Reservoir storage and hydrologic responses to droughts in the Paraná River Basin, Southeast Brazil

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Abstract. Droughts are particularly critical for Brazil because of impacts on water supply and because most ($\sim 70\,\%$) of its electricity is derived from hydroelectric generation. The Paraná Basin (PB), a major hydroelectric producing region with $\sim 32\,\%$ (~ 70 million people) of Brazil's population, recently experience the most severe drought since the 1960s, compromising the water supply for ~ 11 million people in São Paulo city. The objective of this study was to quantify linkages between

5   meteorological and hydrological droughts based on remote sensing, modelling, and monitoring data using the Paraná River Basin in Southeast Brazil as a case study. Two major meteorological droughts were identified in the early 2000s and 2014, with precipitation 20-50 % below the long-term mean. Total water storage estimated from the Gravity Recovery and Climate Experiment (GRACE) satellites declined by $\sim 150\,\mathrm{km}^3$ between Apr 2011 and Apr 2015. Simulated soil moisture storage declined during the drought, resulting in decreased runoff into reservoirs. Reservoir storage decreased $\sim 30\,\%$ relative to the

10   systems maximum capacity. with negative trends ranging from $\sim 17\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ (May 1997 - Apr 2001) to 25 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ (May 2011 - Apr 2015). Storage in upstream reservoirs is mostly controlled by natural climate forcing whereas storage in downstream reservoirs also reflects dam operations. This study emphasizes the importance of integrating remote sensing, modelling, and monitoring data to evaluate droughts and to establish a comprehensive understanding of the linkages between meteorological and hydrological droughts for future management.

1 Introduction

15   Droughts have large scale socioeconomic impacts, responsible for $\sim 35\,\%$ of disaster-related deaths and ~ 200 billion US dollars ($\$$, adjusted to 2012$\$$) in losses globally between 1970 and 2012 (WMO, 2014). In South America, 48 droughts were responsible for 23 % (US\$16.5 billion) of losses caused by disasters (1970 - 2012), including the 1978 Brazilian drought, responsible for a loss of $\sim$US\$ 8 billion (adjusted to 2012\$) (WMO, 2014).

20   There are a variety of different types of droughts, including meteorological, agricultural, hydrological, and socioeconomic (Wilhite and Glantz, 1985). Investigating individual types of drought limits understanding of how they are connected, i.e. how meteorological drought (precipitation deficit) propagates through the hydrological system resulting in socioeconomic drought,

for example. Socioeconomic drought is characterized by the failure to supply economic goods (water, hydroelectric power, etc) as a result of water deficits (Wilhite and Glantz, 1985). Because these drought types are usually related to one another, societal impacts of droughts are often conveyed through linkages between them (Fiorillo and Guadagno, 2009).

Establishing linkages between meteorological and hydrologic droughts is challenging due to the large spatiotemporal variability in water distribution. Increasing availability of remotely sensed (RS) changes in terrestrial total water storage (TWS) data from the Gravity Recovery and Climate Experiment (GRACE) satellites, precipitation, and evapotranspiration (ET) greatly enhances our ability to assess linkages between the different types of droughts (Tapley et al., 2004; Huffman et al., 2007; Mu et al., 2007). In addition to remote sensing data, Global Land Data Assimilation Systems (GLDAS) land surface models (LSMs) provide valuable data on water budgets related to droughts (Rodell et al., 2004).

Meteorological drought indicators, such as the standardized precipitation index (SPI), have been used to forecast hydrologic droughts based on a streamflow Drought Index (Tigkas et al., 2012; Fiorillo and Guadagno, 2009). Major hydrological regimes have been characterized using satellite data (GRACE, TRMM) and GLDAS LSMs (Awange et al., 2014). GRACE satellite data have been used to assess impacts of droughts on TWS in large basins globally (Long et al., 2013; Leblanc et al., 2009).

In Brazil, drought related studies have focused mostly on the Amazon basin (Frappart et al., 2012; Nepstad et al., 2004; Yin et al., 2014) or semi-arid Northeast Brazil (Marengo et al., 2013). However, Southeast Brazil (~ 70 million people), accounting for $\sim 55\%$ of national GDP in 2012 (IBGE, 2014), has been subjected to two major droughts since 2000. The early 2000s drought was responsible for a major energy crisis in Brazil, leading to energy-rationing programs and even blackouts, attributed in part to limited transmission and interconnection (Rosa and Lomardo, 2004). The more recent drought (2014) compromised the water supply for ~ 11 million people in Brazil's largest Metropolis: São Paulo. Reservoir levels in São Paulo's main water supply system (Cantareira System) dropped below 15% of capacity. The 2014 drought jeopardized potable water supplies of ~ 133 cities (~ 28 million people) in the Southeast region (Lobel et al., 2014), where there are ~ 50 reservoirs reservoirs with individual areas exceeding 1000 ha, mostly in the Paraná basin. The 2014 water year (Sep 2013 - Aug 2014) was the driest on record in São Paulo city area since 1962 (Coelho et al., 2015a) with simulated reservoir dynamics changing in response to drought (Coutinho et al., 2015). Analysis of GRACE TWS anomaly data indicate that between Feb 2012 and Jan 2015, total water storage declinedc by $\sim 6\,\mathrm{cm\,yr^{-1}}$ ($56\,\mathrm{km^3\,yr^{-1}}$; totalling $160\,\mathrm{km^3}$) in Southeast Brazil as a result of reduced rainfall (Getirana, 2015). In this context, it is reasonable to ask whether the meteorological forcing is primarily responsible for the socioeconomic droughts in the region. Would an improved electric distribution system avoid the blackouts that occurred in the early 2000s? Is the water crisis in São Paulo solely linked to meteorological factors? Was 2014 also the driest water year in the entire Southeast region in decades? Were these two droughts similar and, if so, did they result in similar impacts? Finding the linkages between different types of droughts is important to answer these questions. Hence, the objective of this study was to address the following questions related to linking meteorological and hydrological droughts in the Paraná River Basin in Southeast Brazil:

- What is the intensity, extent, and duration of the recent droughts?

