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SPATIAL AND TEMPORAL ANALYSIS OF DROUGHT EVENTS IN UPPER PARANÁ RIVER HYDROGRAPHIC REGION (BRAZIL) FROM 1990 TO 2020

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Abstract

The Paraná River Hydrographic Region is of great socioeconomic relevance for Brazil. Therefore, due to the history of droughts in the region, the aims of the current study were to assess rainfall spatial and temporal variability, as well as to analyze drought features based on using the Normalized Percentage Index (NPI) to contribute to water management processes in Upper Paraná River (UPR). The study area encompasses 14 Planning and Management Units, distributed in Goiás, Mato Grosso do Sul, Minas Gerais and São Paulo states. Climate data were obtained from the National Hydrometeorological Network database. A geostatistical analysis of rainfall was carried out, based on the annual series of 408 stations, and subsequently the calculation of NPI for classifying the droughts severity. All periods analyzed (1990-2020) showed spatial dependence (moderate to high), allowing the elaboration of droughts maps. The dry and rainy periods and areas did not indicate direct influence of El Niño-Southern Oscillation (ENSO). The data showed that 2010-2020 was the driest decade of the period, with a greater contribution from the 2019/2020 period, where droughts exceeded 60% of the area for two consecutive years, an event never identified in the last 3 decades. The NPI curves referring to "initial drought" and "mild" allowed verifying years of water crisis when their summed percentages reached at least 50% of the region.

Keywords: Rains. Water management. NPI. Kriging.

Resumo / Resumen

ANÁLISE ESPACIAL E TEMPORAL DE EVENTOS DE SECAS NA REGIÃO HIDROGRÁFICA ALTO RIO PARANÁ DE 1990 A 2020

A Região Hidrográfica do Rio Paraná possui grande relevância socioeconômica para o Brasil. Devido ao histórico de secas na região, o objetivo do presente estudo foi avaliar a variabilidade espacial e temporal das chuvas, bem como analisar as características das secas com base no Índice de Porcentagem Normal (IPN) de modo a contribuir com a gestão da água no Alto Rio Paraná (ARP). A área de estudo compreendeu 14 unidades hídricas de planejamento, distribuídas nos estados de Goiás, Mato Grosso do Sul, Minas Gerais e São Paulo. Os dados climáticos foram obtidos junto a Rede Hidrometeorológica Nacional. Efetuou-se a análise geoestatística dos dados de precipitação, a partir das séries anuais de 408 estações, e posteriormente o cálculo do IPN para classificação da severidade das secas. Todos os períodos analisados (1990-2020) indicaram dependência espacial (moderada-alta), possibilitando a elaboração dos mapas de secas. Os períodos e áreas secas e chuvosas não indicaram influência direta do El Niño-Oscilação Sul (ENOS). Os dados indicaram que 2010-2020 foi o decênio mais seco do período, com maior contribuição em 2019/2020, onde as secas superaram 60% da área, evento nunca identificado nas últimas 3 décadas. As curvas IPN referente a "seca inicial" e "suave" permitiram verificar anos de crise hídrica quando seus percentuais somados atingiram pelo menos 50% da bacia do ARP.

Palavras-chave: Chuvas. Gestão hídrica. IPN. Krigagem.

ANÁLISIS ESPACIAL Y TEMPORAL DE LOS EVENTOS DE SEQUÍA EN LA REGIÓN HIDROGRAFICA DEL ALTO RIO PARANÁ DESDE 1990 HASTA 2020

La Región Hidrográfica del Río Paraná es de gran relevancia socioeconómica para Brasil. Debido a la historia de sequías en la región, el presente estudio tuvo como objetivo analizar la variabilidad espacial y temporal de las precipitaciones, así como las características de la sequía con base en el Índice Porcentual Normal (IPN) con el fin de contribuir a la gestión del agua en el Alto Río Paraná (ARP). El área de estudio comprende 14 unidades hídricas distribuidas en los estados de Goiás, Mato Grosso do Sul, Minas Gerais y São Paulo. Los datos climático se obtuvieron de la Red Hidrometeorológica Nacional. Se realizó un análisis geoestadístico de las precipitaciones, a partir de la serie anual de 408 estaciones, y posteriormente el cálculo del IPN para clasificar la severidad de las sequías. Todos los períodos (1990-2020) mostraron dependencia espacial (moderada-alta), lo que permitió la elaboración de mapas de sequías. Los períodos y áreas secas y lluviosas no indicaron influencia directa de El Niño-Oscilación del Sur (ENOS). Los datos mostraron que 2010-2020 fue la década más seca, con mayor contribución del 2019/2020, donde las sequías superaron el 60% del área, evento nunca identificado en las últimas 3 décadas. Las curvas IPN referidas a "sequía inicial" y "leve" permitieron verificar años de crisis hídrica cuando sus porcentajes sumados alcanzaron al menos el 50% de la región.

Palabras-clave: Palabras clave: Lluvias. Administracion del agua. IPN. Kriging.

INTRODUCTION

Water management involves investigating and understanding climate trends and changes that, along with changes in land use and cover, have straight impact on watershed management processes (KUMAR, et al., 2019; THOMAS & PRASANNAKUMAR, 2016). This research type becomes increasingly challenging due to the frequency of extreme events capable of affecting the natural variability of hydrological processes, as well as of hindering economic development (BHATTI et al., 2016; DUTTA & MAITY, 2021).

Nowadays, several outcomes resulting from atypical changes in climate patterns and rainfall regimes, such as global warming and the warm (El Niño) or cold (La Niña) phases of the El Niño-Southern Oscillation (ENSO) phenomenon (ARYAL et al., 2018; MALLAKPOUR et al., 2018, 2019). This affect extensive areas and influence large-scale hydrological patterns' intensity and seasonality (ROCHA & SANTOS, 2018).

According to Melo (2017), extreme climate and meteorological events have negative impact on rainfall rates in different regions in the country, and it leads to issues, such as water rationing and reduced electric power generation. Consequently, several authors have associated climate change and ocean-atmospheric phenomena with both fluctuations in hydrological conditions and extreme droughts in the Amazon (MARENGO et al., 2013; PEDREIRA JUNIOR et al., 2020), and in the Northeastern (ALMEIDA, 2014), Southeastern (MINUZZI et al., 2006; ABOU RAFEE et al., 2019) and Southern regions in Brazil (BASSO, 2019).

According to the National Meteorological System (SNM), Paraná Hydrographic Region (which comprises important water uses that have economic and social influence on the country) has been showing severe monthly rainfall shortage since October 2019. This factor forced the National Water and Basic Sanitation Agency (NWA) to declare its quantitative water shortage condition as critical, according to Resolution n. 77/2021 (ANA, 2021; AZEVEDO, 2021).

The Normalized Percentage Index (NPI) described by Willeke, Hosking & Wallis (1994) stands out among different drought indices due to its mathematical simplicity and applicability in a single region or station, because it only takes into account rainfall data recorded on a weekly, monthly, seasonal, annual or decadal scale. Thus, NPI has been considered effective on a regional scale, besides being often used to feature meteorological droughts (HAYES, 2006; TEIXEIRA et al., 2013; LIMA, 2016; SALEHNIA et al., 2017). The Upper Paraná River Hydrographic Region (UPR), whose total area covers 254,896 km², presents significant disparity in the availability of hydrological information. Sub-basins located in other states, such as Goiás, Minas Gerais and Mato Grosso do Sul, present rainfall network density up to four times lower than the one recommended by the World Meteorological Organization (WMO, 2008), except for water units in São Paulo State. This issue makes it hard to estimate rainfall data for unsampled locations.

The prevalence of small-scale hydrology has mainly happened due to difficulty in collecting sufficient temporal and spatial data for hydrological analysis to be applied to large basins (ABOU RAFEE et al., 2019). According to Acosta (2014) and Pruski et al. (2012), part of this lack of information has been overcome through regionalization methods aimed at transferring variables, functions or parameters by assuming spatial similarity in homogeneous areas. Despite the hydrological series' availability and quality issue, the theory of regionalized variables (KRIGE, 1951; MATHERON, 1962) based on geostatistics has been successfully used in different hydrological studies focused on spatializing variables, such as temperature and rainfall (JOURNEL & HUIJBREGTS, 1993).

Geostatistics provides valuable tools to assess natural events' distribution, such as spatial and temporal trend analysis (YAMAMOTO & LAMDIM, 2013). This analysis type has been widely used in several rainfall spatialization studies (HU et al., 2019), such as the ones conducted by Muthusamy et al. (2017) in the United Kingdom and by Berndt & Haberlandt (2018) in Northern Germany. Investigations conducted by Malfatti et al. (2018) in Paraná River Basin, by Medeiros et al. (2019) in Paraíba State, and by Ricardi & Lima (2021) in São Paulo State, stand out among Brazilian studies on this topic.

