Identification of Hydrologic Landscapes in Brazilian basins and its application as indicator of water yield and storage

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Abstract: This study aimed to use the Hydrologic Landscapes as environmental classification method in the Piracicaba, Capivari and Jundiaí river basins, validate and use it as an indicator of water yield and storage areas. The method comprises in the same Information Plan (IP) factors that interact with the hydrological cycle in its terrestrial phase. The state of São Paulo, where most of the area is located, constantly suffer from water scarcity. Climate, soil permeability, aquifer permeability, and relief data were used as evaluation units with the aim of identifying favorable areas of water yield/storage. Each pixel received a value of HLR - Hydrologic Landscape Region, which summarizes hydro-geomorphologic characteristics of the site. To evaluate the method efficiency, the annual water yield (R/P) of each sub-basin was calculated using flow data from its main rivers. This data is necessary to identify the factor "*m*" (Fuh's equation), a parameter associated with characteristics of the river basin, such as slope and water infiltration into the soil. The values of water yield and the "*m*" factor corroborate with previous studies, proving that parameters chosen as evaluation units are effective to identify favorable areas for water yield and storage. The classification in Hydrologic Landscapes has proved to be an effective tool in the identification of these areas, which is essential for the optimization of limited financial resources applied in water resources management projects. The results indicate that basins can be considered as water yield areas and, at the same time, have high storage capacity, since the coefficients R / P and factor "*m*" had a positive correlation.

Keywords: hydrologic cycle; hydrologic classification; geoprocessing; watersheds; water yield; water storage.

1. Introduction

Currently, hydrology faces the challenge of finding a classification model of watershed that is holistic, easily applicable, and at the same, time efficient. This appropriate classification would collaborate in the elaboration of hydrological studies and identification of favorable areas to water yield and storage used as domestic, industrial and agricultural supply with high social, economic and environmental importance (Mcdonnell & Woods, 2004; MMA, 2007).

Among the hydrologic classification approaches, high attention is given to the Environmental Classification, which defines classes based on physical and climatic attributes assumed to produce similar hydrologic responses in river basins. It represents a deductive approach to categorize water resources, having the benefit of not requiring an extensive amount of spatial coverage in order to characterize the flow regimes. An advantage of this approach is that it is not reliant on extensive spatial coverage of flow to characterize the flow regime. Instead, spatially comprehensive environmental datasets are often available in Geographic Information Systems (GIS) and are suitable for this purpose. The GIS is also a useful tool in the development of hypotheses and the identification of patterns, defining relationships between predictor and response variables. This classification can play an important role in the monitoring, analysis, and projection of environmental changes. (Detenbeck et al., 2000; Olden et al., 2012; Praskievicz, 2018).

One of the concepts that have been used for environmental classification is the Hydrologic Landscapes. Developed by Winter (2001), is considered flexible and comprehensive. It merges, in terms of unique value, factors that influence the hydrological behavior in the river basins: relief, climate, and soil. This method is used to describe qualitative (water flow over different land cover), and quantitative (synthesizing hydraulic, geological and climate information in a GIS layer) variable.

The Hydrologic Landscapes method is considered a useful tool for environmental management, water quality monitoring, sampling activities, and the identification of priority areas for reforestation, and other projects that required hydrological information on large areas. From a hydrological point of view, this process can be used for the indication of favorable areas to water yield and storage, providing a better understanding of how factors that affect the hydrological cycle may interact with each other and how their combination influence in the water availability. Finally, is also a tool to mitigate the water deficit adverse effects, since it aggregates, at the same layer, climate, slope, soil, and aquifer permeability data. It also facilitates the identification of favorable areas to water yield and storage, supporting reforestation prior areas selection, which would mostly contribute to water resources quality and quantity conservation.

From the concepts of Winter (2001), Wolock et al. (2004) developed a method for the delimitation of Hydrologic Landscapes, which classifies river basins into 20 different groups - Hydrologic Landscapes Regions (HLR). This classification uses geoprocessing and statistical techniques applied to relief, soil texture, precipitation, and rocky bed permeability. Afterward developing the method, Wolock et al. (2004) applied it to all basin in the United States of America and currently are considered pioneers and example of the most efficient attempt of a hydrological classification on large basins.

At a regional scale, Wigington et al. (2013) suggested a more detailed approach: using geophysical data with high spatial resolution than those available at the national. Leibowitz et al. (2016) updated the classification system developed by Wigington et al. (2013) in order to use it under intense snow events, frequent conditions presented in the Pacific Northwest.

Santhi et al. (2008) show that the Hydrologic Landscapes classification is efficient in the prediction of regional base flow, indicating that the qualitative characteristics used in the concept were in agreement with hydrological responses. Carlisle et al. (2010) also found that this method improved the data prediction models that characterize watersheds. Patil et al. (2014) evaluated the efficacy of Wigington et al. (2013) classification comparing it to data from 88 fluviometric stations distributed in the State of Oregon - United States. Brown et al. (2014) proved the effectiveness of the mentioned method in the prediction of hydrological variability in the Southeast of Australia. However, no previous paper addressed this classification for the simultaneous identification of favorable areas to the water yield and storage in watersheds.

Based on the previous description, this study proposes the identification of Hydrologic Landscapes and favorable scenarios for water yield and storage in three hydrological basins (Piracicaba, Capivari, and Jundiaí) located in Brazil.

2. Study area

The study area is a joint major area composed by the Piracicaba, Capivari, and Jundiaí (PCJ) river basins, localized in southeastern Brazil. The total area is about 15,303.67 km² and is spatially located between longitudes 46° and 49° W and latitudes 22° and 23° S, is 92.6% within the Brazilian state of São Paulo and only 7.4% in the state of Minas Gerais.

Due to its proximity to the metropolitan area of São Paulo, the area is under intense anthropic pressure for residential and industrial space. Besides urban pressure, the area has an intense agricultural vocation, considered one of the greatest agroindustrial poles of the Brazilian

Southeast region. Although the area has a great number of springs, all of the economic importance might be compromised due to reducing water availability per capita. In addition to the decreasing water availability, the deforestation of its original vegetation cover (Atlantic Forest), in order to open new areas for agricultural and livestock occupations, has aggravated the environmental problems expected (CBH-PCJ, 2017).

