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Identifying hydrological responses of micro-catchments under contrasting land use in the Brazilian Cerrado

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Abstract

In recent decades, the Brazilian Cerrado biome has been affected by intense land-use change, particularly the conversion of natural forest to agricultural land. Understanding the environmental impacts of this land-use change on landscape hydrological dynamics is one of the main challenges in the Amazon agricultural frontier, where part of the Brazilian Cerrado biome is located and where most of the deforestation has occurred. This study uses empirical data from field measurements to characterize controls on hydrological processes from three first-order micro-catchments $< 1\,\text{km}^2$ in the Cerrado biome. These micro-catchments were selected on the basis of predominant land use including native cerrado vegetation, pasture grass with cattle ranching, and cash crop land. We continuously monitored precipitation, streamflow, soil moisture, and meteorological variables from October 2012 to September 2014. Additionally, we determined the physical and hydraulic properties of the soils, and conducted topographic surveys. We used these data to quantify the water balance components of the study catchments and to relate these water fluxes to land use, catchment physiographic parameters, and soil hydrophysical properties. The results of this study show that runoff coefficients were 0.27, 0.40, and 0.16 for the cerrado, pasture, and cropland catchments, respectively. Baseflow is shown to play a significant role in streamflow generation in the three study catchments, with baseflow index values of more than 0.95. The results also show that evapotranspiration was highest in the cerrado ($986\,\text{mm}\,\text{yr}^{-1}$) compared to the cropland ($828\,\text{mm}\,\text{yr}^{-1}$) and the pasture ($532\,\text{mm}\,\text{yr}^{-1}$). However, discharges in the cropland catchment were unexpectedly lower than that of the cerrado catchment. The normalized discharge was 55 % higher and 57 % lower in the pasture and cropland catchments, respectively, compared with the cerrado catchment. We attribute this finding to the differences in soil type and topographic characteristics, and low-till farming techniques in the cropland catchment, additionally to the buffering effect of the gallery forests in these catchments. Although the results of this study provide a useful assessment of catchment rainfall–runoff controls in the Brazilian Cerrado landscape, further

research is required to include quantification of the influence of the gallery forests on both hydrological and hydrochemical fluxes, which are important for watershed management and ecosystem services provisioning.

1 Introduction

Despite accounting for nearly half of all tropical forests and approximately 6 % of the Earth's land surface, tropical dry forests are underrepresented in published reports on tropical forest research (Sánchez-Azofeifa et al., 2005; Santos et al., 2011; Farrick and Branfireun, 2013). Further, tropical dry forests are recognized as one of the world's most endangered terrestrial ecosystems, as they are threatened by deforestation and climate change impacts (Miles et al., 2006).

Wohl et al. (2012) stated that the available empirical data for tropical forests are insufficient for adequate model parameterization, which includes an understanding of the effects of deforestation on evapotranspiration and runoff ratios. Therefore, they recommended increased efforts to quantify human influence on all aspects of tropical hydrology, with focuses on field-based characterizations and catchment processes. Farrick and Branfireun (2013) supported their conclusion, adding that standard hydrological metrics such as runoff coefficients also lack comprehensive characterization in tropical dry forests.

The Cerrado ecosystem, also called the Brazilian savanna, is South America's largest tropical dry forest and second-most extensive biome. Although public interest in Brazilian deforestation has focused on the Amazon rainforest, most of the deforestation has occurred in the savanna environments in the surrounding areas of the Amazon biome known as the Amazonian agricultural frontier. Of the original 2 million km^2 of cerrado vegetation that existed in Brazil before 1940, approximately 80 % was converted to agricultural crops or pastures during the past four decades (Cavalcanti and Joly, 2002; Klink and Machado, 2005; Sano et al., 2008; Lapola et al., 2014). Indeed, the rapid rise of Brazil as the world's second-highest soybean producer and leading soybean exporter has relied on the clearing of large areas of cerrado vegetation spurred by global demand, agronomic technologies, and supportive government policies (Warnken, 1999; Fearnside, 2001; Mueller, 2005).

It is widely known that the removal of forest cover associated with the cropland expansion shifts water balances by reducing evapotranspiration and increasing streamflow (Bonell, 2005; Brown et al., 2005; Neill et al., 2013). Studies evaluating the impacts of land-use change on hydrological processes in the Amazon are relatively common (Williams and Melack, 1997; Neill et al., 2001; Ballester et al., 2003; Germer et al., 2009; Figueiredo et al., 2010; Richey et al., 2011). However, assessments of the environmental impacts of the Cerrado conversion into commercial agropastoral landscapes are scarce (Jepson et al., 2009; Hunke et al., 2014) despite its importance in maintaining environmental equilibrium within the Cerrado and the surrounding areas of other biomes in Brazil such as Amazonia and Pantanal (Alho, 2012). Although studies such as those by Klink and Moreira (2002), Costa et al. (2003), and Guzha et al. (2013) show that land-cover change in the Brazilian Cerrado alters the water balance, these studies are based mostly on low-resolution datasets. Oliveira et al. (2015) stated that the Brazilian Cerrado is one of the lesser-studied regions regarding the effects of land-use changes on water balance components. Furthermore, the scarcity of weather and discharge data, and information on vegetation, soil and geological characteristics are major limitations for reliable quantification of these land-use change effects. Considering this within the context of an area under massive environmental change, the aforementioned facts become even more crucial.

In fact, the few hydrological characterizations of the Cerrado are often limited to either grey or Brazilian academic literature, which is difficult to access. Evapotranspiration has been the water balance component most studied (da Rocha et al., 2009; Giambelluca et al., 2009). In more recent studies, the emphasis has been on using remote sensing techniques to establish a better understanding of evapotranspiration in large areas of the Brazilian Cerrado (Lathuillière et al., 2012; Scherer-Warren, 2012; Scherer-Warren and Rodrigues, 2013; Oliveira et al., 2014; Ataíde and Baptista, 2015).

However, due to inconsistent field information, these studies have limitations on scale validation and are thus often associated with high uncertainty. Furthermore, other water balance components such as rainfall interception, surface runoff, infiltration, and groundwater recharge are poorly understood (Oliveira et al., 2015).

Approximately 5 % of the Cerrado biome area is occupied by evergreen riparian forest vegetation known as gallery forests (Felfili, 2001). These forests are a typical vegetation formation along rivers in the Brazilian Cerrado (Hoffmann et al., 2005), and they are known for reducing erosion and silting of streams and contributing to the maintenance of the quality of the water resources (Felfili, 1994; Silva Júnior et al., 1996; Parron et al., 2011). Although these gallery forests are environmentally protected zones as legislated in the Brazilian Forest Code, there is no quantitative data to show their direct impacts on watershed discharge dynamics.

An additional factor affecting the hydrological responses to land cover changes is spatial scale. Oliveira et al. (2014) determined that studies at various spatial scales in the Brazilian Cerrado may lead to different outcomes, and Jepson (2005) stated that additional microscale studies are required to more effectively measure human impact in this biome. Studies at the microscale catchment level can integrate several processes in changing landscapes (Campbell et al., 2004) and can be used to assess the influence of landscape fragmentation such as gallery forests on environmental processes, which might not be apparent in mesoscale and macroscale analyses. Due to the lack of data with high temporal and spatial resolution for this region of Brazil, macroscale analyses are often the only alternative. Our study focuses on small headwater catchments because they are the origins of larger rivers, and, as outlined by Guzha et al. (2015), hydrological signatures exhibited in these catchments can provide useful indicators of environmental changes in larger areas.

This study aims to improve our understanding of hydrological processes in active deforestation zones along the Amazonian agricultural frontier in Brazil, through quantification of water balance components in headwater catchments. We focus on the Brazilian Cerrado because in addition to being an important ecological and agricultural region of

Brazil, the Cerrado biome is important for water provisioning services in this country. It encompasses portions of most of the Brazil's hydrographic regions, and the largest hydroelectric plants providing 80 % of the electricity in Brazil are on rivers in the Cerrado (GEO Brazil, 2007; Oliveira, 2014).

The results presented in this paper are part of a collaborative research project (www.carbiocial.de) that aims to investigate viable carbon-optimized land management strategies for maintaining ecosystem services under changing land use and climate conditions in the Southern Amazon. Our study focuses on three micro-catchments in the Cerrado biome under contrasting land use: cerrado sensu stricto, grass pasture for cattle ranching, and crop rotation with soybean and maize. In the pasture and cropland catchments, the original cerrado vegetation has been removed for intensive cattle and cash crop farming since the 1980s.

The main hypothesis offered in this study is that conversion of cerrado vegetation to pastures and cropland changes the soil hydrophysical properties and rainfall–runoff processes, consequently leading to increased streamflow and peak discharges and reduced infiltration rates and groundwater recharge. We investigate this by means of water balance quantification, and analyses of the hydrological feedbacks and catchments' characteristics and responses.

Through this study, we aim to identify the main hydrological responses in these contrasting catchments and answer the following questions:

i. Does cerrado conversion lead to deterioration of soil hydrophysical properties with consequences on the water balance components?

ii. How do the different land-use types affect the hydrological responses in small catchments?

2 Methods

2.1 Study area description

This study was conducted in the municipality of Campo Verde in the state of Mato Grosso, Brazil, within the Cerrado biome. Rainfall in this biome extends from October to April and ranges from 800 to 2000 mm yr^{-1} (Ratter et al., 1997). Soils are highly weathered and acidic with high aluminum concentrations, thus requiring fertilizers and lime for crop production and livestock farming. Cerrado vegetation is influenced by fire regimes, plant-available moisture, soil nutrients, and topography (Mistry, 1998; Furley, 1999). The water table in the Cerrado is usually deep, with a minimum depth of 3 m from the ground surface (Eiten, 1972). The geology in this biome is related to lithologies from the Precambrian to the Tertiary and Quaternary periods (Salgado-Labouriau et al., 1997).

