



# Hydrologic response to large-scale land use and cover changes in the Upper Paraná River Basin between 1985 and 2015

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## Abstract

The Upper Paraná River Basin (UPRB) has undergone remarkable land use and cover changes (LUCC) in recent decades. This paper analyses the hydrologic response to LUCC in the UPRB between 1985 and 2015, using the Soil and Water Assessment Tool (SWAT) model. The impacts of LUCC were examined for annual, wet, and dry season (both during calibrated and validated periods) between 1984 and 2015. The most substantial LUCC were the extensive reduction of the cerrado and the expansion of agriculture areas. The simulations demonstrated that the LUCC caused important changes in basin hydrology. For instance, an increase (decrease) of surface runoff in the wet (dry) season at most UPRB subbasins was observed. In addition, the simulation results revealed a reduction in actual evapotranspiration and an increase in soil moisture in the annual and wet season. Consequently, most of the major rivers of the basin presented an increase (decrease) in their discharge in the wet (dry) period. The major changes in the hydrologic components were observed in the central-western and southern parts of the UPRB. At the river mouth of the UPRB, the LUCC led to an increase in long-term mean discharge values of 4.2% and 1.1% in the annual and wet season and a decrease of about 2.2% in the dry period. This study provides a large-scale modeling and valuable information that could be used to improve planning and sustainable management of future water resources within the basin.

**Keywords** Large-scale modeling · Surface runoff · Actual evapotranspiration · Soil moisture · Discharge · SWAT model

## Introduction

Rapid population growth and economic development have induced extensive Land Use and Cover Changes (LUCC) in recent decades (Lambin et al. 2001; Boserup 2014). LUCC are one of the main factors that affect the hydrological processes within watersheds (DeFries and Eshleman 2004; Cao et al. 2009; Francesconi et al. 2016). The effects of LUCC are dependent on the type of change and the season.

The replacement of natural vegetation by cropland or grassland areas could have a significant effect on the surface runoff and actual evapotranspiration processes (De Roo et al. 2001; Kalantari et al. 2014). Costa et al. (2003) observed an increase in the average annual long-term discharge of the Tocantins River, Southeastern Amazonia, and suggested the conversion of the natural vegetation to cropland and grassland as the cause of the increase. Lin et al. (2015) observed a decrease in surface runoff due to the reduction in soil water storage during dry season over deforestation areas in the south-eastern Fujian Province of China. A significant decrease in the surface runoff has also been observed during the rainy season. However, this decrease under the rainy season has been observed only in situations of forest expansion. For example, Huang et al. (2003) observed a reduction of about 32% in cumulative runoff as a result of afforestation in a watershed of the Loess Plateau, in China. Similar findings were reported by Li et al. (2015) to the Heihe River Basin, China. Grassland to cropland changes may also lead to significant changes. According to Ghaffari

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et al. (2010), an increase of 33% in the surface runoff amount was observed at the Zanjnrood Basin, Northwest Iran, due to grassland to cropland conversion.

Evapotranspiration is an important LUCC-related driver of observed changes in the streamflow. Wang et al. (2014) found alterations in hydrology processes due to LUCC, in which the evaporation decreased by 2.13% and 2.41% between 2000 and 2010 with the decrease of natural vegetation areas. According to some authors, the shallower roots of cropland or grassland compared to natural vegetation reduce the access to deep soil moisture and explain the reduction in the actual evapotranspiration values (Nepstad et al. 1994; Oliveira et al. 2005).

Fu et al. (2003) evaluated the effects of seven land-use types on soil moisture at the Danangou catchment on the Loess Plateau of China. During the rainy season, they reported higher mean soil moisture content in cropland and grassland compared to natural vegetation such as shrubland and woodland. Using the Variable Infiltration Capacity (VIC) model, Costa-Cabral et al. (2008) investigated the influence of LUCC on soil moisture in the Mekong River Basin. The authors reported that the highest values of soil moisture occur more in agricultural areas than forest or grassland during the wet season.

In a large basin, the impacts could be larger and different due to the greater area and heterogeneity of the LUCC (Costa et al. 2003; Rajib and Merwade 2017; Dos Santos et al. 2018; Pokhrel et al. 2018). Therefore, understanding the influence of LUCC on hydrology in small- and large-scale basins is vital for planning the sustainable management of water resources. Because of that, LUCC have aroused the interest of scientific researchers worldwide.

The Upper Paraná River Basin (UPRB) belongs to one of the most important and second largest river basins in South America, the La Plata River Basin. The basin plays a significant role in the Brazilian economy, being responsible for the most extensive livestock, agricultural and biofuel production, transportation of products, and hydroelectricity generation. In addition, according to the Brazilian National Water Agency (ANA), the UPRB has the largest water consumption in South America mostly used for agriculture and industrial activities. In the latest decades, the UPRB has undergone significant LUCC mainly with the deforestation of natural vegetation replaced by cropland and grassland (Tucci 2002; Rudke 2018). For instance, 75.9% of the Atlantic forest biome and 48.5% of the cerrado biome had its original vegetation suppressed (MMA 2011, 2012). At the same time, significant changes in the basin hydrology have been presented (Camilloni and Barros 2003; Antico et al. 2016).

Studies consider LUCC one of the main causes of the hydrologic changes in the UPRB (e.g. Tucci 2002; Doyle and Barros 2011). In this context, hydrological models have played an important help to researchers understand the role

of the LUCC. Hernandez et al. (2018) evaluated the impacts of the agriculture expansion within the eastern part of the UPRB, using the Soil and Water Assessment Tool (SWAT) model. Their simulation results showed that the LUCC led to an increase in the stream flow during the dry period. In the northern parts of the basin, the study performed by Viola et al. (2014) showed scenarios of deforestation in areas in the Grande River subbasin (located between Minas Gerais and São Paulo states). The authors demonstrated through the Lavras Simulation of Hydrology (LASH) model that the decreased vegetation area could increase the water yield, with an increase in the maximum stream flows. Relatively few studies have investigated the effects of LUCC on hydrology throughout the basin, and those have been performed for a local or regional watershed. No analysis by subbasins, but with integrated results for the entire UPRB, has yet been developed. Therefore, studies of this nature are needed using large-scale modeling.

This study aims at using the SWAT model to assess the hydrologic response to LUCC between 1985 and 2015 for the entire UPRB. Besides the simulations performed at a high spatial resolution, the evaluation of the impacts of LUCC was addressed over a 32-year long period from January 1984 to December 2015 for annual, wet, and dry seasons values.

The success or failure of UPRB water use strategies are highly dependent on our understanding of what has happened in recent past decades of its subbasins. The streamflow rates at the main tributaries have increased over decades and is undergoing a transition. There is no evidence to support what the trend will be in the coming decades. Although the increase in streamflow has been widespread in the basin, the LUCC followed different paths in each subbasin, both in terms of time and transition in the types of land cover. This makes the understanding of the streamflow trends a big challenge, highly dependent on the role of each player acting over the different components of the hydrological cycle. Hydrological modeling is the best tool we have to deal with the many uncertainties about the future of the basin. By assessing the hydrologic response to LUCC in the recent decades, we expect to provide useful information for managers and decision makers, especially in strategic areas of the energy production sector.

