

Curve number estimation from Brazilian Cerrado rainfall and runoff data

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Abstract: The Curve Number (CN) method has been widely used to estimate runoff from rainfall events in Brazil; however, CN values for use in the Brazilian savanna (Cerrado) are poorly documented. In this study we used experimental plots to measure natural rainfall-driven rates of runoff under undisturbed Cerrado and under the main crops found in this region, and derive associated CN values from the measured data using five different statistical methods. Curve numbers obtained from the standard USDA Natural Resources Conservation Service (NRCS) table were suitable to estimate runoff for bare soil, soybeans (*Glycine max* [L.] Merr.), and sugarcane (*Saccharum* L.). However, CN values obtained from measured rainfall-runoff data (CN calibrated) provided better runoff estimates than the CN values from the standard table. The best CN values for the bare soil (hydrologic soil group B), soybeans, and sugarcane were 81.2 (78.5 to 83.9), 78.7 (75.9 to 81.5), and 70.2 (67.8 to 72.6). The CN method was not adequate to estimate runoff for the undisturbed Cerrado, bare soil (hydrologic soil group A), pasture, and millet (*Pennisetum glaucum*).

Key words: deforestation—hydrologic models—rainfall—runoff—savanna

The Brazilian Cerrado region provides an important role in water resources dynamics because it distributes fresh water for some of the most important Brazilian rivers. In addition, approximately one half of the outcrop area of the Guarani aquifer system, one of the largest aquifers worldwide, is located in this region (Lucas et al. 2015). Thus, the Cerrado has been considered one of the most important biomes for Brazilian water resources. However, vast areas of this biome have been converted into farmland, and there is little evidence that agricultural expansion will decrease, mainly because Brazil holds great potential for further agricultural expansion in the twenty-first century (Lapola et al. 2014). Some authors have reported variations in hydrological processes promoted by land cover and land use changes in the Cerrado (Costa et al. 2003; Coe et al. 2011; Loarie et al. 2011; Oliveira et al. 2014).

Many models have been developed to evaluate changes in hydrological processes. The Curve Number (CN) method developed in 1954 by the USDA Soil Conservation Service (SCS), currently the Natural Resources Conservation Service (USDA NRCS), is one of the methods most often used to estimate

direct surface runoff from a given rainfall event (Hawkins et al. 2009). Because of the simplicity, versatility, and availability of necessary data, this method has been quite popular within the United States and other countries (Ponce and Hawkins 1996; Sartori et al. 2011; Hawkins et al. 2009). Several hydrologic, soil erosion, and water quality models have used the CN method, such as Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel 1980), Simulator for Water Resources in Rural Basins (SWRRB) (Williams et al. 1985), Agricultural Nonpoint Source pollution model (AGNPS) (Young et al. 1989), Erosion Productivity Impact Calculator (EPIC) (Sharpley and Williams 1990), the soil and water assessment tool (SWAT) (Arnold et al. 1998), CN-based modeling of sediment yield (Mishra et al. 2006; Tyagi et al. 2008), and the CN method coupled with the Revised Universal Soil Loss Equation (RUSLE) model (Gao et al. 2012).

In the CN method, several different factors that affect surface runoff generation, such as soil type, land cover and land use, surface condition, and antecedent runoff condition are incorporated into a single CN parameter (Hawkins et al. 2009). Using data

from small watersheds in the United States, the USDA SCS developed a standard table of curve numbers. The CN values can be obtained by the standard table, however, the CN estimated by in situ data from plots or watersheds are preferable. Errors in the tabulated CN can result in large errors in surface runoff estimation (Hawkins et al. 2009; Soulis et al. 2009). Many authors have reported better runoff estimates from the in situ data than from using tabulated CN (Elhakeem and Papanicolaou 2009; Shi et al. 2009; Tedela et al. 2012; D'Asaro et al. 2014; Ajmal and Kim 2014; Lal et al. 2015).

Tabulated CN derived for rainfall-runoff data were originally computed from a graphical method, where annual runoff and rainfall volumes were plotted to obtain the curve that divides the plotted points into two equal groups, thus corresponding the median CN. In this methodology are considered only one peak flow events for each year (USDA NRCS 2004). Other methods for calculating the CN from rainfall-runoff data include the geometric mean (USDA NRCS 2004); arithmetic mean (Bonta 1997; Tedela et al. 2012); nonlinear, least squares fit (Hawkins 1993); standard asymptotic fit (Hawkins 1993); and lognormal frequency (Schneider and McCuen 2005). However, a consensus is lacking for which method is best or should be used as a standard for CN estimation. Most

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investigations use several methods to estimate the CN and then choose the best method for each condition (Tedela et al. 2012).

The CN method is the most widely used method in Brazil for runoff estimation, despite that the tabulated CN values have not been adapted for Brazilian conditions (Sartori et al. 2011). In addition, there are several sources of uncertainty in the use of the CN method for estimating surface runoff from regions with undisturbed cover (Tedela et al. 2012). Thus, the objectives of this study were to measure natural rainfall-driven rates of runoff under undisturbed Cerrado vegetation and under the main crops found in this region, and to derive associated CN values from the five more frequently used statistical methods. We also evaluated the use of the CN method to estimate runoff in this region and suggested CN values and ranges for the land covers studied.

Materials and Methods

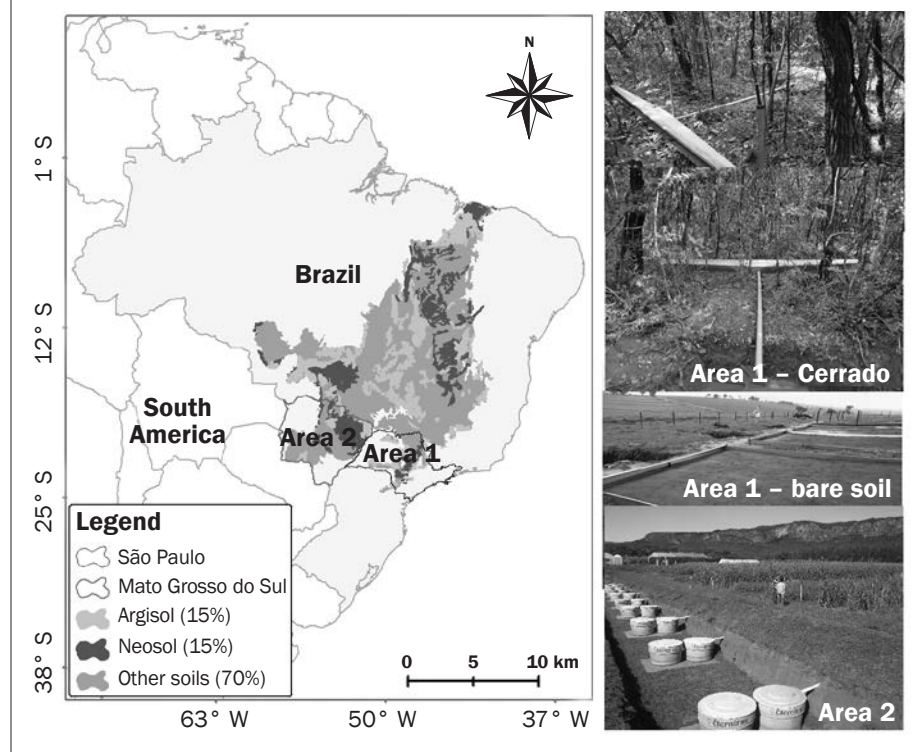
This study was conducted using data from two sites located in the Cerrado region, Instituto Arruda Botelho and UEMS-Aquidauana, referred to throughout the text as Area 1 and Area 2, respectively (figure 1). Table 1 shows a summary of the main characteristics of these sites.

