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Trends in water balance components across the Brazilian Cerrado

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Key Points:
- Water budget for the Brazilian Cerrado was evaluated
- Trends were assessed from remote sensing data, and in observed discharge
- Uncertainties were computed from in situ data

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Abstract We assess the water balance of the Brazilian Cerrado based on remotely sensed estimates of precipitation (TRMM), evapotranspiration (MOD16), and terrestrial water storage (GRACE) for the period from 2003 to 2010. Uncertainties for each remotely sensed data set were computed, the budget closure was evaluated using measured discharge data for the three largest river basins in the Cerrado, and the Mann-Kendall test was used to evaluate temporal trends in the water balance components and measured river discharge. The results indicate an overestimation of discharge data, due mainly to the overestimation of rainfall by TRMM version 6. However, better results were obtained when the new release of TRMM 3B42 v7 was used instead. Our results suggest that there have been (a) significant increases in average annual evapotranspiration over the entire Cerrado of 51 $\pm$ 15 mm yr^{-1}, (b) terrestrial water storage increases of 11 $\pm$ 6 mm yr^{-1} in the northeast region of the Brazilian Cerrado, and (c) runoff decreases of 72 $\pm$ 11 mm yr^{-1} in isolated spots and in the western part of the State of Mato Grosso. Although complete water budget closure from remote sensing remains a significant challenge due to uncertainties in the data, it provides a useful way to evaluate trends in major water balance components over large regions, identify dry periods, and assess changes in water balance due to land cover and land use change.

1. Introduction

The Brazilian Cerrado is one of the most important Brazilian biomes (being the second largest in South America) and covers an area of 2 million km^2 ($\sim$22% of the total area of Brazil). The physiognomies of the Cerrado vary from grassland to savanna to forest. Because of its endemic plant and vertebrate species, this biome has been classified as one of 25 global biodiversity hotspots [*Myers et al*., 2000]. Most of the Cerrado is located in Brazil's central highlands. The region plays a fundamental role in water resources dynamics because it distributes fresh water to the largest basins in Brazil and South America, including the São Francisco, Tocantins, Paraná, and Paraguai. These watersheds are crucial to the provision of water supply for people and animals, to maintaining ecohydrologic functioning, to providing water for industry, agriculture, navigation and tourism, and to hydroelectric energy production.

In the last few decades, the Brazilian savanna (Cerrado) has increasingly been replaced by agricultural crops [*Brannstrom et al*., 2008; *Sano et al*., 2010; *Jepson et al*., 2010]. Average annual deforestation were 0.69%, 0.37%, and 0.32% in 2002–2008 (85,047 km^2), 2008–2009 (7637 km^2) and 2009–2010 (6469 km^2), which are greater than the average annual deforestation rates of 0.44%, 0.40%, and 0.29% for the Amazon during the same periods [*IBAMA/MMA/UNDP*, 2011]. *Marris* [2005] warned that the Brazilian Cerrado is arguably under greater threat than the Amazon rain forest. By 2010, 48.5% of the area of the Cerrado had become devoted to anthropic land use, with only 50.9% remaining as native vegetation and 0.6% as water [*IBAMA/MMA/UNDP*, 2011]. It is, therefore necessary to understand the magnitudes and consequences of these changes on hydrological processes [*Costa et al*., 2003; *Coe et al*., 2011; *Loarie et al*., 2011], at local, regional, and continental scales.

Because 29% of the world's evaporation occurs in tropical forests and 21% occurs in savannas [*Miralles et al*., 2011], changes in land cover type from tropical forest and savanna to pasture and cropland have the potential to directly affect the global water balance. Savannas and forests have been classified as hotspots

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of reduced evapotranspiration (ET) because of deforestation [*Sterling et al*., 2013] and have been associated with shifts in the location, intensity and timing of rainfall events, lengthening of the dry season and changed streamflow [*Wohl et al*., 2012]. However, no consensus has yet emerged regarding the consequences of the Cerrado land cover change on water balance.

The use of ground-based measurements to assess water balance components remains a challenge around the globe, mainly because of inconsistent monitoring combined with high costs and a lack of data transparency and accessibility [*Sheffield et al*., 2009; *Voss et al*., 2013]. Remote sensing presents a valuable tool to help fill these data gaps and has the potential to yield better regional estimates of water balance dynamics and their relationship to climate change [*Sheffield et al*., 2012]. The recent release of the Moderate Resolution Imaging Spectroradiometer (MODIS) ET product MOD16 [*Mu et al*., 2011] permits a more direct accounting of the effects of land use change on ET than was possible in previous research on land use change [*Lathuillière et al*., 2012]. In addition, the high-quality time-series precipitation data generated by the Tropical Rainfall Measuring Mission (TRMM) and the direct measurement of the terrestrial water storage change by the Gravity Recovery and Climate Experiment (GRACE) have been used successfully in several studies [*Spracklen et al*., 2012; *Staver et al*., 2011; *Sheffield et al*., 2009; *Tapley et al*., 2004].

GRACE data provide vertically integrated estimates of changes in total terrestrial water storage (TWS) which include soil moisture, surface water, groundwater and snow. These data have been combined with models from the global land data assimilation system (GLDS) [*Rodell et al*., 2004a], *in situ* measurements, and other remote sensing data, to evaluate groundwater storage changes [*Scanlon et al*., 2012], surface water consumption [*Anderson et al*., 2012], regional flood potential [*Reager and Famiglietti*, 2009], drought [*Teuling et al*., 2013], reservoir storage changes [*Wang et al*., 2011], and water budget closure [*Sheffield et al*., 2009]. Thus, the use of high-quality precipitation, evapotranspiration, and TWS combined with observed data for precipitation and river flow makes it possible to evaluate trends in the water balance components over time.

Sheffield et al. [2009] developed one of the first studies to estimate the large-scale terrestrial water budget purely from remote sensing sources. Since then, several studies have been used remote sensing data to evaluate water balance components or water budget closure. However, the majority of these studies have been conducted in the northern hemisphere [*Wang et al*., 2014]. In addition, evaluations of new released remote sensing data such as TRMM version 7 have been concentrated in the northern hemisphere [*Amitai et al*., 2012; *Chen et al*., 2013]. Therefore, new studies in different conditions of climate, relief, and land cover should be conducted to assess the quality of remote sensing data from the measured data.

The objective of this study is to assess the water balance dynamics for the entire Brazilian Cerrado area, identify recent temporal trends in the major components, and assess the potential consequences of land cover and land use change for the water balance. We use satellite-based TRMM, MOD16 and GRACE data for the period from 2003 to 2010 to quantify the primary water balance components of the region and to evaluate trends. Furthermore, the uncertainties are computed for each remotely sensed data set and the budget closure is evaluated from measured discharge data for the three largest river basins in the Cerrado.

