Determination of the runoff coefficient (C) in catchments based on analysis of precipitation and flow events

Ronalton Machado, Tais Cardoso, Matheus Mortene

Unicamp (University of Campinas) - College of Technology. Street Paschoal Marmo 1888, CEP 13484-332, Jd. Nova Itália, Limeira, SP, Brazil.

Correspondence to: Ronalton Evandro Machado (ronalton@unicamp.br)

Abstract

Runoff coefficient (C) values are tabulated and enshrined in hydrological engineering. Its values are considered to be constant although it may not correspond to reality. In the same catchment, they can vary according to the intensity, temporal and spatial distribution of precipitation events, humidity conditions, soils and land uses. This study had the objective of analyzing extreme events of precipitation and their corresponding flows to obtain experimental runoff coefficients (C) and compare them with the tabulated values. The study was conducted in five experimental catchments in the state of São Paulo, Brazil, with different land uses. The runoff coefficients (C) were obtained from the analysis of hydrograms and using a digital filter, which allowed the separation of the direct runoff, of the total flow. We observed a variation of the flow coefficient values between catchments different from those obtained from the tables. The runoff coefficients had a high correlation with land use. In the catchments with original vegetation cover, such as cerrado and forest, it varied little among the events analyzed, differently from the catchments where land use is diversified, with predominantly agricultural and urban occupation.

Keywords: digital filter, hydrograms, hydrology, land use, watershed.

1. INTRODUCTION

The runoff coefficient (C) is defined as the ratio of the volume of water superficially drained during a rainfall over the total volume of precipitated water during a certain period (Bedient et al. 2013; Júnior, 2015). An important tool in hydrological studies of many engineering projects in urban and rural areas (Şen & Altunkaynak, 2006), the runoff coefficient may indicate the amount of water flowing from particular precipitation and may reflect the impact of natural geomorphological elements on the flow. In addition, flow coefficients are useful for comparison with other watersheds to understand how different landscapes transform precipitation into rainfall events (Che et al., 2018; Blume et al. 2007).

One of the most important factors in the evaluation and determination of the runoff coefficient is precipitation, which may refer to an isolated rainfall, or to a time interval, in which several rains occurred (Júnior, 2015; Campos & Machado, 2018). When the precipitation increases, the initial losses and the infiltration capacity are met. Thus, the runoff increases, resulting in a higher flow coefficient (Tucci, 2000a).

In addition to precipitation characteristics such as intensity, duration and distribution, specific physical aspects of watersheds affect the occurrence and volume of the runoff, such as soil type, vegetation, slope, contribution area and permeability. Permeability of the watershed is related to its ability to absorb water, that is, the greater the occurrence of permeable surfaces, the greater the chance of water infiltrating and reducing the volume of rainfall drained superficially (Wang et al., 2010; Park et al., 2014; Radecki-Pawlik et al., 2014). Soil moisture is also crucial for the control of hydrological processes, especially in the generation of surface runoff. In the early period of the rainy event, much of the precipitation infiltrates the soil, and in the course of rain, the soil reaches its saturation point. After that, all surplus is superficially drained, a volume that can be mathematically determined by the runoff coefficient (Bagarello et al., 2018; Richardson & Amankwatia, 2018). Therefore, the runoff coefficient may vary according to the characteristics of the terrain surface cover, of the physical characteristics and antecedent moisture, and the different types of soils found in a watershed (Nunes et al., 2011).

It can be estimated using tables in which the runoff coefficient is related to the nature of the surface where it occurs. According to Lallam et al. (2018), the effective study of the coefficient is a very complex operation, due to the high number of variables that affect it. This means that the flow coefficients reported in the literature generally transmit less information than necessary (Blume et al., 2007), and therefore their values, when tabulated as if they were constant, may not correspond to reality.

There are still few studies on flow coefficient values obtained from rainfall and flow data in catchment areas. Given this context, this study analyzed extreme events of precipitation and the corresponding flows in catchments with different land uses and soils to obtain values of experimental runoff coefficients and compare them with the tabulated values. These events of precipitation are typical of tropical regions and occur in the summer. It has great intensity and short duration that promotes the rapid elevation of the stream level and causes the higher values of runoff coefficient. It has a localized spatial extension and they're important for catchments (Campos & Machado, 2018). We separated the direct runoff from the base flow using digital filters. Thus, by utilizing the relation between surface runoff volume and precipitated volume, we determined the runoff coefficients for different rainfall-flow events.

2. MATERIAL AND METHODS

2.1 Areas of study

This study was developed with knowledge on rainfall and flow data. We selected monitored catchments with different land uses located in São Paulo, southwestern region of Brazil (Figure 1). General information such as topography (elevation range), land use, soil and geomorphology of the catchments is shown in items 2.2 to 2.5. Information about meteorological and flow measurement data is presented in Table 1.

[Insert Figure 1]
[Insert Table 1]

2.1.1 Tinga catchment

Tinga catchment is located in the Experimental Station of the Department of Forest Sciences of the "Luiz de Queiroz" School of Agriculture (ESALQ/USP) in the city of Itatinga, São Paulo. Its area is 83.57 ha. The dominant relief in the area (Pessotti, 1994) is smooth wavy, consisting of planed tops and slopes of rectilinear or convex forms. To a lesser extent, there is a wavy relief with a slope between 10% and 15% and ramps of rectilinear shape marked by the absence of flat tops. The drainage network is of low density, with rounded headwaters, from closed to open valleys, and restricted alluvial plain.