Area 1. In Area 1, we measured runoff from six plots of 5×20 m or 100 m^2 (16.4×65.6 ft or $1,076 \text{ ft}^2$) with slope steepness of approximately 9%. We used three replications of undisturbed Cerrado and three with bare soil (Ortic Quartzarenic Neosol [RQo], hydrologic soil group A). The plots under Cerrado were installed in an area with approximately 300 ha (741.3 ac) of undisturbed Cerrado located in the municipality of Itirapina, São Paulo State.

The physiognomies of the Cerrado vary from grassland to savanna to forest. In study Area 1, the physiognomy was classified as "cerrado sensu stricto," which is also known as Cerrado woodland, and has a characteristic arborous cover of 50% to 70% and trees with heights of 5 to 8 m (16.4 to 26.25 ft) (Furley 1999). This area has been preserved and there are no records or indications of past fires. The absolute density (number of individuals per unit area) was $15,278 \text{ trees ha}^{-1}$ ($6,183 \text{ trees ac}^{-1}$), with a basal area (area occupied by the cross-section of tree's trunk at breast height) of approximately $27.55 \text{ m}^2 \text{ ha}^{-1}$ ($120 \text{ ft}^2 \text{ ac}^{-1}$) (equivalent to an average tree diameter under 4.5 cm [1.77 in]),

Figure 1

Location of study areas. Area 1 is made up of Cerrado and bare soil (hydrologic soil group A). Area 2 is made up of crops, pasture, and bare soil (hydrologic soil group B). The soil types studied (Argisol and Neosol) represent 30% of the Cerrado total area.



and Shannon diversity index of 4.03 (Reys 2008). The main vegetation species found in the study area were *Vochysia tucanorum*, *Miconia rubiginosa*, *Pterodon pubescens*, *Ocotea pulchella*, *Xylopia aromatica*, *Copaifera langsdorffii*, *Myrcia splendens*, *Bauhinia rufa*, *Virola sebifera*, and *Myrcia guianensis*. Details about the phenology of the study area can be found in Reys (2008) and Reys et al. (2013).

According to the Köppen climate classification, the climate in Area 1 is Cwa humid subtropical, with a dry winter (April to September) and hot and rainy summer (October to March). Convection is the main rainfall generating mechanism, promoting rainfall with high intensity in this region (Rao et al. 1996). To classify the hydrologic soil group of the CN method we collected samples of soils in different soil profile depths in areas under Cerrado and bare soil, and then performed analysis of soil texture, soil bulk density, and porosity. The soil in Area 1 was classified according to the Brazilian Soil Classification System (SiBCS) as RQo with sandy texture, and was considered to be in hydrologic soil group A (table 2).

Area 2. Area 2 is located in the municipality of Aquidauana, Mato Grosso Sul

State. In this area we used 10 plots of 3.5×22.15 m (77.5 m^2) with slope steepness of approximately 5%. We used two replications for pasture (*Brachiaria ruziziensis*), soybeans (*Glycine max*), millet (*Pennisetum glaucum*), sugarcane (*Saccharum spp*) and bare soil (Dystrophic Red Argisol [PVd], hydrologic soil group B). The climate in Area 2 is Aw humid tropical, subject to a dry winter (April to September) and hot and rainy summer (October to March). To classify the hydrologic soil group of the CN method we considered the soil characteristics reported by Schiavo et al. (2010) and the results of water infiltration into the soil using a rainfall simulator (Santos et al. 2014). Area 2 has a PVd, with the main difference being that PVd had less sand and greater clay content in the B horizon compared to RQo (Schiavo et al. 2010), which placed PVd in hydrologic soil group B (table 2).

Farming of Area 2 included pasture before 2009, March common bean (*Phaseolus vulgaris* L.) and September soybeans (*Glycine max* [L.] Merr.) in 2009, corn (*Zea mays* L.) in 2010, and millet and common bean in 2011, after which the area was fallow the remainder of 2011 and 2012. The bare soil

Table 1
Summary of characteristics of the study areas.

Description	Area 1	Area 2
Municipality and state	Itirapina, São Paulo	Aquidauana, Mato Grosso do Sul
Latitude and longitude	22° 10' S, 47° 52' W	20° 27' S, 55° 40' W
Elevation (m)	780	170
Köppen climate classification system	Cwa humid subtropical	Aw humid tropical
Average annual precipitation (mm)	1,500	1,200
Size plots	5 × 20 m (100 m ²)	3.5 × 22.15 m (77.5 m ²)
Total plots (n)	6	10
Slope steepness (%)	9	5
Period of monitoring	November of 2011 to July of 2014	November of 2012 to August of 2014
Number of rainfall-runoff events	85	91
Range of rainfall events (mm)	7.2 to 101.4	7.1 to 129.1
Average of rainfall events (mm)	25.1	30.5

plots in both sites (Areas 1 and 2) were maintained as continuous fallow. To do that, we used the disk harrow at the initiation of the study (before installing the plots with galvanized sheet metal). After the plot installation, we kept in continuous fallow by glyphosate application and manual tillage (using a hand hoe) (Oliveira et al. 2015a).