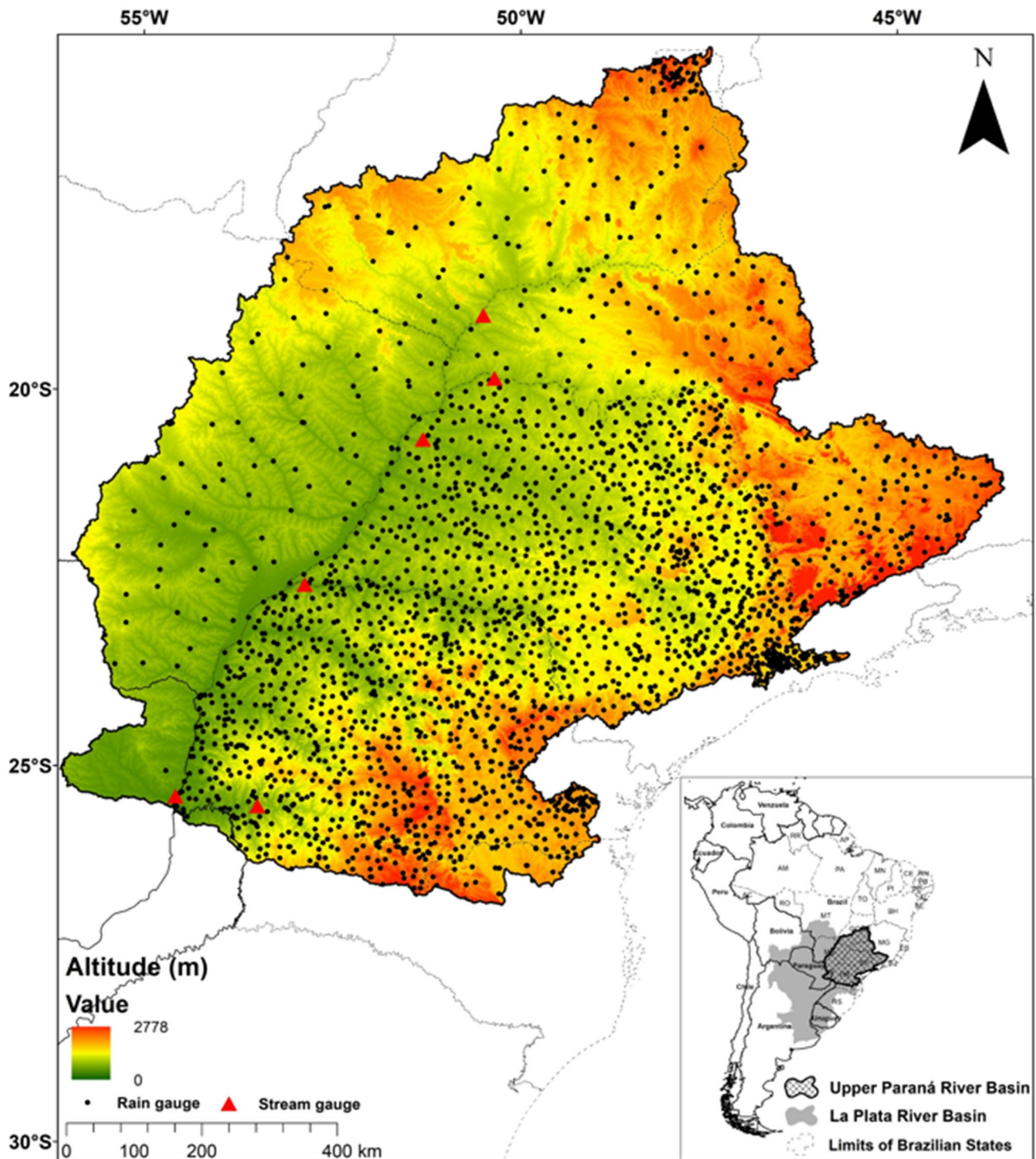
## Material and methods

### Study area

The study area is located in the central-southern region of Brazil, comprising the UPRB, between the coordinates 26° 51' 23.35" and 15° 27' 25.54" S latitude, and 56° 7' 4.61" and 43° 34' 50.61" W longitude. The basin has a drainage

area of 900,480 km<sup>2</sup> and an altitude up to 2778 m above sea level. It covers six Brazilian states: São Paulo (23.5%), Paraná (20.4%), Mato Grosso do Sul (18.9%), Minas Gerais (17.6%), Goiás (15.7%), Santa Catarina (1.2%), and the

Federal District (0.4%), and also includes a small portion of Paraguay (2.3%) (Fig. 1). Currently, the UPRB has an estimated population of more than 65 million inhabitants,



**Fig. 1** Location of the Upper Parana River Basin showing the topographic patterns and the spatial distribution of rain gauges and stream gauges within the basin



approximately one-third of the Brazilian population, of whom 93% live in urban areas (IBGE, 2019).

The UPRB has different climatic areas, with several different synoptic systems affecting regions across the basin. The northern part of the basin is characterized by wet summers and dry winters, which is strongly associated with the presence of the South American Monsoon System (Grimm et al. 2007; Carvalho et al. 2011). On the other hand, in the southern part of the basin, rainfall is spread over all seasons. This occurs due to the influence of baroclinic systems, such as Mesoscale Convective Systems (MCS), South American Low-Level Jet (SALLJ), cold fronts, and South Atlantic Convergence Zone (SACZ) (Velasco and Fritsch 1987; Carvalho et al. 2004). Annual precipitation over the southern part of the basin reaches 1850 mm, while in the northern part does not exceed 1400 mm (Abou Rafee et al. 2020).

### Soil and Water Assessment Tool model

Hydrologic response to LUCC was estimated using the SWAT model with an ArcGIS interface (Arnold et al., 1998, <https://swat.tamu.edu>). SWAT is a semi-distributed and physically-based model used both for small (Ferrant et al. 2011) and large-scale (Rajib and Merwade 2017) river basins applications. The model has been extensively applied for different approaches such as climate change effects on hydrologic processes (Ficklin et al. 2009), LUCC impacts to streamflow, sediment and water quality (Chotpanarat and Boonkaewwan 2018), and climate variability effects on snowmelt (Wu and Johnston 2007). SWAT operates on a daily time step and discretizes the basin into multiple subbasins. Based on user-defined thresholds, each subbasin is further divided into Hydrologic Response Units (HRUs), accounting for the combinations of slope, soil, and land use class. For a further detailed description of the SWAT model, the reader is referred to Neitsch et al. (2011).

