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Special Edition

Estimation of the time of concentration from morphometric and hydrological monitoring parameters in São Paulo state watersheds

Estimativa de tempo de concentração a partir de parâmetros morfométricos e de monitoramento hidrológico em bacias hidrográficas paulistas

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ABSTRACT

Morphometric analyzes support an understanding of the physical characteristics of hydrographic basins and are commonly used to estimate hydrological variables. This work aims to compare the geomorphological characteristics and the time of concentration (Tc) in two watersheds: upper part of the Jundiaí river (139.3 km^2) and Piraí river (209 km^2) belonging to the Jundiaí river basin, state of São Paulo. To calculate the Tc, empirical equations and monitored hydrological data were applied. Applying the US Army Corps of Engineers, Ven te Chow, and Kirpich Tc formulas, the Piraí watershed had the highest Tc, with a mean value of 6.29 h with a maximum difference between the three formulas of approximately 27%. The mean Tc for the Jundiaí watershed was 5.18 h, with a 25% variation between the minimum and maximum calculated values. Applying the hydrological method to the data collected between 2018 and 2021 from the São Paulo State Flood Alert System (SAISP) fluviometric and pluviometric stations, the minimum and maximum calculated values were 6.83 h and 23.33 h, respectively, with mean of 14.4 h. We observed higher values for the Piraí watershed, which has a larger drainage area, with Tc varying from 17 h to 49 h and mean of 36.7 h. Note that the average Tc for the Piraí watershed was almost 2.5 times higher than that of the Jundiaí watershed, despite the almost equal values of slope and length of the thalweg, calculated from the empirical equations. These equations based on morphometric parameters underestimated the Tc compared with the values calculated from the hydrological method, presenting 82% and 64% of error, respectively, for the Piraí watershed and the upper part of the Jundiaí watershed.

Keywords: Watershed; Time of concentration; Morphometric analyzes

RESUMO

Análises morfométricas subsidiam um entendimento das características físicas das bacias hidrográficas e são comumente utilizadas para estimativa de variáveis hidrológicas. O presente trabalho tem como objetivo comparar as características geomorfológicas e o tempo de concentração (Tc) em duas bacias hidrográficas: parte alta do rio Jundiaí (139,3 km2) e rio Piraí (209 km2) pertencentes à bacia hidrográfica do rio Jundiaí, estado de São Paulo. Para o cálculo do Tc foram aplicadas equações empíricas e dados hidrológicos monitorados. Aplicando-se as fórmulas de Tc do Corpo de Engenheiros dos Estados Unidos, de Ven te Chow e de Kirpich, a bacia do rio Piraí apresentou o maior Tc, com valor médio de 6,29 horas com uma diferença máxima entre os resultados da aplicação das formulas de aproximadamente 27%. O Tc médio para o a bacia do rio Jundiaí foi de 5,18 h, com variação de 25% entre o valor mínimo e máximo encontrados. Aplicando-se o método hidrológico aos dados coletados entre 2018 e 2021 em estações fluviométricas e pluviométricas pertencentes ao Sistema de Alerta à Inundações do Estado de São Paulo (SAISP), verificou-se para a bacia do trecho alto do rio Jundiaí um valor mínimo de 6,83 h e um valor máximo de 23,33 h, com um valor médio de 14,4 h. Para a bacia do rio Piraí, que apresenta uma maior area de drenagem, observaram-se valores superiores, com Tc variando de 17 h até 49 h; o valor médio foi de 36,7 h. Observe-se que o Tc médio para a bacia do rio Piraí foi quase 2,5 vezes maior do que o apresentado na bacia do rio Jundiaí, ainda que os valores de declividade e comprimento do talvelgue não divirjam em proporções significativas, como evidenciado nos resultados encontrados aplicando-se as fórmulas empíricas. As fórmulas baseadas em parâmetros morfométricos subestimaram o Tc em relação aos valores calculados pelo método hidrológico, apresentando um erro de 82% e 64% respetivamente para as bacias do rio Piraí e trecho alto do rio Jundiaí.

Palavras-chave: Bacia hidrográfica; Tempo de concentração; Análise morfométrica

1 INTRODUCTION

The accelerated increase in human activities in recent decades implies a significant change in various natural cycles and, therefore, environmental problems associated with water resources and soil degradation are increasingly frequent (STEFFEN *et al*., 2015). The effects of anthropic actions, such as urbanization, change the local hydrological cycle and river characteristics, drastically increasing the discharge peaks and silting processes in river channels (DISCROLL *et al*., 2010).

Approaches in river basins, considered as the unit of analysis and planning, have been increasingly used for the evaluation of hydrological processes, considering biophysical, social and economic variables, which enables an evaluation in appropriate temporal and spatial scales, since the physical, biotic, and anthropic environment interact dynamically in the basin. (TUNDISI, 2008; TUNDISI AND MATSUMURA, 2011; BACK, 2014).

The morphometric analysis can provide relevant information for environmental studies regarding erosion problems, slope instability, flood events, and landslides, allowing an easy comparison with other river basins (TEWARI, MISRA E SHARMA, 2019; MANGAN, HAQ AND BARAL, 2019). The basin's geomorphological characteristics have a complex interrelationship with the hydrological processes (GOERL, KOBIYAMA E SANTOS, 2012; RODRIGUEZ-ITURBE AND VALDES, 1979; RODRIGUEZ-ITURBE *et al*., 1982; GERICKE, 2019), which is still the focus of discussion within the scientific community as one of the major issues to be addressed (BLÖSCHL *et al*. 2018).

The time of concentration (Tc), which is one of various hydrological parameters, related to the physical characteristics of the basin; is the time required for a water particle to superficially travel from the farthest point of the basin to its outlet (MCCUEN, 2009; WORLD METEOROLOGICAL ORGANIZATION AND UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION – WMO and UNESCO, 2012.; RAVAZZANI *et al*., 2019). Time of concentration is one of the most important inputs for hydrological studies, and it is often used for the design of urban drainage systems and for the operational planning of hydraulic structures (ALMEIDA *et al*. 2014; MCCUEN, 2009). Despite the wide diffusion of Tc, it has no exact calculation method, and the methodologies can be subdivided into two groups: computational and theoretical ones (RAVANZZANI *et al*., 2019; GRIMALDI, 2012).

Tc is calculated by computational methods from the observation of the rainfall hyetogram and the result of the discharge hydrograph (THOMAS *et al*. 2000). Empirical methods are based on multiple regressions between direct estimates of Tc and some river characteristics, such as geomorphological, hydrological, and meteorological aspects (RAVAZZANI *et al*., 2019). Gericke and Smithers (2014) show that empirical methods are the most used in unmonitored basins, representing 95% of the methods used; however, they may have large errors in their estimates. Grimaldi (2012) found up to 500% variability between different Tc equations.

