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Water quality indices as a tool for evaluating water quality and effects of land use in a tropical catchment

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Abstract

Human actions are degrading water quality, affecting the health of ecosystems and the availability of potable water for human consumption. Therefore, the monitoring of water systems is essential for recovery and management purposes. This study aimed to investigate the water quality in the environmental protection area (EPA) of Itupararanga Reservoir (Brazil) using water quality indices, pointing out land uses that contributing to the deterioration of water quality. The spatial analysis involved the creation of land use and soil maps of the sub-catchment areas of Itupararanga. Water quality index (WQI), trophic state index (TSI), aquatic life index (ALI), index of minimum variables for the maintenance of aquatic life (IMVMAL) and metals pollution potential index (MPPI) were calculated. The land uses which can affect the water quality on long term were identified. TSI (mesotrophic and hypereutrophic) and ALI showed results above the recommended values were. MPPI presented high values for the elements Al, Cr and Fe. Principal component analysis (PCA) showed spatial variability in the reservoir. In conclusion, the sampling sites with lower water quality were Sorocabuçu and Una, followed by Sorocamirim. These sites probably explain the deteriorated water quality found in sampling point Res1 of the reservoir for all indices analysed.

Keywords: water quality index; spatial correlation; geoprocessing; reservoir

Introduction

The human population is estimated to grow by approx. 8.6 billion people in 2030 (WWAP 2015), increasing the demand for agricultural lands, consumables, feedstock and industries. This growing demand quickly rises the pressure on natural resources, leading to severe environmental impacts (Goenka *et al*. 2015).

Several studies tried to quantify the effects of human activities on the environment in order to support protection and management actions, especially concerning the impacts of land use on water quality (Alsharif and Fouad 2012, Giri and Qiu 2016, Rouse and Norton 2016, Silva *et al*. 2017, Noori *et al*. 2018, Xiong and Hoyer 2018).

The degradation of water takes place mainly via discharge of urban and industrial untreated effluents in water systems as well as by pollution of runoff (Small *et al.* 2018, Xiong and Hoyer 2018). Among all the pollutants discharged in water systems, some trace metals such as cadmium (Cd), lead (Pb) and mercury (Hg) have high toxicity and bioaccumulation capacity in different food chain levels (Corbi *et al.* 2018). Furthermore, the increment of nutrients as N and P in water systems causes algal proliferation, contributing to further water quality degradation via toxins production (Prasanna *et al*. 2012, Beghelli *et al*. 2016, Cardoso-Silva *et al.* 2018, Fernandez and McGarvey 2018).

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Indices like the Water Quality Index (WQI), Trophic State Index (TSI), Aquatic Life Index (ALI), Index of Minimum Variables for the Maintenance of Aquatic Life (IMVMAL) and the Metal Pollution Index (MPPI) were created to support the evaluation of water quality as a result of increasing environmental issues (Carlson 1997, NSF 2010, Lamparelli 2004, Prasanna *et al.* 2012, Cetesb 2017 and Kumar *et al*. 2018). . They provide a simple and effective evaluation of the conservation state of aquatic systems worldwide (Kennedy and Thornton 2001, Tyagi *et al.* 2013).

Studies covering diagnosis and monitoring of water quality of multiple purpose reservoirs are needed because they contribute for the optimisation of resources and investments on the management of catchments around the reservoir (Frascareli *et al*. 2015, Beghelli *et al.* 2016, Cardoso-Silva *et al.* 2018). In addition, geographic information systems (GIS) can be used to support these analyses and environmental monitoring in a fast and precise way (Silva *et al*. 2017, Sales *et al*. 2019).

The goals of this investigation were to demonstrate the use of the mentioned indices (WQI, TSI, ALI, IMVMAL, MPPI) to identify land uses that contribute to the deterioration of the water quality of the Itupararanga Reservoir.