2. Materials and Methods

2.1. Cerrado Area

The Cerrado biome is home to the most important water sources in Brazil. It includes portions of 10 of Brazil's 12 hydrographic regions: the Tocantins (65% of the area of this hydrographic region is in the Cerrado), São Francisco (57%), Paraguai (50%), Paraná (49%), Parnaiba (46%), Occidental Atlantic Northeast (46%), Atlantic East (8%), Amazon (4%), Southeast Atlantic (1%), and Oriental Atlantic Northeast ($<$1%) regions (Figure 1a). These watersheds are crucial to the water supply for people and animals, to maintaining function of ecohydrologic systems in the Cerrado and others biomes such as Pantanal (wetland) and Caatinga (semiarid region), and to providing water for industry, agriculture, navigation and tourism. Furthermore, the Brazilian energy matrix depends on hydroelectricity for more than 80% of its total energy supply, and the largest hydroelectric facilities are on rivers in the Cerrado, such as the Itaipu, Tucuruí, Iha Solteira, Xingó and Paulo Afonso. With regards to groundwater, approximately one half of the outcrop areas of the Guarani aquifer system, one of the world's largest aquifer systems [*Wendland et al*., 2007], is located in the Cerrado

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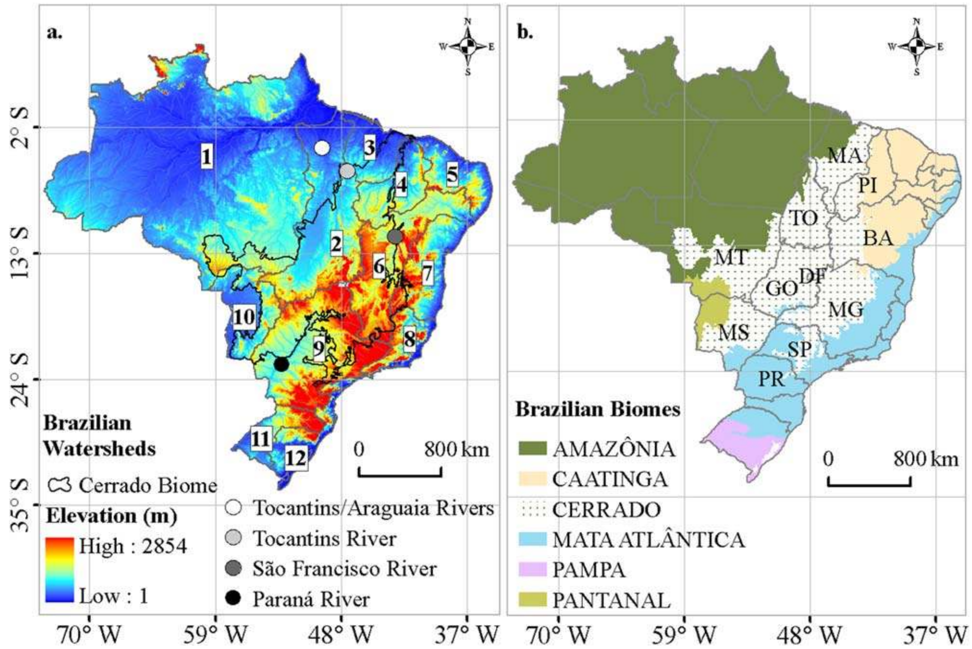

Figure 1. (a) Map of Brazilian watersheds and gages for the observed discharge represented by circles. Watersheds: (1) Amazonica; (2) Tocantins; (3) Oc. A. Northeast; (4) Parnaiba; (5) Ori. A. Northeast; (6) São Francisco; (7) East Atlantic; (8) Southeast Atlantic; (9) Paraná; (10) Paraguai; (11) Uruguai; (12) South Atlantic. (b) The Cerrado biome and its borders with other Brazilian biomes. States: Bahia—BA; Maranhão—MA; Tocantins—TO; Piaui—PI; Mato Grosso do Sul—MS; Mato Grosso—MT; Goiás—GO; Distrito Federal—DF; Minas Gerais—MG; São Paulo—SP; and Paraná—PR.

biome. Therefore, in terms of water resources, this biome is one of the largest and most important in Brazil and South America, and plays a strategic role in Brazilian development in several sectors.

According to the Köppen climate classification system [*Peel et al*., 2007], the predominant climates of the Cerrado (by percentage of the area) are the following: Aw, equatorial, winter dry (83%); Cwb, winter dry, warm temperate, warm summer (8%); Cfa, humid, warm temperate, hot summer (5%); and Cwa, dry winters, warm temperate, hot summer (4%). The average annual precipitation in the Cerrado as a whole is approximately 1500 mm, with lower values (near 700 mm) in the northeast region, in the area of transition from the Cerrado to the Caatinga biome. The highest average annual precipitation (greater than 2000 mm) is in the northwest, in the area of transition from the Cerrado to the Amazon Forest biome. The wet season is from October to March, and the dry season is April to September.

The Cerrado is bordered by four of the five Brazilian biomes (Figure 1b) and therefore has high biodiversity and a large variety of vegetation physiognomies and compositions [*Ratter et al*., 1997]. The vegetation in the Cerrado is usually classified according to the six classes listed in Table 1.

2.2. Data Source

To evaluate the water balance in space and time, we use time-series precipitation data obtained from the Tropical Rainfall Measuring Mission (TRMM 3B42 version 6 and the new release version 7), evapotranspiration from the Moderate Resolution Imaging Spectroradiometer (MODIS) ET product MOD16, and terrestrial water storage from the Gravity Recovery and Climate Experiment (GRACE) for the years from 2003 to 2010.

The TRMM Multi-satellite Precipitation Analysis (TMPA) combines precipitation estimates from various satellite systems, as well as land surface precipitation gauge analysis where feasible. The intent of TMPA

Table 1. Cerrado Vegetation Gradient Classification[a]

Brazilian Names	International Names	Arboreous Cover (%)	Height of Trees (m)
"Campo limpo"	Cerrado grassland	<1	<1
"Campo sujo"	Shrub Cerrado	$<5\%$	<2
"Cerrado ralo"	Shrub Cerrado	5–20	2–3
"Cerrado sensu stricto"	Wooded Cerrado	20–50	3–6
"Cerrado sensu stricto denso"	Cerrado woodland	50–70	5–8
"Cerradão"	Dense Cerrado woodland	50–90	8–15

[a]Source: *Furley* [1999]; *Ferreira and Huete* [2004].

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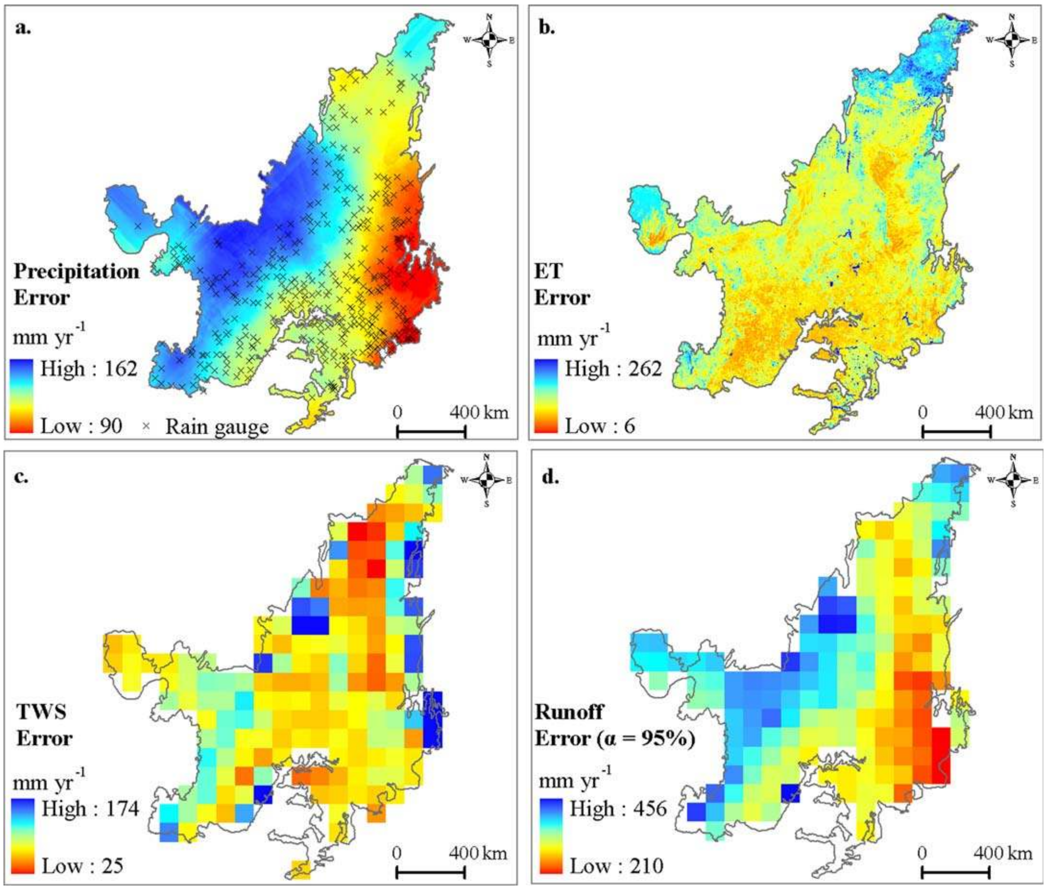

