Chapter 6

Limnological Patterns in a Large Subtropical Reservoir Cascade

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.80632

Abstract

The study identified limnological patterns in the Paranapanema River reservoir cascade, one of the main tributaries of the high Paraná River, La Plata Basin, southeast Brazil. Samplings were carried out in eight reservoirs from a total of 37 sites. We analyzed the water transparency, depth, and vertical profiles of temperature, pH, conductivity, dissolved oxygen, biochemical oxygen demand, total solids, suspended solids, total nitrogen, total phosphorus, chlorophyll *a*, and thermotolerant coliforms. Additionally, the trophic state index for tropical/subtropical reservoirs, the water retention time and morphometric characteristics of each reservoir were calculated. Longitudinal compartmentalization is conspicuous in storage reservoirs, whereas the magnitude of temporal changes is higher in run-of-river systems. The lateral component of spatial heterogeneity was also very important for some reservoirs, determined basically by the entrance of tributary rivers. On the vertical dimension, summer thermal stratification, followed by oxygen decrease in bottom layers, in the central channel and lacustrine zones of deeper and larger reservoirs was observed. The ultraoligotrophic condition prevailed, despite signals of intensive land use for agriculture—recurrent high phosphorus values. The acquired experience provided a baseline for a permanent limnological and water quality program, which subsidizes management actions in the basin.

Keywords: water quality, trophic state, spatial variability, seasonal variability, run-of-river, storage

1. Introduction

River damming for hydropower production is presently a major human interference on fluvial systems, all over the world. In these first decades of the twenty-first century, the construction of 3700 dams is expected, increasing the global hydropower production by 73%. This would correspond to an intensification in the exploitation of the technically feasible hydropower potential from 22 to 39% [1].

Hydropower is crucial in Brazil, representing the main source of electric generation, 107,601 MW of a total of 166.872 MW, according to the database of the Brazilian National Agency of Electric Energy (http://www.aneel.gov.br). The production is distributed in 1321 reservoirs, 220 large ones (>30 MW) and 1101 smaller ones (<30 MW).

Hydroelectric dams are an integrated and complex generation system that provides relatively clean and renewable energy. However, independent of the reservoir design and operation, they promote substantial interference on the ecological structure and functioning of river basins [2] and permanent loss of the regional geodiversity [3, 4].

Classical studies on reservoirs [5, 6] distinguish at least three limnological zones in large reservoirs: the region with strong influence of the incoming river—lotic region; an intermediate transition region; and finally a region similar to lakes, near the dam. However, it is known that in large tropical reservoirs, this multidimensional zonation is greatly influenced by the input of secondary tributaries and by the differential water retention time of each reservoir arm [7–10]. These distinctive areas or compartments in reservoir ecosystems may also change seasonally, in a complex dynamic [5, 7, 11, 12].

The large-scale variability of reservoirs along the main axis is determined by longitudinal gradients of flow velocity, depth, width, particle sedimentation, transparency and light penetration, and thermal stratification [11–13]. Compared to lakes, reservoirs exhibit high watershed area/water body area, shorter but varying retentions times, a rapid aging process related to watershed uses, and high capability to retain organic and inorganic matter [14, 15].

An integrated approach, including continuous monitoring and innovative researches, is required for the understanding of the reservoir ecosystems, giving their inherent complexity, with many components and subsystems that interact intensively in space and time [16].

The present study was planned to discriminate the main limnological patterns of a tropical/subtropical reservoir cascade aiming to provide scientific support for management purposes. We analyzed the morphometric characteristics; operation type; water retention time; physical, chemical, and biological variables as well as the trophic status. The acquired experience served as the base for the establishing of methodological protocols that have been employed in the long-term (permanent) limnological and water quality monitoring program (8 years now) in the Paranapanema River reservoir cascade (southeast Brazil). The two most important premises are: (1) the reservoir operation (run-of-river or storage systems) is determinant for the establishing of distinct limnological patterns and (2) the Paranapanema River reservoir cascade is influenced by the intensification of the agriculture in the watershed.

2. Study area

The Paranapanema River is one of the main tributaries of the Paraná River (La Plata Basin), located between the coordinates 22–26° S and 47–54° W, on the tropical/subtropical boundary. The river, with a length of 929 km, is under federal jurisdiction, because it is the natural border between the states of São Paulo and Paraná.

Since the 1950s, 11 hydropower plants were constructed in the main river course. In last two decades, these reservoirs (eight larger ones) have been intensively studied by researchers of the São Paulo State University, Campus of Botucatu, São Paulo [17, 18].

The reservoirs selected for the study are Jurumirim (JR), Chavantes (CH), Salto Grande (SG), Canoas II (CII), Canoas I (CI), Capivara (CP), Taquaruçu (TQ), and Rosana (RS), arranged in a cascade (upstream → downstream) system. Three of the them, Jurumirim, Chavantes, and Capivara, are storage systems (i.e., with high water retention times), whereas the others are run-of-river systems. The total installed potential is 2241 MW.

For the development of the study, information was obtained at 37 sampling sites (**Figure 1**), whose distribution intended to cover the entire river's continuous (inter-reservoir) variability as well as the internal (intra-reservoir) longitudinal gradient established between the lotic (Paranapanema River entrance) and lentic (dam) areas of each reservoir. Additionally, the influence of important secondary tributaries (river mouths) was also considered. At

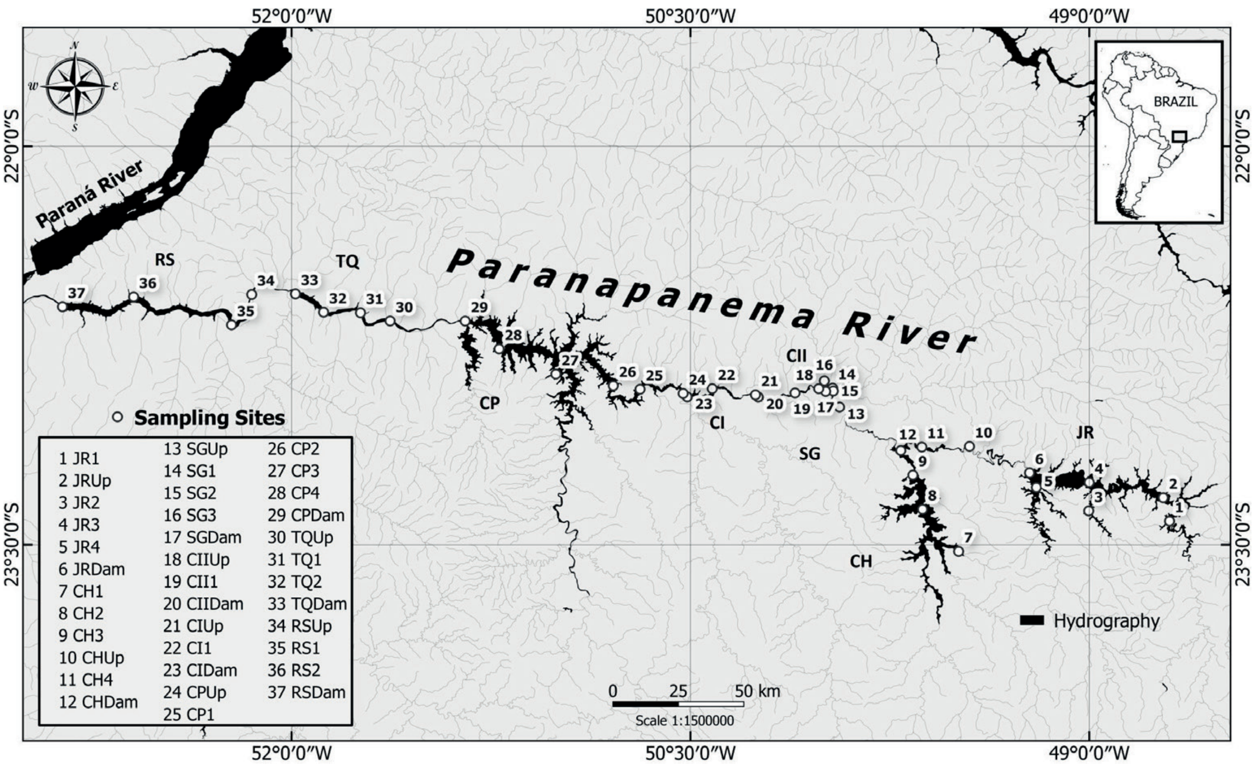

Figure 1. Geographic location of Paranapanema River reservoir cascade and the selected sampling sites.

Reservoir	Sampling site	Coordinates		Altitude (m) (a.s.l.)
Jurumirim	JR1	23°24'39.40"S	48°41'53.80"W	565
	JRUp	23°19'21.90"S	48°43'19.00"W	568
	JR2	23°22'20.80"S	49°0'7.80"W	567
	JR3	23°15'55.40"S	49°0'1.10"W	560
	JR4	23°17'1.90"S	49°11'56.80"W	570
	JRDam	23°13'44.80"S	49°13'29.20"W	563
Chavantes	CH1	23°31'29.50"S	49°29'29.30"W	469
	CH2	23°21'58.90"S	49°37'37.90"W	471
	CH3	23°14'15.00"S	49°39'48.60"W	467
	CHUp	23°7'46.20"S	49°27'2.30"W	468
	CH4	23°7'55.10"S	49°37'47.30"W	477
	CHDam	23°8'41.70"S	49°42'32.40"W	473
Salto Grande	SGUp	22°58'52.60"S	49°56'22.10"W	383
	SG1	22°54'43.60"S	49°57'57.20"W	383
	SG2	22°54'49.60"S	49°58'0.30"W	389
	SG3	22°53'3.20"S	49°59'40.40"W	385
	SGDam	22°53'56.00"S	49°59'27.00"W	389
Canoas II	CIIUp	22°55'5.50"S	49°59'31.50"W	368
	CII1	22°55'42.50"S	50°6'24.00"W	364
	CIIDam	22°56'36.80"S	50°14'42.80"W	367
Canoas I	CIUp	22°56'8.60"S	50°15'19.70"W	348
	CI1	22°54'44.40"S	50°25'5.40"W	348
	CIDam	22°56'35.90"S	50°30'43.10"W	354
Capivara	CPUp	22°55'49.30"S	50°31'38.90"W	329
	CP1	22°54'52.60"S	50°41'22.10"W	326
	CP2	22°54'4.50"S	50°47'24.50"W	322
	CP3	22°51'26.80"S	51°0'22.00"W	335
	CP4	22°45'45.80"S	51°13'10.40"W	332
	CPDam	22°39'27.90"S	51°20'49.80"W	325
Taquaruçu	TQUp	22°39'27.00"S	51°37'46.00"W	277
	TQ1	22°37'36.20"S	51°44'27.00"W	273
	TQ2	22°37'28.00"S	51°52'46.60"W	273
	TQDam	22°33'19.80"S	51°59'7.90"W	271
Rosana	RSUp	22°33'27.50"S	52° 8'59.90"W	260
	RS1	22°40'20.30"S	52°13'32.80"W	268

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Reservoir	Sampling site	Coordinates		Altitude (m) (a.s.l.)
	RS2	22°34'1.10"S	52°35'38.60"W	251
	RSDam	22°36'14.30"S	52°51'42.10"W	241

Table 1. Geographic coordinates and elevations of the sampling sites along the reservoir cascade.

least three to six sampling sites were selected in each reservoir. **Table 1** presents the geographic coordinates as well as the altitude data of the sampling sites, obtained with a Garmin Etrex Vista H GPS.

3. Material and methods

The sampling campaigns for physical, chemical, and biological measurements were carried out in two periods of the year: March—wet season (late summer)—and October—dry season (spring) of 2011. All sites of each reservoir/period were sampled in the same or in two consecutive days.

The limnological variables measured *in situ*, and respective methodologies, are shown in **Table 2**.

Water samples were collected with a Van Dorn bottle at three depths along the water column, corresponding to the surface, middle, and bottom (about 0.5–1.0 m above sediments), for the analyses of nutrient (total nitrogen and phosphorus), total solids, suspended solids, chlorophyll *a*, biochemical oxygen, and thermotolerant coliforms. When filtration was required, Millipore AP40 membranes and vacuum pump were used. For weight determination, a Denver analytical scale (0.00001 g) was used. Laboratory determinations followed methodological principles presented in **Table 3**.

The shore line development index was calculated according to [26]. The theoretical residence time (days) was defined as the ratio of reservoir volume and the flow calculated using the formula: $TRT = V/(Q \times 86{,}400)$, where V = reservoir volume (m^3); Q = mean flow ($m^3\ s^{-1}$); and 86,400 = number of seconds contained in a day. Input data for each reservoir are available at the National Water Agency (Agência Nacional de Águas, in Portuguese) (http://sar.ana.gov.br).

Variable	Methodology
Water transparency (Transp)	Secchi disk depth
Water temperature (Temp)	Eureka multi-parameter probe—vertical profile
Dissolved oxygen (DO)	Eureka multi-parameter probe—vertical profile
pH	Eureka multi-parameter probe—vertical profile
Conductivity (Cond)	Eureka multi-parameter probe—vertical profile
Turbidity (Turb)	Eureka multi-parameter probe—vertical profile

Table 2. Limnological variables measured *in situ*.

The trophic state index was determined in accordance with [27] for tropical/subtropical reservoirs (TSItsr), which includes six categories: (U) ultraoligotrophic (≤51.1), (O) oligotrophic (51.2–53.1), (M) mesotrophic (53.2–55.7), (E) eutrophic (55.8–58.1), (S) supereutrophic (58.2–59), and (H) hypereutrophic (≥59.1), respectively.

The studied parameters (when applicable) were compared with the standard references (**Table 4**) established by the federal framework directive for Class 1 waters—the best possible condition (after the Special Class), with no human use restriction and appropriated for communities' protection (http://www.mma.gov.br/port/conama/res/res05/res35705).

A principal component analysis (PCA) was performed to summarize variation tendencies or patterns for limnological variables during both sampling periods, using the PRIMER v6 statistics package for Windows (Plymouth Routines in Multivariate Ecological Research, www.primer-e.com).

Variable	Methodology
Total nitrogen (TN)	Spectrophotometry [19, 20]
Total phosphorus (TP)	Spectrophotometry [19, 21]
Total solids (TS)	Evaporation/gravimetry (100°C) [22]
Suspended solids (SS)	Gravimetry [23]
Biochemical oxygen demand (BOD)	Incubation 20°C/5 days [22]
Chlorophyll *a* (Chl)	Spectrophotometry [24, 25]
Thermotolerant coliforms (Coli)	Multiple tube MPN [22]

Table 3. Limnological variables measured in the water samples—laboratory analyses.

Variable	Standard reference
pH	6–9
Turbidity	>40 NTU
Dissolved oxygen	>6 mg L^{-1} O_2
Biochemical oxygen demand	>3 mg L^{-1} O_2
Total solids	>500 mg L^{-1}
Total nitrogen	>1.27 mg L^{-1} lentic systems
	>2.18 mg L^{-1} lotic systems
Total phosphorus	>0.020 mg L^{-1} lentic systems
	>0.025 mg L^{-1} intermediate systems*
Chlorophyll *a*	>10 μg L^{-1}
Thermo tolerant coliforms	>200 NMP 100 mL^{-1}

*Water retention time between 2 and 40 days.

Table 4. Standard references established by CONAMA Resolution 357/2005 (conditions for water quality categories for Brazilian aquatic ecosystems) for Class 1 waters.

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4. Results[1]

The general characteristics of the studied reservoirs (morphometry, operation, trophy, etc.) are compiled in **Table 5** and the wide spectrum of conditions certainly influence not only the structure but also the limnological functioning of these ecosystems, as pointed out earlier.