Observed Rainfall-Runoff Events. We used an automated tipping bucket rain gauge (model TB4) to measure rainfall depth at 10 minute intervals. Periods of rainfall were considered to be isolated events when they were separated by periods of precipitation between 0 (no rain) and 1 mm (0.04 in) for at least six hours (Wischmeier 1959). Surface runoff was collected in storage tanks at the end of each plot. Plots under crops and bare soil were built with two or three storage tanks depending on the land cover. Each storage tank had a 310 L (81.9 gal) capacity and one or two splitters of 1/7 (i.e., 1/7 was collected in the second tank and 1/49 in the third tank, depending on the site). In the plots under undisturbed Cerrado, only one storage tank with a capacity of 310 L for each plot was used to collect runoff because of the expected lower runoff amounts from those plots (Oliveira et al. 2015b). The capacities were found to be sufficient throughout the study.

We monitored plots with bare soil and under undisturbed Cerrado (Area 1) from November of 2011 to July of 2014 (85 rainfall-runoff events), and January of 2012 through July of 2014 (65 rainfall-runoff events), respectively. In Area 2, we monitored plots under pasture, soybeans, millet, sugarcane, and bare soil from November of 2012 through August of 2014 (78 and 91 rainfall-runoff events for pasture/crops and bare soil, respectively). The rainfall events

Table 2
Soil characteristics of the study areas.

Soil profile	Sand (g kg ⁻¹)	Silt (g kg ⁻¹)	Clay (g kg ⁻¹)	Hydrologic soil group (USDA NRCS 2004)
Area 1* (Cerrado, 0 to 30 cm)	839	34	127	A (high infiltration rate)
Area 1* (bare soil, 0 to 30 cm)	865	34	101	A (high infiltration rate)
Area 2† (0 to 24 cm)	770	110	120	B (moderate infiltration rate)
Area 2† (50 to 65 cm)	610	140	250	B (moderate infiltration rate)

*Ortic Quartzarenic Neosol (RQo).

†Dystrorphic Red Argisol (PVD).

assessed in Area 1 ranged from 7.2 to 101.4 mm, with an average of 25.1 mm. In Area 2, rainfall events ranged from 7.1 to 129.1 mm (0.28 to 5.08 in), with an average of 30.5 mm (1.2 in). The rainfall-runoff data used in this study may be found in the supplementary information (<https://sites.google.com/site/oliveirapts/publications>).

Estimation of Curve Number from Rainfall-Runoff Data. The CN method is based on the following water budget equation to estimate the storm runoff:

$$Q = P - Ia - F, \quad (1)$$

where Q is total runoff (mm); P is total rainfall (mm) ($P > Q$ and $P > Ia$); Ia is initial abstraction (mm); and F is the amount of surface retention (mm). The SCS premise is that the ratio of water retention to potential water retention is equal to the ratio of surface runoff to potential runoff (USDA 1986; Yu 1998):

$$\frac{Q}{P - Ia} = \frac{F}{S}, \text{ and} \quad (2)$$

$$Ia = \lambda S, \quad (3)$$

where S is potential maximum retention ($S > F$) (mm) and λ (dimensionless) is the initial abstraction ratio, equal to 0.2 according to USDA NRCS (2004). The runoff (Q) is estimated from the combination of the equations 1, 2, and 3 for $F = P - Q$.

$$Q = \frac{(P - Ia)^2}{(P - Ia + S)}, \text{ for } P > Ia, \text{ otherwise, } Q = 0. \quad (4)$$

We computed CN from the rainfall-runoff data from the following five more frequently used statistical methods: the median (USDA NRCS 2004); geometric mean (USDA NRCS 2004); arithmetic mean (Bonta 1997; Tedela et al. 2012); nonlinear, least squares fit (Hawkins 1993); and standard asymptotic fit (Hawkins 1993). For the median and arithmetic mean we computed the potential maximum retention and the CN using the rainfall-runoff measured from the plots according to the following equations (5 and 6), for S , Q , and P in mm (Hawkins 1993).

$$S = 5 \left(P + 2Q - \sqrt{4Q^2 + 5PQ} \right), \text{ and} \quad (5)$$

$$CN = \frac{25,400}{(S + 254)}. \quad (6)$$

These numbers were used to obtain the median and mean for each individual plot.

For the geometric mean, we first calculated the logarithm of the event maximum potential retention S derived using equation 5, $\log S$; determined the arithmetic mean of the series for each experimental plot, $\overline{\log S}$; and then calculated the geometric mean maximum potential retention, $10^{\overline{\log S}}$ (Tedela et al. 2012). Thus, the CN was computed as the following:

$$CN = \frac{100}{\left[1 + \frac{10^{\overline{\log S}}}{254}\right]} \quad (7)$$

We used the nonlinear, least squares fit method by minimizing the sum of squared differences between observed and CN-calculated runoff using equation 4 for each rainfall-runoff event for a given experimental plot. For this method, we used only large storms ($P > 25.4$ mm [1 in]) to avoid bias towards larger CN found with small rainfall events (Hawkins et al. 2009). Table 3 shows the fittings results for each plot.

For the standard asymptotic fit method, we first rank-ordered both the rainfall and runoff time series separately, matching them in pairs from a decreasing order, and then computing the CN values from equations 5 and 6 using the rank-matched pairs (Hawkins 1993). We evaluated the CN values according to three types of behavior identified by Hawkins (1993): standard, complacent, and violent. The standard behavior occurs when the CN values decrease with the total rainfall and tend to approach a near-constant CN (called CN_{∞}) with rainfall increase. This behavior is the most common observed in the literature (Hawkins et al. 2009). To evaluate the data for standard behavior, we used equation 8 (Hawkins 1993):

$$CN(P) = CN_{\infty} + (100 - CN_{\infty})e^{-kP} \quad (8)$$

where the estimated CN_{∞} is taken to be the reference CN and k is the fitting coefficient that describes the $CN(P)$ (CN as a function of precipitation, P) that approaches the asymptotic constant CN_{∞} .

To determine the fitting parameters of the methods, asymptotic and nonlinear least squares was used in the Microsoft Excel (Solver). Fitting statistics for each plot are shown in table 3.

For complacent behavior the calculated event CN decreases with event rainfall increase without approaching an apparent constant value, and the runoff is better described as linearly dependent on rainfall $Q = CP$, where C is the runoff coefficient. Thus, the CN cannot be determined from data that have this behavior because no constant value is clearly approached (Hawkins 1993).

Tabulated CN were obtained for each land cover studied according to cover type and cover description, hydrologic conditions (based on combination factors that affect infiltration and runoff), and hydrologic soil group (USDA NRCS 2004). For the undisturbed Cerrado we used the woodland cover type with good hydrologic condition. For the plots under pasture we used the cover type pasture with good hydrologic condition, and for the plots under soybeans we chose the small grain cover with straight rows and good hydrologic condition. For the plots under sugarcane (limited cover, straight row) and millet (partial cover, straight row) we used CN obtained from Cooley and Lane (1982) for Hawaii that were recommended for use by the USDA (USDA NRCS 2004; Sartori et al. 2011).