According to the Köppen classification, the climate is Cfa, i.e. humid mesothermal, with no defined dry season. The rainiest quarter corresponds to the months from December to February and the driest period to May to August (Pessotti, 1994). The soil of Tinga catchment was classified as red latosol. The land cover of the catchment is predominantly Eucalyptus saligna. Along the creek, there is a ciliary forest totaling 7.6 ha. Table 2 shows the land use classes in the Tinga catchment. Figure 2 shows spatial information of the relief, land use, soils and geomorphology.

[Insert Figure 2]

[Insert Table 2]

2.1.2 Pé de Gigante catchment (PEG)

The experimental PEG catchment underwent hydrological and micrometeorological monitoring and has an area of 1560 ha. It is located in the Vassununga Park of the Institute of Forestry of São Paulo. The area consists mostly of restricted cerrado, in addition to other physiognomies of cerrado and a small area with deciduous forest. The region is characterized by a differentiated relief that ranges from wide to low hills, as well as fluvial plains with a predominance of smooth reliefs and low slopes (0 to 10%) (Bruno, 2009). The Köppen climatic classification of the experimental area is Cwa, with average monthly temperatures ranging from 17.6°C to 23.5°C and the average annual rainfall totaling 1,478 mm. The rainy season occurs between September and April, and the dry season between May and August (Bruno, 2009). The PEG catchment soil was classified as a red neosol. These are deep, porous and well-drained soils with moderate to weak A horizon and medium texture, presenting good physical characteristics for the root development of plants (Batalha, 1997). High levels of sand provide this soil with a good rooting ability in its physical aspects, but a low water retention capacity. Due to the relief to which they are associated and to the low degree of cohesion between particles caused by low clay content, these soils are highly susceptible to natural erosion (Bruno, 2009). Spatial information about the relief, land use, soils and geomorphology are presented in Figure 3.

[Insert Figure 3]

2.1.3 Santa Virgínia catchment (SVG)

The Santa Virgínia catchment (SVG) is located in the Serra do Mar State Park (PESM) and has an area of 120.5 ha. Serra do Mar is a region of escarpment relief with typical plateau border, leveled by the top at altitudes from 800 to 1200 m, predominantly covered by dense ombrophilous forest (Freitas, 2012). In this region, the relief has strong slopes (24 to 37°). The type of soil in the catchment is Cromic Cambisol (Radambrasil, 1983). According to the Köppen classification, the climate is Cfb (köeppen, 1948). It has an average annual precipitation of 1731 mm, with subhumid tropical climate. The average annual temperature is 22.5°C on the coast (from 19°C in winter to 25°C in summer) (Scardua, 1994). Figure 4 shows spatial information of the relief, land use, soils and geomorphology.

[Insert Figure 4]

2.1.4 Marins catchment (BHRM)

The Marins catchment is located in the municipality of Piracicaba, São Paulo, with an approximate area of 5,973 ha. The Marins catchment is of great socio-economic and environmental importance to the region. The water resources coming from this catchment are used to irrigate most of the vegetables that supply the city and region, among other uses (Casagrande, 2005).

According to the Köppen classification, the climate is Cwa of mesothermic type, i.e. humid subtropical with drought in winter, whose rains of the driest month do not reach 30 mm and the temperature of the hottest month is higher than 22°C, while that of the coldest month is below 18°C (Machado & Vettorazzi, 2003). The precipitation and flow data originate from two rain gauges and the hydrosedimentometric station installed in the catchment in 1999, under the responsibility of the Department of Water and Electricity (DAEE) and the Technology Center of Water Resources (CTH) of USP. One of the rain gauges (D4118r) was installed in the upper portion of the catchment. The other pluviograph (D4116r) was installed close to the hydrosedimentometric station. The contributory catchments until the post has approximately 22 km^2 (2200 ha) (Machado, 2002). The land is predominantly used for cultivation of sugarcane and pasture (Table 3 and Figure 5). In the Marins catchment, the predominant soils are Litholic Neosols and Red-Yellow Argisols, with 58% and 42%, respectively (Table 4 and Figure 5).

[Insert Figure 5]

[Insert Table 3]

[Insert Table 4]

2.1.5 Mineirinho catchment

The Mineirinho catchment is located in one of the growth vectors of the municipality of São Carlos, São Paulo, with an area of 585.5 ha, and it underwent hydrological and four rain gauges monitoring. There are various different land uses such as agriculture and mixed-use regions with houses, commerce and services, most notably residential areas (Figure 6). In the area close to the river mouth, a small section of the stream was straightened and buffered to construct a roundabout. Table 5 shows the land use of the catchment. The Köppen climatic classification for São Carlos is Cwa, tropical with humid summer and dry winter or warm weather and dry winter (Lorandi, 1985). The precipitation ranges from 1500 to 1700 mm/year and the average temperature ranges from 18.1°C to 23.1 °C (Martins, 2017). The catchment soil was classified as a red-yellow Latosol, with deep and dystrophic interfluves (Benini, 2005) (Figure 6).