The obtained results, *in situ* and laboratory measurements, are presented following the reservoir's sequence, from upstream toward the mouth. Graphical representations (**Figures 2–33**) are standardized for all reservoirs, including monthly variation of the water level versus flow, vertical profiles of temperature and dissolved oxygen, and intra-reservoir variability (upstream/tail → dam) of transparency, electric conductivity, pH, turbidity, total solids, suspended solids, biochemical oxygen demand, total nitrogen, total phosphorus, chlorophyll *a*, and thermotolerant coliforms.

Variable	JR	CH	SG	CII	CI	CP	TQ	RS
Type (*modus operandi*)*	S	S	R	R	R	S	R	R
Area (km²)	449	400	12	22.5	30.85	576	80.1	220
Perimeter (km)	1286	1085	81	103	120	1550	301	433
Volume (hm³)	7702	9410	63.2	158	220	11,743	754.2	1942
Shore line development index	17.1	15.3	6.6	6.1	6.1	18.2	9.5	8.2
Water retention time (days)	400	335	2	4	6	115	7	17
Maximum measured depth (m)	32	79	10	15	25	40	26	27
Altitude (m) (a.s.l.)	563	473	389	367	354	325	271	241
Age (year)	56	47	60	19	19	40	29	31
T.S.I. $_{tsr}$**	U	U	U	U	O	U	U	U

*Reservoir operation S—Storage; R—Run-of-River.
**Trophic State Index $_{tropical/subtropical\ reservoir}$ (U = ultraoligotrophic; O = oligotrophic).
Minimum (dark gray) and maximum (light gray) values are highlighted.

Table 5. General characteristics of the study reservoirs.

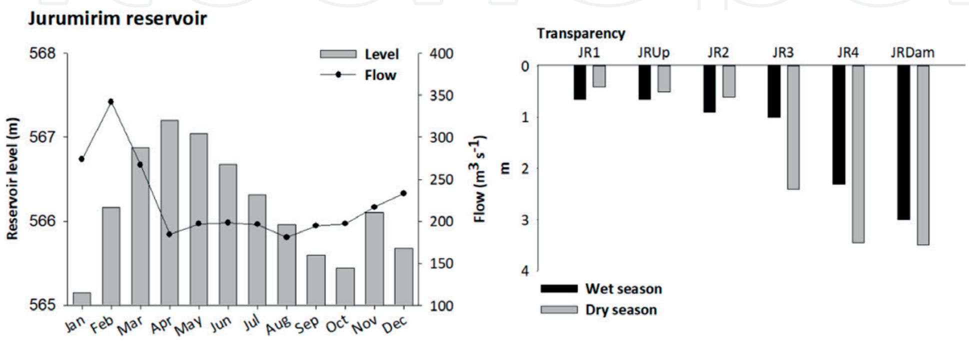

Figure 2. Variation of water level and flow (monthly averages) and transparency (wet and dry seasons) in Jurumirim reservoir.

[1]See also Appendixes 1 and 2.

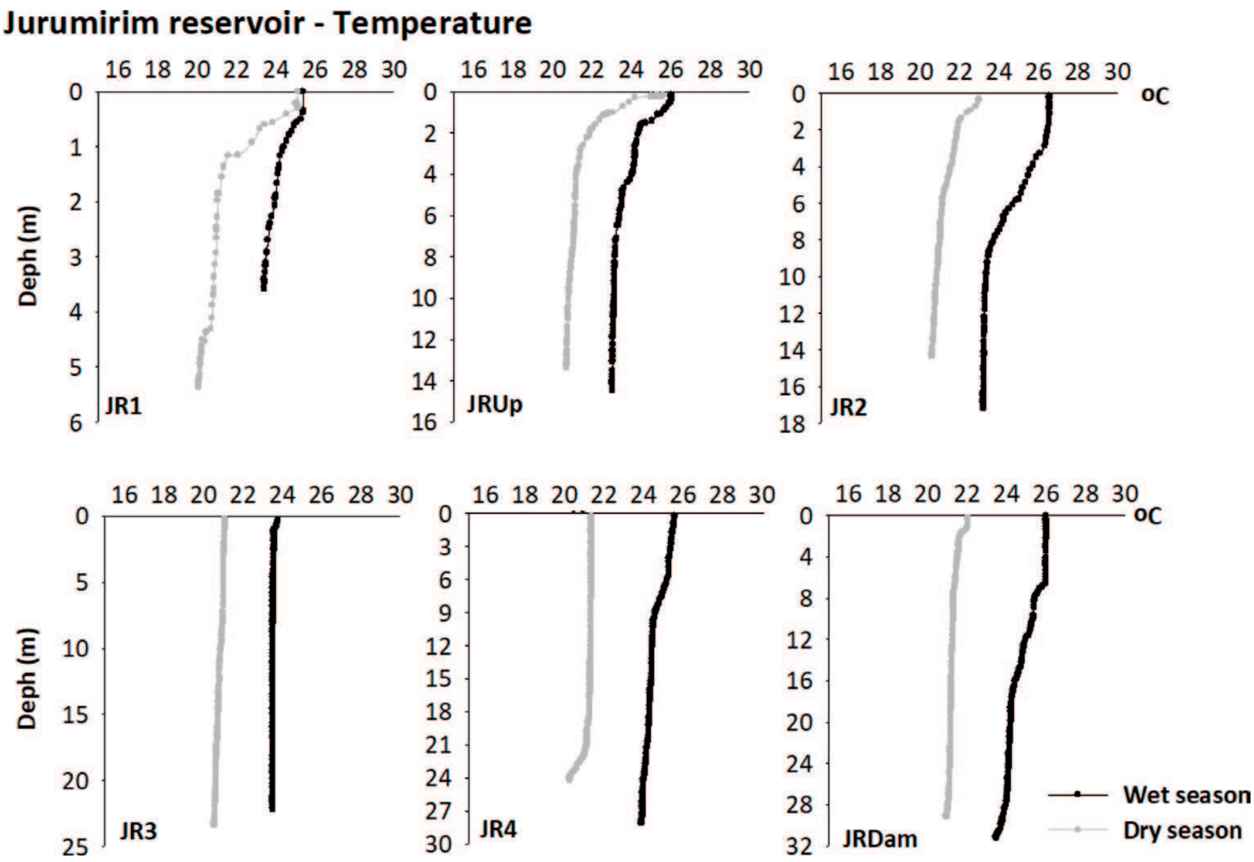

Figure 3. Temperature profiles in Jurumirim reservoir sampling sites during wet and dry seasons.

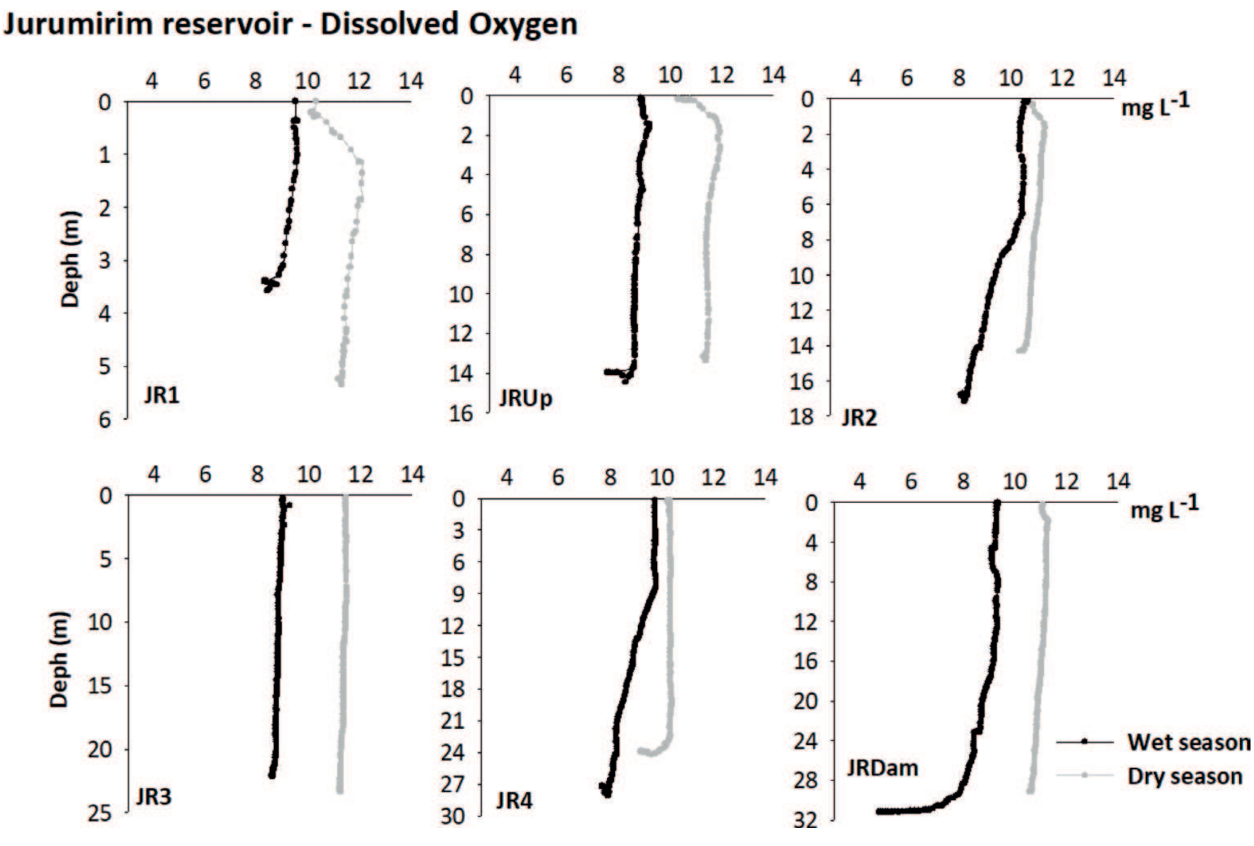

Figure 4. Dissolved oxygen profiles in Jurumirim reservoir sampling sites during wet and dry seasons.

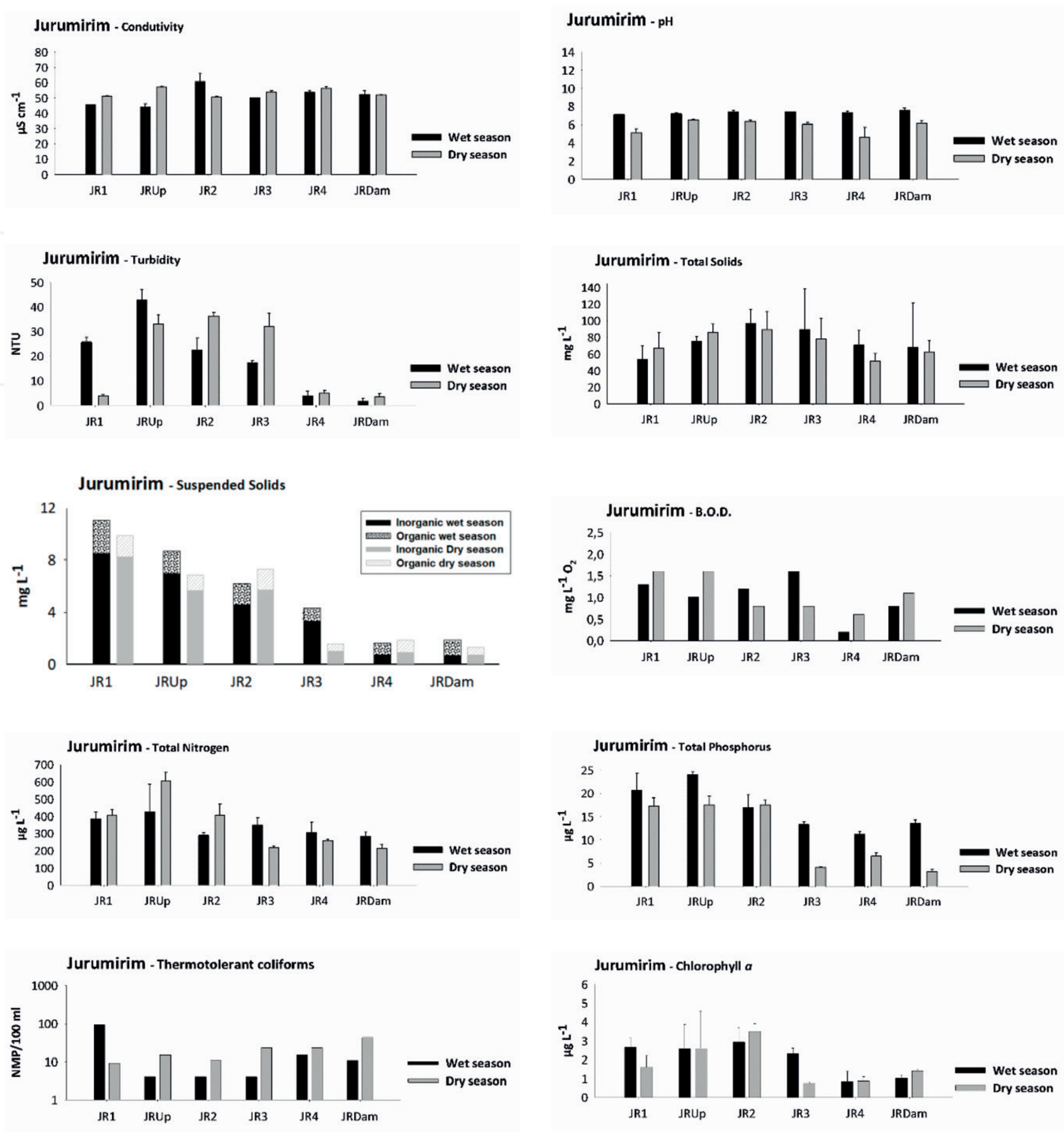

Figure 5. Mean values (+S.D.) of conductivity, pH, turbidity, total and suspended solids, biochemical oxygen demand, total nitrogen, total phosphorus, thermo tolerant coliforms and chlorophyll *a* in Jurumirim reservoir sampling sites during wet and dry seasons.

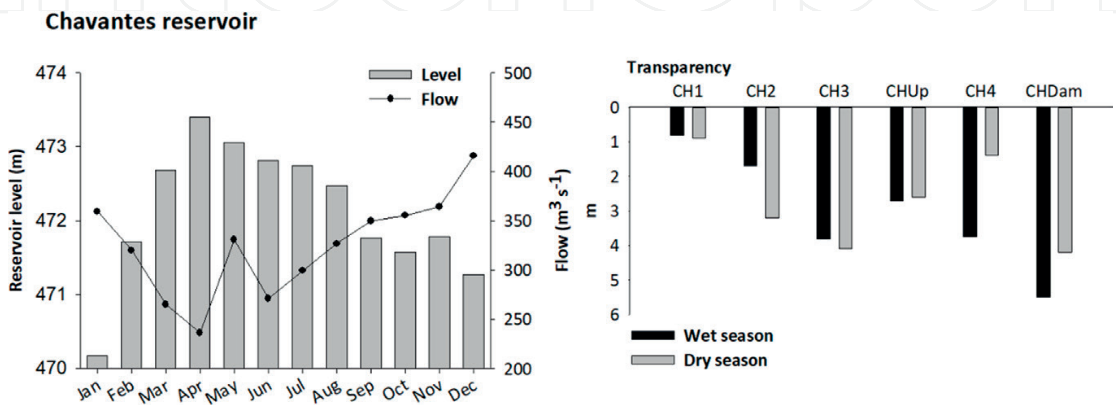

Figure 6. Variation of water level and flow (monthly averages) and transparency (wet and dry seasons) in Chavantes reservoir.