Figure 2. Errors computed for each water balance component.

is to produce a calibration traceable back to the single "best" satellite estimate of global precipitation at fine spatial and temporal scale (0.25° × 0.25° and 3 hourly) over 50°N–50°S [*Huffman et al*., 2007]. The new release of the TRMM (version 7) has been assessed in some regions showing a significant improvement in precipitation accuracy over the last version 6 [*Xue et al*., 2013; *Chen et al*., 2013; *Yong et al*., 2014; *Ochoa et al*., 2014]. In this study, we use the TRMM Multi-satellite Precipitation Analysis data (TRMM 3B42 v6 and v7) provided by National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) available at http://mirador.gsfc.nasa.gov/.

To validate the TRMM 3B42 v6 and v7 data we use pluviometric measurements from 402 rain gauges (see Figure 2a) obtained in the Cerrado area between 2000 and 2005 by the Agência Nacional de Águas (ANA) and downloaded from the ANA website (http://hidroweb.ana.gov.br/). We find the correlation between TRMM and rain gauge data to be significant at the $p = 0.05$ level, with a correlation coefficient greater than 0.8. The monthly and annual values of correlation coefficient, bias, root mean squared error, and standard deviation of differences are presented in Table 2. We also find that while TRMM v6 and v7 data both overestimate the measured data, the v7 provide better results than v6. Therefore, in this study we use TRMM 3B42 v7 to estimate the water balance over the Brazilian Cerrado.

Table 2. Relation Between TRMM Data and Rain Gauges on Monthly and Annual Scales

	Monthly		Annual	
	TRMM v6	TRMM v7	TRMM v6	TRMM v7
Correlation coefficient, R	0.86	0.90	0.82	0.90
Bias (mm)	6.42	5.98	95.73	61.56
Root mean squared error, RMSE (mm)	62.28	53.58	207.05	160.94
Standard deviation of differences, SD (mm)	61.17	52.45	183.63	148.74

We use evapotranspiration data provided by the Moderate Resolution Imaging Spectroradiometer (MODIS) ET product MOD16 (ftp://ftp.ntsg.umt.edu/pub/MODIS/Mirror/MOD16/), which are

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Table 3. Main Features of the Measured Discharge Time Series

Location	River Basin	Area (km^2)	Average Annual Precipitation (mm)	Time Series (Years)
22° 42′S and 53° 10′W	Paraná	670,000	1450	1985–2010
11° 33′S and 43° 16′W	São Francisco	345,000	950	1955–2012
5° 47′S and 47° 28′W	Tocantins	298,559	1600	1974–2012
3° 45′S and 49° 38′W	Tocantins/Araguaia	742,300	1700	1978–2012[a]

[a]This time series was not used to evaluate water budget because in the measured data was not continuous through the study period (2003–2010). This time series was used to evaluate long time trends in the Tocantins/Araguaia River Basin.

available at 1 km^2 spatial resolution and temporal resolution of 8 day, monthly, and annual intervals. ET is estimated using a recently improved algorithm [*Mu et al*., 2011] that uses remote sensing inputs (MODIS satellite observations of land cover, leaf area index, albedo and fraction of absorbed photosynthetically active radiation) and daily meteorological inputs (air pressure, air temperature, humidity, and radiation) to estimate ET using the Penman–Monteith equation. *Ruhoff et al*. [2013] intercompare 8 day average MOD16 ET estimates and flux tower measurements between 2000 and 2002 for the sugarcane plantation and the natural Cerrado vegetation in Brazil, and find correlation coefficients and root mean squared errors of R = 0.82, RMSE = 0.46 mm d^{-1} for sugarcane, and R = 0.78, RMSE = 0.78 mm d^{-1} for Cerrado. They conclude that the MOD16 data provides accurate ET estimates, mainly over the long term (monthly and annual scales), and thus shows potential for spatial and temporal monitoring of ET in Brazil. *Loarie et al*. [2011] use data from 10 eddy covariance flux towers to validate ET estimates from MOD16 for the Brazilian Cerrado between 2000 and 2006. Their results indicate that, compared with observed data, annual ET averages vary less than ±4% for the savanna areas, ±5% in the tropical forest areas and ±13% in pasture/agriculture areas of the Cerrado.

The Gravity Recovery and Climate Experiment (GRACE) satellites have provided, since mid-2002, measurements of month-to-month variations of Earth's gravity field by measuring the distance between two orbiting satellites. Variations in Earth's gravity field are attributed to changes in terrestrial water storage (TWS) after removal of atmospheric and ocean bottom pressure changes [*Tapley et al*., 2004]. These data have been successfully used for hydrological studies in regions larger than 200,000 km^2 [*Famiglietti and Rodell*, 2013]. The GRACE project provides time variable GRACE global gravity solutions from three processing centers: Geoforschungs Zentrum Potsdam (GFZ), the Jet Propulsion Laboratory (JPL), and the Center for Space Research (CSR) at the University of Texas. We use the direct measurement of TWS provided by GRACE release 05, available with spatial resolution of 1° × 1° [*Landerer and Swenson*, 2012]. GRACE land data were processed by Sean Swenson (NASA MEaSUREs Program), and are available via the Jet Propulsion Laboratory's TELLUS website at http://grace.jpl.nasa.gov with monthly temporal resolution.

To evaluate the water budget closure, we use observed discharge data from the three largest river basins in the Cerrado, Paraná, São Francisco and Tocantins (Figure 1a). The data are available at http://hidroweb.ana.gov.br/, and the main features of time series of discharge studied are presented in the Table 3.

2.3. Water Balance Dynamics

The water balance equation (equation (1)) is based on the principle of mass conservation, also known as the continuity equation. To analyze the water balance of the Cerrado biome, we use a simplified equation, considering only the largest inputs and outputs at the monthly and annual timescales.

$$\frac{dS}{dt} = P - ET - Q \tag{1}$$

where S is the water storage change with time, P is precipitation, ET is evapotranspiration and Q is runoff.