[Insert Table 5]

[Insert Figure 6]

2.2 METHODS

Based on data from the pluviographs installed in the catchments, we selected and analyzed extreme precipitation events with potential for generation of surface runoff and their respective flows to separate the surface runoff volume from the base volume in the hydrograph. Separating the direct runoff from the base flow is a procedure that allows to understand the magnitude and the dynamics of the discharge of groundwater and the processes of direct runoff in watersheds (Brodie & Hostetler, 2005). It also allows to analyze the influence of several factors on the base flow and direct runoff, for example, via analysis of the influence of adopting practices for water and soil conservation in the reduction of flow peaks and the increase of the minimum flows in periods of drought (Miranda et al., 2014; Vasconcelos et al., 2013). There are some methods for separation of flows, such as chemical analyses of certain substances identified as tracers, methods that are based on curve fittings through graphical analysis of hydrographs and digital filters of physical basis. We used the digital filter method proposed by Arnold (1999).

The digital filter technique was originally used in the analysis and processing of signals to separate those of high frequency from those of low frequency. In this method, high-frequency waves can be associated with direct runoff, and low-frequency waves can be associated with base flow (Lim et al., 2005). The sum of both frequencies would correspond to the total flow of the hydrograph. Although the technique has no actual physical basis, it is objective and reproducible (Arnold et al., 1995), this automated digital filter technique can be suitably compared to the estimates measured in the field.

The filter equation is:

$$q_t = \beta \; q_{t-1} + (1+ \beta)/2^* \; (Q_t - Q_{t-1}) \qquad (1)$$

Where q_t is the filtered surface flow (rapid response) in time t (one day), Q is the original flow and β is the filter parameter (0.925). The value of 0.925 was determined by Nathan & Mcmahon (1990) and Arnold et al. (1995) to give realistic results compared to manual separation techniques. The base flow, b_t, is calculated with the following equation:

$$b_t = Q_t - q_t \quad (2)$$

The calculation of the surface runoff coefficient (C), relative to a rainfall event, was carried out by verifying the total volume flowed through the separation between this and base volume, using the digital filter, and the total precipitated on the catchment, according to the relation below:

$$C = Vs/Vp \quad (3)$$

Where, C – runoff coefficient; Vs – surface runoff volume; Vp – precipitated volume.

3. RESULTS AND DISCUSSION

After analyzing the rainfall-flow data at different seasons and selecting flood events from the Tinga, Pé de Gigante, Santa Virgínia, Marins and Mineirinho catchments with a digital filter, we found a variation of the values of the runoff coefficient between the rainfall-flow events selected different from the tabulated values. Table 6 shows the information of the events analyzed for the five catchments.
[Insert Table 6]

Table 7 shows the values for experimental surface runoff coefficients for six of these events. These coefficients (C_1-C_6) represent the data obtained in different dates and years* and the CT is the tabled runoff coefficient (McCuen, 2017; Gribbin, 2014; Anderson & McDonnell, 2005). To eliminate the effects of antecedent rainfall and soil moisture, we selected isolated precipitation events. The exception was the values of Tinga – C5= 0.024; PEG – C2= 0.038; SVG – C6= 0.0003; BHRM – C3= 0.36, Mineirinho – 0.15, which were obtained from the analysis of two consecutive precipitation events. The values were higher than the C values generated in the hydrograms that present an isolated precipitation event. This is probably because, after a precipitation event, the soil is already saturated or partially saturated, that is, the increase in soil moisture also increases the C value after the second precipitation event. Although rainfall and antecedent soil moisture are quite significant in the higher or lower values of the runoff coefficients, land use and soil type are factors that control the superficial runoff.

[Insert Table 7]

From the Tinga catchment, we selected a sequence of hydrographs and precipitation with different types of behavior from 2011. The C values of Table 8 and Figure 7 show the hydrographs and precipitations that occurred in each event and the values of runoff coefficients. Figures 7a and 7c show the events in which the direct runoff was greater than the base flow, as there were more intense rains and consequently higher surface runoff. For less intense rains the tendency is that most of the water volume infiltrates in soils, especially in those occupied with eucalyptus (infiltration rate > rainfall intensity) (Zuquette & Palmai, 2006). This occurred in the hydrograph of Figures 7b, 7d, 7e and 7f. In the less intense precipitation events, the base flow was greater than the surface runoff. Figure 7f shows the hydrograph resulting from the analysis of two consecutive precipitation events. For this analysis in which two precipitation events occur in sequence, the C value was 0.024 (Table 7) higher than the C values of the other hydrographs that were analyzed in isolation.

In the observed hydrographs, the base flow predominated. The exception was two events whose direct runoff predominated. There was little variation in the runoff coefficient values for this catchment, possibly due to the uniformity of land use and cover. The behavior of hydrographs and the response of the catchment to precipitation events were influenced by land use/occupation, which is predominantly characterized by eucalyptus (78.94%) and native vegetation (8.67%) on Red Latosol soil. Latosols are one of the thirteen orders of soils according to the Brazilian Soil Classification System. These soils consist of a material that is mineral predominantly, very weathered, with a B-latossolic diagnostic horizon and high infiltration capacity. They represent more than 50% of the Brazilian territory and are the most important order in agricultural terms (Neto & Loper, 2009).

[Insert Table 8]

[Insert Figure 7]

The runoff coefficient values were obtained from the events analyzed between 2012-2013 for the Pé de Gigante (PEG) catchment (Figure 8 and Table 9). In all events, the base flow was greater than the surface runoff. Considering that the type of land use and cover determines, in part, the hydrological behavior of a catchment, in this catchment the greatest cover of the land is the Cerrado biome under Red Latosol, which has a medium, deep, porous and well-drained texture, presenting good physical characteristics for root development of plants and water infiltration (Batalha, 1997). This condition favors water infiltration into the soil and the generation of base flow. These results show the importance of the Cerrado biome associated with the soil of high infiltration capacity to maintain a perennial river.