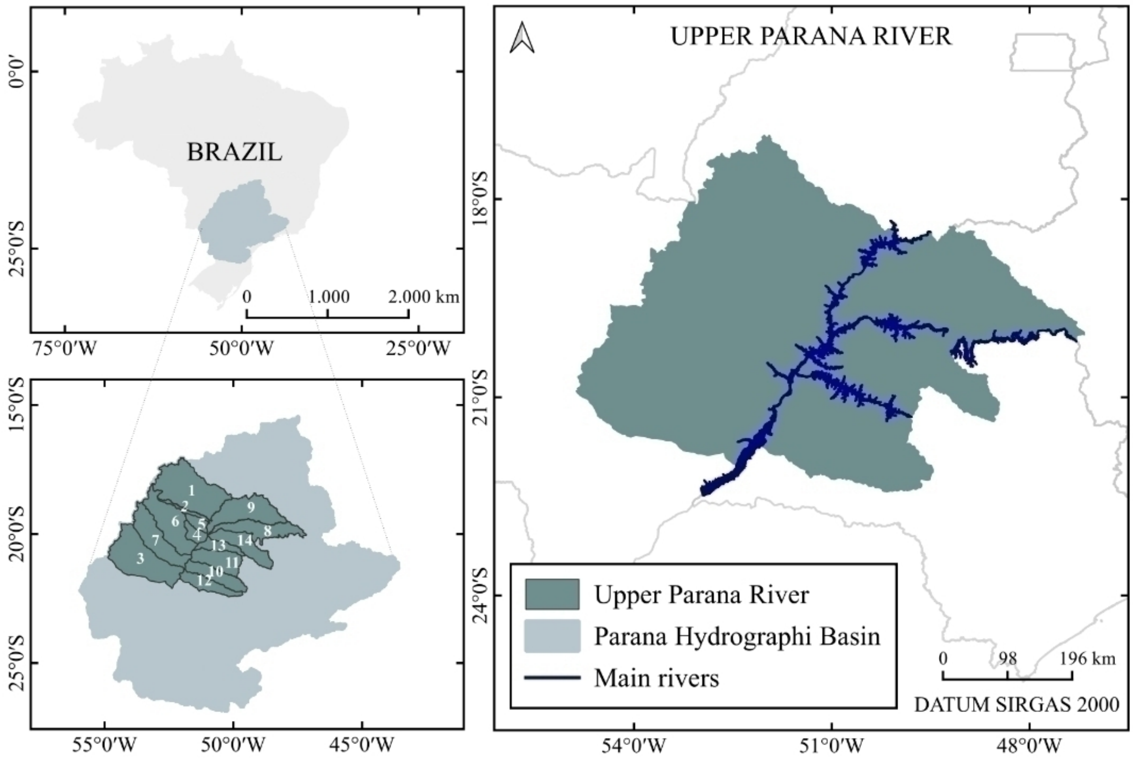
In light of the foregoing, the aims of the current study were to assess rainfall spatial and temporal variability, as well as to analyze drought features based on using the Normalized Percentage Index (NPI) to contribute to water management processes in Upper Paraná River region.

MATERIALS AND METHODS

Study Site and Data Collection

The UPR region (Figure 1) encompasses 14 State Water Resources Planning and Management Units (UEPGRHs); its total area covers 254,896 km² (30% of Paraná Hydrographic Region) and houses approximately 5,358,974 inhabitants (ANA, 2019). According to Kopen's classification, climate in this region is of the Aw type – it corresponds to the tropical dry humid climate of Central Brazil – and its main active air masses comprise the Tropical Atlantic (mTa), Atlantic Polar (mPa) and the atmospheric rivers from the Amazonian region (AZEVEDO, 2021).

Figure 1 - Location of Upper Paraná River region and its constituent sub-basins

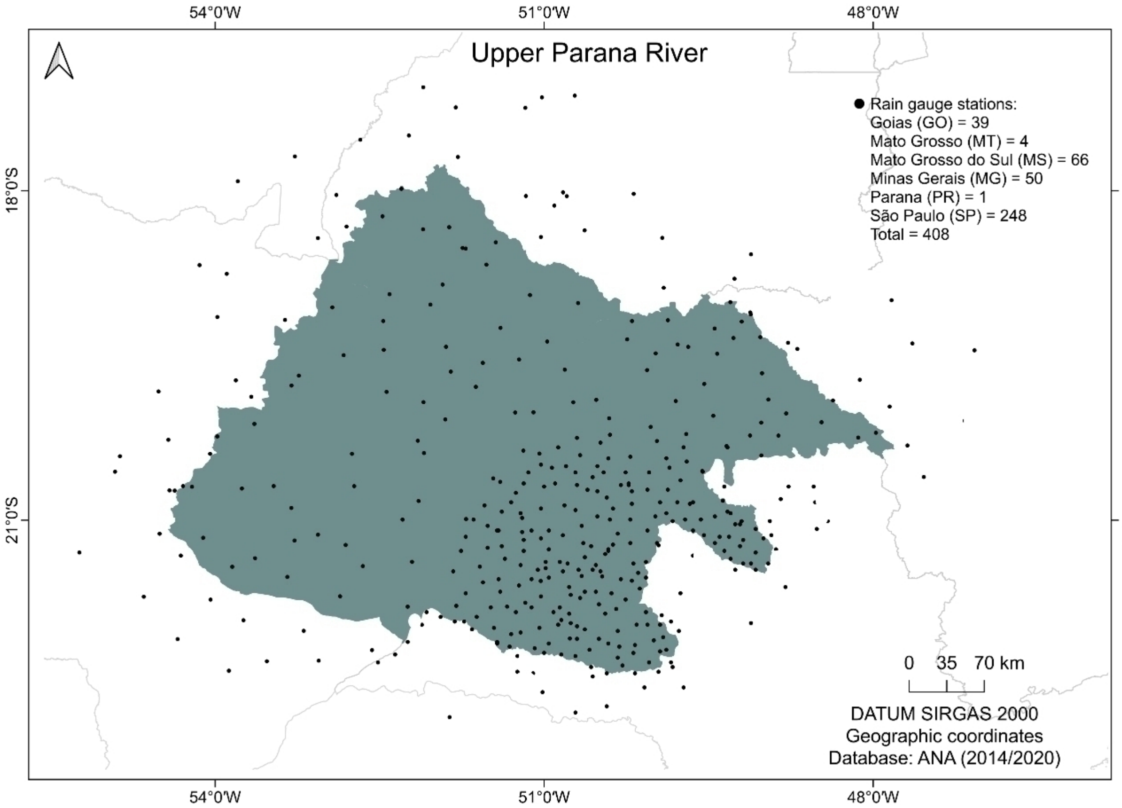


1=Baixo Paranaíba; 2=Aporé; 3=Pardo; 4=Quitéria; 5=Santana; 6=Sucuriú; 7=Verde; 8=Baixo Rio Grande; 9=Baixo Rio Paranaíba; 10=Aguapeí; 11=Baixo Tietê; 12=Peixe; 13=São José dos Dourados; 14=Turvo-Grande.

Source: ANA (2014) - Edited

Rainfall data recorded for the study site were compiled in the Hidroweb tool, v.3.1.1 (SNIRH, 2021). Historical data comprising the period from 1990 to 2020, as well as 341 stations and additional 67 stations (border stations) with complete data of varying sizes, were taken into consideration to fully cover the study site. In total, data from 408 rainfall stations were used in the analysis, they were distributed, as shown in Figure 2. It is worth emphasizing that not all stations had complete monitoring data for the entire investigated timeframe.

Figure 2 - Rainfall stations presenting data recorded from 1990 to 2020



Source: ANA (2014); SNIRH (2021) - Edited

Data Processing

Descriptive statistical analysis was carried out for initial rainfall data featuring purposes. Subsequently, data were subjected to spatial dependence analysis in GeoStatistics for the Environmental Sciences software - Gamma Design (GS+) version 7.0 (ROBERTSON, 2004). Experimental semivariogram was calculated for each investigated year, based on Equation 1 (YAMAMOTO & LANDIM, 2013):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(X_i) - Z(X_i + h)]^2$$

wherein, *N(h)* refers to the number of experimental observation pairs *Z(Xi)* and *Z(Xi+h)* at a regular distance *h*.

The following criteria were initially taken into consideration for semivariogram fitting purposes: a) the smallest sum of squared deviations (SSD); b) the highest spatial determination coefficient (R^2); and c) the highest spatial dependence evaluator (SDE), based on Equation 2. The following SDE interpretation was used: ≤ 25% weakly dependent, > 25% and ≤ 75% moderately dependent, and > 75% highly dependent (LIMA et al., 2020).

$$SDE = \left(\frac{C}{C_0 + C}\right).100$$

wherein, "C" is contribution and "C+C0" is the sill.

The final fitting model-selection process was based on the highest correlation coefficient (r) between the observed and cross-validated (CV) values. After this procedure was over, ordinary kriging interpolation was performed, as described in Equation 3 (YAMAMOTO & LANDIM, 2013):

$$Z^*(x_0) = \sum_{i=1}^{N} \lambda_i Z(X_i) \quad \text{, with} \quad \sum_{i=1}^{N} \lambda_i = 1$$

wherein, "Z*" is the value to be estimated at the unsampled point *x0*; "N" is the number of measured values *z(xi)* involved in the estimation process, and "*λi*" are weights associated with each measured value *z(xi)*.

Normalized Percentage Index (NPI) was applied based on using annual rainfall maps to estimate rainfall deviation from normal values. This measurement was carried out by multiplying the quotient between the current rainfall at a given station and the regular rainfall by 100, as shown in Equation 4 (LIMA, 2016).

$$P = \left(\frac{Pr_{p(current)}}{Pr_{p(regular)}}\right)100$$

wherein, P is the regular rainfall rate, “Pr p(regular)” is the measured rainfall at a given location or station, and “Pr p(current)” is to the long-term mean rainfall recorded for the investigated location- the last two values are expressed in mm. Finally, NPI value was deduced by subtracting 100 from P in order to classify drought intensity based on the scale shown in Table 1.