According to Gericke (2015) medium to large hydrographic basins (> 20 km^2) represent a greater characterization challenge, due to heterogeneity in land cover and its use, and the non-uniform precipitation.

In Brazil, several studies characterized different types of basins based on morphometric parameters, limiting the discussion to hydrogeomorphological relationships with possible basin trends to present flood events, on the other hand, the studies evaluating the results of Tc empirical equations for Brazilian basins, from monitored hydrological data are relatively scarce (MAMÉDIO, CASTRO E CORSEIL, 2018; MOTA *et al*., 2017, KOBIYAMA *et al*., 2006; MALUTTA *et al*., 2017; INNOCENTE *et al*, 2017; JUNIOR E BOTELLO, 2011; INNOCENTE, *et al*., 2019).

The objective of this work is to characterize and comparatively analyze the geomorphological characteristics and the Tc from empirical equations and from hydrological data monitored in two watersheds (upper part of the Jundiaí river and the Piraí river) belonging to the Jundiaí watershed, in the state of São Paulo. Together, these two watersheds area is larger than 100 km^2. They supply water for populous cities and encompass regions of strong industrial and service activity, being subject to a high degree of water stress. Thus, this study is of academic, public, and water resources managers interest in general.

2 MATERIALS AND METHODS

2.1 Location of study area

Figure 1 shows the two chosen watersheds: the watershed of the upper stretch of the Jundiaí River (simply named here as Jundiaí River watershed), with 139.3 km^2, comprising the municipalities of Mairiporã, Atibaia, Jarinu, and Campo Limpo Paulista; and the Piraí River watershed, in the municipalities of Cabreúva, Itu, and Salto, with 209 km^2. They are within the Water Resources Management Unit

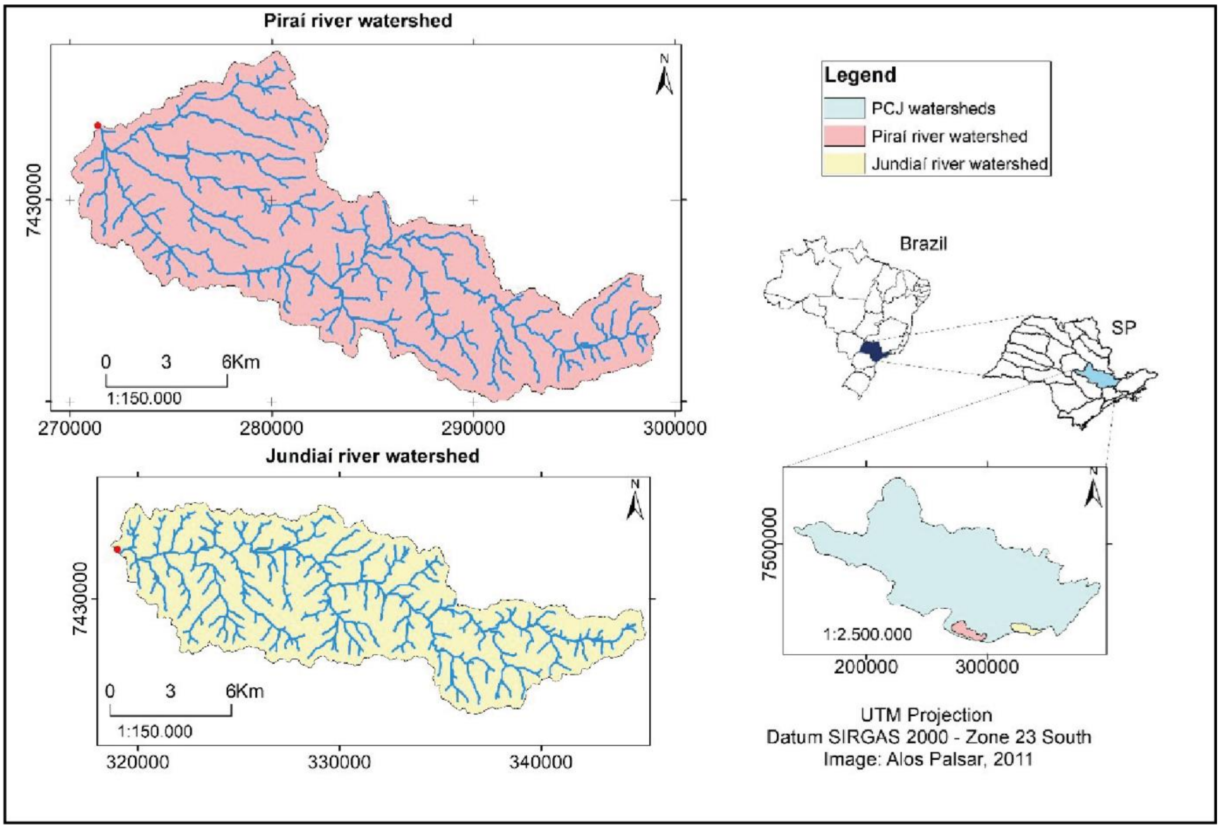
No. 5 of the state of São Paulo, comprised of the Piracicaba, Capivari, and Jundiaí (PCJ) river basins.

According to Alvares' *et al*. (2013) climate classification, the Jundiaí watershed is between the subtropical humid Cfb zones, influenced by the oceanic climate, lacking dry seasons, and may comprise warm to temperate summers; and the Piraí watershed also presents Cfb climate in the eastern portion but in the extreme west of the basin the climate changes to Cfa type with warmer summers. Another common feature of the studied watershed is the red-yellow argisols (OLIVEIRA *et al*., 1999).

2.2 Morphometric parameters

The Digital Elevation Models (DEM) from the Japanese satellite ALOS (Advanced Land Observing Satellite), obtained from the Alaska Satellite Facility, were used to get the initial physical characteristics of the two analyzed watersheds. This model has a spatial resolution of 12.5 m and is a radiometrically corrected product from the global DEM (SRTM) and Landsat 8 satellite images having also undergone a resampling of the original 30 m DEM (MEZA, 2020). These images were incorporated into a geographic information system (Arc Gis®) to delimit the watersheds and to estimate the morphometric parameters.

Figure 1 – Location of the studied watersheds



Source: Authors, 2021

A defined methodological procedure was applied for the automatic extraction of the drainage network in each watershed, which routinely involves the following steps: identification and filling of spurious depressions, definition of the preferential flow direction, obtaining the matrix with the accumulated drainage area, and definition of the flow accumulation threshold (MORAIS E SALES, 2016; SOUZA E ALMEIDA, 2014; FAN *et al*, 2013).

The chosen software implements predetermined algorithms for each one of these steps, defined by Jenson and Domingue's (1988) theory for the depression filling phase; the so-called eight flow direction method (D8) defines the flow directions of the rivers proposed by O'Callaghan and Mark (1984). Defining the minimum limit for the initial formation of runoff is one of the points that requires greater attention due to the direct relationship with the formation of a drainage network more or less ramified and actually representing of the reality (FAN *et al*., 2013). In this case, this value was chosen by the trial-and-error method comparing the drainage network generated for different proposed limits with the basins satellite images, also considering that the accumulation threshold did not exceed the conditions established by the DEM resolution used.