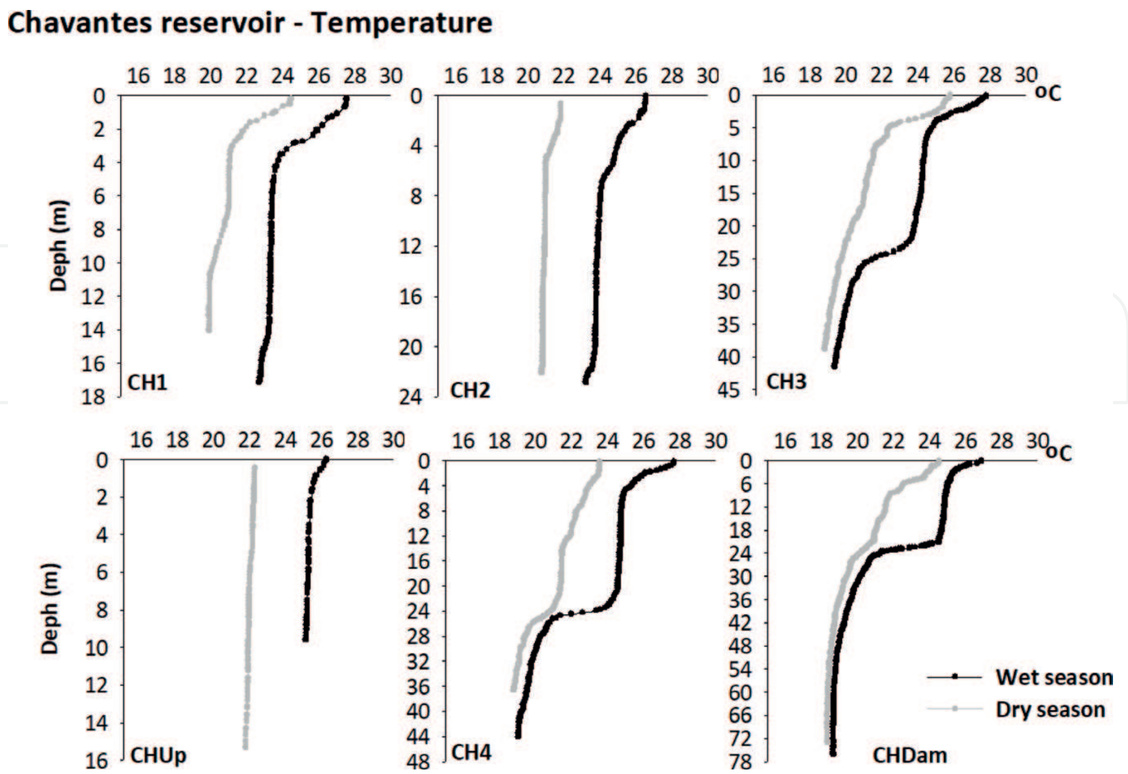

Figure 7. Temperature profiles in Chavantes reservoir sampling sites during wet and dry seasons.

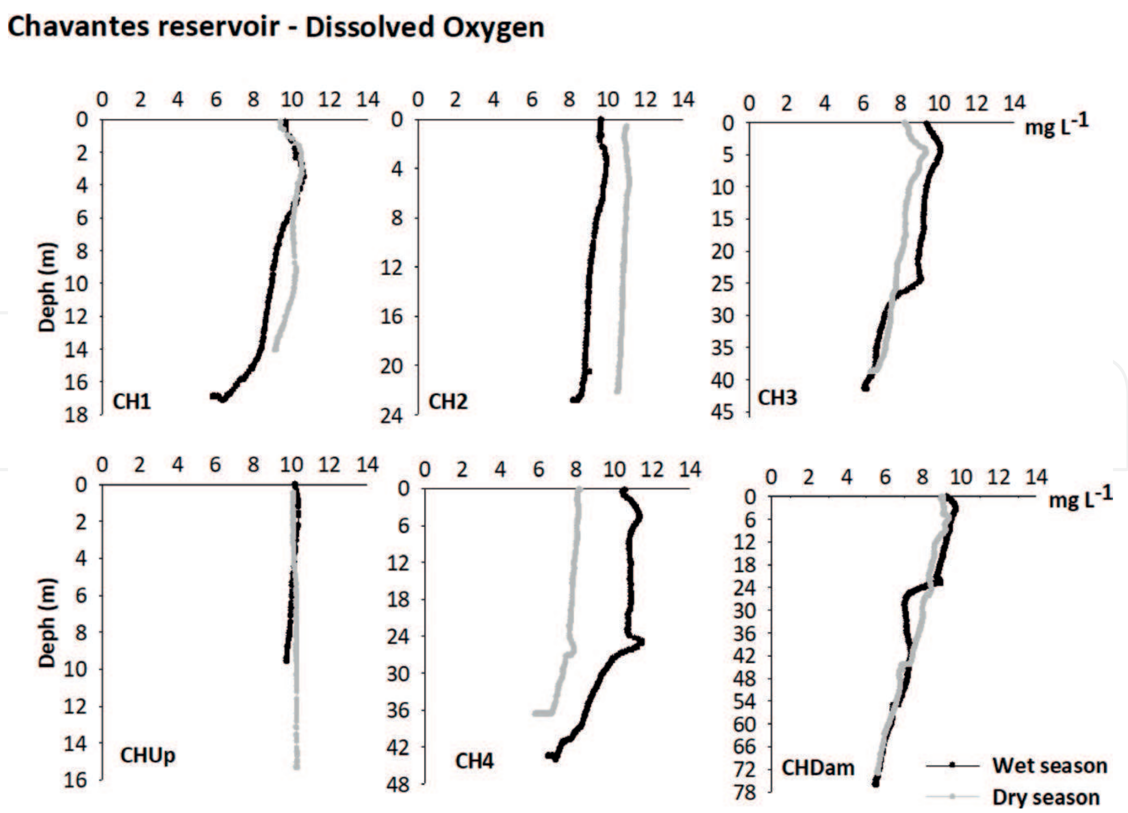

Figure 8. Dissolved oxygen profiles in Chavantes reservoir sampling sites during wet and dry seasons.

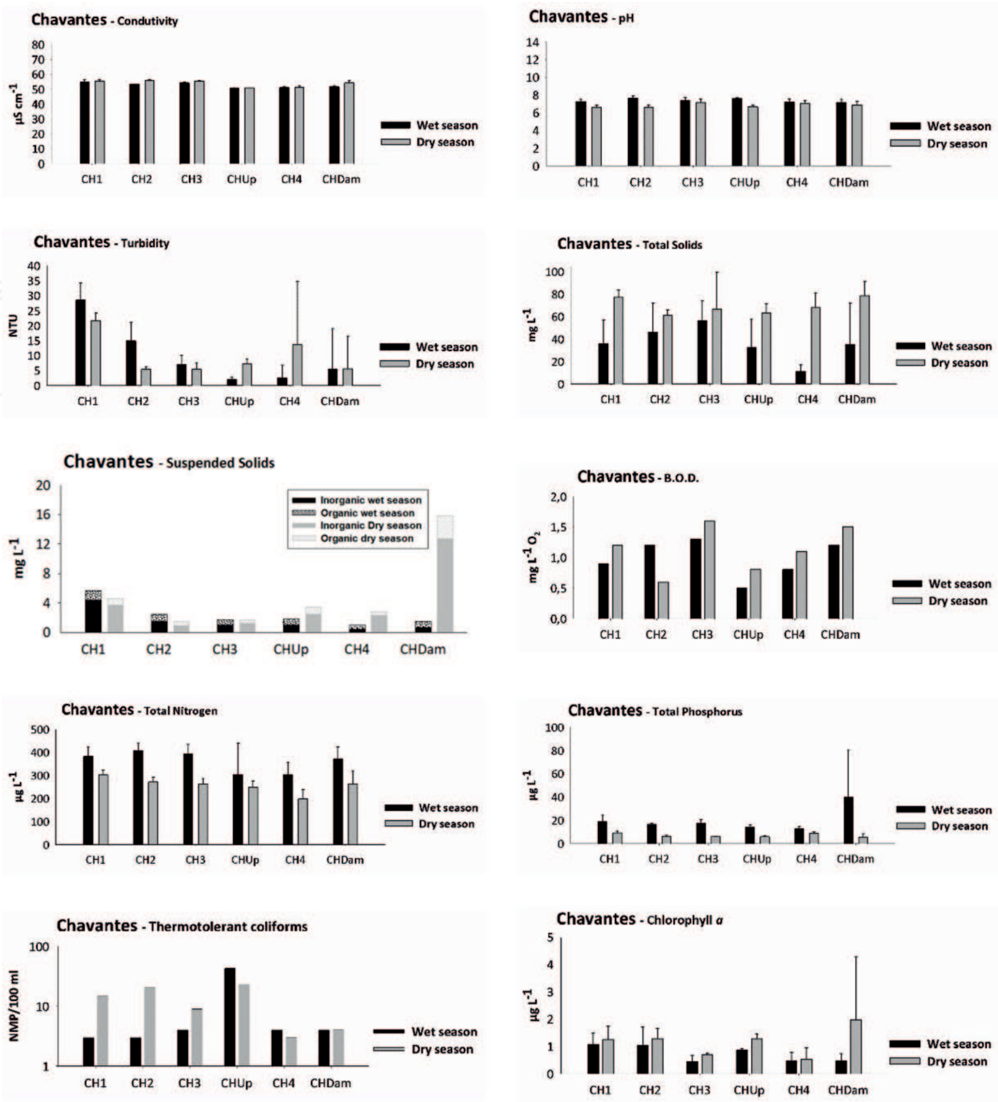

Figure 9. Mean values (+S.D.) of conductivity, pH, turbidity, total and suspended solids, biochemical oxygen demand, total nitrogen, total phosphorus, thermotolerant coliforms and chlorophyll *a* in Chavantes reservoir sampling sites during wet and dry seasons.

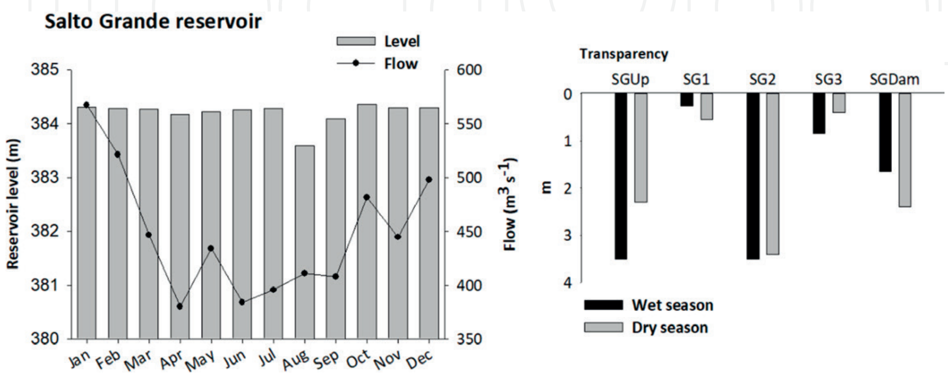

Figure 10. Variation of water level and flow (monthly averages) and transparency (wet and dry seasons) in Salto Grande reservoir.

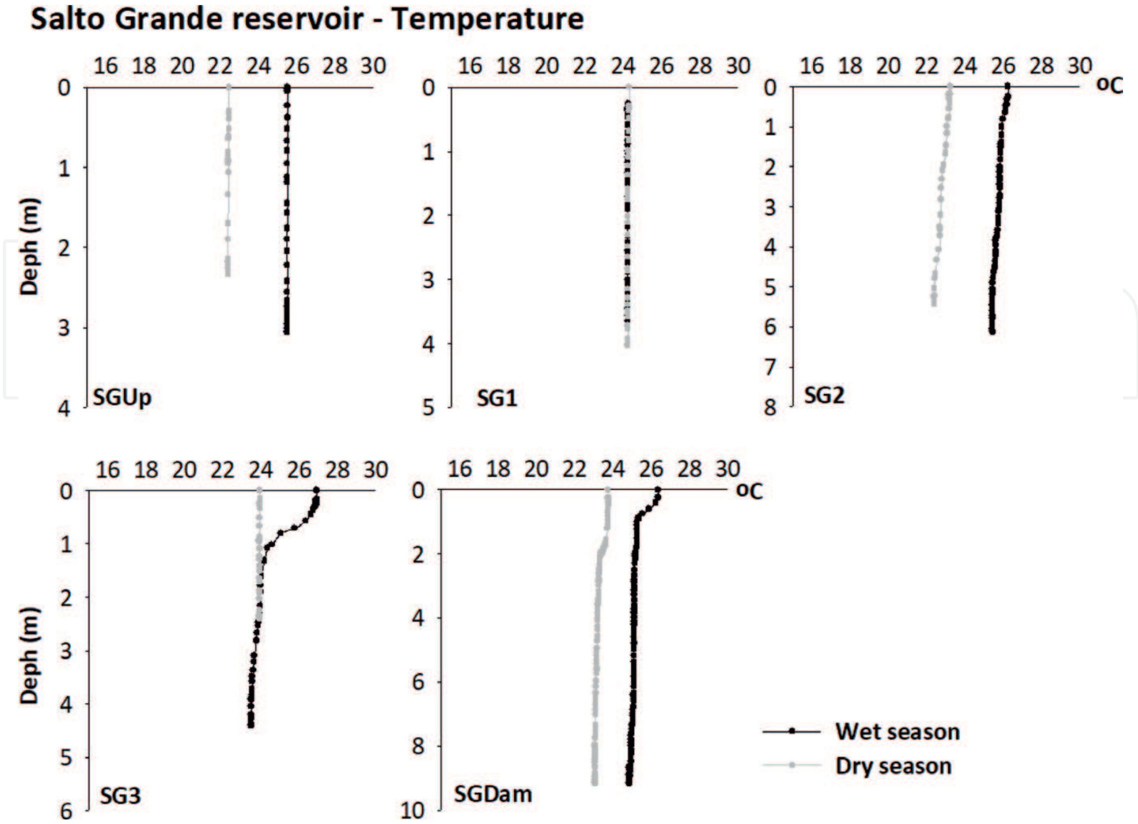

Figure 11. Temperature profiles in Salto Grande reservoir sampling sites during wet and dry seasons.