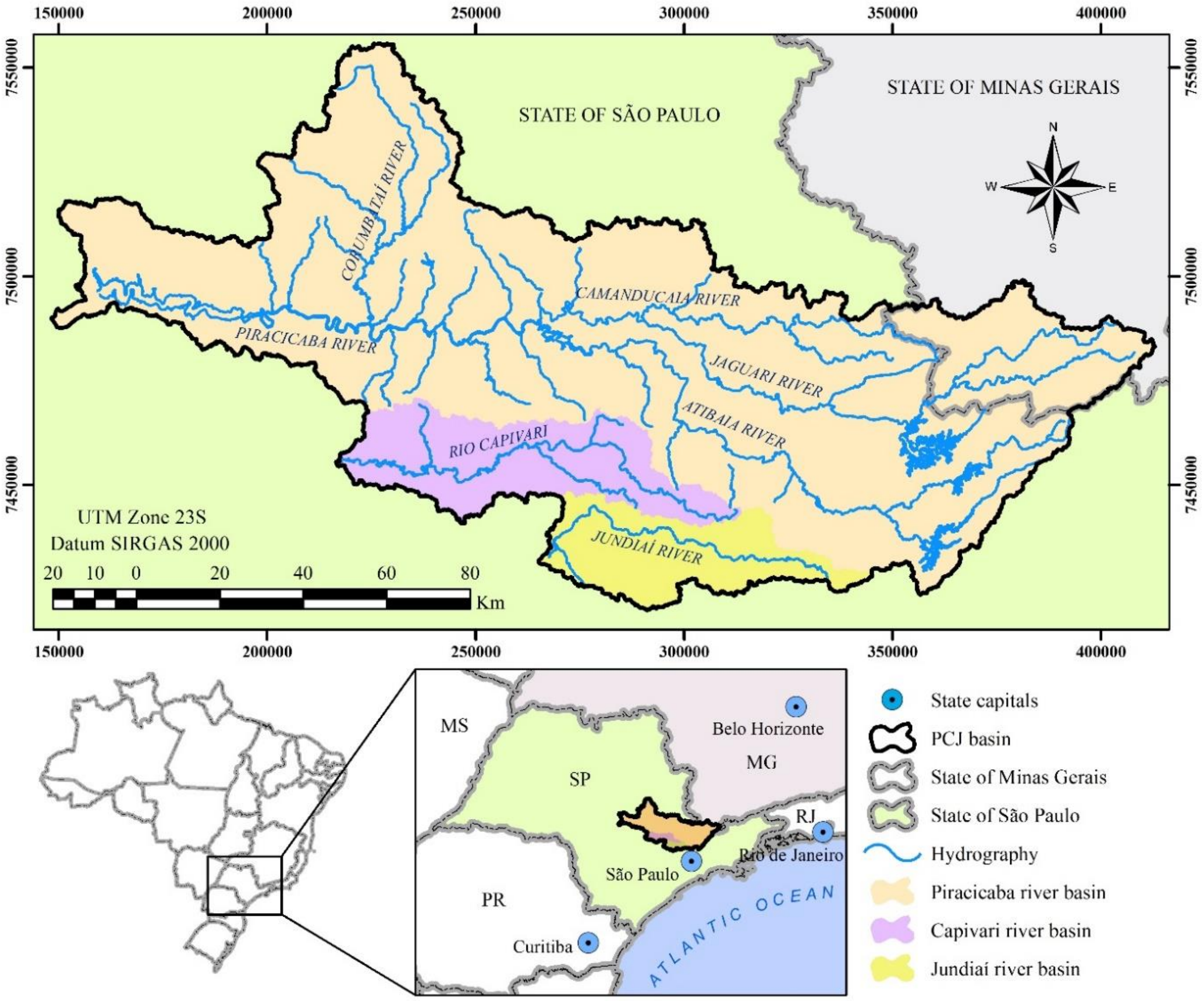

Fig. 1. Location of Piracicaba, Capivari, and Jundiaí river basin in the national context.

3. Material and methods

3.1. Evaluation unit’s database sources

For the relief hydrological evaluation unit, we used a Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 30m (USGS, 2017).

Soil permeability influences on the infiltration and is described by means of saturated hydraulic conductivity parameter. Since high values are directly associated to great water flows and moves through the soil (Libardi, 2010), it is of high importance its accurate determination in order to compose the soil permeability assessment unit, as also used by Wigington et al. (2013) and Wolock et al. (2004).

The saturated hydraulic conductivity (K) was estimated based on Rawls & Brakensiek (1985) soil properties (Equation 1). The values of soil porosity, the percentage of sand and clay on each soil type comes from laboratory tests carried out by Oliveira (1999).

$$\begin{aligned} K = 10\exp(&19.5234POR - 8.96847 - 0.02821PC + 0.00018107PS \\ &- 0.009412PC^2 - 8.395215POR^2 + 0.077718PSPOR \\ &- 0.00298PS^2POR^2 - 0.09492PC^2POR^2 + 0.0000173PS^2PC \\ &+ 0.2733PC^2POR + 0.001434PS^2POR - 0.0000035PC^2PS) \end{aligned} \tag{1}$$

Where: K is the saturated hydraulic conductivity (mm/h); POR is the soil porosity (%); PS is the sand percentual (%); and PC is the clay percentual (%).

Climate information, precipitation (P) and potential evapotranspiration (ETP) from the basin were synthesized in a single index by mean of the Feddema Moisture Index (Feddema, 2005), as described in Equation 2. The values are staggered from -1.0 to 1.0, where the lowest value represents an arid condition and the highest, a humid condition.

$$If = \begin{cases} 1 - \mathrm{ETP}/\mathrm{P} \ se \ \mathrm{P} > \mathrm{ETP} \\ 0 \ se \ \mathrm{P} = \mathrm{PET} \\ \mathrm{P}/\mathrm{ETP} - 1 \ se \ \mathrm{P} < \mathrm{ETP} \end{cases} \tag{2}$$

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

The precipitation data used in the study is a mean value of 15-year historical series length (2001 to 2015) from meteorological stations located inside the PCJ basins. Evapotranspiration values were calculated by the method of Thornthwaite & Mather (1955), which uses as the main variable mean air temperature data from the same stations.

Fetter (2001) affirms that aquifers permeability is directly related to the specific flow. Therefore, for the generation of the evaluation unit for the permeability of the aquifers, we used specific flow (Qe) data. All flow values were estimated based on physical properties of aquifers and wells from São Paulo's state government by SAP (Sistema Ambiental Paulista). Table 1 summarizes all database source used in the determination of the four evaluation units.

Table 1. Data sources for evaluation units' determination.

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 types map	1:250.000	São Paulo Forest Institute (ROSSI, 2017)
	Soil	Soil physical 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	Comitê PCJ (CBH-PCJ, 2017)

3.2. Identification of Hydrologic Landscapes

The development of the method used on the present classification of Hydrologic Landscapes in the PCJ area is based on previous works developed by Wolock et al. (2004), Wigington et al. (2013), Brown et al. (2014), with some adjustments needed to a better representation under tropical conditions.

Differently from the works developed by Wolock et al. (2004) and Wigington et al. (2013), in which the classification had the objective to classify each sub-basin with a single HLR value, the classification proposed in this study used a pixel-by-pixel procedure, as adopted by Brown et al. (2014). All the units used in the generation of the Hydrologic Landscapes were reclassified into three classes, the same process done in Wigington et al. (2013).

The Hydrologic Landscapes classification in the PCJ basins was based on the overlapping of four hydrological evaluation units selected according to the concepts of Hydrologic Landscapes presented by Winter (2001): relief, soil permeability, aquifer permeability, and climate. The steps developed in GIS were processed in ArcGIS 10.4. For the classes identification, the data obtained from the four parameters were reclassified using the Natural Breaks (Jenks) statistical method, identifying breakpoints that best group similar values and, simultaneously, maximizing the difference between classes based on the smallest error possible (Fernandes, et al., 2012).

After reclassifying the data, we layered the evaluation units in the same information plan (IP), obtaining the Hydrologic Landscapes classes or Hydrological Landscape Regions (HLR). By this process, each HLR is responsible for storing four different information from the four assessment units.

The values used for reclassification of the parameters in the evaluation units and the classification assigned for each range are presented in Table 2.

Table 2. Evaluation units' classes.