Finally, the area and perimeter were delimited on the same spatial scale for both watersheds. The flow direction from the source to the outlet was followed to trace the topographic profile of the main course for both cases. The Hidrobacias® software was used for the secondary calculation of some of the morphometric evaluated parameters. Table 1 briefly shows each one of these parameters, as defined by Back (2014), Das (2021), and Sadhasivam *et al*. (2020).

2.3 Soil usage and coverage characteristics

To compare the land cover and uses of the watersheds, the PCJ Committee/PCJ Basin Agency (2020) watershed plan was used. The classification was made from 1 m spatial resolution orthophotos taken in 2010 and 2011, provided by the São Paulo Metropolitan Planning Company (EMPLASA).

Table 1 – Morphometric parameters for the characterization of watersheds

Morphometric parameters	Definition	Abbreviation/Equation	Reference
Drainage area	Total catchment area	A	/
Perimeter	Lenght of the line representing the watershed of the basin	P	/
Main stream lenght	Thalweg length	L	/
Stream order	Hierarchization of the river's branches within the hydrographic basin	O	Strahler (1952)
Compactness coefficient	Ratio of the basin perimeter to the circumference of a circle of the same area	$K_c = 0.282 \frac{P}{\sqrt{A}}$	Gravelius (1914)

Continued...

Table 1 – Conclusion

Morphometric parameters	**Definition**	**Abbreviation/Equation**	**Reference**
Form factor	Ratio of the catchment area to the square of the axial length of the basin	$K_f = \frac{A}{{L_x}^2}$	Horton (1932)
Drainage density	Ratio of the total length of the rivers in the basin to its drainage area	$D_r = \frac{N}{A}$	Horton (1945)
Average runoff extension index	Average route that the water takes until it reaches the river	$E_{ms} = \frac{1}{4D_b}$	Villela and Mattos (1975)
Sinuosity index	Ratio of the distance from source to outlet in a straight line to the total length of the river	$I_s = \frac{100(L - E_v)}{L}$	Mansikkaniemi (1970)
River slope (S1)	Ratio of the difference in altitude from source to outlet to the length of the main river	$S1 = \frac{Hmax - Hmin}{L}$	Hadley and Schumm (1961)
Circularity ratio	Ratio of the area of the basin to the area of a circle with circumference equal to the basin perimeter	$I_C = \frac{4\pi A}{P^2}$	Miller (1953), Strahler (1964)
Altimetric difference	Maximum and minimum height difference	$R = Hmax - Hmin$	Das (2021)
Elongation ratio	Ratio of a circle with the same area of the basin to its maximum length	$R_e = 1.1284\frac{\sqrt{A}}{L}$	Schumm (1956)
Relative perimeter	Ratio of the area to the perimeter of the basin	$P_f = \frac{A}{P}$	Schumm (1956)

Source: Authors, 2021

2.4 Time of concentration (Tc)

To calculate the times of concentration, the empirical formulas were used, following the recommendations proposed by Silveira (2005), according to the physical characteristics of the basins related to their size, use, and land cover, found in the previous items. Among the chosen equations are those proposed by the US Army Corps of Engineers (Equation 1), by Ven Te Chow (Equation 2), and by Kirpich (Equation 3), where the only input variables are the length of the main thalweg L and the river slope $S1$. The three chosen equations are applicable to basins with rural characteristics, and according to the study carried out by the same author, they are the ones with the best performance when compared with observed data.

$$Tc = 0.191 \times \frac{L^{0.76}}{S^{0.19}} \quad (1)$$

$$Tc = 0.160 \times \frac{L^{0.64}}{S^{0.32}} \quad (2)$$

$$Tc = 0.0663 \times \frac{L^{0.77}}{S^{0.385}} \quad (3)$$

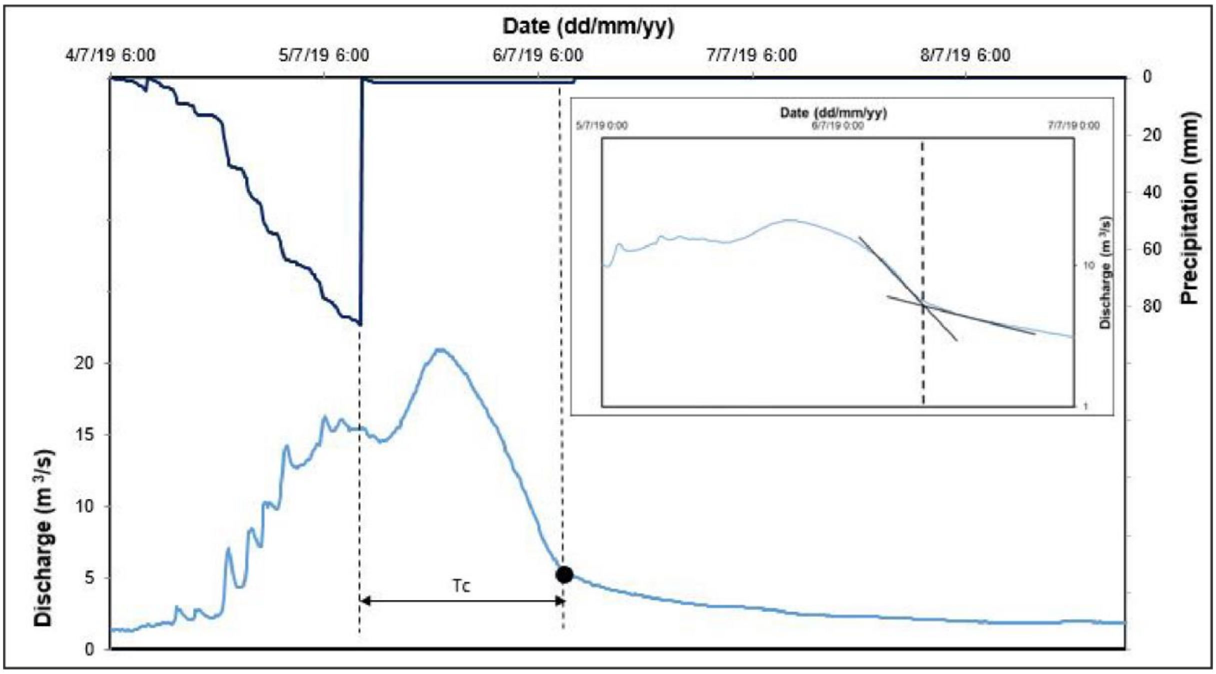
Although Kirpich's equation was designed for smaller basins (MOTA and KOBIYAMA, 2015), it was used in this study following the suggestions of Silveira (2005), who found good estimates of Tc for basins up to 12,000 km^2.