It is important to make clear that there are three antecedent runoff conditions (ARC), I, II, and III, which provide a measure of the runoff variation expected for a specific rain from all remaining unexplained sources, including soil moisture status. ARC I and III represent the runoff distribution limits for a given CN, and II is the central trend (Sartori et al. 2011). Therefore, reference CN values reported in the standard table and in the present study are assumed to be ARC II.

Uncertainties and Statistical Analyses. We assessed uncertainties in CN estimates for each method. For the median, we used the range of CN determinate from each rainfall-runoff event. For geometric and arithmetic mean methods we used the standard deviation computed from all CN values estimated. For nonlinear least squares fit and asymptotic CN, we computed the standard error (SE) using values of runoff observed (Q_i), and runoff computed (Q_{ci}) from the CN obtained by each method and the number of observations of rainfall-runoff (n) as the following equation:

$$SE = \sqrt{\frac{\sum_{i=1}^n (Q_i - Q_{ci})^2}{n}} \quad (9)$$

We evaluated the computed runoff obtained from each method with observed runoff values using the mean bias (difference between observed and estimated runoff), coefficient of determination (R^2), and the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe 1970), equation (10):

$$NSE = 1 - \frac{\sum_{i=1}^n (Q_i - Q_{ci})^2}{\sum_{i=1}^n (Q_i - \bar{Q})^2} \quad (10)$$

We used the Student's t -test with a 95% confidence level in order to evaluate the significance of the linear correlation between the runoff observed and estimated. Furthermore, we used one-way ANOVA with a Tukey post hoc test at the 95% confidence level to assess if there were significant differences between the mean observed and estimated runoff from all methods studied.

Results and Discussion

CN values for plots under undisturbed Cerrado ranged from 49.3 (nonlinear, least squares fit) to 73.9 (median) (table 4). For the crop-covered plots we found the smallest CN for pasture (45.2 by the nonlinear least squares) and the greatest for soybeans (85.5 by the geometric mean) and for sugarcane (79.6 by the geometric mean) (table 4). Plots with bare soil in Area 1 (RQo, hydrologic soil group A) had smaller CN than plots with bare soil in Area 2 (PVd, hydrologic soil group B). This was expected because, despite the large sand concentration in the upper profile of the PVd, the clay in the B horizon promoted faster soil saturation and more surface runoff than did the RQo.

We noted greater ranges of CN values in the plots under Cerrado, pasture, and crops than the plots with bare soil (table 4). This occurred mainly due to changes in vegetation cover and the soil surface cover during the year that tended to cause differing responses on the interception and soil surface roughness. In undisturbed Cerrado, the leaf-drop late in the fall season promoted a good soil cover for the following seasons of winter and spring, thus facilitating increased water retention (Oliveira et al. 2015a). Furthermore, in undisturbed areas the leaf litter and the more porous soil tended to cause an increase of infiltration and water storage, rather than rapid overland flow (McCulloch and Robinson 1993). On pastures the soil cover tends to change with the wet and dry

Table 3
Fitting statistics for asymptotic and nonlinear least squares methods.

Plot	Asymptotic					Nonlinear least squares			
	Sample size	CN _∞	k (mm ⁻¹)	R ²	SE (CN)	Sample size	CN	R ²	SE (mm)
Cerrado 1*	64	35.3	0.025	0.997	0.65	23	49.3	0.045	2.2
Cerrado 2*	64	35.3	0.026	0.996	0.80	23	49.4	0.070	2.2
Cerrado 3*	64	31.0	0.020	0.998	0.44	23	49.3	0.020	2.1
Bare soil 1*	81	73.3	0.043	0.613	3.22	27	63.4	0.111	8.3
Bare soil 2*	81	73.8	0.039	0.565	3.45	28	65.5	0.178	9.2
Bare soil 3*	81	64.7	0.031	0.831	2.77	26	65.9	0.133	7.2
Bare soil 1†	91	81.2	0.045	0.579	2.67	40	79.3	0.563	18.1
Bare soil 2†	91	81.3	0.047	0.606	2.53	40	79.1	0.585	17.5
Soybeans1†	78	78.7	0.078	0.557	2.78	33	70.7	0.242	27.2
Soybeans 2†	78	79.0	0.090	0.629	2.29	33	69.2	0.144	14.6
Millet 1†	78	56.3	0.041	0.977	1.52	33	51.2	0.079	7.3
Millet 2†	78	56.9	0.041	0.968	1.80	33	53.6	0.119	8.5
Pasture 1†	78	45.4	0.029	0.998	0.86	33	45.2	0.003	3.1
Pasture 2†	78	47.1	0.031	0.994	1.09	33	46.7	0.033	3.9
Sugarcane 1†	78	67.7	0.065	0.916	2.08	33	63.2	0.152	13.4
Sugarcane 2†	78	70.2	0.075	0.853	2.38	33	65.9	0.241	12.7

Notes: CN_∞ and k are fitted from the asymptotic equation (equation 8). CN is the curve number corresponding to the least squares fitting for S in equation 5. R² is the coefficient of determination computed using observed and computed values of CN (for the Asymptotic method) and runoff (for the nonlinear least squares method), respectively. SE is the standard error (equation 9). R² and SE are used to evaluate the fit obtained in each method.

*Area 1.

†Area 2.

seasons and density of livestock. For the plots under crops, changes in vegetation cover and the soil surface cover occur during the agricultural cycle (tillage to harvest). Sartori et al. (2011) found CN values for sugarcane ranging from to 44.2 (full cover, near the harvest period) to 87.1 (bare soil), which are consistent with our findings (table 4).

We found complacent behavior in the plots under undisturbed Cerrado (i.e., no constant value was clearly approached [figure 2]), and thus no satisfactory CN were determined (Hawkins 1993). Runoff coefficients (total runoff divided by total rainfall) for the Cerrado were small, ranging from 0.001 to 0.030, with an average of 0.005. In complacent behavior the runoff coefficients usually range from 0.005 to 0.05 (Hawkins et al. 2009). Therefore, in these cases the CN is inappropriate and the runoff is more aptly modeled by the equation $Q = CP$, where C is the runoff coefficient. However, it is important to make clear that for a longer time series (larger and extreme rainfall-runoff events) some of the complacent plots might show standard or violent behavior.

