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Identification of Hydrologic Landscapes in Brazilian river basins and their application as indicators of water yield and storage

Abstract: This study applies the Hydrologic Landscapes (HL) classification method to the Piracicaba, Capivari, and Jundiaí (PCJ) River Basins, southeastern Brazil, with the aim of identifying areas favorable for both water yield and storage. The PCJ region is one of the most socioeconomically important yet water-scarce areas of Brazil, making the identification of hydrologic units essential for sustainable management. The methodology integrated four key evaluation units—relief, soil permeability, aquifer permeability, and climate—into a single information plan (IP) using Geographic Information Systems (GIS). Each 30 m × 30 m pixel was assigned to a Hydrologic Landscape Region (HLR), providing a high-resolution classification of hydrologic conditions. To validate the approach, annual streamflow data from 27 gauging stations (2001–2020) were used to calculate the ratio of water yield to precipitation (R/P) and the non-dimensional m parameter from Fuh's equation, which reflects basin slope, infiltration, and storage capacity. Results identified 57 HLRs within the PCJ basins. Water yield was more strongly associated with soil hydraulic conductivity, while water storage capacity (represented by m) was influenced primarily by aquifer permeability and slope. Favorable HLRs for water yield were concentrated in mountainous areas with permeable soils and humid climates, whereas favorable storage conditions were located in flatter terrains with high aquifer permeability. Importantly, areas with high R/P values often coincided with high m values, demonstrating that basins can simultaneously support both water production and storage. The study demonstrates that HL classification is a cost-effective and transferable tool for identifying priority areas for conservation, water security, and resource allocation in regions under water scarcity.

Keywords: hydrologic cycle; hydrologic classification; geoprocessing; river basins; water yield; water storage.

1. Introduction

Currently, hydrology requires the development of holistic, practical, and efficient river basin classification models. An appropriate classification system supports hydrological studies and enables the identification of areas favorable for water yield and storage—resources that are essential for domestic, industrial, and agricultural purposes, with significant social, economic, and environmental implications (McDonnell & Woods, 2004; MMA, 2007).

Among the existing approaches, environmental classification stands out by defining classes from physical and climatic attributes assumed to produce similar hydrological responses. This deductive method does not depend on long-term hydrometric series but instead uses widely available environmental datasets in Geographic Information Systems (GIS), which are powerful tools for hypothesis testing, pattern identification, and linking predictor and response variables. Environmental classification also plays a vital role in monitoring, analyzing, and forecasting environmental change (Detenbeck et al., 2000; Olden et al., 2012; Praskievicz, 2018).

The Hydrologic Landscapes (HL) framework, proposed by Winter (2001), is one of the most recognized environmental classification methods. It integrates climate, relief, and soil into a single value, supporting both qualitative assessments and quantitative analyses through GIS. By combining multiple environmental variables, the HL concept provides a flexible and comprehensive approach for analyzing hydrological behavior at different spatial scales.

The HL method has proven useful for environmental management, water quality monitoring, sampling strategies, and prioritizing areas for reforestation and other hydrologically informed interventions. From a hydrological perspective, it allows the identification of areas favorable for water yield and storage, while supporting targeted actions to mitigate the effects of water deficits and optimize basin management. Its ability to integrate climate, slope, soil, and aquifer permeability into a single analytical layer makes it particularly suitable for planning under water scarcity conditions.

Building on the concepts of Winter (2001), Wolock et al. (2004) developed a classification method that assigns river basins into 20 distinct groups, called Hydrologic Landscape Regions (HLRs). Their framework combined geoprocessing and statistical analyses of relief, soil texture, precipitation, and bedrock permeability, and was applied to all U.S. basins, becoming one of the most successful large-scale hydrologic classification efforts.

At regional scales, subsequent studies refined the HL approach. Wigington et al. (2013) employed higher-resolution geophysical data, while Leibowitz et al. (2016) adapted the method to the Pacific Northwest, a region influenced by snowfall. Santhi et al. (2008) demonstrated its effectiveness in predicting baseflow, Carlisle et al. (2010) highlighted improvements in prediction models, and Patil et al. (2014) and Brown et al. (2014) validated its application in Oregon and Australia, respectively. These advances confirm the method's robustness across distinct hydrologic and climatic contexts.

Despite these advances, no previous study has applied HL classification specifically to simultaneously identify areas favorable for both water yield and storage in Brazilian river basins. Addressing this gap is crucial, given the growing pressure on water resources and the need for tools that guide cost-effective conservation and management. Therefore, this study aims to classify Hydrologic Landscapes and delineate favorable scenarios for water yield and storage in the Piracicaba, Capivari, and Jundiaí River Basins (PCJ), southeastern Brazil.

2. Materials and methods

2.1. Study area

The study area comprises the combined Piracicaba, Capivari, and Jundiaí (PCJ) River Basins, located in southeastern Brazil. Covering approximately 15,303.67 km², it spans between longitudes 46° and 49° W and latitudes 22° and 23° S. The region lies predominantly within the state of São Paulo (92.6%), with a smaller portion (7.4%) in Minas Gerais.

The climate in the basins is classified as Humid Subtropical (PCJ Basin Agency, 2014). Annual rainfall ranges from 1,195 mm to 1,609 mm, with an average of 1,440 mm. The region follows a typical subtropical pattern, with a rainy summer from October to March and a dry winter from April to September (CBH-PCJ, 2017).

The region is subject to intense anthropogenic pressure from residential and industrial expansion. Alongside this urban sprawling, the PCJ River Basins also support strong agricultural activity, making them one of the most important agro-industrial hubs in southeastern Brazil. Despite the abundance of springs, the region's economic potential may be jeopardized by declining per capita water availability. Environmental challenges are further compounded by the deforestation of the original Atlantic Forest cover to make way for agriculture and livestock, intensifying concerns related to water resources and ecosystem degradation (CBH-PCJ, 2017). In these scenarios, the basins stand out as a strategic territory for assessing hydrological risks (Machado et al., 2025).