- What are the droughts impacts on terrestrial total water storage and reservoir storages?

– How do the droughts propagate through the hydrologic system?

– How do different reservoirs respond droughts?

The Paraná basin (PB) was selected as a case study because of the severity of recent droughts and widespread impacts on water supply and hydroelectricity generation. To answer these questions, we used remotely-sensed total water storage anomalies from GRACE (Section 2.1, SI Section S3.4), remotely-sensed and ground-based gridded rainfall datasets (Section 2.1, SI Section S3.3), remotely sensed ET (Section 2.1, SI Section S3.3), simulated soil moisture storage and runoff from four LSMs (2.1, SI Section 3.2), and monitoring data from 37 reservoirs (2.1, SI Section 3.1). We use (i) statistical indices to characterize meteorological and hydrologic droughts (Section 2.2, SI Section S4.3), (ii) tests statistics to evaluate the impacts on reservoir storage (Section 2.2, SI Sects. 4.1 and 4.2) and (iii) studied differences and similarities between individual reservoirs (Section 2.2, SI Section S4.4).

Unique aspects of this study include the comprehensive assessment of droughts using a variety of remote sensing, modelling and monitoring approaches and indicators, comparison of multiple droughts and related hydrologic impacts, and variety of scales of analyses from regional reconnaissance using GRACE satellites to local reservoir responses. This study builds on previous studies, such as the reconnaissance evaluation of drought in Southeast Brazil based on GRACE satellite data by Getirana (2015) by expanding remote sensing, modelling, and monitoring data. The area of the Paraná River Basin is much greater than evaluated in some previous analyses that were restricted to São Paulo city (Coelho et al., 2015b, a; Coutinho et al., 2015). The large areal extent allows surface reservoir impacts to be assessed at local to system scales, considering upstream-downstream drought impacts based on observed reservoir storage (RESS) data. The results of this study should enhance our understanding of linkages between meteorological and hydrologic droughts to better manage water resources in this region and similar other regions.

2 Study area, data and methods

The study area ($\sim 800,000\,\mathrm{km}^2$) comprises the contributing basins to 35 reservoirs within the Paraná basin and two other nearby reservoirs (Três Marias and Paraibuna) because they are in areas affected by the 2014 drought (Fig. 1, Table S2). This basin was originally covered by Cerrado and Mata Atlantica biomes which have been replaced by pasture (44 %), annual crops (24 %), sugarcane (9 %) with original Cerrado and forests only occupying 7-9 % each of the land area (FEALQ, 2014).

The Paraná Basin covers parts of seven Brazilian states (SP, MG, DF, GO, MS, PR and SC) (Fig. 1). Population in the basin (~ 60 million, 2010) represents 32 % of the Brazilian population (SI, section S2.1), including the most populated city in Brazil (São Paulo), with ~ 11 million people in 2015.

Mean rainfall is $\sim 1,500\,\mathrm{mm\,yr}^{-1}$ and temperature is $\sim 23\,^\circ\mathrm{C}$ (1980-2014) (Xavier et al., 2015). There are ~ 50 reservoirs in the basin, with the primary purpose of generating hydroelectricity. Due to data limitations, only 37 of the 50 reservoirs were considered in this study. The maximum storage capacity of the 37 reservoirs is $\sim 250\,\mathrm{km}^3$.

The reservoirs in São Paulo's main water supply system (Cantareira) have individual storage capacities ranging from 0.1 - $1 \, \text{km}^3$. Extended dry periods can be critical for the Cantareira and other surface systems. Since the 1960s, five droughts (1977, 1984, 1990, 1992, 2001, 2012 and 2014) reduced reservoir storage supplies for São Paulo (Coelho et al., 2015a).

2.1 Data sources and processing

5   This section provides a general overview of the data sets used in this study. Additional details are provided in SI, Section S3.0. Ground-based rainfall data (P_{obs}) from ~ 1270 gauges (Fig. S3) for the period 1995 - 2013 were interpolated to a $0.25° \times 0.25°$ grid by Xavier et al. (2015). Remotely sensed rainfall estimates (P_{Sat}) were derived from the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) 3B43 version 7 product.

The GRACE-based monthly variations in total water storage (TWS) from Apr 2002 through Apr 2015 were obtained from
10   the University of Texas Center of Space Research (CSR) (Bettadpur, 2012). Standard GRACE spherical harmonic processing procedures were followed to reduce noise while minimizing signal loss, including truncation to degree and order 60, destriping (Swenson and Wahr, 2006), and application of a 250 km smoothing filter (Zhang et al., 2015). Filtered monthly TWS fields in spherical harmonic format were converted to gridded $1° \times 1°$ solutions to match outputs from land surface models spatially.

The analysis of soil moisture (SM) and runoff (R_{off}) is based on outputs from four Land Surface Models (LSM) from
15   GLDAS 1.0: Noah, Mosaic, VIC, and CLM (Rodell et al., 2004). Descriptions of the LSMs and GLDAS are provided in Section S3.2, SI. The ET datasets used were derived from the global ET algorithm (ETGlob) developed by Zhang et al. (2010) and from MOD16 global evapotranspiration product (Mu et al., 2011) (SI, section S3.3).

Daily data on inflow, outflow, water level and storage for 37 reservoirs were downloaded from the Brazilian Water Agency (ANA, Agência Nacional de Águas) web site for the period Jan 1995 - Jun 2015.

20   ### 2.2 Data analyses

The Standardized Precipitation Index (SPI) was selected as the meteorological drought index because it is probabilistic, its implementation is relatively simple, and its interpretation is spatially invariant (Guttman, 1998). We used the 12 month SPI based on historical monthly rainfall data relative to a 35-year time span (1980-2015).