The average runoff coefficients for the plots with bare soil (hydrologic soil groups A and B) and under soybeans, sugarcane, millet, and pasture (hydrologic soil group B) were

0.173, 0.281, 0.185, 0.087, 0.040, and 0.020, respectively. The runoff coefficient was greater for the soybeans (hydrologic soil group B) than for the bare soil (hydrologic soil group A) because of the hydrologic soil group difference. For the plots with bare soil and under crops we noted that the CN values decreased with the total rainfall, tending to approach a near-constant CN with rainfall increase, which was the standard behavior (figure 3).

The standard asymptotic fit and nonlinear least squares methods presented similar CN values, and in general, were less than those in the standard table. On the other hand, central tendency methods (median and geometric and arithmetic means) produced values greater than those in the standard table (figure 4). Also, we found that the differences between computed and tabulated tended to increase for smaller values of CN (table 4 and figure 4). Previous studies also have reported that the central tendency methods tend to produce greater CN than do the standard asymptotic fit and the USDA NRCS tabulated values (Stewart et al. 2012; D'Asaro et al. 2014; Lal et al. 2015).

We compared the surface runoff estimated using the CN values presented in table 4 with observed runoff and we found negative values of NSE for the plots under undis-

turbed Cerrado, bare soil (hydrologic soil group A), pasture, and millet. Negative NSE values indicate poor fit between measured and predicted values, such that the average of the measured values is a better predictor of runoff than are the model predicted values. Therefore, our results suggested that the CN method was not suitable to estimate runoff under these land covers. In general, for these land cover types the modeled runoff overestimated the small observed runoff, particularly for the Cerrado, pasture, and millet. For the bare soil (hydrologic soil group A), our results indicated that the amount of rainfall was not the main factor controlling surface runoff generation. The intense rainfall events and periods with several consecutive rainfall events, which promote high soil moisture contents, may have had more influence on the runoff process. For example, a large rain (73.8 mm [2.9 in]) that occurred in the dry season promoted less runoff (13.7 mm [0.54 in]) than a smaller rain event in the wet season (27.4 mm [1.08 in], 19.7 mm [0.78 in], rain and runoff, respectively) (see supplementary information at <https://sites.google.com/site/oliveirapts/publications>).

Table 5 shows the mean bias, coefficient of determination (R²), and NSE only for the plots with positive NSE and significant cor-

relations ($p < 0.05$) between observed and estimated runoff. The central tendency methods (median and geometric and arithmetic means) overestimated (negative bias) the surface runoff for all plots, whereas asymptotic and nonlinear least squares underestimated runoff (positive bias). We found that the values of R^2 and NSE were similar between the methods studied; however, the standard asymptotic fit showed better values for all cover types (table 5).

We computed the mean of observed and estimated runoff for the plots presented in table 5. The Tukey multiple comparison tests indicated that the means of estimated runoff for all methods were not significantly different ($p > 0.05$) from the observed runoff except for the case of the nonlinear, least squares fit in the plot with bare soil (hydrologic soil group B) (figure 5). This method underestimated the mean observed runoff by 35%. Our results also showed that there was not a significant difference between the mean runoff estimated by the central tendency methods (median and geometric and arithmetic means) (figure 5). In a choice between these central tendency methods, Tedela et al. (2012) reported that the geometric mean was the better choice. This was due to the calculation of the 95% or 90% confidence intervals that allow for a probabilistic definition of the uncertainty observed in event CN.

There was a significant correlation ($r = 0.43$, $p < 0.001$) between rainfall depth and observed runoff in the Cerrado. However, the largest runoff values were found for more intense rainfall events, or in periods with several consecutive rainfall events. This may indicate that other Cerrado hydrological factors, such as interception of rain by trees or by the forest floor litter, may have a major influence on runoff. Rainfall events of high intensity and short duration result in less interception than do low intensity, long duration events; and if rainfall is not continuous, even for short periods during an event, greater values of interception result (Crockford and Richardson 2000). Some authors have also shown that the soil macroporosity has a strong influence on runoff generation processes and is greater in undisturbed forest than for crops, pasture, and bare soil (Shougrakpam et al. 2010; Beven and Germann 2013). Furthermore, there were changes in the canopy, forest floor, and soil moisture during the year generated mainly

Figure 2

Complacent behavior for plots under undisturbed Cerrado using rank-ordered rainfall and runoff. Figures (a), (b), and (c) refer to plots 1, 2, and 3, respectively. The CN₀ (dashed line) is the threshold under which no runoff is projected to occur ($P = 0.25$) and was computed by equation $CN_0 = 2,540 / [25.4 + (P / 2)]$, for P in millimeters. CN = curve number.

