034(t+15)^{-0{,}659}[-0{,}478 - 0{,}9046\,Ln(Ln(T/T-1)] \quad (2)$$

where: I = Precipitation intensity (mm/min); T = Rainfall return period (years); t = Rainfall duration (min).

The Curve Number Method (CN) was used to estimate surface runoff (Pe) and the resulting hydrograph. This method was selected for its applicability in determining peak discharge and the complete hydrograph generated by the maximum design precipitation. The steps adopted were:

a) Conversion of total precipitation into flow, based on Equations (3) and (4).

$$P_e = \frac{(P-0{,}2S)^2}{P+0{,}8S}\text{ , para P > 0,2S} \quad (3)$$

$$S = \frac{25400}{CN} - 254 \quad (4)$$

where: Pe = Effective precipitation (mm); P = Maximum precipitation (mm); S = Potential infiltration (mm), related to CN.

Generation of the hydrograph based on the dimensionless unit hydrograph of the NRCS (Natural Resources Conservation Service), a hydrological tool that represents the

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response of a watershed to uniform precipitation, taking into account its physical and hydrological characteristics. The hydrograph uses the relationships between the peak time (Tp), the duration of maximum precipitation, and the dimensionless coefficients t/T_p and q/q_p, respectively, the relationship between the real-time (t) and the peak time (Tp) of the basin, and the relationship between the flow at a given time (q) and the peak flow (qp) of the basin. Calculation of the drainage coefficient and design flow using the convolution process, allowing the determination of the peak discharge (qp). To define the CN, the weighting of the areas of the land use classes identified in the generated maps was used, as suggested by Targa (2011). The hydrograph was generated by the sum of the dimensional unit hydrographs, applied to each time interval of effective precipitation.

The input hyetograph was prepared in intervals of 0.25 hours, with rainfall distribution based on the first quartile of the classification, proposed by Huff (1967). The accumulated precipitation was converted into effective precipitation using the CN equations, and the variation in each time interval was calculated by Equation (5).

$$\Delta P_e = P_e(t+1) - \frac{P_e(t)}{\Delta P_e} \qquad (5)$$

Finally, the values of t/Tp_p and q/qp extracted from the dimensionless unit hydrograph were used to generate, through Equation (6), the final hydrograph, which results from the sum of the dimensional unit hydrographs obtained for each rainfall pulse.

$$q_p = 2{,}08\ {}^{\Delta P_e}\!/_{T_p} \qquad (6)$$

This calculation shapes the peak discharge (qp) of the hydrograph generated by each ΔPe.

At the end of the analyses, the aim is to contribute to strengthening studies and guidelines focused on water resilience, in order to allow hydrological systems to respond efficiently to increasing anthropogenic pressures. At the same time, the aim is to promote environmental balance by proposing sustainable management strategies that consider changes in land use and coverage and their impacts on the hydrological regime.

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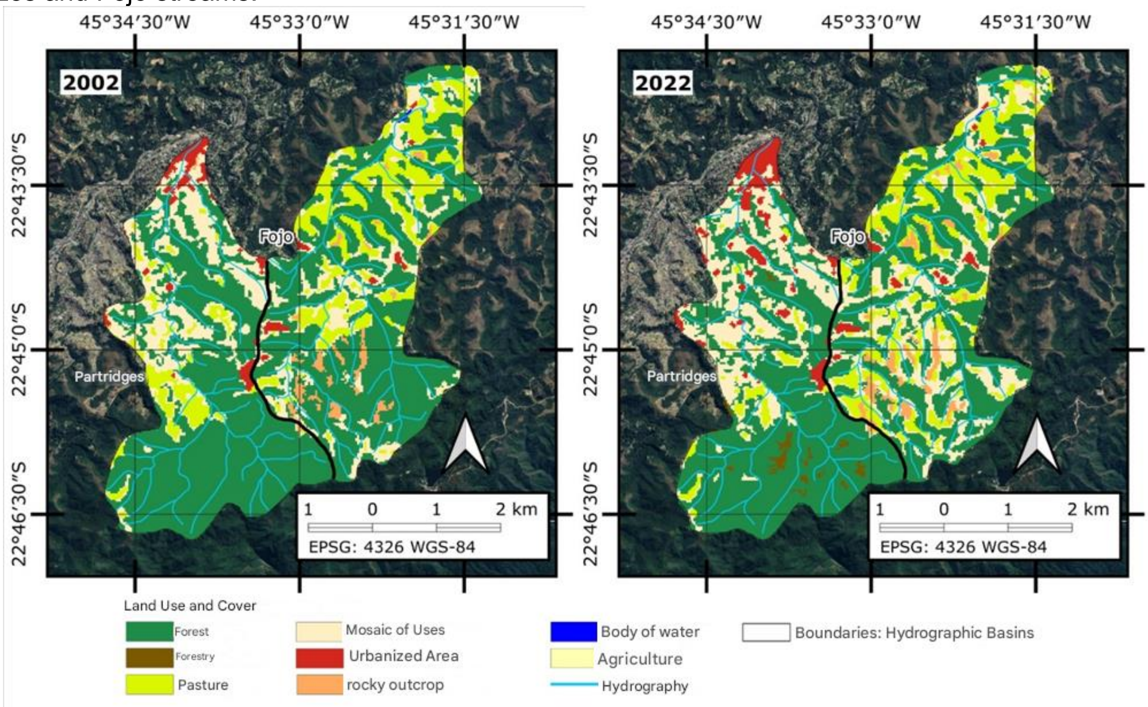
RESULTS