The Streamflow Drought Index (SDI) was selected as the hydrologic drought index because it is analogous to SPI in that
25   it is computationally inexpensive, easy to implement, and reduces the drought characterization to a simple severity versus frequency relationship (Nalbantis and Tsakiris, 2008). In addition, it is not data demanding as it requires only streamflow data (SI, Section S4.3). For practical purposes, drought onsets were classified when SPI/SDI were <-1 for at least 6 months.

The statistical significance of trends in monthly reservoir storage were investigated by applying a modified version of the ranked-based non-parametric Mann-Kendall test (MK) (Kendall, 1975). The MK method is used to avoid making assumptions
30   regarding the distribution of the data and reducing sensitivity to outliers (Hamed, 2008). To overcome possible issues due to positive correlation in the analyzed time series (SI, Section S4.2), we adopted a modified MK trend test for seasonal data with serial correlation (Hirsch and Slack, 1984).

Hierarchical clustering (HC) was used to group the reservoirs and is a commonly adopted approach to identify similar groups among hydrological time series (Brito Neto et al., 2015). The similarities among elements are measured by a distance function (Bailey, 1994). In this study, the objects used to generate the clusters are time series of monthly reservoir storage (SI, Section S4.4).

3   Results

3.1   Meteorological droughts

Two distinct droughts were identified in the Paraná Basin between 1995 and 2015 based on SPI (Fig. 2). The first drought began in Oct 1999 and extended through Aug 2000, during which SPI was ≤ -1.25, characterizing a moderate to severe drought ($-2 \leq \text{SPI} \leq -1$). This drought was followed by a moderate dry year as the average SPI was ~ -0.6 during the rainy season of 2001 (Dec - Feb). The second driest period occurred between Feb 2014 and Nov 2014, with SPI ≤ -1.20 (Fig. 2). The first drought is hereafter referred to as the early 2000s drought and the second drought, the 2014 drought. The 2014 rainfall deficit was previously identified as part of a prolonged drought (2012 - 2015) by Getirana (2015), who applied break tests to TWSA time series and found a change occurring in Feb 2012. Although our analysis of GRACE-based TWS also indicates an abrupt change between 2011 and 2012, this change in TWS reflects a hydrological drought.

The intensity and duration of the drought is spatially variable. Rainfall anomalies in water year (WY) 2001 (Sep 2000 - Aug 2001) was more negative over the eastern and northern part of the Paraná Basin whereas the spatial extent of the 2014 drought was greater as most of PB experienced a reduction of ~ 20 - $40\,\%$ in annual rainfall (Fig. 3; SI, section S5.6). Most of the reservoirs are in areas where rainfall deficits ranged from 20 - 50 % of the long-term average (1982-2015). The negative rainfall anomalies decreased towards the southwest portion of the basin which experienced a positive anomaly of up to 20 %. Between 2002 and 2009, two periods of average rainfall with different inter-annual ranges were found followed by an extremely wet year (WY 2010), mainly over the southeastern part of the PB (Fig. 3), after which rainfall systematically decreased.

3.2   GRACE Total Water Storage Anomaly and Component Storages

The GRACE satellite data provide valuable information on regional extent of drought impacts on total water storage (TWS) (Fig. 4). The GRACE monitoring period (2002 - 2015) does not include the 2001 drought period. The spatial resolution of GRACE satellites is coarse (~ 100 - $200\,\text{km}^2$). The GRACE data show greater depletion in TWS (~ -60 to $\sim -90\,\text{mm}\,\text{yr}^{-1}$ between Apr 2011 and Apr 2015) in Southeastern Brazil, which corresponds to the northeast part of PB. This range encompasses the results reported for the period between Feb 2012 and Jan 2015 by Getirana (2015) whose findings indicate a water depletion rate of $-61\,\text{mm}\,\text{yr}^{-1}$ in southeastern Brazil ($\sim 920\,\text{km}^2$), corresponding to $\sim 160\,\text{km}^3$ over three years. The spatial extent of the negative TWSA (Fig. 4) is generally consistent with the spatial distribution in the negative rainfall anomaly in WY 2014 (Fig. 3).

GRACE-TWSA shows large seasonal variability that can be accounted for by seasonal fluctuations in soil moisture storage (SMS) from LSMs and monitored RESS (Fig. 5). Interannual variability in GRACE TWS shows anomalously wet years in 2007 and 2010, related to elevated rainfall. SMS and RESS were also above average in those years. The peak TWS in Jan 2007 shows the rapid response of the system to the peak in SPI during the same period (Fig 2). Note that SPI was low or close to

5 1 between 1999 and 2006; therefore, the peak TWS was not preceded by high rainfall in 2006. There is a long-term decline in TWS from Apr 2011 to Apr 2015 ($\sim 37\,\mathrm{km^3\,yr^{-1}}$, $\sim 42\,\mathrm{mm\,yr^{-1}}$), totalling 148 $\mathrm{km^3}$. Depletion in TWS ($\sim 42\,\mathrm{mm\,yr^{-1}}$) is greater than that in SMS and RESS combined ($\sim 24\,\mathrm{mm\,yr^{-1}}$) by $\sim 40\,\%$. The discrepancy may be related to depletion in deep SMS or groundwater storage (GWS). Simulated SMS from LSMs is restricted to the upper 2 m of the soil profile.

3.3 Analysis of Combined Reservoirs as an Equivalent System

10 There is strong evidence (probability $\geq 95\,\%$) that the early 2000s (p-value = 0.027) and 2014 (p-value = 0.01) droughts resulted in significant depletion of the total reservoir storage based on the MK U test. This depletion corresponds to a reduction of $\sim 40\,\mathrm{km^3}$ ($\sim -17\,\%$) in WY 2001 and $\sim 34\,\mathrm{km^3}$ ($\sim -15\,\%$) in WY 2014 of the average storage volume and of $\sim 90\mathrm{km^3}$ ($\sim -33\,\%$) and $\sim 86\,\mathrm{km^3}$ ($\sim -31\%$) below the equivalent system maximum capacity.

