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Article

Effects of Hydrological Drought Periods on Thermal Stability of Brazilian Reservoirs

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Abstract: Droughts can impact ecosystem services provided by reservoirs. Quantifying the intensity of droughts and evaluating their potential effects on the thermal stability of reservoirs are subjects that demand greater attention, due to both the importance of temperature on aquatic metabolism and the climate change scenarios that predict an increase in the frequency of extreme weather events. This study aimed to investigate drought periods in ten Brazilian reservoirs and to discuss their effects on each reservoir's thermal stability. The Standardized Precipitation Index at a twelve month timescale (SPI-12) was applied to identify the hydrological drought periods. One-dimensional vertical hydrodynamic modeling was used to simulate the water balance and the thermal dynamics in the reservoirs. Schmidt Stability Index (St) was calculated to assess the thermal stability of the reservoirs. The drought periods identified by the SPI-12 are related to decreasing water levels of the reservoirs, but the dam operating strategies and the upstream influence of cascading reservoirs are important drivers of fluctuations. A significant difference in St between wet and dry conditions was found only during summer for all reservoirs. Thus, this study identified alterations in thermal regime during drought periods according to the seasons and the reservoirs characteristics.

Keywords: Standardized Precipitation Index; hydrodynamic model; Schmidt Stability; reservoirs

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1. Introduction

Thermal stability in lakes and reservoirs varies according to morphology, local weather, extreme weather conditions, and climate change projections [1–5]. Drought events, projected to intensify in many regions worldwide in a climate change context, can impose profound impacts on water resources, and as a result, there might be a shift in the ecosystem services they provide, e.g., agriculture irrigation, drinking water supply, hydropower generation, groundwater recharge, and ecosystem maintenance [6]. Economic and social consequences can range far beyond the immediately impacted areas [7]. Brazil is a megadiverse country, which is home to 10% to 15% of all known species estimated in the world [8]. In this context, changes in hydroclimatic conditions related to extreme weather conditions can affect fauna and flora composition and distribution. Drought consequences to Pantanal hydrology during 2019–2020 impacted the biodiversity of one of the world's largest wetlands because of the rapid spread of fire in this very dry set of conditions [9].

Drought is usually defined as a water shortage for an extended period caused by a deficiency of rainfall [10]. It begins with a meteorological anomaly in precipitation and air temperature that leads to cascading effects on other physical variables [11], thereby assessed from different perspectives classified as meteorological, agricultural, hydrological, and socioeconomic droughts [10]. Hydrological drought occurs when the deficiency of precipitation contributes to an inadequate surface or subsurface water supply, such as lower than mean stream flow, groundwater level, and reservoir level [10]. In this regard, a hydrological drought occurred within one month after a meteorological drought started in the Gediz River Basin of Turkey [12].

The Standardized Precipitation Index (SPI) is one of the most popular indexes to characterize drought on timescales ranging from 3 to 48 months [13]. On short timescales, the SPI is closely related to agricultural drought, while at longer timescales, the SPI can be related to groundwater and reservoir storage, or hydrological drought [14]. In addition, the SPI is applied in the Early Warning Systems from the Global Drought Observatory (https://edo.jrc.ec.europa.eu, accessed on 7 October 2022), the United States National Drought Mitigation Center (https://droughtmonitor.unl.edu, accessed on 16 August 2022), and Brazil's Center for Monitoring and Early Warning of Natural Disasters (https://monitordesecas.ana.gov.br, 14 July 2022) to drought monitoring and risk management [7].

The drought intensity was first defined for SPI values following four categories: mild, moderate, severe, and extreme drought [15]. A modification to the limits of drought categories and application of daily datasets for SPI calculation instead of monthly total precipitation was also proposed [13]. Drought monitoring systems in the United States and Brazil classify the index results into five drought categories, on which the index range defines the severity of a drought: Abnormally Dry (D0), Moderate Drought (D1), Severe Drought (D2), Extreme Drought (D3), and Exceptional Drought (D4).

The temporal and spatial characteristics of drought events are widely studied since they may be considered the most frequent, chronic, and severe natural hazard worldwide [13,14,16]. However, despite the action of the Early Warning Systems, drought impacts, such as in water security, are rarely continuously monitored [11]. Most of Brazil had the most severe and intense drought events in almost the last 60 years, in the period from 2011 to 2019 [17]. The effects were related to an increase in water conflicts (hydropower generation, irrigated agriculture, water supply, and navigation), a decrease in agricultural production, and an increase in the occurrence of forest fires. The drought impacts on the hydrodynamics of reservoirs have been evaluated by modeling [18]; however, no correlations with some of the drought indexes were applied. In this regard, the direct effects of droughts on reservoir physical characteristics remain unclear. As a disturbance in the thermal profile often mediates further changes in chemical and biological processes with repercussions on water uses, understanding how droughts change hydrodynamics is of critical importance for water management.

Moreover, the comprehension of the relationship between air temperature, water temperature, and thermal stratification is relatively well-known through the application of hydrodynamic models and processing tools such as LakeAnalyzer [19–21]. However, the drought effects related to long periods of higher air temperatures and lower precipitation due to drought intensity have received little attention, which is especially so for the effects on reservoirs' thermal alterations. The aim of this study is to assess the hydrological drought effects on the thermal dynamics of tropical and subtropical reservoirs located in Brazil. This research investigates the relationship between drought severity and drought impacts on the thermal regime of reservoirs, as well as discusses some consequences for ecosystem services and water uses.

2. Materials and Methods

2.1. Study Sites

We selected ten Brazilian reservoirs (Figure 1) based on the following conditions: (i) bathymetrical, hydrological, and meteorological data available for model input; (ii) in-situ water level and water temperature measurements available for model calibration and validation; (iii) recent hydrological drought event occurrence at the study site; (iv) similar usage, like drinking water supply and/or hydropower generation; and (v) residence times higher than three months. The reservoirs are located in different climate zones in central–south Brazil, and they are characterized by varied morphometric features and thermal regimes (Table 1).

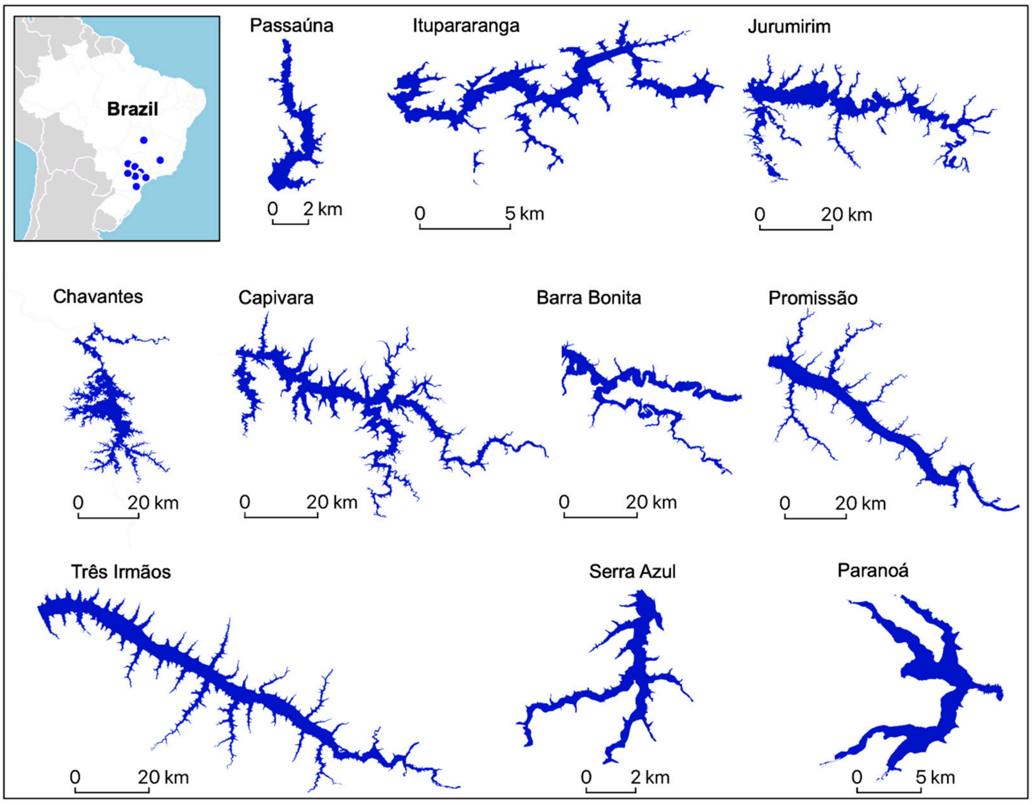


Figure 1. Study site locations and reservoir morphometries. The characteristics are described in Table 1.