Table 1 - Normalized Percentage Index (NPI) classification

NPI (%)	Intensity
90 a ≥ 100	Extremely high humidity
70 a 90	High humidity
50 a 70	Moderate humidity
30 a 50	Low humidity
10 a 30	Initial humidity
0 a 10	Normal+
-10 a 0	Normal-
-30 a -10	Initial drought
-50 a -30	Mild dry
-70 a -50	Moderate drought
-90 a -70	Severe drought
-100 a -90	Extreme drought

NPI values were quantified in SPRING 5.3 environment (CAMARA et al., 1996), based on applying Equation 4 to annual rainfall maps in Spatial Language for Algebraic Geoprocessing (SLALG). NPI classes (Table 1) were adjusted based on Gois (2005) and Fernandes et al. (2009). Final maps were edited in QGIS 3.4 software (QGIS, 2021).

RESULTS AND DISCUSSION

Descriptive statistical analysis

The 1990-2020 historical series of total annual rainfall rates in Upper Paraná River region was subjected to descriptive statistical analysis. Results have shown that the series' mean rainfall values ranged from 1,178.34 mm (1999) to 1,759.31 mm (2009). These values were close to those recorded for areas with tropical humid-dry climate in Central Brazil (MENDONÇA et al., 2007) and to the annual rainfall mean of 1,543 mm recorded for Paraná Hydrographic Region (ANA, 2015). Moreover, 1999 (1,178.34 mm), 2002 (1,202.44 mm), 2019 (1,215.43 mm), 1994 (1,216.91 mm), 2014 (1,243.78 mm), 2010 (1,283.10 mm) and 2020 (1,298.51 mm) were the years recording total rainfall values lower than 1,300 mm. These years matched critical water shortage periods (ANA, 2021; MELO, 2017; ZAVATTINI, 2009).

According to Pimentel-Gomes & Garcia's (2002) classification, 26 years (83.87%) of the analyzed period presented medium data variability (10% < CV < 20%), whereas 5 years of it (16.13%) recorded high data variability (20% < CV < 30%). This finding indicated geostatistical analysis' feasibility.

Geostatistical analysis of rainfall data

According to semivariogram adjustment measures shown in Table 3, rainfall events in Upper Paraná River region have showed spatial dependence over the entire investigated period (from 1990 to 2020). The spherical model showed the best fit for 14 of all 31 analyzed years and it indicated intermediate/medium spatial ranges (YAMAMOTO & LANDIM, 2013). Gaussian and exponential models, which oftentimes account for shorter and more distant ranges, have shown the best fit for 9 and 8 years, respectively.

Semivariographic adjustments have also indicated spatial determination coefficients (R^2) ranging from 0.848 to 0.992, as well as ranges (R) from 112,800 m (1998) to 824,456 m (1995). Smaller scope periods (1998 and 2017) mainly comprised isolated events and presented a more heterogeneous spatial aspect, unlike periods of larger scope observed in 1995, 1997 and 2008.

Caram (2007) carried out a study in Minas Gerais State and observed better fits for the spherical model, which recorded ranges from 189,600 m to 1,040,000 m. Assad and Pinto (2012) also pointed out the spherical model as the best fit for annual rainfall interpolation in São Paulo State. This model recorded range of 45,000 m based on data comprising the period from 1957 to 1997. Malfatti et al. (2018) identified homogeneous rainfall regions (from 1980 to 2010) in Paraná River basin, and observed good accuracy for the spherical and Gaussian theoretical models, as well as smaller errors and greater spatial dependence for the exponential model.

Based on Table 3, and according to Zimback's classification (2001), the Spatial Dependence Evaluator (SDE) has indicated high spatial dependence (>75%) in 23 of 31 analyzed years, as well as moderate spatial dependence in the other 8 years (>25% and ≤ 75%), whereas Cross Validation (CV) recorded correlation coefficient (r) ranging from 0.44 to 0.81. Based on semivariographic adjustment parameters shown in Table 2, estimates calculated through ordinary kriging have met the geostatistics principles and enabled plotting appreciable total annual rainfall distribution maps for the UPR region.

Table 2 - Semivariogram adjustment measures

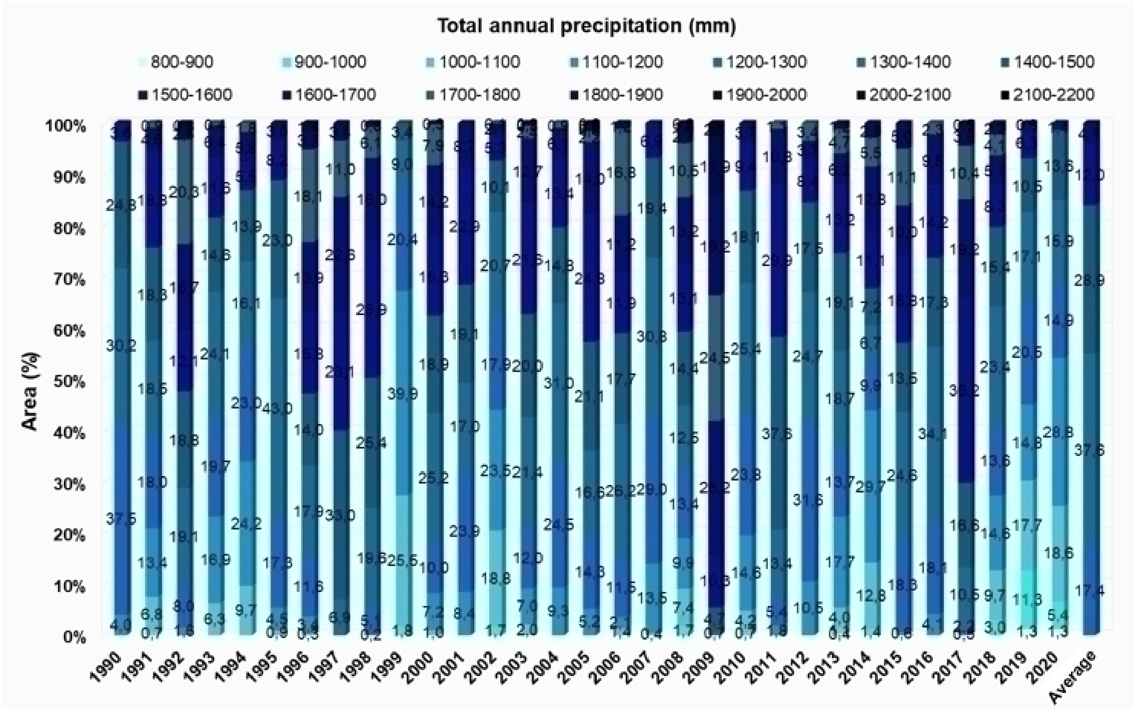
Year$_{(a*)}$	Model$_{(b)}$	C_o	C_o+C	R(m)	R²	SSD	SDE (%)	Cross Validation		
								a	B	r
1990$_{(330)}$	gau	1.52x10^{4}	6.50x10^{4}	599,289	0.990	5.22x10^{7}	76.6	171.44	0.868	0.44
1991$_{(347)}$	gau	1.92x10^{4}	8.91x10^{4}	478,046	0.986	1.67x10^{8}	78.4	59.55	0.958	0.61
1992$_{(354)}$	gau	1.52x10^{4}	1.15x10^{5}	505,759	0.972	7.74x10^{8}	86.8	115.04	0.920	0.63
1993$_{(360)}$	sph	1.37x10^{4}	5.35x10^{4}	424,000	0.982	5.16x10^{7}	74.4	76.24	0.943	0.57
1994$_{(369)}$	gau	1.36x10^{4}	7.94x10^{4}	507,491	0.964	4.03x10^{8}	82.9	69.36	0.942	0.59
1995$_{(374)}$	gau	1.62x10^{4}	1.02x10^{5}	824,456	0.876	3.59x10^{9}	84.2	-8.69	1.008	0.54
1996$_{(380)}$	sph	1.26x10^{4}	7.48x10^{4}	415,000	0.936	4.69x10^{8}	83.2	99.82	0.928	0.62
1997$_{(374)}$	gau	1.46x10^{4}	9.78x10^{4}	763,834	0.875	2.55x10^{9}	85.1	-52.56	1.031	0.63
1998$_{(377)}$	exp	4.50x10^{3}	3.98x10^{4}	112.800	0.961	1.51x10^{7}	88.7	374.98	0.747	0.46
1999$_{(362)}$	gau	1.81x10^{4}	5.87x10^{4}	677.232	0.964	1.78x10^{8}	69.2	-120.92	1.101	0.59
2000$_{(364)}$	sph	1.72x10^{4}	7.11x10^{4}	533,000	0.983	1.04x10^{8}	75.8	40.49	0.971	0.66
2001$_{(282)}$	sph	1.55x10^{4}	5.07x10^{4}	518,000	0.848	5.21x10^{8}	69.4	40.51	0.970	0.60
2002$_{(276)}$	sph	9.10x10^{3}	4.99x10^{4}	408,000	0.979	5.99x10^{7}	81.8	43.26	0.964	0.68
2003$_{(281)}$	exp	1.55x10^{4}	7.90x10^{4}	600,000	0.958	2.30x10^{8}	80.4	135.83	0.902	0.59
2004$_{(276)}$	sph	9.60x10^{3}	5.60x10^{4}	524,000	0.992	2.97x10^{7}	82.9	52.08	0.961	0.72
2005$_{(279)}$	sph	1.06x10^{4}	6.97x10^{4}	456,000	0.980	1.41x10^{8}	84.8	104.58	0.925	0.65
2006$_{(274)}$	gau	1.67x10^{4}	9.20x10^{4}	471,118	0.969	3.93x10^{8}	81.9	-3.14	1.001	0.80
2007$_{(267)}$	sph	1.29x10^{4}	4.04x10^{4}	377,000	0.980	2.15x10^{7}	68.1	25.33	0.981	0.55
2008$_{(270)}$	sph	1.70x10^{3}	1.41x10^{5}	747,000	0.981	9.46x10^{8}	98.8	92.59	0.932	0.78
2009$_{(271)}$	exp	1.77x10^{4}	6.08x10^{4}	450,000	0.937	1.41x10^{8}	70.9	180.99	0.898	0.48
2010$_{(272)}$	exp	6.50x10^{3}	6.22x10^{4}	594,000	0.974	1.08x10^{8}	89.5	137.57	0.893	0.60
2011$_{(268)}$	sph	1.24x10^{4}	4.85x10^{4}	471,000	0.962	1.03x10^{8}	74.4	132.39	0.909	0.55
2012$_{(272)}$	exp	1.02x10^{4}	4.75x10^{4}	408,000	0.950	8.38x10^{7}	78.5	10.90	0.991	0.63
2013$_{(270)}$	exp	7.60x10^{3}	6.30x10^{4}	339,000	0.977	7.72x10^{7}	87.9	156.78	0.887	0.64
2014$_{(269)}$	gau	1.09x10^{4}	1.45x10^{5}	651,251	0.975	1.07x10^{9}	92.5	-1.94	1.00	0.81
2015$_{(177)}$	sph	2.26x10^{4}	9.24x10^{4}	600,000	0.960	4.48x10^{8}	75.5	93.33	0.936	0.65
2016$_{(174)}$	sph	2.00x10^{4}	6.40x10^{4}	489,000	0.930	3.21x10^{8}	68.8	67.53	0.952	0.64
2017$_{(174)}$	exp	1.13x10^{4}	4.74x10^{4}	197,700	0.880	8.90x10^{7}	76.2	120.81	0.920	0.57
2018$_{(213)}$	sph	1.21x10^{4}	1.11x10^{5}	596,000	0.963	8.36x10^{8}	89.1	150.85	0.885	0.69
2019$_{(206)}$	sph	2.57x10^{4}	8.79x10^{4}	553,000	0.955	3.68x10^{8}	70.8	93.42	0.921	0.56
2020$_{(120)}$	exp	1.23x10^{4}	6.98x10^{4}	423,000	0.900	4.46x10^{8}	82.4	27.62	0.977	0.65