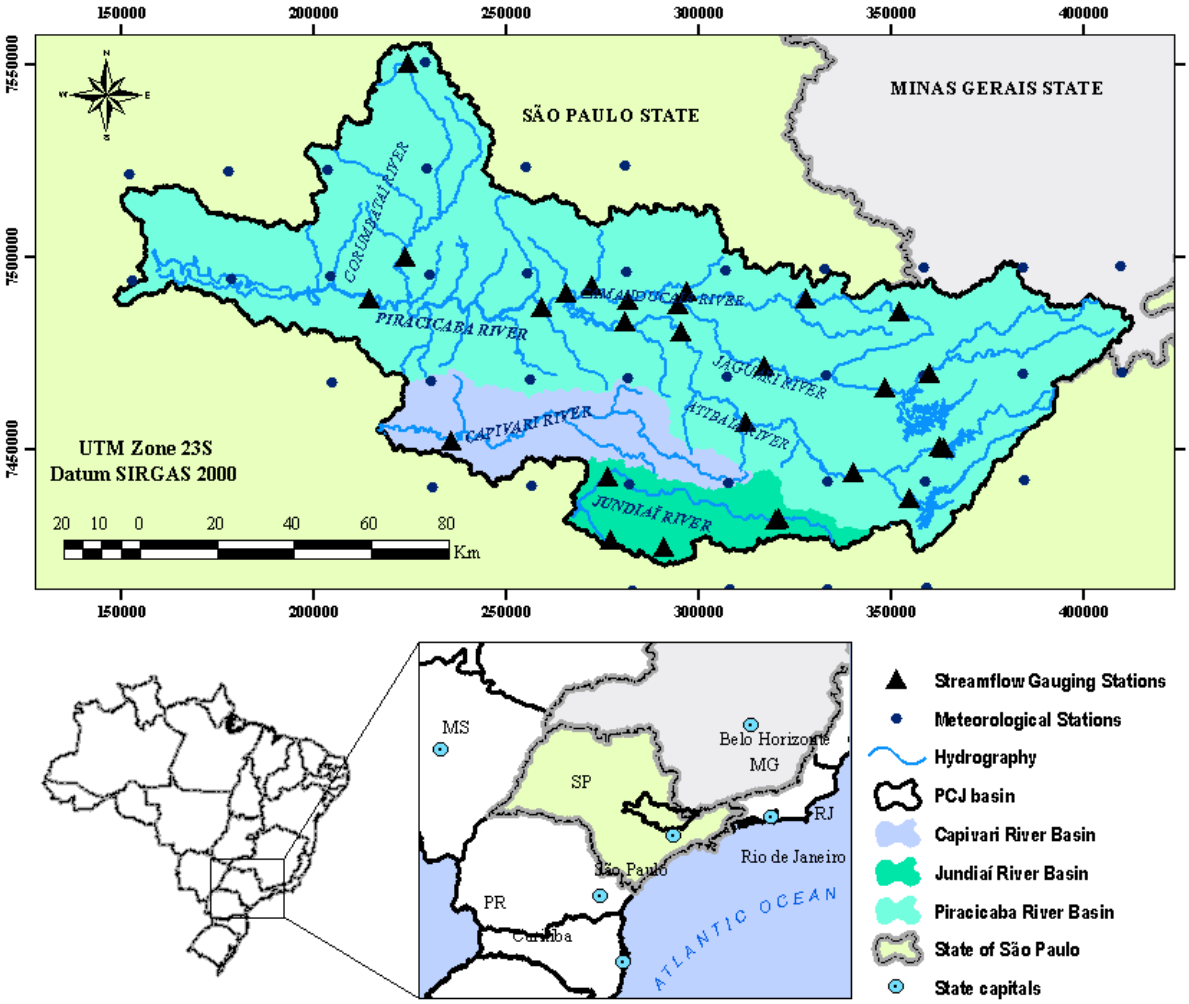


Fig. 01. Location of the Piracicaba, Capivari, and Jundiaí River Basins within Brazil.

2.2. Identification of Hydrologic Landscapes

The development of the Hydrologic Landscapes classification method for the PCJ region was based on previous studies by Wolock et al. (2004), Wigington et al. (2013), and Brown et al. (2014), with adjustments to better reflect tropical conditions. Unlike Wolock et al. (2004) and Wigington et al. (2013), who assigned a single HLR value to each sub-basin, the present study adopted a pixel-by-pixel classification approach, as proposed by Brown et al. (2014). All variables used to generate the Hydrologic Landscapes were reclassified into three classes, following the same procedure applied by Wigington et al. (2013).

The classification of Hydrologic Landscapes in the PCJ River Basins was based on the integration of four hydrologic evaluation units selected according to the conceptual framework established by Winter (2001): relief, soil permeability, aquifer permeability, and climate. The GIS-based processing was conducted in ArcGIS. For class definition, the data for each parameter were reclassified using the Natural Breaks (Jenks) method, which identifies

breakpoints that best group similar values while maximizing inter-class differences and minimizing classification error (Fernandes et al., 2012).

After reclassification, the evaluation units were overlaid into a single information plan (IP), resulting in the Hydrologic Landscape Regions (HLRs). Each HLR incorporates data from all four hydrologic units. Table 1 shows the reclassification ranges and corresponding classes for each parameter.

Table 1. Classes of the units evaluated.

Unit	Parameter	Values	Class
Relief	Slope (%)	$S \leq 8$	Flat
		$8 < S \leq 20$	Transitional
		$S > 20$	Mountain
Aquifer permeability	Aquifer specific flow (mm/h)	$Q_e \leq 30$	Low
		$30 < Q_e \leq 60$	Moderate
		$Q_e > 60$	Hight
Soil permeability	Saturated Hydraulic Conductivity (mm/h)	$K \leq 50$	Low
		$50 < K \leq 115$	Moderate
		$K > 115$	Hight
Climate	*Feddema* Moisture Index	$If \leq 0.24$	Moist
		$0.24 < If \leq 0.30$	Wet
		$If > 0.30$	Very wet

2.3. Database sources for evaluation units

For the slope-based hydrological evaluation unit, we utilized a Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM), which has a 30-meter spatial resolution (USGS, 2017).

Soil permeability, which affects water infiltration, was assessed using the saturated hydraulic conductivity (K) parameter. Since high conductivity values are directly linked to greater water flow and movement through the soil (Libardi, 2010), accurately determining this variable is essential for constructing the soil permeability evaluation unit, as also adopted by Wigington et al. (2013) and Wolock et al. (2004). Saturated hydraulic conductivity (K) was obtained from Oliveira (1999). The scientific bulletin compiled by Oliveira (1999) describes the physical-hydraulic properties of the soils in the region where the basins are located.

Climate data, including precipitation (P) and potential evapotranspiration (ETP) from the basin, were synthesized into a single index using the Feddema Moisture Index (Feddema,

148 2005), as shown in Equation 1. Values range from -1.0 to 1.0, where lower values indicate arid
149 conditions and higher ones represent humid conditions.

$$If = \begin{cases} 1 - \mathrm{ETP}/\mathrm{P} \; se \; \mathrm{P} > \mathrm{ETP} \\ 0 \; se \; \mathrm{P} = \mathrm{PET} \\ \mathrm{P}/\mathrm{ETP} - 1 \; se \; \mathrm{P} < \mathrm{ETP} \end{cases} \quad (1)$$

150 Where: *If* is the Feddema Moisture Index; ETP is the mean annual potential evapotranspiration (mm); and P is the
151 mean annual precipitation (mm).

152 The precipitation data used in this study represent the mean annual values from a 20-
153 year historical series (2001–2020) obtained from meteorological stations located along the
154 basin under the responsibility of the National Institute of Meteorology (INMET), the Center for
155 Meteorological and Climatic Research Applied to Agriculture (CEPAGRI) of the University of
156 Campinas (UNICAMP), and the 'Luiz de Queiroz' College of Agriculture (ESALQ). These
157 data were interpolated from the study by Xavier et al. (2022) (Figure 1). Evapotranspiration
158 was calculated using the Thornthwaite & Mather (1955) method, which relies primarily on
159 mean air temperature data from the same stations.

160 Aquifer permeability is directly related to specific flow (Fetter, 2001). Therefore, to
161 generate the evaluation unit for aquifer permeability, specific flow (Qe) data were used. The
162 flow values were obtained from aquifers and wells recorded in the SAP (Sistema Ambiental
163 Paulista) database, managed by the São Paulo State Government. Table 2 summarizes all data
164 sources used in determining the four evaluation units.

165 Table 2. Classes of the units evaluated.

Evaluation unit	Input data	Data description	Data type/scale	Data sources
Relief	Topography	DEM (Digital Elevation Model)	Raster, 30m	Shuttle Radar Topography Mission – SRTM (USGS, 2017)
Soil permeability	Soil	Soil type map	1:250.000	São Paulo Forest Institute (ROSSI, 2017)
	Soil	Soil physical-hydraulic properties	-	"Solos da folha de Piracicaba" (Oliveira, 1999).

Aquifer permeability	Hydrogeology	Specific flow rate (mm/h)	1:100.000	DataGeo SISTEMA AMBIENTAL PAULISTA – São Paulo's State Government (http://datageo.ambiente.sp.gov.br/app/)
Climate	Meteorological	Precipitation (mm)	annual	Xavier et al. (2022)

2.4. Method validation

Zhou et al. (2015) examined the relationship between annual water yield (R) and various parameters used as evaluation units in the identification of Hydrologic Landscapes. Their findings underscore the importance of comparing the relative influence of each parameter on water yield and storage within a river basin. To represent the proportion of precipitation that contributes to water yield, a dimensionless index—expressed as the ratio (R/P) of annual water yield (R) to annual precipitation (P)—is commonly used (Duan et al., 2016).