ANALYSIS OF CHANGES IN LAND USE AND COVER IN THE SUB-BASINS

The mapping of land use and occupation, obtained from data from MapBiomas (2024), of the Perdizes and Fojo sub-basins, located in the municipality of Campos do Jordão, SP, in the years 2002 and 2022, is presented in Figure 2. It shows the changes that occurred over this period, highlighting changes in the classes of land use and cover. Figure 2 illustrates the comparative maps of land use and cover for the years 2002 and 2022 in the sub-basins of the Perdizes and Fojo streams, highlighting the spatial patterns of transformation in the region.

Figure 2. Comparative maps of land use and cover for the years 2002 and 2022 in the sub-basins of the Perdizes and Fojo streams.



Source Authors.

The changes in land use and cover in the Perdizes and Fojo sub-basins, in the municipality of Campos do Jordão, SP, were quantified and are presented in Table 1. A comparative analysis between the years 2002 and 2022 highlights significant changes in the existing land cover types.

The Forest class, which was predominant in 2002, covered 857 ha (67.7%) in the Perdizes sub-basin and 826 ha (59.4%) in the Fojo sub-basin. However, in 2022, a reduction of 6% and 18% was observed, respectively, in these areas. The Silviculture class emerged as a land cover type only in 2022, restricted to the Perdizes sub-basin.

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The Pasture cover, in 2002, encompassed 85.6 ha (6.8%) in the Perdizes sub-basin and 265.3 ha (19.1%) in the Fojo sub-basin. In 2022, this coverage exhibited distinct behaviors: a 53.8% reduction in the Perdizes sub-basin and an 8.9% increase in the Fojo sub-basin. The Mosaic of Uses class should be highlighted, which, in Brazil, is associated with transitional areas between rural and urban environments, such as small farms, orchards, vegetable gardens, and recreational spaces with lawns, or a mix of pastures, naturally regenerating areas and agriculture. In 2002, this class represented 21.9% and 17.1% of the Perdizes and Fojo sub-basin areas, respectively. By 2022, an increase of 24.9% in the Perdizes sub-basin and 24.7% in the Fojo sub-basin was recorded, mainly replacing pasture and forest areas.

Table 1. Land use and occupation classes in the Fojo and Perdizes sub-basins and the CN values selected based on the hydrological characteristics of the sub-basins.

Land Use and Occupation	Perdizes Sub-basin (ha)		Fojo Sub-basin (ha)	
	2002	**2022**	**CN**	**2002**
Forest	857.19	804.13	42	826.05
Silviculture	-	21.61	62	-
Pasture	85.55	39.50	75	265.27
Mosaic of Uses	277.46	315.24	70	237.86
Urbanized Area	43.10	78.75	90	14.31
Water Body	-	4.06	90	1.30
Rock Outcrop	1.63	1.63	90	43.99
Agriculture	2.03	2.03	75	1.46
Total	**1267**	**1267**	-	**1390**

Source. Prepared by the authors.

The urbanized area also showed considerable expansion. In the Perdizes sub-basin, it increased from 43.1 ha in 2002 to 78.75 ha in 2022, while in the Fojo sub-basin, the growth was from 14.3 ha to 19.96 ha over the same period. As shown in Figure 3, urbanization advanced over the Mosaic of Uses areas, indicating that as these properties receive infrastructure improvements, especially those aimed at the hospitality sector, they tend to consolidate as typical urban agglomerations.