$_{(a*)}$ =number of stations (all periods were processed with at least 30 pairs in the first lag); $_{(b)}$ = adjustment, where: sph = spherical; exp=exponential; gau=gaussian; Co=nugget effect; C=variance; C_o+C=Sill; R=range; R²=coefficient of spatial determination; SSD=sum of squares of deviations; SDE=spatial dependence evaluator; a=y intercept; B=Regression coefficient; r=correlation coefficient.

Rainfall events in the UPR Region

Based on Figure 3, rainfall intensity distribution (according to mean values recorded between 1990 and 2020) throughout the investigated basin can be divided into 5 different intervals, which ranged from 1,200 mm to 1,700 mm. The area recording the lowest rainfall rate (1,200 - 1,300 mm) corresponds to 17.4% of the total investigated area, as well as covers Paraná River bed and part of UEPGRHs in São Paulo State (10, 11, 12, 13 and 14). Areas recording the highest rainfall volume (1,500 - 1,700 mm) were identified in the Western/Northwestern zone of UEPGRHs 1, 2 and 6, as well as in the Eastern zone of UEPGRH 8 - they accounted for 16.1% of the total investigated area.

Figure 3 - UPR region's area rate per total annual rainfall interval (1990-2020)



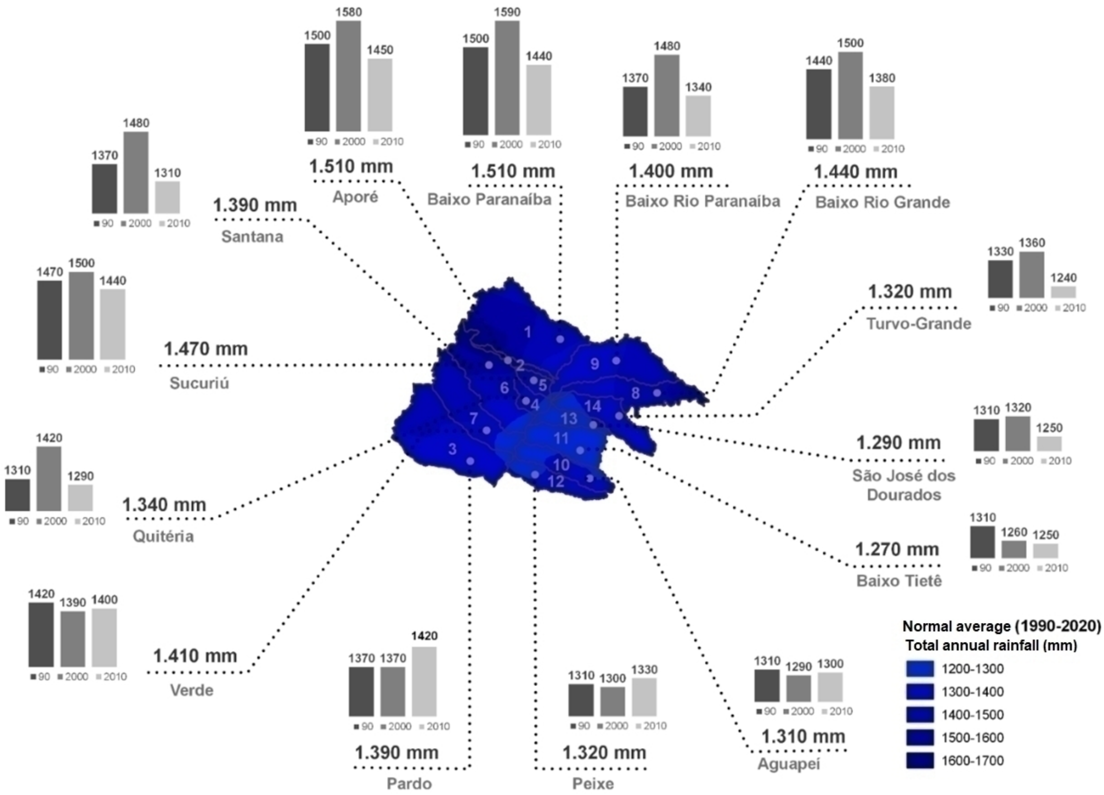
In comparison to the regular mean rainfall value recorded for the entire investigated period (which indicated 1,400 mm), 2009 was the wettest year in the historical series. It recorded mean annual rainfall equivalent to 1,740 mm (24.3% higher than the mean value recorded for the entire series). Moreover, 58.1% of Upper Paraná River region recorded rainfall rates higher than the mean interval (1,200 mm - 1,700 mm) observed during the investigated period. Total annual rainfall value recorded in 1997 and 2017 reached 1,560 mm; both years presented rainfall rates 11.4% above average (Figure 3).

As the driest year in the analyzed period, 1999 recorded rainfall rates 16.43% below the general average (Figure 3). Critical years, such as 2002 and 2014, recorded total annual rainfall equal to 1,250 mm (44% of the investigated area recorded rainfall rates below the average) and 1,340 mm(43.9% of the investigated area recorded rainfall values below the average), respectively. On the other hand, rainfall rates in 2014 (in the remaining area) reached the highest limits of the average and offset the lack of observed rainfall events. Therefore, it was not considered a critical year for the entire Upper Paraná River region.

The evolution of areas presenting smaller rainbands (800 to 1,000 mm) in 2019 and 2020 accounted for triggering gradual total annual rainfall drop by 12.86% in 2019 (1,220 mm) and 13.57% in 2020 (1,210 mm), in comparison to the overall mean rainfall rate - 45% and 54.1% of the investigated area, respectively, maintained annual rainfall rates below the average for two consecutive years. From the spatial perspective, 2019 and 2020 were the most critical of the last 31 years, since they were featured by unprecedented range of rainfall intervals (from 800 to 1,000 mm).

Figure 4 presents the regular total mean annual rainfall rates recorded for each UEPGRH, as well as their respective mean rainfall variation graphs (mm) plotted for the 1990s, 2000s and 2010s. It was done to help better understanding rainfall behavior in the UEPGRHs forming the UPR region.

Figure 4 - Total annual precipitation of normal average in UEPGRHs of the UPR region and its decadal averages (1990-2020)



Based on Figure 4, if one takes into consideration the regular mean rainfall rate observed over the last 31 years (1990 to 2020), UEPGRHs 1 (Baixo Paranaíba) and 2 (Aporé) recorded higher rainfall rates than the other sub-basins, both UEPGRHs totaled 1,510 mm of total annual rainfall rate. These values are consistent with the mean annual rainfall rate estimated by Cardoso et al. (2014) for Goiás State (1,500 mm).