Table 1. Characteristics of the reservoirs.

Reservoir	Climate [1]	Main Use [2]	Max. Depth (m)	Surface Area (10^6 m^2)	Total Volume (10^6 m^3)	Residence Time (Days)	Thermal Regime Classification
Passaúna	Cfb	WS	16.5	9.0	59	292	Polymictic
Itupararanga	Cwa	WS, HP	23.0	29.0	286	245	Polymictic
Jurumirim	Cfa	HP	39.5	485.0	7900	346	Polymictic
Chavantes	Cfa	HP	75.5	419.0	9400	284	Polymictic
Capivara	Cfa	HP	56.0	623.7	11,700	95	Polymictic
Barra Bonita	Cwa	HP	23.5	226.0	3160	91	Polymictic
Promissão	Cwa	HP	24.5	522.0	8110	141	Warm monomictic
Três Irmãos	Cwa	HP	45.6	654.0	11,460	442	Warm monomictic
Serra Azul	Cwa	WS	47.3	9.1	82	373	Warm monomictic
Paranoá	Aw	WS, HP	38.0	37.5	498	299	Warm monomictic

Notes: [1] Cfb: Temperate oceanic; Cfa: Humid subtropical; Aw: Tropical savanna; Cwa: Dry-winter humid subtropical [22]. [2] WS: Drinking water supply; HP: Hydropower generation.

2.2. Drought Assessment

The Standardized Precipitation Index was applied to identify the occurrence of drought periods. The SPI considers monthly precipitation data (Equations (1) and (2)) [14] and was calculated using the R package SPEI [23] at a timescale of 12 months (SPI-12) with Gamma probability distribution (Equations (3) and (4)).

$$SPI = s \cdot \frac{t - (0.010328 \cdot t + 0.802853)t + 2.515517}{((0.001308t + 0.189269) + 1.432788) + 1} \quad (1)$$

$$t = \sqrt{ln \frac{1}{H(X)^2}} \quad (2)$$

$$G_x(x) = \frac{(\frac{x}{\beta})^{\gamma-1} e^{(\frac{-x}{\beta})}}{\beta\Gamma(\gamma)} \quad (3)$$

$$\Gamma(\gamma) = \int_0^\infty x^{\gamma-1} e^{-x} dx \quad (4)$$

A timescale of 12 months or longer is recommended to evaluate hydrological impacts [24]. The monthly precipitation time series were obtained from different meteorological stations situated as close as possible to the studied reservoirs (Table 2).

Table 2. Meteorological stations and available data periods.

Reservoir	Meteorological Station (Code and Name—INMET [25])	Altitude (masl)	Latitude and Longitude (Datum WGS-84)	Time Period (YYYY-MM)
Passaúna	83842—Curitiba	924	−25.45, −49.23	1990-01–2021-01
Itupararanga	83851—Sorocaba	598	−23.48, −47.43	2006-09–2018-12
Jurumirim	A725—Avaré	654	−23.21, −49.23	2006-09–2021-10
Chavantes	A821—Joaquim Tavora	522	−23.13, −49.73	2006-11–2021-10
Capivara	A718—Rancharia	350	−22.66, −51.36	2006-09–2021-10
Barra Bonita	A741—Barra Bonita	534	−22.47, −48.58	2008-04–2021-05
Promissão	A735—José Bonifácio	408	−21.09, −49.92	2007-09–2021-05
Três Irmãos	A704—Três Lagoas	329	−20.78, −51.71	2001-09–2021-05
Serra Azul	A535—Florestal	754	−19.89, −44.42	2008-06–2021-05
Paranoá	A001—Brasília	1161	−15.79, −47.93	1990-01–2021-03

The severity of the hydrological drought was classified into five categories according to the U.S. and Brazil Drought Monitor: Abnormally Dry (D0), Moderate Drought (D1), Severe Drought (D2), Extreme Drought (D3), and Exceptional Drought (D4) (Table 3). One category was considered to characterize wet periods, called Normal/Wet (W), because the analysis of drought periods was emphasized in this study.

Table 3. Range of SPI values on each drought category following the U. S. Drought Monitor (2022).

Category	Range	Reference Color
W—Normal/Wet	SPI ≥ -0.5	
D0—Abnormally Dry	$-0.7 < \text{SPI} < -0.5$	
D1—Moderate Drought	$-1.2 < \text{SPI} < -0.8$	
D2—Severe Drought	$-1.5 < \text{SPI} < -1.3$	
D3—Extreme Drought	$-1.9 < \text{SPI} < -1.6$	
D4—Exceptional Drought	SPI ≤ -2.00	

2.3. Hydrodynamic Simulations

The General Lake Model (GLM) was used for simulating water balance and thermal stratification in the reservoirs. GLM is a one-dimensional hydrodynamic process-based model that is freely available. The model computes the water temperature, salinity, and density gradients in vertical profiles for a horizontally layered lake structure, considering the effects of hydrological and meteorological forcing [26]. GLM has also been applied to simulate changes in lake temperature and stratification metrics with low bias during extreme weather events [27].

Time series of hydrological and meteorological data, bathymetry, water temperature, and salinity in the inflows and outflows were used as input data for the hydrodynamic simulations. Those data were provided by the hydropower private companies, water utility companies, and governmental agencies [25,28–31]. The reservoirs' water levels and water temperature profiles were calibrated based on measured data. The measured data of water temperature were obtained in field monitoring by research projects, water utility companies, or governmental environmental agencies that are managers of the reservoirs. Due to a lack of available data, we did not conduct model validation for the Passaúna, Jurumirim, Chavantes, Capivara, and Paranoá reservoirs. More detailed information on the model setup and calibration for the Itupararanga, Serra Azul, Barra Bonita, Promissão, Três irmãos, Capivara, Chavantes, Jurumirim, and Passaúna reservoirs can be found in [5,18,32–34]. The calibration metrics of model performance for level and temperature of all reservoirs are presented in the results.

2.4. Thermal Regime

The analysis of the drought effects on the reservoirs' thermal regimes was carried out by computing physical indices along the simulation period using the R package rLakeAnalyzer [35]. Simulation results of water temperature were post-processed in R from the file in NetCDF format at every 0.1 m of the layer thickness. The water level data of each reservoir was also taken into account to calculate the physical indices. Since GLM has a Lagrangian grid, the simulated water temperature was interpolated onto a regular data matrix. For the interpolation, we decided to fill the gaps on the new regular grid using the simulated values from the top of the layers. By doing this, we expected to better preserve the natural differences between layers and stratification.

Among the physical indices, the Schmidt Stability (St) was selected to assess the thermal stability based on simulated water temperatures. This index describes the resistance to mechanical mixing due to the potential energy inherent to the stratification of the water column, and it was calculated following [36] (Equation (5)):

$$St = \frac{g}{A_0} \int_0^{zm} (z - z_g) A(z) \rho(z) dz \tag{5}$$

where g is the acceleration due to gravity, A_0 is the surface area of the reservoir, $A(z)$ is the area of the reservoir at height z, $\rho(z)$ is the water density at height z, z is the water depth, z_m is the maximum depth, and z_g is the height to the center of the volume of the lake, defined by [37]:

$$z_g = \frac{\int_0^{zm} z A(z) dz}{\int_0^{zm} A(z) dz} \tag{6}$$

Schmidt Stability has been extensively used in the scientific literature to characterize the thermal processes in lakes and reservoirs [38–41]. High St values represent strong thermal stratification that requires high energetic inputs to mix the vertical water column. Schmidt Stability values were compared among periods of different drought intensities to provide a quantitative assessment of changes in the reservoir's physical dynamics.