That dimensionless index is expressed in Fuh's theoretical equation (Equation 2), which describes the relationship between the annual water yield (R) and precipitation (P), the climatic wetness index (P/ETP), and a parameter m that reflects the physical characteristics of the river basin (Fuh, 1981). This model is considered highly effective for predicting hydrological responses, as it links river basin physical attributes with hydrologic data (Zhou et al., 2015).

$$\frac{R}{P} = \left(1 + \left(\frac{P}{ETP}\right)^{-m}\right)^{\frac{1}{m}} - \left(\frac{P}{ETP}\right)^{-1} \quad (2)$$

Where: R is the mean annual water yield (mm); P is the mean annual precipitation (mm); ETP is the mean annual potential evapotranspiration (mm); and *m* is a non-dimensional parameter.

According to Zhou et al. (2008), the non-dimensional parameter *m* characterizes basin features such as area, slope, land use and cover, soil texture, and depth. Zhou et al. (2015) noted that this parameter reflects the basin's water retention capacity, which varies according to its physical attributes. Higher *m* values indicate greater retention capacity, likely due to a combination of preserved vegetation cover, large contributing areas, gentle slopes, and high soil infiltration rates. In contrast, lower values suggest reduced retention capacity, typically associated with sparse vegetation, small contributing areas, steeper slopes, and low soil infiltration potential.

188 To calculate the mean annual water yield (mm), we used 20-year historical series (the
189 same period used for rainfall and evapotranspiration data) from Xavier et al. (2022). The flow
190 data were obtained from 27 streamflow gauging stations (Department of Water and Electric
191 Energy -Departamento de Águas e Energia Elétrica – DAEE) (Figure 1).

192 **3. Results and discussion**

193 After determining and classifying all evaluation units and overlaying the data, we
194 identified 57 HLRs within the PCJ River Basins. Each region was classified based on relief,
195 aquifer permeability, soil permeability, and climate. The corresponding classification for each
196 parameter is represented by a letter, as illustrated in Fig. 02.

197 Among the identified HLRs, FLLM and MLLV stand out, covering 10.38% and 9.10%
198 of the basin area, respectively. The FLLM HLR was classified as “flat areas with low-
199 permeability aquifers, low-permeability soils, and a semi-humid climate,” while the MLLV
200 HLR was described as “strongly undulating areas with low-permeability aquifers, low-
201 permeability soils, and a very humid climate.” Both share the combination of low-permeability
202 aquifers and low-permeability soils. In such soils, the water infiltration capacity is reduced,
203 causing greater surface runoff, which gains velocity in steep slope areas. This process can lead
204 to a decrease in aquifer recharge, soil erosion, flooding, and siltation of watercourses (MMA,
205 2007).

206 The situation of reduced permeability in the basins becomes evident when considering
207 all HLRs classified as having “low aquifer permeability” together with “low soil permeability.”
208 This combination describes a scenario in which approximately half of the basin area (48.8%)
209 shows unfavorable conditions for water storage and aquifer recharge, when analyzing soil and
210 aquifer permeability. This finding highlights the importance of implementing protection and
211 management projects, especially in areas favorable to infiltration and water storage within the
212 basin.

213 The ideal condition for increasing aquifer recharge in the basin would be the
214 combination of high soil and aquifer permeability in regions where the climate evaluation unit
215 is classified as very humid. However, all areas with high humidity indices were associated with
216 low aquifer permeability. HLRs under these conditions (FLLV, FLMV, TLLV, TLMV, MLLV,
217 MLMV) account for 34% of the total basin area.
218

3.1. Validation

The values of R/P and *m* factor used for method validation are presented in Fig. 03, which correlates the R/P ratio with the Feddema Moisture Index (A), slope (B), and saturated hydraulic conductivity (C). The x-axis values represent the mean of each parameter within the contributing areas of the streamflow gauging stations. These averages were calculated using a shapefile of each station's drainage area, allowing for the extraction of the mean Feddema Moisture Index, slope, and saturated hydraulic conductivity for each river basin. The resulting relationships are illustrated in Fig. 03.

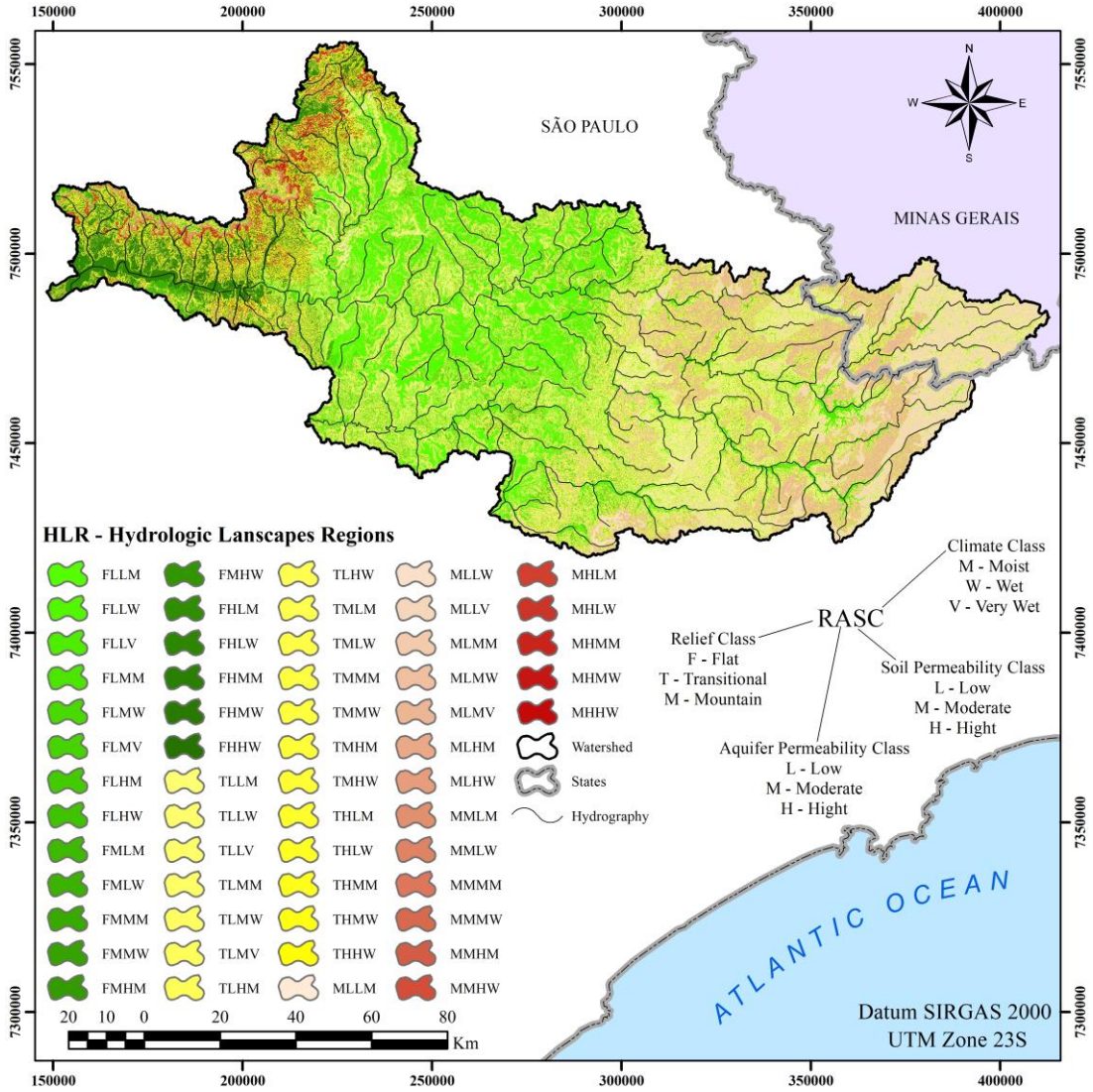


Fig. 02. Hydrologic Landscape Regions (HLRs) identified in the Piracicaba, Capivari, and Jundiaí River Basins.

Fig. 03A shows a weak and nearly negligible correlation between the R/P and the Feddema Moisture Index, with a coefficient of determination close to zero ($R^2 = 0.006$). Despite the weak correlation, the trend indicates a positive relationship, suggesting that more humid areas tend to exhibit higher water yield.