### Data and model setup

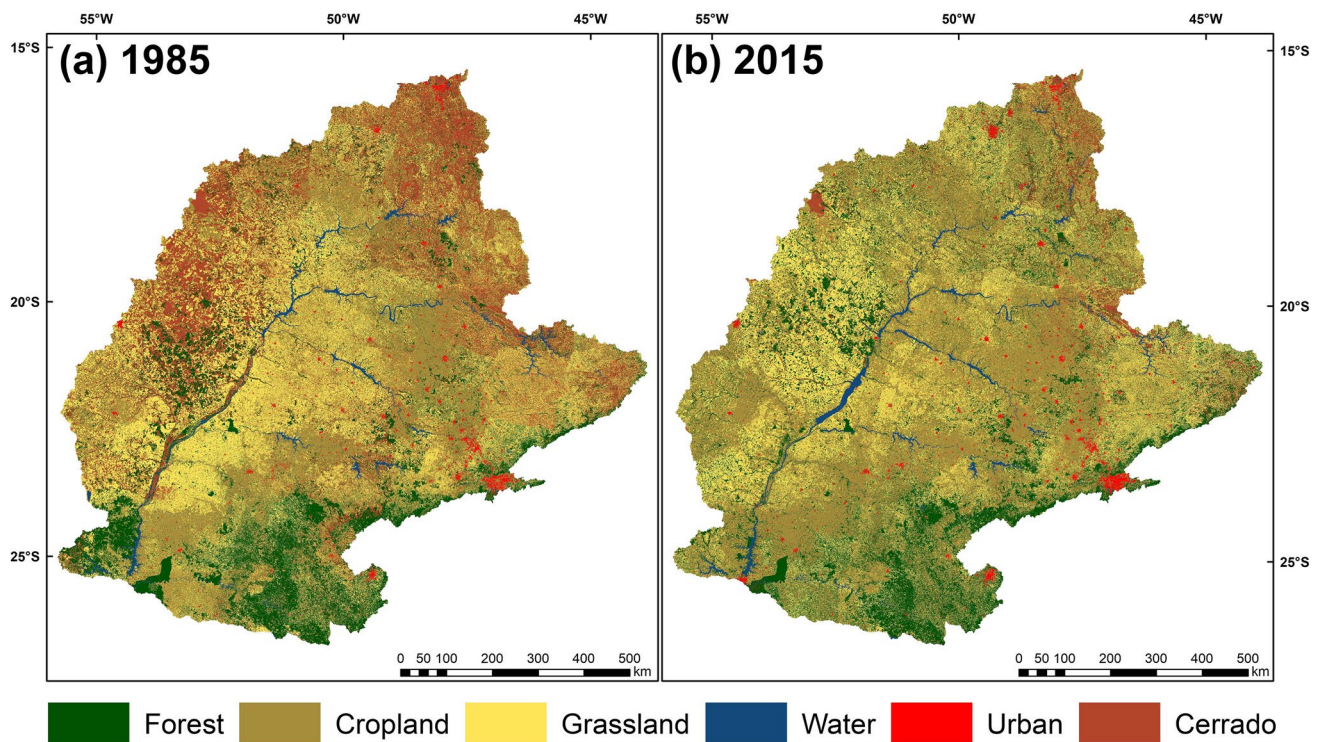
The daily climatic data were organized for the simulation period from 1979 to 2015, with the first 5 years used for warm-up the model (1979–1983), the following 21 years for calibration (1984–2004), and the last 11 years for validation (2005–2015). The precipitation database was built using daily rainfall series from 2,494 rain gauge stations within the basin (black dots on Fig. 1) provided by the ANA. The data were interpolated to a spatial resolution of 0.1 degree using the Inverse Distance Weighted (IDW) method following a previous study (Abou Rafee et al. 2019). Daily minimum and maximum temperature, solar radiation, relative air humidity, and wind speed data were derived from the National Centers for Environmental Prediction—Climate Forecast System Reanalysis (CFSR) at 38-km grid spacing (Saha et al. 2010,

2014). Topographic data at a 90-m resolution obtained from the Shuttle Radar Topography Mission (SRTM) (available at <http://srtm.csi.cgiar.org/srtmdata/>) were used. The soil data were the same used by Abou Rafee et al. (2019), based on the information provided by the Brazilian Agriculture Research Corporation (EMBRAPA, Dos Santos 2018), except for the Paraguayan portion of UPRB, which was derived from the Harmonized World Soil Database (HWSD, available at <http://www.fao.org/nr/land/soils/>). To evaluate the performance of the model, monthly naturalized flows over the period 1984–2015 from ANA and the Brazilian National Electrical System Operator (ONS) were used.

Two land use and cover (LUC) scenarios under unchanged climatic conditions were simulated. The two scenarios correspond to the validated LUC classifications for the years 1985 and 2015 performed by Rudke (2018) and Rudke et al. (2019). Both LUC were generated at a spatial resolution of 30 m using pixel-based image classifiers, with the Support Vector Machine (SVM) algorithm. Based on Rudke (2018) and Rudke et al. (2019) generated classifications, the LUCC maps for the UPRB were reclassified into six major classes: forest, cropland, grassland, water, cerrado (Brazilian savanna), and urban areas (Fig. 2).

The SWAT model project for the UPRB was built with the highest possible spatial discretization. The slopes were divided into five classes ranging between 0–3%, 3–8%, 8–20%, 20–45%, and > 45%. The basin was discretized into 5,187 subbasins with an average drainage area of 173 km<sup>2</sup> (Fig. 3). To represent the spatial heterogeneity across the UPRB, these subbasins were further divided into HRUs using a defined threshold for both simulations of 5% for LUC, 10% for soil, and 20% for slope classes. As a result, 44,635 (LUC 2015) and 50,272 (LUC 1985) HRUs were generated. The Soil Conservation Service curve number (CN) (USDA Soil Conservation Service, 1972) and the Penman–Monteith (Monteith J. L. 1965) methods were used to compute the surface runoff and potential evapotranspiration, respectively. For groundwater flow SWAT considers shallow (unconfined) and deep (confined) aquifers, which are responsible for returning flow to the stream and flow outside the basin, respectively (Neitsch et al. 2011).

The best-fit calibration parameters by Abou Rafee et al. (2019) were used. Abou Rafee et al. (2019) applied the SWAT model to estimate monthly discharge values for the UPRB considering LUC from 2015 for the same period as the current study (1984 – 2015). Using the multi-site calibration technique (Leta et al. 2017), Abou Rafee et al. (2019) calibrated and validated the model for 78 outlets using the Sequential Uncertainty Fitting (SUFI-2) algorithm (Abbaspour et al. 2004), available in SWAT-CUP (Soil and Water Assessment Tool Calibration and Uncertainty Program, Abbaspour 2015). In addition to Abou Rafee et al. (2019), the current study applied monthly