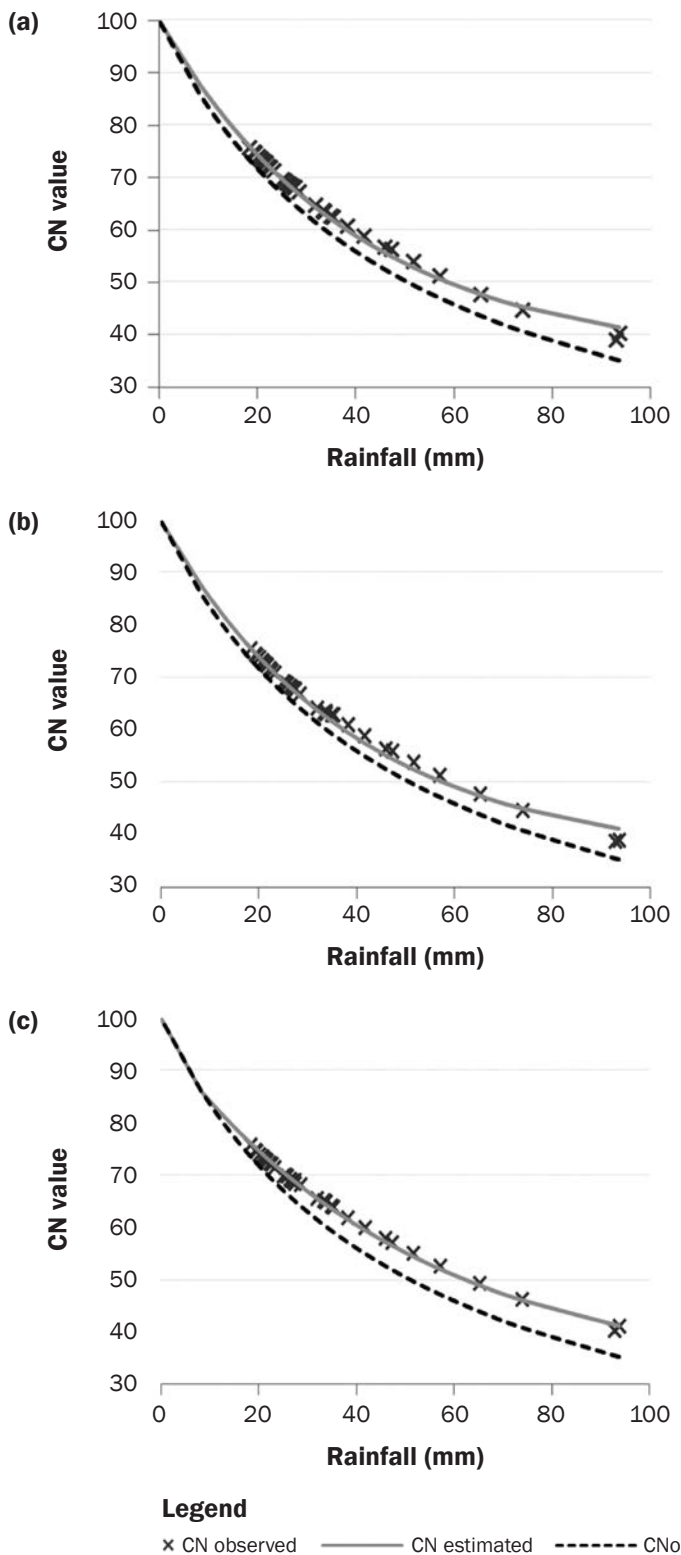


Figure 3

Standard behavior in plots under bare soil and croplands using rank-ordered rainfall and runoff: (a) bare soil—hydrologic soil group A; (b) bare soil—hydrologic soil group B; (c) soybeans; (d) sugarcane; (e) millet; and (f) pasture. The CNo (dashed line) is the threshold under which no runoff is projected to occur ($P = 0.25$) and was computed by the equation $CNo = 2,540 / [25.4 + (P / 2)]$, for P in millimeters. CN = curve number.

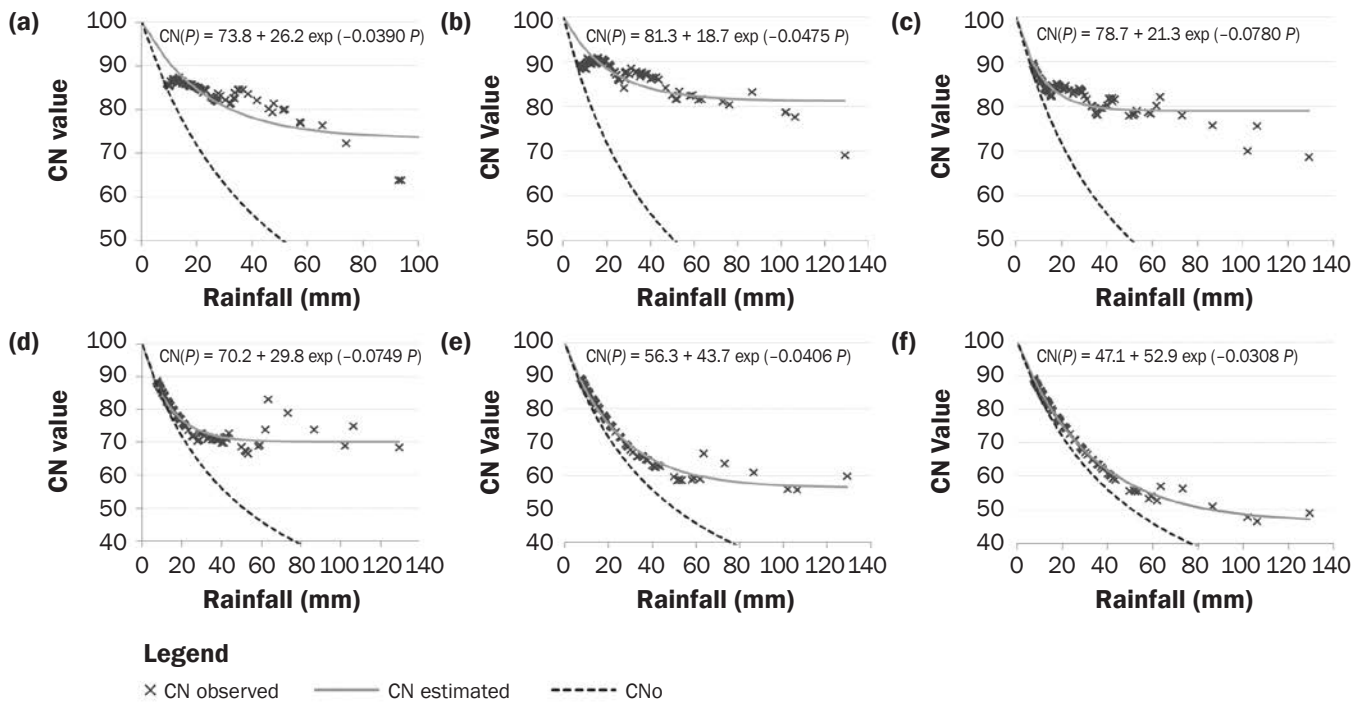


Table 4

Tabulated and estimated curve numbers (and uncertainty ranges) from this study in the Brazilian Cerrado.