To reduce the effects of spatial variability, three headwater micro-catchments less than 1 km^2 in spatial extent were selected (Fig. 1). These catchments are approximately 30 km from the urban center of Campo Verde city (15.552° S, 55.168° W) and are situated in the watershed of the *das Mortes* River, the major tributary of the Araguaia River, which is approximately 2600 km in length. The climate in this region is tropical wet and dry, and the mean annual precipitation is 1800 mm yr^{-1}. Rainfall is highest from December to March, and the dry season extends from May to September. The dominant soils in this region are Ferralsols (IUSS Working Group WRB, 2014), also known as Oxisols (Soil Survey Staff, 2014) or *Latossolos Vermelhos-Amarelos Acriférricos/Alumínicos* (Brazilian Soil Classification, EMBRAPA, 2006).

With an area of 78 ha, the cerrado catchment is located within the boundaries of the *Rancho do Sol* farm (15.797° S, 55.332° W) and is covered mostly by cerrado sensu stricto vegetation type, which is characterized in its majority by *Leguminosae*, *Compositae*, *Myrtaceae*, and *Rubiaceae* plant species (Ratter et al., 1997). The 58 ha pasture catchment is located on the *Gianetta* farm (15.805° S, 55.336° W) approximately one km from the cerrado catchment and it is covered by *Brachiaria* grass species, a common grass species for feeding cattle. The cropland catchment (15.743° S, 55.363° W) has an area of 93 ha and is located on the *Santa Luzia* farm about 6 km from the other two micro-catchments of this study. This cropland area is used for mechanized rainfed agriculture based on crop rotation of soybean from October to January and maize from February to July.

The soils in the cerrado and pasture micro-catchments are Arenosols (IUSS Working Group WRB, 2014) characterized by sandy loam texture, which are correlated with *Entisols Quartzipsamments* (Soil Survey Staff, 2014) and *Neossolos Quartzenicos* (Brazilian Soil Classification, EMBRAPA, 1998). Soils in the cropland catchment are Ferralsols (IUSS Working Group WRB, 2014) characterized by clay loam texture, which are correlated with *Oxisols* (Soil Survey Staff, 2014) and *Latossolos Vermelhos Distróficos de textura argilosa* (Brazilian Soil Classification, EMBRAPA, 2006).

Although each catchment was selected on the basis of its specific predominant land use, gallery forests exist in all three micro-catchments following the stream channel (Fig. 1). The width of the gallery forest within each catchment varies from 50 to 250 m. These forests are complex environments, not well characterized (Marimon et al., 2010) and contain approximately 30 % of the known plant species of the Cerrado biome (Felfili et al., 2000). Due to their location along the watercourses, these forests are usually surrounded by cerrado vegetation, and their sustenance is mainly due to the higher soil water availability (Silva Júnior, 2001). The physiognomies of the gallery forests are different from those of the dominant savanna of the Cerrado biome (Felfili and Silva-Júnior, 1992). Studies report gallery forests with higher Leaf Area Index (LAI) values compared to the cerrado vegetation (Hoffmann et al., 2005; Paiva, 2008), trees with heights up to 40 m (Felfili, 1997), and higher plant biodiversity (Santiago et al., 2005; Silva Júnior, 2005).

2.2 Catchment instrumentation

In this subsection, we describe the components of the hydrological monitoring system installed in each catchment and the catchment characterization undertaken. We present results from data collected from October 2012 to September 2014. However, some data gaps exist in the time series owing to field equipment failure.

2.2.1 Topographic survey

To define the catchment boundaries and topographic features, we used the Quarryman® Auto-Scanning Laser System (ALS) LaserAce Scanner 300p laser profiling system (Measurement Devices Ltd., UK). Because the dense vegetation in the cerrado micro-catchment affected the use of the laser scanner, this catchment was surveyed by using a ProMark™ differential Global Positioning System (dGPS) instrument (Ashtech, USA). The gallery forests were also surveyed by using the dGPS instrument and a Geodetic Rover System (GRS1) GPS (Topcon, USA) with an integrated TruPulse® 360° B distance measurement system (Laser Technology Inc., USA). We used the topographic data obtained from these surveys to develop Digital Elevation Models (DEM) for the catchments at 5 m resolution and to calculate catchment attributes such as Topographic Wetness Index (TWI) and slope.

2.2.2 Rainfall and weather data

To account for rainfall spatial variability, we instrumented each catchment with three tipping bucket rain gauges with data loggers (Tinytag®, Gemini, UK) that recorded precipitation values every 10 min with a 0.2 mm resolution.

We installed a WS-GP1 weather station (Delta-T, UK) within the cropland catchment and recorded total solar radiation, net solar radiation, temperature, relative humidity, wind speed and direction, and rainfall at 10 min intervals. Using this weather data, reference evapotranspiration was quantified by using the Penman–Monteith equation following the procedure presented by Allen et al. (1998):

$$E_{\mathrm{To}} = \frac{0.408\Delta(R_\mathrm{n} - G) + \gamma\frac{900}{T+273}u_2(e_\mathrm{s} - e_\mathrm{a})}{\Delta + \gamma(1 + 0.34u_2)}, \tag{1}$$

where E_{To} is the reference evapotranspiration (mm day^{-1}), R_{n} is the surface net radiation (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_{s} is the saturation vapor pressure (kPa), e_{a} is the actual vapor pressure (kPa), $e_{\mathrm{s}} - e_{\mathrm{a}}$ is the saturation vapor pressure deficit (kPa), Δ is the slope vapor pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}).

We applied water stress and crop coefficients to estimate the actual evapotranspiration (E_{T}) according to the following equations presented by Allen et al. (1998):

$$E_{\mathrm{T}} = K_{\mathrm{s}} K_{\mathrm{c}} E_{\mathrm{To}}, \tag{2}$$

$$K_{\mathrm{s}} = \frac{\mathrm{TAW} - D_{\mathrm{r}}}{(1-p)\,\mathrm{TAW}}, \tag{3}$$

$$\mathrm{TAW} = 1000(\theta_{\mathrm{FC}} - \theta_{\mathrm{WP}}) Z_{\mathrm{r}}, \tag{4}$$

$$D_{\mathrm{r},i} = D_{\mathrm{r},i-1} - (P_i - \mathrm{RO}_i) - I_i - \mathrm{CR}_i + E_{T_{\mathrm{c},i}} + \mathrm{DP}_i, \tag{5}$$

where E_{T} is the actual evapotranspiration, K_{s} is the water stress coefficient (dimensionless), K_{c} is the crop coefficient, TAW is the total available water, RAW is the readily available water, θ_{FC} is the water content at field capacity (m^3 m^{-3}), θ_{WP} is the water content at the wilting point (m^3 m^{-3}), Z_{r} is the rooting depth (m), p is the average fraction of TAW that can be depleted from the root zone before moisture stress occurs (dimensionless), $D_{\mathrm{r},1}$ is the root zone depletion at the end of day i (mm), $D_{\mathrm{r},i-1}$ is the water content in the root zone at the end of the previous day (mm), P_i is the precipitation on day i (mm), RO_i is the runoff from the soil surface on day i (mm), I_i is the net irrigation depth on day i that infiltrates the soil (mm), CR_i is the capillary rise from the groundwater table on day i (mm), $E_{\mathrm{Tc},i}$ is the crop evapotranspiration on day i (mm), and DP_i is the water loss from the root zone by deep percolation on day i (mm). The selected values for some of these variables are shown in Table 1. The θ_{WP} was obtained using the pedotransfer function determined by Nunes et al. (2015) for the same three micro-catchments. For this study, we did not consider the I_i and CR_i in the calculation because there is no irrigation and the water table is more than 1 m from the root zone in the study areas. According to Zeleke and Wade (2012), RO_i is often considered negligible in the E_T estimation and was thus not considered in this study.

The crop factor (K_c) values are shown in Table 1. For the cropland catchment, we adjusted the K_c values in accordance with the crop development stages of soybean and maize planted in this area. A relatively uniform canopy of orchard-like vegetation with trees up to 5 m tall covers the entire cerrado catchment throughout the year. Therefore, we used constant K_c values for the cerrado vegetation. The E_T values for each type of land use were area-weighted and summed to obtain the total actual evapotranspiration estimation for each micro-catchment.

We obtained the LAI and rainfall interception values for the cerrado vegetation, pasture, soybean, and maize from the published reports in order to support further analysis. Additionally, we estimated canopy interception in the cerrado vegetation on a rainfall event basis using the analytical single-storm model by Liu (1997) reformulated by Carlyle-Moses and Price (2007) for sparse forests:

$$I_\mathrm{c} = c\left\{C_\mathrm{mc}\left[1-\exp\left(-\frac{1}{C_\mathrm{mc}}\right)P_\mathrm{g}\right]\times\left[1-\frac{E_\mathrm{c}}{R}\right]+\frac{E_\mathrm{c}}{R}P_\mathrm{g}\right\} \tag{6}$$

where c is the canopy cover fraction (dimensionless), C_mc is the storage capacity per unit area of the canopy and trunks (mm), P_g is the gross rainfall per event (mm), E_c is the mean within-rainfall evaporation rate per unit area of canopy (mm h^{-1}), and R is the mean rainfall intensity (mm h^{-1}). The canopy cover fraction was estimated as $1-p$, where p is the throughfall coefficient. Both C_mc and p were estimated by using the LAI in the Eqs. (7) and (8), according to Pitman (1989). The parameters used in this estimation are shown in Table 1.

$$p = \exp(-1.457\mathrm{LAI}) \tag{7}$$

$$C_\mathrm{mc} = 0.196\mathrm{LAI} \tag{8}$$

2.2.3 Soil physical and hydraulic properties

One disturbed sample and two undisturbed soil core samples (4.8 cm × 5.2 cm) were taken from 15 points along a transect from the crest to the stream valley in each catchment at depth intervals of 0–10, 10–20, 20–40, and 40–60 cm to determine bulk density, saturated hydraulic conductivity (K_{sat}), particle size distribution, total porosity, macroporosity, microporosity, and field capacity. Soil bulk density was estimated by using undisturbed samples dried in an oven at 105 °C (Burke et al., 1986). Undisturbed core samples were used to determine K_{sat} by using the constant-head permeameter method in the laboratory. Particle size distribution of the soils was measured by using the pipette method (Gee and Bauder, 1986) after chemical dispersion and removal of organic matter and carbonates. Total porosity was quantified by the cylinder volume method (EMBRAPA, 1997); the macroporosity, $\theta \geq 0.05$ mm, was determined by the table tension method (EMBRAPA, 1997); and the microporosity was obtained from the difference between the two aforementioned parameters. Additionally, field capacity moisture content values were estimated in the laboratory by using the pressure membrane method (Richards, 1947). We used Pearson's correlation analysis for intercomparison of obtained soil properties.