Evaluation units	Parameter	Values	Classes
Relief	Slope (%)	$d \leq 8$	Flat
		$8 < d \leq 20$	Transitional
		$d > 20$	Mountain
Aquifer permeability	Aquifer specific flow (mm/h)	$Qe \leq 30$	Low
		$30 < Qe \leq 60$	Moderate
		$Qe > 60$	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

3.3. Method validation

ZHOU et al. (2015) correlated the annual water yield (R) with some parameters used here as evaluation units in the Hydrologic Landscapes identification process and the findings suggest the necessity to compare the influence that each parameter exerts on the water yield and storage in the basin. The ratio between the annual water yield and the mean annual precipitation is used to obtain a dimensionless index that best represents the precipitated portion that contributed to water yield (Duan et al., 2016).

The Fuh's theoretical equation (Equation 03) describes a pattern between the annual water yield coefficient (R/P), the wetness index (P/ETP) and the physical characteristics of the watershed (m) (Fuh, 1981). It is considered a very efficient method to predict hydrological responses by associating physical characteristics of the watersheds with hydrological data (Zhou et al., 2015).

$$\frac{R}{P} = \left(1 + \left(\frac{P}{ETP}\right)^{-m}\right)^{\frac{1}{m}} - \left(\frac{P}{ETP}\right)^{-1} \tag{3}$$

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 the dimensionless coefficient of watershed characteristic.

According to Zhou et al. (2008), the dimensionless parameter *m* describes the characteristics of the basin, such as area, slope, land use and cover, soil texture, and depth. Zhou et al. (2015) observed that this parameter indicates the capacity of the river basin to retain water, varying according to the physical characteristics. High values of *m* indicate an increase in water retention capacity, probably due to the combination of a preserved vegetation cover, large contribution area, soft slopes, and high infiltration capacity. In contrast, lower values indicate a decrease in water retention, probably due to a reduced vegetation cover, small contribution area, steeper slopes, and small soil infiltration capacity.

In the calculations of the mean annual water yield (mm), we used historical series with 15 years length (the same period used in rainfall and evapotranspiration data) from 27 fluviometric stations. The flow data comes from the DAEE – Departamento de Águas e Energia Elétrica.

4. Results and discussion

After the determination and classification of all the evaluation units and data overlap, we identified 57 HLR's (Hydrologic Landscape Region) in the PCJ basins. Each unit received a classification referring to the relief, aquifer permeability, soil permeability, and climate, and each letter represents the classification assigned in its respective evaluation unit, as shown in Fig. 2.

4.1. Validation

The obtained values of water (R/P) and *m* factor used for method validation are presented in Fig. 3, correlating R/P ratio with Feddema Moisture Index (A), slope (B) and saturated hydraulic conductivity (C) parameters. The values on the abscissa coordinates are the mean of each of the three parameters in the areas obtained from the fluviometric stations. The average of the three parameters was calculated with the aid of a shapefile with the contribution area of the stations, that is, for each contribution area of each fluviometric station was calculated the average of the Feddema Moisture Index, slope, and saturated hydraulic conductivity. The relationships are shown in Fig. 3.

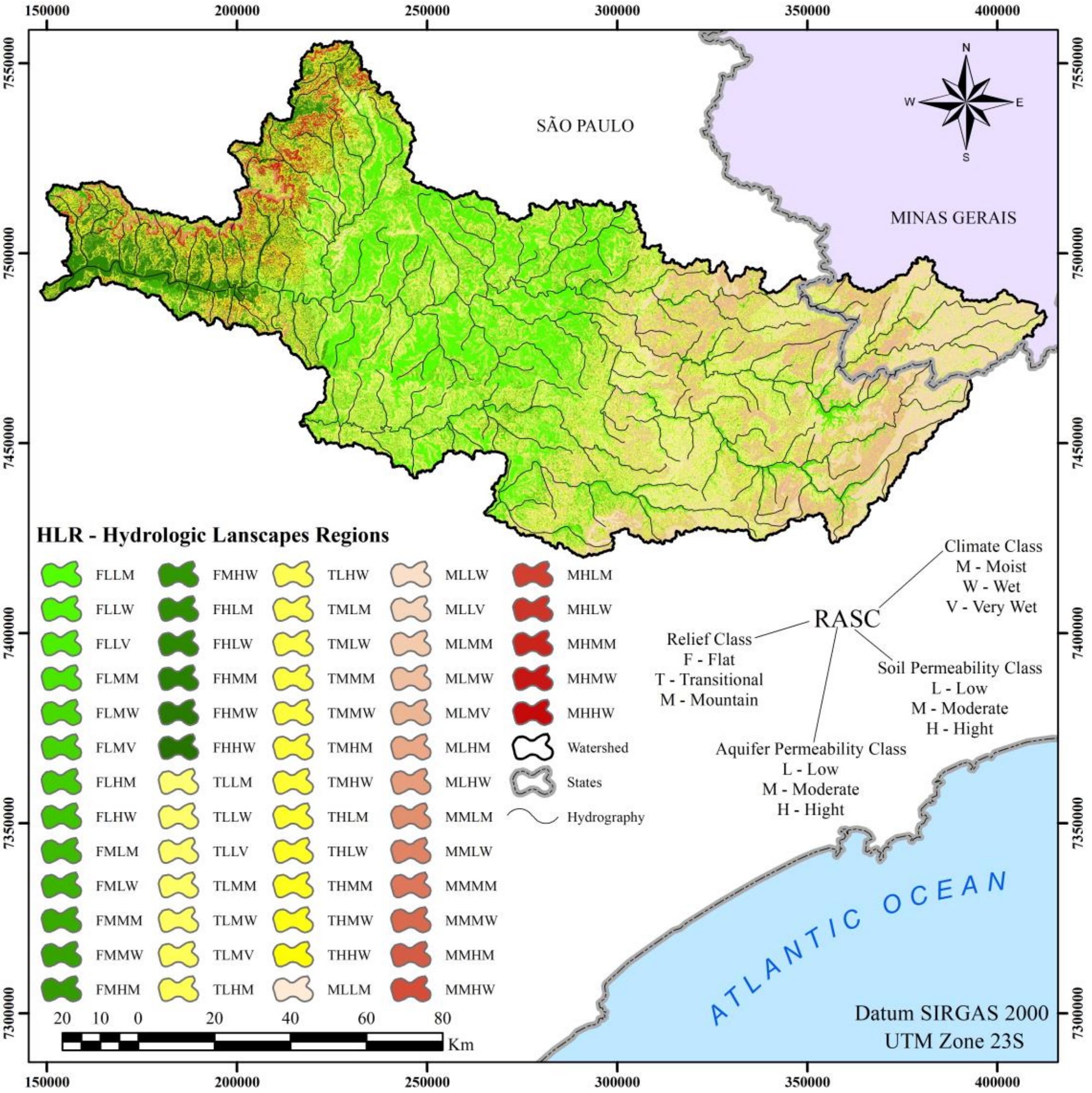

Fig. 2. Hydrologic Landscapes Regions identified in the Piracicaba, Capivari, and Jundiaí river basins.

Fig. 3A shows a weak, and even negligible, the correlation between water yield (R/P) and Feddema Moisture Index, with a coefficient of determination very close to zero (R^2 = 0.006). However, even with a weak correlation, the tendency indicates a positive correlation, where areas that are more humid are associated with areas with high water yield.