Each monthly GRACE grid represents the mass anomaly defined as the difference in the masses for that month (m) and the baseline average over January 2004 to December 2009. As the GRACE data are given as mass anomalies for approximately 30 day observation periods at irregularly spaced intervals, the computation of monthly TWS change to approximate dS/dt is not straightforward. In this study, the simple derivative method is used to estimate TWS change at a monthly scale. This method corresponds to the difference between two GRACE data points, which represents the average change in storage between the observation periods [*Long et al*., 2014; *Wang et al*., 2014]:

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$$\frac{dS}{dt} \approx \frac{TWS}{dt} \approx \frac{TWS(t+1)-TWS(t)}{\Delta t} \quad (2)$$

To make the other water balance components comparable with the TWS change at monthly steps, we use the monthly average of precipitation (TRMM), evapotranspiration (MOD16), and observed discharge to account for their contribution to the mass change [*Rodell et al*., 2004b; *Sheffield et al*., 2009; *Wang et al*., 2014]:

$$\frac{dS}{dt} = \left(\frac{P_{(t+1)}+P_t}{2}\right) - \left(\frac{ET_{(t+1)}+ET_t}{2}\right) - \left(\frac{Q_{(t+1)}+Q_t}{2}\right) \quad (3)$$

We use equation (3) to estimate d*S/*d*t* and to assess the TWS change from GRACE at monthly scale. Furthermore, these results are used to discuss the seasonality of water balance in the Brazilian Cerrado. The annual water budget is computed to estimate the runoff as the residual of equation (1) and the results are assessed from the observed discharge (Table 3). In addition, the results of annual water balance components are used to estimate trends in each water balance component across the Brazilian Cerrado (see section 2.4).

2.4. Uncertainty and Trend Analysis

The computed annual runoff is obtained as a residual of precipitation (TRMM), evapotranspiration (MOD 16) and terrestrial water storage (GRACE) (equation (1)). Uncertainties in the runoff estimates are determined for each pixel from the method of moments (MOM) derived from a first order approximation of the Taylor series expansion [*Refsgaard et al*., 2007]. If the components are independent of each other (no covariance between any two components), this MOM expansion reduces to Gaussian error propagation [*Armanios and Fisher*, 2014]. Such an approach has been used reliably in numerous hydrological studies where the water budget was computed from GRACE and other remote sensing data [*Rodell et al*., 2004b; *Sheffield et al*., 2009; *Armanios and Fisher*, 2014; *Voss et al*., 2013; *Long et al*., 2014]. The 95% confidence limits on the residual (runoff) are calculated as $\pm 2\sigma_{\text{runoff}}$.

$$\sigma_{runoff} = \sqrt{\sigma^2{}_{TRMM} + \sigma^2{}_{MOD16} + \sigma^2{}_{GRACE}} \quad (4)$$

where σ is the error estimated to each component.

The error estimated in TRMM v7 data is computed as the standard deviation of differences between TRMM and the value at each of the 402 corresponding rain gauges (see section 2.2), and then an error map is developed by kriging. To estimate the error in MOD16 data we use the Cerrado land cover map of 2010 [*IBAMA/MMA/UNDP*, 2011] to find the regions corresponding to native Cerrado and anthropic (pasture/agriculture) vegetation. Then we use the error values estimated by *Loarie et al*. [2011] for these two land cover types ($\pm$4% for the Cerrado and $\pm$13% in pasture/agriculture areas) to estimate the uncertainties associated with the average ET values (2003–2010) for the entire Cerrado.

GRACE data have two distinct causes of error. The first is the loss of signal due to measurement error (based on the GRACE footprint) and the second is the "leakage" error (the contamination of a signal with a stronger adjacent signal) [*Reager and Famiglietti*, 2013]. Thus, data preprocessing is necessary, which includes application of a destriping filter and a spherical harmonic filter cutoff at degree 60, with subsequent rescaling to restore much of the energy removed by these filtering processes [*Swenson and Wahr*, 2006; *Proulx et al*., 2013]. The gridded fields of leakage, GRACE measurement errors, and scale factor have been processed by Sean Swenson (NASA MEaSUREs Program), and are available at http://grace.jpl.nasa.gov. The total error at each GRACE grid point is obtained by summing leakage and measurement errors in quadrature according to *Landerer and Swenson* [2012]. More details about GRACE error estimation is provided by *Landerer and Swenson* [2012] and *Swenson and Wahr* [2006]. Errors in TWS change used in equation (4) were computed from uncertainties in TWS anomaly for back and forward months added in quadrature [*Long et al*., 2014].

We analyze the annual values of precipitation, evapotranspiration, terrestrial water storage and runoff obtained from remote sensing data, and observed long-term discharge data to determine if there are statistically significant trends in the study period. The trend analysis is performed at each pixel using the Mann-Kendall test with Sen's slope estimates, with a 0.05 significance level (95% confidence level) using Matlab 7.12.0 (the p value is the probability of getting a value of the test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true––i.e., time series values are independent,

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Table 4. Studies of Evapotranspiration in the Brazilian Cerrado[a]

Latitude	Longitude	State	Years	Precipitation	Land Cover	Evapotranspiration	Method	Authors
21° 37′S	47° 38′W	SP	2005–2009	1478	Cerrado sensu stricto	830.5 mm yr^{-1}	Eddy covariance	*Bruno* [2009]
21° 35′S	47° 36′W	SP	2004–2005	1217	Cerrado sensu stricto	981.0 mm yr^{-1}	Eddy covariance	*Bruno* [2009]
21° 35′S	47° 36′W	SP	2005–2006	725	Cerrado sensu stricto	820.0 mm yr^{-1}	Eddy covariance	*Bruno* [2009]
21° 35′S	47° 36′W	SP	2006–2007	1721	Cerrado sensu stricto	994.0 mm yr^{-1}	Eddy covariance	*Bruno* [2009]
21° 35′S	47° 36′W	SP	2007–2008	1618	Cerrado sensu stricto	942.0 mm yr^{-1}	Eddy covariance	*Bruno* [2009]
15°56′S	47° 53′W	DF	2001–2003	1440	Cerrado Denso	823.0 mm yr^{-1}	Eddy covariance	*Giambelluca et al.* [2009]
15°56′S	47°53′W	DF	2001–2003	1440	Campo Cerrado	689.0 mm yr^{-1}	Eddy covariance	*Giambelluca et al.* [2009]
15°56′S	47°51′W	DF	1998–1999	1017	Campo Sujo	861.9 mm yr^{-1}	Eddy covariance	*Santos et al.* [2003]
15°56′S	47°53′W	DF	1996–1998	1500	Cerrado denso	dry season = 1–4 mm d^{-1} and wet season = 5–8 mm d^{-1}	Water balance in soil (depth of 7.5 m)	*Oliveira et al.* [2005]
15°56′S	47°53′W	DF	1996–1998	1500	Campo Sujo	dry season = 0–9 mm d^{-1} and wet season = 4–5 mm d^{-1}	Water balance in soil (depth of 4 m)	*Oliveira et al.* [2005]
15°33′S	47°36′W	DF	2002–2006	1453	Cerrado sensu stricto	dry season = 20–25 mm month^{-1} and wet season = 75–85 mm month^{-1}	Water balance in soil (depth of 7 m)	*Garcia-Montiel et al.* [2008]
11°24′S	55°19′W	MT	1999–2000	2095	Transitional Amazonia–Cerrado forest	2.82 (± 0.33) mm d^{-1}	Eddy covariance	*Vourlitis et al.* [2002]
9° 49′S	50° 08′W	AM	2003/2004 2004/2005 2005/2006	1692 1471 1914	Transitional Amazonia–Cerrado forest	1361 mm yr^{-1} 1318 mm yr^{-1} 1317 mm yr^{-1}	Eddy covariance	*Borma et al.* [2009]

[a]Years = length of record, Elevation (m), Precipitation = average annual precipitation (mm), Methods = evapotranspiration calculation methods. States: AM, Amazonas; MT, Mato Grosso; DF, Distrito Federal and SP, São Paulo.

identically distributed). We use the statistically significant values of Sen's slope at each pixel to create trends maps using ArcGis 9.3 software.