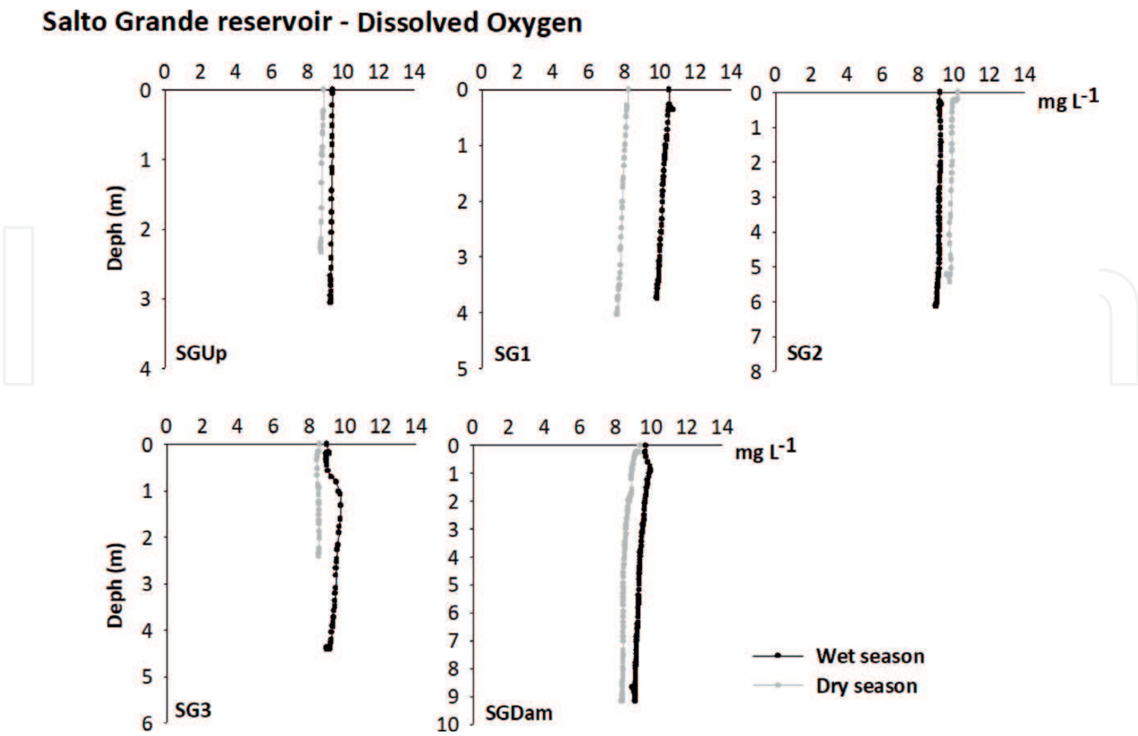

Figure 12. Dissolved oxygen profiles in Salto Grande reservoir sampling sites during wet and dry seasons.

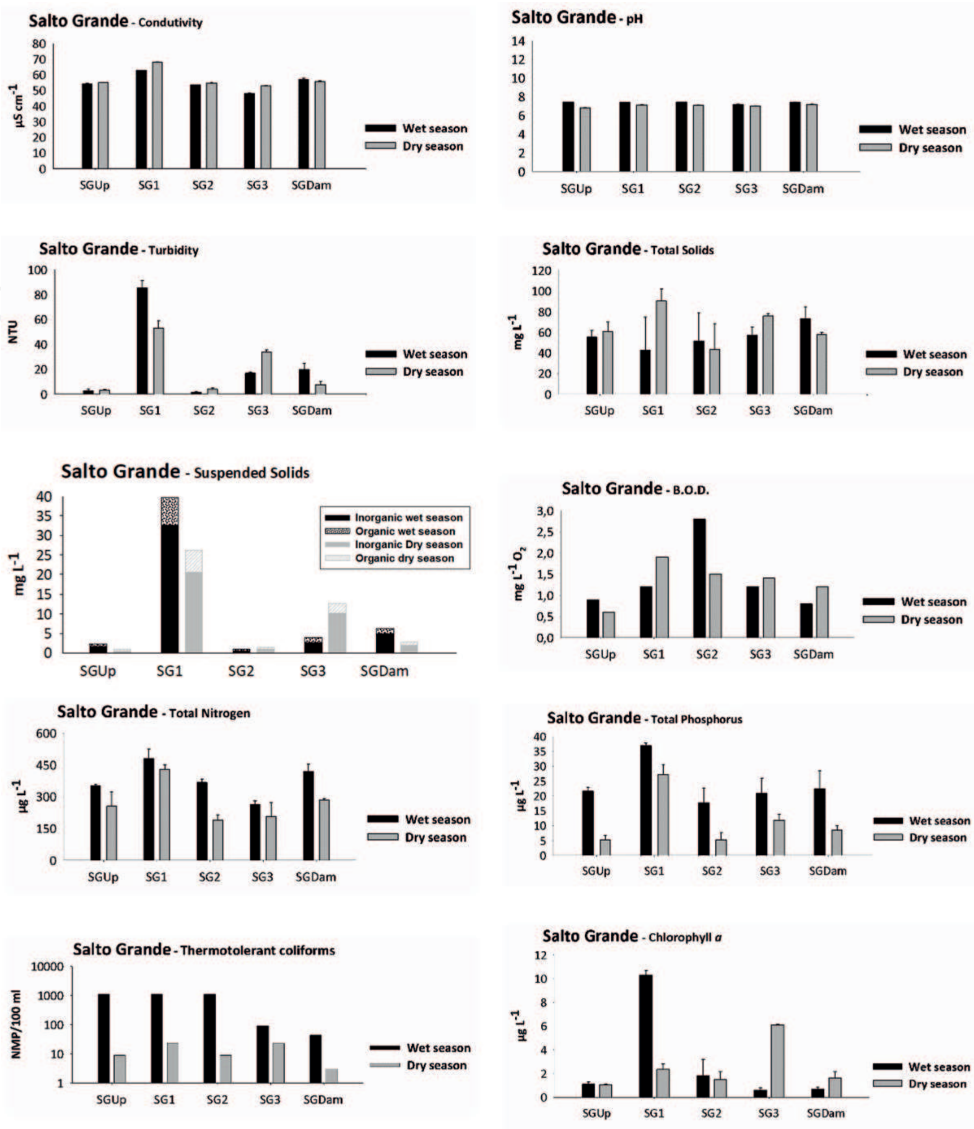

Figure 13. Mean values (+S.D.) of conductivity, pH, turbidity, total and suspended solids, biochemical oxygen demand, total nitrogen, total phosphorus, thermotolerant coliforms and chlorophyll *a* in Salto Grande reservoir sampling sites in the 2011 wet and dry seasons.

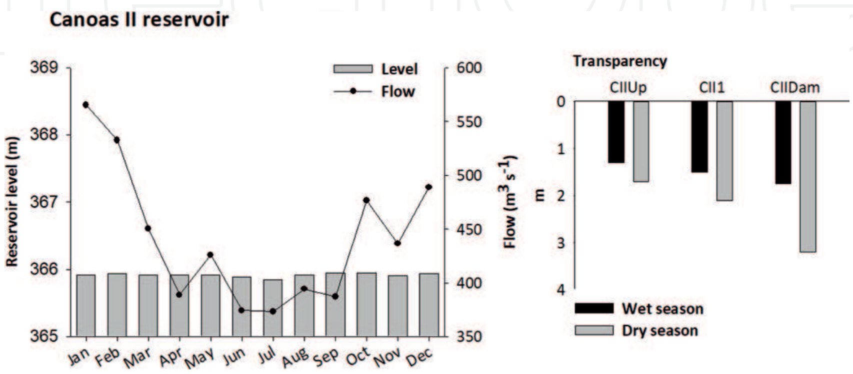

Figure 14. Variation of water level and flow (monthly averages) and transparency (wet and dry seasons) in Canoas II reservoir.

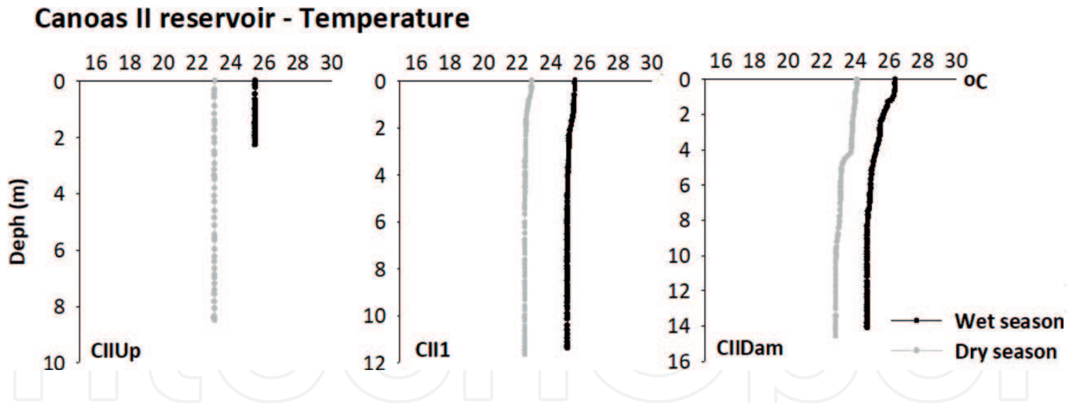

Figure 15. Temperature profiles in Canoas II reservoir sampling sites during wet and dry seasons.

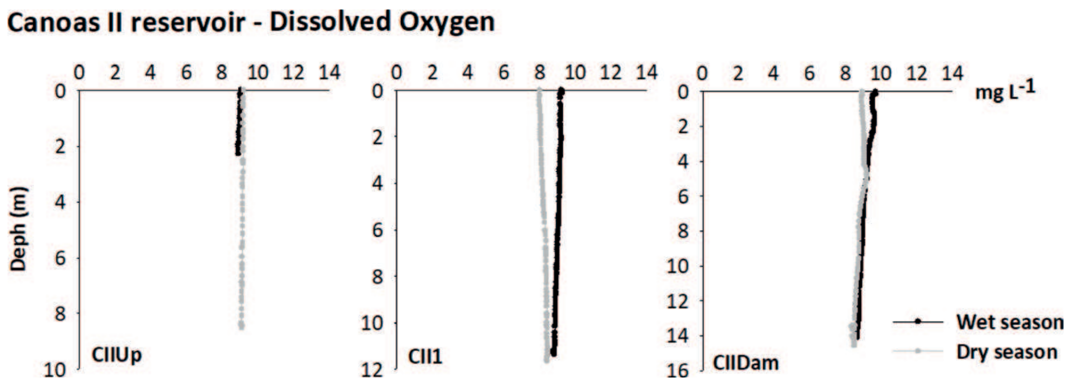

Figure 16. Dissolved oxygen profiles in Canoas II reservoir sampling sites during wet and dry seasons.

5. Inter-reservoir variability

The Paranapanema River reservoir cascade exhibits a wide variability of conditions, when compared the distinct physical dimensions. Salto Grande, the oldest reservoir (60 years), is smaller, with area of 12 km^2; perimeter of 81 km; volume of 63 hm^3; and a very low water retention time, only 2 days. Conversely, the Capivara reservoir (40 years) has the highest area, perimeter, and volume—576 km^2, 1550 km, and 11,743 hm^3, respectively. Capivara is also the most dendritic reservoir, with a shore line development index of 18.2. The two newer (19 years) reservoirs, Canoas I and Canoas II, have the lowest shore line development index, 6.1. The first reservoir in the series, Jurumirim, has the highest water retention time, annual mean of 400 days, followed by the second, Chavantes, with 335 days. The water accumulated in these two upstream reservoirs is fundamental for the flow control along the entire cascade. For both, there was an increase in water release at the end of the dry season (September and October) to supply bellow hydropower plants and, consequently, a decrease in water retention time. In these two storage reservoirs, as well as in Capivara (retention time of 115 days), there is an accentuated fluctuation in the water level, between 2 and 4 m along the studied year. This annual amplitude can be even higher, depending on the year, up to 9 m in Capivara, but not necessarily coupled to the rain/dry regime [17]. In the other reservoirs, operated as run-of-river systems (retention time between 2 and 17 days), the level fluctuation is minimum (<0.5 m). Data show that flow is intensively manipulated in order to keep the best condition for hydroelectric generation. The absolute flow values tend to increase along the river, as expected, from 181 m^3 s^{-1}

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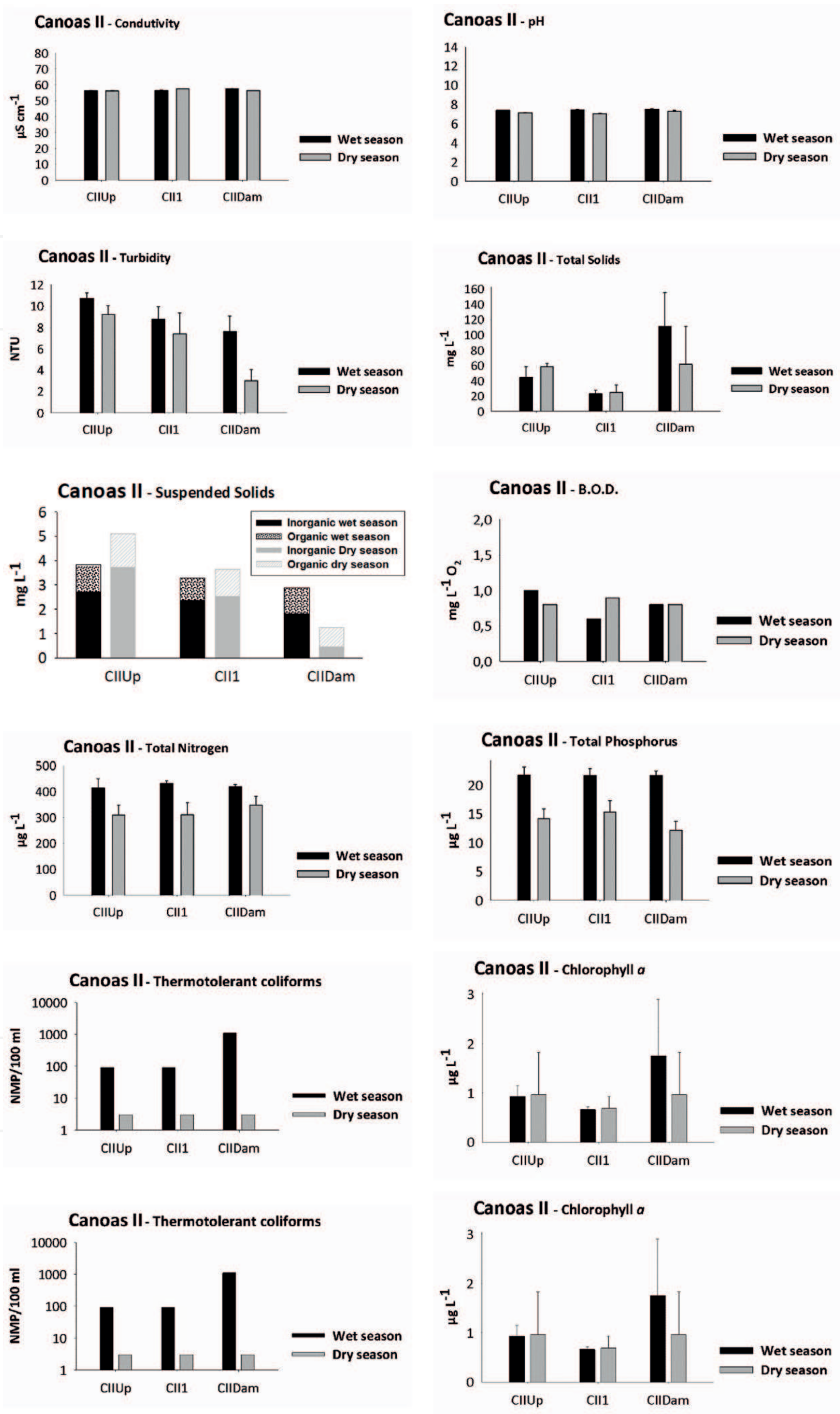

Figure 17. Mean values (+S.D.) of conductivity, pH, turbidity, total and suspended solids, biochemical oxygen demand, total nitrogen, total phosphorus, thermotolerant coliforms and chlorophyll *a* in Canoas II reservoir sampling sites during wet and dry seasons.