In Fig. 3B, we also found a weak correlation (R^2 = 0.015) of water yield and mean slope values. Similarly, the tendency line of the graph presented a positive angular coefficient, where the ratio R/P increases following the slope angle. The values presented in the PCJ basins of the R/P with slope corroborated with the results presented by Zhou et al. (2015), which results from all over the world are presented.

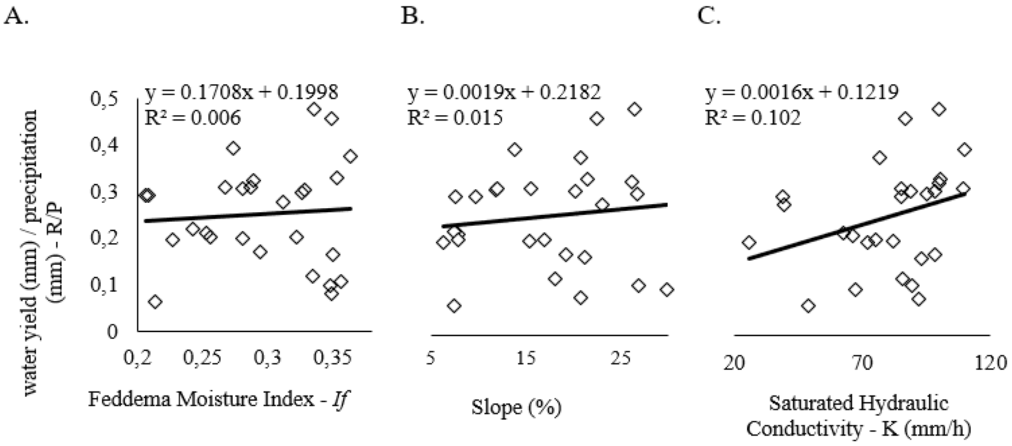

Fig. 3. Relationship of the water yield "R/P" with the Feddema Moisture Index (A), slope (B) and saturated hydraulic conductivity (C), in the Piracicaba, Capivari, and Jundiaí river basins.

Among the three data presented, the soil hydraulic conductivity has the strongest correlation ($R^2 = 0.102$) with water yield (Fig. 3C). Additionally, it also has the largest angular coefficient of them, meaning that water yield in the PCJ basins is more directly related to the saturated hydraulic conductivity of the soil than slope or Feddema Moisture Index.

According to Zhou et al. (2008), the dimensionless parameter *m* describes watersheds characteristics that influence water flow, being useful on the comparison of soil hydraulic conductivity and slope data. We calculated mean values of saturated hydraulic conductivity and slope for each value of *m* using a shapefile with the contribution area of the fluviometric stations since the flow is an essential parameter for the determination of the *m* factor. The relation of the two parameters with the *m* factor is given in Fig. 4.

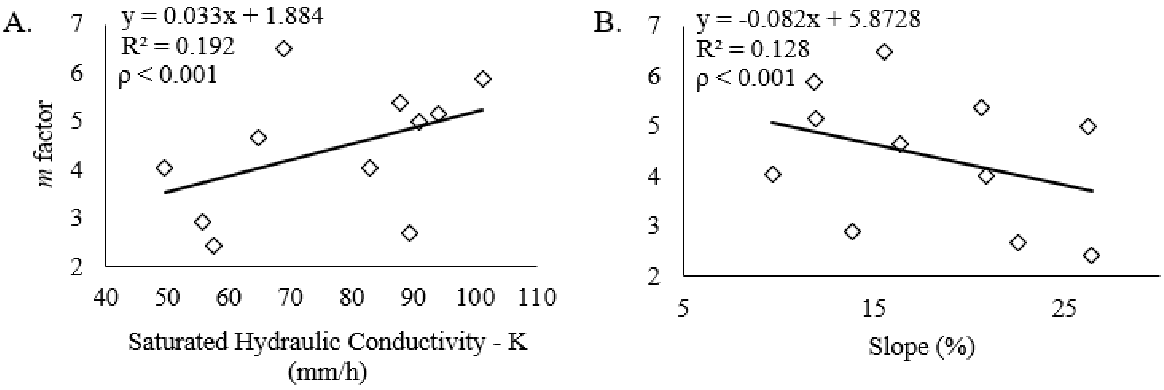

Fig. 4. Relationship of the *m* factor with the saturated hydraulic conductivity (A) and slope (B), in the Piracicaba, Capivari, and Jundiaí river basins.

A correlation between the saturated hydraulic conductivity (K) and the *m* factor, with $R^2 = 0.192$, is observed in Fig. 4A. There is also a tendency to increase the values of *m* as higher values of K appears, confirming the suggestions from Zhou et al. (2015). The slope also has a similar correlation ($R^2=0.128$) with the *m* factor in the study area, as given in Fig. 4B. However, in opposite to the findings presented in Fig. 4A, it has a negative correlation where high values of *m* indicate low values of the slope. This is confirmed by Zhou et al. (2015), in which higher values of *m* occur due to smooth slopes.

When analyzing individually the aquifer specific flow (Qe) values used as a parameter in the aquifer permeability evaluation unit, there was no representative correlation with the water yield or with *m* factor. The *m* factor also did not have a correlation with Feddema Moisture Index, confirming the prepositions of Zhou et al. (2015) that the *m* factor is only related to physiographic characteristics, not climatic ones.

4.2. Water yield and Storage in the Hydrologic Landscapes

In order to evaluate the Hydrologic Landscapes Regions according to their water yield and storage capacity, we calculated the mean water yield and m factor values for each HLR. Fig. 5 presents the values obtained of R/P in each HLR regarding the climate, aquifer permeability and relief classification.

It can be noticed that the mean values of the water yield behave according to criteria variations defined in the evaluation units, mainly for climatic and aquifer permeability variations. In order to facilitate the understanding of the influence of each parameter, relief classifications have a different color for each subclass, as the aquifer permeability classes have a gradient of the previous color selected.

The slope was not a critical parameter influencing the water yield in the basin since the values did not vary significantly. Regardless of the slope, the areas with high and moderate aquifer permeability presented a pattern, where climate had a critical role in water yield values. The HLRs with high and moderate aquifer permeability and high values of water yield have, mostly, a wet climate. On the other hand, areas with low R/P values have a moist climate.

High water yield value in areas with high and moderate aquifer permeability is expected due to the occurrence of saturated zones on areas with elevated saturated hydraulic conductivity. According to Poehls & Smith (2009), the hydraulic conductivity inside of a saturated zone is, in most cases, larger than in the vadose zone. In these areas the pores are almost filled with water supporting adhesion and cohesion properties, favoring water flow into aquifers and the water yield.