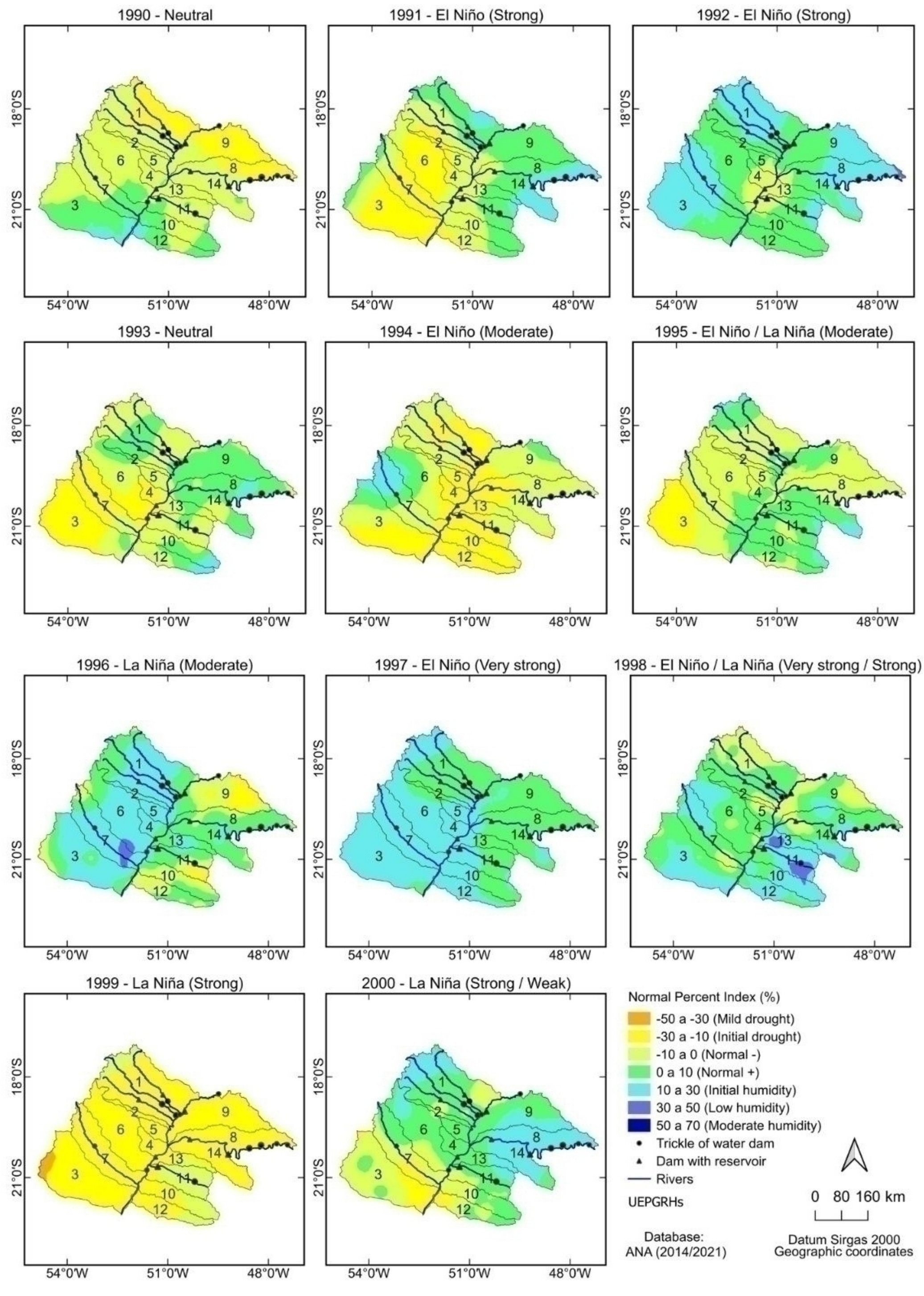
Mato Grosso do Sul was the state whose UEPGRHs presented the highest annual rainfall variation (1,340 mm to 1,510 mm), as shown in Figure 4. Zavattini (2009) identified different rainfall areas in the Upper Paraná River axis, where Paranaíba (Eastern UPGRH 5) and Três Lagoas (Eastern UEPGRH 7) regions recorded similar rhythmic rainfall events with less expressive indices (1,400 mm, on average) and downward trend. Maximum rainfall volume in planteau divisor region (Western UEPGRHs 3, 6 and 7) ranged from 1,700 mm to 2,000 mm.

UEPGRHs in São Paulo State (Figure 4) recorded the worst regular mean rainfall rates, which ranged from 1,270 mm (Baixo Tietê) to 1,320 mm (Peixe). They were followed by UEPGRHs 4 (Quitéria - 1,340 mm) and 5 (Santana - 1,390 mm) in Mato Grosso do Sul State, which were adjacent to Paraná River headwaters, as well as by UEPGRH 3 (Pardo - 1,390 mm), which was located in the lower section of UPR region. Values estimated for UEPGRHs in São Paulo State were within the rainfall threshold determined by Wolf et al. (2014) for the State's Western/Northwestern region (from 1,197 to 1,396 mm), and the one determined by Marcuzzo (2013) for the same area (1,360 mm).

Normal Percent Index (NPI) Mapping

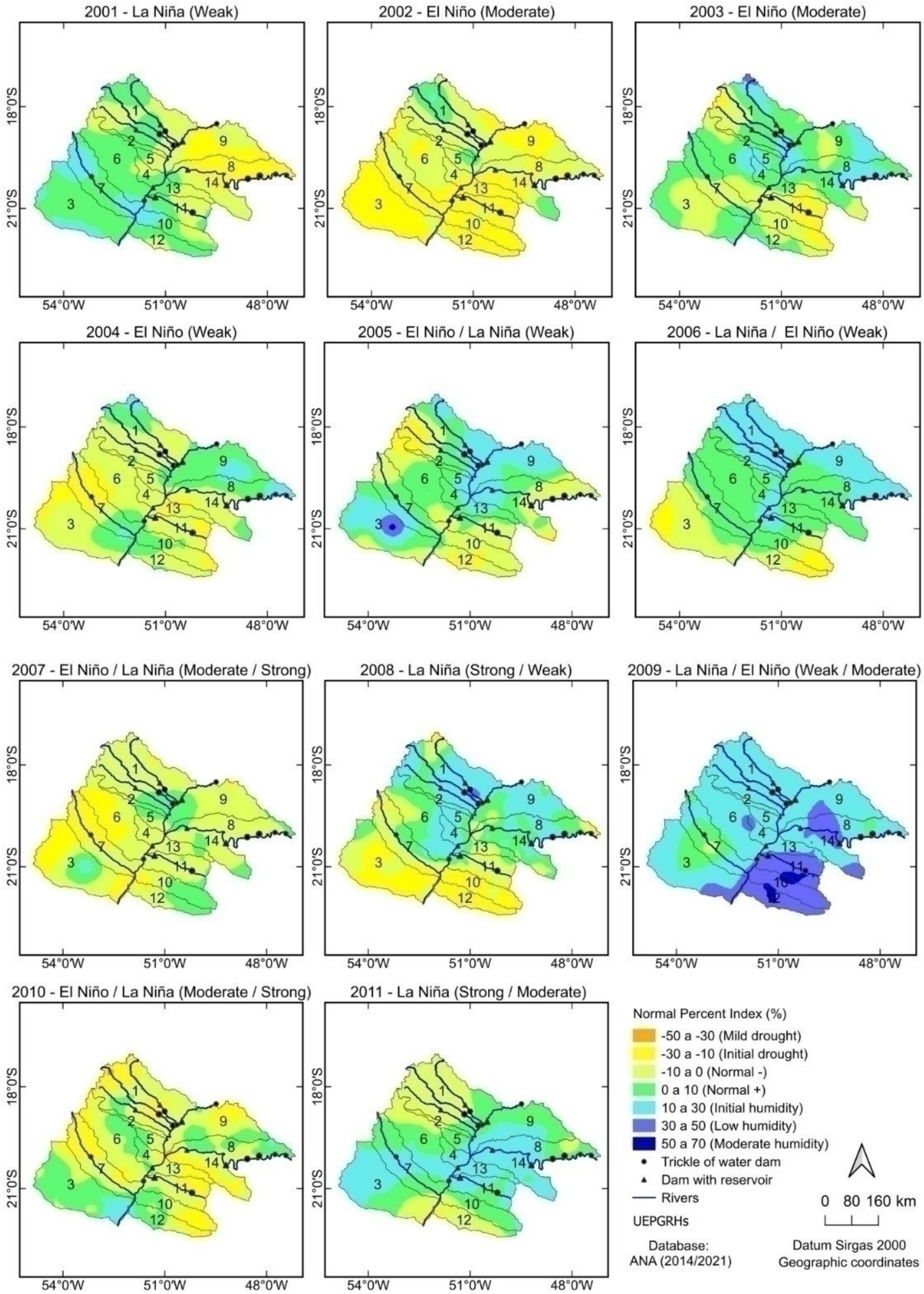
Normal Percentage Index (NPI) maps are shown in Figures 5, 6 and 7. According to them, there was high incidence of initial-to-mild drought in water units located in Mato Grosso do Sul State, mainly in UEPGRH 3 (Pardo), as well as in São Paulo State, mainly in UEPGRHs 10 (Aguapeí), 11 (Baixo Tietê) and 12 (Peixe), over all 31 analyzed years. Lower values of negative rainfall deviations were observed at the edges of UEPGRHs in Minas Gerais (8 and 9) and Goiás (1) states, respectively, and it led to NPI intensities closer to the regular mean value. Although 2009 was classified as the rainiest year in the herein investigated historical series (Figure 3), it recorded incidence of initial-to-moderate humidity (deviation >10 to 70%),which was featured by the transition period from weak La Niña to moderate El Niño, in 90.5% of Upper Paraná River region, as shown in Figure 8. The other periods presenting higher humidity rates in more than 50% of the investigated area were only observed in 1997 (54.02%) and 2017 (59.31%), due to incidence of initial-to-low humidity rates (deviation > 10 to 50%) in the Center-Western and Center-Southern regions of Upper Paraná River.