To calculate the Tc from the hydrological data, the time between the end of the event's excess rain and the first recession point of the flow hydrograph must be considered. This point represents the time it takes for the flow to be considered as base flow (THOMAS *et al*. 2000). As reported by Kobiyama *et al*. (2006), due to difficulties in defining the exact time of completion of the effective rain, the end of the precipitation event was used, the inflection point was located visually by using a semi-logarithmic graph and, as proposed in Ravazzani *et al*. (2019), the criterion used for selecting events was based on events that exceeded the first flow quartile. Figure 2 shows an example of this procedure.

The fluviometric and pluviometric stations are in each one of the watershed's outlets, both in the São Paulo State Flood Alert System (SAISP). The monitoring station for the Jundiaí River, is located at coordinates −46.760284, −23.208778, with data collection every 10 minutes in the period between 11/14/2018 and 03/31/2021. In the Piraí river, the station is in the catchment for the municipality of Salto, with coordinates −47.2343, −23.19064, and the data acquisition was carried out every hour between 01/01/2018 and 09/10/2021.

Empirical equations were evaluated from descriptive statistics, taking as error the standardized difference between the mean of the values observed in the monitored events and those calculated from the equations.

Figure 2 – Calculation of the time of concentration for a rainfall event in the Jundiaí watershed (6/7/2019)



Source: Authors, 2021

3 RESULTS AND DISCUSSIONS

Table 2 shows the results of the calculated morphometric parameters for the two watersheds. The Jundiaí river basin has a lower form factor value, a higher elongation ratio, and sinuosity index below 20%, making it a very straight river in this high section of the basin. For the Piraí river basin, the river can be considered as winding in Charlton's (2008) categorization or as rambling (MANSIKKANIEMI, 1970).

Table 2 – Calculated morphometric parameters for Jundiaí and Piraí river watersheds

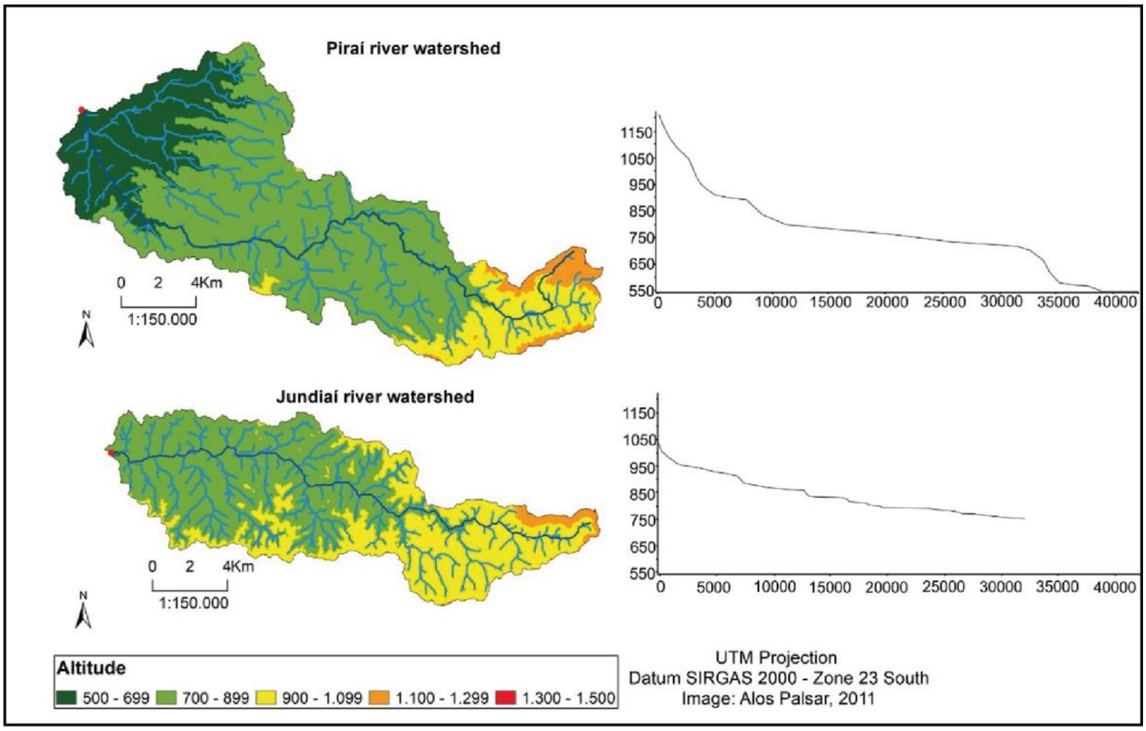
Parameter \ Watershed	Jundiaí	Piraí	Ratio Piraí/Jundiaí
Drainage area (km^2)	139.3	209.0	1.5
Perimeter (km)	79.1	99.3	1.3
Main stream lenght (km)	32.0	42.2	1.3
Stream order	4	6	-
Compactness coefficient	1.90	1.94	1.0
Form factor	0.2	0.24	1.2
Circularity ratio	0.28	0.27	1.0
Altimetric difference (m)	580	769	-
Elongation ratio	0.5	0.55	1.1
Relative perimeter (km)	0.57	0.48	0.8
Drainage density (km/km^2)	1.73	1.36	0.8
Average runoff extension index (km)	0.14	0.18	1.3
Sinuosity index (%)	19.06	35.07	1.8
River slope *S1* (m/m)	0.016	0.018	1.1

Source: Authors, 2021

The Piraí watershed has the largest catchment area and height difference between its source and outlet, contrasting with its lowest drainage density value. However, for both basins, this last parameter is lower than 2.0, which to Beltrame (1994), cited by Back (2014), considered as a median class.

Figure 3 shows the altimetric map of each watershed and its respective drainage network; note that in both of then the pattern with greater notoriety is of the dendritic type, related to poor geological control of the rocky substrate of the basins and/or a uniformity in the strengths of these rocks (CHARLTON, 2008; BACK, 2014), which agrees with the geomorphological characteristics of the basins. All of them are in the Atlantic Plateau domain with predominance of the Red-Yellow Latosol type soils over crystalline basement rock (Consorcio Profill-Rhima, 2020).