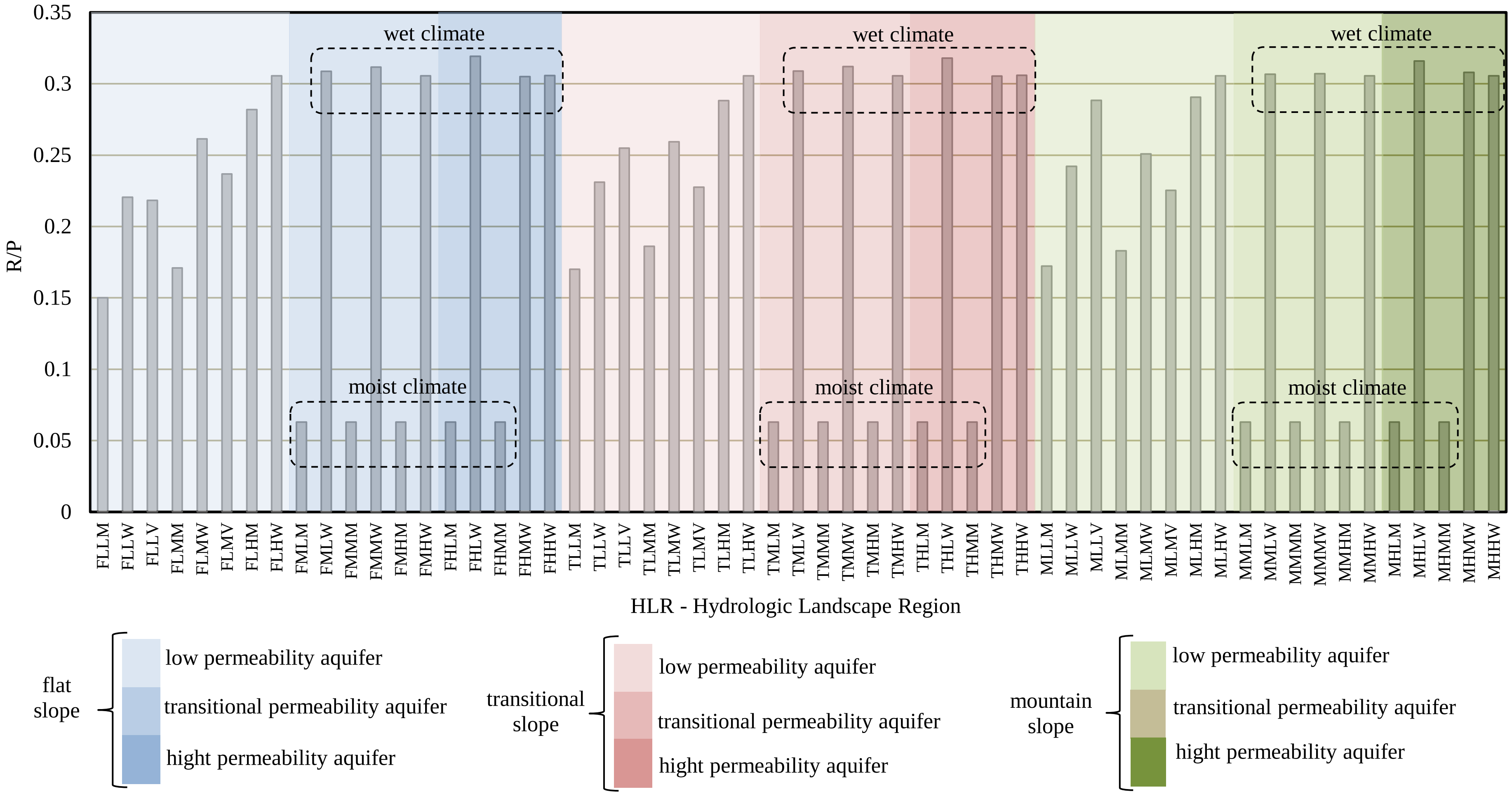

Fig. 05. Mean of water yield in the HLRs of the Piracicaba, Capivari, and Jundiaí river differentiating according to the climate, relief and aquifer permeability.

There is a pattern of R/P values in the HLRs under low aquifer permeability observed in the three types of slope, where there is a gradual rise in the water yield. To evaluate the behavior of these areas, we separated the HLRs included in these ranges and calculated the mean values of the Feddema Moisture Index and the saturated hydraulic conductivity. The values are given in Fig. 6.

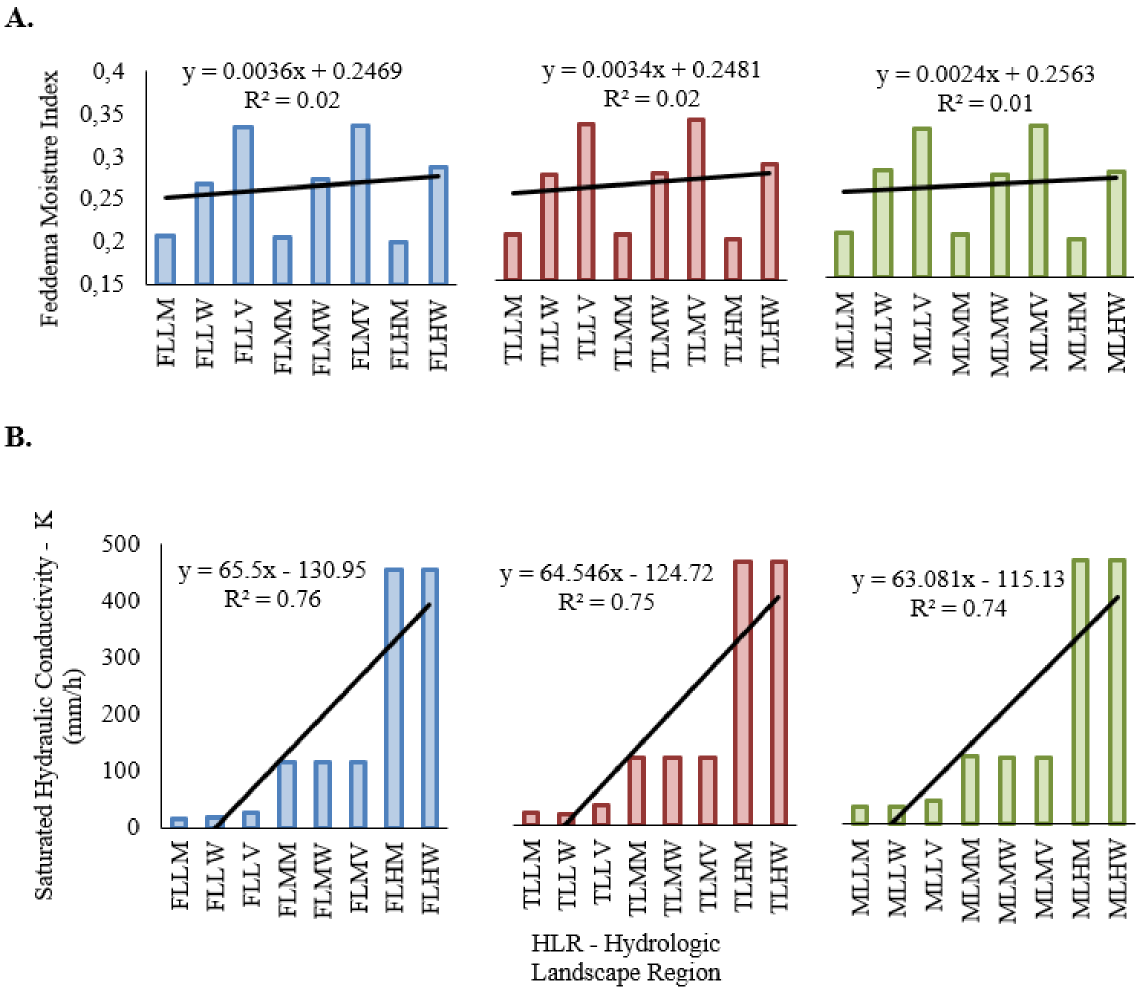

Fig. 06. Mean values of Feddema Moisture Index (A) and saturated hydraulic conductivity (B) in HLRs classified as low aquifer permeability in the Piracicaba, Capivari, and Jundiaí river basins.