2.2.4 Soil moisture measurements

Time Domain Reflectometry (TDR) was used to measure the volumetric soil moisture content on a fortnightly basis with eight access tubes installed to a depth of 140 cm. In each catchment, we installed the access tubes in two transects along a toposequence of landscape positions from the upper slope to the low-gradient valley bottom. We used a TRIME-PICO T3 probe (IMKO™ Micromodultechnik GmbH, Ettlingen, Germany) to measure the volumetric soil moisture content at 20 cm depth intervals to 140 cm. Since the TRIME probe measures water content in an elliptical field, three measurements were taken at each depth increment and were averaged to account for local variability in the moisture content.

2.2.5 Catchment discharge

At the outlet of each catchment, an adjustable weir was installed. During the rainy season from October to April, the weirs were maintained as rectangular weirs; in the dry season with low flows from May to September, a v-notch contraction was inserted. At a distance of 2 m upstream of each weir, a DS 5X (OTT, USA) water level sensor was installed to measure and record the water level at 10 min intervals. For the rectangular weir, we used the standard flow equation (Eq. 9) based on the Bernoulli equation to quantify catchment discharge. For the v-notch weir, the Kindsvater–Shen equation (Eq. 10) and respective calibration adjustment functions (Eqs. 11 and12) were used to quantify discharge:

$$Q = \frac{2}{3} C_{\mathrm{dr}} b \sqrt{2g} h^{\frac{3}{2}}, \tag{9}$$

$$Q = \frac{8}{15} C_{\mathrm{e}} \sqrt{2g} \tan\left(\frac{\theta}{2}\right) h_{\mathrm{e}}^{\frac{5}{2}}, \tag{10}$$

$$K_{\mathrm{h}} = 0.001\left[\theta\left(1.395\theta - 4.296\right) + 4.135\right], \tag{11}$$

$$C_{\mathrm{e}} = \theta\left(0.02286\theta - 0.05734\right) + 0.6115, \tag{12}$$

where Q is the discharge over the weir ($\mathrm{m}^3\,\mathrm{s}^{-1}$), C_{dr} and C_{e} are the effective discharge coefficients for the rectangular and v-notch weirs, respectively (dimensionless), b is the weir length (m), θ is the v-notch's angle (radians), h is the upstream head above the weir's crest (m), h_{e} is the effective head ($h + K_{\mathrm{h}}$), and K_{h} is the head-adjustment factor.

In each catchment, we conducted discharge calibration measurements with an acoustic digital current meter (ADC, OTT, USA) during field visits to estimate the C_{dr} factor for each catchment. The obtained values were 0.74, 0.65, and 0.62 for the cerrado, pasture, and cropland catchments, respectively.

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2.2.6 Hydrograph analysis

We analyzed the obtained discharge data with the recursive digital filter method (Eckhardt, 2005) for baseflow separation. From this analysis, we obtained baseflow and direct flow components. The runoff coefficient (R_C) was quantified as the ratio of total discharge to total rainfall. The runoff ratio (R_R) was computed as the ratio of total direct flow to total rainfall during a stormflow, and the baseflow index (BFI) is given as the ratio of baseflow to total discharge. For this study, we considered direct flow as the difference between the total discharge and the baseflow. We calculated the flow duration curves to compare the differences in high, low, and median flows across the catchments (Vogel and Fennessey, 1994). Catchment flashiness indices were obtained by using the method described by Baker et al. (2004). The discharge data were area normalized to allow comparisons of these indices between the catchments.

2.2.7 Water balance

On the basis of the hydrometeorological time series data, we quantified the water balance for each study catchment as:

$$\mathrm{d}S/\mathrm{d}t = P - Q - E_\mathrm{T}, \tag{13}$$

where $\mathrm{d}S/\mathrm{d}t$ is the water storage variation in time, P is the rainfall, Q is the discharge out of the catchment, and E_T is the actual evapotranspiration. Thus, $\mathrm{d}S/\mathrm{d}t$ includes water fluxes that could not be measured, such as lateral and vertical groundwater losses.

3 Results

3.1 Catchment physiographic attributes

The slope distribution for each catchment, derived from the DEMs, are shown in Fig. 2. The average slope of the cerrado and pasture catchments is approximately

8 %, whereas the cropland catchment generally has a flat terrain with an average slope of 3 %. The cumulative slope distribution (Fig. 3) shows that the cerrado and pasture catchments have similar slope ranges with values between 0 and 10 % with higher values in the cerrado catchment. In the cropland catchment, about 80 % of the slope values are lower than 2 %.

Table 2 shows a summary of the topographic characteristics of the three micro-catchments, and Fig. 4 shows the TWI. The data are distinguished for the gallery forest and Predominant Land Use (PLU) areas. The cropland catchment has the largest area of 93.2 ha, followed by the cerrado and pasture catchments with 77.8 and 58.4 ha, respectively. The gallery forests represent less than 10 % of the total areas in all micro-catchments.

Figure 4 shows that the areas in the cerrado and pasture catchments with higher TWI have a very small extent and linear form, which represents a low overland flow potential in these catchments. The cropland catchment shows high TWI values in its flat upper part with an average slope of 2.4 %. According to field observations, this flat upper part of the cropland normally retains most of the overland flow, and the TWI values in the remaining area of this catchment show that the water drainage follows several small pathways leading to the gallery forest. The cumulative TWI distributions (Fig. 5) display similarities between the cerrado and pasture catchments, with most of the values between 5 and 16, and the cropland catchment with predominance of higher values.

3.2 Precipitation characteristics

The monthly total rainfall in each micro-catchment during the two-year study period is shown in Fig. 6. As shown in Table 3, between October 2012 and September 2014, the total rainfall was 3392 mm in the cerrado, 3560 mm in the pasture, and 3338 mm in the cropland. The highest daily rainfall values were recorded on 2 March 2014, for the cerrado catchment, and on 30 January 2013, for the pasture catchment, both at 64 mm day^{-1}. That for the cropland catchment was 67 mm day^{-1} on 24 November 2012.

Figure 7 shows scatter plots of the daily rainfall. The cropland catchment is located 6 km from the other two catchments; thus, rainfall from this catchment exhibited some differences from the other two catchments. The coefficients of determination for the daily rainfall values were 0.44 and 0.41 for the cropland and cerrado and the cropland and pasture, respectively. The low correlation of daily rainfall between the cropland and the other micro-catchments is typical owing to the high spatial variability of the rainfall in this region of South America (Lenters and Cook, 1999; Jones and Carvalho, 2002; Carvalho et al., 2002; Lincoln et al., 2005; Vera et al., 2006).

Table 3 summarizes the selected rainfall characteristics for each hydrological year monitored in the three micro-catchments. For all three, the wet season in 2013–2014 had a lower contribution to the total annual rainfall than that in 2012–2013. This result can be explained by some atypical rainstorms in the dry season. For example, rainstorms on 24 and 25 July 2014, with 67 mm in the cerrado, 65 mm in the pasture, and 35 mm in the cropland catchments, in addition to a higher amount of rainfall at the beginning and at the end of the dry season of 2013–2014, represented an additional of 100 to 200 mm in all of the studied micro-catchments. The wet day dynamics in both wet seasons were generally constant (Table 2).

The micro-catchments are characterized by similar rainfall intensity patterns (Fig. 8). The majority of the rainstorms in the study catchments occurred between noon and mid-afternoon with a mean intensity of 28 mm h^{-1} and peaks up to 130 mm h^{-1}. The duration of the rainstorms in all study micro-catchments typically varied from 30 to 90 min.

From the total rainfall in the cerrado catchment, the estimated canopy interception was 7 %, which represents a throughfall of 93 %. The measured throughfall values for the cerrado sensu stricto vegetation type in other studies were 89 % (Lilienfein and Wilcke, 2004) and 95.0 % (Honda, 2013), which are comparable to our results. Stemflow, which was not estimated in this study, was lower than 1 % in both aforementioned studies.

The rainfall interception values reported for event-based measurements for soybean are 11–24 % (Lilienfein and Wilcke, 2004), 45.9 % (Bispo, 2007), and 47.7 % (Bäse et al., 2012). Maize has comparable interception potential with values of 31 % (Silva et al., 1994) and 47 % (Silva Júnior, 2013). In the case of pasture, Silva Júnior (2013) reported rainfall interception of a *Brachiaria* grass specie of around 15 %.

3.3 Soil physical and hydraulic properties

Table 4 shows the main soil properties of the three study micro-catchments. The cerrado and pasture catchments have comparable soil properties. The pasture catchment shows higher bulk density in the top layer compared to the cerrado catchment. The gallery forest and the PLU areas of the cerrado catchment show the same bulk densities at 1.43 ± 9 % $\mathrm{g\,cm^{-3}}$, whereas the bulk density values found in the gallery forest area of the pasture catchment are substantially lower than those in its PLU area. Analogically the bulk density values in the gallery forest of the cropland catchment are lower than those in the PLU area.

Figure 9 shows the relationship between the soil properties in the gallery forest (upper panel) and PLU (lower panel) areas in the three catchments. As expected, the total porosity presented an inverse correlation to the bulk density in the three micro-catchments. Further, for all study areas, the microporosity showed a high correlation to the field capacity with coefficients of determination of 0.96 ($p < 0.0001$) for cerrado, 0.97 ($p < 0.0001$) for pasture, and 0.93 ($p < 0.0001$) for cropland catchments.

In the cerrado and pasture catchments, the correlation of the macroporosity to K_{sat} was 0.75 ($p < 0.0001$) and 0.70 ($p < 0.0001$), respectively. The microporosity and macroporosity in the cerrado and pasture catchments exhibited comparable values, with a predominance of the macroporosity between 60 and 70 % of the total porosity. The predominance of macroporosity is related to the soil structural and textural characteristics of these catchments, with a high frequency of stable soil aggregates and a sandy texture of more than 85 % sand content. In contrast, the total porosity in the cropland catchment is dominated by ca. 75 % micropores due to the high clay content (58 ± 7 %).