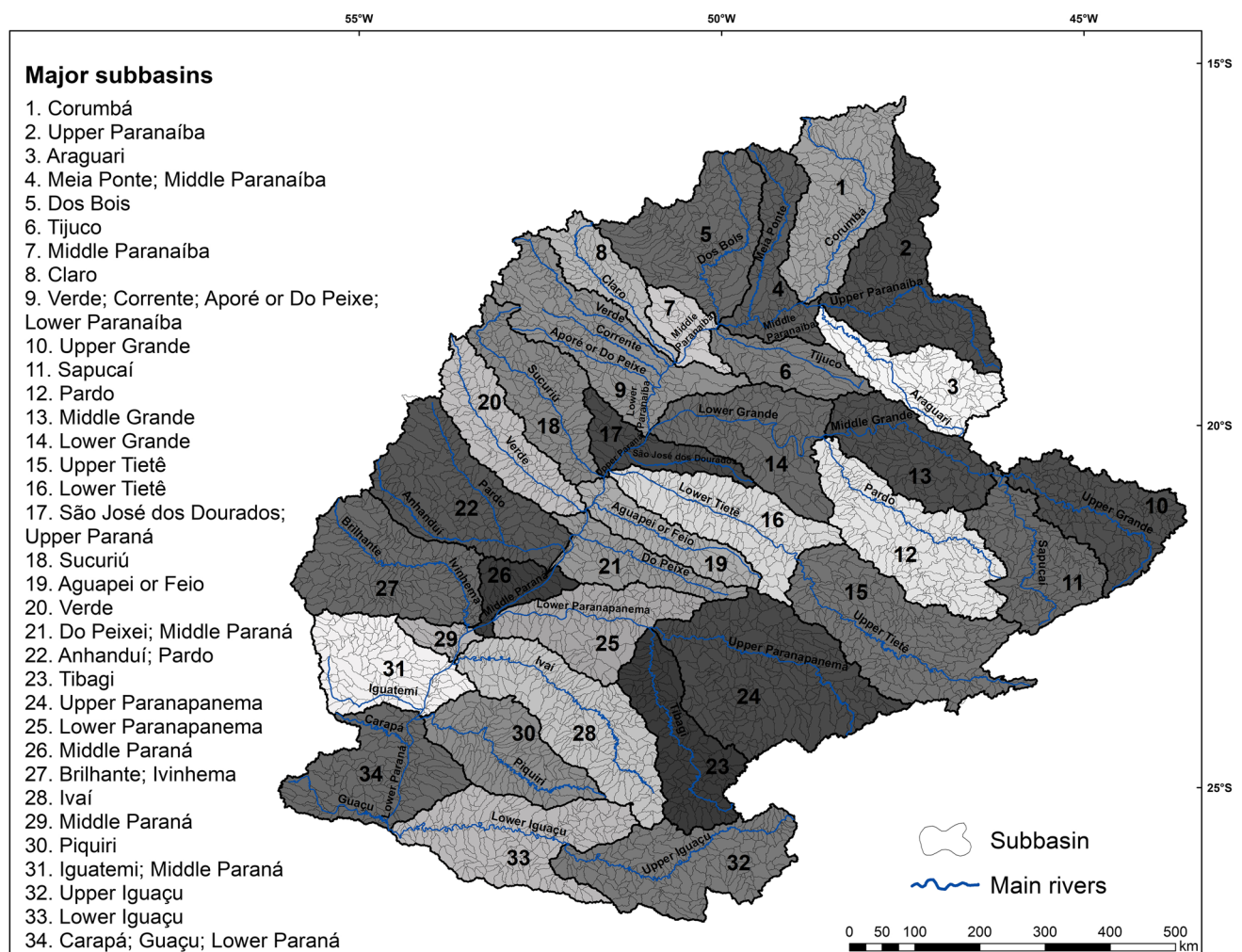
**Fig. 2** Land use and cover (LUC) classes for 1985 (a) and 2015 (b)

manual calibration for parameters related to plant growth to adjust the Leaf Area Index (LAI) curve for forest, cerrado, and grassland using the modified plant growth module provided by Strauch and Volk (2013). Although SWAT has been applied for tropical basins, previous studies reported that its plant growth module is not suitable in a system that has perennial tropical vegetation since the model was originally designed for temperate areas (Wagner et al. 2011; Van Griensven et al. 2012; Strauch and Volk 2013; Alemayehu et al. 2017). The LUC data from 2015 was used in the calibration process and to evaluate the performance of the model.

### Analysis of the effects of land use and cover changes

The effects of LUCC on the hydrologic components were evaluated based on a hydrological modeling project properly calibrated and validated for the UPRB. As reported in Abou Rafee et al. (2019), calibration and validation involved 78 outlets, over the 1984–2015 period, with satisfactory or better performance in all analyzed objective functions (Percent bias, Coefficient of determination, Nash–Sutcliffe efficiency, Kling–Gupta efficiency, and Ratio of standard deviation of observations to root mean square error). Based on this successful modeling project, the following procedures related to the effects of LUCC were performed:

- I. To address the main LUCC between 1985 and 2015 in the basin, 9 major transitions of four LUC classes were calculated: Cerrado to forest; Grassland to forest; Cropland to forest; Forest to grassland; Cerrado to grassland; Cropland to grassland; Forest to cropland; Cerrado to cropland; and Grassland to cropland.
- II. To identify the effects of LUCC on hydrology within the UPRB, the surface runoff, actual evapotranspiration, soil moisture, and discharge were analyzed.
- III. The aforementioned hydrologic components were calculated by the relative change for the simulation with the LUC from 2015 relative to the simulation with LUC from 1985. Changes were examined for annual (hydrological year, from October to September), wet (October–March), and dry (April–August) seasons considering the calibrated and validated period from 1984 to 2015.
- IV. The hydrological variables were calculated using the 5,187 watersheds discretization of the UPRB; however, the results were illustrated and interpreted for the 34 major subbasins as shown in Fig. 3.



**Fig. 3** Subbasin discretization, major subbasins, and main rivers of the Upper Parana River Basin

## Results and discussion

### Soil and Water Assessment Tool model performance

The average monthly simulated LAI values at the major subbasin level (as divided in Fig. 3) are available in the Supplementary Material (Figures S1, S2, S3, and S4). SWAT vegetation parameters were manually calibrated to match the magnitude and shape of LAI following previous studies (Hoffmann et al. 2005; Bucci et al. 2008; Negrón Juárez et al. 2009). The main sensitive parameters were the minimum LAI for plant and maximum potential LAI followed by the total number of heat units to bring plant maturity. The estimated values of LAI ranged between 2.5 and 5.5  $\text{m}^2 \text{m}^{-2}$  for forest, 0.7 and 2.5  $\text{m}^2 \text{m}^{-2}$  for cerrado, and 0.5 and 2.0  $\text{m}^2 \text{m}^{-2}$  for grassland, and from 0 to 3.0  $\text{m}^2 \text{m}^{-2}$  for cropland. As found by previous studies (Alemayehu et al. 2017; Lamparter et al. 2018), the modified plant growth module proposed by Strauch and Volk (2013) was more

suitable to represent the values of LAI for tropical perennial vegetation. Natural vegetation LAI varies seasonally with the highest values during the wet season (October–March), and lowest values in the dry season (April–September) due to the dormancy period. Forested areas within the UPRB correspond to Atlantic Forest, a Brazilian biome that has several forest formations, including deciduous and perennials forests. Therefore, LAI presents great seasonality, reducing the photosynthetic capacity of the forest during the dry season. In perennial forests with a shorter dry season (approximately 3 months) such as the Amazon Rain Forest, values of LAI are higher and the monthly variation is lower because deep roots and phenology increase the efficiency of photosynthesis during periods of abundant solar radiation but low water availability (Morton et al. 2014; Saleska et al. 2016; Manoli et al. 2018). In turn, the cerrado biome has at least five ecosystem physiognomies with several types of trees and grasses densities, ranging from open shrub to tree savanna and gallery forests (Cruz Ruggiero et al. 2002;



Hoffmann et al. 2005). This causes lower values of LAI and greater seasonality, corresponding to vegetation that decreases its photosynthetic capacity during the dry season (see Figures S1, S2, and S3). LAI values from the current study are comparable to the simulated by Dos Santos et al. (2018), who used SWAT to evaluate the impacts of LUCC on hydrology in the Iriri River basin in the Brazilian Amazon. Their results showed LAIs with annual averages of 4.02, 1.25, and 1.09  $m^{-2} m^{-2}$  (versus 3.53, 1.49,

and 1.23  $m^{-2} m^{-2}$  in this study) for the forest, cerrado, and grassland, respectively.