The predominant soils in the municipality of Campos do Jordão are Cambisols, classified by Santos et al. (2011), located in strongly undulating to steep terrains, with severe restrictions for agricultural, pastoral, and forestry uses due to their susceptibility to disaggregation (Oliveira, 1999). According to Sartori et al. (2005), these soils belong to Hydrological Group C. Based on the table of calibrated CN values for Brazil (Setzer &

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Porto, 1979), CN values were assigned to each land use and occupation class under average moisture conditions, as presented in Table 1.

COMPARATIVE HYDROLOGICAL ANALYSIS OF THE SUB-BASINS (2002-2022)

The data necessary for the calculation of the design flow, through the construction of the hyetograph and unit hydrograph, are detailed in Targa (2011) and are presented in Table 2. The morphometric characteristics of the sub-basins used for the analysis were obtained from Santos et al. (2012).

Table 2. Morphometric and hydrological characteristics of the Fojo and Perdizes sub-basins are necessary for the calculation of the design photographs and hydrographs.

Parameters	Perdizes	Fojo
Channel length – L (Km)	8.81	9.64
Watershed area – A (Km²)	12.70	13.97
Equivalent basin slope – Ieq (m/km)	37.46	44.61
Basin concentration time – Tc (h)	1.25	1.25
Time between peak rainfall and hydrograph peak – tp (h)	0.88	0.88
Hydrograph peak rise time - Tp (h)	1.50	1.50
Hydrograph peak flow – qp (m³/s)	1.75	1.92
Hydrograph base time – Tb (h)	2.35	2.36

Source. Prepared by the authors.

Considering the morphometric characteristics of the study area, the total length of the main channel is 8.81 km for the Perdizes sub-basin and 9.64 km for the Fojo sub-basin, with equivalent slopes of 37.5 m/km and 44.61 m/km, respectively. These parameters result in an approximate Concentration Time (Tc) of 1.25 hours for both sub-basins, indicating that water falling at the farthest point of the basin takes about 75 minutes to reach the outlet.

With the concentration-time equal to the duration of maximum rainfall and using 15-minute rainfall pulses, the maximum rainfall values corresponding to return periods of 10, 25, 50, and 100 years were calculated using Equation 3, as presented in Table 3.

Based on the CN values presented in Table 1, the weighted CN values were calculated, considering changes in land use and occupation in 2002 and 2022. For the sub-basins, the values obtained were 55.180 and 58.567 for the Fojo stream and 52.108 and 53.589 for the Perdizes stream, respectively.

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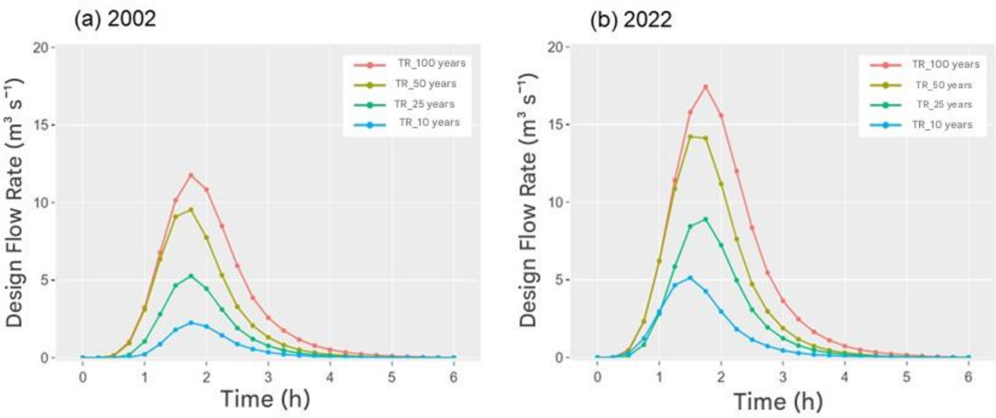
Table 3. Maximum rainfall for return periods of 10, 25, 50, and 100 years for 15-minute rainfall pulses in the Fojo and Perdizes sub-basins.

t (min)	TR (Years) 10	25	50	100
15	25.98	29.61	32.31	34.98
30	37.23	42.26	45.99	49.69
45	44.38	50.34	54.76	59.15
60	49.63	56.31	61.27	66.20
75	53.79	61.08	66.48	71.85

Source Authors.