The climate-related values (Feddema Index), shown in Fig. 6A, did not correlate with increased water yield in low aquifer permeability areas, where the coefficients of determination were between 0.01 and 0.02. However, in the three bands there is an upward sloping tendency, meaning that, even with a low correlation, there is an increase in water yield related to the climate.

Fig. 6B shows that the saturated hydraulic conductivity values of the soil presented the same pattern previously showed in Fig. 5, where is observed low R/P values in areas classified with low aquifer permeability. The low aquifer permeability is associated ($R^2 = 0.7$) with more permeable soils that favor water flowing to streams, increasing water yield in the basin.

In order to evaluate the potential water storage in the basin, it was necessary to obtain the mean values of *m* factor in each HLR, shown in Fig. 7. The HLRs classified as high and moderate aquifer permeability had the highest mean values of *m* factor. It indicates that the parameter used exerts a strong influence on *m* and that the parameter is of essential importance in the identification of favorable areas to water storage in the area. As in the R/P ratio (Fig. 5), the mean values of *m* presented the same pattern over different relief classifications, showing the poor parameter interference in the *m* factor.

In order to better analyze the chosen parameters, influence in the *m* factor, the HLRs were separated into three groups according to the *m* values. After the reclassification, the averages of the four parameters (aquifer specific flow, saturated hydraulic conductivity, slope, and Feddema Moisture Index) were calculated in the respective areas, as are shown in Table 3.

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

Group	***m* factor**	**HLR's**	**Qe 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

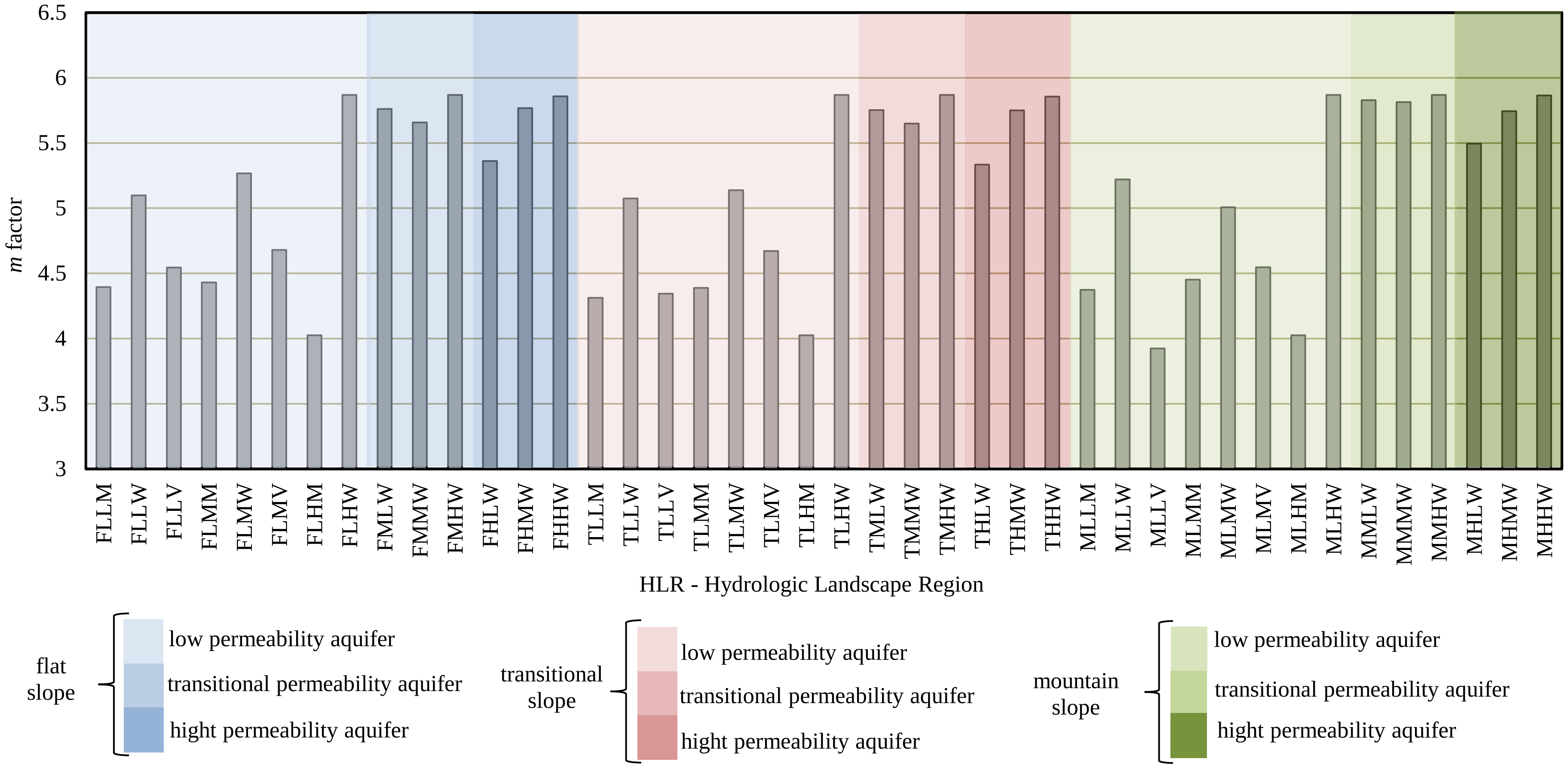

Fig. 07. Mean of *m* factor values in the HLRs of the Piracicaba, Capivari, and Jundiaí river basins differentiating according to relief and aquifer permeability.

4.3. Identification of favorable HLRs to water yield and storage

The method applied in this study summarizes in the same layer information from four evaluation units, in which each pixel presents one of the three classifications available for each one of these units. However, it is important to identify which classes of assessment units are most favorable for water yield and storage in the basins. The analyses performed previously in the validation stage showed that all of the parameters used as evaluation units interfered somehow in water yield data and *m* factor, serving as a reference for choosing the favorable classes for water yield and storage. Therefore, we identified two favorable scenarios for water yield and other two for water storage in the PCJ basins. The criteria for defining the scenarios are described in Tables 4 and 5.

Table 04. Hydrologic Landscapes Regions selected as favorable to water yield in the Piracicaba, Capivari, and Jundiaí river basins.

	Criteria (classes)	
Evaluation units	Scenario 01	Scenario 02
Relief	Moutain	Moutain
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 Landscapes Regions selected as favorable to water storage in the Piracicaba, Capivari, and Jundiaí river basins.

	Criteria (classes)	
Evaluation units	Scenario 01	Scenario 02
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

4.3.1 Criteria selection of HLRs favorable to water yield

According to Abiy & Melesse (2017), more pronounced slopes favors surface runoff, which difficult the water infiltration into the soil. In the results presented in Fig. 5, it was observed that the average of R/P did not vary significantly according to different slope classifications. However, looking closer to some parts in the basin (Fig. 3B), more steep areas are related to higher water yield values. In this way, the mountain class of the relief is the most favorable to water yield in the basin.