The K_{sat} distribution for the three catchments is shown in Fig. 10. The K_{sat} values in the cerrado and pasture catchments are higher than that in the cropland catchment. This result indicates a high infiltration potential in the cerrado and pasture, which is related to the sandy texture and the high macroporosity. The high K_{sat} values in these two catchments also indicate a limited surface runoff contribution to the streamflow. This characteristic is typical of Arenosols owing to their coarse textures and high permeability.

3.4 Soil moisture dynamics

Figure 11 shows the annual variation in soil moisture in the gallery forest and PLU areas. The measured soil moisture content in the three catchments ranged from 10 to 40 %. The highest soil moisture values were noted in the gallery forest areas. Overall, the values in the gallery forests were 55 % higher in the cerrado and cropland catchments, and 164 % in the pasture catchment, than in the PLU areas. The lower soil moisture values in the PLU areas of the cerrado and pasture catchments than those of the cropland catchment are related to the significantly lower field capacity, at 15 % (vol.), and preferential vertical water flow pathways, which is associated with the dominance of soil macroporosity. Similar soil moisture dynamics as those noted in the cerrado were reported by Lima (2000) and Lima et al. (2001) in a catchment covered with cerrado vegetation. With a field capacity moisture content of about 35 % vol., the cropland catchment retained more soil moisture in the upper 60 cm.

During the dry season, the soil moisture in the cerrado catchment reaches values as low as the permanent wilting point (PWP); consequently no water is available to plants in the 0–80 cm soil layer (Reichardt, 1985). The cerrado vegetation includes a variety of deep- and shallow-rooted plants, the latter of which are mostly herbaceous plants and grass species that wilt in the dry season.

3.5 Evapotranspiration

The daily values of E_T are presented in Fig. 12; and Table 5 shows the annual and total area-weighted amounts of E_T. For 2012–2013 and 2013–2014, the highest total E_T was observed in the cerrado catchment at 979 and 993 mm, followed by the cropland catchment at 854 and 803 mm and the pasture catchment at 515 and 549 mm, respectively. The average non-area-weighted E_T values were 2.7 mm day^{-1} for the cerrado vegetation, 1.4 mm day^{-1} for the grassland vegetation, 3.7 mm day^{-1} for soybean, 2.3 mm day^{-1} for maize, and 3.0 mm day^{-1} for the gallery forests. Giambelluca et al. (2009), Oliveira et al. (2014), and Dias et al. (2015) quantified comparable values for the cerrado vegetation. Our E_T results for soybean and maize are in accordance with the values reported by Lathuillière et al. (2012), who used remote sensing techniques. However, they reported higher values for the grassland vegetation compared to our results. We can attribute this difference to the lower K_c values assumed in our study due to grassland degradation.

Figure 12 also shows that between July 2013 and October 2013, the cropland catchment had the lowest E_T. This period coincides with the time between the harvesting of maize and the sowing of the following soybean crop in the PLU area. Thus, the observed E_T is mainly evaporation from bare ground and E_T from the gallery forest area.

3.6 Catchment discharge, hydrograph analysis, and water balance

The normalized discharge values (Fig. 13) show that the pasture catchment had the highest values for most of the study period. The mean discharge was 1.2 mm day^{-1} in the cerrado catchment, 2.0 mm day^{-1} in the pasture catchment, and 0.7 mm day^{-1} in the cropland catchment. During the wet season, the mean discharge was 1.5 mm day^{-1} in the cerrado catchment, 2.2 mm day^{-1} in the pasture catchment, and 0.9 mm day^{-1} in the cropland catchment. In the dry season, the mean flow was 0.9 mm day^{-1} in the cerrado catchment, and 1.6 mm day^{-1} in the pasture catchment, and 0.4 mm day^{-1} in the cropland catchment.

Flow duration curves (FDCs) were derived from the daily discharge data of the three catchments (Fig. 14). The FDCs show that the high flows (Q5) were similar for all three catchments. However, a wide difference was noted in the low flows (Q95) with the cropland catchment exhibiting the lowest values and highest decrease. The FDCs curves show a flat slope in the middle to low flows, which indicates that low flows are sustained by the baseflow contribution.

Table 6 shows a summary of the hydrological indices derived for the study catchments. For the two-year study, the highest streamflow amount occurred in the pasture catchment at 1416 mm, followed by the cerrado at 914 mm and the cropland catchment at 525 mm. However, the runoff coefficients were relatively low (< 0.5) for all catchments, with the highest noted in the pasture catchment. The R_C was 50 % higher in the pasture than that in the cerrado catchment, and that in the cropland catchment was 60 % lower compared to the cerrado catchment. The BFI shows a high baseflow contribution to total discharge in all catchments, with ratios of more than 95 %. These results are in accordance with the ratio of the baseflow and rainfall (BF : P) shown in Table 4 and the findings in the FDCs curves (Fig. 14), in which the average discharge shows a low frequency of exceedance. The flashiness indices around 0.05 generally show low discharge variability, particularly for the pasture catchment.

To evaluate the influence of land cover on the hydrological dynamics in the catchments, hydrographs are plotted for selected rainstorms basis of specific rainstorms (Fig. 15a–c). For the rainstorm on 25 October 2013, 27.3 mm of rain produced 0.20 mm of direct flow with a peak flow rate of 0.06 mm 10 min^{-1} in the cerrado catchment; 39.9 mm of rain produced 0.17 mm of direct flow at peak flow rate of 0.10 mm 10 min^{-1} in the pasture catchment; and 30.5 mm of rain produced 0.01 mm of direct flow at peak flow rate of 0.01 mm 10 min^{-1} in the cropland catchment. An example of a multi-peak event is shown in the hydrograph of 7 February 2014 (Fig. 15a and b), which shows 49.9 mm total rainfall and 0.51 mm direct flow in the cerrado catchment and 45.4 mm of rainfall and 0.27 mm of direct flow in the pasture catchment. Another rainstorm event in the cropland catchment on 10 February 2014, produced 49.4 mm of rain and 0.04 mm of direct flow. No increase was observed in the direct flow response over the wet season in the three micro-catchments. However, the hydrographs also show a subsequent baseflow increase in the second half of the wet season, which is attributed to the increase in soil moisture during this period. This baseflow increase is lower in the cerrado and pasture catchments than that in the cropland catchment, which we ascribe to the lower water holding capacity of the sandy soil texture in the pasture and cerrado catchments compared with the cropland catchment.

The overall water balance is shown in the Table 7. The pasture catchment had a lower evapotranspiration and therefore a higher total discharge compared with the other catchments. The water balance in the cropland catchment shows higher groundwater recharge and soil water storage ($\mathrm{d}S/\mathrm{d}t$) of 578 $\mathrm{mm\,yr^{-1}}$.

4 Discussion

4.1 The effects of land use change on soil characteristics

Although the cerrado and pasture catchments have the same soil type and comparable characteristics, the pasture catchment showed higher bulk densities. We attribute this higher bulk density to differences in the root systems between the *Brachiaria* grass in the pasture, with fine and shallow roots, and the cerrado vegetation, which includes a variety of plants with fine and coarse roots, and, additionally, to the compaction caused by the cattle ranching and machinery use in the pasture catchment. While the gallery forest and the PLU areas of the cerrado catchment show the same bulk densities, the bulk density values found in the gallery forest area of the pasture catchment are substantially lower than those in its PLU area. This result is particularly noticeable at a soil depth of 20 cm and it is typical due to soil compaction caused by grazing cattle (Drewry et al., 2008). We attribute the lower bulk density values in the gallery forest area in comparison to the PLU area of the cropland catchment to compaction caused by the use of heavy farm machinery.

The measured K_{sat} values in the cropland catchment are significantly lower than those in the other catchments. However, the K_{sat} varied spatially in the cropland catchment from 3 to 573 mm h^{-1}. We attribute this variability to the use of heavy farm machinery with well-defined route planning and field operations in the cropland catchment. It is likely that areas in which the K_{sat} values are very low are susceptible to Hortonian overland flow during high-intensity rainstorms, as observed in the PLU area of the cropland catchment during field campaigns. Conversely, the gallery forest area of this catchment shows low TWI values and consequently low overland flow generation potential. The K_{sat} in the cropland catchment decreased more than five times after the 10–20 cm depth interval. This indicates a higher subsurface lateral flow generation in this catchment. Our results are supported by other studies (Scheffler et al., 2011; Hunke et al., 2015) in which farming practices, particularly soybean cultivation, are reported to enhance subsoil compaction.

The K_{sat} values in the PLU area of the cropland catchment were lower than those in the gallery forest area at the 0–20 cm soil depth, which can be attributed to the intensive use of heavy agricultural machinery and no-till farming in the PLU area. The high K_{sat} values found in the cerrado and pasture exceed the observed peak rainfall intensities, which is likely to restrain the overflow generation in these catchments.

The gallery forests in the three micro-catchments offer a unique perspective for identifying the changes in soil physical properties due to land-use change. Although the bulk density and total porosity values are comparable between the PLU and gallery forest of the cerrado catchment, this similarity is not evident in the soils of the gallery forest and the PLU areas of the pasture and cropland catchments, thus indicating changes in the soil properties of the upper soil layer of these catchments. Changes in the soil properties as a result of modern agriculture were reported by Hamza and Anderson (2005); subsequent increases in stream discharge due to these changes have also been reported (Costa et al., 2003; Martínez and Zinck, 2004).

4.2 The effects of land use on hydrological responses

Evapotranspiration is a major component of the water balance in tropical regions. The cerrado catchment had the highest E_T value during our two-year study period compared with that observed in the pasture and cropland catchments. We attribute this result to the constant cerrado vegetation throughout the year and its deeper roots, which ensures higher E_T even during the dry season. The reduced E_T in agricultural areas was also observed by Oliveira et al. (2014) and Dias et al. (2015) while analyzing the dynamics of the water balance components in the deforested areas of the Amazonian agricultural frontier. In line with other studies analyzing the hydrological impacts of deforestation on small watersheds (Neill et al., 2011; Recha et al., 2012), the lowest E_T values were observed in the pasture catchment, whereas the cropland catchment exhibit high E_T values only during the crop growing season.