Figures 3 and 4 present the design flow curves for the Fojo and Perdizes stream sub-basins, respectively, in the municipality of Campos do Jordão, SP, comparing the years 2002 (3a and 4a) and 2022 (3b and 4b) for return periods of 10, 25, 50, and 100 years. In both sub-basins, a significant increase in peak flows was observed in 2022, especially for higher return periods, such as 50 and 100 years.

Figure 3. Design flow curves for the Fojo stream sub-basin: 2002 (a) and 2022 (b).



Source. Prepared by the authors.

This behavior reflects changes in land use and land cover over the period, with emphasis on the expansion of urbanized areas, which reduced infiltration capacity and intensified direct surface runoff. In addition, the 2022 curves show a reduction in the time of concentration, indicating a more pronounced hydrological behavior, possibly related to urban densification and the replacement of forest areas by impermeable surfaces. These results highlight the cumulative impacts of anthropogenic transformations in the basins and reinforce the need for sustainable management and water resilience strategies to mitigate the risks associated with increased surface runoff.

Figure 4 shows the design flow curves for the Perdizes river basin, comparing the years 2002 (Figure 4a) and 2022 (Figure 4b), with return times of 10, 25, 50, and 100

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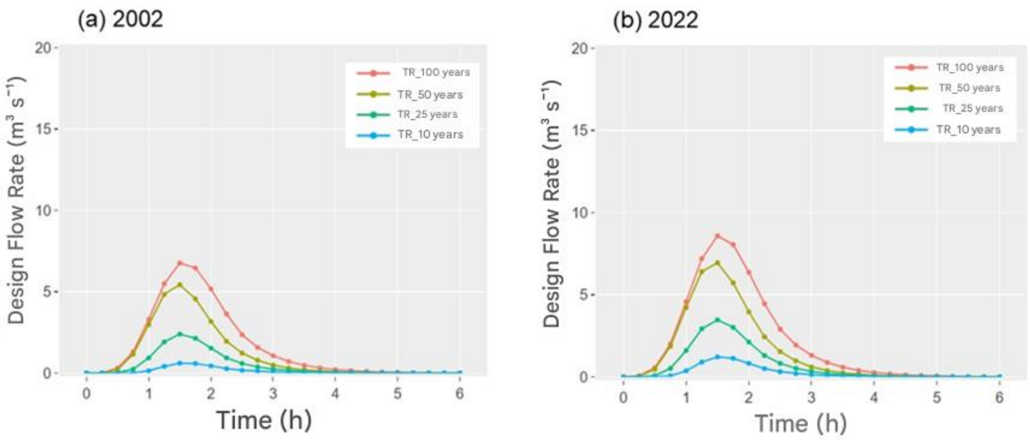
years. There was a noticeable increase in peak flows in 2022 compared to 2002, especially for longer return periods, such as 50 and 100 years. This increase reflects the changes in land use and land cover that occurred over the period, with emphasis on the expansion of urbanized areas, which reduced infiltration capacity and increased direct surface runoff. In addition, the steeper shape of the curves in 2022 suggests a reduction in the time of concentration, possibly associated with urban densification and the replacement of forest areas with impermeable surfaces. These results highlight the hydrological impacts of the urbanization process in the basin, demanding management and mitigation strategies aimed at water resilience.

Figure 4. Design flow curves for the Perdizes stream sub-basin: 2002 (a) and 2022 (b).



Source. Prepared by the authors.

What is different between Figures 3 and 4 is the magnitude of peak flows and the behavior of the hydrological curves in the Fojo and Perdizes stream sub-basins. In both years analyzed (2002 and 2022), peak flows are higher in the Fojo sub-basin, reaching approximately 18 m³/s in 2022 for the 100-year return period, while in the Perdizes sub-basin the maximum values reach approximately 7 m³/s. This difference can be attributed to the larger size of the area and the greater average slope of the Fojo sub-basin, which favors faster and more intense runoff.

In addition, in 2022, the hydrographs presented higher peaks in both sub-basins due to the increase in maximum rainfall values. Changes in land use and occupation between 2002 and 2022, especially the reduction of forest areas by 6% in the Perdizes sub-basin and 18% in the Fojo sub-basin, also contributed to the increase in flows. The replacement of forests by pastures and urbanized areas reduced the infiltration capacity, intensifying surface runoff. According to Santos et al. (2012), infiltration rates in areas of native vegetation are 298 mm/h, while in pastures they fall to 63 mm/h, which highlights the direct impact of changes in land use on the hydrological behavior of the sub-basins.