Land cover	NRCS table	Median	Geometric mean	Arithmetic mean	Nonlinear least squares	Asymptotic
Cerrado 1*	30	73.9 (37.6 to 89.1)	73.1 (59.9 to 83.1)	71.7 (59.7 to 83.8)	49.3 (47.1 to 51.5)	—
Cerrado 2*	30	73.3 (37.4 to 89.3)	72.7 (59.5 to 82.9)	71.4 (59.3 to 83.4)	49.4 (47.1 to 51.6)	—
Cerrado 3*	30	73.7 (38.4 to 89.3)	73.3 (60.4 to 83.2)	72.0 (60.2 to 83.7)	49.3 (47.2 to 51.5)	—
Bare soil 1*	77	85.7 (52.6 to 99.6)	86.9 (72.9 to 94.2)	84.2 (74.5 to 93.9)	63.4 (61.3 to 63.4)	73.3 (70.1 to 76.6)
Bare soil 2*	77	86.9 (52.6 to 95.8)	86.8 (76.0 to 93.1)	84.7 (75.2 to 94.1)	65.5 (63.4 to 67.7)	73.8 (70.4 to 77.3)
Bare soil 3*	77	85.0 (52.7 to 95.8)	85.0 (74.2 to 91.7)	83.1 (73.5 to 92.6)	65.9 (63.8 to 68.0)	64.7 (62.0 to 67.5)
Bare soil 1†	86	89.3 (61.8 to 98.2)	89.1 (79.1 to 94.6)	86.9 (78.5 to 95.3)	79.3 (77.9 to 80.7)	81.2 (78.5 to 83.9)
Bare soil 2†	86	88.2 (62.3 to 98.2)	88.9 (78.5 to 94.6)	86.7 (78.1 to 95.3)	79.1 (77.6 to 80.5)	81.3 (78.8 to 83.8)
Soybeans1†	75	83.4 (43.8 to 98.7)	85.5 (70.7 to 93.5)	82.4 (71.2 to 93.7)	70.7 (68.4 to 72.9)	78.7 (75.9 to 81.5)
Soybeans 2†	75	83.8 (38.5 to 98.2)	85.1 (70.0 to 93.4)	82.1 (70.4 to 93.7)	69.2 (66.8 to 71.6)	79.0 (76.7 to 81.3)
Millet 1†	69	76.8 (33.5 to 89.7)	75.9 (61.9 to 85.8)	74.1 (61.6 to 86.6)	51.2 (49.3 to 53.0)	56.3 (54.8 to 57.8)
Millet 2†	69	76.8 (34.7 to 89.7)	75.9 (62.2 to 85.8)	74.2 (61.8 to 86.6)	53.6 (51.7 to 55.5)	56.9 (55.1 to 58.7)
Pasture 1†	61	75.7 (32.8 to 90.5)	73.7 (58.4 to 84.8)	71.8 (58.2 to 85.4)	45.2 (43.5 to 47.0)	45.4 (44.5 to 46.2)
Pasture 2†	61	75.6 (32.8 to 89.7)	73.9 (59.3 to 84.6)	72.1 (59.1 to 85.2)	46.7 (45.0 to 48.4)	47.1 (46.0 to 48.2)
Sugarcane 1†	78	79.1 (33.0 to 96.2)	78.8 (63.1 to 89.0)	76.3 (63.2 to 89.4)	63.2 (60.8 to 65.6)	67.7 (65.6 to 69.8)
Sugarcane 2†	78	79.3 (33.7 to 98.2)	79.6 (63.3 to 89.8)	76.9 (63.9 to 89.9)	65.9 (63.6 to 68.3)	70.2 (67.8 to 72.6)

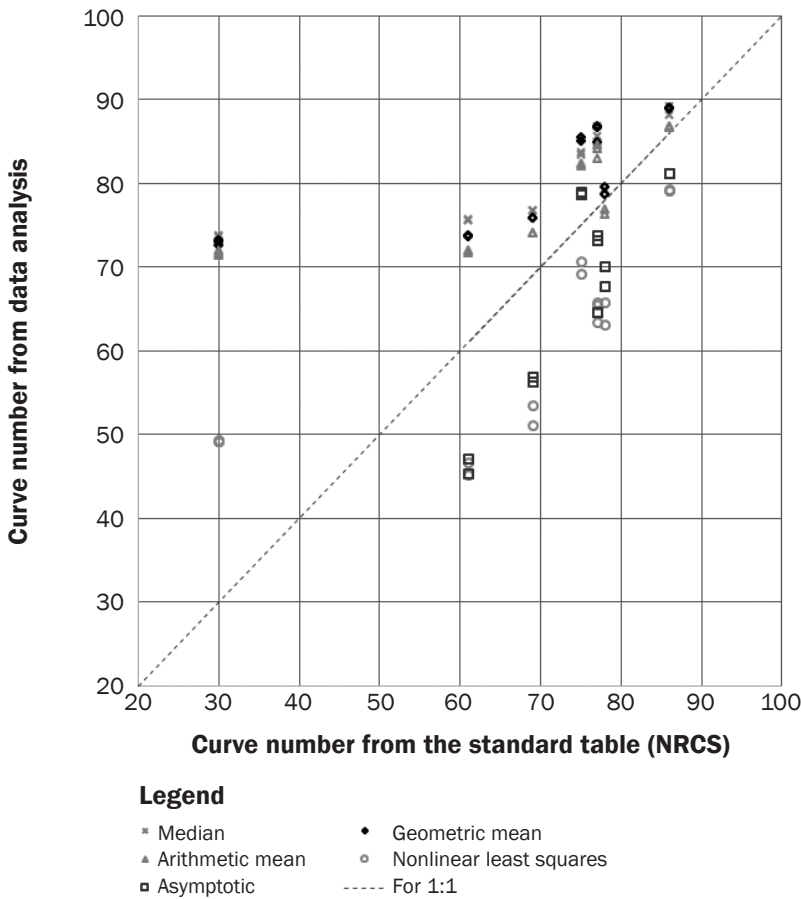
Notes: NRCS = USDA Natural Resources Conservation Service. No data in the Asymptotic column is due to complacent behavior (i.e., curve number could not be determined from data because no constant value was clearly approached). Uncertainties were defined for each method in the "uncertainties and statistical analyses" section.

*Area 1.

† Area 2.

Figure 4

Comparisons between computed curve numbers (CN) from different methods and tabulated CN.



the SCS-CN method under native Cerrado vegetation, it is necessary to take into account these interception processes, particularly by the forest floor litter. This implies that the initial abstraction ratio (λ) may be different than 0.2, which was suggested by the USDA NRCS (2004), because the initial abstraction consists mainly of interception, infiltration during early stages of the storm, and surface depression storage (USDA NRCS 2004). Therefore, future studies should investigate the runoff generation in the Cerrado using the complete hydrograph or using rainfall simulators to estimate appropriate values for the initial abstraction ratio.

We found that CN obtained from the standard table values were not adequate to estimate runoff for the undisturbed Cerrado. Tedela et al. (2012) also concluded that tabulated CN did not accurately estimate runoff in a forest in the United States. However, the standard table and other CN methods presented reasonable results for bare soil and croplands (tables 4 and 5). The best CN values for the bare soil (hydrologic soil group B), soybeans, and sugarcane, taking into account the greatest R^2 and NSE, were 81.2 (78.5 to 83.9), 78.7 (75.9 to 81.5), and 70.2 (67.8 to 72.6), respectively. These results could be useful to evaluate the hydrological process changes caused by land use and land cover changes in the Cerrado (Oliveira et al. 2014).

by the weather and the vegetation dynamics that also tended to produce different responses on runoff response (Giambelluca et al. 2009; Oliveira et al. 2015a).