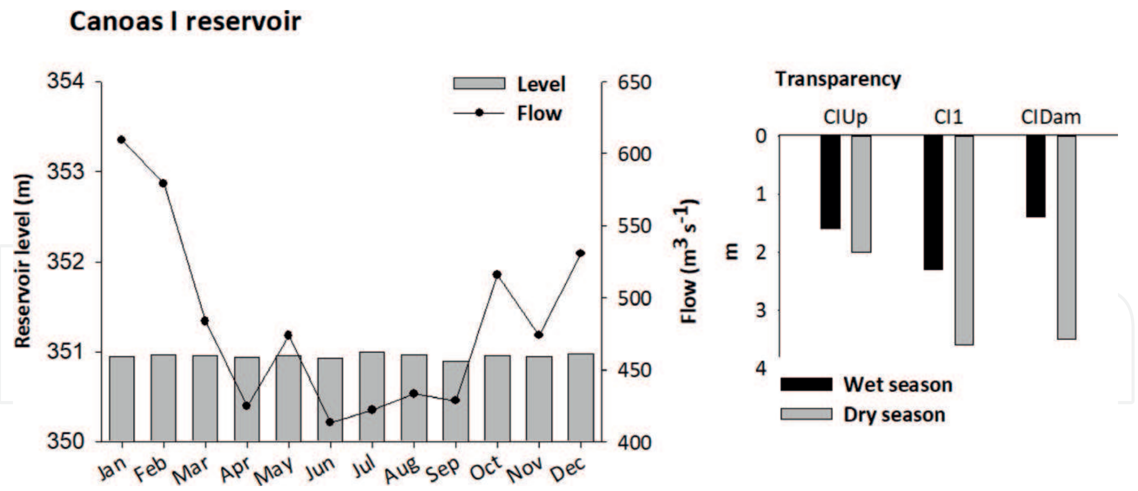

Figure 18. Reservoir level and flow variation throughout the year (monthly average) and water transparency at the Canoas I reservoir sampling sites in the 2011 wet and dry seasons.

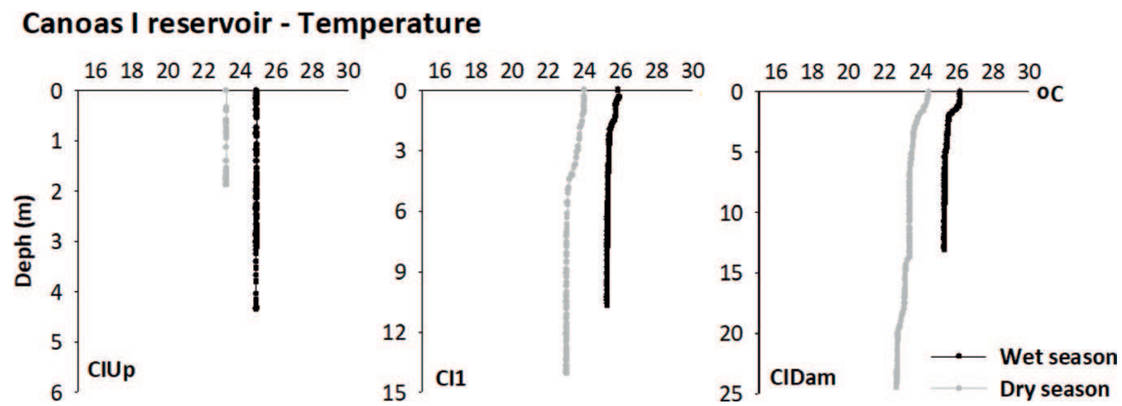

Figure 19. Temperature profiles in Canoas I reservoir sampling sites during wet and dry seasons.

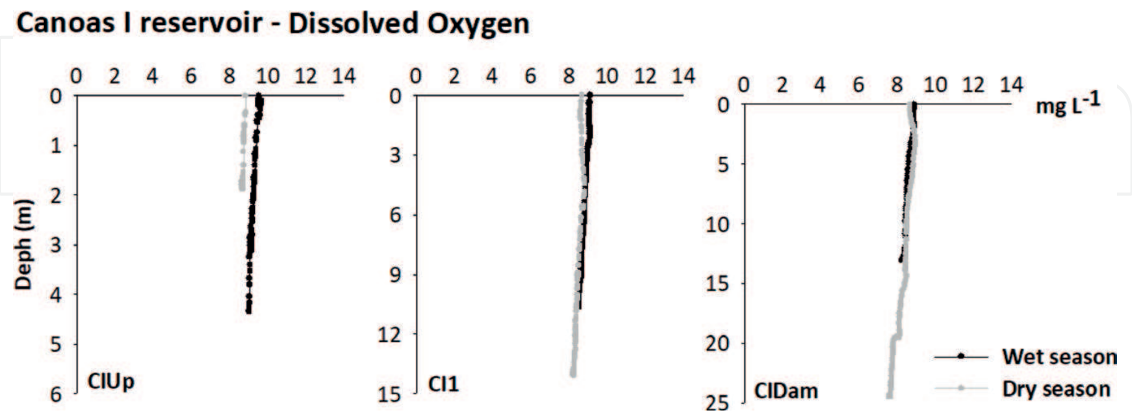

Figure 20. Dissolved oxygen profiles in Canoas I reservoir sampling sites during wet and dry seasons.

registered in Jurumirim (August—dry season) to 1679 $m^3 s^{-1}$ in Rosana (February—rainy season). Ref. [19] analyzed bellow dam releases of Capivara and Taquaruçu reservoirs (ninth and tenth in the cascade) in short periods of time (24 h cycles), showing that differences between

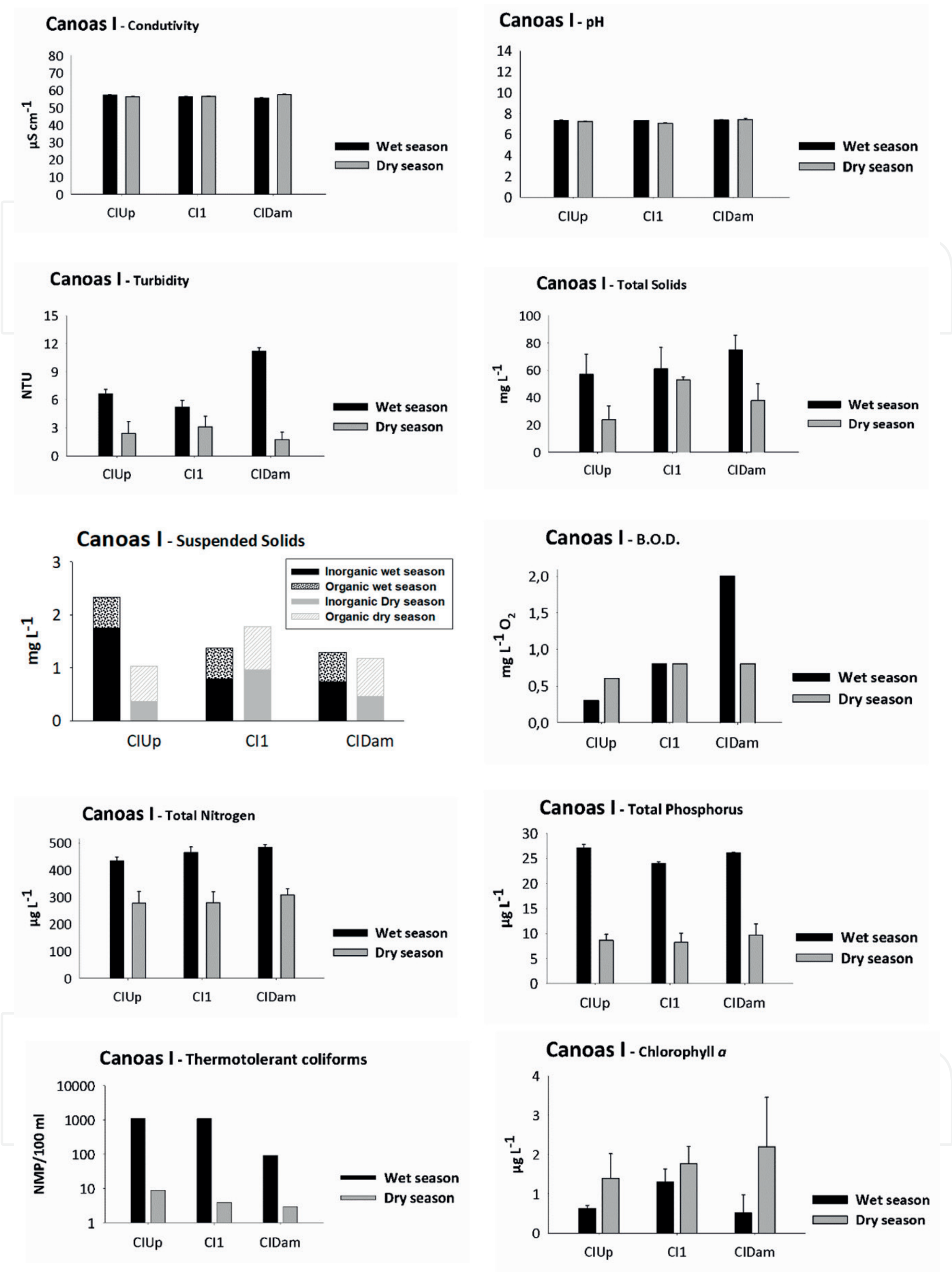

Figure 21. Mean values (mean, +S.D.) of conductivity, pH, turbidity, total and suspended solids, biochemical oxygen demand, total nitrogen, total phosphorus, thermo tolerant coliforms and chlorophyll *a* in Canoas I reservoir sampling sites during wet and dry seasons.

flow peaks reached impressive 1500 $m^3 s^{-1}$. The authors demonstrated that the effects of these hourly discharge variations are significant on the limnological variables' dynamics, especially when intake to the turbines comes from hypolimnion (bottom layers) such as in Capivara

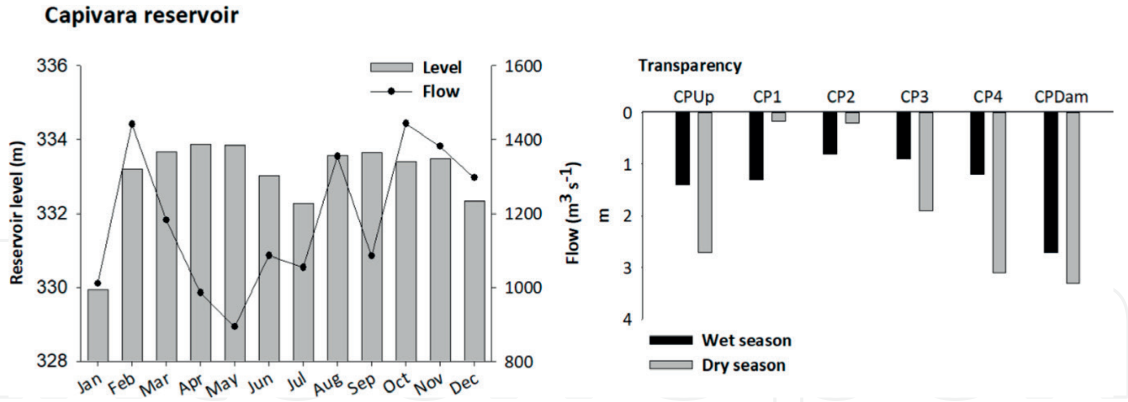

Figure 22. Variation of water level and flow (monthly averages) and transparency (wet and dry seasons) in Capivara reservoir.

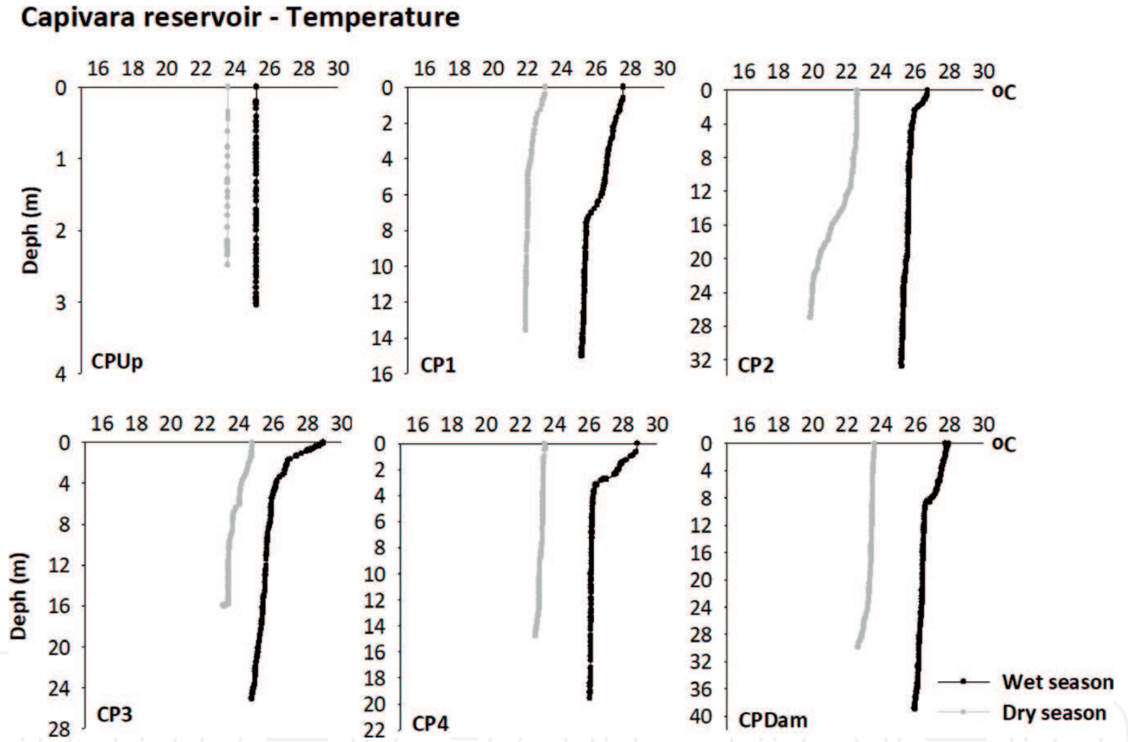

Figure 23. Temperature profiles in Capivara reservoir sampling sites during wet and dry seasons.

dam. In this case, there is a transference of low oxygenated waters, disturbing the limnological and biota rehabilitation of bellow dam river stretches, whose importance has already been evidenced [29–32]. However, this recovery process may not be effective in reservoir cascades, where the distance between consecutive reservoirs is too short. In case of Paranapanema, the longest inter-dam stretch is about 110 km, between Canoas I and Capivara.

The heat accumulation in the reservoir's water mass contributes to an increase of temperature along the cascade. Mean values for the water column varied from 21.4°C (sampling site 12) to 26.9°C (sampling site 33) in wet-summer and from 19.7°C (sampling site 12) to 24.6°C (sampling site 36) in dry-spring. The first corresponds to Chavantes dam, the deepest site in the cascade, and the other value to the two last reservoirs, Taquaruçu and Rosana, respectively.