Figure 4 shows the observed and simulated monthly discharge at the main rivers of the UPRB that have available data. The simulated monthly discharge was consistent with observed data at the main rivers of the UPRB. However, the model tends to underestimate the low flow as well as overestimate the most extreme high flows. According to the performance rating proposed by Moriasi et al. (2007) and

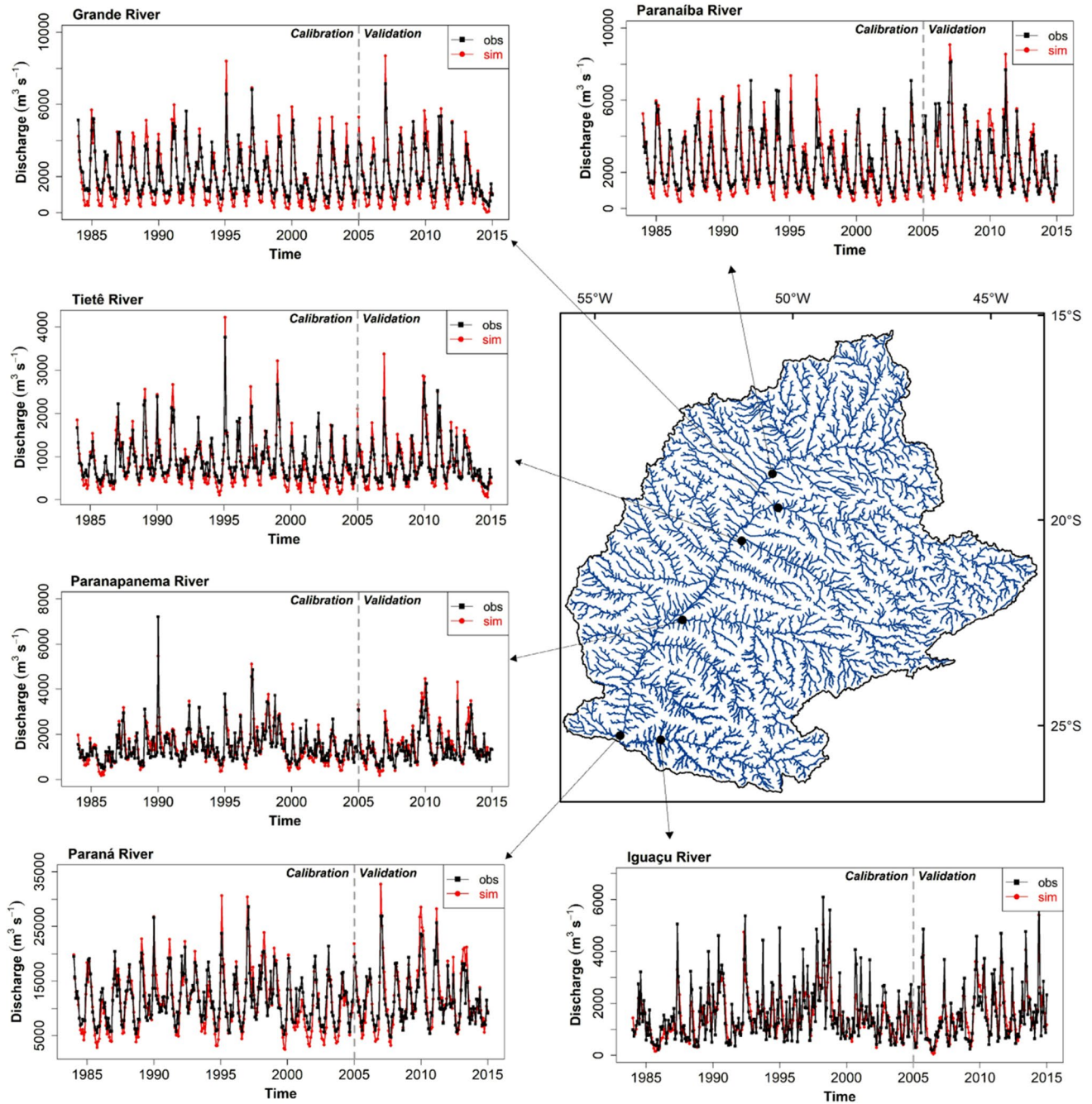
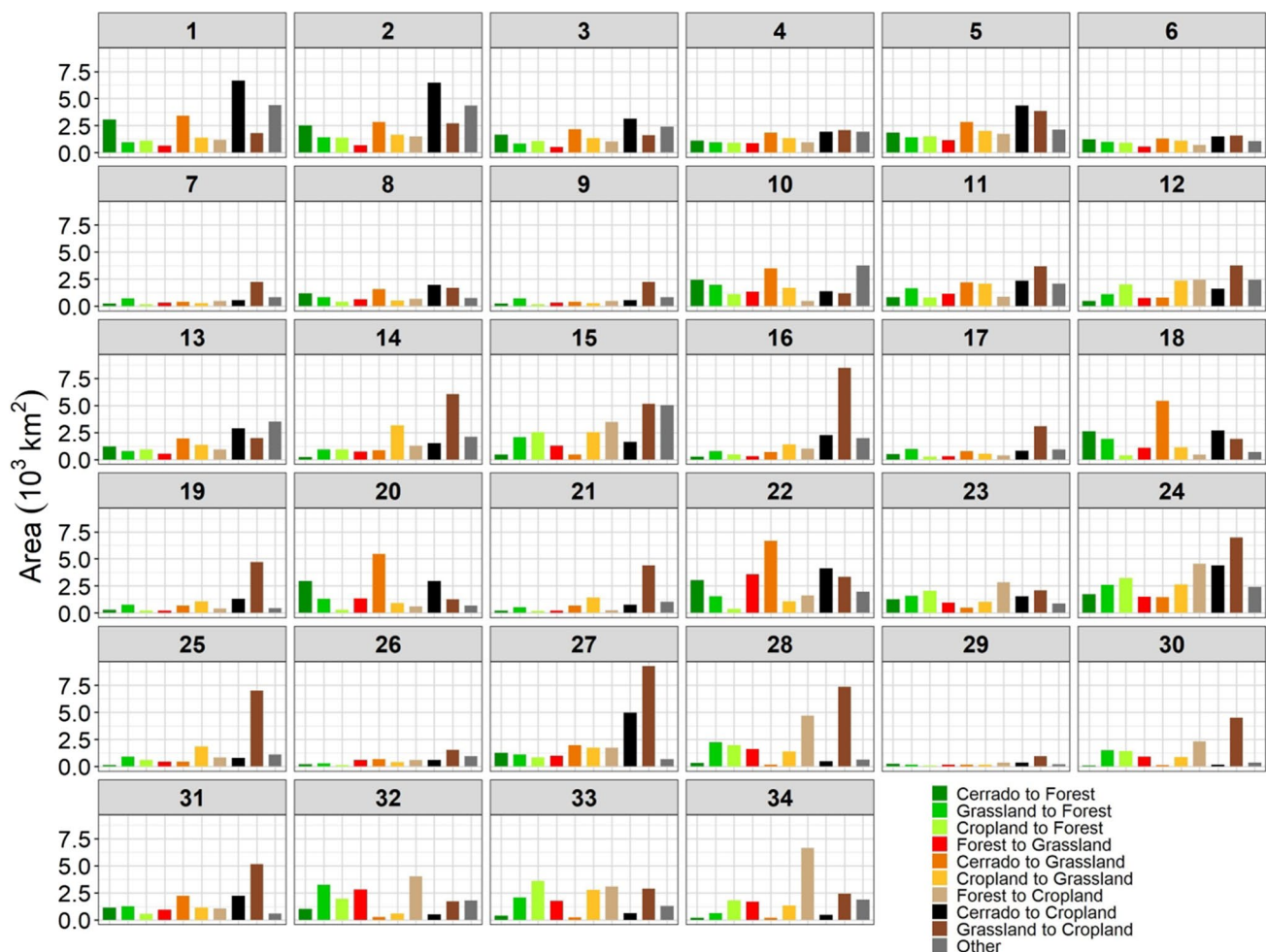