In Fig. 03B, a weak correlation was also observed between the R/P and mean slope values ($R^2 = 0.015$). The trend line shows a positive slope, indicating that the R/P ratio increases with steeper terrain. The values obtained for the PCJ River Basins align with the global results reported by Zhou et al. (2015), reinforcing the consistency of this pattern across different geographic regions.

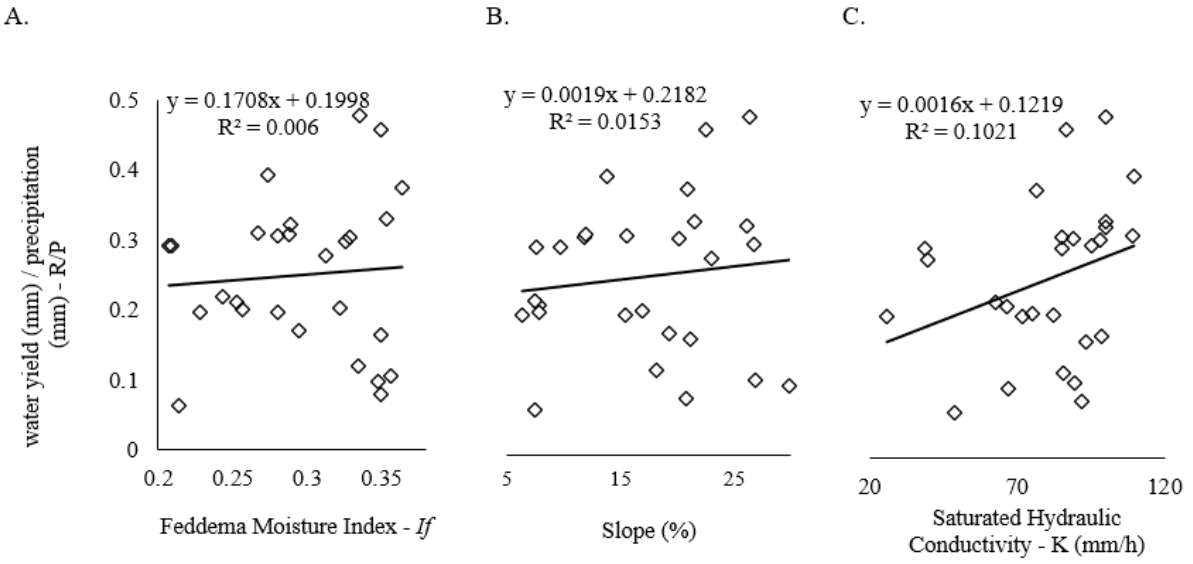


Fig. 03. Relationship between the annual water yield and precipitation ratio (R/P) and Feddema Moisture index (A), slope (B), and saturated hydraulic conductivity (C) for the Piracicaba, Capivari, and Jundiaí River Basins.

Among the three parameters analyzed, hydraulic conductivity showed the strongest correlation with water yield ($R^2 = 0.102$) (Fig. 03C). It also presented the highest angular coefficient, indicating that water yield in the PCJ River Basins is more directly influenced by soil hydraulic conductivity than by slope or the Feddema Moisture Index.

According to Zhou et al. (2008), the dimensionless parameter *m* represents river basin characteristics that affect water flow, making it useful for comparing variables such as saturated hydraulic conductivity and slope. To analyze this relationship, we calculated the mean values of both parameters for each *m* value using shapefiles of the contribution areas for the streamflow stations, given that discharge is essential for determining the *m* factor. The relationship between *m* and the two parameters is illustrated in Fig. 04.

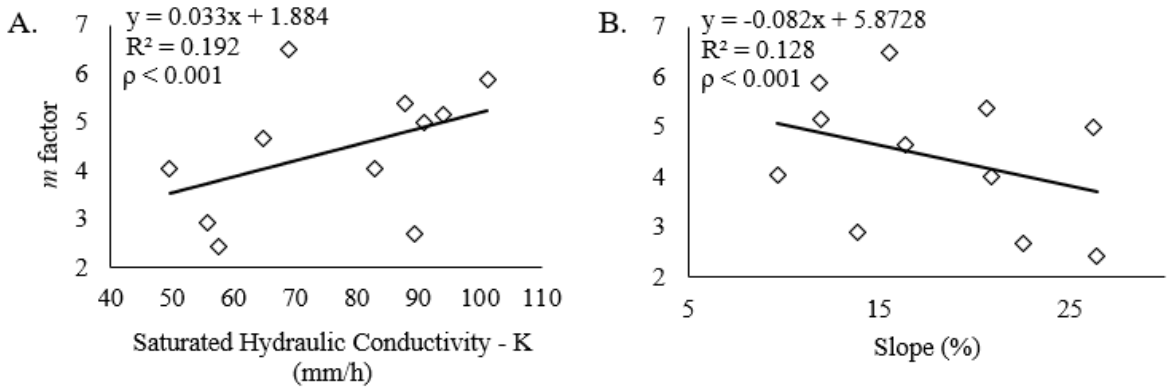


Fig. 04. Relationship between the *m* factor and saturated hydraulic conductivity (A) and slope (B) in the Piracicaba, Capivari, and Jundiaí River Basins.

Fig. 04A shows a correlation between saturated hydraulic conductivity (K) and the *m*-factor ($R^2 = 0.192$); *m* rises as K increases, mirroring the trend reported by Zhou et al. (2015). Slope exhibits a similar but weaker relationship with *m* in the study area ($R^2 = 0.128$; Fig. 04B); however, unlike the K–*m* trend, this association is inverse, in which higher *m* values correspond to gentler slopes, again supporting the finding of Zhou et al. (2015) that smooth terrain favors larger *m*.

Specific flow (Q_e), which was used here to characterize aquifer permeability, did not correlate appreciably with water yield nor with *m* factor when evaluated separately. Likewise, *m* showed no relationship with the Feddema Moisture Index, reinforcing the conclusion of Zhou et al. (2015) that *m* is governed only by physiographic, not climatic, factors.

3.2. Water yield and storage in the Hydrologic Landscape Regions

To evaluate water yield and storage capacities within Hydrologic Landscape Regions (HLRs), average water yield and m-factor values were calculated for each region. Fig. 05 shows R/P ratios for each HLR categorized by climate, aquifer permeability, and relief classifications.

The results demonstrate that mean water yield values reflect variations primarily influenced by climate and aquifer permeability within evaluation units. To clearly represent parameter influences, relief subclasses are color-coded distinctly, while aquifer permeability classes use gradient shades of their base colors.

Slope did not significantly influence water yield within the basin. Regardless of slope variation, areas characterized by high and moderate aquifer permeability exhibited a consistent pattern, highlighting climate as the dominant factor affecting water yield. Regions with high and moderate aquifer permeability and elevated water yield predominantly exhibited wet climates, whereas areas with lower R/P ratios corresponded to moist climates.

High water yield in areas of high and moderate aquifer permeability is expected due to saturated zones with elevated hydraulic conductivity. Poehls and Smith (2009) indicate that hydraulic conductivity in saturated zones typically exceeds that of vadose zones, as pores in saturated conditions facilitate water adhesion and cohesion, promoting aquifer recharge and enhancing overall water yield.