Figure 3 – Hypsometric map and longitudinal profiles of the Piraí river and the upper part of the Jundiaí river

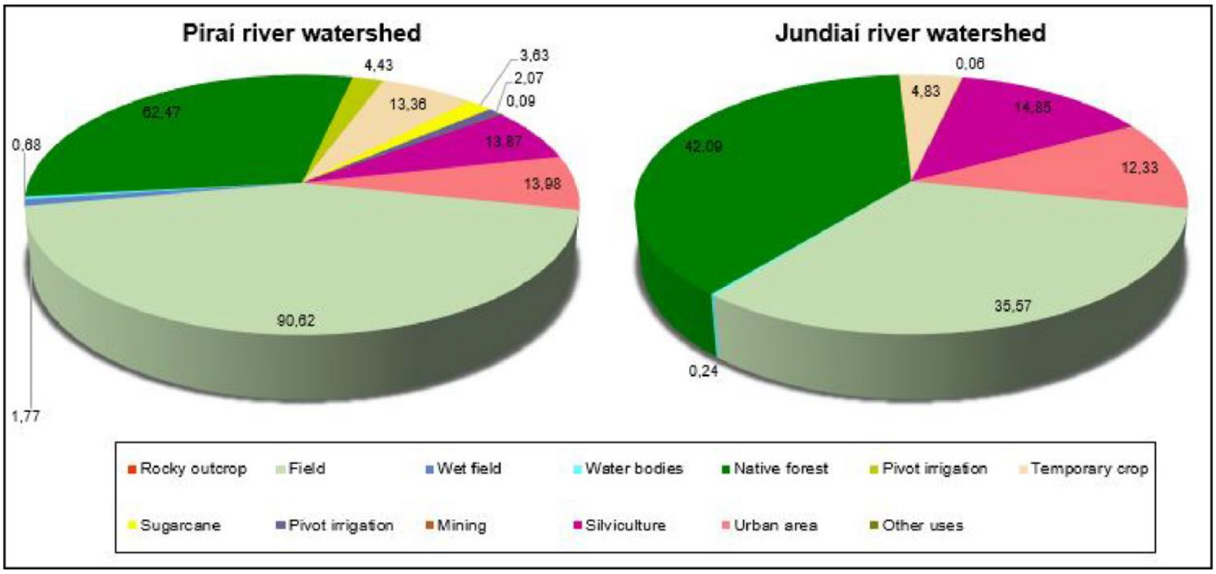


Source: Authors, 2021

Considering the land use and cover in these watersheds, in general, the predominant classes are fields and native forest with a lower percentage of forestry, urbanized areas and temporary farming. Figure 4 shows the percentage of the different land uses and cover for each one of the watersheds. The Jundiaí river watershed has the highest percentage of native forest and forestry in relation to its total area, and the urbanized area is the lowest in the Piraí watershed.

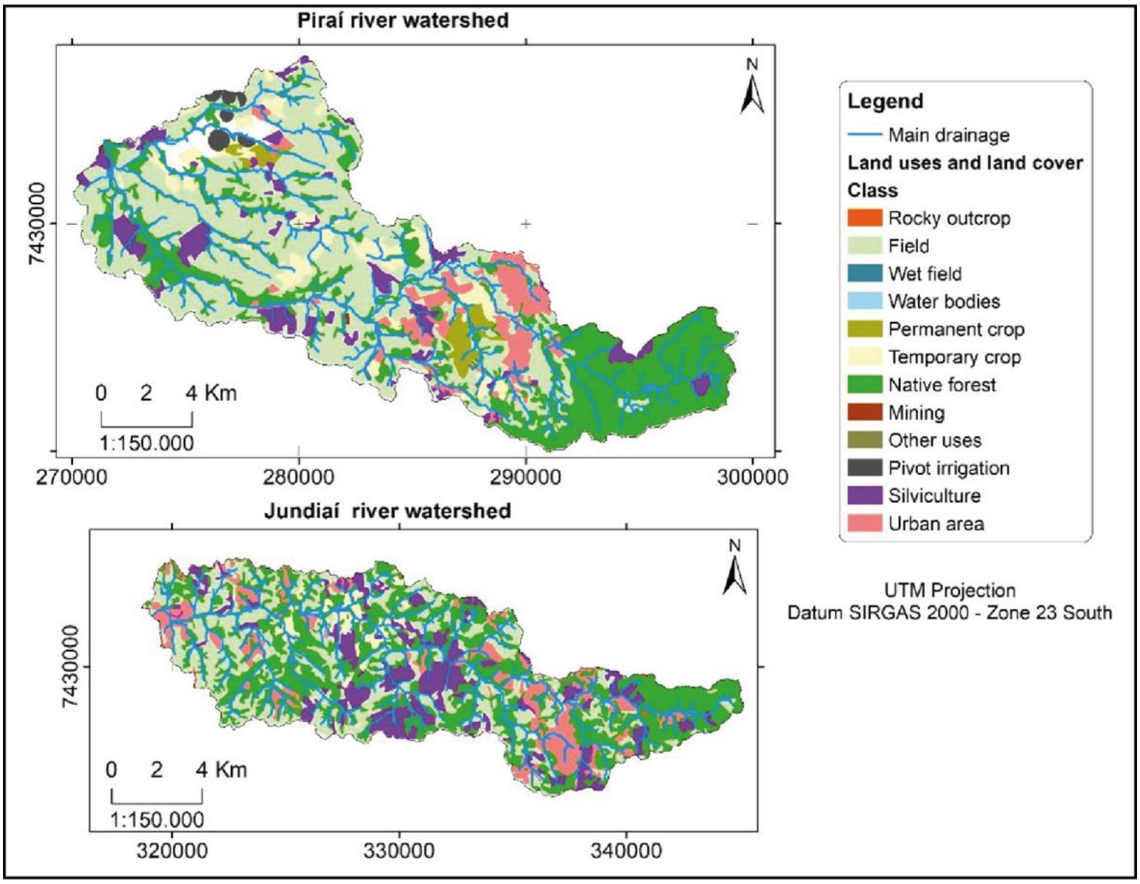
Figure 5 shows the map for each watershed, with the distribution of these classes, evidencing the portion of native forest in the headwaters of the Piraí and Jundiaí rivers. The Piraí watershed is the only one that encompasses areas with sugarcane crops and with pivot for irrigation close to its outlet.

Figure 4 – Percentages of land use and land cover for each watershed, in km^2



Source: Authors, 2021

Figure 5 – Land use and cover map for each watershed



Source: Adapted from Consorcio Profill-Rhima, 2020

We applied the time of concentration equations of the US Army Corps of Engineers, Ven Te Chow, and de Kirpich suggested for rural basins form both watersheds. The Piraí watershed had the highest Tc, mean of 6.29 hours with around 27% difference between the result from each equation. Mean Tc for the Jundiaí watershed was of 5.18 h, with around 25% between minimum and maximum calculated values. Table 3 shows that the ratio of the values obtained by the empirical methods for the Piraí and the Jundiaí river is of 1.2 to 1.3 and is close to the ratio of the length to the slope of the main river, shown in Table 2.

Table 3 – Time of concentration for the studied watersheds, calculated from the empirical equations

Tc (h) / **Watershed**	**Jundiaí**	**Piraí**	**Ratio Piraí/ Jundiaí**
Corps of Engineers	5.83	7.03	1.2
Ven Te Chow	5.06	6.33	1.3
Kirpich	4.68	5.52	1.2

Source: Authors, 2021

Table 4 shows the 10 events for the Jundiaí river and 7 events for the Piraí river used for the Tc calculation based on the hyetogram and hydrograph. For the Jundiaí river, we obtained a minimum value of 6.83 h and a maximum of 23.33 h, with a mean of 14.4 h. For the Piraí river, which has a larger drainage area, we observed higher values, with Tc from 17 h to 49 h, and mean of 36.7 h. Note that the average time for the Piraí watershed was almost 2.5 times longer than that of the Jundiaí watershed, despite the similarity between the values of slope and length of the thalweg, observed in the results from the empirical equations.