Fig. 4 Comparison between the observed and simulated monthly discharge at the main rivers of the Upper Paraña River Basin



**Fig. 5** Area ( $10^3 \text{ km}^2$ ) of the main transitions of LUC between 1985 and 2015 at the major subbasins of The Upper Paraná River Basin. **1.** Corumbá; **2.** Upper Paranaíba; **3.** Araguari; **4.** Meia Ponte-Middle Paranaíba; **5.** Dos Bois; **6.** Tijuco; **7.** Middle Paranaíba; **8.** Claro; **9.** Verde-Corrente-Aporé or Do Peixe-Lower Paranaíba; **10.** Upper Grande; **11.** Sapucaí; **12.** Pardo; **13.** Middle Grande; **14.** Lower Grande; **15.** Upper Tietê; **16.** Lower Tietê; **17.** São José dos Doura-

dos-Upper Paraná; **18.** Sucuriú; **19.** Aguapei or Feio; **20.** Verde; **21.** Do Peixei-Middle Paraná; **22.** Anhanduí-Pardo; **23.** Tibagi; **24.** Upper Paranapanema; **25.** Lower Paranapanema; **26.** Middle Paraná; **27.** Brilhante-Invinheima; **28.** Ivaí; **29.** Middle Paraná; **30.** Piquiri; **31.** Iguatemi-Middle Paraná; **32.** Upper Iguaçú; **33.** Lower Iguaçú; **34.** Carapá-Guaçu-Lower Paraná

Thiemig et al. (2013), the simulations ranged from satisfactory to very good in the statistical indices presented in Table S1 (available in the Supplementary Material). During the calibration period (1984–2004), the percent bias (PBIAS) ranged from -0.2 to 6.4, the coefficient of determination ( $R^2$ ) from 0.71 to 0.88, the Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970) from 0.7 to 0.8, the Kling-Gupt efficiency (KGE) (Gupta et al. 2009) from 0.7 to 0.9, and the ratio of the standard deviation of observations to root mean square error (RSR) (Moriassi et al. 2007) from 0.44 to 0.55. For the validation period (2005–2015), the simulations reached index values up to 0.7 for PBIAS and 0.92 for  $R^2$  (at Grande river), and, 0.84 for NSE, 0.88 for KGE, and 0.4 for RSR (at Paranaíba river). It is important to mention that the discharge values currently estimated have higher

accuracy compared to the results presented by Abou Rafee et al. (2019). The reason for the improved simulation was the better calibration of LAI by using the modified plant growth module (Strauch and Volk 2013).

### Detection of land use and cover transitions

Figure 5 shows the total area of the main transitions of LUC between 1985 and 2015 at the major subbasin level. Overall, there was simultaneously deforestation and afforestation in different areas mainly within the central-western and northern parts of the basin. Cerrado had the greatest reduction of  $173 \times 10^3 \text{ km}^2$ , which represents deforestation of about 19.2% of the original area in 1985. Cerrado was replaced mainly by cropland ( $75 \times 10^3 \text{ km}^2$ ),



followed by grassland ( $59 \times 10^3 \text{ km}^2$ ), and forest ( $39 \times 10^3 \text{ km}^2$ ).

In contrast, the cropland class had the greatest gain with more than  $250 \times 10^3 \text{ km}^2$ . The expansion of agriculture occurred mainly in the central and southern parts of the UPRB. In the central portion of the basin, almost  $125 \times 10^3 \text{ km}^2$  of grassland areas were replaced by cropland between 1985 and 2015. Most of these areas were replaced mainly by sugarcane cultivation due to the high demand for bioenergy in the form of ethanol and raw material for the thermoelectric power plants (Rudorff et al. 2010; Adami et al. 2012). Also, this growth is largely caused by the development of agricultural mechanization, climate conditions, population growth, and economic factors (Mueller and Mueller, 2016). Particularly, in the southern part of the basin, the main reason for the expansion of cropland was the construction of the Itaipu hydroelectric power plant (1974–1985) at the triple border of Brazil, Argentina, and Paraguay. This construction made an important contribution to rapid population growth in the region (Baer and Birch, 1984).

Besides, the UPRB had a considerable gain in forest cover ( $\sim 120 \times 10^3 \text{ km}^2$ ), mostly through the plantation of exotic tree species. The reforestation and the afforestation have been concentrated mostly in the central-western and northern parts of the UPRB. The increase in forests is mainly related to the transitions of the LUC classes of cerrado, grassland, and cropland to Eucalyptus plantations. According to the Brazilian Association of Forest Plantation Producers, the growth of Eucalyptus in Brazil has been mainly driven by the profit growth generated that is up to six times greater than the one of livestock production. Besides economic issues, Gonçalves et al. (2008) pointed out that the increase of Eucalyptus plantation is due to the investments in research and technology in the last decades, which improved seed or clonal plantations.