Comparing the negative trends in RESS, the recent drought was more intense than the earlier drought: between 1997 and

15 2001, the equivalent RESS decreased by $17.1\,\mathrm{km^3\,yr^{-1}}$ relative to 25.3 $\mathrm{km^3\,yr^{-1}}$ between 2011 and 2015 (SI, Fig. S10). The reservoir system responded rapidly to the meteorological shifts. RESS was lowest at the beginning of the water year 2001; SPI values indicate the meteorological drought began in Oct 1999, when SPI ~ -1.3. During the wet period of 2002, the reservoir systems began to recover and by early 2003 the reservoirs were operating at normal capacity, even though SPI indicated a normal-to-moderately dry condition. Additional information about the recovery/depletion of reservoirs in a spatial context is

20 presented in SI, Section S5.5

3.4 Drought propagation through the system

Variations in precipitation translate to changes in soil moisture storage (SMS) that affect runoff (Roff) and ultimately impact RESS. SMS and $\mathrm{R_{off}}$ were similarly affected by the early 2000s drought (Fig. 2). After 2001, the almost one decade of relatively normal rainfall was insufficient for SMS and $\mathrm{R_{off}}$ to recover from the drought. Not even the extreme wet period in 2010/2011

25 resulted in SMS and $\mathrm{R_{off}}$ recovery. Given that rainfall continued to decrease in the following years, the negative trend in SMS and $\mathrm{R_{off}}$ persisted.

The average temperature in the Paraná basin decreased by $\sim 0.04\,^{\circ}\mathrm{C\,yr^{-1}}$ within the past 20 years (SI, Fig. S9). However, the analysis of both temperature and ET were inconclusive regarding their impacts on reservoir storage change. Further information about these variables is provided in SI (Section S5.2).

30 The analysis of $\mathrm{R_{off}}$, SMS and TWSA provides insights into the mechanisms that may explain the reservoir responses to droughts. According to SPI, the rainfall regimes during both droughts are similar; however, the greater impacts on reservoir storage in 2014 is likely explained by different antecedent soil moisture conditions. The fact that SMS did not recover after the early 2000s drought implies that higher rainfall amounts would be required for recovery to overcome the cumulative SMS

deficit. The extremely wet conditions in 2010/2011 were only sufficient to partially replenish the reduced SMS. Runoff can be classified as infiltration excess (when rainfall exceeds the infiltration rate of the soils) or saturation excess (when soils are close to saturation).Therefore, R_{off} is highly sensitive to SMS conditions. If rainfall is insufficient to recover SMS, then R_{off} cannot recover either. After 2010/2011, SMS, R_{off}, and TWS continued to decline, hence, the main inflow to the reservoirs (river

5   discharge), which depends on runoff and baseflow (groundwater discharge to streams), also decreased. The years preceding the early 2000s drought were wetter than those preceding the 2014 drought: SPI exceeded 1.5 (severely wet) throughout most of the 1997 through 1999 period, and SMS and Roff were more than 20 % higher than the following years. Therefore, SMS links meteorological drought to R_{off}, which is the primary input to RESS.

3.5   Cluster analysis applied to reservoir storage

10   Changes in RESS reflect the impacts of climate extremes through SMS and R_{off} and also reservoir management for hydroelectricity and water supply. Therefore, reservoir storage reflects a balance between climate forcing and dam operations. Cluster analysis suggested that the reservoirs could be subdivided into six groups (G1, G2, ...,G6) based on the time series signal of monthly storage (Figs.6 and 7). The hierarchical tree of the groups and linkages between them is shown in a dendrogram (Fig. S11). Although dam are managed primarily by humans, dam operations are also constrained by non-human-controlled vari-

15   ables (e.g. natural inflows) and legal obligations to maintain outflows exceeding a minimum value (Q_{min_out}) at all times. The compliance with Q_{min_out} aims to guarantee multiple uses of water resources and is defined by the Electric System National Operator (ONS - Operador Nacional do Sistema Elétrico) for each hydroelectric power plant (HEP). Hence, even though the released outflow from a given reservoir may be reduced to control the decline in storage during a drought, the reservoir will, eventually, experience some depletion given the need to observe Q_{min_out}. Here, we sought to identify how human control and

20   natural forcing dictate the responses in each reservoir.

3.5.1   Natural controls

The reservoirs in group 1 (G1, 15 out of 37) are characterized by well-defined seasonal variations, with good correspondence between storage change and natural input to the contributing basins (Figs. 6, 7). In general, their storage through time is similar to that described by the equivalent system of reservoirs in terms of depletion during the early 2000s and 2014 droughts. Within

25   G1 reservoirs, the inflows compare well with SPI, indicating a major role of natural forcing on reservoirs responses.

Similarly, comparison between SPI, SDI and RESS in G3 reservoirs also suggests their responses are strongly affected by natural variability (Figs. S37 - S40). Different responses between G1 and G3 reservoirs can be explained by climatological variations (Fig. 7). The main climatic difference between G1 and G3 reservoirs is the pronounced dry season that occurs in the climate sub-types Cwa (humid subtropical), Cwb (temperate highland tropical) and Aw (tropical wet and dry) in G1 reservoirs

30   whereas rainfall is more evenly distributed throughout the year in the sub-type Cfa (humid subtropical) in G3 reservoirs. The occurrence or absence of dry winters affects the seasonal distribution of inflows to reservoirs, hence, impacting the seasonal signal in reservoir storage. Good correspondence between reservoir response and precipitation regime is not restricted to reservoirs in the upper part of the basin, i.e. reservoirs with no upstream reservoir affecting their inflow. What happens in the

other cases is that the natural inflow (from undisturbed basins - UB) contributes to the total inflow that explains the reservoir storage change as much as the regulated discharge delivered by the reservoir(s) upstream or the outflow from upstream mimics natural discharge variations (SI, section S5.7).