DISCUSSION

The results obtained show that changes in land use and cover in the sub-basins of the Fojo and Perdizes streams caused significant changes in hydrological behavior throughout the period analyzed (2002–2022). The hydrographs demonstrated a significant increase in peak flows and a reduction in the time of concentration, especially in areas with greater slope and urbanization, such as the Fojo stream sub-basin. While the expansion of urbanized areas and land use mosaics reduced infiltration capacity, the replacement of forested areas by pastures intensified direct surface runoff. This scenario is corroborated by the infiltration rate values presented by Santos et al. (2011), which indicate 298 mm/h in forested areas and only 63 mm/h in pasture areas, reflecting the sensitivity of the sub-basins to changes in land use.

The analysis of the data reveals that the Fojo sub-basin, due to its larger size and steeper slope, is more vulnerable to extreme hydrological events, as demonstrated by the higher peak flows compared to the Perdizes sub-basin. As pointed out by Ferreira et al. (2023a; 2023b), this behavior reinforces the importance of preventive and mitigation actions aimed at regions of greater susceptibility, mainly due to the disorderly urban expansion observed near the outlets of the sub-basins.

From a methodological point of view, the CN (Curve Number) method proved to be an efficient tool for estimating surface runoff and for constructing hydrographs, enabling the quantification of the impacts of changes in land use. However, it is important to recognize some limitations of this method, such as the need for local calibration of CN values and its dependence on updated data on land use and occupation. The sensitivity of the model to cartographic errors and the lack of continuous time series of hydrological data can also influence the results, suggesting the need to combine CN with other approaches, such as field measurements and more complex modeling.

Given this scenario, this study answers the initial question by demonstrating that changes in land use and land cover directly impact the hydrological regime, altering the flow rates and response time of sub-basins. The application of the CN method, associated with geoprocessing tools, made it possible to identify critical areas and quantify the hydrological transformations throughout the analyzed period.

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Finally, it is necessary to advance sustainable management strategies to strengthen the water resilience of sub-basins, in line with the Sustainable Development Goals (SDGs) of the 2030 Agenda. The implementation of green infrastructure, such as permeable pavements, infiltration areas, and the creation of buffer zones in critical areas, is recommended. In addition, reforestation actions and control of disorderly urban expansion are essential to mitigate hydrological impacts and promote environmental balance. From a future perspective, consideration of climate change scenarios and intensification of continuous monitoring is essential to anticipate risks and guide public policies that ensure efficient management of water resources.

This more integrated and preventive approach will allow hydrological systems to respond efficiently to anthropogenic pressures, while contributing to environmental and urban sustainability in the Campos do Jordão region, SP.

CONCLUSION

The general objective of this study was to investigate the impacts of changes in land use and land cover on the hydrological regime of the Fojo and Perdizes river sub-basins, in the municipality of Campos do Jordão, SP, using the CN (Curve Number) method and geoprocessing tools to estimate design flows. The research made it possible to identify the increase in peak flows and the reduction in the concentration-time, especially in the year 2022, in response to the expansion of urbanized areas and the reduction of forest areas.

As a scientific contribution, the study demonstrated the direct relationship between changes in land use and hydrological alterations, highlighting the impact of urbanization and the expansion of pastures on surface runoff. The use of the CN method, integrated with geoprocessing techniques, proved to be a robust and accessible approach for hydrological modeling, offering technical subsidies that can support environmental planning and actions to mitigate the risks associated with increased surface runoff.

Among the practical and social contributions, the following stand out: the possibility of guiding public policies for sustainable water management and soil management, in addition to providing fundamental information for controlling disorderly urbanization, preserving remaining forest areas, and implementing green infrastructure in the sub-basins analyzed. Such strategies can mitigate problems such as flooding, erosion, and silting, ensuring water resilience and improving the quality of life of the local population.

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The main limitation of the research is related to the dependence on calibrated CN values, which, despite being widely used, may not fully capture the local specificities of the sub-basins studied. In addition, the scarcity of continuous observational hydrological data restricted the more accurate validation of the generated hydrographs, making it necessary to use estimation methods based on secondary parameters and available literature.

For future research, it is suggested that direct field measurements be carried out, including infiltration, flow, and land use data, to improve the local calibration of the models and increase the accuracy of the estimates. Additionally, it is recommended to apply more complex hydrological models, such as SWAT or HEC-HMS, which allow simulations of climate change and urban growth scenarios. Finally, future studies could explore the implementation of nature-based solutions to mitigate hydrological impacts, such as the use of permeable pavements, recovery of degraded areas, and creation of buffer zones in critical areas of the basins.

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