The largest areas of LUCC were the conversion from grassland to cropland that occurred within the Brilhante/Invinheima (27) and Lower Tietê (16) subbasins, which reached up to 8,490 and 9,250  $\text{km}^2$ , respectively. Besides, in the Carapá/Guaçu/Lower Paraná (34) subbasin, 6,640  $\text{km}^2$  of forests were replaced by cropland areas. It is also worth mentioning that the increase of cropland happened over areas that were previously covered with cerrado. Deforestation of cerrado contributed to an increase of up to 6,550  $\text{km}^2$  in cropland areas in the Corumbá (1) and Upper Paranaíba (2) subbasins. Still, cerrado reductions also had a significant contribution to the grassland expansion. For example, about 6,670  $\text{km}^2$  of cerrado were deforested, being replaced by grassland in the Anhanduí/Pardo (22) subbasin. As mentioned before, the central-western and northern parts of the basin were the ones that most had afforestation in the last recent decades. For example, the transition from cerrado to

forest in the Corumbá (1) and Anhanduí/Pardo (22) subbasins contributed to a forest cover increase of up to 3,070 and 3,040  $\text{km}^2$ , respectively.

### Effects of land use and cover changes on hydrology

The two simulated scenarios for the LUC from 1985 and 2015 were compared. The effects of LUCC on hydrologic components within the basin are illustrated in Table S2, in the Supplementary Material, showing the changes in surface runoff, actual evapotranspiration, and soil moisture. These changes were calculated considering the long-term means (1984–2015) from the difference between LUC2015 and LUC1985 simulated hydrologic variables for annual (October–September), wet (October–March), and dry (April–September) season values.

Overall, the LUCC caused an increase in the annual and wet season surface runoff, while a decrease in the dry period. The calculated mean values show that the increases at the major subbasins level reach up to 19.3 and 15.7 mm in the annual and wet season runoff, respectively. In contrast, the decrease overtakes -2.0 mm in the dry season. The effects are remarkable at the Corumbá (1), Upper Paranaíba (2), and Carapá-Guaçu-Lower Paraná (34) subbasins. In these regions, a major cause for the increase in surface runoff is the substantial removal of the cerrado and forest vegetation, replaced mainly by cropland and grassland (see Fig. 5 and Table S2). In addition, it was observed a significant increase up to 14.4 mm in the Verde-Corrente-Aporé or Do Peixe-Lower Paranaíba (9), Middle Paranaíba (7), Lower Tietê (16), Brilhante-Invinheima (27), Piquiri (30) watersheds. However, in these regions, an expressive reduction of cerrado and grassland areas replaced by cropland was observed. Similar results were reported by previous studies elsewhere (Ghaffari et al. 2010; Baker and Miller 2013).

Small catchments presented a decrease in surface runoff during the wet season (see Supplementary Material, Figure S5). This could be attributed to the increase in forest areas due to the afforestation (e.g. cerrado to forest) and reforestation (e.g. grassland to forest), as reported by previous studies investigating the impacts of LUCC on surface runoff and water yield (e.g. Huang et al. 2003; Li et al. 2015).

In SWAT, the surface runoff is estimated by the Curve Number (CN) method (USDA Soil Conservation Service 1972). CN varies spatially according to land use, soil type, and slope. It can be easily interpreted by the order of higher values: Urban > Cropland > Grassland > Cerrado > Forest. Consequently, the increase or decrease in the generated runoff during the period could be explained by the major conversions of LUC in the basin such as from cerrado to cropland, or from grassland to cropland. Also, CN has temporal variation due to changes in soil moisture. During the dry

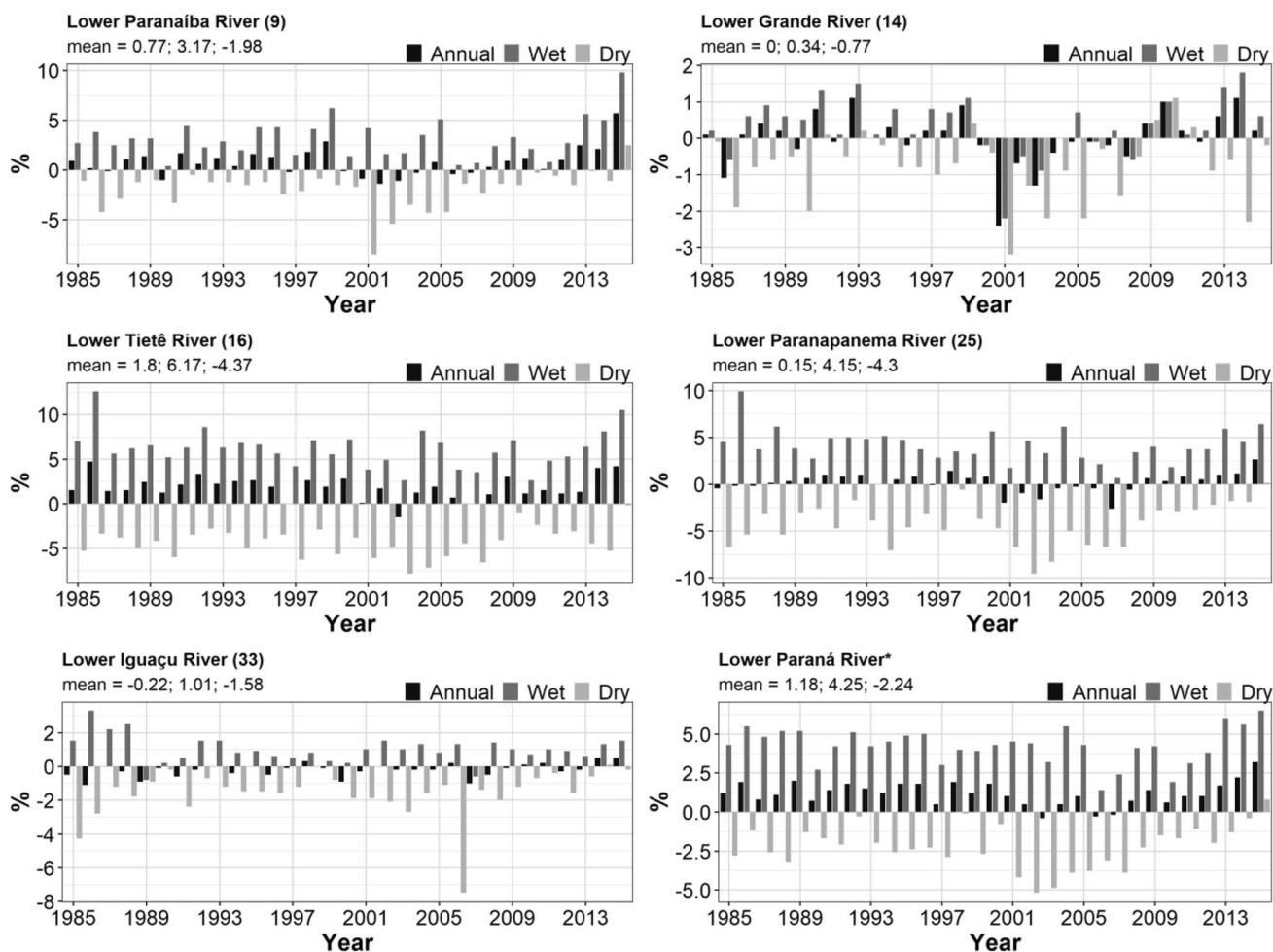
season, a possible explanation for the decreasing amounts of surface runoff is due to the reduction in the water content storage (Lin et al. 2015).