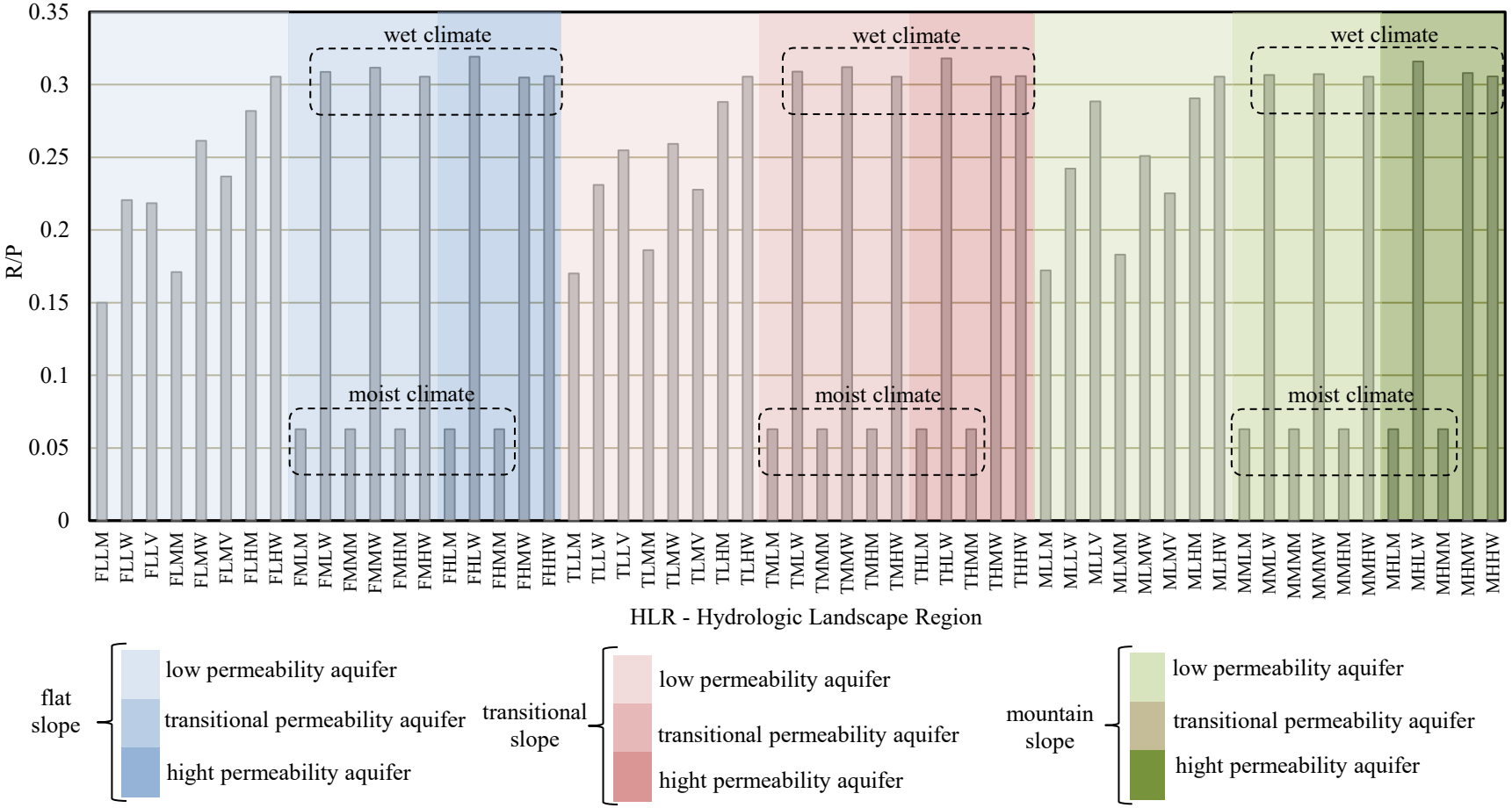


Fig. 05. Mean annual water yield and precipitation ratio (R/P) for Hydrologic Landscape Regions in the Piracicaba, Capivari, and Jundiaí River Basins, differentiated by climate, relief, and aquifer permeability.

In HLRs characterized by low aquifer permeability, the R/P ratio rises progressively from gentle to steep slopes. To clarify this trend, we isolated those HLRs and calculated their mean Feddema Moisture Index and saturated hydraulic conductivity. The resulting values are summarized in Fig. 06.

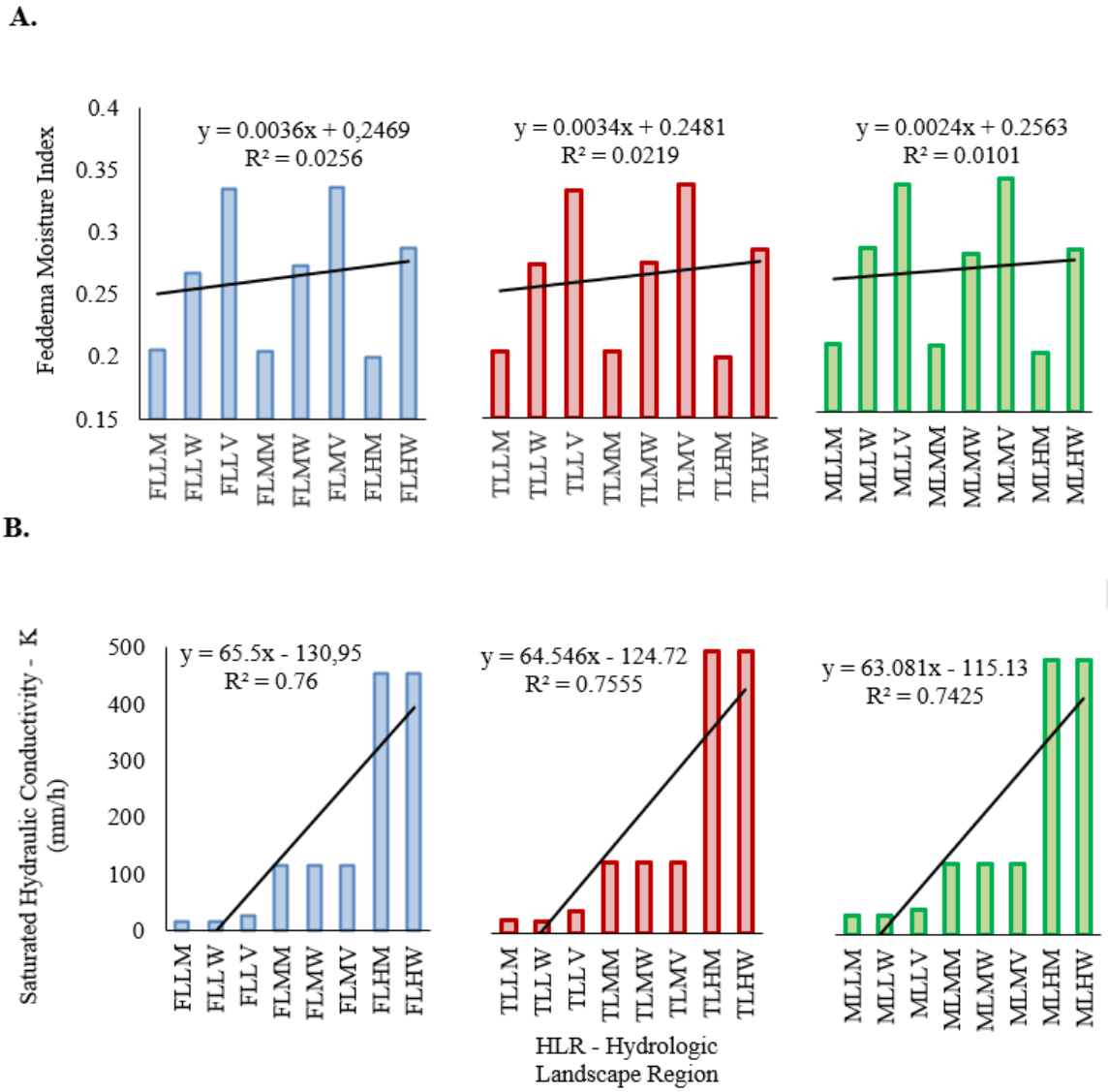


Fig. 06. Mean Feddema Moisture Index (A) and saturated hydraulic conductivity (B) for Hydrologic Landscape Regions (HLRs) with low aquifer permeability in the Piracicaba, Capivari, and Jundiaí River Basins.

Climate-related values (Feddema Index), shown in Fig. 06A, displayed weak correlations with increased water yield in low aquifer permeability areas, with coefficients of determination ranging from 0.01 to 0.02. Nevertheless, all slope classes showed an upward trend, indicating that—even with weak correlation—the climate contributes to rising water yield.

Fig. 06B shows that soil saturated hydraulic conductivity followed the same trend as observed in Fig. 05, with lower R/P ratios in areas classified with low aquifer permeability. These areas are associated ($R^2 = 0.7$) with more permeable soils, which promote surface runoff into streams and increase basin water yield.