2.5. Data Analysis

Descriptive statistics were computed based on the simulated water level, temperature, and St. A normalization of water surface temperature and St was applied based on its maximum value for each reservoir for comparison among drought intensities and a better understanding of the influence of seasonality. A 14-day moving average was applied for better characterization of seasonality and for reducing the noise level. Pair-grid diagrams [42] were built for an exploratory data analysis to understand the relationships among St, precipitation, water level, and wind.

An analysis of variance (one-way ANOVA) was performed to evaluate the seasonal and spatial correlation between thermal stratification and drought or wet periods for each studied reservoir due to the considerable influence of seasonality on St values. Twelve wet months (SPI-12 ≥ -0.5) and twelve dry months (SPI-12 < -0.5) were selected among the whole simulation period for each reservoir to obtain a balanced dataset of St values. When there were more than twelve months in dry or wet conditions, they were undersampled. The higher values of SPI-12 for wet or dry conditions were the main undersampling criterion. Another criterion was to include different months in the datasets. The one-way ANOVA was performed with a significance level of $p < 0.05$.

3. Results

3.1. Drought Period Identification

All ten reservoirs experienced exceptional droughts over the study period (Figure 2). According to Figure 2, Abnormally Dry (D0) and Moderate Drought (D1) are the most frequent categories of droughts found in the Itupararanga, Chavantes, and Serra Azul reservoirs. Extreme drought periods were identified in all of the reservoirs, with the distinctions of the Passaúna reservoir and the Paranoá reservoir, with 6.0% and 4.6% of the time experiencing D4 drought, respectively (Figure 2). These results impact water availability with potential implications for water supply since Passaúna, Itupararanga, Serra Azul, and Paranoá are drinking water supply reservoirs.

3.2. Reservoir Thermal Regime

The General Lake Model successfully reproduced both the water level and the thermal regime along the simulation periods (Figure 3) with relatively good performance according to root mean square error (RMSE) for the calibration period (Table 4). Itupararanga, Barra Bonita, Promissão, Três Irmãos, and Serra Azul reservoirs had an additional dataset applied to the model validation (Table 4). Passaúna and Serra Azul reservoirs presented lower water level oscillations compared to the other eight reservoirs, which are also used for hydropower generation. In addition, GLM was able to represent water level fluctuations due to drought periods. Drought periods occurred both when the water level was low and when the water level was high in all the studied reservoirs (Figure 3). In addition, the drought was observed in both periods of stratification and mixing of reservoirs, according to the time-depth temperature contour graph of simulated temperature (Figure 3).

3.3. Schmidt Stability

Precipitation values are coherent with drought periods, but the correlation with St varies for each reservoir (Figure 4a). The water level usually reduces during a drought period; this result was observed in Passaúna, Itupararanga, and Chavantes. Promissão and Três Irmãos, in turn, presented the opposite conditions. The other reservoirs presented drought periods distributed along high and low water levels (Figure 4b). The wind relationship with St is observed in Figure 4c. Itupararanga was the most stable reservoir, between all 10 analyzed, in terms of the relationship between St and water level, during the drought period. Independent of the drought classification, its Schmidt number maintained around zero. Paranoá became more stable during extreme drought and Três Irmãos during exceptional drought. All other SPI-12 categories and water levels appeared to increase St's range (Figure 4b).

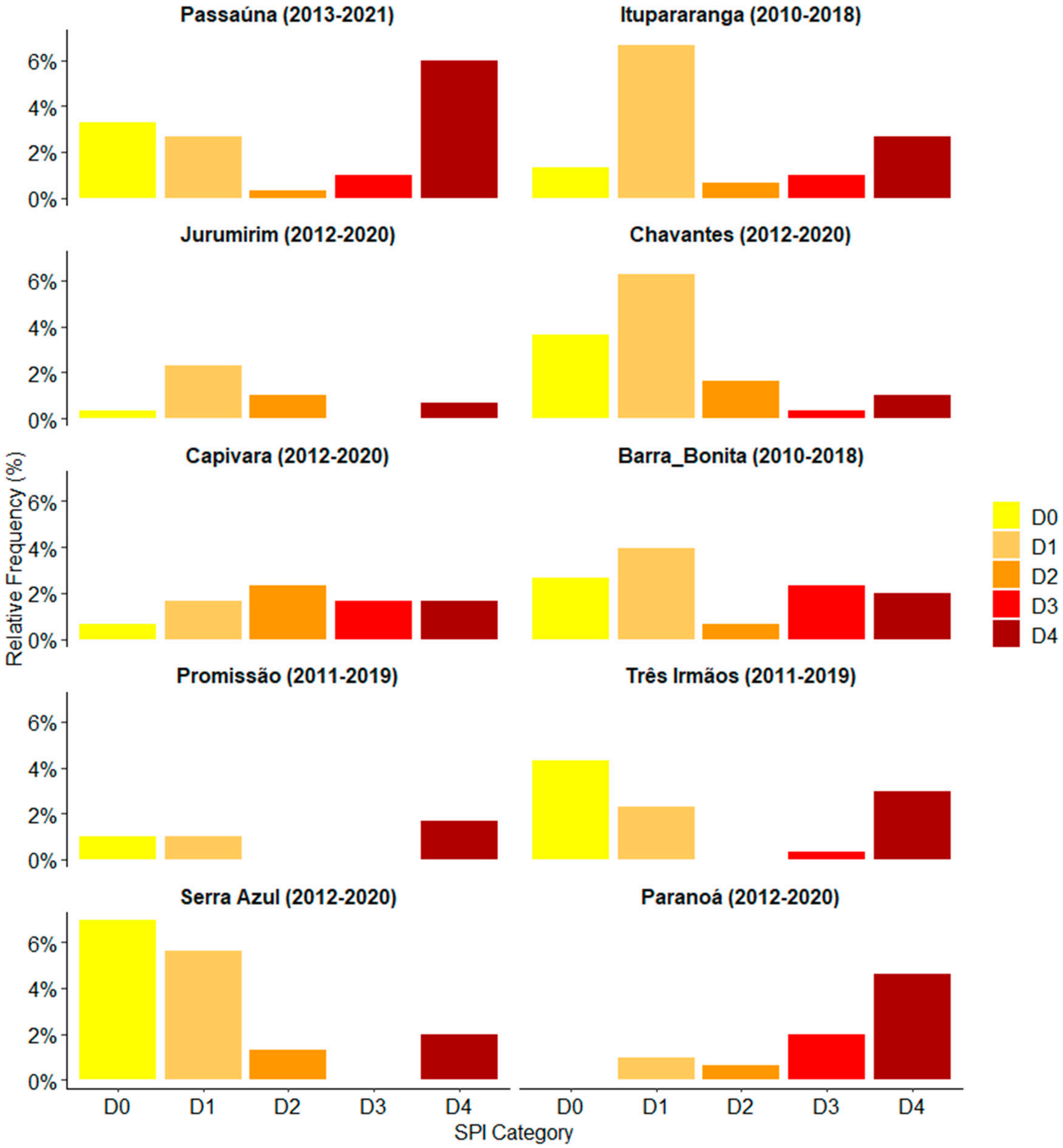
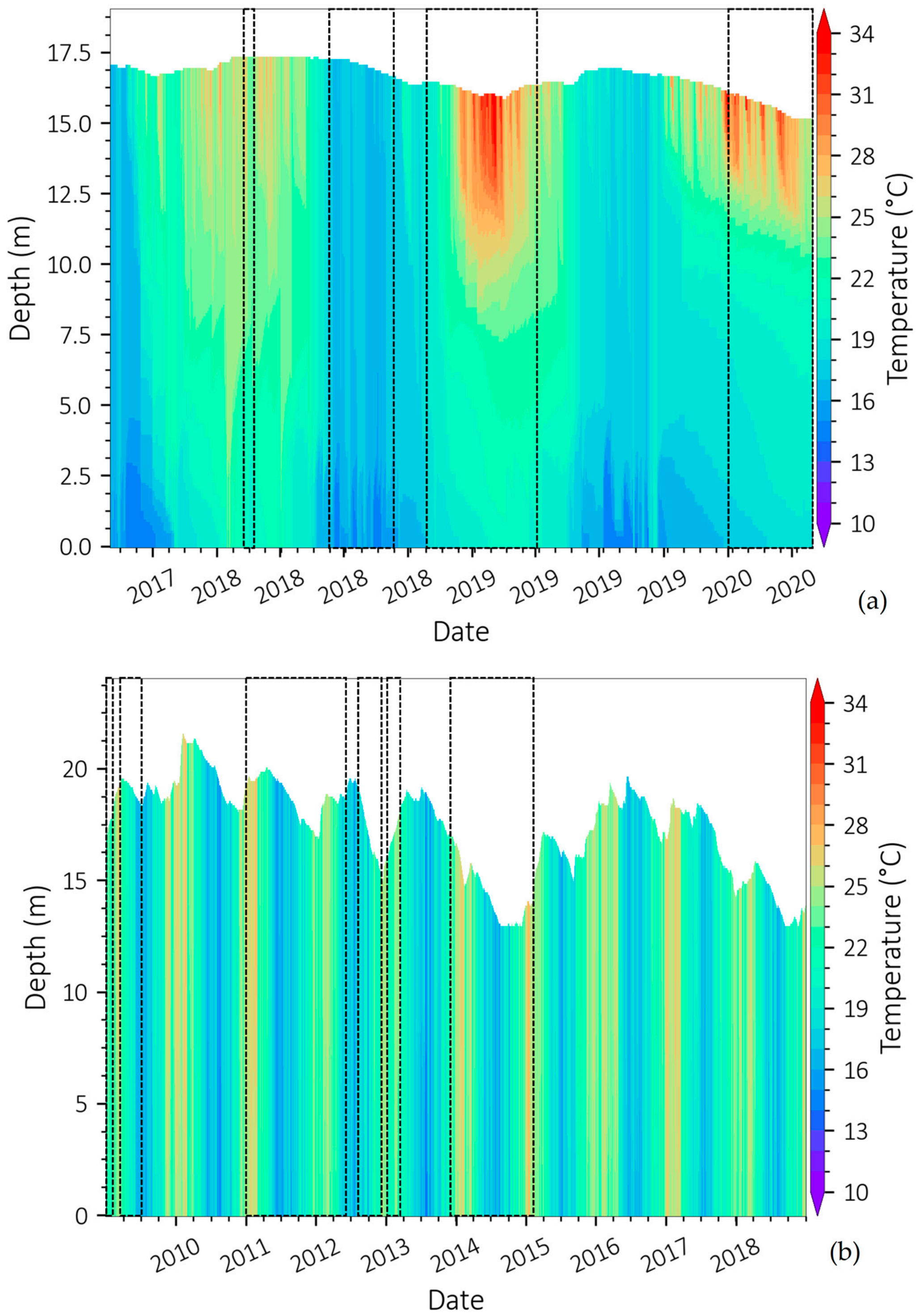