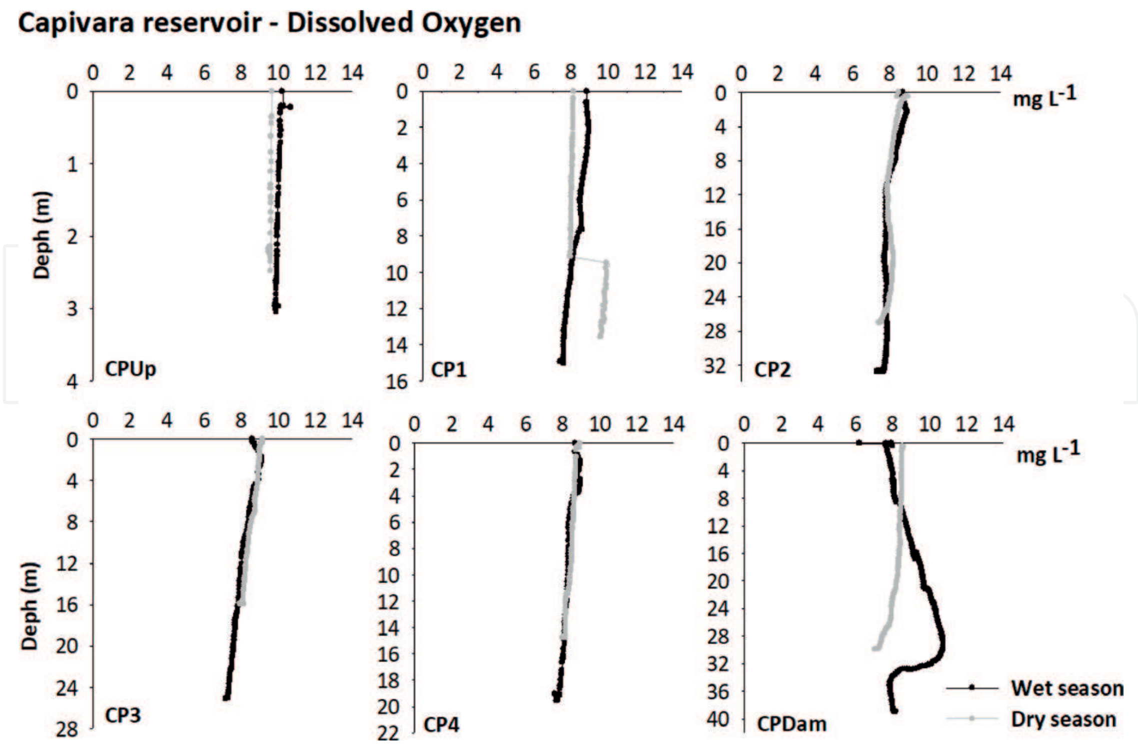

Figure 24. Dissolved oxygen profiles in Capivara reservoir sampling sites during wet and dry seasons.

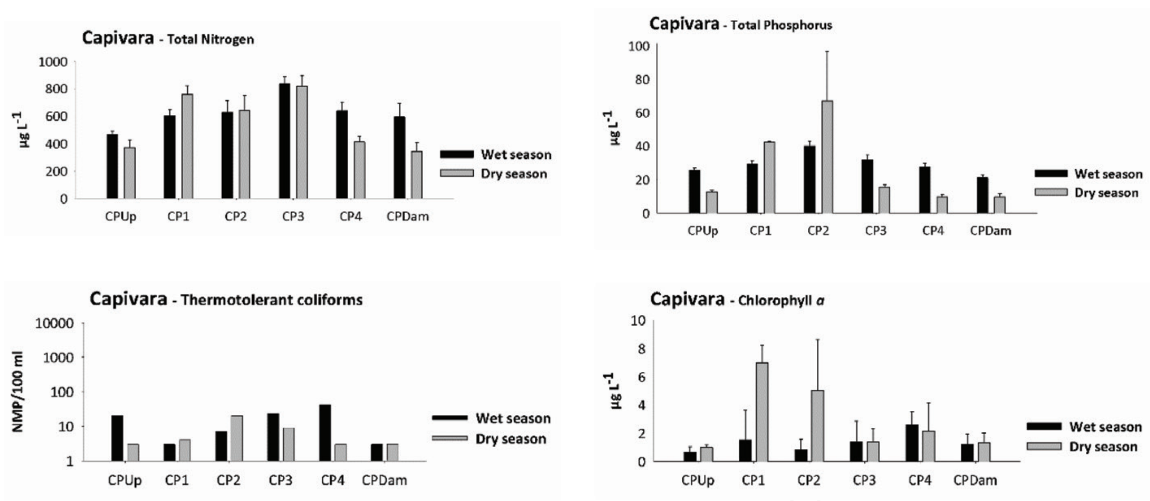

Figure 25. Mean values (+S.D.) of conductivity, pH, turbidity, total and suspended solids, biochemical oxygen demand, total nitrogen, total phosphorus, thermotolerant coliforms and chlorophyll *a* in Capivara reservoir sampling sites during wet and dry seasons.

Principal component analysis, performed to provide an ordination and synthesis of the data set, evidenced the main spatial and temporal trends (**Table 6**; **Figure 34**). The organization during the dry period was mainly represented by Component 1 (explaining 30.7% of data variability) and the wet season by Component 2 (17.6% of data variability). The first component was negatively correlated with transparency and depth, grouping sampling sites (dam zones and central channel sites) of the storage reservoirs: Jurumirim and Chavantes. Sampling stations of Salto Grande, Capivara and Rosana, were associated to the positive side

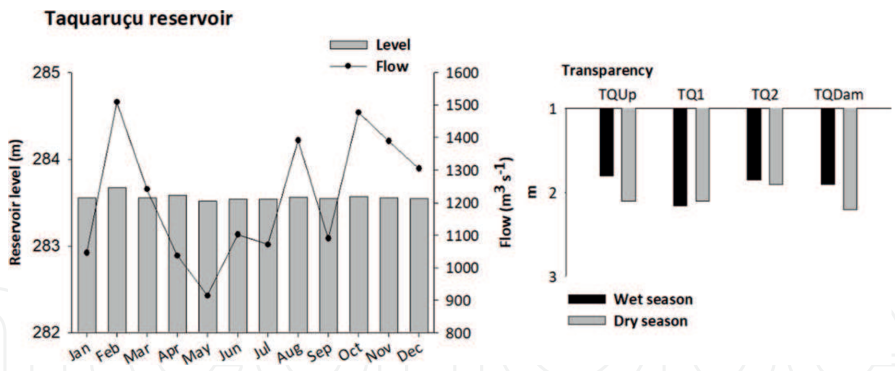

Figure 26. Variation of water level and flow (monthly averages) and transparency (wet and dry seasons) in Taquaruçu reservoir.

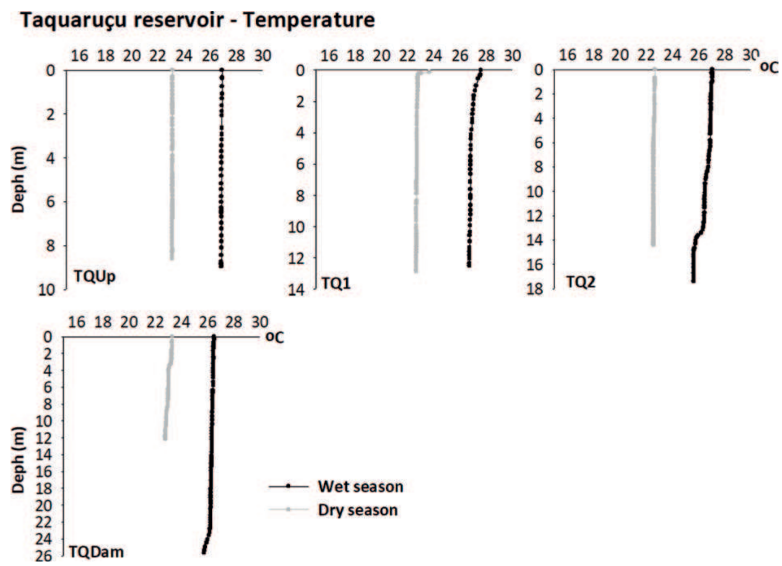

Figure 27. Temperature profiles in Taquaruçu reservoir sampling sites during wet and dry seasons.

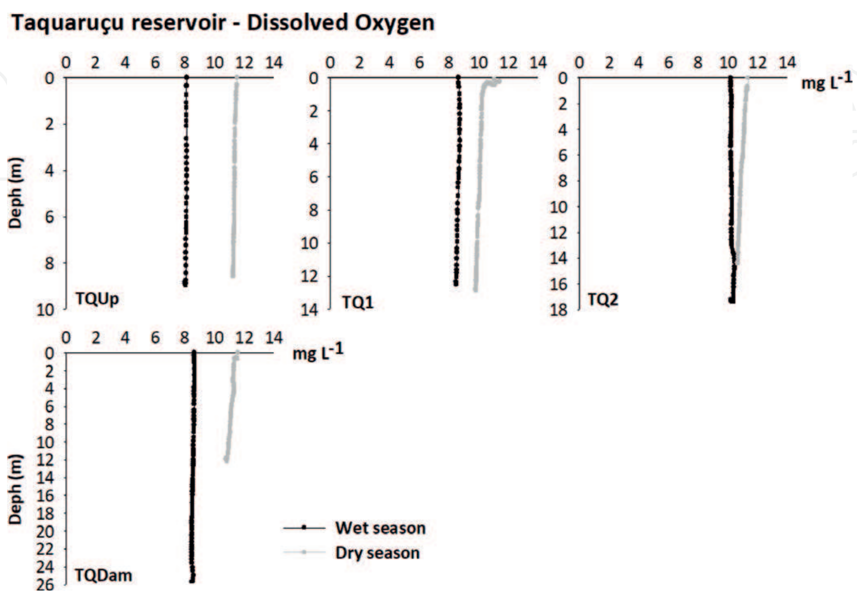

Figure 28. Dissolved oxygen profiles in Taquaruçu reservoir sampling sites during wet and dry seasons.

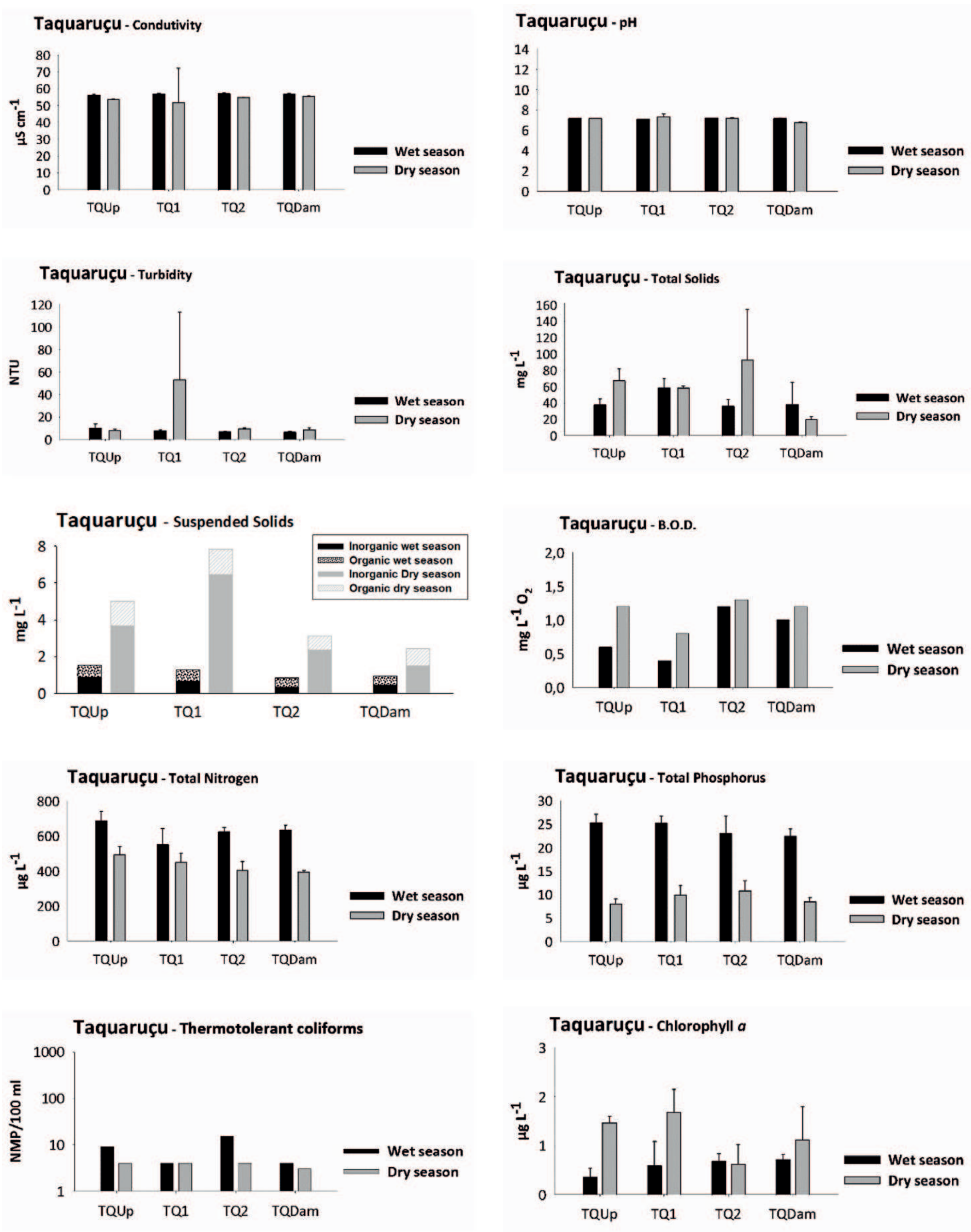

Figure 29. Mean values (mean, +S.D.) of conductivity, pH, turbidity, total and suspended solids, biochemical oxygen demand, total nitrogen, total phosphorus, thermo tolerant coliforms and chlorophyll *a* in Taquaruçu reservoir sampling sites during wet and dry seasons.

of Component 1, determined by suspended solids, nutrients, and chlorophyll (more eutrophic conditions). During the wet season, most sampling stations were associated to the negative side of Component 2, correlated with higher values of temperature, pH, nutrients, and lower concentrations of dissolved oxygen.

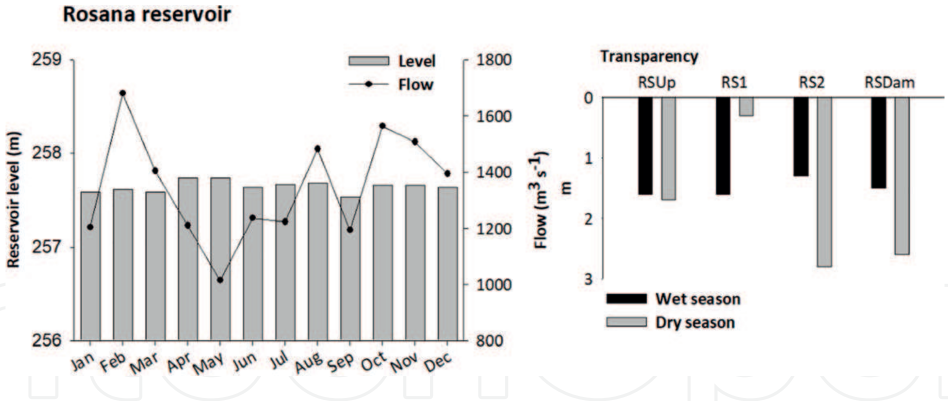

Figure 30. Variation of water level and flow (monthly averages) and transparency (wet and dry seasons) in Rosana reservoir.

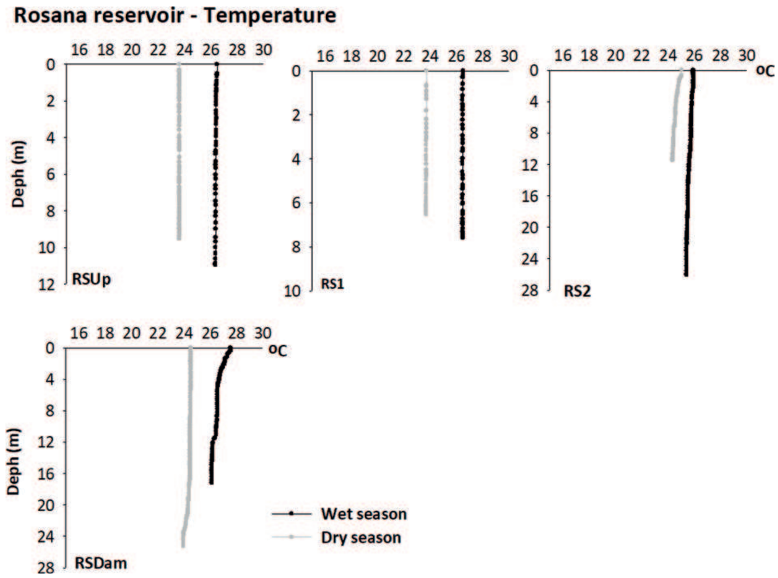

Figure 31. Temperature profiles in Rosana reservoir sampling sites during wet and dry seasons.