Figure 6 shows the comparison between the results obtained by both methods for both watersheds. All values extracted by the hydrological method were above the values calculated from the empirical formulas for both river basins, with a percentage error of 82% and 64% between the mean Tc, considering the Tc estimates from the hydrological records as the correct value.

These values are consistent with those found in other studies in Brazil, such as those carried out by Mamedo *et al*. (2018), which obtained differences of up to 88% between the Kirpich's equations and the Tc calculated in three river basins in Rio Grande do Sul. Another study in a coastal basin, carried out by Innocente (2019), resulted in an underestimation of 600% when comparing the medians of the time of concentration based on equations and those ones obtained from monitored data.

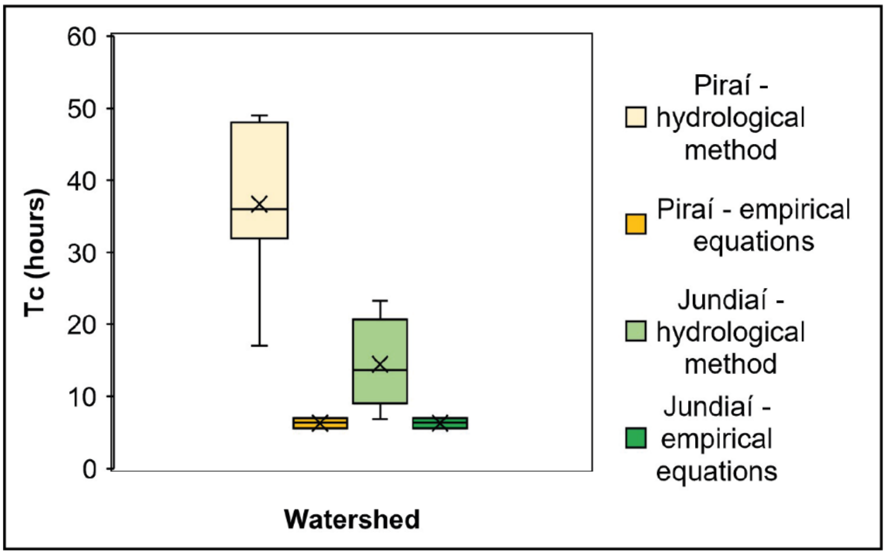
Table 4 – Discretization of rainfall events for the evatuated watersheds, with their respective time of concentration, for each event, calculated from the hydrological monitoring data

Jundiaí river watershed		**Piraí river watershed**	
End date of event	Tc (hours)	End date of event	Tc (hours)
2/12/18 6:10	20	4/3/18 12:00	40
25/12/18 23:50	13.6	6/1/19 20:00	48
5/1/19 17:20	6.8	8/3/19 7:00	17
27/1/19 1:10	14.5	10/4/19 7:00	35
17/2/19 10:10	23.3	25/11/19 7:00	36
6/7/19 9:50	22.6	29/11/19 22:00	32
31/12/20 18:00	7.6	12/2/20 14:00	49
3/1/20 20:20	9.5		
9/1/20 23:00	12.3		
12/2/20 0:00	13.6		

Source: Authors, 2021

McCuen (2009) highlights that due to differences in the roughness and slope of the basins (surface flow) and main watercourses (channel flow), the Tc estimates, based only on the characteristics of the main watercourse are underestimated on average by 50% and, consequently, when carrying out hydraulic projects, peak discharge estimates will be 30% to 50% overestimated. Other factors, such as the heterogeneity of precipitation may be related to the differences in the Tc, even more with the increase of the basin size, as reported by Gericke (2019).

Figure 6 – Comparison between the time of concentration calculated from hydrological data and by empirical equations, for Piraí and Jundiaí watersheds



Source: Authors, 2021

4 CONCLUSIONS

Evaluating the physical parameters of the watersheds showed similar drainage density values and hydrographic network patterns, described as dendritic type, which can result from the similarity of the geological substrate of the two watersheds, red-yellow latosol-type soils on crystalline rocks.

The watershed of the upper part of the Jundiaí River has a more elongated shape with straight river characteristics with a low shape coefficient and elongation ratio, and a predominance of native vegetation and grasslands. The Piraí watershed has a larger area and has a land use and coverage like that of the Jundiaí river, but with areas for sugarcane cultivation, including irrigation pivots. The ratio of the Tc calculated with the empirical methods for the Piraí watershed to that of the upper Jundiaí watershed was 1.3 – the same order of magnitude as the ratio of the main drainage length of the two basins. However, the ratios of the Tc calculated by the hydrological method are almost 2.5 times, which suggests that the morphometric characteristics are insufficient for the accurate estimation of this parameter, needing the incorporation of the spatiotemporal heterogeneities of the basins.

In the studied cases, the three chosen formulas (Corps of Engineers, Ven Te Chow, and Kirpich) underestimated the Tc compared with the values calculated by the hydrological method, with an error of 82% and 64%, respectively, for the Piraí and Jundiaí watersheds. For both case studies, the Kirpirch equation resulted in the greatest underestimations.

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REFERENCES

ALMEIDA, I.K.; ALMEIDA, A.K.; STEFFEN, J.L.; SOBRINHO, T. A. Model for Estimating the Time of Concentration in Watersheds. **Water Resour. Manag**, 30, 4083–4096. 2016. DOI: 10.1007/s11269-016-1383-x.

ALVARES, C.A.; STAPE, J.L.; SENTELHAS, P.C.; GONÇALVES, J.L.M.; SPAROVEK, G. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, v. 22, n. 6, p. 711-728, 2013. DOI: 10.1127/0941-2948/2013/0507. Disponível em: https://www.schweizerbart.de/papers/metz/detail/22/82078/Koppen_s_climate_classification_map_for_Brazil. Acesso em: 20 jul. 2021.

BACK, Á. J. **Bacias hidrográficas: Classificação e caracterização física**. Florianópolis: EPAGRI, 2014. 162p.

BELTRAME, A.V. **Diagnóstico do meio físico de bacias hidrográficas – modelo e aplicação**. Florianópolis: Ed. UFSC, 1994. 112p.

BLÖSCHL, G. *et al*. Twenty-three unsolved problems in hydrology (UPH) – a community perspective. **Hydrological Sciences Journal**, v. 64, p. 1141 – 1158, 2019. DOI: 10.1080/02626667.2019.1620507.

CHARLTON, R. **Fundamentals of fluvial geomorphology.** London: Routledge, 2008.