The cropland catchment showed the largest catchment area, lower K_sat values, and the lowest values in discharge over the wet and dry seasons. We attribute this finding to the clayey soil texture in this catchment and its associated high water storage capacity. This catchment also has generally flatter terrain and thus attenuated stormflow generation during rainfall events than those in the cerrado and pasture catchments. Furthermore, precision farming with low-till techniques practiced in this landscape has been reported as a land use management approach with lower environmental impact (Bongiovanni and Lowenberg-Deboer, 2004; Bramley et al., 2008; Jenrich, 2011), which we also ascribe as a contributing factor to the obtained hydrologic responses.

Because of the similar topographic and soil characteristics a comparison of the streamflow between the cerrado and pasture catchments is more meaningful than with the cropland catchment. Thus, we attribute the discharge differences between the cerrado and pasture principally to the land use differences in these catchments. Similarly, increases in discharge due to conversion of natural vegetation to grasslands in the agricultural frontier of the Brazilian Amazon have also been reported in other studies (Costa et al., 2003; Chaves et al., 2008; Coe et al., 2009; Davidson et al., 2012; Guzha et al., 2015). As reported by Bruijnzeel (2005) and Muñoz-Villers and McDonnell (2013), this increase is dependent mostly on the differences in E_T and soil compactation between the cerrado and pasture vegetation.

The runoff ratios (R_Rs) were very small in all micro-catchments (Fig. 15); generally less than 1 % of rainfall is drained as direct flow out of the catchments. Low R_Rs were also found in the catchments in the Brazilian Cerrado with average R_Rs of 1 % by Lima (2000), 3 % by Silva and Oliveira (1999), and 4 % by Alencar et al. (2006). Our findings show that surface runoff has a limited contribution to the discharge in the studied micro-catchments. The low R_Rs and the short lag time of 0–30 min between rainfall and discharge peaks suggest that the direct flow generation process is established only in the valley bottom areas of each catchment, which are covered by gallery forests. Any surface runoff generated from the catchments has limited effects on catchment discharge because the gallery forests act as a buffer zone in controlling downslope water movement and thus attenuate the potential discharge peaks from these micro-catchments.

Our results show that the change in soil water storage and groundwater recharge were highest in the cropland at 578 mm yr^{-1}, followed by the pasture at 540 mm yr^{-1} the cerrado at 252 mm yr^{-1}. These results are in accordance with those reported by Wendland et al. (2007), who showed groundwater recharge rates of 145–703 mm yr^{-1} for pasture landscapes in Brazil. Our findings of lowest values for $\mathrm{d}S/\mathrm{d}t$ in the cerrado catchment support the results of Oliveira (2014), who reported that the undisturbed Cerrado landscapes exhibit higher infiltration rates than pasture and cropland.

In our study, water balance errors are likely to exist owing to uncertainties in the quantification of actual evapotranspiration, recharge, and changes in groundwater storage. Although our study provides insights into catchment hydrological fluxes as influenced by land-use changes and gallery forests in the Brazilian Cerrado, further studies should focus on more accurate measurements of evapotranspiration and changes in groundwater recharge and storage.

Additionally, Giglio and Kobiyama (2013) reported that studies on rainfall interception in the Brazilian Cerrado are limited and that the few existing studies do not include the land cover differences resulting from Cerrado deforestation. Understanding rainfall–runoff processes under different land use regimes and during different vegetation development stages is an important factor in water resources management in this region. For example, our results show that the higher discharge peaks in the cropland catchment coincide with the harvesting of soybeans, for which we attribute the absence of vegetation influence, i.e. no rainfall interception. This consequently increases the moisture content of the topsoil and reduces the infiltration rates, thus contributing to the discharge generation and its higher peaks.

Although various studies have reported increased discharge after natural vegetation clearing (Coe et al., 2009; Hayhoe et al., 2011; Neill et al., 2011; Moraes et al., 2006; Recha et al., 2012; Gholami, 2013), our study results do not entirely reflect this observation. In this study, we expected a higher discharge in the catchments with cleared cerrado vegetation. While the pasture catchment showed higher discharge rates for most of the monitored period, the cropland did not show the same pattern. We believe that comparisons between grass and cerrado vegetation, which often have similar physical and soil characteristics in the Brazilian Cerrado (Santos et al., 2009), more accurately show hydrological differences emanating from the applied land use.

The results obtained in this study do not show that cerrado vegetation promotes sustained dry-season flow associated with greater wet-season infiltration as evidenced in forests (Ogden et al., 2013). In fact, the role of cerrado vegetation in the water balance is not sufficiently understood. Empirical studies to assess the manner in which cerrado vegetation conversion to agricultural land affects the recharge are needed to understand the water balance in this biome. Additionally, we suggest more efforts in field-based E_T estimation experiments regarding the different land use types in the Brazilian cerrado and further assessments of the relationship between riparian vegetation and the hydrological processes.

The gallery forests act as a main water retention area. Our hydrograph analysis and soil moisture results indicate that these areas are responsible for the most active discharge generation processes, including the maintenance of most of the discharge during the dry season. However, we were unable to completely quantify the role of this vegetation as buffers for the hydrological impacts due to land use change in the catchment. Such an undertaking would require monitoring of the water fluxes through the catchment into the gallery forest, which is often difficult in cash crop farms in this region owing to the frequent field activities using heavy machinery. The ecosystem services provided by gallery forests are not only related to catchment stream discharge regulation but can also include hydrochemical and nutrient transport in catchments (Beechie et al., 2010; Parron et al., 2011; Weisberg, 2013).

5 Conclusions

We investigated the hydrological responses of three micro-catchments under contrasting land use in the Brazilian Cerrado. Hydrological and meteorological data were collected from 2012 to 2014. The selected cerrado and pasture catchments are adjacent and have similar physiographic properties and rainfall patterns whereas the cropland catchment, located 6 km away, exhibits different topographic and soil characteristics. All three catchments have well-defined gallery forests along the streams.

Soil characteristics and soil moisture content showed significant differences between the PLU and gallery forest areas in the pasture and cropland catchments, thus indicating the influence of land-use change. In comparison to the cerrado and pasture catchments, the markedly low discharge from the cropland catchment can be attributed to generally flat topographic characteristics of this catchment; its clayey soil, which promotes higher soil water storage capacity; and increased surface depression storage due to farming practices.

Although the results of our study show marked differences in annual water balance, peak discharge, and evapotranspiration, there is no clear indication that the clearing of natural cerrado vegetation results in increased surface runoff in the three catchments. However, we observed increased streamflow in the pasture catchment compared to the cerrado catchment. Our results also show that baseflow is a major driver of these observed streamflow differences, with highest BF : P ratio for the pasture catchment. Runoff ratios obtained from this study show a minimal contribution – less than 1 % – of direct flow to stream discharge.

We recommend additional efforts in research on hydrological processes in the changing Brazilian Cerrado with emphasis on the E_T and recharge quantification. In this context, the riparian vegetation, which according to our results act as a main water retention areas, might play a significant role by contributing to baseflow during the dry season discharge and buffering the effects of land-use changes on the observed hydrological signatures in these catchments. Our observations could be significant, particularly in support of the new Brazilian forest code that protects gallery forests and riparian habitats for ecosystem services provisioning, water quantity and quality management.

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Table 1. Parameters used for the canopy interception and E_T estimation, and vegetation characteristics.

	Gallery Forests	Cerrado	Pasture	Soybean				Maize			
				Initial	Devel.	Mid	Late	Initial	Devel.	Mid	Late
K_c	1.1	1.0	0.8 (wet) and 0.3 (dry)	0.6	1.2	1.5	0.9	0.4	0.8	1.2	0.9
Crop development stages (days)	–	–	–	10	35	35	30	30	50	60	40
LAI	3.3	1.1 (wet) and 0.7 (dry)	1.2	0.1	2.7	6.0	4.0	1.0	3.5	3.5	1.5
Soil water depletion fraction (p)	0.5	0.6	0.6	0.5	0.5	0.6	0.9	0.5	0.5	0.5	0.8
Max. root depth (m)	5.0	3.0	0.2	1.4				1.2			
References	LAI (Paiva, 2008), K_c (Compaoré, 2006), root depth (Jackson et al., 1999)	K_c (Lima, 2001), LAI (Hoffmannet al., 2005) root depth (Canadell et al., 1996)	LAI (Almeida, 2012), K_c and p (Allen et al., 1998), root depth (Silva et al., 2014)	K_c (Farias et al., 2001), LAI (Souza et al., 2009), p (FAO, 2015a), root depth (Torrion et al., 2012)				K_c (Guimarães and Albuquerque, 2004), LAI (Braz et al., 2005), p (FAO, 2015b), root depth (Manfron et al., 2003)			

Table 2. Topographic characteristics of the three micro-catchments.

	Cerrado			Pasture			Cropland		
	Gallery Forest	PLU Area	Total Area	Gallery Forest	PLU Area	Total Area	Gallery Forest	PLU Area	Total Area
Area (km^2)	0.0496 (6.4 %)	0.7284 (93.6 %)	0.7780 (100 %)	0.0379 (6.5 %)	0.5461 (93.5 %)	0.5840 (100 %)	0.0824 (8.8 %)	0.8496 (91.2 %)	0.9320 (100 %)
Average Elevation (m)	770.1	813.9	811.1	775.3	820.8	817.8	775.3	788.4	787.2
Average slope (%)	13.3	8.1	8.4	6.8	7.7	7.7	4.9	2.4	2.8

Table 3. Rainfall characteristics in the three micro-catchments.