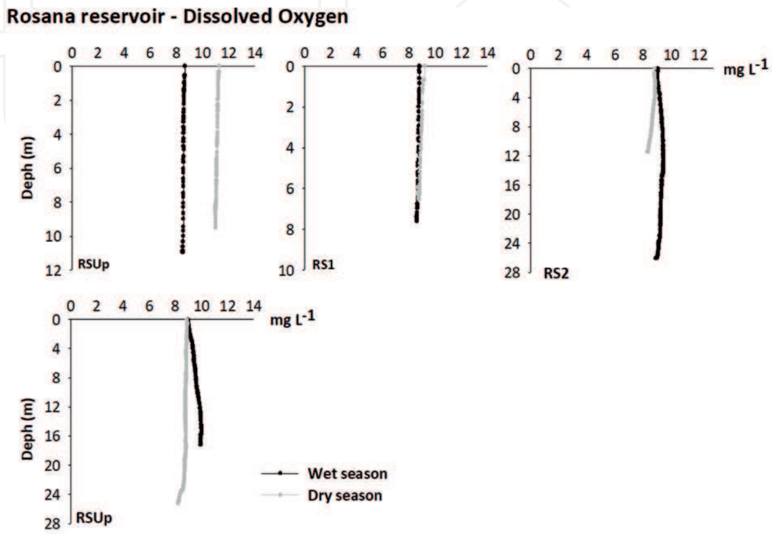

Figure 32. Dissolved oxygen profiles in Rosana reservoir sampling sites during wet and dry seasons.

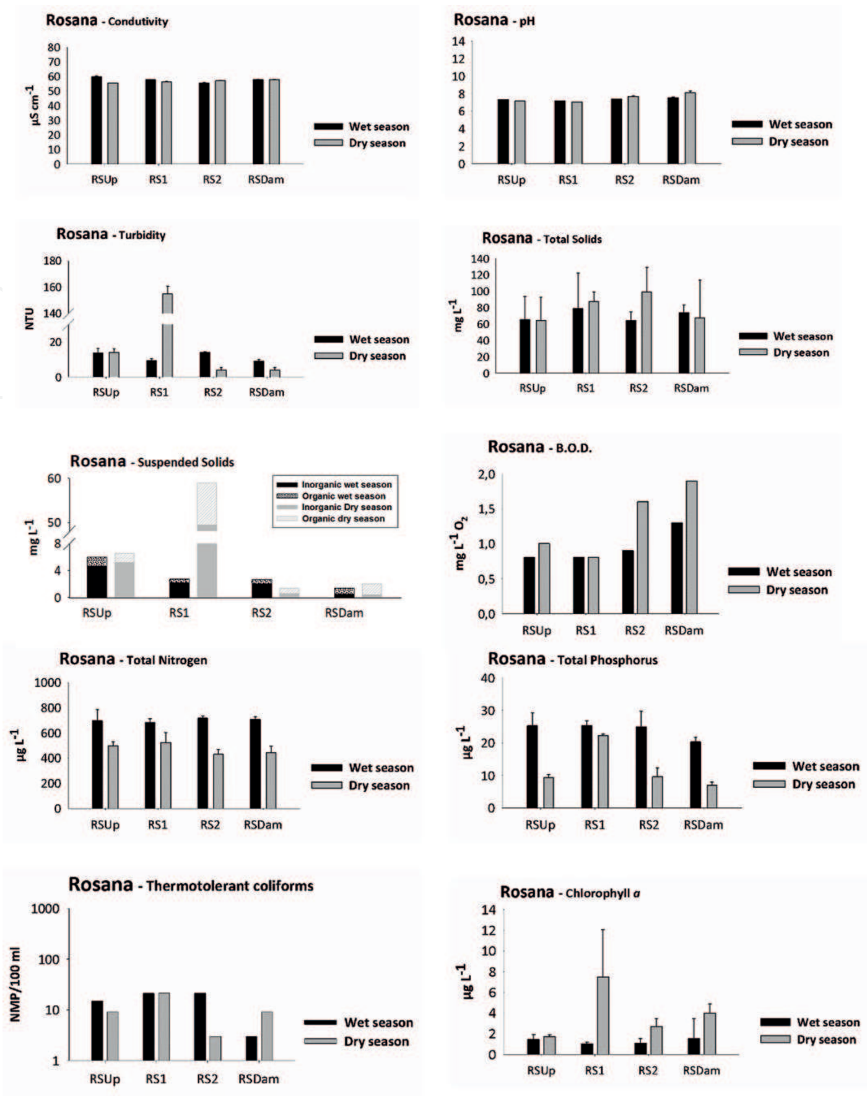

Figure 33. Mean values (mean, + S.D.) of conductivity, pH, turbidity, total and suspended solids, biochemical oxygen demand, total nitrogen, total phosphorus, thermotolerant coliforms and chlorophyll *a* in Rosana reservoir sampling sites during wet and dry seasons.

The predominant trophic state classification for the studied reservoirs was ultraoligotrophic, except for Canoas I, which was oligotrophic. A few results, from a total of 74 individual samples or mean values in case of vertical profiles, were not in conformity with the standard references of the federal legislation for Class 1 waters [28]: 2 values of pH, 6 of turbidity, 1 of chlorophyll, 6 of thermotolerant coliforms, and 19 of total phosphorus. This indicates punctual and isolated sources of degradation. The only exception is phosphorus, above the limit in 25.6% of the measurements. A detailed comparison of the Paranapanema River reservoirs based on distinct water quality and trophic indices is presented by [18]. The study corroborates the good environmental condition of the river but also evidences some negative effects (e.g., phosphorus) associated to the land use intensification—boom of the agrobusiness, especially for the reservoirs in the middle river basin during the wet season [17].

Another potential eutrophication problem is the expansion of cage-aquaculture [33]. This activity has been intensified in the recent years, mainly in Canoas I and Canoas I reservoirs.

Limnological variables	PC1 (30.7%)	PC2 (17.6%)
Transparency	−0.405	−0.020
Depth	−0.125	0.052
Temperature	0.061	−0.545
pH	0.022	−0.420
Conductivity	0.100	−0.184
Turbidity	0.403	0.095
Dissolved oxygen	−0.048	0.251
Biochemical oxygen demand	0.143	0.124
Total solids	0.199	0.061
Inorganic suspended solids	0.415	0.191
Organic suspended solids	0.390	0.165
Total nitrogen	0.225	−0.372
Total phosphorus	0.284	−0.381
Chlorophyll *a*	0.343	0.184
Thermotolerant coliforms	0.089	−0.130

Table 6. Principal component analysis scores (PC1 and PC2) based on the limnological characteristics of the Paranapanema River reservoir cascade.

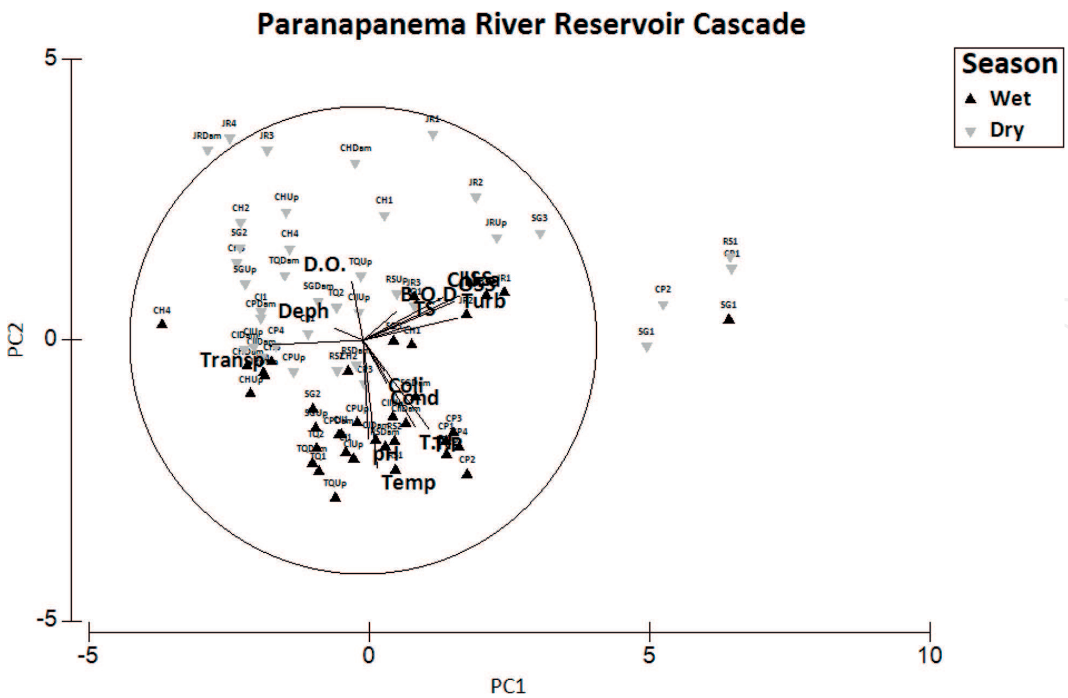

Figure 34. Graphical results of the principal component analysis (PC1 and PC2) of Paranapanema River reservoir cascade based on the limnological variables and using the seasonality as the factor or ordination. For abbreviations see **Tables 1–3**.

http://dx.doi.org/10.5772/intechopen.80632

6. Intra-reservoir spatial organization—longitudinal dimension

Conspicuous longitudinal gradients (upstream lotic zone → lacustrine dam zone) were observed in the studied reservoirs, especially for the larger storage ones. Classical studies pointed out that compartmentalization enhances the spatial and temporal complexity of reservoirs [5, 13, 34]. This structural characteristic has been verified for several Brazilian reservoirs [7, 10–12, 35, 36].

The Secchi disk transparency, a very simple (easy and cheap) measurement, but limnologically not trivial, is a robust indicator of the presence of distinct water masses along the main axis of a reservoir. In Jurumirim, we registered a clear increasing of transparency toward the dam, about five times in wet season and nine times in dry season. The opposite trend, a longitudinal decrease, occurred for turbidity and suspended solids.

Other variables that indicate well-defined longitudinal gradients were nitrogen, phosphorus, and chlorophyll, whose concentrations reduce toward the dam.

The Chavantes reservoir exhibits an additional spatial complexity due to the existence of "two longitudinal axes," instead of one. An axis corresponds to the former Itararé River Valley (stations CH1, CH2, and CH3), laterally inserted into the Paranapanema River, the other axis (stations CHUp, CH4, and CHDam). In general, variables such as turbidity, suspended solids, total nitrogen, and total phosphorus (in this case only for wet season) exhibited lower values in the Paranapanema axis, compared to the Itararé axis. In both spatial axes, there was a transparency increase toward the dam, with higher values in the Paranapanema, 6.9 and 8.7 times in wet and dry seasons, respectively.

Different from the previously mentioned reservoirs, in Canoas I, Canoas II, Taquaruçu, and Rosana, all run-of-river systems (retention time between 4 and 17 days), the longitudinal gradient was moderate or even a relative homogeneous condition was found. For instance, in Taquaruçu during both campaigns and in Canoas II and Rosana during the wet campaign, the maximum difference along the reservoirs' main axes was only 0.4 m, despite the distance of tens of kilometers between sampling points. For these reservoirs, the magnitude of changes seems to be more relevant on the temporal scale—alternating between dry (winter/early spring) and rainy (late spring/summer) periods. Nutrient concentrations (nitrogen and total phosphorus), for instance, are clearly higher in the wet season.

Very low, and probably transient, transparency in some sampling sites of Rosana and Capivara during the dry season can be attributed to atypical rain events in the upstream areas of both reservoirs immediately (2 days) before sampling. The sediment loads introduced by tributaries (Cinzas River in Capivara and Pirapó River in Rosana) resulted in a remarkable local increase in mineral turbidity (~155 NTU).

The results of Capivara, whose water retention time of 115 days is higher than in run-of-river and lower than in upstream storage reservoirs, demonstrate the importance of both spatial compartmentalization and seasonal variation on the physical and chemical characteristics. The spatial variability is determined by longitudinal gradient and tributary rivers' (more eutrophic waters') contributions. The concentrations of nutrients (nitrogen and phosphorus) varied widely among the different compartments of the reservoir. The main tributary of the Capivara reservoir is the Tibagi River (its mouth corresponds to the sampling site CP3), which drains agricultural areas intensively cultivated and is the second largest river in the whole basin, after the Paranapanema.

In the Salto Grande reservoir, despite its small size, the spatial complexity is high, due to the influence of a large reservoir (Chavantes) located upstream and the entrance of secondary tributary river (Pardo River), which introduces high loads of nutrients and suspended solids [1, 17, 37]. The transparency of water, for example, is higher in the upstream region (SGUp and SG2) and lower at the mouth of the Pardo River (SG1), with a difference of 3.3 m and 2.9 in wet and dry season, respectively. The opposite pattern of variation, as expected, was verified for turbidity and suspended solids, with values lower than 5 NTU at SGUp and SG2 (wet and dry seasons) and higher than 80 NTU in SG1 (wet season).

In addition to the river's prevalent longitudinal pattern of physical, chemical, and biotic organization [38], the results of Capivara and Salto Grande are very important to show that the lateral dimension, mostly the effects of tributaries' entrance, should not be neglected if one aims to understand the spatial structure and functional processes of large rivers and reservoir ecosystems.

7. Intra-reservoir spatial organization: vertical dimension

The development of thermal stratification, commonly followed by chemical differences, is a profound modification in riverine ecosystems after damming. Interactions with the atmosphere are enhanced due to the increase of the exposed surface area, higher water retention time, and reduction in advective transport of mass and energy. In the Paranapanema reservoir cascade, we observed a strong thermal stratification in Chavantes, the deepest reservoir, during summer. Maximum difference between epilimnion (25°C) and hypolimnion (18°C) layers, of 7°C, was verified at the sampling point near the dam (CH12). Other two sampling sites, CH3 and CH4, in the central channel also exhibited a well-defined thermal stratification. The oxygen along the water column decreased approximately from 3 to 4 mg L^{-1}.

During summer, we also observed stratification at the dam zone of the other two storage reservoirs, Jurumirim and Capivara, with differences between layers of 3 and 2°C, respectively. In Jurumirim, particularly, there was a remarkable drop (about 5 mg L^{-1}) of dissolved oxygen in deeper layers, certainly the effect of an extended period (late spring/summer) of stratification. The upstream compartments of these larger reservoirs (especially CHUp, CPUp) were characterized by homogeneous physical and chemical profiles, indicating a continuous mixture regime.

Surficial stratification, probably ephemeral, due to intense solar heating in summer was observed in some sampling sites (e.g., SGDam, SG3, CP3, CP4).

For the other reservoirs, run-of-river systems, isothermal conditions or a slightly gradual decrease of temperature with depth was observed, resulting in a homogeneous or relatively homogeneous distribution of the other variables measured along the water column.