CONSÓRCIO PROFILL-RHAMA. **Plano de Recursos Hídricos das Bacias Hidrográficas dos Rios Piracicaba, Capivari e Jundiaí, 2020 a 2035: Relatório Final**. Piracicaba (SP), 2020. 712 P.

DAS, S. Hydro-geomorphic characteristics of the Indian (Peninsular) catchments: Based on morphometric correlation with hydro-sedimentary data. **Advances in Space Research**, v. 67, n. 8, p. 2382-2397, 2021. DOI: 10.1016/j.asr.2021.01.043. Disponível em: https://doi.org/10.1016/j.asr.2021.01.043. Acesso em: 30 jul. 2021.

DRISCOLL M, CLINTON S, JEFFERSON A, MANDA A, MCMILLAN S. Urbanization Effects on Watershed Hydrology and In-Stream Processes in the Southern United States. Water. 2(3):605-648, **2010**. DOI: 10.3390/w2030605.

FAN, F.M.; COLLISCHONN, W.; SORRIBAS, M.V.; PONTES, P.R.M. Sobre o início da rede de drenagem definida a partir dos modelos digitais de elevação. Revista **Brasileira de Recursos Hídricos**, 18, 241-257, 2013. DOI: 10.21168/rbrh.v18n3.p241-257.

GERICKE, O.J. GIS Applications to Investigate the Linkage between Geomorphological Catchment Characteristics and Response Time: A Case Study in Four Climatological Regions, South Africa. **Water**, 11, 1072, 2019. DOI: 10.3390/w11051072.

GERICKE, O.J.; SMITHERS, J.C. Review of methods used to estimate catchment response time for the purpose of peak discharge estimation. **Hydrol. Sci. J.**, 59, 1935–1971, 2014.

GLOBAL WATER PARTNERSHIP y INTERNACIONAL NETWORK OF BASIN ORGANIZATION. Manual para la Gestión Integrada de Recursos Hídricos en Cuencas. Francia. (2009). 112 p.

GOERL, R. F.; KOBIYAMA, M.; SANTOS, I. Hidrogeomorfologia: Princípios, Conceitos, Processos e Aplicações. **Revista Brasileira de Geomorfologia** - v. 13, nº2, p.103-111, 2012.

GRAVELIUS, H. Flusskunde. Goschen Verlagshan dlung Berlin. Em: Zavoianu, I. (Ed.), Morphometry of drainage basins. Amsterdam: Elsevier, 1914.

GRIMALDI, S, PETROSELLI, A, TUARO, F, and PORFIRI, M. Time of concentration: a paradox in modern hydrology. **Hydrological Sciences Journal** 57 (2): 217–228, 2012. DOI: 10.1080/02626667.2011.644244.

HADLEY, R.F.; SCHUMM, S.A. **Sediment sources and drainage basin characteristics in the Upper Cheyenne River basin.** USGS water supply paper 1532-B, p 137-196, 1961.

HORTON, R.E. Drainage-basin characteristics. **Trans. Am. Geophys**. Union 13, p. 350–361, 1932. DOI: 10.1029/TR013i001p00350.

HORTON, R. Erosional development of streams and their drainage basins: hidrophysical approach to quatitative morphology. **Geological Society of American Bulletin**, New York, v.56. p. 275–370, 1945. DOI: 10.1130/0016-7606(1945)56[275:edosat]2.0.co;2. Disponivel em: https://doi.org/10.1130/0016-7606(1945)56[275:EDOSAT]2.0.CO;2. Acesso em: 31 jul. 2021.

INNOCENTE, C; PEREZ, A. B.; SÁ, J. H. M.; ARIENTI, P. F.; CHAFFE, P. L. B. Combinando geromorfologia e padrões hidrodinâmicos do escoamento de base para melhorar a estimativa do tempo de concentração. In: XXIII Simpósio Brasileiro de Recursos Hídricos, 2019, Foz do Iguaçú. XXIII Simpósio Brasileiro de Recursos Hídricos, 2019.

INNOCENTE, C; CHAFFE, P. L. B.; MOTA, A. A.; GRISON, F.; KOBIYAMA, M. Análise do tempo de concentração em quatro bacias experimentais. In: XXII Simpósio Brasileiro de Recursos Hídricos, 2017, Florianópolis. Simpósio Brasileiro de Recursos Hídricos, 2017.

INSTITUTO DE PESQUISAS TECNOLÓGICAS (IPT) & DEPARTAMENTO DE ÁGUAS E ENERGIA ELÉTRICA (DAEE). **Cadastramento de pontos de erosão e inundação no Estado de São Paulo**. São Paulo. IPT, 2012 (Relatório Técnico 131.057 – 205).

JENSON, S. K.; DOMINGUE, J. O. Extracting topographic sctruture from digital elevation data for geographic information system analysis. **Photogrammetric Engineering and Remote Sensing**, Maryland, USA, v. 54, no. 11, p. 1593-1600, 1988.

JUNIOR, J. E. F.; E BOTELHO, R. G. M. Análise comparativa do tempo de concentração: um estudo de caso na bacia do rio Cônego, município de Nova Friburgo/RJ. XIX Simpósio Brasileiro de Recursos Hídricos, 2011, Maceió. Simpósio Brasileiro de Recursos Hídricos, 2011.

KOBIYAMA, M; GRISON, F.; LINO, J. F. L.; SILVA, R. V. Estimativa morfométrica e hidrológica do tempo de concentração na bacia do campus da UFSC, Florianópolis-SC. ABRH. I Simpósio de Recursos Hídricos Sul-Sudeste. 2006.

MALUTTA, S.; Pscheidt, J. C.; NETO, t. g.; THIESEN, A.; POMPÊO, A.; BONUMÁ, N. B. Estimativa do tempo de concentração na bacia hidrográfica do campus da UFSC em Joinville. In: Simpósio Brasileiro de Recursos Hídricos, 2017, Florianópolis. Simpósio Brasileiro de Recursos Hídricos, 2017.

MAMÉDIO, F. M. P.; CASTRO, N. M. R.; CORSEUIL, C. W. Tempo de concentração para Bacias Rurais Monitoradas na Região do Planalto Basáltico no Sul do Brasil. **REGA - REVISTA DE GESTÃO DE ÁGUA DA AMÉRICA LATINA**, v. 15, p. 1-17, 2018.

MANGAN, P.; HAQ, M. A.; BARAL, P. Morphometric analysis of watershed using remote sensing and GIS—a case study of Nanganji River Basin in Tamil Nadu, India," **Arab. J. Geosci.,** v. 12, n. 6 2019. DOI: 10.1007/s12517-019-4382-4. Disponível em: https://doi.org/10.1007/s12517-019-4382-4. Acesso em: 30 jul. 2021.

MANSIKKANIEMI, H. The sinuosity of rivers in northern Finland. **Publicationes Instituti Geographici Universitatis Turkuensis**, v.52, p.16-32, 1970.