[Insert Figure 8]

[Insert Table 9]

Table 10 and Figure 9 show the hydrograph and C values for the Santa Virgínia (SVG) catchment, respectively. Some precipitation events analyzed occurred in very close periods. There was little variation in the runoff coefficient calculated for each event. Out of the six events shown, four presented greater base flow than surface runoff (Figures 9b, c, d, e). Rainfall intensity varied between 12.95 mm/h and 78.23 mm/h for the studied period. The hydrograph resulting from a complex precipitation event (Figure 9f) presented direct runoff (56.5%) greater than the base flow (43.5%). Data analysis preceding this event confirmed the existence of a previous precipitation event, which increased the soil moisture and consequently the soil saturation.

The SVG catchment is characterized by native forest cover and clay soils with low activity and low base saturation in most of the first 100 cm of the B-horizon Haplic Cambisols (EMBRAPA, 2006). The forest cover intercepts rainwater, decreases its speed, and protects and improves the soil hydrologic conditions due to the organic layer that accumulates on the surface (plant litter), allowing the infiltration process to occur slowly (Neary et al., 2009; Andréassian, 2004; Brown et al, 2005).

[Insert Table 10]

[Insert Figure 9]

To calculate the mean precipitation of the Marins catchment (BHRM), which has two rain gauges, we used the Thiessen method. Hydrographs of the six flood events in 1999 and 2000 during different months are presented in Figure 10. We observed that the average of the direct runoff (64.87%) was higher than the average of base flow (35.13%).

[Insert Table 11]

Lallam et al. (2018) quantified the influence of certain parameters on the runoff coefficient values of watersheds, and the vegetation cover is the most impacting one (vegetation density and degree of plant development). BHRM has a predominant coverage of sugarcane (approximately 70% of land use). The management of sugarcane has two distinct phases: first, furrowing of the soil for planting, and second, maintenance over a period. During the furrowing phase, the structures of the surface layer are destroyed, and the infiltration rate is very high. According to EMBRAPA (2018), the period between January and March is considered ideal for the growth of sugarcane, since it presents good conditions of temperature and humidity, ensuring the development of the gems (Fietz et al., 2015). The highest direct runoff observed occurred during this period because precipitation is not intercepted by any vegetation cover.

During this study period, rainfall intensity ranged from 11.8 mm/h to 58.9 mm/h. Castilho & Filho (2000) analyzed the interception of rainfalls from February to December 1999 in a sugarcane crop in a cultivation area in the city of Campinas, São Paulo, located in the same climatic region (approximately 75 km of the BHRM). According to the author, in this period the total incident precipitation analyzed was 778.9 mm, of which 39.5% were intercepted and 60.5% represented the water depth in the soil. As sugarcane develops, the amount of precipitation intercepted by the vegetation cover represents an important part of the water balance. Tomasini et al. (2010) analyzed the effect of different soil cover in sugarcane cultivation area on the surface runoff in the erosion between the furrows. The authors verified that the effects of the sugarcane canopy and residue promoted the increase of the hydraulic roughness and the volumes of interception by the vegetation, reducing the runoff. As previously mentioned, soil texture, moisture and compaction, vegetation management and cover, as well as precipitation intensity can influence the runoff and consequently the runoff coefficient value. As direct runoff and base flow alternated in discharge formation (Figures 10a-f), different C values were expected for each period. The variation between all experimental runoff coefficient values ranged between 0.011 and 0.35, concerning the tabled runoff coefficient value (0.31).

[Insert Figure 10]

Figure 11 shows the hydrograph of the events and Table 12 shows the runoff coefficient values obtained from the events analyzed between 2014 and 2015 in the Mineirinho catchment. Only 12 events were analyzed. A hydric crisis occurred in the region between 2014 and 2015, causing precipitation levels to drop much below annual averages and resulting in lower river flow. We used the Thiessen method to calculate the mean precipitation of this catchment, which has four rain gauges, three installed in the inside. In all events, the direct flow was greater than the base flow. The catchment has diversified land use, with a predominance of residential use with area of low and medium density. The catchment has undergone an urbanization process since the 1970s (Aprígio, 2012). The values of C indicate that urbanization is a significant factor controlling the runoff in the catchment. The rapid runoff response of highly urbanized watersheds is due to increased imperviousness and development of artificial (typically concrete) drainage systems (Rose & Peters, 2001). However, the soil is extremely sandy, with good internal drainage, low erodibility and low runoff generation potential (Almeida, 2009). These soils, due to their characteristics, belong to hydrological group B, according to the SCS methodology (Sartori, et al., 2005).

[Insert Figure 11

[Insert Table 12]

The graphs presented in Figure 12 show the degree of variability in C values around the main value of the sample. Between the catchments, an increase in the runoff coefficient is observed as the area increases. Catchments with larger areas – BHRM (2200 ha) and PEG (1560 ha) – presented higher runoff coefficients than SVG (120.5ha) and Tinga (83.57ha), with smaller areas of contribution. This result is not always expected, because watersheds with larger areas tend to have greater water infiltration in the soil since they are generally flattered regions (Gomi et al., 2008). However, the runoff coefficients of the PEG (1560 ha) were smaller than the Mineirinho catchment (585.5 ha). Only the watershed size is not a determining factor as an indicator of high or low runoff coefficients, and other characteristics of the watershed have to be considered, such as slope, soil type and use and occupation of land (Lemma et al., 2018). According to Merz et al. (2006), surface characteristics of watersheds are more impacting in C values than its area of contribution.