8. Concluding remarks

As previously mentioned, this study has a "historical" importance, because since then it was established a permanent limnological and water quality monitoring program in the Paranapanema River reservoir cascade. Eight consecutive years of continuous and standardized evaluation produced valuable information, which has subsidized important management actions in this large water basin of southeast Brazil.

The larger (and dendritic) storage reservoirs exhibit a well-marked longitudinal compartmentalization, considerable water level fluctuation as well as summer thermal stratification in the central channel and lacustrine zones toward the dam, followed by oxygen decrease in bottom layers. Conversely, run-of-river reservoirs are morphometrically simpler, the spatial complexity is moderate with minor variation in the water level and a continuous mixing regime. Nevertheless, the second kind of reservoirs is less resilient to seasonal changes (dry-wet periods).

In addition to the expected upstream-dam gradients, the lateral component of the spatial heterogeneity was very important for some reservoirs, determined basically by the entrance of tributary rivers which transport considerable loads of nutrients and sediments from intensively cultivated lands.

Finally, it is important to highlight that most measurements were in conformity with the federal standard references for Class 1 waters (good water quality). Exceptions are locally restricted. This fact is corroborated by the predominant low trophic state (77% of ultraoligotrophic determinations). The Paranapanema River reservoir cascade is a strategic regional hydric resource. This is particularly important for the state of São Paulo, the most populous and industrialized state of the country, where important fluvial systems are hypereutrophic and heavily polluted [39] and the metropolitan area of São Paulo city is already facing recurrent water crises, in quantity and quality.

Acknowledgements

The authors are grateful to Dr. Norberto Castro Vianna, from Duke Energy, Geração Paranapanema, the company in charge of hydropower generation in the Paranapanema reservoir cascade (presently China Three Gorges, Brazil) that provides financial support and technical partnership. We also thank the graduate and undergraduate students that kindly helped during field work expeditions and laboratory analyses and the Foundation of the Biosciences Institute—State University of São Paulo (FUNDIBIO) for administrative support (contract 0100015003).

Conflict of interest

None.

Appendix 1: Limnological variables (mean values for the water column) measured in the Paranapanema River reservoir cascade during the wet season

Wet season	Secchi (m)	Deph (m)	Temp. (°C)	pH	Cond. ($\mu S\ cm^{-1}$)	Turb. (NTU)	DO ($mg\ L^{-1}$)	BOD ($mg\ L^{-1}\ O_2$)	TS ($mg\ L^{-1}$)	Inorg. SS. ($mg\ L^{-1}$)	Org. SS ($mg\ L^{-1}$)	TN ($\mu g\ L^{-1}$)	TP ($\mu g\ L^{-1}$)	Chl. *a* ($\mu g\ L^{-1}$)	Thermo Coli (NMP/100 mL)
JR1	0.6	5.1	24.1	7.1	45.5	26.0	9.1	1.3	53.3	8.5	2.6	382.7	20.7	2.6	93
JRUp	0.6	15.0	23.7	7.2	44.4	43.0	8.7	1.0	75.0	6.9	1.7	424.5	24.1	2.6	4
JR2	0.9	18.0	24.1	7.4	60.6	25.5	9.4	1.2	97.0	4.6	1.6	288.9	17.0	2.9	4
JR3	1.0	23.3	23.5	7.4	49.8	17.3	8.8	1.6	89.7	3.3	1.0	349.4	13.3	2.3	4
JR4	2.3	28.8	24.3	7.3	53.6	3.7	8.7	0.2	71.0	0.7	0.9	304.6	11.2	0.8	15
JRDam	3.0	32.0	24.8	7.6	52.3	1.7	8.6	0.8	68.3	0.7	1.2	283.2	13.6	1.0	11
CH1	0.8	17.8	23.7	7.2	54.9	28.5	8.7	0.9	36.0	4.4	1.3	382.6	19.0	1.1	<3
CH2	1.7	24.0	24.3	7.6	53.2	14.8	9.2	1.2	46.0	1.5	1.0	406.0	16.6	1.0	<3
CH3	3.8	48.0	22.6	7.4	54.1	7.0	8.3	1.3	56.3	1.0	0.7	393.0	17.5	0.4	4
CHUp	2.7	10.0	25.4	7.6	50.7	2.0	10.1	0.5	32.7	1.0	0.8	303.3	14.2	0.9	43
CH4	3.7	45.0	22.3	7.2	51.0	2.5	9.6	0.8	11.3	0.4	0.5	301.9	12.8	0.5	4
CHDam	5.5	74.4	21.4	7.2	51.6	5.4	7.7	1.2	35.3	0.6	0.9	372.2	39.8	0.5	4
SGUp	3.5	3.5	25.5	7.4	54.2	2.3	9.4	0.9	55.3	1.6	0.7	349.9	21.6	1.1	>1100
SG1	0.2	4.4	24.2	7.4	62.7	85.4	10.2	1.2	42.3	32.5	7.1	480.5	36.9	10.3	>1100
SG2	3.5	6.4	25.7	7.4	53.3	1.4	9.2	2.8	51.3	0.5	0.6	367.0	17.7	1.8	>1100
SG3	0.8	4.9	25.0	7.2	47.9	16.7	9.2	1.2	57.0	2.7	1.3	263.4	20.9	0.6	93
SGDam	1.6	10.2	25.1	7.4	57.1	19.6	9.4	0.8	73.0	5.0	1.3	418.8	22.4	0.7	43
CIIUp	1.3	8.0	25.5	7.4	56.2	10.7	9.0	1.0	44.7	2.7	1.1	414.4	21.8	0.9	93
CII1	1.5	12.4	25.1	7.4	56.5	8.8	9.0	0.6	23.0	2.4	0.9	432.2	21.7	0.7	93
CIIDam	1.7	13.0	25.2	7.5	57.4	7.6	9.1	0.8	110.7	1.8	1.0	418.5	21.7	1.8	>1100

Wet season	Secchi (m)	Deph (m)	Temp. (°C)	pH	Cond. (µS cm⁻¹)	Turb. (NTU)	DO (mg L⁻¹)	BOD (mg L⁻¹ O_2)	TS (mg L⁻¹)	Inorg. SS. (mg L⁻¹)	Org. SS (mg L⁻¹)	TN (µg L⁻¹)	TP (µg L⁻¹)	Chl. *a* (µg L⁻¹)	Thermo Coli (NMP/100 mL)
CIUp	1.6	4.0	24.9	7.3	57.3	6.7	9.3	0.3	57.0	1.7	0.6	434.0	27.1	0.6	>1100
CI1	2.3	9.0	25.4	7.3	56.1	5.2	8.8	0.8	61.0	0.8	0.6	463.8	23.9	1.3	>1100
CIDam	1.4	14.2	25.5	7.4	55.5	11.2	8.6	2.0	74.7	0.7	0.5	485.0	26.1	0.5	93
CPUp	1.4	3.0	25.2	7.3	55.3	9.8	10.0	1.2	69.7	0.4	0.5	468.5	25.5	0.6	21
CP1	1.3	16.0	25.6	7.1	63.9	14.2	8.0	1.2	81.7	3.0	1.0	602.2	29.3	1.5	<3
CP2	0.8	33.0	25.9	7.4	65.2	25.2	8.2	1.3	79.7	3.4	0.9	626.1	40.2	0.8	7
CP3	0.9	26.0	25.9	7.0	48.2	18.8	8.1	0.6	94.3	2.9	1.3	834.7	31.9	1.4	23
CP4	1.2	20.0	26.4	7.3	56.1	12.6	8.3	0.4	104.3	4.2	1.2	638.7	27.7	2.6	43
CPDam	2.7	40	26.6	7.2	55.5	8.9	8.9	0.8	92.0	1.1	0.6	592.9	21.1	1.2	<3
TQUp	1.8	9.5	26.8	7.1	56.4	9.8	8.1	0.6	37.7	0.9	0.6	686.3	25.3	0.3	9
TQ1	2.1	13.0	26.9	7.1	56.9	7.7	8.6	0.4	58.3	0.7	0.6	551.9	25.2	0.6	4
TQ2	1.8	18.0	24.4	7.2	57.0	6.6	10.3	1.2	36.0	0.3	0.5	624.3	23.0	0.7	15
TQDam	1.9	26	26.3	7.2	56.9	6.4	8.6	1.0	38.0	0.5	0.5	634.4	22.4	0.7	4
RSUp	1.6	11.0	26.4	7.3	60.0	13.7	8.6	0.8	65.3	4.6	1.4	696.4	25.2	1.4	15
RS1	1.6	8.5	26.5	7.2	57.6	9.4	8.7	0.8	78.7	2.2	0.6	683.1	25.3	1.0	21
RS2	1.3	27.0	25.6	7.3	55.4	14.0	9.2	0.9	64.0	2.0	0.6	716.0	24.9	1.1	21
RSDam	1.5	18.0	26.5	7.6	57.7	9.0	9.6	1.3	74.0	0.5	0.9	707.2	20.3	1.5	<3

Values not in conformity with the Class 1 standard references in gray.

Appendix 2: Limnological variables (mean values for the water column) measured in the Paranapanema River reservoir cascade during the dry season

Dry season	Secchi (m)	Deph (m)	Temp. (°C)	pH	Cond. (µS cm^{-1})	Turb. (NTU)	DO (mg L^{-1})	BOD (mg L^{-1} O_2)	TS. (mg L^{-1})	Inorg. SS (mg L^{-1})	Org. SS (mg L^{-1})	TN (µg L^{-1})	TP (µg L^{-1})	Chl. *a* (µg L^{-1})	Thermo Coli (NMP/100 mL)
JR1	0.4	4.7	20.8	5.1	51.2	3.8	11.3	1.6	67.3	8.2	1.6	404.3	17.3	1.6	9
JRUp	0.5	13.0	21.5	6.5	57.3	33.1	11.4	1.6	85.7	5.7	1.2	604.6	17.6	2.6	15
JR2	0.6	18.0	21.5	6.4	50.4	36.3	10.9	0.8	89.3	5.7	1.6	404.8	17.6	3.5	11
JR3	2.4	25.0	21.2	6.0	53.9	32.1	11.3	0.8	78.3	1.0	0.6	217.3	4.1	0.7	23
JR4	3.4	25.0	21.1	4.6	56.3	5.1	10.3	0.6	51.7	0.9	0.9	259.4	6.5	0.9	23
JRDam	3.5	29.0	21.3	6.1	51.9	3.7	11.2	1.1	62.7	0.7	0.6	214.7	3.1	1.4	43
CH1	0.9	15.0	21.0	6.6	55.3	21.6	9.8	1.2	77.3	3.7	0.9	302.0	9.0	1.2	15
CH2	3.2	23.0	21.0	6.6	56.1	5.4	10.8	0.6	61.3	0.9	0.6	271.7	6.2	1.3	21
CH3	4.1	40.0	20.5	7.1	55.6	5.4	7.8	1.6	66.7	1.2	0.5	264.1	6.0	0.7	9
CHUp	2.6	16.0	22.0	6.7	50.8	7.2	10.2	0.8	63.3	2.4	1.0	249.4	5.9	1.3	23
CH4	1.4	37.8	20.9	7.1	51.1	13.6	7.5	1.1	68.3	2.3	0.5	197.9	8.8	0.5	3
CHDam	4.2	79.2	19.7	6.9	54.1	5.6	7.5	1.5	78.7	12.7	3.1	264.0	5.3	2.0	4
SGUp	2.3	2.3	22.4	6.8	54.8	3.1	8.8	0.6	60.7	0.6	0.5	254.2	5.2	1.0	9
SG1	0.5	4.0	24.2	7.1	67.9	53.2	7.8	1.9	90.3	20.5	5.7	428.0	27.2	2.3	23
SG2	3.4	5.8	22.7	7.1	54.6	3.9	9.9	1.5	43.7	1.0	0.5	190.8	5.2	1.5	9
SG3	0.4	2.7	23.9	7.0	52.9	33.6	8.5	1.4	76.0	10.1	2.5	206.9	11.8	6.1	23
SGDam	2.4	10.7	23.3	7.1	55.8	7.7	8.7	1.2	57.7	2.0	0.8	283.1	8.5	1.6	<3
CIIUp	1.7	9.5	23.0	7.1	56.2	9.2	9.1	0.8	58.7	3.7	1.4	308.8	14.1	1.0	<3
CII1	2.1	12.6	22.5	7.0	57.4	7.4	8.3	0.9	24.7	2.5	1.1	310.0	15.3	0.7	<3
CIIDam	3.2	15.5	23.2	7.3	56.4	3.0	8.8	0.8	61.7	0.4	0.8	346.8	12.1	1.0	<3

Dry season	Secchi (m)	Deph (m)	Temp. (°C)	pH	Cond. (µS cm⁻¹)	Turb. (NTU)	DO (mg L⁻¹)	BOD (mg L⁻¹ O_2)	TS. (mg L⁻¹)	Inorg. SS (mg L⁻¹)	Org. SS (mg L⁻¹)	TN (µg L⁻¹)	TP (µg L⁻¹)	Chl. *a* (µg L⁻¹)	Thermo Coli (NMP/100 mL)
CIUp	2.0	2.0	23.2	7.2	56.3	2.4	8.9	0.6	23.7	0.4	0.7	278.6	8.6	1.4	9
CI1	3.6	14.9	23.2	7.0	56.6	3.1	8.5	0.8	52.7	1.0	0.8	279.0	8.2	1.8	4
CIDam	3.5	25.2	23.2	7.4	57.5	1.7	8.3	0.8	37.7	0.5	0.7	306.9	9.7	2.2	<3
CPUp	2.7	2.7	23.5	7.1	57.3	2.8	8.0	1.2	56.0	0.2	0.9	371.4	12.9	1.0	<3
CP1	0.2	12.5	22.1	7.0	55.0	144.5	8.4	1.9	113.7	39.7	4.5	760.7	42.4	7.0	4
CP2	0.2	27.3	21.3	6.8	58.3	88.7	8.1	1.6	113.7	17.3	2.6	640.7	67.2	5.0	20
CP3	1.9	16.5	23.8	7.1	48.3	11.0	8.5	0.5	74.0	1.7	0.9	818.7	15.6	1.4	9
CP4	3.1	16.8	23.2	7.3	54.0	3.2	8.4	0.8	57.3	0.5	0.6	413.8	9.8	2.2	<3
CPDam	3.3	29.5	23.3	7.2	53.1	2.8	9.6	0.4	174.7	0.3	0.8	343.2	9.8	1.3	<3
TQUp	2.1	9.5	23.1	7.2	53.8	7.9	11.3	1.2	67.0	3.7	1.3	494.8	8.0	1.5	4
TQ1	2.1	12.8	23.0	7.3	51.7	53.0	8.5	0.8	58.7	6.5	1.4	450.0	9.9	1.7	4
TQ2	1.9	15.0	22.6	7.2	54.8	9.5	9.4	1.3	92.7	2.4	0.8	403.9	10.8	0.6	4
TQDam	2.2	16.0	23.0	6.8	55.5	8.3	11.1	1.2	19.7	1.5	0.9	395.3	8.5	1.1	<3
RSUp	1.7	11.9	23.6	7.2	55.3	13.9	11.1	1.0	64.3	5.1	1.4	498.6	9.3	1.7	9
RS1	0.3	7.0	23.7	7.0	56.3	154.8	8.9	0.8	87.3	49.5	9.4	521.8	22.2	7.5	21
RS2	2.8	13.4	24.6	7.7	57.0	4.0	8.7	1.6	99.3	0.6	0.8	429.2	9.5	2.7	<3
RSDam	2.6	25.9	24.4	8.1	57.7	3.9	8.7	1.9	67.7	0.4	1.6	443.6	6.8	4.0	9

Values not in conformity with the Class 1 standard references in gray.

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