To assess potential water storage in the basin, mean m-factor values were calculated for each HLR, shown in Fig. 07. HLRs classified as having high or moderate aquifer permeability exhibited the highest mean *m* values, indicating the strong influence of this parameter. This confirms the m-factor's importance in identifying areas with favorable conditions for water storage. As observed with R/P ratios (Fig. 05), *m* values remained consistent across different relief classes, suggesting slope has minimal influence on m.

To further examine the influence of the selected parameters on m, HLRs were grouped into three categories based on their *m* values. For each group, average values of aquifer specific flow, saturated hydraulic conductivity, slope, and the Feddema Moisture Index were calculated. These results are presented in Table 3.

Table 3. Mean values of aquifer specific flow (Q_e), saturated hydraulic conductivity (K), slope, and Feddema Moisture Index (*If*) for each *m*-factor group.

Group	***m* factor**	**HLR's**	***Q_e* aquifer (m^3/s)**	**K (mm/h)**	**Slope (%)**	***If***
1	$m \leq 4.68$	FLLM; FLLV; FLMM; FLMV; FLHM; TLLM; TLLV; TLMM; TLMV; TLHM; MLLM; MLLV; MLMM; MLMV; MLHM	5.82	70.92	18.51	0.30
2	$4.68 < m \leq 5.36$	FLLW; FLMW; FHLW; TLLW; TLMW; THLW; MLLW; MLMW	13.62	61.29	11.36	0.27
3	$m > 5.36$	FLHW; FMLW; FMMW; FMHW; FHMW; FHHW; TLHW; TMLW; TMMW; TMHW; THMW; THHW; MLHW; MMLW; MMMW; MMHW; MHLW; MHMW; MHHW	92.77	181.68	17.32	0.28

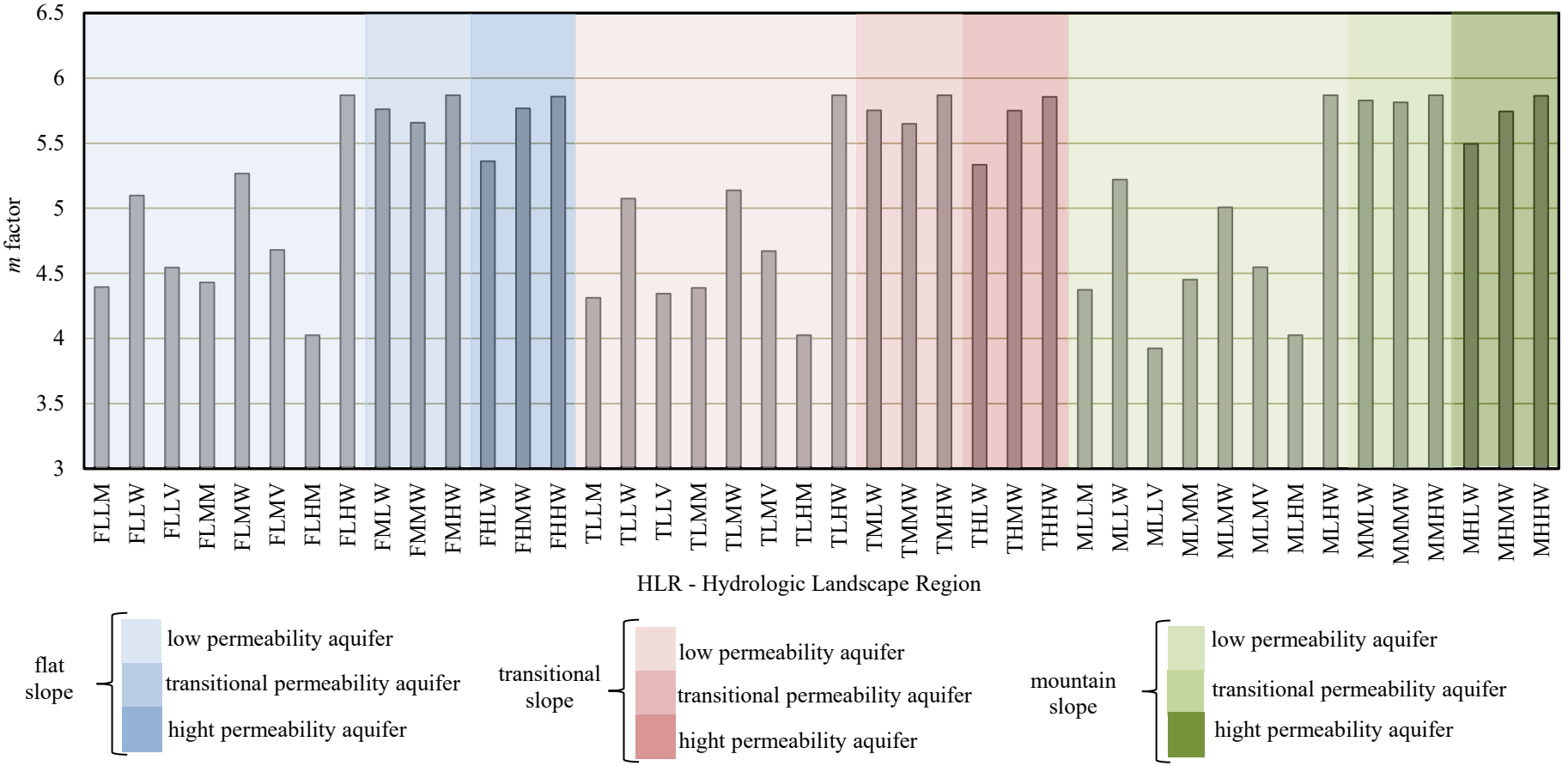


Fig. 07. Mean *m*-factor values for the Hydrologic Landscape Regions (HLRs) in the Piracicaba, Capivari, and Jundiaí River Basins, differentiated by relief and aquifer permeability.

3.3. Identification of favorable HLRs for water yield and storage

The method applied in this study integrates data from four evaluation units into a single layer, where each pixel is classified into one of three categories for each unit. However, it is crucial to identify which combinations of classification units are most favorable for water yield and storage across the basin.

Previous validation analyses confirmed that all four parameters used in the evaluation units—climate, relief, aquifer permeability, and specific flow—contribute to variations in water yield and the m-factor. These findings provide the basis for selecting the most favorable classes for both water yield and storage.

Based on this, we defined two favorable scenarios for water yield and two for water storage within the PCJ River Basins. The criteria used to define these scenarios are detailed in Tables 4 and 5.

Table 04. Hydrologic Landscape Regions identified as favorable for water yield in the Piracicaba, Capivari, and Jundiaí River Basins.

	Criteria (classes)	
Evaluation units	Scenario 1	Scenario 2
Relief	Mountain	Mountain
Soil permeability	Hight	Low
Climate	Wet and Very Wet	Wet and Very Wet
Aquifer permeability	all	all
Identified HLRs	MLHW, MMHW, MHHW	MLLW, MLLV, MMLW, MHLW

Table 05. Hydrologic Landscape Regions identified as favorable for water storage in the Piracicaba, Capivari, and Jundiaí River Basins.

	Criteria (classes)	
Evaluation units	Scenario 1	Scenario 2
Relief	Flat	Flat and Transitional
Soil permeability	Hight	Hight
Climate	Wet and Very Wet	Wet and Very Wet
Aquifer permeability	Hight	Hight
Identified HLRs	FHHW	FHHW, THHW

3.3.1 Criteria for selecting HLRs favorable to water yield

According to Abiy and Melesse (2017), steeper slopes promote surface runoff, reducing water infiltration into the soil. While Fig. 05 shows no significant variation in average R/P across different slope classes, localized analysis (Fig. 03B) reveals that steeper areas tend to produce higher water yields. Thus, relief areas classified as "mountain" are considered most favorable for water yield in the basin.