Although G6 reservoirs are similar to G1 reservoirs in terms of having a well-defined seasonal variations with good corre-
5 spondence between precipitation variability and reservoir storage change, G6 reservoirs seem to deplete/recover more slowly than those in G1. The reservoirs of the Cantareira System are included within G6 reservoirs (Fig. S53). This system experi-enced major depletion as result of natural water stress imposed by the recent drought (2014) combined with high demand from São Paulo metropolitan area. The total rainfall in the 2014 water year was 1150 mm, $\sim 25\%$ lower than the average since 1995, resulting in SPI ≤ -2 (extremely dry). The lowest reservoir levels registered in the storage of the system (early 2015) reached
10 $\sim 10\%$ of the total capacity, making the impacts of the 2014 drought unique.

3.5.2 Anthropogenic controls

Reservoirs in G2 and G5 do not show distinct seasonal variations, indicating that their responses are mainly governed by how they are operated and how the upstream dam is operated, given that all reservoirs in these groups are downstream of other hydroelectric power plants. In addition, the natural component of the total inflow is minimal because the upper undisturbed
15 basin accounts for a small fraction of the total contributing area (Figs. S32 - S36 and S47 - S50). As a result, SPI fluctuations are not always reflected in reservoir storage. In such cases, analysis of SDI is inconclusive as it cannot provide information on natural discharge variability unless the human-controlled component of Q is removed.

For example, storage doubled in the Jaguará reservoir (G2) between 2001 and 2005 (0.04 to $\sim 0.08\,\mathrm{km}^3$) even though SPI and SDI indicate the onset of a meteorological and hydrological drought (Fig. S34). That period was followed by an extremely
20 wet year (2007/2008) but the rainfall increase was not reflected in the inflow (SDI~ 0) or in increased reservoir storage. Finally, no significant depletion was found during the extremely dry period in 2014. The main difference between G2 and G5 reservoirs is the change in average reservoir level (mainly after 2002), positive for G2 and negative to G5, displayed by most of those reservoirs (Fig. 6).

3.5.3 Natural and Anthropogenic controls

25 Responses in G4 indicate that these reservoirs are equally controlled by natural and operational forcing. The natural component is reflected in the seasonality of storage variation. Their location in the PB, downstream to large reservoirs (Figs. S42-S47), makes them vulnerable to anthropogenic controls. Similar to G2 and G5 reservoirs, storage changes in G4 reservoirs are highly affected by dam operations, which implies that a precipitation deficit can be compensated by reducing outflow and benefiting from regulated discharge from upstream. However, persistence of low inflow may require operation that drastically reduces
30 reservoir storage to maintain $Q_{\mathrm{min\_out}}$. That is precisely what happened at the M. M. Moraes Hydroelectric Power Plant (Fig. S43) in 2014 as the Electric System National Operator (ONS - Operador do Sistema Elétrico) decided to reduce the reservoir level by $\sim 8\,\mathrm{m}$.

3.6 Implications for Water Resources

GRACE reconnaissance data provide valuable information for water resources assessment as monthly changes in TWS over large regions can be monitored. Such information can be used to assess the regional responses of the hydrological system to climate and anthropogenic forcing. Data on the components that make up TWS (SMS and GWS) are generally limited. SMS data are derived primarily from land surface models. Ground-based monitoring of SMS is limited but should be expanded to assess the reliability of SMS estimates from land surface models. GWS can be estimated from GRACE TWS by subtracting the other components of water storage (RESS and SMS); however, uncertainties in these estimates can be high. Monitoring networks of GWS would be extremely beneficial, particularly because GWS can provide information to estimate baseflow to streams.

This study emphasizes the evolution of drought from meteorological drought through SMS changes to hydrologic drought and ultimately impacting RESS. Assessing the relative importance of natural and anthropogenic controls on RESS is critical with natural forcing dominant in upstream and some downstream reservoirs, and anthropogenic controls primarily in downstream reservoirs. Optimal management of reservoirs to reduce impacts of future droughts requires an understanding of the controls on reservoir storage and relative importance of natural and anthropogenic controls. Relating SPI to SMS, R_{off}, and RESS links meteorological drought to the hydrologic system within a regional context. This study emphasizes the role of antecedent SMS in controlling R_{off} and, ultimately, impacting reservoir responses to drought. Continuous monitoring of SMS would be extremely beneficial in determining when R_{off} might occur in response to precipitation related to drought recovery and would also help with assessing floods because SMS can be used for predicting runoff and streamflow responses to increase/reduced rainfall. Monitoring GWS would also be beneficial for estimating baseflow to streams that provide inflow to reservoirs.

Because rainfall is spatially variable and dam operation affects downstream reservoirs, distinct impacts on reservoirs were identified depending on their position within the Paraná Basin. For most reservoirs, including the Cantareira System, meteorological droughts were reflected in the hydrological system through reduced inflow to the reservoirs. These reduced inflows have important implications for water management because they reflect the reservoir system vulnerability to droughts. The vulnerability to recent droughts in São Paulo underscores the need for reservoir storage expansion but also reinforces the urgency for diversifying the water sources to enhance drought resilience. In other cases, the upstream reservoirs performed an important role in regulating river discharge and, hence, reducing meteorological drought impacts on inflow to downstream reservoirs. We are not suggesting that new dams should be built, as it may result in significant adverse environmental impacts; however, reservoir infrastructure has been shown to be an important structural measure to combat droughts, given their capacity in regulating river discharge (Braga et al., 2012).