Figure 2. Histograms of relative frequencies of SPI-12 for each reservoir, according to drought categories: Abnormally Dry (D0), Moderate Drought (D1), Severe Drought (D2), Extreme Drought (D3), and Exceptional Drought (D4).

Seasonal variation in surface water temperature showed a regular cycle of increase (in summer) and decrease (in winter) in all reservoirs (Figure 5a). Schmidt Stability also showed this similar pattern, but with less regularity since its value is characteristic for each reservoir, even though St can be altered by precipitation and wind patterns (Figure 5b).



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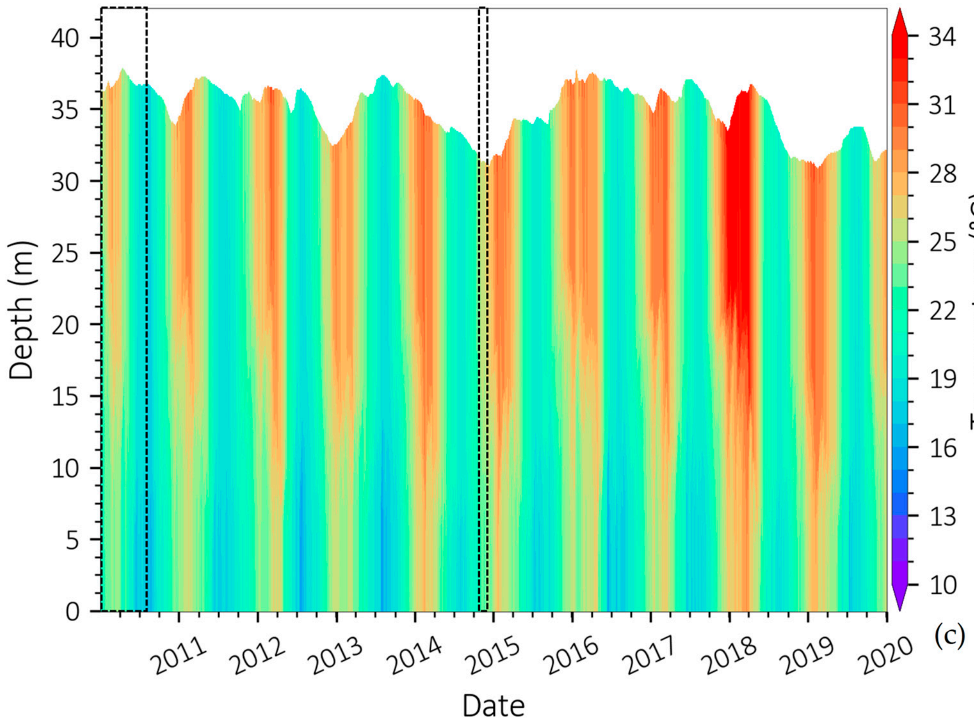