3. Results and Discussion

3.1. Evaluation of Estimated Errors

Figure 2a shows that the main source of uncertainty in the computed runoff of the water budget is uncertainty in the TRMM data. In general, TRMM data from version 6 tend to overestimate rainfall in the Brazilian Cerrado, mainly in the southern portion, although there is underestimation in northeastern areas as well. Previous studies have reported overestimation in southern Brazil, and underestimation in the northeastern Cerrado and Amazon regions [*Franchito et al*., 2009; *Rozante et al*., 2010]. However, we find that the new version 7 of TRMM notably reduces the bias from the measured precipitation data from 9.5 to 6%. Other similar research has shown significant improvement for TRMM 3B42 v7, thus indicating its potential for application in hydrological studies [*Amitai et al*., 2012; *Xue et al*., 2013; *Chen et al*., 2013]. Furthermore, to evaluate overall annual water balance these errors are reasonable, representing less than 10% of the annual rainfall average over the entire Cerrado.

Figure 2b shows that the errors estimated for ET are largest in the northern and smallest in the central and southern regions. We use the PROBIO land cover [*PROBIO*, 2004] and MOD16 ET data to evaluate the ET range in 2002 for the main cover classes of the Cerrado biome (Table 4), and find that the ranges of ET values obtained by MOD16 are similar to values obtained in previous studies that used eddy covariance flux towers or measurements of soil water balance (Tables 4 and 5). For example, for the "Cerrado sensu stricto" we find mean and standard deviation values of 938.6 ± 323.2 mm yr^{-1} for the ET obtained from MOD16 data, whereas the values reported in the literature for this cover type range from 830.5 to 994.0 mm yr^{-1} (Table 4). ET values of reforestation presented in Table 4 are similar to the values obtained in studies of eucalyptus, i.e., 1179.5 ± 78.5 mm yr^{-1} [*Cabral et al*., 2010], which is the main type of reforested former cropland in the Cerrado area. The average of 2.6 ± 0.9 mm d^{-1} reported by *Meirelles et al.* [2011] for the *Brachiaria brizantha* pasture in the Brazilian savanna region is comparable to

Table 5. Average and Standard Deviation of Annual Evapotranspiration in the Cerrado Biome in 2002

Main Land Cover[a]	Evapotranspiration (mm yr^{-1})	Area[b] (%)
"Cerradão"	1272.0 ± 363.7	1.19
"Cerrado sensu stricto denso"	1268.5 ± 313.0	5.82
Savanna ("cerrado sensu stricto")	938.6 ± 323.2	46.88
Reforestation	1040.8 ± 258.1	1.01
Cropland	731.0 ± 239.4	10.32
Pasture	720.7 ± 202.6	29.29

[a]The main land cover classes, PROBIO map, year 2002, 1:250,000.
[b]Percentage of area occupied by the land cover types.

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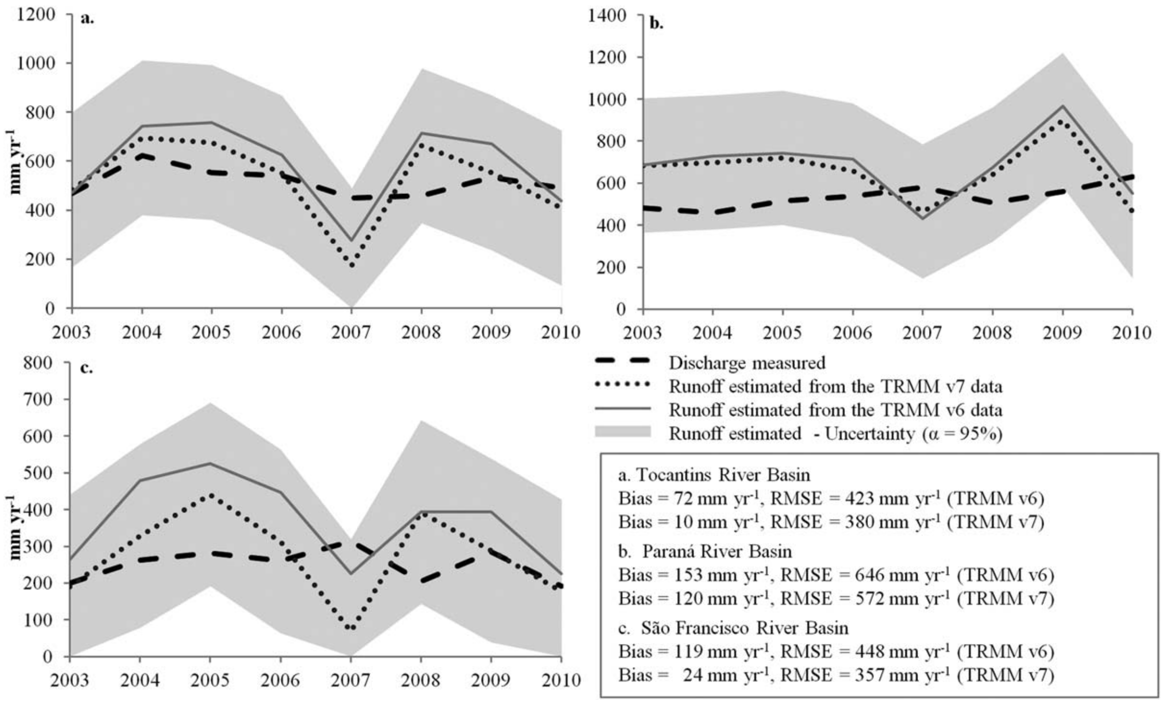

Figure 3. Comparison between runoff estimated and observed discharge. The area in gray color represents the uncertainty estimated with 95% significance in accordance with equation (2).

the annual values presented in Table 4. Croplands are not classified in the used PROBIO map, so no comparison between ET results for cropland cover is done.

The total errors from GRACE (the sum of leakage and measurement errors in quadrature) (Figure 2c) are in agreement with those reported in the literature [*Landerer and Swenson*, 2012; *Proulx et al*., 2013]. Runoff uncertainties, at 95% significance (Figure 2d), are larger, and for some regions and years are larger than estimated runoff (Figure 3). However, the estimated values are similar to those from previous studies such as *Sheffield et al*. [2009] and *Armanios and Fisher* [2014], in which runoff was obtained as a residual of remote sensing data. We note that the greatest uncertainty values are concentrated in the western region, but in general the values are less than 300 mm yr^{-1} (Figure 2d).