Materials and Methods

Study area

The area of investigation is located at the unit of water resources management of Sorocaba and half of the section of Tiete River (UWRM number 10), which includes the rivers Una, Sorocabuçu and Sorocamirim (Fig. 1). The Itupararanga Reservoir is formed by a dam constructed after the confluence of these three rivers, supplying water for one million people (Conceição *et al*. 2015). The reservoir as well as the Sorocabuçu, Sorocamirim and Una rivers are protected by Brazilian State Law nº 10.100/1998 and nº

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11.579/2003, respectively.

Figure 1. Study area and sampling points

The EPA Itupararanga has an average altitude of 919 m and a slope ranging of 0 to 53% (Simonetti *et al*. 2019). The vegetation cover includes native ombrophylous forest on the margins of the right arm of the reservoir as well as silviculture. Concerning the geomorphology, the EPA Itupararanga is on the border between Atlantic Plateau and the Peripheral Depression (Forest Foundation 2010). The lithology is represented by São Roque and Embu domains. The first one is composed by metasedimentary and metabasic rocks and the second by gneisses (Forest Foundation 2010).

Sampling procedures

Surface water (0-20 cm depth) samples were collected from seven sampling sites in the reservoir and Sorocabuçu, Sorocamirim and Una rivers (Fig. 1) using a plastic bucket. All samples were stored in polyethylene bottles until analysis (APHA 1999).

The study was performed in two different periods (December 2016 and August 2017) in order to evaluate the influence of seasonality in the water quality. The average daily rainfall of the first and second periods were 9.2 mm and 2.97, respectively. The annual precipitation for 2016 was 1832.5 mm and for 2017 was 2039.8 mm. The precipitation data were provided by a large Brazilian Aluminium Company (Companhia Brasileira de Alumínio, CBA), which has the right to explore the reservoir via concession.

In-situ and off-site analyses

The physicochemical variables pH, temperature (Temp – ºC), dissolved oxygen (DO –

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mg/L), turbidity (Turb - NTU) and total dissolved solids (TDS - mg/L) were measured using a multiparameter probe Horiba U-50.

The analysis total nitrogen (TN – mg/L), total phosphorous (TP – mg/L) and total residue (TR – mg/L), biological oxygen demand (BOD - mg/L) were performed at the Laboratory of Chemistry and Microbiology of Unesp-ICTS. HACH® kits (Hach, USA) were used for TP determination (method 8190) with a HACH® DR 2800 spectrophotometer. Chl-a was determined by spectroscopic method proposed by Lorenzen (1967) and Wetzel and Likens (1991) via acetone extraction.

TR was determined via the gravimetric method, which consisted in calculate the difference between the dry and initial weight of a beaker with 100 mL of sample at 105 °C in a dry oven. Enumeration of thermotolerant coliforms (TC) was performed in a certified laboratory in the municipality of Sorocaba by APHA Standard Methods (2012).

Analysis of metals in water

Samples taken for total metals (TM) and dissolved metals (DM) determination were acidified using HNO_3 (pH<2) at the day of sampling and kept in refrigerator for preservation purposes until analysis. The samples for DM analysis were previously filtered through 0.45 µm membranes before the acidification step, following the procedure recommended by APHA Standard Methods (1999).

The TM and DM samples were digested using hydrochloric acid (HCl) and nitric acid (HNO3) according to method 3005A of USEPA (1992) in order to oxidise organic matter and release metal ions to the solution. The metals (Al, Fe, Mn, As, Ba, Cd, Co, Cr, Cu, Mo, Ni, Pb and Zn) in digested samples were measured using an Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES Agilent Technologies 700 series).

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Water Quality Indices

Water Quality Index (WQI)

The WQI has scale varying between 0 and 100 and it is broadly used for water quality monitoring by the Environmental Company of São Paulo State, Brazil (Cetesb 2017) originally developed by the National Sanitation Foundation in the United States (NSF, 2010).