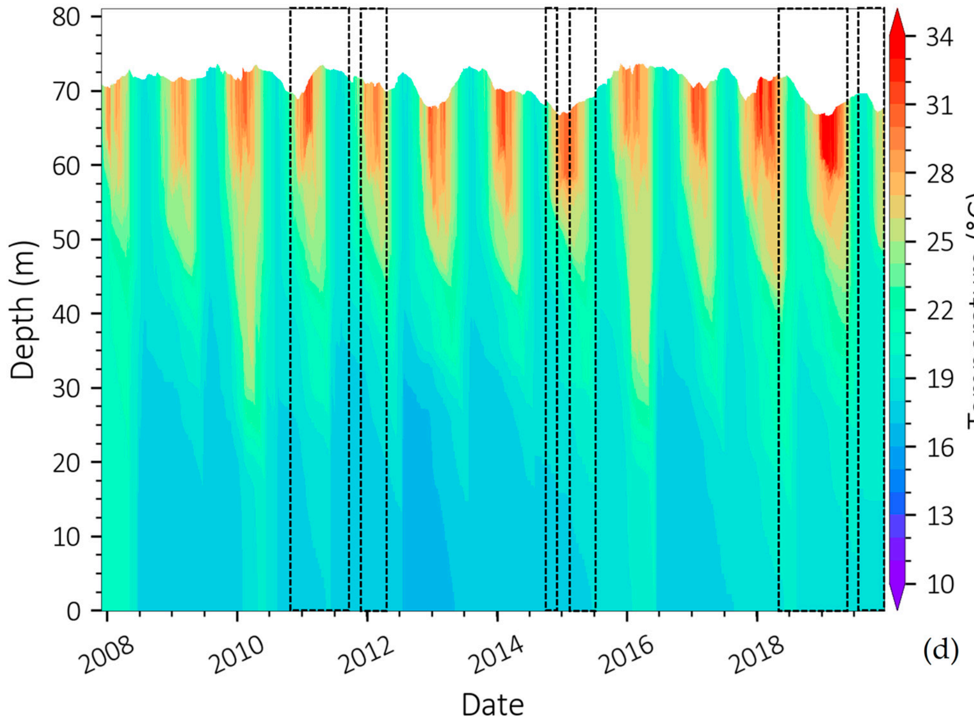

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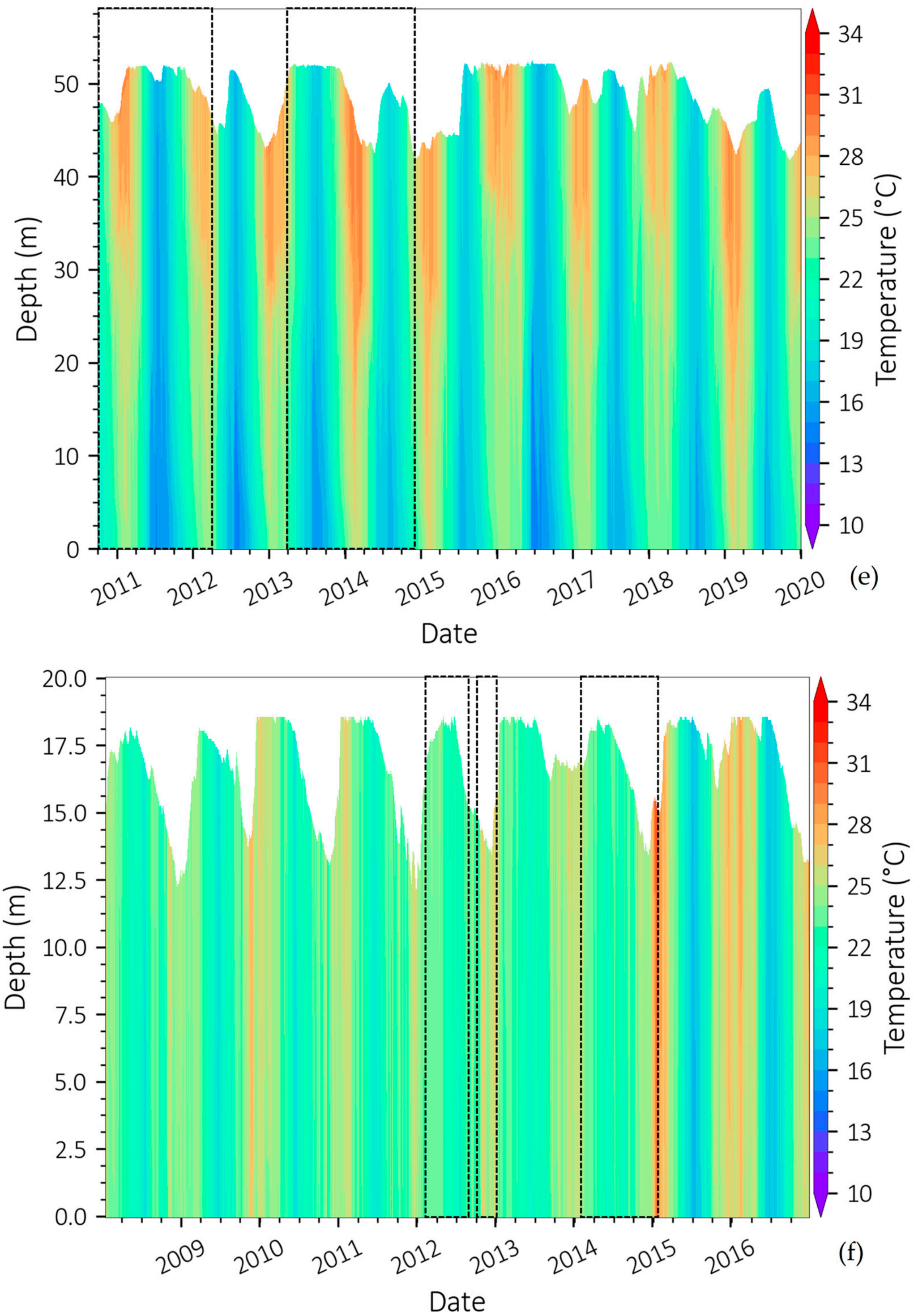

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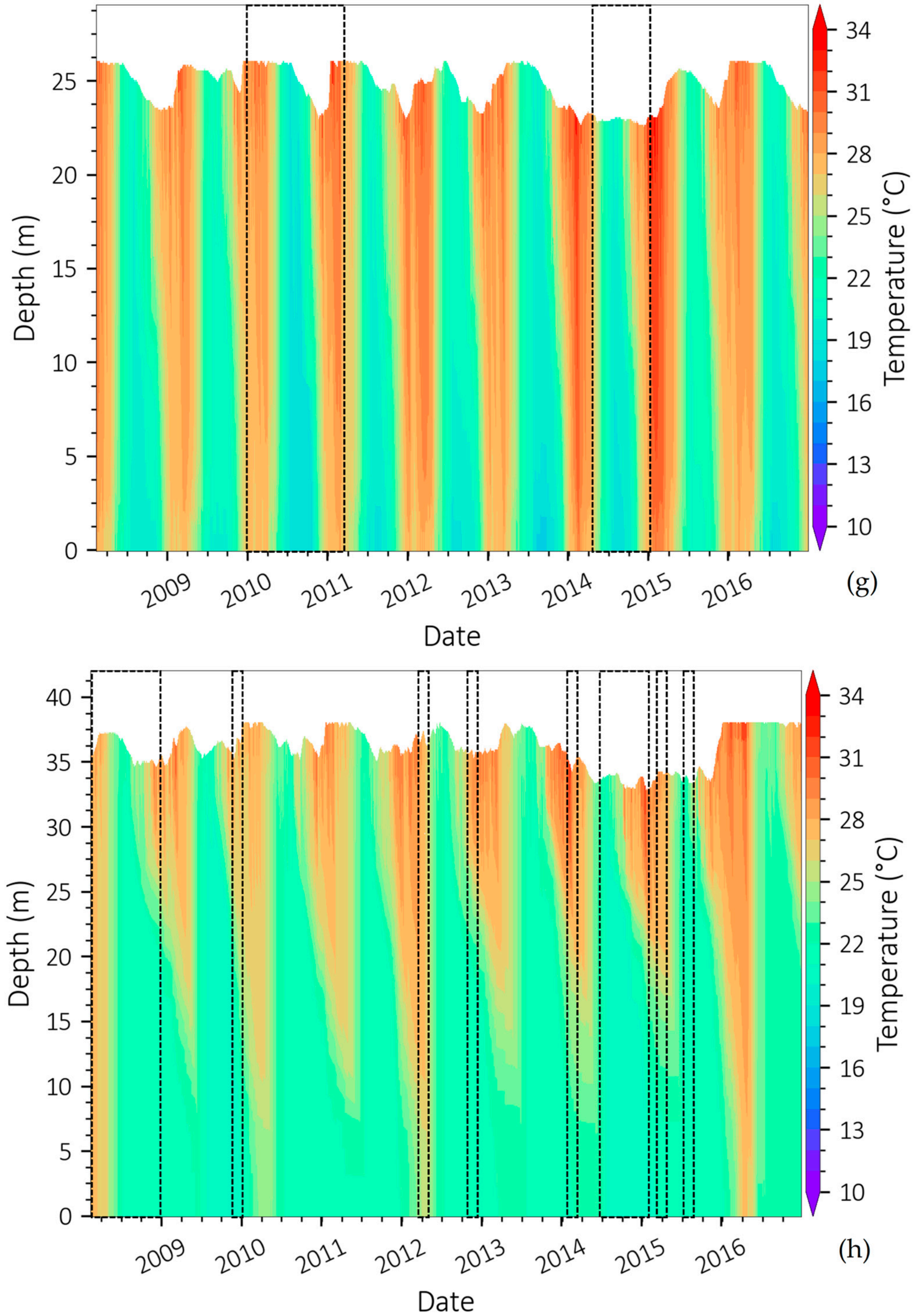