The group analysis of reservoirs indicates that the responses of individual reservoirs are ultimately controlled by the balance between climatic forcing and reservoir operations. The system response, including upstream-downstream location of reservoirs, needs to be considered when assessing drought impacts. Reservoir operations can benefit from conjunctive-optimization in

which the operation of upstream and downstream reservoirs are accounted for along with weather forecasting and past water storage information.

4 Conclusions

Regional intense droughts in southeast Brazil have caused major depletion in water resources. We analyzed remote sensing, monitoring, modelling data to identify linkages between meteorological and hydrological droughts. Based on SPI, two major meteorological droughts occurred in the Paraná basin between 1995 and 2015. A moderate to severe drought ($-2 \leq \mathrm{SPI} \leq -1$) occurred in the early 2000s with $\mathrm{SPI} \leq -1.25$ between Oct 1999 and Aug 2000. The second driest period occurred between Feb and Nov 2014, with $\mathrm{SPI} \leq -1.20$. Droughts intensity and duration are spatially variable. The 2014 drought was more critical over the northeastern part of the study area, with rainfall anomalies ranging between -20 to $-60\,\%$, resulting in SPI values ≤ -2.0 for 6-12 months in some cases (e.g. Furnas reservoir, Fig. 7).

The recent drought monitored by GRACE satellites shows depletion of TWS of $\sim 37\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ ($42\,\mathrm{mm}\,\mathrm{yr}^{-1}$) over four years from 2011 to 2015 in the Paraná Basin, totaling $\sim 150\,\mathrm{km}^3$. Simulated SMS and monitored RESS together decreased by $24\,\mathrm{mm}\,\mathrm{yr}^{-1}$, accounting for $\sim 60\,\%$ of TWS depletion. This recent drought was preceded by an earlier drought (early 2000s) that occurred prior to GRACE monitoring. Reduced rainfall and negative SPI during this drought translated to low SMS and reduced runoff (SDI anomalies) decreasing RESS by $\sim 30\,\mathrm{km}^3$ in 2001 relative to the average storage volume. Depletion of reservoir storage caused by the early 2000s and 2014 droughts correspond to a $\sim 31\,\%$ reduction relative to the reservoir equivalent system maximum capacity. Two negative short-term trends in RESS were found during the studied period: $-17.1\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ (1997-2001) and $25.3\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ (2011-2015), totalling 68 and 101.2 km^3, respectively.

The period between these two droughts is characterized by slightly below average to near normal rainfall; however, rainfall levels were insufficient to overcome the cumulative water deficit that built up during the early drought. Low SMS compromised recovery even after the severely-wet year in 2010. As a result, the system storage reserves were low going into the recent drought and were rapidly depleted during 2014.

While GRACE satellites provide data on regional water storage depletion and recovery related to drought, SMS and $\mathrm{R_{off}}$ from LSMs link meteorological drought to hydrologic drought as shown by streamflow anomalies (SDI) that are reflected in inflows anomalies to the reservoirs. However, detailed assessment of drought impacts on reservoir storage requires more thorough analysis of reservoirs at the local scale. Clustering analyses in this study revealed three groups of reservoirs (15 reservoirs) with storage controlled mainly by natural climatic forcing, two groups (9 reservoirs) controlled mainly by reservoir operations and one group (6 reservoirs) controlled by a combination of natural and anthropogenic forcing (dam operations). The analysis highlights the importance of reservoir location within the system (upstream vs. downstream) in determining the dominant controls on drought impacts on reservoir storage.

This study emphasizes the importance of integrating remote sensing, modelling and monitoring data to quantify the duration, extent, and severity of regional droughts and their impacts on water resources, specifically reservoir storage; system evaluation and detailed analysis of individual reservoirs to determine controls on reservoir response to drought (e.g. natural climate forcing

versus dam operations), and the importance of this comprehensive understanding on the linkages between the meteorological and hydrologic droughts for future management.

Author contributions. The first author collected and processed the data from GLDAS, ANA and ONS. ZZ processed and analysed the data from GRACE. EW and BS analysed the data and commented on the paper, which was written by DM and BS.

5   **5   Data availability**

All the data used in this study is hosted by the Laboratory of Computational Hydraulics of the University of São Paulo and is available at http://albatroz.shs.eesc.usp.br/?q=dados-de-pesquisa.