It indicates the level of contamination of a water system by evaluating the following nine water quality parameters (weight of each one is given in parenthesis), which are defined to be relevant for public water supply: DO (0.17); TC (0.15); pH (0.12); biological oxygen demand (BOD, 0.10); TN (0.10); TP (0.10); Turb (0.08); TR (0.08). The WQI is calculated according to equation 1 (Cetesb 2017):

$$WQI = \prod_{i=1}^{n} qi^{wi} \tag{1}$$

where: WQI is a number between 0 and 100; qi: quality of the i-th parameter, (number between 0 and 100); wi: weight of the i-th parameter (number between 0 and 1). The results are classified in the categories: excellent ($79 < WQI \leq 100$), good ($51 < WQI \leq 79$), regular ($36 < WQI \leq 51$), bad ($19\ WQI \leq 36$) and very bad ($WQI \leq 19$).

Trophic State Index (TSI)

The TSI is a tool for classification of water systems of different trophic status for temperate environments, proposed by Carlson (1977). The index used in this study was modified by Lamparelli (2004) for tropical and subtropical environments.

The variables TP and Chl-a are used for lentic environments. The TSI is composed of the sub-indices trophic state index for chlorophyll-a (TSI(Chla)) and trophic state index for total phosphorus TSI(TP), which were calculated through equations (2) and (3):

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$$\text{TSI(Chla)} = 10x(6 - \frac{(0.92 - 0.34x(ln\,Chla))}{(ln\ \ 2)} \quad (2)$$

$$\text{TSI(TP)} = 10x(6 - \left(1.77 - \frac{0.42x(ln\,TP)}{ln\ \ 2}\right) \quad (3)$$

where: TSI(Chla) is the trophic state index for chlorophyll a; Chl-a is the chlorophyll a concentration (µg/L); TSI(TP) is trophic state index for total phosphorus; TP is total phosphorus concentration (µg/L).

TSI is then calculated through the equation 4 and the sampling sites were classified in one of the following trophic states: oligotrophic (TSI < 44), mesotrophic (44 < TSI < 54), eutrophic (55 < TSI < 74) or hypereutrophic (TSI > 74) (Cetesb 2017).

$$TSI = \frac{(TSI(TP) + (TSI(Chla))}{2} \quad (4)$$

Aquatic Life Index (ALI)

The ALI gives information about the water quality in order to protect aquatic fauna and flora (Cetesb 2017). The index reflects the presence of contaminants which impact aquatic organisms. However, the calculation of ALI (equation 5) requires the previous calculation of the TSI and the index of minimum variables for the maintenance of aquatic life (IMVMAL).

$$ALI = (IMVMAL\ x\ 1.2) + TSI \quad (5)$$

Essential variables (EV) and toxic substances (TS) are necessary for determination of IMVMAL, which is calculated through equation 6:

$$\text{IMVMAL} = \text{EV x TS} \quad (6)$$

The EV includes parameters linked to DO and pH. The group of TS (mg/L) is composed by Cd; Cr; dissolved Cu; total Pb; Hg; Ni; Zn and surfactants. Therefore, IMVMAL ranges from 1 to 9 and it is subdivided in four quality groups: good = 1; regular = 2; bad = 3 and 4; very bad ≥ 6 (Cetesb 2017).

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After calculation of ALI the samples were classified in the categories excellent (ALI ≤ 2.5), good (2.6 ≤ ALI ≤ 3.3), regular (3.4 ≤ ALI ≤ 4.5), bad (4.6 ≤ ALI ≤ 6.7) or very bad (ALI ≥ 6.8) (Cetesb 2017).

Metal Pollution Potential Index (MPPI)

MPPI was calculated, based on the index used by Prasanna *et al.* (2012), using reference values based on maximum limits defined by Brazilian Environment National Council (CONAMA) Resolution Nº 397/08 for each potentially toxic metal (Cd, Pb, Cr, Ni and Hg) as well as elements that cause organoleptic changes in water such Al, Cu, Fe, Mn and Zn. CONAMA Resolution Nº 357/05 sets provisions for classification of water resources in Brazil as well as the water quality standards for each defined class.