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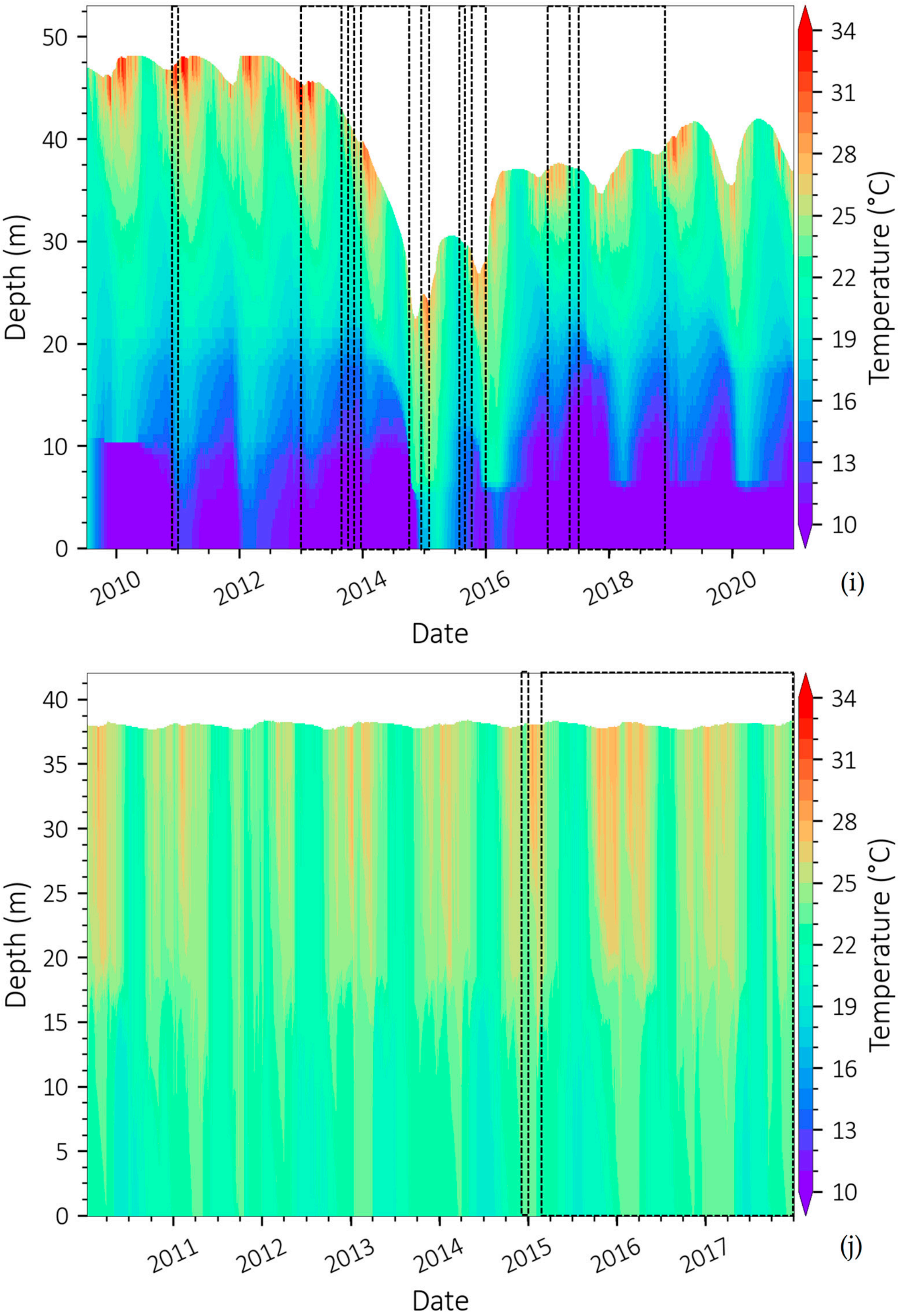
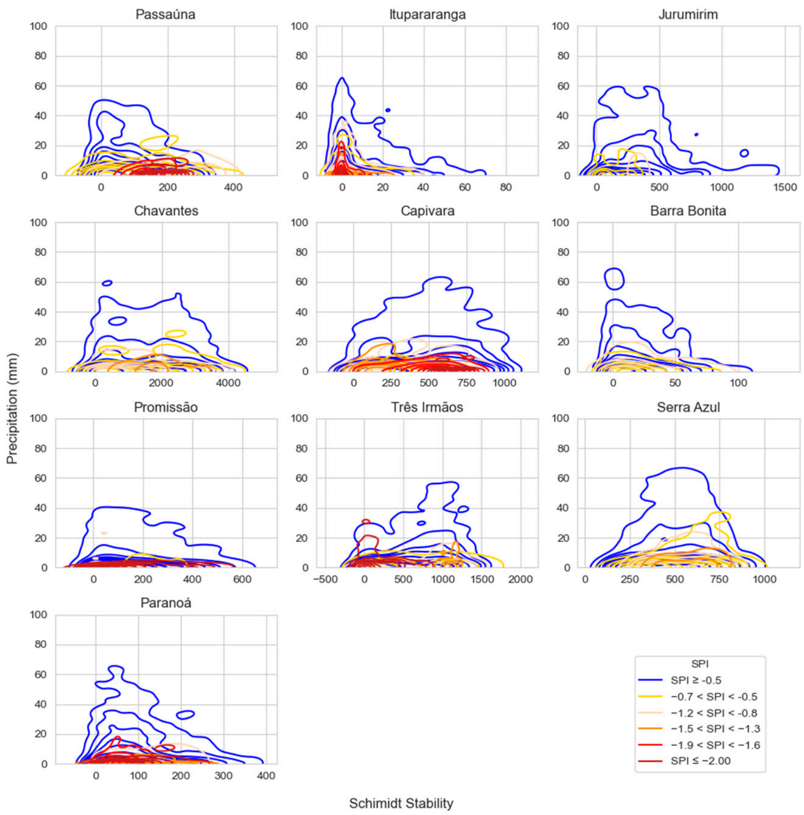


Figure 3. Time-depth temperature contour graph from General Lake Model (GLM) simulated temperature for each reservoir: (**a**) Passaúna; (**b**) Itupararanga; (**c**) Jurumirim; (**d**) Chavantes; (**e**) Capivara; (**f**) Barra Bonita; (**g**) Promissão; (**h**) Três Irmãos; (**i**) Serra Azul; (**j**) Paranoá. Drought periods are highlighted with a dashed line (SPI-12 ≤ -0.5).

Table 4. Simulation, calibration, and validation periods for each reservoir and model performance metric (root mean square error—RMSE) for water level and temperature.

Reservoir	Simulation Period (YYYY-MM-DD)	Calibration Period Validation Period (YYYY-MM-DD)	RMSE	
			Water Level (m)	Temperature (°C)
Passaúna	2017-08-01/2020-04-30	2018-03-01/2019-02-28	0.35	1.02
Itupararanga	2009-01-01/2019-03-31	2009-01-01/2013-12-31	0.63	1.30
		2014-01-01/2019-03-31	0.45	1.34
Jurumirim	2009-01-01/2019-12-16	2011-03-01/2011-11-01	0.00	1.37
Chavantes	2009-01-01/2019-12-16	2011-03-01/2011-11-01	0.00	1.37
Capivara	2009-01-01/2019-12-16	2011-03-01/2011-11-01	0.00	0.96
Barra Bonita	2008-01-15/2016-12-31	2008-01-15/2012-12-31	0.93	1.79
		2013-01-29/2016-12-31	0.89	1.82
Promissão	2008-12-02/2016-12-31	2008-02-12/2012-12-31	0.23	1.91
		2013-01-28/2016-12-31	0.21	1.66
Três Irmãos	2008-02-12/2016-12-31	2008-02-12/2012-12-31	0.51	1.37
		2013-02-26/2016-12-31	2.24	1.46
Serra Azul	2009-01-01/2016-12-31	2009-01-01/2012-12-31	0.74	1.33
		2013-01-29/2016-12-31	0.74	2.06
Paranoá	2010-01-11/2017-12-31	2010-01-11/2017-12-31	0.29	1.09