		2012–2013			2013–2014	
	Cerrado	Pasture	Cropland	Cerrado	Pasture	Cropland
Total Rainfall (mm)	1543	1595	1653	1848	1964	1685
Total wet season rainfall (mm)	1408 (91 %)	1462 (92 %)	1489 (90 %)	1555 (84 %)	1639 (83 %)	1425 (85 %)
Number of wet days in the wet season	164 (77 %)	167 (75 %)	147 (69 %)	185 (77 %)	181 (73 %)	183 (72 %)
Number of wet days following a wet day in the wet season	133 (82 %)	139 (81 %)	113 (71 %)	165 (83 %)	160 (81 %)	165 (77 %)
Number of dry days following a dry day in the wet season	51 (31 %)	49 (31 %)	72 (43 %)	28 (21 %)	35 (26 %)	33 (27 %)

Results between parentheses represent the percentage of the annual total value.

Table 4. Soil physical properties for the three micro-catchments.

Micro-catchment	Depth (cm)	BD ($g\,cm^{-3}$)	TP (%)	MaP (%)	MiP (%)	FC (%)	K_{sat} ($mm\,h^{-1}$)	Sand (%)	Silt (%)	Clay (%)
Cerrado	0–10	1.43 ± 9 % (1.43 ± 9 %)	49.2 ± 8 % (49.4±10 %)	31.8 ± 12 % (26.9±13 %)	17.4 ± 35 % (22.5±36 %)	15.9 ± 36 % (20.5±40 %)	559.5 ± 38 % (361.1 ± 15 %)	85.8 ± 10 % (83.7 ± 8 %)	2.4 ± 95 % (2.64 ± 109 %)	11.9 ± 54 % (13.6±27 %)
	10–20	1.47 ± 6 % (1.55)	45.8 ± 5 % (45.7)	30.8 ± 18 % (28.3)	15.0 ± 32 % (17.5)	13.2 ± 37 % (16.1)	611.7 ± 45 % (363.4)	88.9 ± 2 % (81.3 ± 9 %)	1.5 ± 75 % (3.73 ± 78 %)	9.6 ± 10 % (15.0±29 %)
	20–40	1.52 ± 4 %	42.9 ± 7 %	27.0 ± 18 %	15.9 ± 32 %	14.7 ± 32 %	515.56 ± 56 %	87.4 ± 1 %	1.3 ± 37 %	11.3 ± 7 %
	40–60	1.51 ± 3 %	42.1 ± 2 %	25.2 ± 24 %	16.9 ± 36 %	15.6 ± 36 %	509.6 ± 33 %	86.2 ± 1 %	1.9 ± 49 %	11.9 ± 10 %
Pasture	0–10	1.56 ± 3 % (1.23±10 %)	44.4 ± 3 % (53.5 ± 4 %)	28.1 ± 8 % (33.0 ± 9 %)	16.4 ± 10 % (20.4±16 %)	15.5 ± 10 % (19.3±19 %)	399.0 ± 40 % (297.3 ± 52 %)	88.4 ± 1 % (86.0 ± 2 %)	1.5 ± 40 % (2.1 ± 8 %)	10.1 ± 9 % (11.9±12 %)
	10–20	1.57 ± 3 % (1.37 ± 3 %)	45.7 ± 3 % (49.8 ± 5 %)	32.1 ± 5 % (32.0±10 %)	13.6 ± 10 % (17.8 ± 9 %)	12.9 ± 9 % (16.6±13 %)	655.6 ± 15 % (666.5 ± 46 %)	89.2 ± 1 % (86.6 ± 2 %)	0.9 ± 97 % (2.1 ± 48 %)	9.9 ± 10 % (11.3±22 %)
	20–40	1.56 ± 3 % (1.41 ± 3 %)	46.4 ± 4 % (50.3 ± 1 %)	32.9 ± 7 % (33.6 ± 7 %)	13.5 ± 10 % (16.7±16 %)	12.8 ± 10 % (15.8±18 %)	705.1 ± 17 % (611.3 ± 25 %)	87.8 ± 1 % (86.7 ± 2 %)	1.7 ± 28 % (1.9 ± 27 %)	10.5 ± 5 % (11.4±14 %)
	40–60	1.52 ± 3 % (1.44 ± 4 %)	43.0 ± 6 % (46.5±11 %)	28.8 ± 7 % (30.2±12 %)	14.3 ± 6 % (16.3±10 %)	13.4 ± 8 % (15.7±11 %)	510.4 ± 30 % (411.8 ± 24 %)	88.6 ± 1 % (88.8 ± 2 %)	1.3 ± 39 % (1.4 ± 67 %)	10.1 ± 10 % (9.8 ± 6 %)
Cropland	0–10	1.18 ± 14 % (0.86 ± 9 %)	59.1 ± 8 % (69.1 ± 9 %)	10.5 ± 40 % (22.5 ± 3 %)	48.7 ± 10 % (46.6±12 %)	39.4 ± 12 % (40.7±14 %)	42.9 ± 154 % (130.4 ± 68 %)	26.5 ± 56 % (35.4±18 %)	16.0 ± 41 % (13.1 ± 14 %)	57.6 ± 17 % (51.5±16 %)
	10–20	1.19 ± 11 % (0.95±10 %)	56.9 ± 7 % (60.1 ± 8 %)	13.6 ± 33 % (15.0±18 %)	43.3 ± 13 % (45.7±17 %)	35.9 ± 14 % (39.9±19 %)	166.9 ± 93 % (302.8 ± 12 %)	25.5 ± 50 % (29.2±35 %)	22.0 ± 37 % (16.0 ± 5 %)	52.5 ± 14 % (54.8±20 %)
	20–40	1.16 ± 11 % (0.94±13 %)	57.1 ± 9 % (63.3±11 %)	16.2 ± 35 % (15.6±47 %)	41.0 ± 10 % (47.6±30 %)	34.2 ± 13 % (41.1±31 %)	95.5 ± 163 % (69.9 ± 83 %)	25.3 ± 57 % (26.0±35 %)	19.4 ± 29 % (13.0 ± 40 %)	55.4 ± 19 % (61.0±23 %)
	40–60	1.19 ± 9 % (1.07 ± 3 %)	56.7 ± 9 % (57.8 ± 1 %)	11.8 ± 29 % (14.8±41 %)	44.9 ± 9 % (43.1±13 %)	36.7 ± 11 % (37.2±12 %)	51.9 ± 162 % (53.3 ± 55 %)	19.4 ± 12 % (23.8±32 %)	21.4 ± 12 % (9.9 ± 40 %)	59.3 ± 6 % (66.4±17 %)

BD = Bulk Density, TP = Total Porosity, MaP = Macroporosity, MiP = Microporosity, FC = Field Capacity, K_{sat} = Saturated Hydraulic Conductivity.
Results are expressed in terms of average and relative standard deviation. Between parentheses are results exclusively for the gallery forest area, and the results without parentheses are related to the Predominant Land Use (PLU) areas of each micro-catchment.

Table 5. Area-weighted evapotranspiration in the three micro-catchments and respective totals.

	Cerrado E_T (mm)			Pasture E_T (mm)			Cropland E_T (mm)		
Hydrological Year	Gallery Forest	PLU area	Total Area	Gallery Forest	PLU area	Total	Gallery Forest	PLU area	Total
2012–2013	72	907	979	66	449	515	108	746	854
2013–2014	67	926	993	65	484	549	100	703	803
Total E_T	139	1833	1972	131	933	1064	208	1449	1657

Table 6. Hydrological analyses and indices for the catchments.

	Cerrado		Pasture		Cropland	
	2012–2013	2013–2014	2012–2013	2013–2014	2012–2013	2013–2014
Discharge (mm)	453	461	724	692	273	252
RC	0.29	0.25	0.45	0.35	0.17	0.15
Flashiness	0.1145	0.1015	0.0567	0.0517	0.1370	0.0537
BFI	0.96	0.97	0.98	0.96	0.96	0.99
BF : P	0.28	0.24	0.45	0.34	0.16	0.15

Table 7. Annual and total water balance for the study catchments.

	Rainfall (P, mm)			Discharge (Q, mm)			Evapotranspiration (E_T, mm)			Recharge and change in storage (dS/dt, mm)		
	2012–2013	2013–2014	Total	2012–2013	2013–2014	Total	2012–2013	2013–2014	Total	2012–2013	2013–2014	Total
Cerrado	1543	1848	3391	453	461	914	979	993	1972	111	394	505
Pasture	1595	1964	3559	724	692	1416	515	549	1064	356	723	1079
Cropland	1653	1685	3338	273	252	525	854	803	1657	526	630	1156

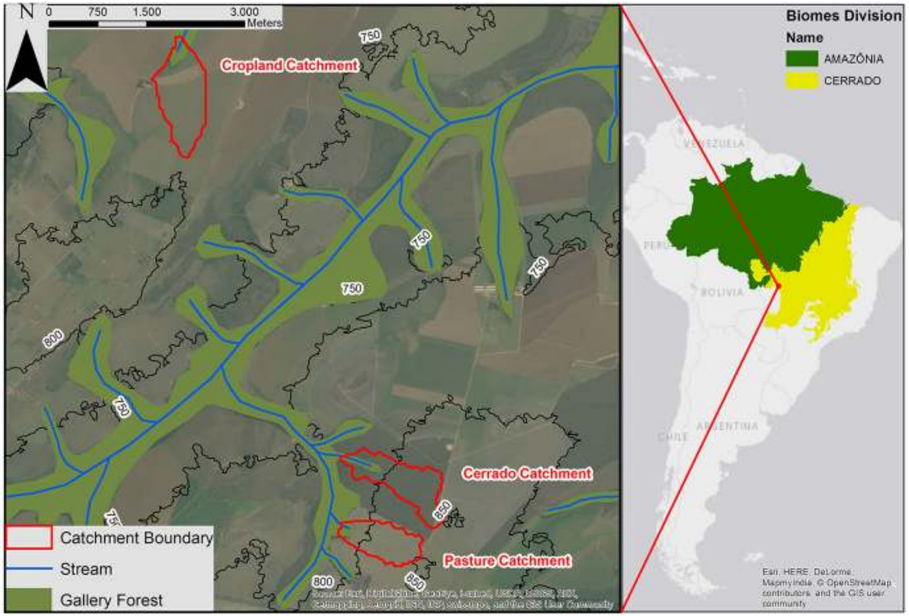

Figure 1. Cerrado, pasture, and cropland micro-catchments locations.

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Figure 2. Slope (%) of the catchments calculated from the Digital Elevation Models (DEMs).