The Itupararanga reservoir as well as the inflows studied in this work were classified into Class 2. This classification is based on water quality standards required for specific uses of water, which includes public supply, recreation, agriculture, protection of aquatic communities and fishing. The MPPI is calculated according to equation (7), where values below 1 indicate low pollution potential by metals and values above 1 represent high pollution potential. This index can be easily replicated according to the legislation of each country.

$$MPPI = \sum_{i=1}^{n} \frac{Mc}{Ml} \qquad (7)$$

Where: MPPI is metal pollution index, which ranges between 0 and 2; Mc is the concentration of metals measured in the water; Ml is the legislative limit of each metal (CONAMA 397/08).

The evaluation of the sub-catchment in which includes the main water supply reservoir of the EPA Itupararanga was evaluated by the spatial distribution of the WQI, ALI and TSI indices using the inverse of the distance weighted (IDW), widely used for

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variables in environmental studies (Lima *et al*. 2003, Varouchakis and Hristopulos, Gong *et al*. 2014; Silva *et al*. 2018). Interpolation was performed according to the sample points presented in Fig. 2.

Figure 2. Interpolation sampling points in Itupararanga Reservoir

Spatial analysis and for delineation of land uses

The information plan related to land use of the EPA Itupararanga was prepared from rectification of maps of homogenous units of urban soil use (UHLU) and land cover of the State of São Paulo with scale of 1:100.000 provided by Coordination of Environmental Planning of the São Paulo State (CPLA).

The rectification was performed in different steps. First, the maps of CPLA were reclassified in 10 new land use classes and the second part consisted in the rectification of agricultural areas around the reservoir by visual inspection from orbital images (2017) available on software Google Earth Pro. The images were vectorised and exported afterwards to software ArcGis 10.4.1.

Multivariate statistical analysis

The data set to statistical analysis was calculated using the mean values from each catchment's land use and water quality data set from dry and wet season (see supplementary material). The data set was standardised by score-z. ANOVA was performed with precipitation data from each sub-catchment to evaluate the temporal heterogeneity.

With the standardized data set a principal component analysis (PCA) and Cluster analysis with Ward method distance was carried out with whole data set. The software PAST 3.14 was used for all calculations (Hammer *et al*. 2001).

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Results and Discussion

Land use in EPA Itupararanga

The multiple uses of Itupararanga Reservoir change the environment around it, reflecting the importance of studies that contemplate the impacts caused from the transformations originated from different soil use types. Therefore, maps of the land use of Itupararanga catchment and sub-catchments were created (Fig. 3).

Figure 3. Land uses on EPA Itupararanga

The Itupararanga Reservoir area is covered mainly by forests (32.67%) and herbaceous vegetation (23.64%), as seen in Table 1.

Table 1. Distribution of land use/cover classes in different sub-catchments of Itupararanga Reservoir

Sorocabuçu sub-catchment presented the largest percentage of forest cover (56.31% or 114 km^2), followed by Sorocamirim (42.78% or 157.51 km^2). The most preserved areas (higher percentage of tree cover) are on the northern margin of the reservoir. The southern margin had different cover types like urban, agriculture, exposed soils and herbaceous. The forest cover classification did not discriminate among different forest types and therefore, areas classified as forests can include silviculture areas (eucalyptus).

The urban areas made up 15.82% of the sub-catchment of the reservoir that corresponded to 40.77 km^2. The most and least urbanised catchments were Sorocamirim and Una which had respectively 102.23 and 16.20 km^2 of extension. The urbanisation process causes a significant change in the hydrological dynamics since large areas are impermeabilized, which increases direct run-off, water speed and consequently erosion

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susceptibility (Schaefer *et al*. 2002, Simonetti *et al*. 2019). Furthermore, urban areas can decrease water infiltration into the soil and reduce evapotranspiration, which can interfere in the pluvial regime on the catchment (Silva *et al*. 2018).