The water yield in the basin was obtained from water flow data, which is composed of the sum of the surface and underground flow. Alvarenga et al. (2012) and Borges et al. (2005) cite the hydraulic conductivity of the soil as an essential factor for the underground flow, where higher values of K are associated with high water infiltration rate into soil, inhabiting runoff.

However, the Piracicaba, Capivari, and Jundiaí river basins have high water yield in areas with high values of saturated hydraulic conductivity, as shown in Fig. 3C, possibly due to the low percolation of water to the aquifers, where approximately 83% of the basin is classified as "low aquifer permeability". In this way, two scenarios were analyzed, the main one, using the HLRs with classifications in "high soil permeability" as favorable situation, and another scenario using the "low soil permeability" class as the second alternative.

Regarding the estimated values of aquifer specific flow (Qe), there was no correlation with the water yield values. When looking at the average values of water yield in the HLRs, high values of water yield are found in the three permeability classes of the aquifer. The results obtained are inconclusive to indicate which class of evaluation units of the aquifer permeability is favorable for water yield in the PCJ river basins. The choice of the three classes of permeability of the aquifer (low, moderate and high) is then justified to compose the favorable scenarios to water yield in the PCJ basins.

Finally, it was identified that the areas classified as "wet" climate had higher R/P values (Fig. 5), that is, favorable areas for water yield. Thus, the classes selected to compose the favorable scenarios to water yield in the basin are the HLRs classified as "wet" and "very wet".

4.3.2 Criteria selection of HLRs favorable to water storage

Instead of water yield, watersheds with less steep slopes facilitate the water infiltration into the soil. The slope of the study area showed a correlation with the *m* factor (Fuh’s equation), where higher values of *m* are present in areas with a smooth slope (Fig. 4B). This relationship has supported the choice of the "flat" class of the relief evaluation unit as favorable to water storage in scenario 1 (Abiy and Melesse, 2017). However, when calculating the average of the *m* factor of the HLRs, no substantial interference was identified according to the different classes of relief, justifying the choice of classes "flat" and "transitional" to compose scenario 2.

There are several factors that influence hydraulic conductivity and their correlations, making it difficult to generalize and establish relationships between the permeability coefficient and other soil physical attributes, since the synergy of them determine water flow and not the isolation of each one. It is also necessary to consider other competing factors, such as mineralogy, structure, and porosity. Thus, the use of soil hydraulic conductivity values and assumptions about its use should consider specific criteria from the study area (Mesquita & Moraes, 2004).

It was found that higher values of saturated hydraulic conductivity are associated with high values of the *m* factor are favorable water storage in the basin (Fig. 4A). Thus, the choice of HLRs classified as "high" in the evaluation unit of soil permeability is feasible, as confirmed by Alvarenga et al. (2012) and Borges et al. (2005).

The HLRs classified in the evaluation unit of moderate and high aquifer permeability presented a high mean value of the *m* factor, as shown in Fig. 7. It confirms Foster and Hirata (1988), where geological formations with high permeability are associated with high water storage capacity. Therefore, it is justifiable the use of this the "high" class in the aquifer permeability in both favorable scenarios for water storage in the Piracicaba, Capivari, and Jundiaí river basins.

According to Glasser et al. (2007), the high volume of rainfall is of essential importance for the greater infiltration of water in the soil. Thus, the classes selected to compose the scenarios favorable to water storage in the basin are HLRs classified as "wet" and "very wet".

4.3.3 Location of HLRs favorable areas to water yield and storage

After justifying and selecting the classes of each evaluation unit favorable to water yield and storage in the basin, it became necessary the identification of which HLRs presented such classes. Fig. 8 shows the location of favorable areas to water yield and storage in the Piracicaba, Capivari, and Jundiaí river basins according to scenario 1, while Fig. 9 shows the same data for scenario 2.

It is observed in Fig. 8 that favorable areas for water yield and storage considering scenario 1 are located downstream of the Piracicaba basin, mostly in the sub-basin of the Corumbataí river, an important water supply area for the municipalities of Rio Claro and Piracicaba. These areas are also located on the Guarani aquifer, the main aquifer in terms of the water volume stored in the State of São Paulo, reinforcing the importance of its conservation and conscious use (Sindico et. al., 2018; Elliot & Bonotto, 2018).

When comparing favorable water storage scenarios 1 and 2, there is an increase in area due to the greater range in the choice of classes in the relief assessment unit. In the second scenario, two classes of relief were chosen (flat and transitional), unlike scenario 1, where only the “flat” class was considered.

The second scenario of water yield, shown in Fig. 9, presented a greater coverage in the basins when compared to scenario 1, justified by the higher occurrence of soils classified with "low permeability" in the basins. It is worth mentioning the high occurrence of favorable areas within the state limit of Minas Gerais, highlighting the importance of a national effort in implementing projects and public policies for the protection and conservation of water resources.

In the central area of the Piracicaba river basin there are important urban centers, such as the city of Piracicaba and Campinas, which demand large amounts of water. However, none of the identified favorable areas for water yield and storage are around these cities. The favorable areas are mostly located upstream of these urban centers and in the sub-basin of the Corumbataí river, emphasizing the importance of the conservation of the areas close to springs in order to prevent any water scarcity on the area.

In Fig. 8, most of the areas chosen as scenario 01 for water yield and storage are very close to each other because they share the same soil and climatic permeability configurations. The proximity of areas favorable to water yield and storage can increase the effectiveness of management projects that aim to conserve water availability and optimize financial resources investments. The geographical proximity between the areas of scenario 1 is justified when comparing the R/P mean values and m factor in the HLRs, shown in Fig. 10.

Fig. 10 shows that the "m" coefficient, which characterizes the watershed, is directly associated ($R^2=0.46$) to water yield, confirming that the HLRs with the highest water yield values are also areas with high water storage. The values are statistically significant.

The correlation between m factor and R/P corroborates the choice of the criteria adopted in scenarios 1 of water yield and storage in the basin regarding climate (wet and very wet) and soil permeability (high permeability) evaluation units.

The values of m factor and R/P were obtained from fluviometric stations data and were assigned to contribution area, so the different types of Hydrologic Landscapes with same numeric contribution area received the same m and R/P value. As seen, each watershed can present several types of Hydrologic Landscapes, being possible that an HLR be considered favorable to water yield and another favorable to water storage, being both located in the same river basin. Hydrologic Landscape Regions with high values of R/P and *m* factor concentrated in the same watershed prove that river basins can promote water yield and have high storage capacity.