(**a**)

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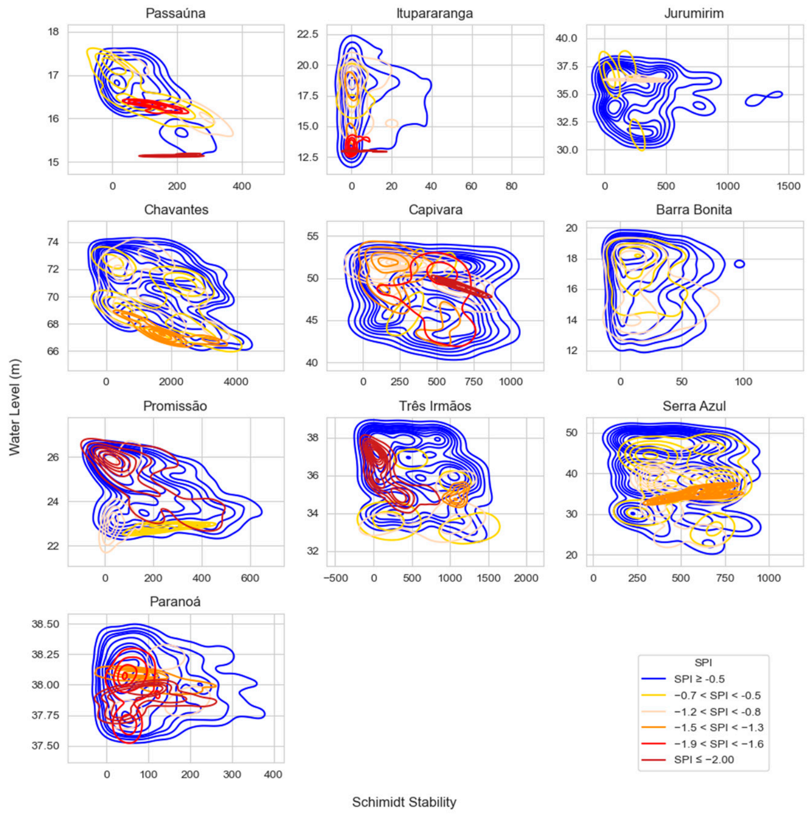

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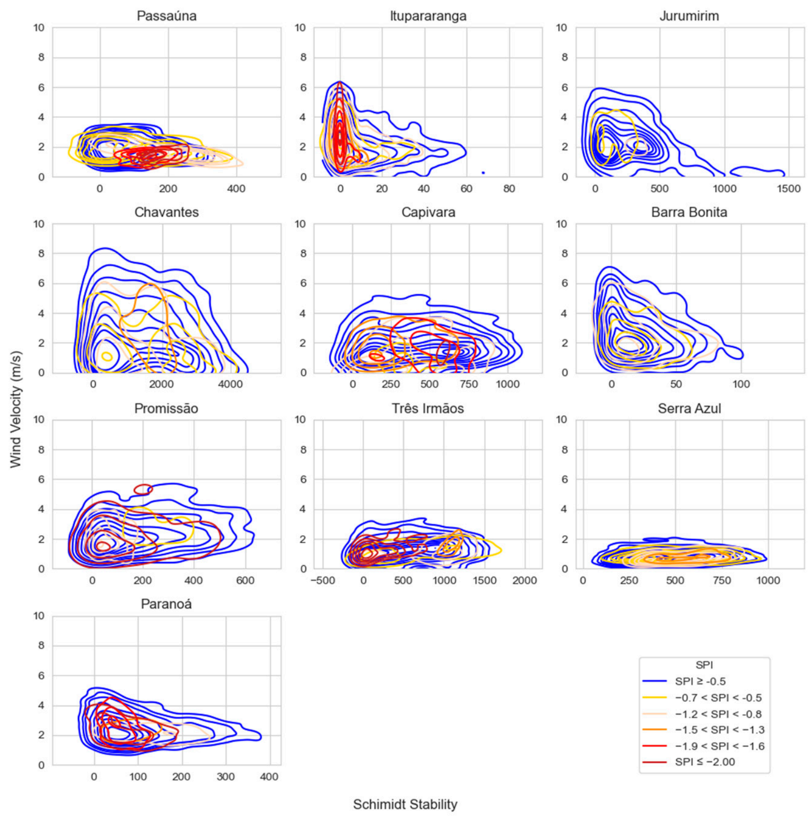
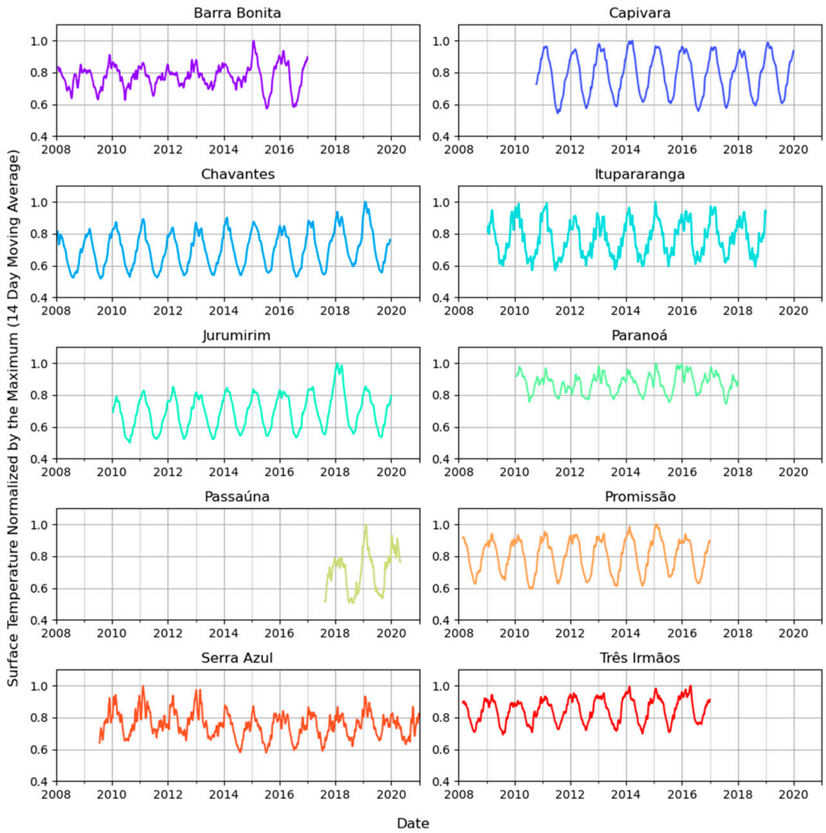
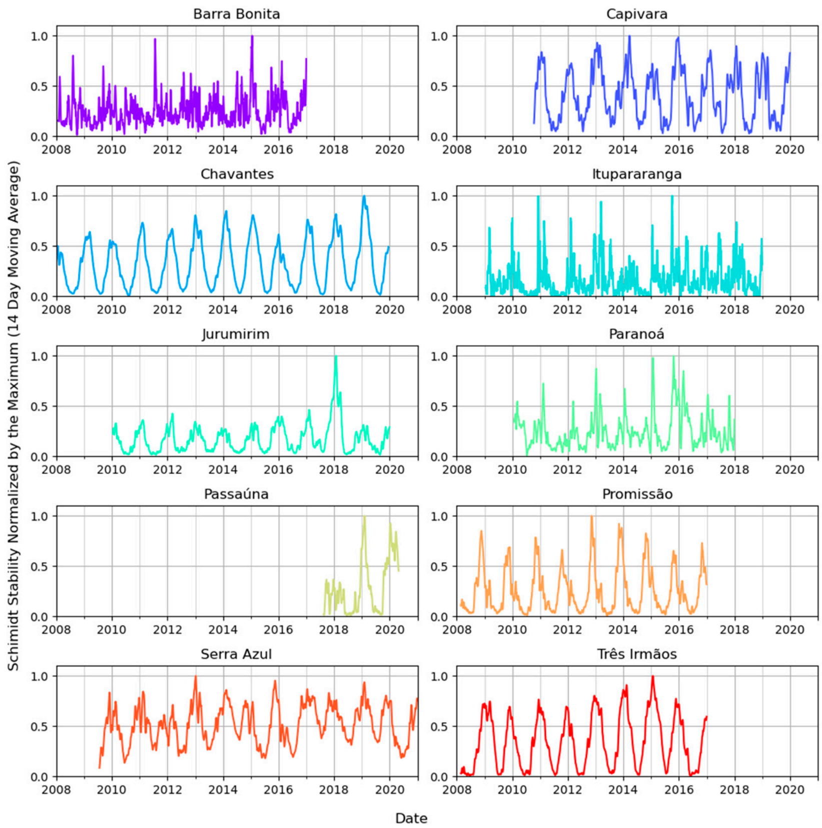


(**c**)

Figure 4. Pair-grid diagrams of (**a**) Precipitation, (**b**) Water Level, and (**c**) Wind velocity versus Schmidt Stability, according to SPI-12 classification, from each reservoir.