The inter-quartile amplitude was smaller and had symmetrical distribution similar to the median for Tinga, PEG and SVG catchments (Figure 12). These catchments showed few outlets compared to the number of events analyzed, 3.8%, 3.1% and 2.9%, respectively. The differences are apparent both in the median runoff coefficients as well as in the maximum and minimum. The 25% quantiles were 0.05 for Marins and 0.07 for Mineirinho. while for Tinga, PEG and SVG catchments were 0.006, 0.006 and 0.05, respectively. The 75% quantiles were 0.19, 0.11, 0.009, 0.009

and 0.09 for Marins, Mineirinho, Tinga, PEG and SVG catchments, respectively. The runoff coefficient values were variable in catchments (mainly Marins and Mineirinho) and highly variable between catchments. The catchments with native vegetation (forest and cerrado) have the smallest runoff coefficients while the Marins and Mineirinho catchments have the largest runoff coefficients (diversified land use). The median runoff coefficient at Marins catchment was the highest of all catchments. Furthermore, compared to the other catchments with native vegetation, the median runoff coefficient (0.12) for Marins catchment was 15 times higher than Tinga and PEG (0.008), and 1.5 times higher than SVG (0.08). The median runoff coefficient (0.09) at Mineirinho catchment was also greater compared to the catchments covered with native vegetation, 11.25 times higher than Tinga and PEG (0.008), and more than 1.13 times higher than SVG (0.08). The land use in this catchment has been changing since 1970, when undergoing an urbanization process. The population-density increase was accompanied by an increase in imperviousness that caused changes in watershed hydrologic characteristics.

These variations in the values of the runoff coefficient may be related to changes in land use, but also to other factors, such as soils (layers, porosity), relief (aspect, slope), and precipitation (height, duration and intensity). According to Huff et al. (2000), Crouzeilles & Curran (2016), cited by Zhang et al. (2017), theoretically, as watershed size increases, more heterogeneities in landscape, topography, climate, geology and vegetation, resulting in greater buffering ability to watershed disturbances such as change in land uses, thus being less sensitive to a given level of forest cover change compared to smaller watersheds. However, for catchments (small watershed), the factors of relief, soil and geology are more homogeneous, which eliminates their influences on the catchment’s response (Merz et al., 2006; Cerdan et al., 2004).

The five catchments are located in the same hydrological region (humid subtropical zone) and the soil of the catchments did not differ in terms of water infiltration capacity and reduction of surface drainage, which eliminates climatic and soil factors from the variation of the runoff coefficient values between catchments. As for the morphometric index, the slope of the main stream was 2.2%, 2.0%, 7.1%, 1.1% and 2.2% for the Tinga, PEG, SVG, Marins and Mineirinho catchments, respectively. The slope and the length of the mainstream are two factors that influence surface drainage and are used in most equations to calculate the time of concentration of the watershed. Catchments with short times of concentration present a stronger tendency to flood. The lowest slope of the main stream belonged to the Marins catchment, which had the highest runoff coefficient and diversified land use. On the other hand, the biggest slope of the main stream belonged to the SVG. The SVG catchment is located in a region of escarpment relief in Serra do Mar. In this region, the relief has strong slopes (24 to 37°). However, predominantly covered by dense ombrophilous forest. Compared with the region of escarpment relief of the SVG catchment, the Marins catchment transports more runoff, even with the relatively low relief. The slope of the mainstream in the remaining catchments was similar despite the difference in soil coverage. The Tinga and PEG catchments had plant coverage from woods and the Mineirinho catchment had a predominantly urban land use. Catchments with bigger slope and coverage from native vegetation (SVG and PEG catchments) had the lowest variations in C values, whereas the catchments with varying land uses had the highest values and variations of C (Marins and Mineirinho catchments).

The runoff coefficients determined for these three catchments (Tinga, PEG e SVG) are very low, which is probably due to the lack of anthropogenic influences such as soil compaction, homogeneity of land use and especially the interception of vegetation (the catchments are covered with native vegetation). Therefore, flow that occurs near the interface of the organic/mineral horizon, typical of forest areas, may infiltrate more deeply into the soil and may not contribute to the flow of the catchment storm (Badoux et al., 2006). The C values varied in the other catchments with more land use diversity. The spatial arrangement of areas of given land use within a catchment is significant for runoff coefficients at the catchment scale (Cerdan et al., 2004). The high variability in C from the Marins catchment was potentially associated with seasonal variations in soil surface conditions. Its soil physical conditions such as surface roughness and soil compaction are altered by the harvest cycle of the sugarcane, mail culture of catchment (67.6%). In the Mineirinho catchment, outlets represented 33.3% of samples and presented asymmetrical amplitude. Land use is characterized by urban occupation (42.9%), agriculture (10.1%), forest (12.9%) and grass (25.5%). The higher percentage of native vegetation (forest and cerrado) in the SVG, Tinga and PEG catchments can certainly explain the differences in the runoff coefficients. These results show that soil surface condition was the main factor controlling the runoff coefficient at the scale of catchments.