In contrast to surface runoff, a decrease in the actual evapotranspiration mainly in the annual and wet season was observed. The greatest decreases are observed over the central-western (e.g. Anhanduí-Pardo subbasin) and southern parts (e.g. Carapá-Guaçu-Lower Paraná subbasin) For instance, in these watersheds, it was observed a mean decrease up to 107, 88, and 34 mm in the annual, wet and dry seasons, respectively. Similar to surface runoff, this is likely because of the natural vegetation suppression that was replaced by cropland areas. Besides the area of LUCC, the different magnitude of evapotranspiration reduction within the subbasins could be associated with available soil water and the incidence of solar radiation (Da Rocha et al. 2009; Cabral et al. 2012; Wang et al. 2014). The reduction in the actual evapotranspiration values is explained by the shallower roots of cropland or grassland compared to natural

vegetation (forest or cerrado), which leads to less access to deep soil. Also, the mean LAI values are smaller which consequently decreases the transpiration.

It is important to highlight that even in the dry season, in the Carapá-Guaçu-Lower Paraná (34) and Lower Iguazu (33) subbasins there is a significant increase in the amounts of surface runoff and decrease in the actual evapotranspiration. Besides the influence of LUCC, the precipitation in this region in the dry period is different from the other parts of the basin. In these parts of the UPRB, the precipitation is spread out throughout the year and reaches between 700 and 900 mm between April and September (see Supplementary Material, Figure S6). The occurrence of precipitation in this period is associated mainly with cold fronts that are common in winter (June–August) (De Jesus et al. 2016).

The impacts of LUCC on soil moisture storage ranged from a mean increase up to 150 mm to a decrease up to 66 mm within the major subbasin level. Similar to surface runoff, it was observed mainly an increase in the wet and



**Fig. 6** Temporal evolution of relative changes (%) in discharge for annual, wet and dry seasons under the scenarios for the year 2015 relative to 1985 at the main rivers of the Upper Parana River Basin.

At the top left of the plots are shown the mean values and the name of the rivers with the respective number of the subbasin. \*The last graph represents the river mouth of the Upper Parana River Basin

annual values, and a decrease in the dry season. The higher values of soil moisture during the wet season are explained by the reduction of actual evapotranspiration. As previously mentioned, it occurred as a result of the removal of cerrado areas and the expansion of cropland in the basin.

Figure 6 shows the temporal evolution of relative changes (%) in discharge under the scenario for the year 2015 relative to 1985. Values for annual, dry, and wet seasons were calculated considering the river mouth of the main rivers from the major subbasin level of the UPRB. The rivers that have the highest values of discharge and significant changes in LUC in the upstream subbasins are shown. The remaining results at the last outlet of the rivers from the 34 major subbasins of the UPRB are available in Figure S7, in the Supplementary Material.

The simulation results revealed that the LUCC between 1985 and 2015 had an expressive impact on discharge values. Overall, the LUCC implied an increase in the annual's and wet season's discharges at the main rivers of the UPRB. This can be clearly seen at the Lower Tietê, Anhanduí, Ivinhema, and Guaçu rivers. For instance, an increase of more than 29% in annual mean discharge values at the Guaçu river was observed. All of these rivers contain in the upstream subbasins a significant decrease in natural vegetation (forest or cerrado) replaced mainly by grassland and cropland. Besides, a decrease in the dry season discharge, except for Anhanduí and Guaçu rivers was observed. A mean decrease of more than 4% was observed at the Lower Tietê, Lower Parapanema, and Sucuriú rivers. This behavior decreases the effect of annual increased discharge in many rivers of the basin. For example, at the river mouth of UPRB, over the lower Paraná River, it was observed an increase in the annual discharge of only 1.13%, an increase of 4.25% in the wet, and a decrease of only 2.24% in the dry season.

Surface runoff is one of the major contributors to discharge. Thereby, the changes in annual and wet season discharge values are likely associated with the increase of generated runoff in the subbasins. The results presented are consistent with other large-scale simulations (e.g. Costa et al. 2003).

Consequences of possible future LUCC may affect several sectors of socioeconomic development within the basin. The UPRB provides around 40% of Brazilian and 90% of Paraguayan energy consumption produced through hydroelectric energy (ANEEL 2020). The results showed that the LUCC implied an expressive decrease in mean discharge during the dry season (April–September) that could compromise the energy supply. For instance, two of the areas damaged by the effects of LUCC are the Lower and Upper Parapanema subbasins. The reduction of up to 10% in dry season's discharges between 1984 and 2015 (as shown in Fig. 6) at the Parapanema river may have affected the production of 11 hydropower plants at the subbasins, which together provide almost 2400 MW of electricity. The

decrease in discharge can also cause drought affecting the transportation of products through river paths, such as the waterway Tietê-Paraná, which is more economical comparing to the road mode (Toloi et al. 2016). In addition, the reduction of discharge during the dry period can affect the public and industrial water supply as well as the agricultural and livestock development.

Besides, the changes in LUC can increase the probability of flooding within several subbasins. A clear example is the increase of more than 9,500 km<sup>2</sup> of cropland mostly due to deforestation of forests at the Carapá-Guaçu-Lower Paraná subbasin. The simulations showed that these LUCC induced higher amounts of surface runoff which consequently increased 54% of mean discharge during the wet season (October–March) at the Guaçu river. This subbasin is located in an area with frequent MCS activity which is the main responsible for extreme precipitation events over the region (Velasco and Fritsch 1987; Durkee and Mote 2010).

## Summary and conclusions

This paper analyzed the hydrologic response to LUCC between 1985 and 2015 in the UPRB. The effects of LUCC on hydrologic variables were addressed for the hydrological annual (October–September), wet season (October–March), and dry season (April–September) using the calibrated and validated SWAT model from January 1984 to December 2015. The following conclusions can be drawn:

- I. Satisfactory SWAT calibration and validation of monthly discharge and LAI values were achieved for the main rivers of the UPRB. Thereby, the proposed project could be used not only for evaluating LUCC but also for climate change and climate variability scenarios.
- II. Simulation results revealed that most of the major subbasins presented an increase in the runoff generated and soil moisture amounts in the annual and wet season values, while a decrease in the dry season. In contrast, a significant decrease in actual evapotranspiration in the annual and wet season values was observed.
- III. The major changes in the hydrologic components in the UPRB were observed in the central-western and southern parts following the largest areas of LUCC.
- IV. Overall, LUCC in the basin caused an increase (decrease) in discharge in the wet (dry) season. For hydrology annual values, several largest rivers had little changes in their discharge due to the compensation of discharge in the wet and dry season. A clear example is the Paraná River at the mouth of the UPRB, which had a mean increase in annual dis-



charge of 1.13%, while in the wet and dry seasons, an increase and decrease of 4.25 and -2.24%, respectively, were observed.

This work is the first to address the LUCC over the whole UPRB at a high spatial resolution simulation. The provided results were presented and discussed at 34 major subbasins that have not been covered by previous research. Therefore, the outcomes of this study have valuable information that can be used to improve the planning and sustainable management as well as to support strategies to minimize the impacts of LUCC on water resources in the UPRB.

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## Declarations

**Conflict of interest** The authors declare no competing interests.

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