(a)



(b)

Figure 5. Seasonal variation of the Surface Temperature (**a**) and the Schmidt Stability (**b**) normalized by the maximum and expressed by a 14-day moving average along the years for each reservoir.

As was indicated in the previous graphs there was a relation between seasons and St values. In this regard, the statistical test (ANOVA-one way) has shown significant differences in St results between wet (SPI-12 $\geq$ 0.5) and dry (SPI-12 < 0.5) periods for all reservoirs in summer (Table 5).

Table 5. Schmidt Stability results of ANOVA one-way to test the significance between drought and normal/wet conditions for each reservoir and each season of the year. Significant *p*-values are shown in bold.

Reservoir	4 Seasons (Significance Test)							
	Summer		Autumn		Winter		Spring	
	F	*p*	F	*p*	F	*p*	F	*p*
Passaúna	338.89	**0.000**	251.37	**0.000**	46.41	**0.000**	26.76	**0.000**
Itupararanga	6.82	**0.010**	2.38	0.124	1.30	0.255	9.31	**0.003**
Jurumirim	32.48	**0.000**	10.88	**0.001**	49.35	**0.000**	12.03	**0.001**
Capivara	65.87	**0.000**	77.55	**0.000**	0.60	0.439	21.12	**0.000**
Chavantes	161.09	**0.000**	4.39	**0.038**	122.69	**0.000**	22.39	**0.000**
Barra Bonita	24.51	**0.000**	0.65	0.422	5.19	**0.024**	0.01	0.916
Promissão	16.35	**0.000**	0.12	0.731	2.17	0.143	5.63	**0.019**
Três Irmãos	485.67	**0.000**	62.64	**0.000**	0.74	0.392	12.75	**0.000**
Serra Azul	5.30	**0.022**	995.97	**0.000**	841.30	**0.000**	105.23	**0.000**
Paranoá	62.10	**0.000**	7.86	**0.006**	25.71	**0.000**	1.26	0.262

4. Discussion

4.1. Impacts of Drought Periods on the Management of Reservoirs

The application of SPI-12 analysis for drought periods identification was useful for multipurpose reservoirs, especially where water level fluctuation was correlated to dam operation, due to hydropower generation as well as the existence of cascade reservoirs along the same river. Although there are other drought indexes that consider hydrological parameters directly, multiple variables or inputs are needed for calculations [24]. In addition, the SPI application has some advantages such as the availability of code to run the index free, the low input variables, and how daily data is not required. These advantages facilitate the adoption of SPI by the managers of the hydropower private companies, water utility companies, and governmental agencies. In addition, the low data requirements for SPI computation permit the application of this index even in places with low temporal resolution for monitoring data availability.

Despite the low frequency of time with drought period occurrence, a frequency of extreme drought periods of 6.0% and 4.6% created serious problems for water security. When the drought period persists for more than one year, the water supply systems are severely impacted. The southeast of Brazil faced a severe drought in 2014 and 2015. Due to that event, Serra Azul reservoir, which supplies water for the metropolitan region of Belo Horizonte, experienced a significant decrease in water level. For this period, drinking water had to be supplied by other sources and emergency measures cost more than US$ 32 million [18]. The annual average rainfall in the Itupararanga basin in 2014 was over 2/3 of its long-term annual value (1572 mm). As a consequence, the dam operator adopted a strategy to reduce the outflow, which eventually increased the residence time (453 days) to maintain regular hydropower generation and drinking water supply, yet even so the reservoir water level saw a significant decrease in 2014 [5]. South Brazil also had an exceptional drought period, during which a water emergency was declared from 2020 to 2022. The metropolitan region of Curitiba must adopt water rationing measures and some alternative measures with high costs involved [43].

During a water emergency related to a drought occurrence, the alterations on reservoirs' thermal regime, which have implications for water quality, are not considered as the main subject of management actions. These implications should be monitored since during low water levels related to drought periods, concentrations of chlorophyll can increase, with an occurrence of cyanobacterial blooms (*Cylindrospermopsis raciborskii*) as previous study pointed out [44]. In addition, drought periods with lower water levels and intensified near-bed mixing can increase internal loading, which is an important factor for phytoplankton growth in the lacustrine zone of the reservoirs [45].

4.2. Effects of Drought on Reservoirs' Thermal Stability

The reservoir stratification can be modified by drought in three different ways: change the magnitude of St value in comparison to wet periods, alteration of the stratification duration [5,18], and modification of the period of time of the stratification occurrence [4]. Stratification is promoted by conditions often arising during droughts, usually related to an increase in temperature, and this condition can increase the incidence and persistence of stratification and harmful algal blooms [3,46,47]. Temperature increases and increased stratification can also result in lower dissolved oxygen, especially in the hypolimnion of lakes and reservoirs [48]. Itupararanga is the most stable reservoir in drought periods, especially when there are extreme and exceptional droughts independent of wind speed (Figure 4c). The findings of this study suggest that distinct behavior (Figure 3) may also be connected to morphometric and morphology characteristics, since the reservoirs Jurumirim, Chavantes, and Capivara are long, dendritic, and polymitic. Jurumim and Capivara have similar behaviors, but Capivara's mixing is characterized by lower temperatures than Jurumirim while Chavantes shows stronger stratifications. Jurumirim and Capivara appear to transfer temperature into greater depths, since they have lower maximum depths than Chavantes. Also, Chavantes may have reduced proportional influence of external forcings and less proportional evaporation, since its surface area is lower, and its maximum depth is higher than the other two making it more difficult to warm in temperature at greater depths (Table 1 and Figure 3). In general, drought periods include stratification periods, but not necessarily the strongest ones, even though it can happen (e.g., Chavantes in mid-2018). Accordingly, Jurumirim is the most unstable (has the weakest stratifications, lower Schmidt) followed by Capivara. Chavantes is the most stable when comparing to Jurumirim and Capivara (Figure 5b).

The significant difference between drought and wet periods in St values for all the reservoirs in the summer indicated that there is an alteration in thermal regime during drought periods in this season. In addition, most of the studied reservoirs have higher St mean values during drought periods (Barra Bonita, Chavantes, Promissão, Serra Azul, Três Irmãos, Passaúna, and Paranoá reservoirs). However, environmental factors such as wind intensity can affect mixing during drought periods as seems to occur in the Itupararanga, Capivara, and Jurumirim reservoirs.

5. Conclusions

This study contemplated an integrated preliminary analysis of ten multipurpose reservoirs, including water supply in some cases, located in different places of Brazil. Such analysis was carried out focusing on drought periods, which are classified by SPI-12 index to verify possible similarities in their behavior. All reservoirs, except Passaúna and Paranoá, faced extreme drought during the analyzed periods. The behavior of the reservoirs was simulated using a unidimensional hydrodynamic model for the periods of data availability for each reservoir.

It became clear that drought periods alter the thermal regime depending on the season and the reservoirs' characteristics such as morphometry. This study has identified alterations in thermal regimes during drought periods in the summer. Additionally, external factors (e.g., wind intensity and rain) may influence reservoirs' mixing during drought periods.

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