Figure 5 - NPI Index recorded for Upper Paraná River region from 1990 to 2000



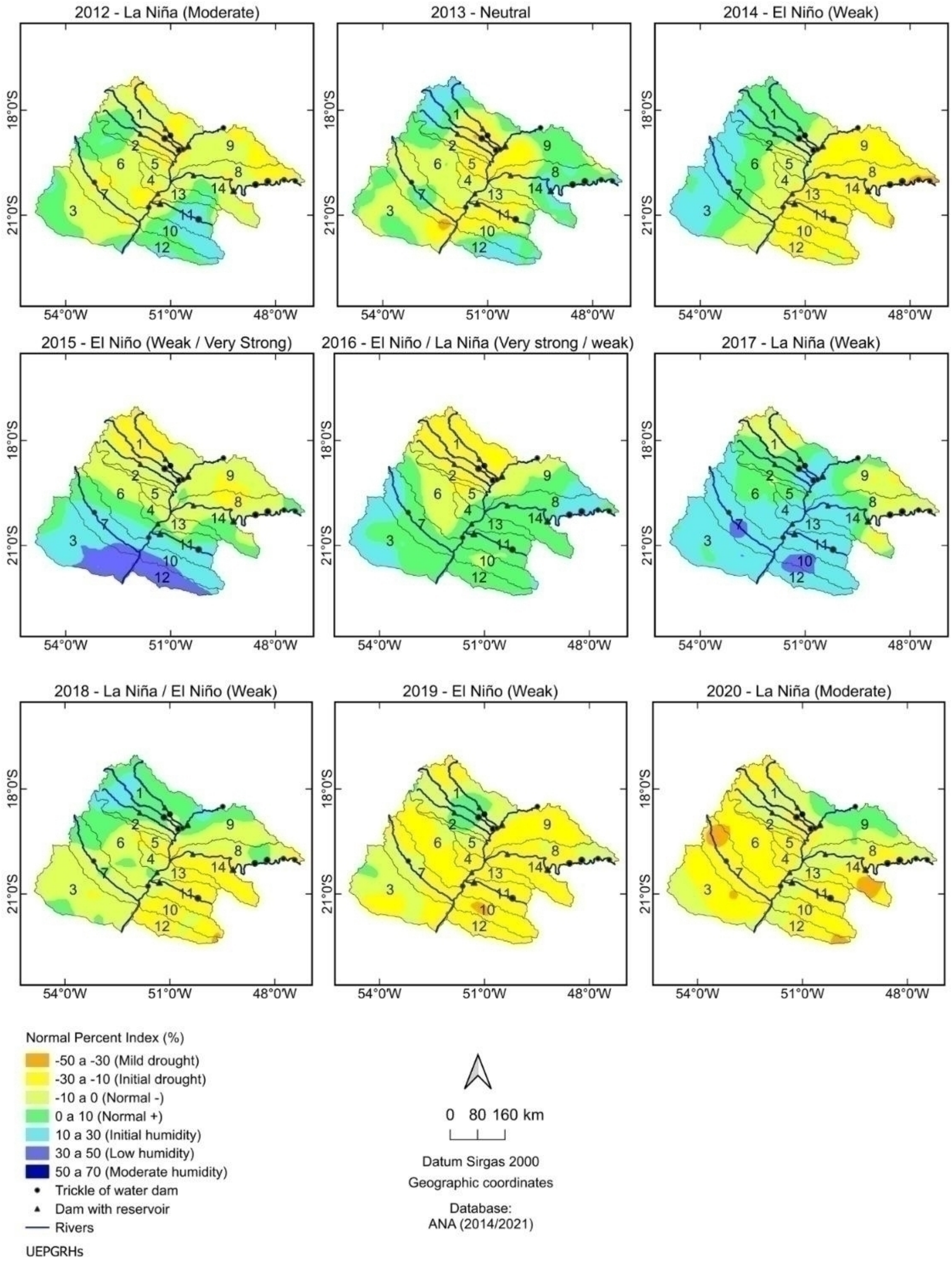
1=Baixo Paranaíba; 2=Aporé; 3=Pardo; 4=Quitéria; 5=Santana; 6=Sucuriú; 7=Verde; 8=Baixo Rio Grande; 9=Baixo Rio Paranaíba; 10=Aguapeí; 11=Baixo Tietê; 12=Peixe; 13=São José dos Dourados; 14=Turvo-Grande.

Figure 6 - NPI Index recorded for Upper Paraná River region from 2001 to 2011



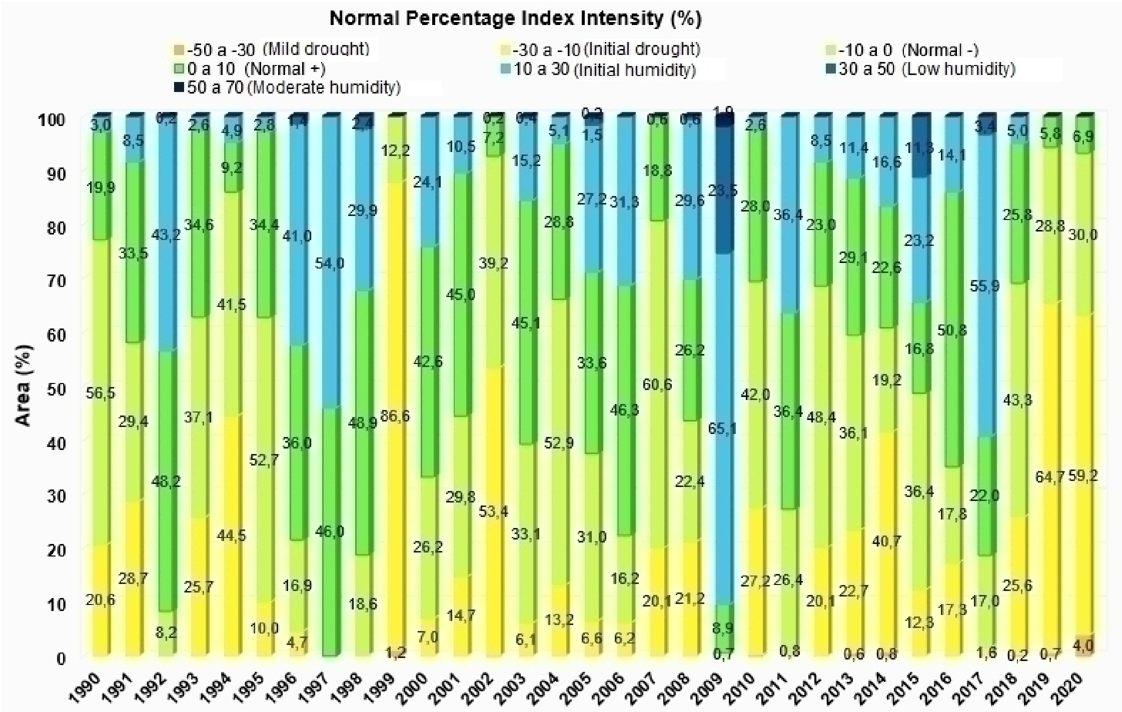
1=Baixo Paranaíba; 2=Aporé; 3=Pardo; 4=Quitéria; 5=Santana; 6=Sucuriú; 7=Verde; 8=Baixo Rio Grande; 9=Baixo Rio Paranaíba; 10=Aguapeí; 11=Baixo Tietê; 12=Peixe; 13=São José dos Dourados; 14=Turvo-Grande.

Figure 7 - NPI Index recorded for Upper Paraná River region from 2012 to 2020



1=Baixo Paranaíba; 2=Aporé; 3=Pardo; 4=Quitéria; 5=Santana; 6=Sucuriú; 7=Verde; 8=Baixo Rio Grande; 9=Baixo Rio Paranaíba; 10=Aguapeí; 11=Baixo Tietê; 12=Peixe; 13=São José dos Dourados; 14=Turvo-Grande.

Figure 8 - UPR area rates per Normal Percentage Index intensity



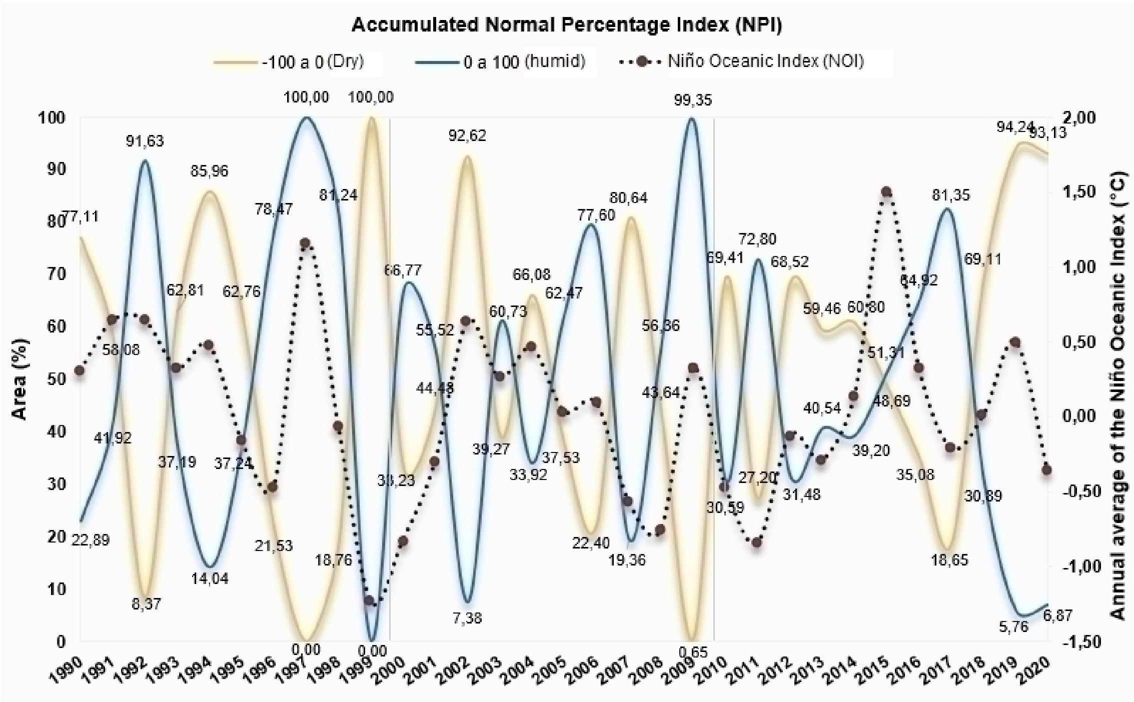
With respect to drought events, 1999 (strong La Niña period) was identified as the driest year in the investigated historical series. It recorded initial drought (from -10% to -30%) in all 14 UEPGRHs, which partly affected units 1, 10, 11 , 12 and 13, as well as mild drought (-30 to -50%) to the Southwest of unit 3; drought events reached 87.8% of the UPR region (Figure 8).