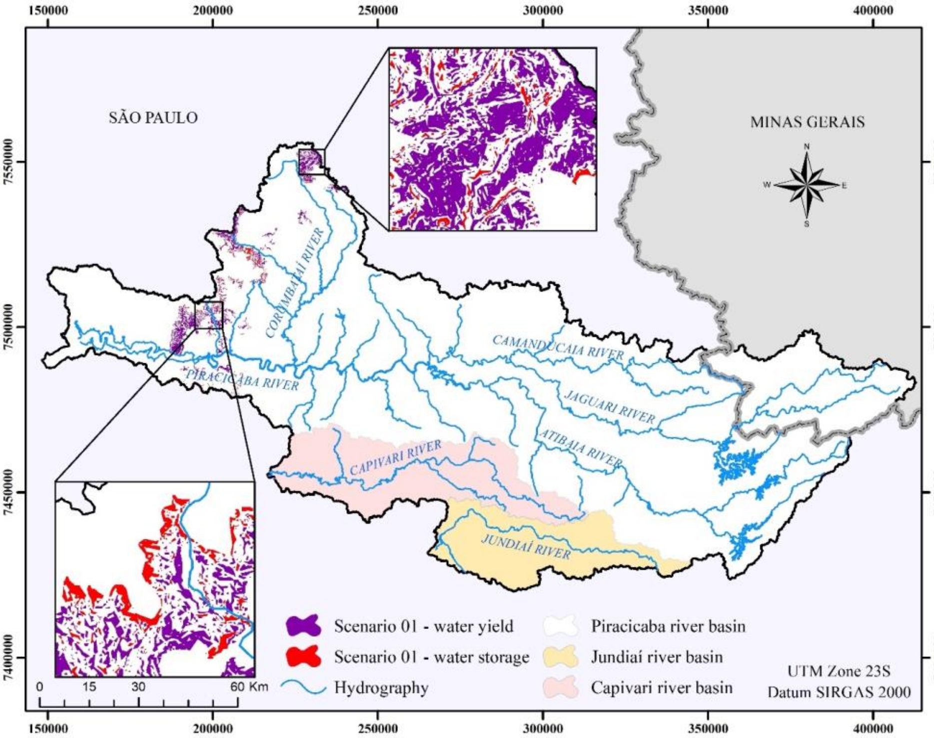

Fig. 8. Favorable areas for water yield and storage in the Piracicaba, Capivari and Jundiaí river basins considering scenario 1.

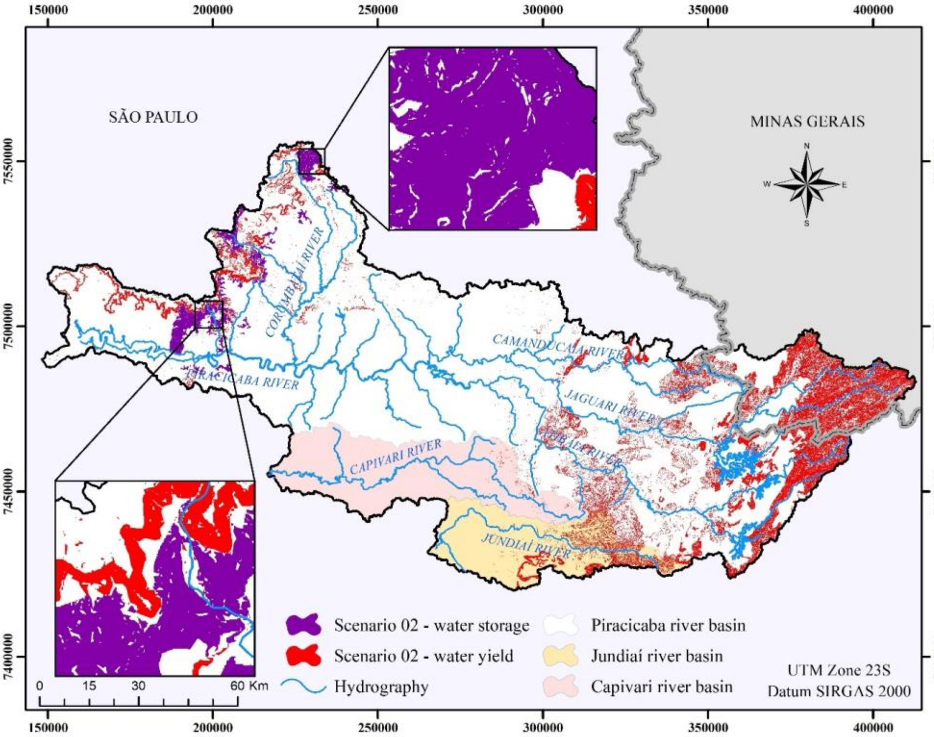

Fig. 9. Favorable areas for water yield and storage in the Piracicaba, Capivari and Jundiaí river basins considering scenario 2.

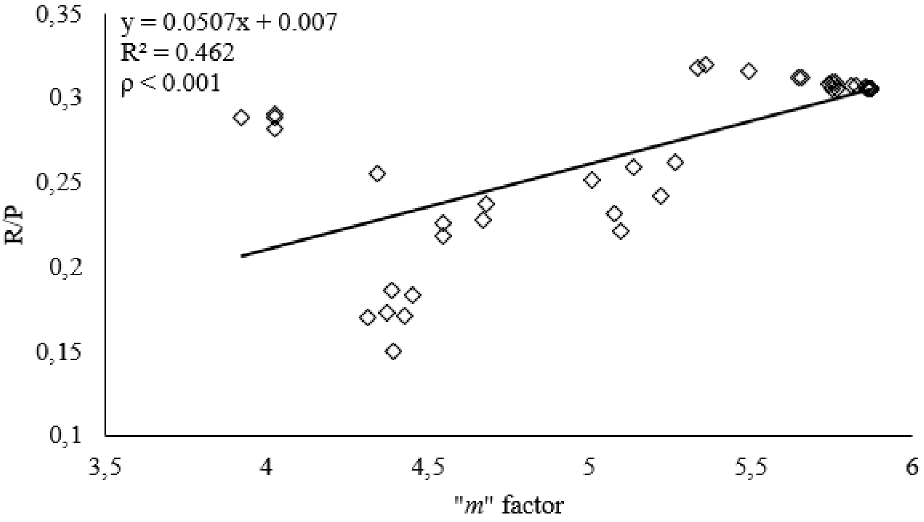

Fig. 10. Relationship of the coefficient of watershed characteristic *m* with water yield (R/P) storage in the Piracicaba, Capivari, and Jundiaí river basins.

5. Conclusions

The Hydrologic Landscapes method used here as an environmental classification in the Piracicaba, Capivari and Jundiaí river basins has proved to be a powerful tool in identifying favorable areas to water yield/storage and also establishing water patterns over different physiographical conditions (climate, relief, soil, and aquifer).

In this study, the data were not separated into micro-basins, which allowed the assignment of one HLR for each 30m (pixel-by-pixel classification). Thus, it was possible to identify favorable areas to water yield and storage with accuracy, allowing the optimization of financial resources applied to water protection and management projects. The grouping of areas according to their hydrological configurations, as classified in Hydrologic Landscapes, favors the identification of patterns where without this junction, their visualization would not be so clear. Therefore, the identification of Hydrologic Landscapes in watersheds can help a better understanding of how the physiographic factors interact with each other and influence the water yield and storage.

Most of the favorable areas for water yield and storage selected in scenario 1 were identified in the Corumbataí river basin. The region has high R/P (ratio between the annual water yield and mean annual precipitation) and *m* values, indicating that watersheds can be considered, at the same time, favorable to water yield and have high storage capacity. The results also show that the parameters chosen in the evaluation units behave differently in water yield and *m* factor values.

Some parameters represent a greater contribution to water storage in the basin, while others offer greater interference for the water yield. Finally, it is important to note that the interactions between the parameters observed in this study describe the conditions presented in the Piracicaba, Capivari, and Jundiaí river basins, and do not necessarily present themselves as a general rule for all river basins, being necessary to analyze and study other cases in particular.

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