[Insert Figure 12]

4. CONCLUSIONS

We determined the runoff coefficients (C) in five experimental catchments, with different land uses, using a digital filter for separating the base flow from the surface runoff. From the relationship between surface runoff volume and precipitated volume, we determined the C values and compared them with the tabulated values. The values obtained in the experimental catchments were very different from each other and from the tabulated values. As the tabulated values were obtained in experimental plots, they do not reflect reality, since each catchment has different characteristics (geological, climatic and physiographic factors of the region, soil type, land uses, among others) and more complex hydrological processes. Although the tabulated C values overestimated the values obtained in experimental catchments, and although the higher the C value, the lower the risk of the hydraulic work failing, care is required when choosing these values for estimating maximum discharge in engineering projects. Since C is used to calculate maximum flow according to the Rational method by Wilken (1978), many authors make severe restrictions to this method, not due to its core concept, which is valid, but due to the way it is employed, namely with use of completely empirical coefficients whenever data is impossible to acquire or missing in order to determine the C coefficient values covering various complex factors. Land use had a high correlation with runoff coefficients in this study. In the catchments with original vegetation cover, such as the cerrado (PEG catchment) and forest (SVG catchment), the runoff coefficient varied little compared to the remaining events analyzed, different from the catchment where land use and occupation are predominantly agricultural (BHRM catchment) and mainly in catchments with urban occupation (Mineirinho catchment). In urban areas, artificial modifications tend to increase peak discharge, such as soil sealing, urban drainage and river channelization. While the forest intercepts most of the rain due to large leaf areas compared to grassland or agricultural land and increased the permeabilities of forest soils (Andréassian, 2004; Brown et al., 2005).

ACKNOWLEDGEMENTS

Funding: This research was funded by FAEPEX/Unicamp

Acknowledgments: *The authors thank Espaço da Escrita – Pró-Reitoria de Pesquisa – UNICAMP - for the language services provided* . ESALQ/USP, IAG/USP, IAG/USP, DAEE and LabSin (EESC) for giving in the rain and flow data.

DATA AVAILABILITY

I confirm that the data will be available

REFERENCES

ALMEIDA, T., L. Implicações ambientais dos processos de atenuação de lixiviado em locais de disposição de resíduos sólidos urbanos. 2009. 192p. Tese (Doutorado) - Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2009.

ANDERSON, M. G. & MCDONNELL, J. J. (2005) Encyclopedia of Hydrological Sciences. 1nd Edition, John Wiley & Sons.

ANDRÉASSIAN, V., 2004. Water and forests: from historical controversy to scientific debate. Journal of Hydrology, 291: 1-27.

APRÍGIO, P. O. Avaliação de modelos de simulação de cargas difusas em bacias urbanas. Dissertação (Mestrado) - Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2012.

ARNOLD, J.G.; ALEEN, P.M. B., 1995. Automated Base Flow Separation and Recession Analysis Techniques.

ARNOLD, J.G., 1999. Automated Method's for estimating baseflow and Florida is highly dependent on ground water mates of baseflow and recharge.

BAGARELLO, V.; STEFANO, C.; VITO, F.; VICENZO, P. Comparing theoretically supported rainfall−runoff erosivity factors at the Sparacia (South Italy) experimental site. Hydrological Processes (Online), Chichester, v. 32, n. 4, p. 507-515, Feb 15 2018. https://doi.org/10.1002/hyp.11432

BATALHA, M.A., 1997. Análise da vegetação da ARIE Cerrado Pé de Gigante (Santa Rita do Passa Quatro, SP). Univ. Fed. São Paulo.

BADOUX, A., WITZIG, J; GERMANN, P. F.; KIENHOLZ, H.; LUSCHER, P.; WEINGARTNER, R.; HEGG, C. (2006). Investigations on the runoff generation at the profile and plot scales, Swiss Emmental, Hydrol. Processes, 20, 377 – 394, doi:10.1002/hyp.6056.

BEDIENT, P., HUBER, W., AND VIEUX, B. (2013). Hydrology and floodplain analysis, 5th Ed., Pearson Publishing, NJ.

BENINI, R. M. Cenários de ocupação urbana e seus impactos no ciclo hidrológico na bacia do córrego do Mineirinho. Dissertação (Mestrado). Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2005.

BLUME, T., ERWIN, Z., BRONSTERT, A., 2007. Rainfall-runoff response, event-based runoff coefficients and hydrograph separation. Hydrol. Sci. J. 52, 843–862.

BRODIE, R.S.; HOSTETLER, S., 2005. A review of techniques for analysing baseflow from stream hydrographs. Proc. NZHS-IAH-NZSSS Conf. 28.

BROWN, A.E.; ZHANG, L.; McMAHON, T.; WESTERN, A.W.; VERTESSY, R.A., 2005. A review of paired catchment studies for determining change in water yield resulting from alterations in vegetation. Journal of Hydrology, 310: 28-61.

BRUNO, R.D., 2009. Balanço de água em microbacias de cerrado restrito e eucalipto: Um estudo de caso com medidas observacionais.

CAMPOS, M. De R.; MACHADO, R. E. Time distribution of intense rainfalls at Campinas, Brazil. International Journal of Advanced Engineering Research and Science (IJAERS) [Vol-5, Issue-11, Nov- 2018] https://dx.doi.org/10.22161/ijaers

CASAGRANDE, C.A., 2005. Diagnóstico ambiental e análise temporal da adequabilidade do uso e cobertura do solo na Bacia do Ribeirão dos Marins, Piracicaba–SP.