After 1999 (Figure 8), the period presenting drought events in more than 50% of Upper Paraná River region refers to 2019 and 2020, when, 65.4% and 63.16% of this region experienced severe and initial-to-mild drought, respectively. It was followed by 2002, when 53.44% of the investigated region recorded drought events. These years meet historical drought scenarios highlighted by Melo (2017) and ANA (2021a), such as the ones often observed in UEPGRHs located in São Paulo and Mato Grosso do Sul states, in 1999/2002, 2013/2014 and 2019/present day.

Curves of accumulated dry and wet rates - normal-dry (0 to -100) and normal-wet (0 to 100) - of the NPI index, as well as the annual Oceanic Niño Index (ONI) variation, are shown in Figure 9 to help better understanding this issue.

According to Figure 9, the behavior of NPI indices in Upper Paraná River region has changed in the 2010s. It was featured by increased persistence in negative deviations that have changed the behavioral pattern of the accumulated curves. Notably, both drought events recorded in 2019 and 2020, which presented sum of negative deviations greater than 90% of the investigated area, have indicated worsened drought scope in the UPR region. The same threshold was reached in 1999 and 2002, which were previously determined as critical years.

Figure 9 - Variation in accumulated NPI area rates in the UPR region (from 1990 to 2020)



Likewise, the incidence of accumulated positive humidity in more than 90% of the UPR region (Figure 9) has indicated 1992, 1997 and 2009 as the wettest years. However, in 1992 the 90% percentage is made up of 56.4% of the area with normal humidity (-10 to 10%) and only 43.2% of initial humidity (10 to 30%).

Overall, the variation observed in Oceanic Niño Index appears to be associated with drought (Figure 9) and annual rainfall (Figure 3) rates in the UPR region, either due to similarity between periods recording higher rainfall rates (1997 and 2015), which meet higher El Niño intensity (mean annual ONI > 1°C) or to La Niña incidence in years recording rainfall rates below the normal average (1999, 2012 and 2020).

If one takes into consideration the context presented in Figure 9, which refers to Figure 4, the 2010s were identified as the driest decade in the historical series due to high La Niña incidence rate in the country, with emphasis on Southeastern Brazil. Most drought studies carried out in Southeastern Brazil in the last decade have focused on the 2013/2014 events (COELHO et al., 2016; JARDIM, 2015; MARENGO et al., 2015; MARENGO & ALVES, 2016; BRAGA & MOLION, 2018), whose results have indicated a reduced rainfall scenario that was also reported by IPCC and INPE projections (MARENGO & ALVES, 2016). These projections, in their turn, have indicated incidence of the most severe and long-lasting droughts in subsequent years, as observed in the 2019 and 2020 events.

Featuring annual droughts in the UEPGRHs of the UPR region

Areas undergoing initial-to-mild drought (-10 to -50%) in each water unit were measured to identify the UEPGRHs mostly affected by droughts throughout the historical series (1990 to 2020), as shown in Table 3.

Table 3 - Territorial extension of accumulated droughts in UEPGRHs to the UPR region (1990 to 2020)

UEPGRH	Area (km²)	Accumulated drought (initial to mild)		Average drought (1990-2020)	
		(%)	(km²)	%.year^{-1}	km².year^{-1}
1	43,814.0	536.5	235,062.1	17.306	7,582.6
2	2,756.7	437.8	12,068.9	14.123	389.3
3	39,419.4	757.7	298,680.8	24.442	9,634.9
4	5,372.1	645.8	34,693.0	20.832	1,119.1
5	4,181.6	563.0	23,542.4	18.161	759.4
6	27,193.0	561.5	152,688.7	18.113	4,925.4
7	24,184.0	734.0	177,510.6	23.677	5,726.1
8	26,882.0	621.5	167,071.6	20.048	5,389.4
9	18,750.0	654.1	122,643.8	21.100	3,956.3
10	13,196.0	853.1	112,575.1	27.519	3,631.5
11	15,588.0	774.4	120,713.5	24.981	3,894.0
12	10,769.0	868.0	93,474.9	28.000	3,015.3
13	6,783.0	712.0	48,295.0	22.968	1,557.9
14	16,007.0	668.2	106,958.8	21.555	3,450.3
Upper Parana River	254,896	669.3	1,705,979.1	21.590	55,031.5

1=Baixo Paranaíba; 2=Aporé; 3=Pardo; 4=Quitéria; 5=Santana; 6=Sucuriú; 7=Verde; 8=Baixo Rio Grande; 9=Baixo Rio Paranaíba; 10=Aguapeí; 11=Baixo Tietê; 12=Peixe; 13=São José dos Dourados; 14=Turvo-Grande.

Based on Table 4, UEPGRHs 12 (868% = 28%.year^{-1}), 10 (853.10% = 27.52%.year^{-1}) and 11 (774.4% = 24 .98%.year^{-1}) in São Paulo State, as well as units 3 (757.7% = 24.44%.year^{-1}) and 7 (734% = 23.68%.year^{-1}) in Mato Grosso do Sul State, were confirmed as the units presenting the highest incidence of accumulated drought, a fact that indicated lower rainfall rates in the low UPR region. Extreme Northwestern sub-basins 2 (437.8% = 14.12%.year^{-1}) and 1 (536.5% = 17.31%.year^{-1}) recorded the lowest drought accumulation rates. In total, 1,705,979.1 km² of accumulated area in Upper Paraná River region were affected by droughts from 1990 to 2020. This area corresponds to 55,031.5 km² per year (21.63% of the total area), on average.

Figures 10 and 11 show annual variations in accumulated drought rates recorded for each UEPGRH and federative unit in Upper Paraná River region, from 1990 to 2020. It was done to help better visualizing the units/states mostly contributing to drought rates.

Although UEPGRHs 12, 10 and 11 in São Paulo State recorded the highest accumulated area rates (867.98%, 853.07% and 774.4%, respectively), which indicated greater drought evolution in comparison to their total areas, these units only account for 4.2%, 5.2% and 6.1% of the UPR region, respectively. Therefore, the UEPGRHs mostly contributing to accumulated dry area extension throughout the study site comprised units 3, 1 and 7, whose drought coverage area encompassed298,680.8 km² (757.71%), 235,062.1 km² (536.54%) and 177,510.6 km² (734.04%), respectively.

Figure 10 – Annual variation in accumulated dry areas in UEPGRHs belonging to the UPR region (1990-2020)

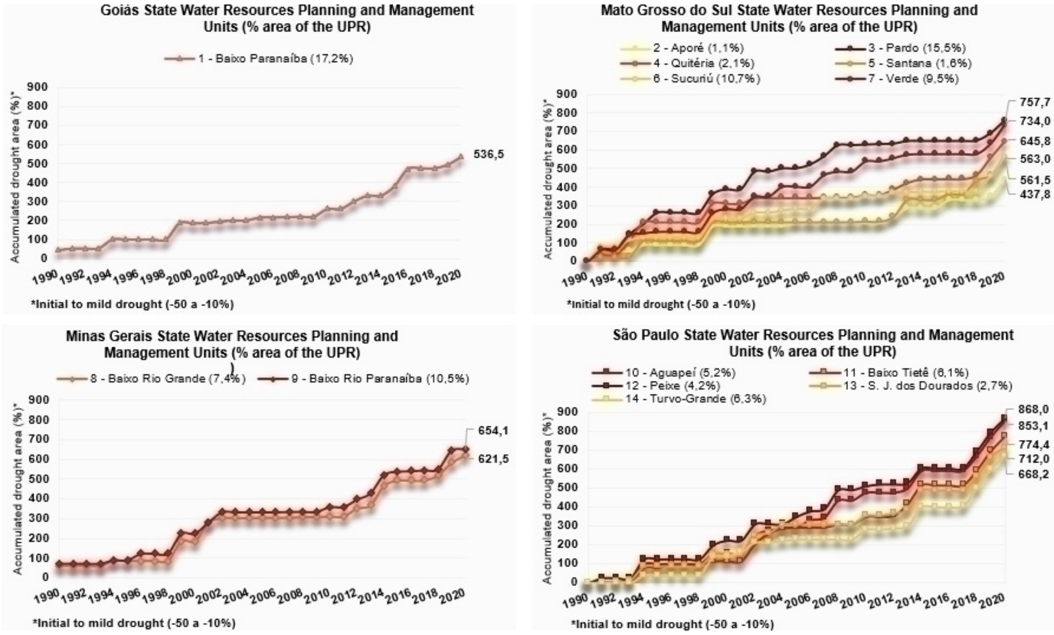
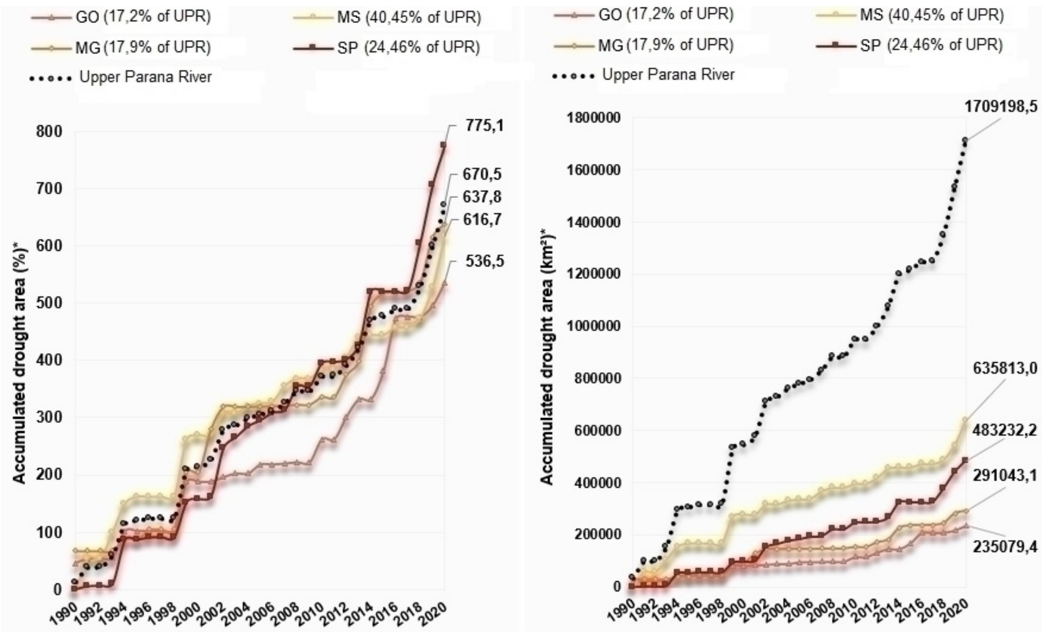