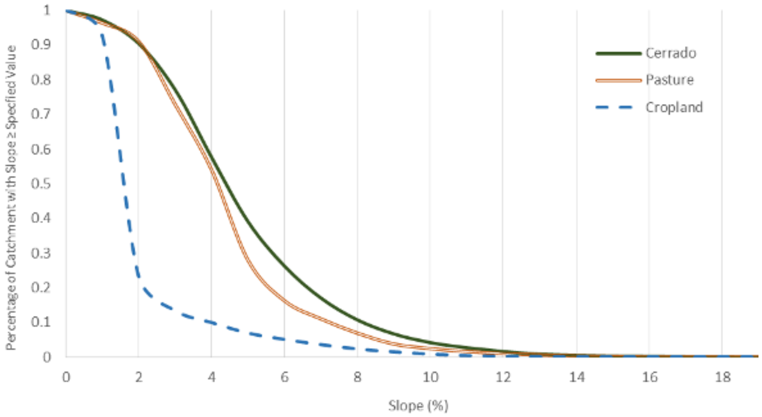

Figure 3. Cumulative slope distribution for the three catchments.

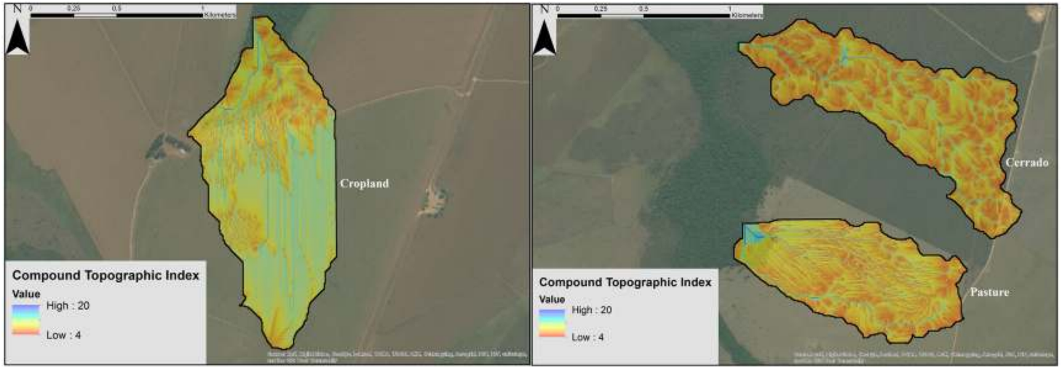

Figure 4. Topographic Wetness Indices (TWI) of the three micro-catchments.

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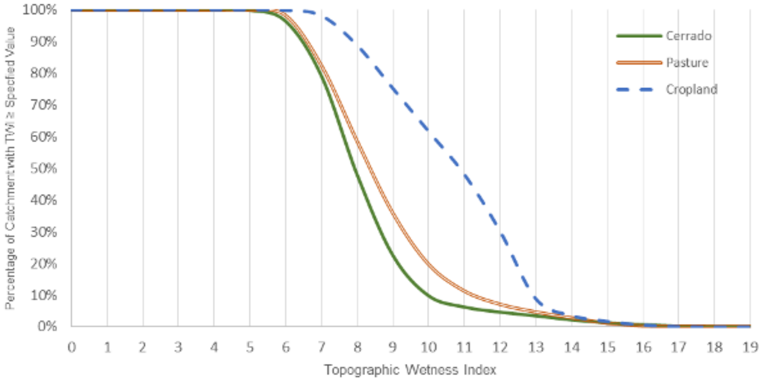

Figure 5. Cumulative Topographic Wetness Index (TWI) distribution for the three catchments.

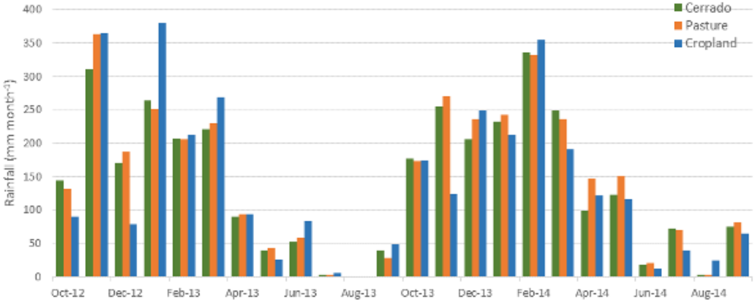

Figure 6. Monthly total rainfall per micro-catchment.

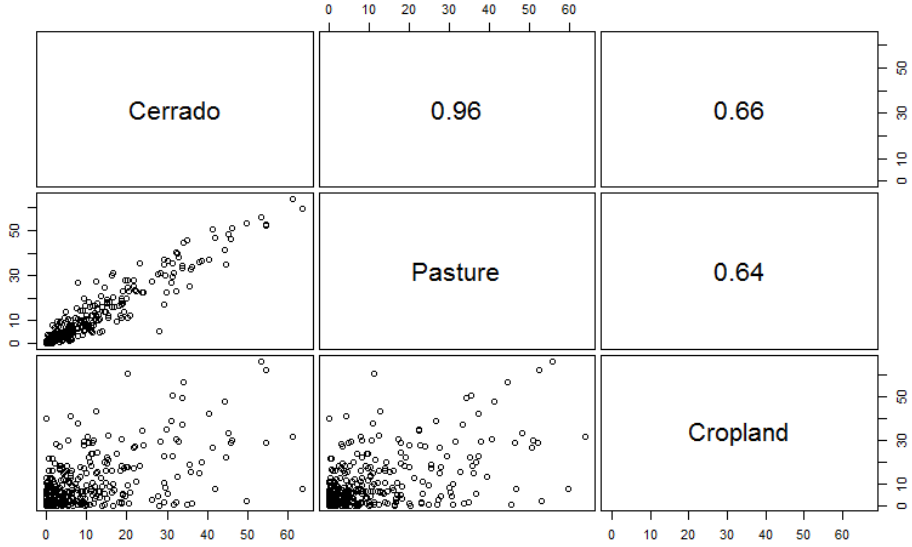

Figure 7. Scatter plots of daily rainfall for the study catchments and respective correlations.

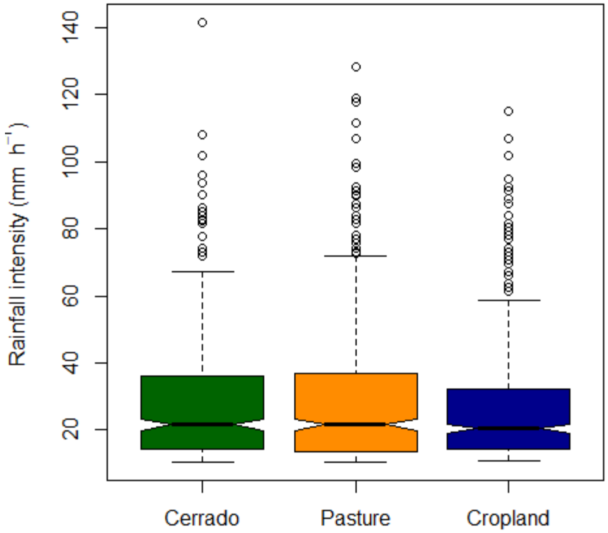

Figure 8. Boxplot of rainfall intensity ($\mathrm{mm\,h^{-1}}$).

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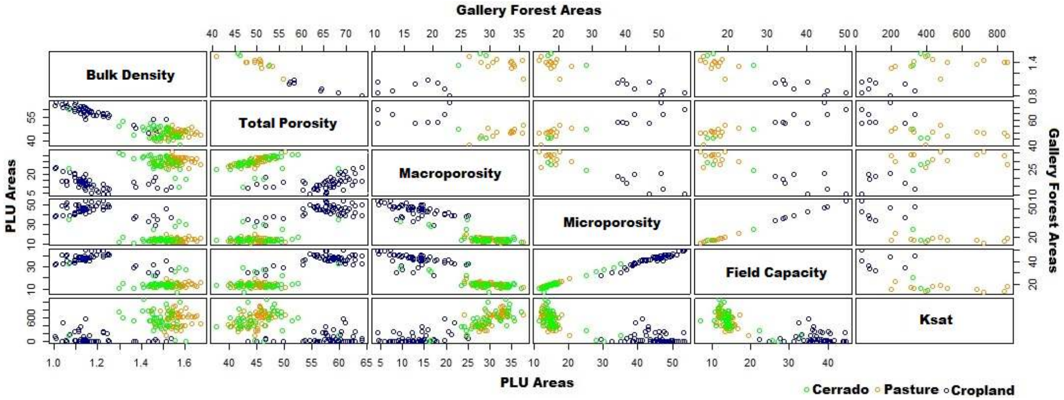

Figure 9. Scatter-plot matrix of six soil property values in the gallery forest (upper panel) and Predominant Land Use (PLU; lower panel) areas in the three micro-catchments.

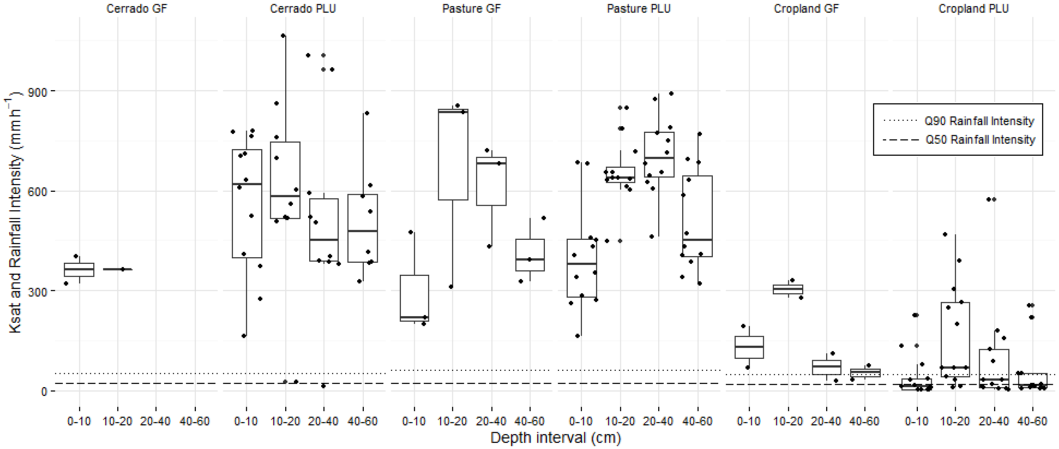

Figure 10. 50th and 90th percentiles of the rainfall intensity, and boxplot and data distribution of K_{sat} results in various soil depths in the micro-catchments.