On undisturbed Cerrado, precisely measured canopy interception ranged from 4% to 20% of gross rainfall, and measured stem-flow values were generally less than 1% of

the gross precipitation (Oliveira et al. 2015b). Retention by forest floor litter has not yet been evaluated for the Cerrado. Many authors have concluded that forest floor properties are key factors in controlling soil hydrological processes (Molina et al. 2007; Keith et al. 2010; Neris et al. 2013). To obtain satisfactory results in predicting runoff using

Summary and Conclusions

In this study we undertook a first approach to quantify surface runoff and estimate CN for the undisturbed Cerrado and for the main crops found in this region. We measured natural rainfall-driven rates of runoff under undisturbed Cerrado and bare soil (hydrologic soil group A) using three repli-

Table 5

Evaluation of the computed runoff obtained from each method with observed runoff values.

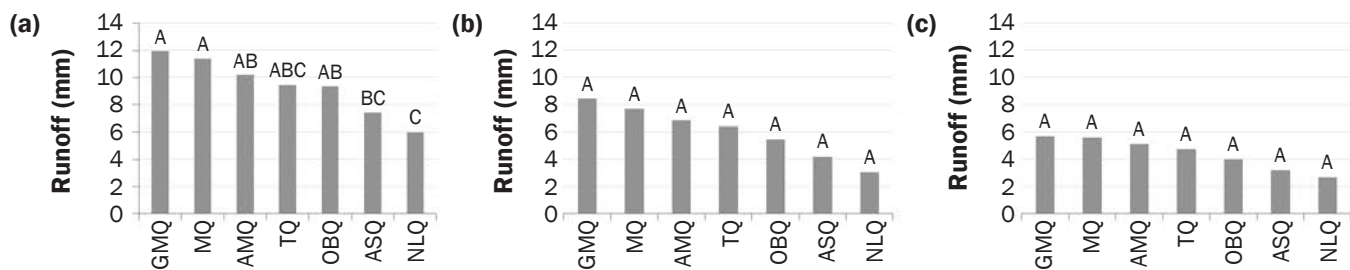
Land cover	Tabulated			Median			Geometric mean			Arithmetic mean			Nonlinear least squares			Asymptotic		
	Bias	R^2	NSE	Bias	R^2	NSE	Bias	R^2	NSE	Bias	R^2	NSE	Bias	R^2	NSE	Bias	R^2	NSE
Bare soil 1*	-0.10	0.72	0.55	-2.60	0.73	0.34	-2.40	0.73	0.36	-0.70	0.72	0.51	3.60	0.70	0.58	2.80	0.71	0.61
Bare soil 2*	-0.01	0.66	0.41	-2.00	0.67	0.27	-2.60	0.67	0.21	-0.80	0.66	0.38	3.40	0.64	0.51	2.40	0.65	0.52
Soybeans 1	2.30	0.57	0.51	-1.00	0.58	0.34	-2.30	0.57	0.18	-0.50	0.58	0.39	3.20	0.55	0.44	5.40	0.58	0.50
Soybeans 2	2.20	0.49	0.42	-1.30	0.51	0.21	-2.10	0.51	0.12	-0.40	0.51	0.31	3.40	0.44	0.33	0.90	0.50	0.40
Sugarcane 1	-1.60	0.45	0.31	-2.00	0.45	0.25	-1.90	0.45	0.27	-1.00	0.46	0.37	1.00	0.39	0.35	0.70	0.44	0.43
Sugarcane 2	-1.10	0.59	0.52	-1.60	0.58	0.47	-1.70	0.58	0.45	-0.70	0.59	0.55	1.30	0.58	0.50	0.80	0.60	0.58

Notes: Bias = mean of the difference between observed and estimated runoff. NSE = Nash-Sutcliffe Efficiency. R^2 = coefficient of determination.

*Dystrophic Red Argisol, hydrologic soil group B.

Figure 5

The ranked means of observed and computed runoff for (a) bare soil—hydrologic soil group B, (b) soybeans, and (c) sugarcane from the Tukey means test to $\alpha = 95\%$ for the geometric mean curve number (GMQ), median curve number (MQ), arithmetic mean curve number (AMQ), tabulated curve number (TQ), observed runoff (OBQ), asymptotic curve number (ASQ), and nonlinear-least-squares-fit curve number (NLQ). Mean runoff with the same letter are not significantly different from each other ($p > 0.05$) as tested with ANOVA followed by Tukey post hoc test at the 95% confidence values.



cated plots of 5×20 m (16.4×65.6 ft) for each treatment, and from 10 plots of 3.5×22.15 m (11.5×72.67 ft), with two replications for pasture, soybeans, millet, sugarcane, and bare soil (hydrologic soil group B). We monitored these plots between November of 2011 and August of 2014.

Our results indicated that the CN method was not adequate to estimate runoff for the undisturbed Cerrado, bare soil (hydrologic soil group A), pasture, and millet. Therefore, in these cases the CN is inappropriate and the runoff is more aptly modeled by the equation $Q = CP$, where C is the runoff coefficient.

The central tendency methods (median and geometric and arithmetic means) gave higher CN than the standard asymptotic fit, nonlinear, least squares fit, and the standard table. These higher CN resulted in an over-estimation of the estimated runoff for all plots, whereas asymptotic and nonlinear least squares underestimated runoff. However, the standard asymptotic fit showed better results for runoff estimation for bare soil, soybeans, and sugarcane than the other studied methods.

CN obtained from the standard table were suitable to estimate runoff for bare soil, soybeans, and sugarcane. However, CN values obtained from rainfall-runoff data (CN calibrated) provide better runoff estimates than the CN values from the standard table. In addition, we found that there were not significant differences between the mean runoff values estimated by the central tendency methods (median and geometric and arithmetic means).

The best CN values for the bare soil (hydrologic soil group B), soybeans, and sugarcane were 81.2 (78.5 to 83.9), 78.7 (75.9 to 81.5), and 70.2 (67.8 to 72.6), respectively. These CN values and ranges provide guidance for application of the CN

technique in ungauged watersheds, and to evaluate the CN calibration in other similar regions. Furthermore, our results provide benchmark values that could be useful to evaluate past and future land use changes using hydrologic models and measurements in the Cerrado region. It is important to make clear that there is still much work to be done in the Cerrado region in order to find adequate CN values for all of the different land covers and land uses. This study contributes toward that goal.

Acknowledgements

This study was supported by grants from the Fundação de Amparo à Pesquisa do Estado de São Paulo - FAPESP (10/18788-5, 11/14273-3, 12/03764-9 and 15/05134-0) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq (470846/2011-9). The authors are grateful to the Arruda Botelho Institute (IAB) and São José farm that have allowed us to develop this study in the undisturbed Cerrado. USDA is an equal opportunity provider and employer. Finally, we appreciate valuable comments and careful reviews from editor and the anonymous reviewers who helped to improve this manuscript.

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