Acknowledgements. The first author would like to thank the National Council for Scientific and Technological Development (CNPq- Conselho Nacional de Desenvolvimento Científico e Tecnológico) for the financial support (Grant agreement numbers 206857/2014-4 and
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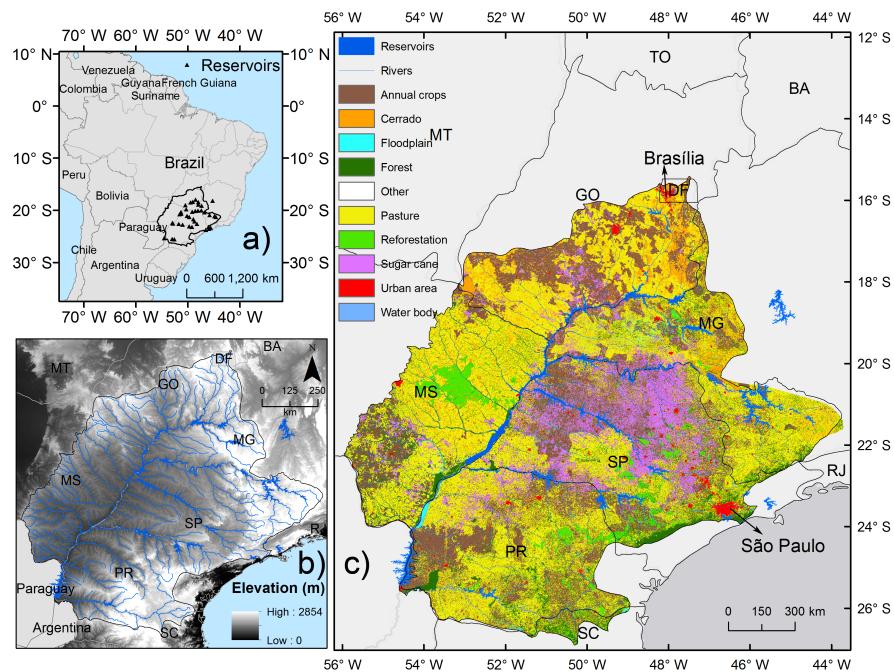
Figure 1. (a) The Paraná River Basin in the national context. (b) The analysed reservoirs are highlighted in dark blue in the digital elevation map (30 x 30 m) and in (c) the 2012 land use map (FEALQ, 2014). States include: Distrito Federal (DF), Goiás (GO), Minas Gerais (MG), São Paulo (SP), Paraná (PR), Santa Catarina (SC) and Mato Grosso do Sul (MS).
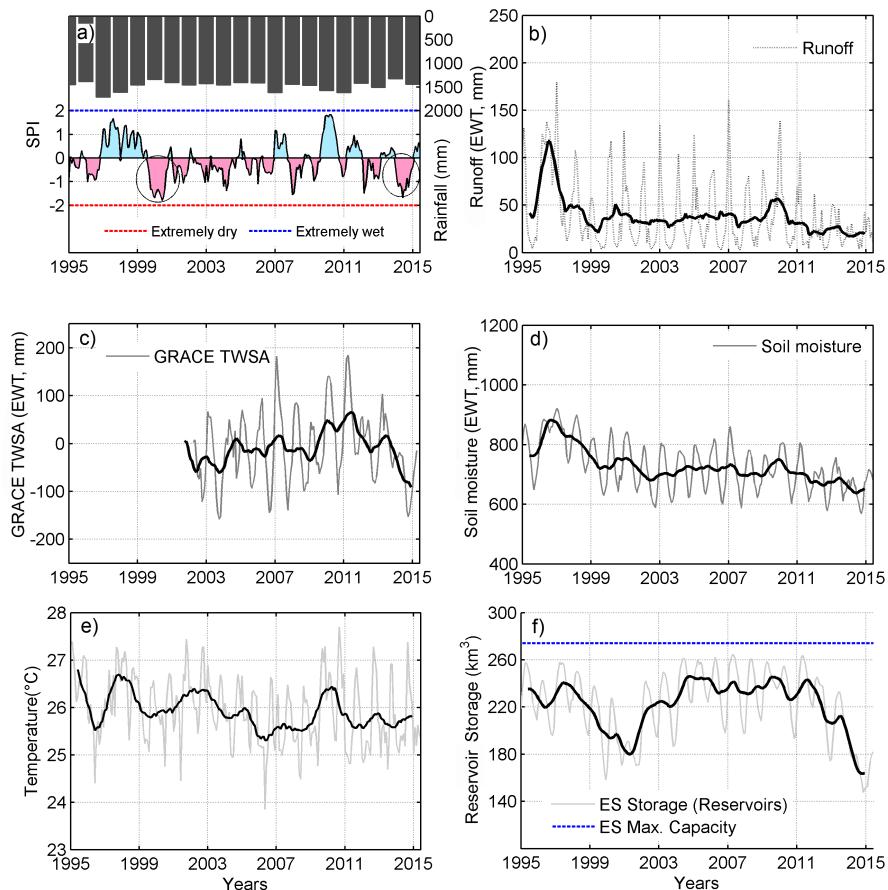
Figure 2. Time series of (a) rainfall and SPI, (b) runoff, (c) GRACE total water storage anomaly (TWSA), (d) soil moisture, (e) temperature and (f) reservoir storage in the equivalent system (ES). (a) Standardized Precipitation Index (SPI) categories include: extremely wet (SPI>2); severely wet ($1.5 \leq$ SPI < 2); moderately wet ($1 \leq$ SPI < 1.5); wet ($0.5 \leq$ SPI < 1); normal ($-0.5 \leq$ SPI < 0.5); moderately dry ($-1 <$ SPI ≤ -0.5); dry ($-1.5 <$ SPI ≤ -1); severely dry ($-2 <$ SPI ≤ -1.5); extremely dry (SPI <-2). (b) runoff, (c) GRACE total water storage anomaly (TWSA) and (d) soil moisture are expressed in equivalent water thickness (EWT).
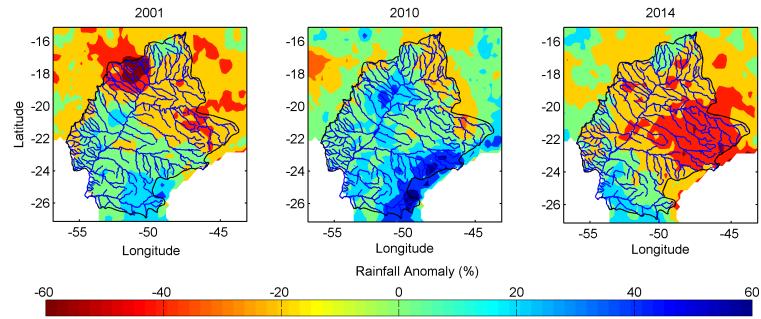