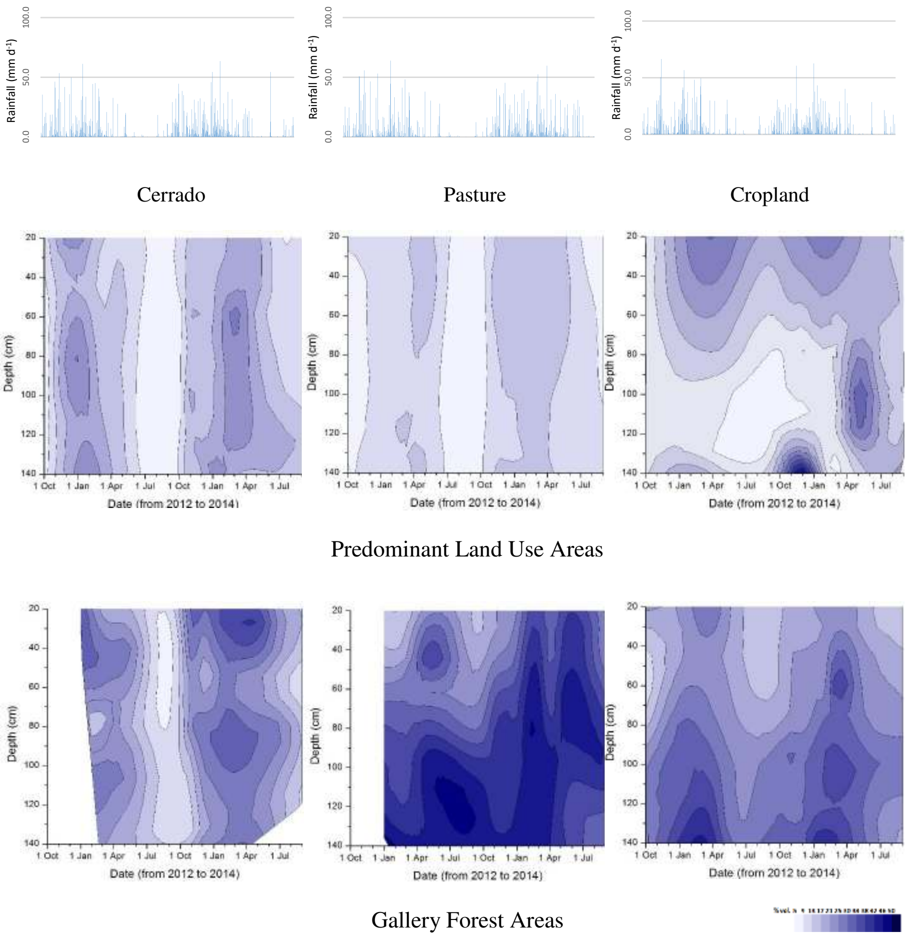

Figure 11. Time series of rainfall (mm day^{-1}) and soil moisture (% vol.) in the gallery forest and the Predominant Land Use (PLU) areas of the cerrado, pasture and cropland micro-catchments.

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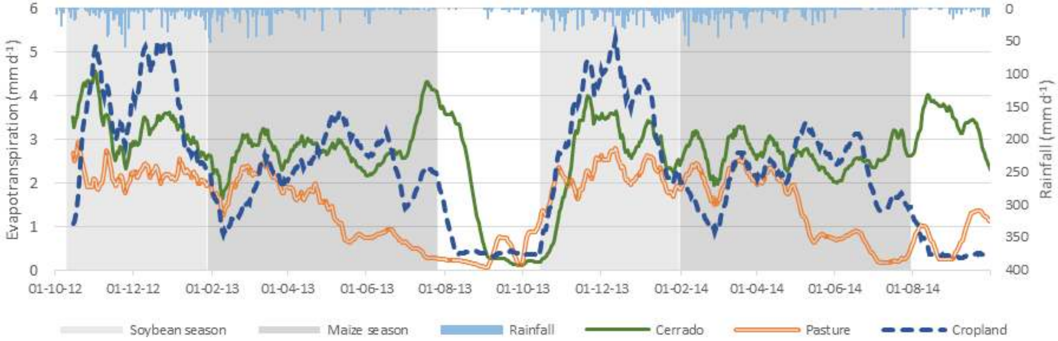


Figure 12. 15 day moving average for evapotranspiration and daily areal average rainfall for the three micro-catchments.

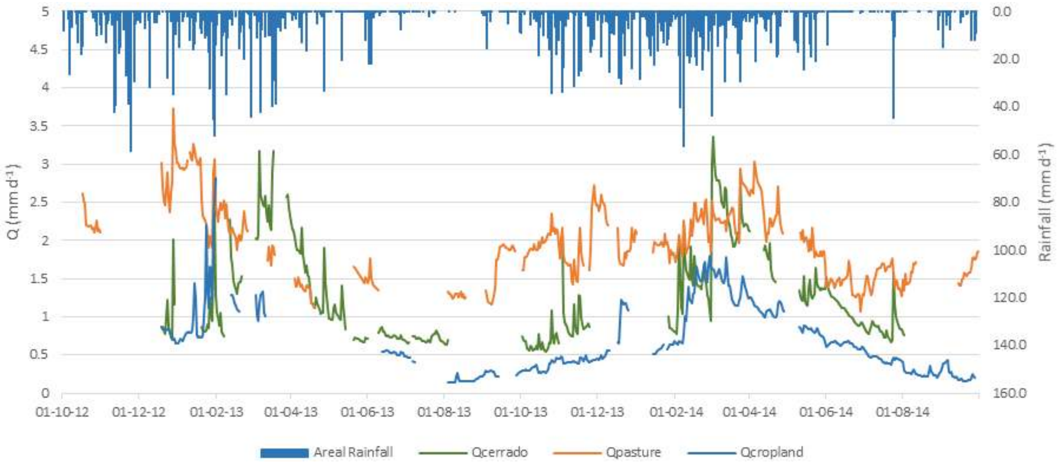


Figure 13. Normalized daily discharges and areal average rainfall in the three micro-catchments.

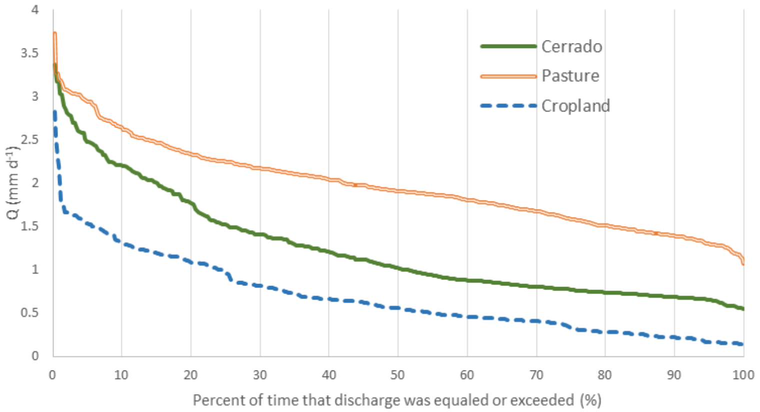
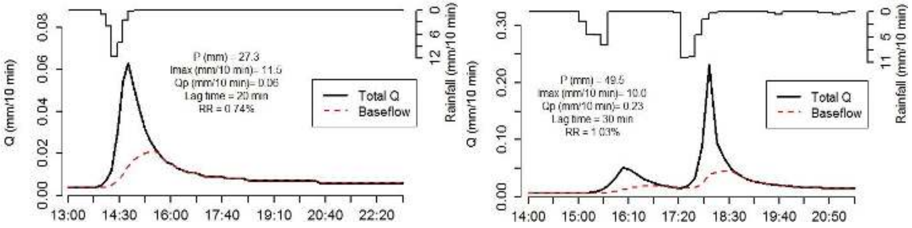
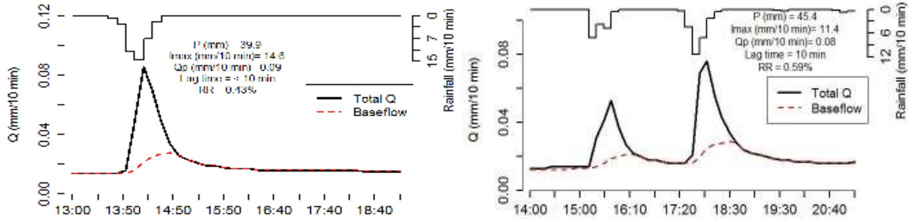


Figure 14. Flow duration curves for daily normalized discharge data from the three micro-catchments.



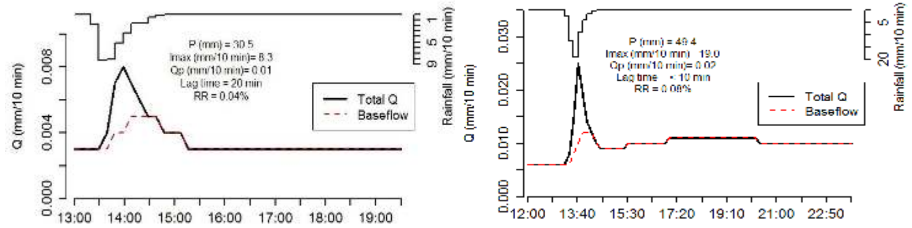
Event on October 25, 2013. Event on February 7, 2014.

(a) Cerrado



Event on October 25, 2013. Event on February 7, 2014.

(b) Pasture



Event on October 25, 2013. Event on February 2, 2014.

(c) Cropland

Figure 15. Storm hydrographs for selected rainstorms in the three micro-catchments, where I_{max} is the maximum rainfall intensity, and Q_{p} is the peak flow rate.