CASTILHO, C. G.; FILHO, J.T., 2000. Interceptação de chuvas na cultura da cana-de-açúcar (Saccharum Officinarum ssp.). Eng. Agrícola.

CERDAN, O; BISSONNAIS, Y. LE; GOVERS, G.; LECOMTE, V.; VAN OOST, K.; COUTURIER, A.; KING, C.; DUBREUIL, N. Scale effect on runoff from experimental plots to catchments in agricultural areas in Normandy. Journal of Hydrology 299 (2004) 4–14.

CHE, D.; LIANG, A.; LI, X.; MA, B. Remote Sensing Assessment of Safety Risk of Iron Tailings Pond Based on Runoff Coefficient. Sensors 2018, 18, 4373. doi: 10.3390/s18124373

CROUZEILLES, R., CURRAN, M., 2016. Which landscape size best predicts the influence of forest cover on restoration success? A global meta-analysis on the scale of effect. J. Appl. Ecol. 53, 440–448.

EMBRAPA, 2018. Plantio da cana-de-açúcar. https://www.agencia.cnptia.embrapa.br/gestor/cana-de-acucar/arvore/CONTAG01_33_711200516717.html

EMBRAPA, 2006. Sistema Brasileiro de classificação de solos. Embrapa Solos -

Empres. Bras. Pesquisa. Agropecuária.

FIETZ, C.R.S.; COMUNELLO, C.; FLUMIGNSN, E.; DANILTON, L., 2015. Cana-de-Açúcar: Risco Climático para Plantios de Inverno na Região Sul de Mato Grosso do Sul. Comun. Técnico 209 1–9.

FREITAS, H.C., 2012. Energia Nuclear na Agricultura A influência dos transportes advectivos na estimativa do balanço de CO2 do ecossistema: Um estudo de caso para a mata atlântica com uso.

GOMI, T., SIDLE, R.C., MIYATA, S., KOSUGI, K., ONDA, Y. (2008). Dynamic runoff connectivity of overland flow on steep forested hill slopes: Scale effects and runoff transfer. Water Resources Research, 44, W08411. http://dx.doi.org/10.1029/2007WR005894.

GRIBBIN, J. E. (2014) Introduction to hydraulics and hydrology with applications for stormwater management. 4nd Edition, Delmar Cengage Learning.

HUFF, D., HARGROVE, B., THARP, M., GRAHAM, R., 2000. Managing forests for water yield: the importance of scale. J. Forest. 98 (12), 15–19.

JÚNIOR, A.R.B., 2015. Elementos de Hidrologia Aplicada - UFOP - Universidade Federal de Ouro Preto 92–155.

KÖEPPEN, W., 1948. Fundo de Cultura Econômica, México. KREBS.

LALLAM F., MEGNOUNIF A., GHENIM A.N. 2018. Estimating the runoff coefficient using the analytic hierarchy process. Journal of Water and Land Development. No. 38 p. 67–74. doi: 10.2478/jwld-2018-0043

LEMMA, T.M.; GESSESSE, G.D.; KASSA, A.K.; EDOSSA, D.C. Effect of spatial scale on runoff coefficient: Evidence from the Ethiopian highlands. Int. Soil Water Conserv. Res. 2018, 6, 289–296. doi: 10.1016/j.iswcr.2018.08.002

LIM, K. J.; ENGEL, B. A.; TANG, Z.; CHOI, J.; KIM, K. S.; MUTHUKRISHMAN, S.; TRIPATHY, D., 2005. Automated Web GIS based hydrograph analysis tool, WHAT. J. Am. Water Resour. Assoc. 41, 1407–1416.

LORANDI, R. Caracterização dos solos das áreas urbanas e suburbanas de São Carlos (SP) e suas aplicações. 1818p.Thesis (Doutorado em Agronomia) – Escola Superior de Agricultura Luiz de Queiroz, Universidade de São Paulo, Piracicaba, 1985.

McCuen, R.H. (2017) Hydrologic Analysis and Design. 4nd Edition, Prentice-Hall.

MACHADO, R.E., 2002. Simulação de escoamento e de produção de sedimentos em uma microbacia hidrográfica utilizando técnicas de modelagem e geoprocessamento. Thesis (Doutorado em Agronomia) - – Escola Superior de Agricultura Luiz de Queiroz, Universidade de São Paulo, Piracicaba, 2002.

MACHADO, R.E., VETTORAZZI, C.A., 2003. Simulação da produção de sedimentos para a microbacia hidrográfica do Ribeirão dos Marins (SP). Rev. Bras. Ciência do Solo 27, 735–741.

MARTINS, R. G. Modelagem da carga de poluição difusa em escala de bacia com valores de concentração média por evento a partir de dados de uma rede de monitoramento local. 2017. 178 f. Thesis (Doutorado em Hidráulica e Saneamento) – Universidade de São Paulo, São Paulo, 2017.

MERZ, R., BLÖSCHL, G., PARAJKA, J. 2006. Spatio-temporal variability of event runoff coefficients. Journal of Hydrology, 331, 591–604. https://doi.org/10.1016/j.jhydrol.2006.06.008

MIRANDA, A. C. R.; MARTINEZ, M. A.; CECON, P.R., 2014. Métodos de separação dos escoamentos superficial direto e subterrâneo: Estudo de caso para a bacia do Rio das Velhas. RBRH - Rev. Bras. Recur. Hídricos 19, 169–181.