Figure 3. Rainfall anomaly relative to the 1982-2015 mean for three water years: 2001 (Sep 2000 - Aug 2001), 2010 (Sep 2009 - Aug 2010) and 2014 (Sep 2013 - Aug 2014).
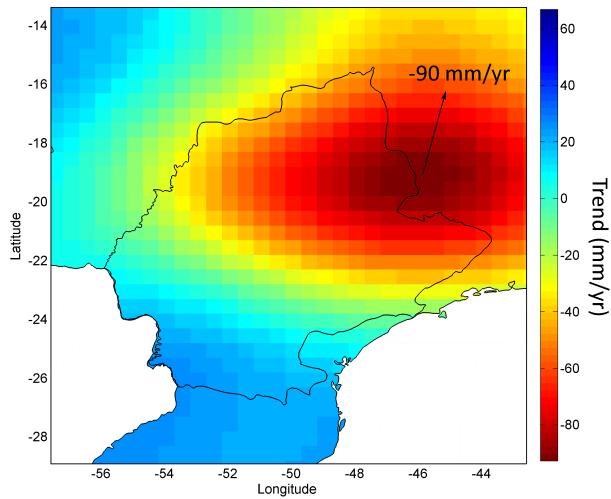
Figure 4. Spatial trends of TWS between Apr 2011 and Apr 2015
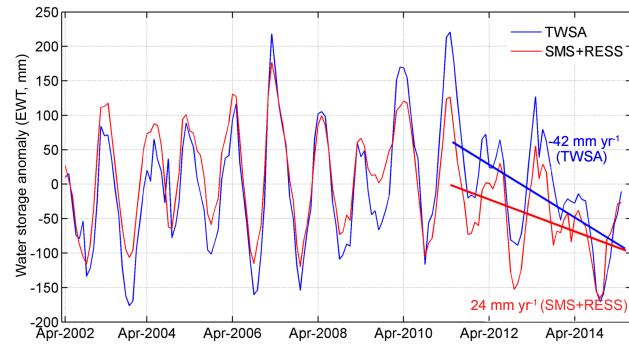
Figure 5. Water Storage Anomalies from GRACE TWS, soil moisture storage (SMS) and reservoir storage (RESS), all expressed as equivalent water thickness. Use
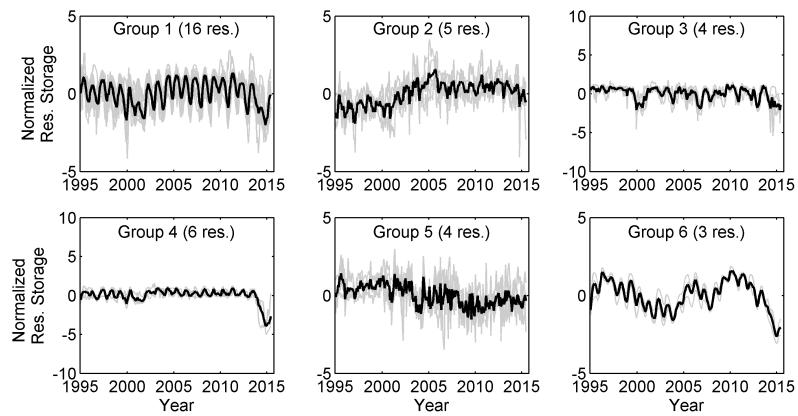
Figure 6. Time series of monthly reservoir storage of the 6 reservoir groups. Individual reservoirs are in light grey. Black lines show the group average.
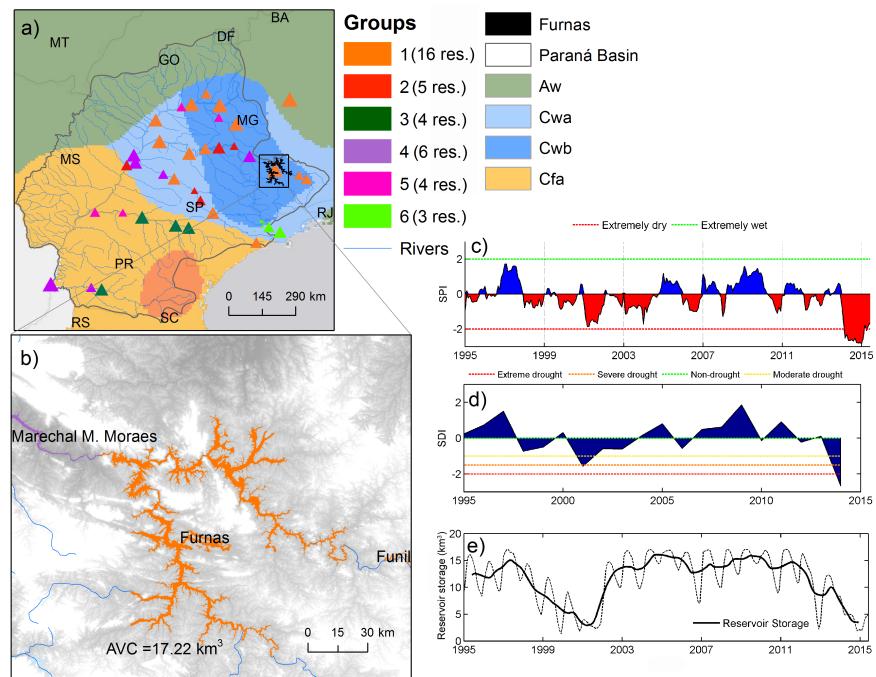
Figure 7. (a) The 37 analyzed reservoirs in the context of the Paraná Basin clustered in six groups and the number of elements per group. (b) Example of a typical reservoir from group 1 (16 reservoirs): Furnas hydroelectric power plant (HEP). Time series of monthly rainfall relative to the contributing area of Furnas HEP and inflow to Furnas reservoir were used to derive the Standardized Precipitation Index (SPI) (c) and Streamflow Drought Index (SDI) (d). Furnas monthly storage is shown in km3 (e). Hydrologic dry conditions are defined by the following states: SDI≥ 0: non-drought, $-1 \leq$SDI<0: Mild drought, $-1.5 \leq$SDI$<$-1: Moderate drought, $-2 \leq$SDI$<$-1.5: Severe drought and SDI$<$-2: extreme drought.