The runoff computed as a residual of the water budget equation using the TRMM v6 data overestimates the *in situ* discharge, due mainly to TRMM v6 overestimation of the rainfall. Similar results are reported by [*Sheffield et al*., 2009] and [*Gao et al*., 2010]. However, we note an improvement in results when the runoff is computed using the TRMM v7 data (Figure 3). The biases for Tocantins and São Francisco river basin when using TRMM v7 are around 7 times less than the biases computed using TRMM v6. The uncertainties estimated for runoff (presented at 95% significance) are high, and for some regions and years are larger than the runoff estimate itself (as obtained from the water budget equation). However, its important to note that the measured discharge values are themselves not precise, with uncertainties ranging between 2% (under ideal conditions) to over 20% [*Sauer and Meyer*, 1992]. Further, we find the behavior of increases and decreases in the estimated runoff and measured discharge to be similar, except for 2007 in the Paraná and São Francisco River basins, which indicate a slight increase in discharge whereas the estimated runoff decreases in that year.

3.2. Water Budget and Trends in the Cerrado

The water storage change (d*S*/d*t*) computed from equation (1) shows a significant correlation with TWS change obtained from GRACE data for all watersheds studied (Figures 4d–4f). Our results indicate that GRACE data may represent the TWS change in the Brazilian Cerrado satisfactorily; allowing assessment of the seasonality of the water balance in this region. These results are consistent with those reported by *Almeida et al*. [2012] and *Frappart et al*. [2013] for the Amazon region. The El Niño events of 2007 and 2010

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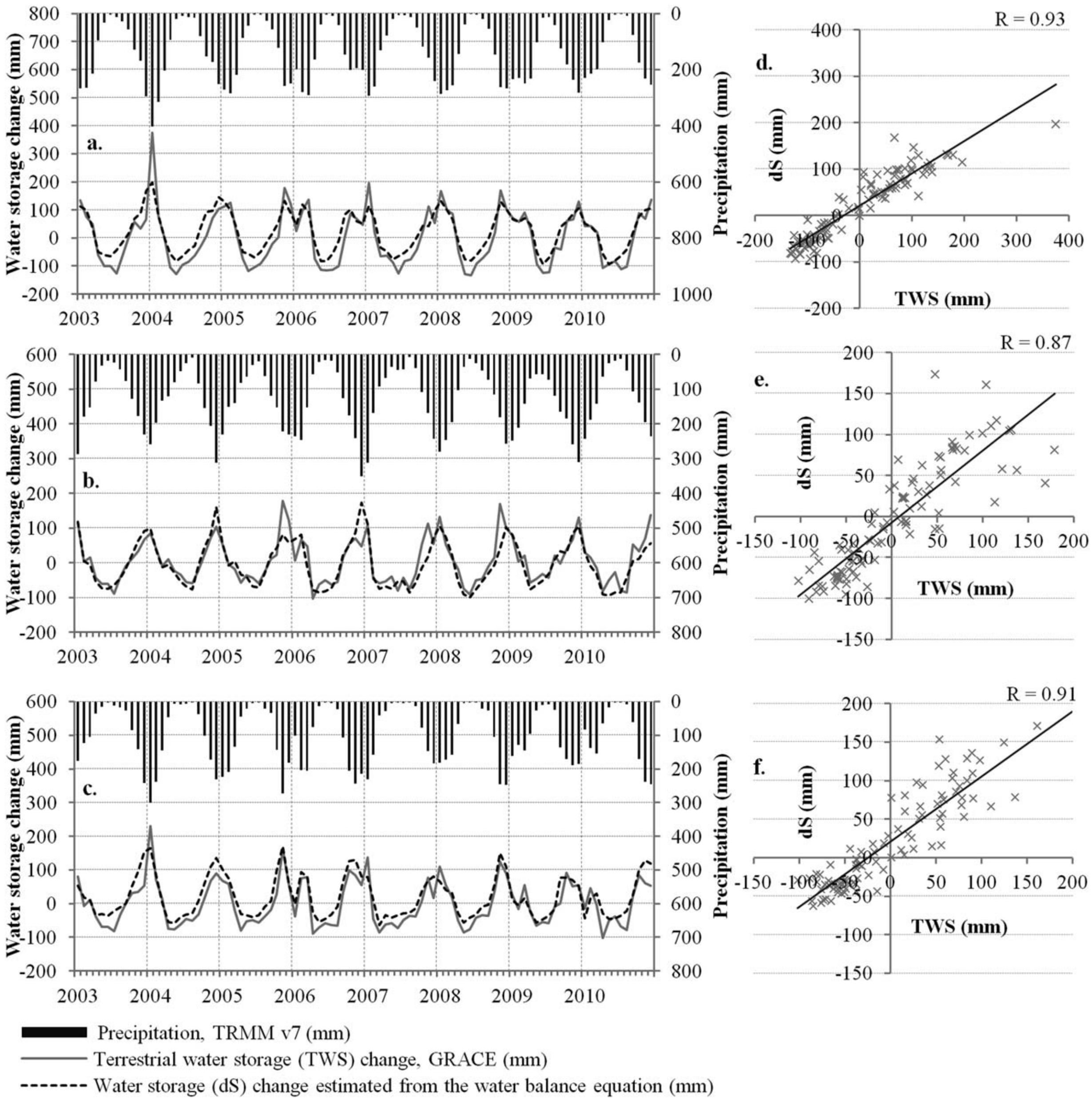

Figure 4. Monthly water storage change (dS) estimated from the water balance equation (equation (1)) and the TWS obtained from GRACE data, and coefficients of correlation between them, (a and d) the Tocantins River basin, (b and e) the Paraná River basin, and (c and f) the São Francisco River basin.

are probably responsible for the major droughts in the watersheds studied. In these years the drought season was longer than in the other years; i.e., the amount of rainfall between April to September (dry season in the Cerrado) was low, causing less water storage and more dryness in the period (Figures 4a–4c). In 2007, the total rainfall in those months was on average 40% lower than the average rainfall (260 mm, 310 mm, and 152 mm) in the same period in Tocantins, Parana and São Francisco river basins, respectively.

There is a correspondence in time of the severe 2010 drought in the Amazonia [*Lewis et al*., 2011], with the one experienced in the Brazilian Cerrado, though the 2005 Amazonian drought was not recorded in the Cerrado with the same severity [*Marengo et al*., 2008]. Although the drought years observed for the Tocantins, São Francisco, and Paraná River basins occurred in similar periods (Figures 4a–4c), it is possible to identify different features in each river basin, mainly between São Francisco and Tocantins, the driest and the wettest basins, respectively. The São Francisco river basin had lower precipitation and water storage than the Tocantins River basin (on average less than 28% and 70%, respectively).