Water yield in the basin, derived from both surface and subsurface flows, is influenced by soil hydraulic conductivity. As noted by Alvarenga et al. (2012) and Borges et al. (2005), higher K values enhance subsurface infiltration while limiting surface runoff. However, in the Piracicaba, Capivari, and Jundiaí River Basins, high water yield is observed in areas with high saturated hydraulic conductivity (Fig. 03C), due to limited percolation to aquifers—about 83% of the basin is classified as having "low aquifer permeability." To address this, two scenarios were defined: Scenario 1, where HLRs with "high soil permeability" are considered favorable, and Scenario 2, where the "low soil permeability" class is included.

Regarding aquifer specific flow (Q_e), no clear correlation with water yield was found. High water yields were observed across all aquifer permeability classes. As such, no single class emerged as definitively favorable. All three permeability classes—low, moderate, and high—were therefore included in the favorable water yield scenarios.

Lastly, areas classified under "wet" climate showed the highest R/P values (Fig. 05), identifying them as favorable for water yield. Consequently, HLRs classified as "wet" and "very wet" were selected for the favorable water yield scenarios.

3.3.2 Criteria for selecting HLRs favorable for water storage

River basins with less steep slopes promote greater water infiltration into the soil, rather than contributing to water yield. In the study area, slope showed a correlation with the *m* factor from Fuh's theoretical equation, with higher *m* values found in areas of gentle slope (Fig. 04B). This relationship supports the selection of the "flat" relief class as favorable for water storage in Scenario 1 (Abiy and Melesse, 2017). However, the average *m* factor across the HLRs did not vary significantly among different relief classes, justifying the inclusion of both "flat" and "transitional" classes in Scenario 2.

Higher values of saturated hydraulic conductivity were associated with higher *m* factor values, indicating favorable conditions for water storage in the basin (Fig. 04A). Thus, selecting HLRs classified as "high" in the soil permeability evaluation unit is appropriate, as also supported by Alvarenga et al. (2012) and Borges et al. (2005). HLRs with moderate to high

aquifer permeability also exhibited high average *m* values (Fig. 07), confirming the findings of Foster and Hirata (1988), who reported that highly permeable geological formations are associated with greater water storage capacity. Therefore, including the "high" permeability class in both favorable scenarios for water storage in the Piracicaba, Capivari, and Jundiaí River Basins is justified.

According to Glasser et al. (2007), high rainfall volume is crucial for increasing water infiltration into the soil. Consequently, HLRs classified as "wet" and "very wet" were selected for the scenarios favorable to water storage in the basin.

3.3.3 Location of HLRs favorable to water yield and storage

Once the favorable evaluation unit classes for water yield and storage were identified and justified, it was necessary to determine which HLRs contained these conditions. Fig. 08 illustrates the spatial distribution of areas favorable to water yield and storage in the Piracicaba, Capivari, and Jundiaí River Basins under Scenario 1, while Fig. 09 presents the same for Scenario 2. In Scenario 1 (Fig. 08), favorable areas are primarily located downstream in the Piracicaba basin, particularly in the Corumbataí River sub-basin, a critical water supply source for the municipalities of Rio Claro and Piracicaba. These areas also overlap the Guarani Aquifer, the largest aquifer in São Paulo State in terms of stored water volume, emphasizing the need for its protection and sustainable use (Sindico et al., 2018; Elliot & Bonotto, 2018).

When comparing Scenarios 1 and 2 for water storage, Scenario 2 shows a broader spatial extent due to the inclusion of a wider range of relief classes. While Scenario 1 considered only the "flat" class, Scenario 2 incorporated both "flat" and "transitional" relief classes in the assessment.

As shown in Fig. 09, Scenario 2 also presented greater spatial coverage of favorable water yield areas across the basins, primarily due to the wider distribution of soils classified as having "low permeability." Notably, many of these favorable areas are located within the state boundary of Minas Gerais State, underscoring the need for coordinated national initiatives and public policies aimed at water resource protection and conservation.

In the central portion of the Piracicaba River basin lie major urban centers such as Piracicaba and Campinas, both of which have high water demand. However, none of the areas identified as favorable for water yield and storage are located near these cities. Instead, they are primarily situated upstream, particularly in the Corumbataí River sub-basin.

As illustrated in Fig. 08, most Scenario 1 areas favorable to water yield and storage are clustered closely together, a result of similar soil and climatic permeability conditions. This

spatial proximity enhances the efficiency of water resource management projects by improving coordination and optimizing investment in infrastructure and conservation. The close distribution of favorable HLRs is supported by the similarity in their mean R/P ratios and *m* factors, as shown in Fig. 10. There is a statistically significant positive correlation ($R^2 = 0.46$) between the *m* coefficient—an indicator of river basin behavior—and water yield. This demonstrates that HLRs with high water yield also exhibit high storage potential.

The strong correlation between the *m* factor and R/P ratio supports the criteria adopted in Scenario 1, particularly the selection of evaluation units with favorable climate conditions ("wet" and "very wet") and soil types with high permeability.

Both the *m* and R/P values were derived from streamflow data and assigned to specific contributing areas. Consequently, all HLRs within the same contributing area received identical *m* and R/P values. Because a single river basin may include multiple HLR types, it is possible for one HLR to be favorable for water yield and another for water storage, even within the same basin. The presence of HLRs with high *m* and R/P values concentrated in a single river basin reinforces the dual capacity of river basins to support both water production and storage.

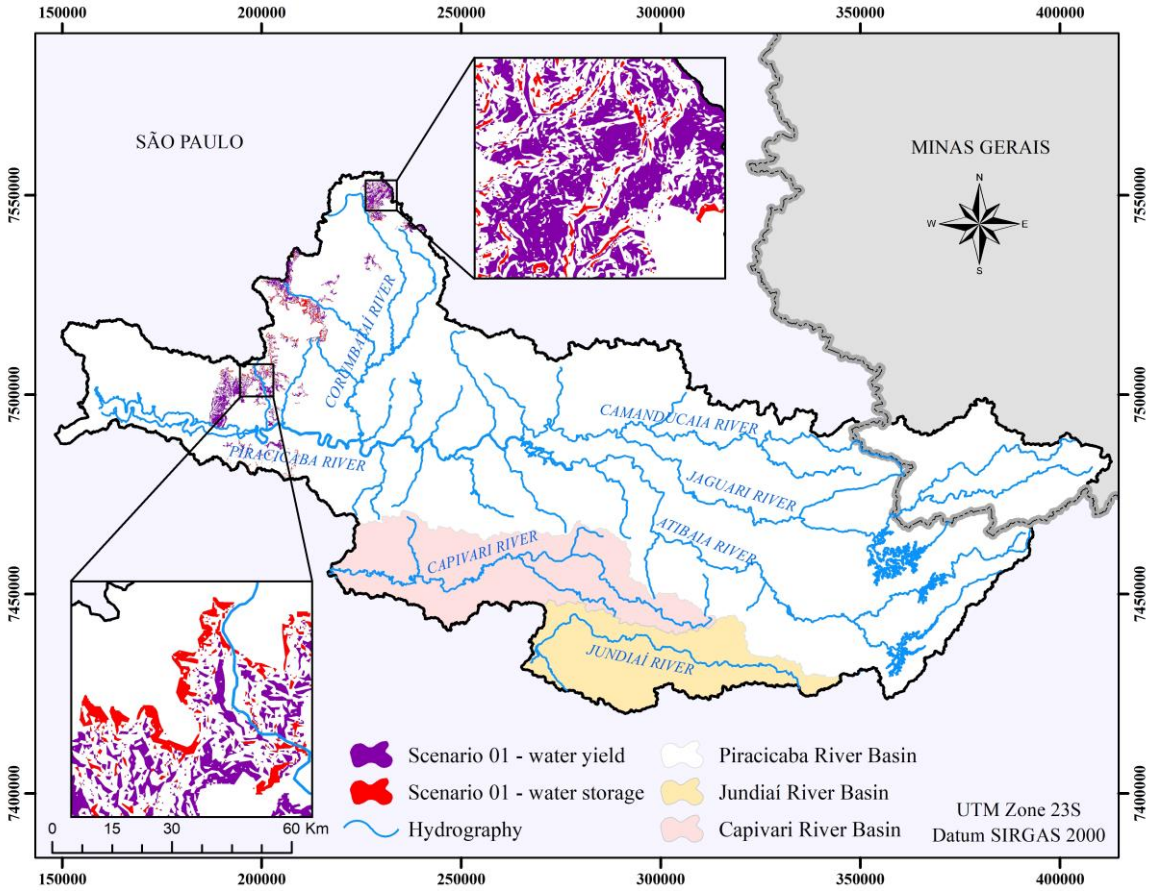


Fig. 08. Favorable areas for water yield and storage in the Piracicaba, Capivari and Jundiaí River Basins under Scenario 1.