MCCUEN, R. H. Uncertainty Analyses of Watershed Time Parameters. **Journal of Hydraulic Engineering**, v. 14, n. 5, p. 490–498, 2009. DOI: 10.1061/(ASCE)HE.1943-5584.0000011. Disponível em: https://doi.org/10.1061/(ASCE)HE.1943-5584.0000011. Acesso em: 30 jul. 2021.

MCCULLOCH, J. S. G., ROBINSON, M. History of forest hydrology. **Journal of Hydrology**, v. 150, p. 189-216, 1993. DOI: 10.1016/0022-1694(93)90111-L. Disponível em: https://doi.org/10.1016/0022-1694(93)90111-L. Acesso em: 30 jul. 2021.

MEZA, J. C. Análisis comparativo de los modelos digitales de elevaciones SRTM y MDE-Ar 2.0 para la identificación de áreas de peligrosidad por inundaciones y anegamientos en un área urbana de llanura. **Geográfica Digital**. v. 17, p. 44-60, 2020. DOI: 10.30972/geo.17334015. Disponível em: https://revistas.unne.edu.ar/index.php/geo/article/view/4015. Acesso em: 31 jul. 2021.

MILLER, V.C. **A quantitative geomorphic study of drainage basin characteristics on the Clinch Mountain area, Virginia and Tennessee, Project NR 389–402**. Technical report 3. Department of Geology. ONR, Columbia University, New York, 1953.

MOTA, A.A.; Kobiyama, M. Reconsiderações sobre a Fórmula de Kirpich para o cálculo de tempo de concentração. **Revista Brasileira de Recursos Hídricos**, v. 20, p. 55-59, 2015.

MORAIS, R. C. S.; SALES, M. C. L. Extração Automática de Drenagem: uma Análise Comparativa a Partir de Diferentes Ferramentas e Bases de Dados. **Revista Brasileira de Geografia Física.** v.09, n.06, 1849-1860 2016.

O'CALLAGHAN, J. F.; MARK, D. M. The extraction of drainage networks from elevation data. **Computer Vision, Graphics, and Image Processing**, ScienceDirect, Elsevier B. V, Amsterdam, v. 28, p. 323-344, 1984.

OLIVEIRA, J.B., CAMARGO, M.N., ROSSI, M., CALDERANO FILHO, B. **Mapa pedológico do Estado de São Paulo: legenda expandida**. Campinas: Instituto Agronômico/EMBRAPA Solos; v. 1. 64 p. 1999.

RAVAZZANI, G., BOSCARELLO, L., CISLAGHI, A., MANCINI, M. Review of Time-of-Concentration Equations and a New Proposal in Italy. **Journal of Hydrologic Engineering**, v. 24, 10. 2019. DOI: https://orcid.org/0000-0002-6850-0883.

RODRIGUEZ-ITURBE, I. and VALDES, J. B.: The geomorphologic structure of hydrologic response, **Water Resour. Res**., 15, 1409–1420, 1979.

RODRIGUEZ-ITURBE, I., GONZALEZ-SANABRIA, M., and BRAS, R. L.: A geomorphoclimatic theory of the instantaneous unit hydrograph, **Water Resour. Res**., 18, 877–886, 1982.

SADHASIVAM, N., BHARDWAJ, A., POURGHASEMI, H.R, KAMARAJ, N. P. Morphometric attributes-based soil erosion susceptibility mapping in Dnyanganga watershed of India using individual and ensemble models. **Environ Earth Sci**, v. 79, p. 360, 2020. DOI: 10.1007/s12665-020-09102-3. Disponível em: https://doi.org/10.1007/s12665-020-09102-3. Acesso em: 31 jul. 2021.

SCHUMM, S.A. The evolution of drainage systems and slopes in Badlands at Perth Amboy. **Geological Society America Bulletin**, v. 67, p. 597-646, 1956. DOI: http://dx.doi.org/10.1130/0016-7606(1956)67[597:eodsas]2.0.co;2.

SILVEIRA, A. L. L. Desempenho de Fórmulas de Tempo de Concentração em Bacias Urbanas e Rurais. **RBRH – Revista Brasileira de Recursos Hídricos.** v. 10, n.1, p. 5-23, 2005. DOI: 10.21168/rbrh.v10n1. p5-29. Disponível em: https://www.abrhidro.org.br/SGCv3/publicacao.php?PUB=1&ID=29&SUMARIO=896. Acesso em: 29 jul. 2021.

SOUZA, J. O. P. DE; ALMEIDA, J. D. M. DE. Modelo digital de elevação e extração automática de drenagem: dados, métodos e precisão para estudos hidrológicos e geomorfológicos. **Boletim de Geografia**, v. 32, n. 2, p. 134 - 149, 2014.

STEFFEN, W. *et al.* The trajectory of the Anthropocene: The Great Acceleration. **The Anthropocene Review.** v. 2, n. 1, p. 81-98, 2015. DOI:10.1177/2053019614564785. Disponível em: https://journals.sagepub.com/doi/10.1177/2053019614564785. Acesso em: 30 jul. 2021.

STRAHLER, A.N. Hypsometric (area altitude) analysis of erosional topography. **Geology Society American Bulletin**, v.63, n.10, p.1117-1142, 1952. DOI: 10.1130/0016-7606(1952)63[1117:HAAOET]2.0.CO;2. Disponível em: https://doi.org/10.1130/0016-7606(1952)63[1117:HAAOET]2.0.CO;2. Acesso em: 30 julho. 2021.

STRAHLER, A. N. **Quantitative geomorphology of drainage basins and channel networks.** In: Chow. V.T. Handbook of applied hydrology. New York: McGraw-Hill Book Company.

TEWARI, N. K; MISRA, A. K; SHARMA, A. Assessment of geomorphological and hydrological variations in Bhagirathi River Drainage sub-basin with the help of morphometric studies, **Journal of Taibah University for Science**, 13:1, 1006-1013, 2019. DOI: 10.1080/16583655.2019.1670888.

THOMAS, W. O., MONDE, M. C., & DAVIS, S. R. (2000). Estimation of time of concentration for Maryland streams. Journal of the Transportation Research Board, 1720, 95–99.

TUNDISI, J. G. Novas perspectivas para a gestão de recursos hídricos. **Revista USP**, (70), 24-35, 2006. DOI: https://doi.org/10.11606/issn.2316-9036.v0i70p24-35.

TUNDISI, J. G. & MATSUMURA-TUNDISI T. Recursos Hídricos no Século 21. Oficina de textos. 328 pp. 2011.

VILLELA, S. M.; MATTOS, A. **Hidrologia aplicada**. São Paulo: McGraw-Hill do Brasil, 1975, 245 p.

WORLD METEOROLOGICAL ORGANIZATION E UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION. International Glossary of Hydrology, WMO Report No. 385, Geneva, 2012.

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