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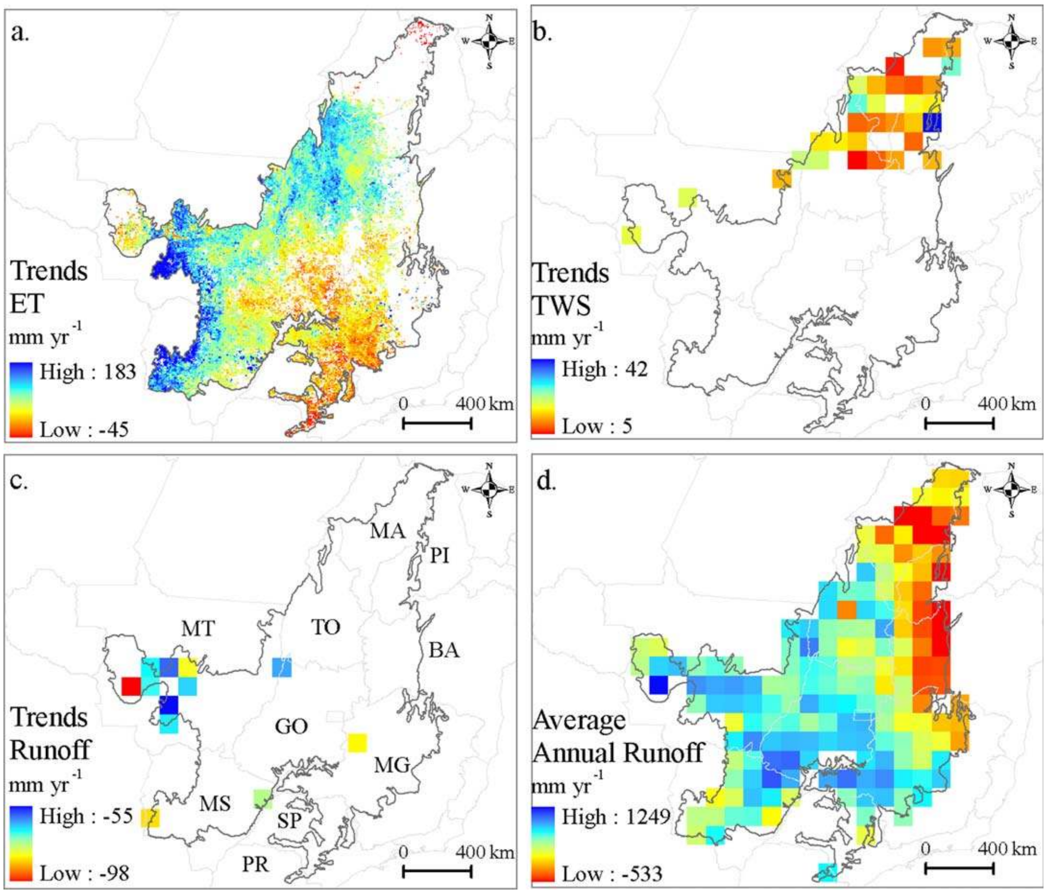

Figure 5. Significant trends in annual water balance components between 2003 and 2010 for: (a) evapotranspiration, (b) terrestrial water storage, and (c) runoff. White means no trend. We did not find any significant trends in annual precipitation. (d) Average annual runoff (2003–2010). Each trend analysis was evaluated using Mann-Kendall test and with Sen's slope estimates (95% confidence level).

The major drought occurred in 2007, when annual precipitation (1201 mm) was ~20% less than the mean for the entire period. The States of Bahia-BA, the north of Minas Gerais-MG, Piaui-PI and Maranhão-MA had several regions with water deficits (ET > P). This can be noted in the São Francisco River basin where some of these states are located (Figure 5d). These regions have borders with the Caatinga biome and receive less rainfall and more radiation than other regions of the Cerrado [*Hastenrath*, 2012], consequently less water storage and runoff (Figures 4c and 5d). The 2007 drought was considered severe especially in the north of Minas Gerais-MG and in the Brazilian northwest, with a shortage on water availability, accompanied by crop loss and hydroelectric production loss. On November 2007, the Sobradinho reservoir (which has water springs in the Cerrado area) stored only 15% of its total volume capacity, and an emergency was decreed in 158 cities in the State of Paraiba [*Marengo*, 2008].

The annual ET tended to decrease in the western part of Mato Grosso-MT, North of Maranhão-MA and part of São Paulo-SP and Minas Gerais-MG up to 45 mm yr^{-1} on average during the study period (Figure 5a). The states of MT and MA had the greatest deforestation index, representing about 40% of the total deforestation between 2002 and 2010 [*IBAMA/MMA/UNDP*, 2011]. However, we find a significant trend of increasing annual ET on average over the entire Cerrado of 51 ± 15 mm yr^{-1}, and changes as large as 183 mm yr^{-1} averaged over the western parts of Mato Grosso and Mato Grosso do Sul (near the Pantanal––wetland Biome) and northern parts of Tocantins-TO (near the Amazon rainforest Biome) (Figure 5a). Our results are consistent with those presented by *Zeng et al*. [2012], who found the global land ET increased from 1982 to 2009 with the Amazon and part of Cerrado biome having the highest rates of ET increase.

We can suggest at least three hypotheses to explain the increase in annual ET. The first is that anthropic activities that reduce ET, such as deforestation, can be offset by other anthropic activities that act in an

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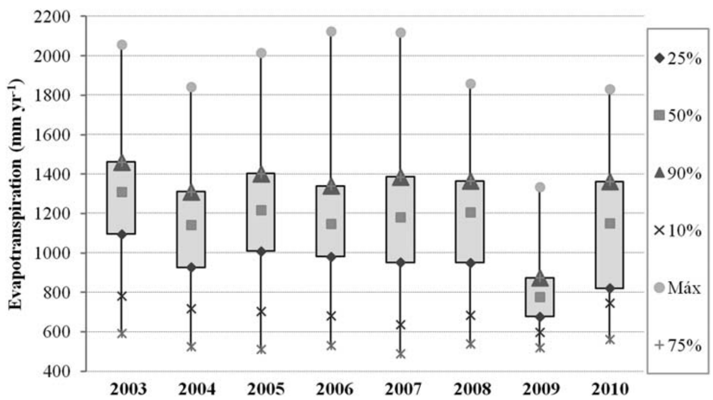

Figure 6. Evapotranspiration in an area of 45 km^2 that was deforested in 2009, located in the State of Maranhão-MA (42.87°W 3.32°S). We used the values of all the pixels (Number of pixels, N=54) in this polygon to develop this figure.

opposite manner, such as irrigation and reservoir creation [*Gordon et al*., 2005; *Sterling et al*., 2013]. The second is that the land use change in the Cerrado biome of the pasture to crops [*Phalan et al*., 2013] could have increased the ET in the study period. To evaluate this hypothesis, we examine annual ET data in an area of the 45 km^2 that was deforested in 2009, located in the State of Maranhão-MA (42.87°W 3.32°S). These data indicate that the initial consequence of deforestation was an ET decrease of 36% (429 mm) between 2008 and 2009, followed in the second year by an ET increase to a level near the predeforestation level (Figure 6). In other words, new crop cultivation in the area of deforestation decreased the ET for only a year, after which it returned to a level not statistically different from the original native vegetation. *Loarie et al*. [2011] reported similar results in two other Cerrado areas (located in States of Mato Grosso-MT and São Paulo-SP). They found that conversion of Cerrado to pasture led to a decrease of ET, whereas conversion of pasture to sugarcane led to an increase of ET. Therefore, land use and land cover change promote changes in ET, and for large regions with multiple types of land use change and weather variation it becomes difficult to evaluate changes in this component, due to compensation between activities that increase and decrease ET [*Gordon et al*., 2005]. The third hypothesis is that the ET increases have been accelerating due to increased evaporative demand associated with rising radiative forcing, atmospheric CO_2 concentrations, and temperatures [*Jung et al*., 2010]. All these hypotheses must be carefully studied in the future with a long enough data period to evaluate the factors that are influencing the ET changes in this region.