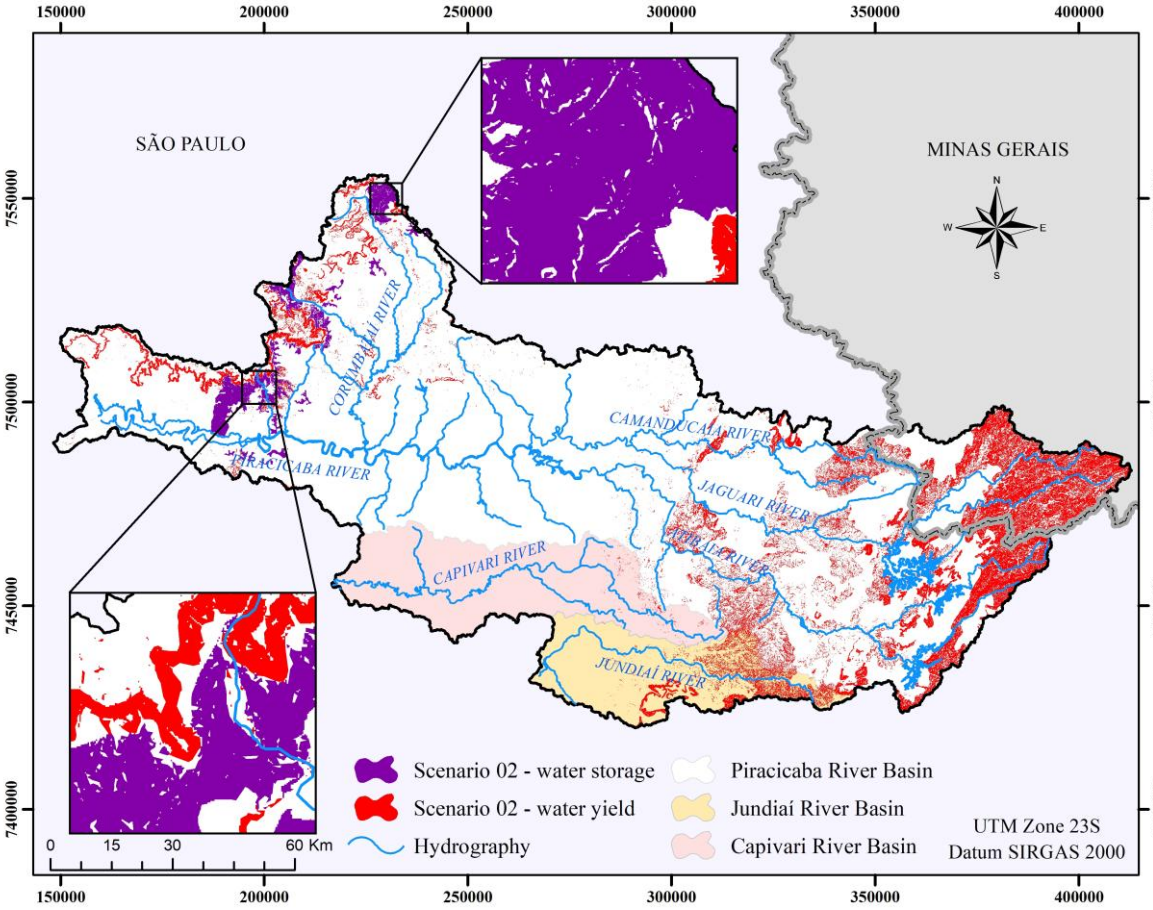


Fig. 09. Favorable areas for water yield and storage in the Piracicaba, Capivari and Jundiaí River Basins under Scenario 2.

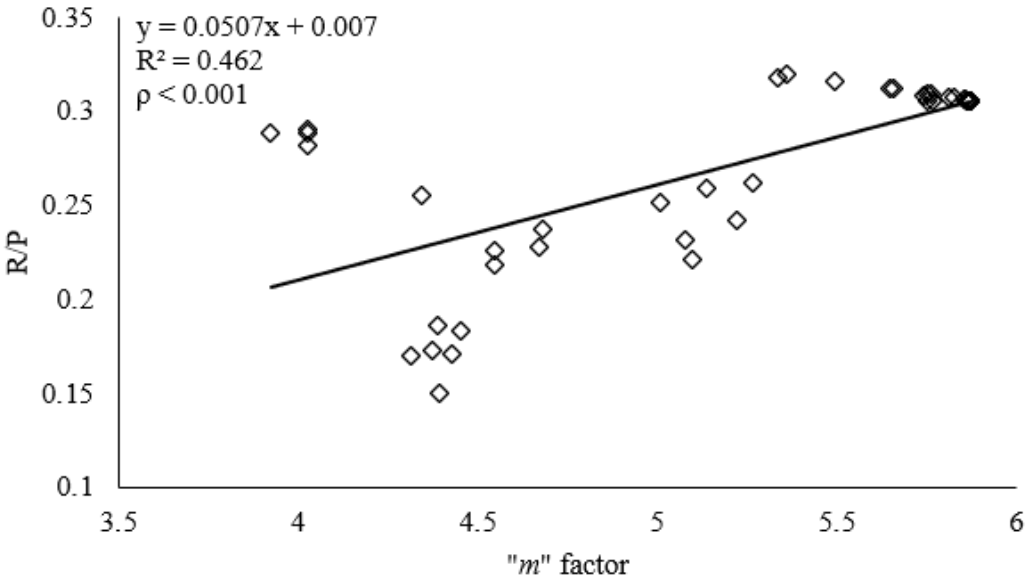


Fig. 10. Relationship between the river basin characteristic coefficient *m* and the water yield and precipitation ratio (R/P) and storage in the Piracicaba, Capivari, and Jundiaí River Basins.

4. Conclusions

The Hydrologic Landscapes (HL) method used for environmental classification in the Piracicaba, Capivari, and Jundiaí River Basins proved to be an effective tool for identifying areas favorable to water yield and storage, as well as for revealing water distribution patterns across varying physiographic conditions—namely climate, relief, soil, and aquifer characteristics.

Unlike traditional approaches based on micro-basins, this study applied pixel-by-pixel classification, assigning one HLR to each 30-meter resolution cell. This method allowed for precise identification of favorable areas for water yield and storage, enhancing the potential for more targeted and cost-effective investments in water conservation and management initiatives. Grouping areas by their hydrological configurations using HLRs enabled the visualization of spatial patterns that would otherwise be difficult to detect. Consequently, the delineation of Hydrologic Landscapes enhances the understanding of how physiographic factors interact to influence both water yield and storage potential.

Most of the favorable areas identified in Scenario 1 were located in the Corumbataí River basin, which exhibited high R/P values (the ratio of annual water yield to mean annual precipitation) and high *m* coefficients, indicating that certain river basins can simultaneously support high water yield and significant storage capacity. The results also demonstrate that the parameters selected for each evaluation unit influence water yield and the *m* factor differently.

While some parameters have a stronger impact on water storage potential, others are more directly associated with water yield. It is important to emphasize that the interactions among parameters described in this study are specific to the Piracicaba, Capivari, and Jundiaí River Basins. These findings should not be generalized to other basins without further localized analysis.

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Open Research

The hydrological data used for method validation in the study are available at https://ph.spaguas.sp.gov.br/Fluviometricos and https://github.com/AlexandreCandidoXavier/BR-DWGD.

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