Figure 11 - Annual variation in accumulated drought rates observed for federative units belonging to the UPR region (1990-2020)

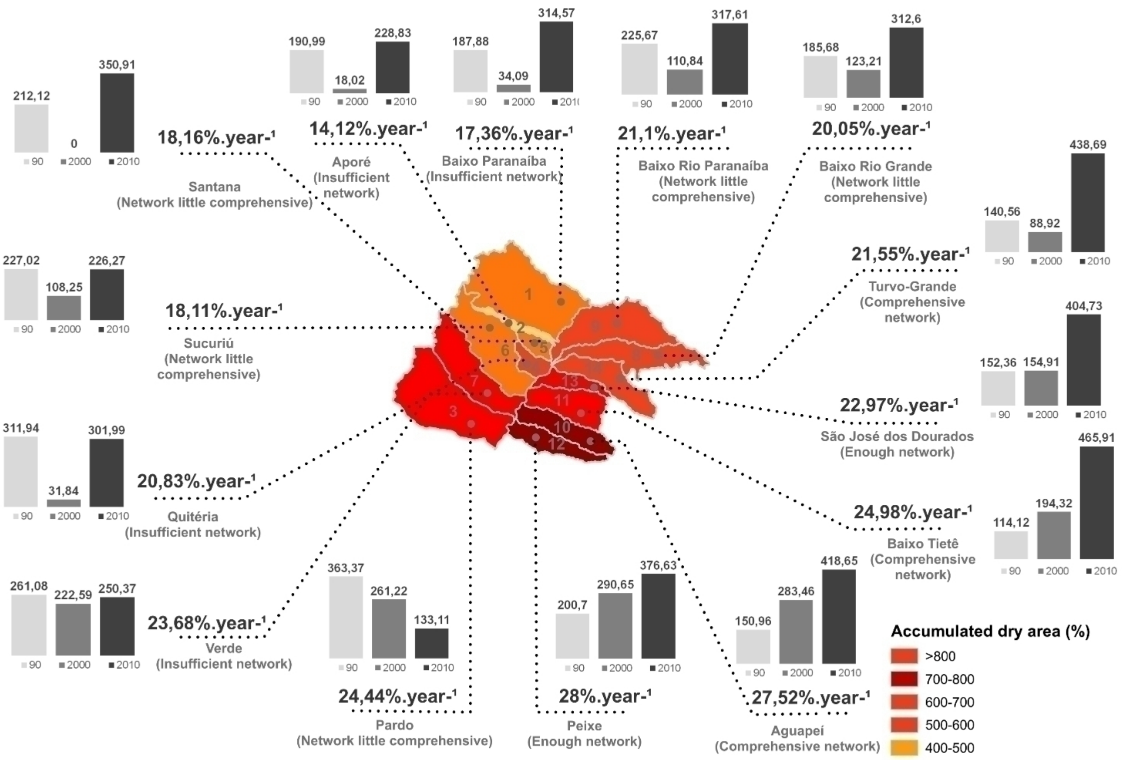


Similarly, based on Figure 11, the UEPGRHs in São Paulo State, altogether, accounted for 24.46% of Upper Paraná River region (62,343 km²), and recorded the highest dry area accumulation rate (75.1%) in the state. In other words, they presented the greatest drought progression in this region, as well as exceeded the drought accumulation rate in Mato Grosso do Sul State, in an area equivalent to 40.45% of the study site (103,106.8 km²), in 2013.

However, based on the analysis applied to the rate of accumulated dry area in km², although the evolution of droughts in São Paulo (775.1%) and Minas Gerais (637.8%) states was greater than that in other federative units, Mato Grosso do Sul (616.7%) State was the federative unit mostly contributing to the UPR region when it comes to territorial extension (Figure 11), since it reached 635,813 km² (approximately 37.2% of the accumulated total). It was followed by São Paulo (28.27%), Minas Gerais (17.03%) and Goiás (13.75%) states. Thus, UEPGRH 1, in Goiás State, was the unit presenting the least drought evolution over time, as well as the one that least contributed to the total drought rate recorded for the Upper Paraná River region.

Because the highest accumulation of dry areas in the UPR region was identified in the 2010s, accumulated droughts in each water unit during the 1990s, 2000s and 2010s were quantified and presented in Figure 12, together with the drought accumulated over the investigated period.

Figure 12 - Mean decadal and accumulated drought rates recorded for UEPGRHs belonging to the UPR region (1990-2020)



Based on the interdecadal variation observed in the herein identified drought areas (Figure 12), all water units - except for UEPGRHs 3 (Pardo), 4 (Quitéria), 6 (Sucuriú) and 7 (Green), in Mato Grosso do Sul State - recorded higher accumulated dry area values in the 2010s (which was determined as the driest decade in the historical series) than in the 1990s and 2000s, as well as higher drought intensity in 8 of the 14 analyzed sub-basins. Based on the accumulated and mean drought values (Table 4), the most critical UEPGRHs (i.e., the ones showing the highest drought incidence) were split into 5 categories, as shown in Figure 13, which highlights the UEPGRHs' rainfall network classification.

UEPGRHs mostly contributing to the drought scenario in the 2010s (Figure 12) were sub-basins 11 (Baixo Tietê), which recorded mean accumulated area of 42.35%; 14 (Turvo-Grande), which recorded mean accumulated area of 39.88%; 10 (Aguapeí), which recorded 38.06%; and 13 (São José dos Dourados), which recorded 36.79%. UEPGRHs 14, 10 and 7 were the most severely affected units due to incidence of areas undergoing higher drought intensity (deviation from -50 to -30%) in 2019 and 2020. Droughts over São Paulo State's water units have intensified in the last decade. Consequently, areas presenting lower rainfall rate in the UPR region are mostly concentrated in Northwestern São Paulo State.

On the other hand, if one take into consideration the accumulated drought rate from 1990 to 2020, UEPGRHs 10 and 12 were the most critical units with more than 800% of accumulated drought, whereas the dry area in unit 2 ranged from 400% to 500%. This finding points towards lower drought incidence. All analyzed units – except for the UEPGRHs in São Paulo State - presented non-comprehensive or inferior rainfall network, a fact that worked as warning to units presenting significant drought rates and insufficient rainfall network (Figure 12).

CONCLUSIONS

Rainfall events in the analyzed UPR Region have shown spatial dependence throughout the investigated period-of-time (1990-2020). This factor enabled spatializing rainfall events and plotting NPI maps. From the geostatistical perspective, rainfall data have shown moderate-to-high spatial dependence, as well as spatial determination coefficients (R^2) ranging from 0.848 to 0.992, in addition to ranges (R) from 112,800 m (1998) to 824,456 m (1995).

Comparative analysis between annual rainfall values and ENSO phases did not indicate straight influence on rainfall variations in the UPR region from 1990 to 2020. However, the 1997 and 2015 rainfall events met the highest El Niño intensities, whereas La Niña took place in drier years, such as 1999, 2012 and 2020.

Mato Grosso do Sul and São Paulo states were the federative units mostly contributing to droughts observed in the UPR region. On the other hand, the 2010s were the driest decade in the analyzed period. The biggest highlight was observed in the 2019/2020 period, when droughts reached more than 60 % of the UPR area for two consecutive years – such an event had never been identified in the previous 3 decades. The UPR region experienced water crisis when the NPI curves (referring to the "initial" and "mild" drought classes) reached at least 50% of the total basin area. Therefore, the herein adopted methodology presented great versatility and it can be applied to any river basin.

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