Figure 5b indicates that a significant increasing trend in annual terrestrial water storage (TWS) with average changes of 11 $\pm$ 6 mm yr^{-1}, in the States of Maranhão-MA, Piaui-PI, and Tocantins-TO, northeast region of the Brazilian Cerrado. The TWS values tend to increase with changes in land uses that promote more infiltration, percolation, and groundwater recharge. Note that the native Cerrado tends to promote more infiltration than areas used for pasture and cropland. Meanwhile, the canopy interception values in the native Cerrado vegetation are approximately 20% of gross rainfall [*Oliveira et al*., 2014] and the greater use of water by native Cerrado vegetation for transpiration [*Giambelluca et al*., 2009] tends to result in smaller groundwater recharge than for pasture and cropland [*Lucas et al*., 2012]. In a Cerrado region, *Wendland et al*. [2007] found values of groundwater recharge ranging from 145 to 703 mm yr^{-1} in pasture, 324–694 mmyr^{-1} in orange citrus, and 37–48 mm yr^{-1} in Eucalyptus. Therefore, increasing trends in TWS found in the northeast region of the Brazilian Cerrado may indicate a deforestation process or other changes in the land use and cover that promot more infiltration and groundwater recharge, such as crops or pasture.

Despite the fact that precipitation does not show a significant trend during the study period, probably because of the relatively short time series available, we find that estimated annual runoff tends to decrease by an average of 72 $\pm$ 11 mm yr^{-1} in a few isolated spots and in the western of the State of Mato Grosso-MT (Figure 5c). From the analysis using the long-term data (1952–2012), we note a significant trend in decreasing discharge for the Tocantins (18.3 km^3 yr^{-1}) and Tocantins/Araguaia (40.3 km^3 yr^{-1}) River basins (Figures 7a and 7b); whereas we do not find any trend in the São Francisco and Paraná River basins (Figures 7c and 7d). In two watersheds located in the headwater of Tocantins and Araguaia Rivers (areas = 175,360 km^2 and 82,632 km^2), previous studies have reported that annual mean discharge increased 24% from the 1979 to 1998, and 25% between 1970 and 1990 in these two rivers, respectively [*Costa et al*., 2003; *Coe et al*., 2011]. However, the difference between the watersheds sizes studied in the present paper and in these two previous studies may have caused different results. Some previous large-

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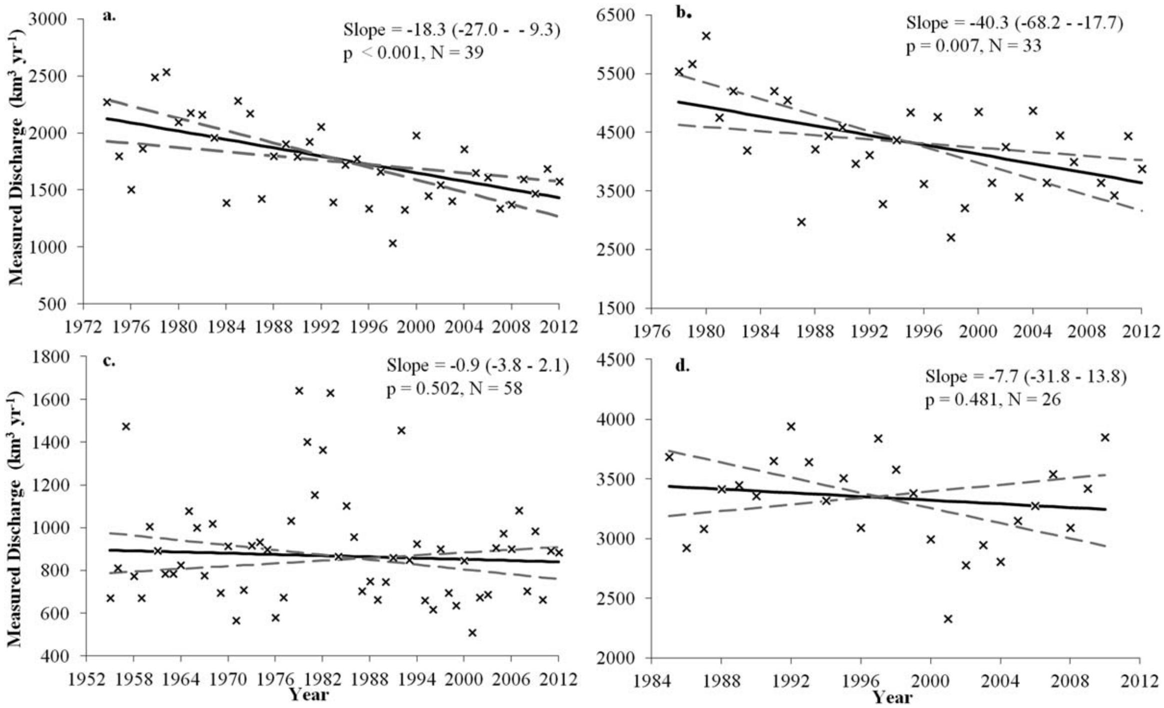

Figure 7. Long-term of observed annual discharge for: (a) Tocantins River; (b) Tocantins/Araguaia River basin; (c) São Francisco River basin; and (d) Paraná River basin. Where the p values less than 0.05 show significant trend to measured discharge.

scale studies have presented results that do not agree with the results from a more detailed scale [*Wilk et al*., 2001; *Costa et al*., 2003]. In other words, the response times for watersheds are dependent on the scale studied. Thus, in small watersheds it is usually easier to find a response to land use and land cover changes on the water balance components than in large watersheds.

4. Conclusions

We evaluate the water budget for the Brazilian Cerrado from remote sensing data of precipitation (TRMM), evapotranspiration (MOD16), and terrestrial water storage (GRACE) for the period from 2003 to 2010. We assess trends in each water balance component obtained from remote sensing data, and in observed discharge using the Mann-Kendall test and with Sen's slope estimates with a 0.05 significance level. The uncertainties are computed for each remotely sensed data set and the budget closure is evaluated from *in situ* discharge data for the three biggest river basins in the Cerrado, Paraná, São Francisco and Tocantins.

The main source of water budget uncertainty in the estimated runoff arises from errors in the TRMM precipitation data. In general, TRMM v6 data tend to overestimate the ground-measured rainfall in the Brazilian Cerrado, mainly in the southern part, although there is an underestimation in the northeast. However, our results show that the new version of TRMM 3B42 v7 notably reduces the bias between TRMM and the measured precipitation data from 9.5 to 6%, thus improving its potential application in hydrological studies.

We note that the water storage change (dS/dt) computed as a residual of the water budget equation using remote sensing data (TRMM and MOD16) and measured discharge data shows a significant correlation with TWS change obtained from the GRACE data for all watersheds studied. The results indicate that the GRACE data may provide a satisfactory representation of water storage change for large areas in the Brazilian Cerrado.

We conclude that water budget closure from remote sensing remains a challenge due to uncertainties in the data. However, this approach demonstrates the potential to evaluate trends in water balance components over large regions, identify drier periods, and assess changes in water balance due to land cover and land use changes.

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Our results also indicate that deforestation promotes a significant decrease in evapotranspiration at the local level. However, deforestation alone cannot account for all of the recent changes in water balance in the Cerrado, because other anthropic activities such as irrigation and reservoir creation also act to modify the water balance. In other words, the response time to watershed change is dependent on the scale studied. Therefore, water balance results obtained for small areas can be different that those over larger areas, illustrating the need to study the responses at different scales.

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