NATHAN, R. J.; MCMAHON, T.A., 1990. Evaluation of automated techniques for baseflow and recession analysis. Water Resour. Res. 26, 1465–1473.

NEARY, D. G.; ICE, G. G.; JACKSON, C.R., 2009. Linkages between forest soils and water quality and quantity. For. Ecol. Manage. 2269–2281.

NETO, P. J. C.; LOPER, E.W., 2009. Caracterização física do Latassolo Vermelho distrófico da fazenda Escola da fazu. Agronomy 21–26.

NUNES, F. G.; FIORI, A. P.; FIRPO, G., 2011. Estimativa de coeficientes de escoamento superficial na bacia hidrográfica do rio Atuba: Curitiba e região metropolitana - Paraná/ Brasil. Bol. Parana. Geociências 64, 27–39.

PARK, D. G; SANDOVAL, N.; LIN, W.; KIM, H.; CHO, Y. H.A case study: Evaluation of water storage capacity in permeable block pavement. KSCE Journal of Civil Engineering, Seoul, v. 18, n. 2, p. 514-520, 03 2014. https://doi.org/10.1007/s12205-014-0036-y

PESSOTTI, F.E.S., 1994. Levantamento detalhado dos solos do Horto de Itatinga. ESALQ - Esc. Super. Agric. ``Luiz Queiroz´´ - USP.

RADAMBRASIL. 1983. Projeto Radambrasil: levantamento de recursos naturais. IBGE. Rio de Janeiro.

RADECKI-PAWLIK, A.; WALEGA, A.; WOJKOWSKI, J.; PIJANOWSKI, J. Runoff formation in terms of changes in land use - Msciwojow water reservoir area/ Odplyw powierzchniowy w rejonie zbiornika wodnego Msciwojow w swietle planowanych zmian urbanistycznych. Journal of Water and Land Development, Raszyn, v. 23, n. 1, p. 3-10, 2014. doi: 10.1515/jwld-2014-0024

ROSE, S. & PETER, M. E. Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. Hydrol. Process. 15, 1441–1457 (2001) DOI: 10.1002/hyp.218

RICHARDSON, C.P.; AMANKWATIA, K. GIS-Based Analytic Hierarchy Process Approach to Watershed Vulnerability in Bernalillo County, New Mexico. Journal of Hydrologic Engineering, New York, v. 23, n. 5 05 2018. doi: 10.4236/jwarp.2019.112007.

SARTORI, A.; GENOVEZ, A. M.; LOMBARDI NETO, F. Classificação Hidrológica de Solos Brasileiros para a Estimativa da Chuva Excedente com o Método do Serviço de Conservação do Solo dos Estados Unidos Parte 2: Aplicação. RBRH – Revista Brasileira de Recursos Hídricos Volume 10 n.4 Out/Dez 2005, 19-29.

SCARDUA, F.P., 1994. Caracterização hidrológica de uma microbacia hidrográfica experimental da Estação Experimental de Ciências Florestais de Itatinga, ESALQ/USP. ESALQ - Esc. Super. Agric. ``Luiz Queiroz´´ - USP 93.

ŞEN, Z.; ATUNKAYNAK, A., 2006. A comparative fuzzy logic approach to runoff coefficient and runoff estimation. Hydrol. Process. 20, 1993–2009.

TOLENTINO, M. Estudo crítico sobre o clima da região de São Carlos. São Carlos: EdUFSCar, 2007.

TOMASINI, B. A.; VITORINO, A. C. T.; GARBIATE, M. V.; SOUZA, C. M. A.; SOBRINHO, T.A., 2010. Infiltração de água no solo em áreas cultivadas com cana-de-açúcar sob diferentes sistemas de colheita e modelos de ajustes de equações de infiltração. Eng. Agrícola 30, 1060–1070.

TUCCI, C.E.M., 2000a. Coeficiente de escoamento e vazão máxima de bacias urbanas. RBRH - Rev. Bras. Recur. Hídricos 5, 61–68.

VASCONCELOS, V.; HADDAD, R.M., 2013. Quantificação de componentes de vazão por meio de filtros recursivos: Estudo de caso para a Bacia do Rio Paracatu (SF-7), Brasil. Rev. do Inst. Geociências - USP.

ZHANG, M.; LIU N.; HARPER, R.; LI, QIANG; LIU, KUAN; WEI, XIAOHUA; NING, DINGYUAN; HOU, YIPING; LIU, SHIRONG. A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. Journal of Hydrology, Volume 546, March 2017, Pages 44-59 https://doi.org/10.1016/j.jhydrol.2016.12.040

ZUQUETTE, L.V., PALMAI, J.B., 2006. Avaliação da taxa de infiltração e escoamento superficial dos arenitos da formação Botucatu. Rev. Bras. Geociências 36, 49–60.

WANG, D. C; WANG, L. C.; CHENG, K. Y.; LIN, J. D. Benefit Analysis of Permeable Pavement on Sidewalks. International Journal of Pavement Research and Technology, Jhongli City, v. 3, n. 4, p. 207-215, 07 2010. http://www.ijprt.org.tw/files/sample/V3N4%286%29.pdf

WILKEN, P. S. (1978). Engenharia de drenagem superficial. São Pulo: CETES, 477p.