The catchment of Una River had the highest percentage of agricultural lands (16.59%). Sorocamirim had nevertheless the largest extension (39.73 km²). These areas can be linked to the diffuse pollution as discussed by Simonetti *et al*. (2019). The authors analysed the risks associated with soils in permanent preservation areas (PPA) of the EPA Itupararanga and demonstrated that 73.8% of the sub-catchments that constitute the EPA are not able to ensure the water quality of the tributaries although they present vegetation. The study showed that the Una sub-catchment has the highest risks related to PPA, such as urban occupation, agricultural plantations and deforested areas.

The urban green areas had just 0.07% in the sub-catchment of the reservoir, but they have high importance to increase the environmental quality of urbanised areas. Silva *et al*. (2018) emphasised that green cover in urban areas improves the air quality, thermal comfort and quality of life as well as providing noise reduction and food for urban fauna.

Exposed areas made up 4.49% (11.56 km^2) on the sub-catchment of the reservoir, the highest percentage in all EPA Itupararanga. However, these areas may represent temporary crops because they were not mapped in this study. These areas are susceptible to erosion in rainfall events, resulting in soil loss and transport of particles by runoff water to the reservoir.

Herbaceous plants covered 23.64% of the reservoir catchment, especially the northern areas of the reservoir. This class contemplates grasses and forbs (including pasture areas). The Una sub-catchment presented the highest percentage of this soil use

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type, while Sorocabuçu had 17.06% and Sorocamirim 15.43%. The substitution of the original vegetation by agriculture can change regionally the climate and even in a global scale due to deforestation and soil compaction according to Kalnay and Cai (2002).

Unoccupied areas cover 0.12% of EPA Itupararanga. These areas are important due to the risks of impacts caused by industrial plants which can discharge pollutants in water and soils.

Water Quality of the Itupararanga reservoir and main sub-catchments

Evaluation of quality indices

The WQI was good or excellent for all sampling points in all periods. Concerning the sampling sites at the inflows, the WQI was lower in the wet season in Sorocabuçu and Una (60 for both) than in the dry season (Una=62; Sorocabuçu=68). These results can suggest that the surrounding activities, surface runoff and erosion during rainfall can drives a decrease of water quality in these tributaries. The WQI for Sorocamirim was 72 in the dry season and 70 in the dry period which classifies the water as “Good”.

The worst WQI value in the reservoir was found in the dilution of the tributaries for both periods analysed (78 for rainy period and 69 for dry period). The data results presented in Fig. 4 were spatialized and interpolated using the IDW method.

Figure 4. Interpolation of Water Quality Index (WQI) of the samples taken in Itupararanga Reservoir.

It is possible to verify a variation of the IDW along the reservoir in both periods as demonstrated in Fig. 4. The WQI had an increasing trend from Res-2 to Res-4 during the rainy season due to the dilution of the pollution derived from the main inflows,

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which has lower WQI. However, the WQI had an opposite trend from Res-5 to Res-7 due to a possible pollution loads close to these sampling points, which was already observed in the past (Frascareli *et al*. 2018 and Cardoso-Silva *et al*. 2018).

The worst WQI was observed for Res-1 in the dry season, when there is a higher concentration of pollutants present in the water due to higher input from more degraded waters from Sorocabuçu, Sorocamirim and Una rivers. Fig. 5 presents the spatial distribution of the IDW for the trophic state index along the reservoir in both periods.

Figure 5. Spatial distribution of Trophic State Index (TSI) of the sampling sites in Itupararanga Reservoir

Trophic state index (TSI) presented higher values for Res-1 when compared to other sampling sites at the reservoir, being classified as supereutrophic in the wet season and hypereutrophic in the dry season. Other points (Res2-Res7) had a higher TSI on average during dry season that can be explained to accumulation of nutrients due to lower rainfall. The values of TSI of the sampling sites in EPA Itupararanga were presented in Fig 6.

Figure 6. Trophic State Index (TSI) of the sampling sites in EPA Itupararanga

In contrast, TSI(Chl-a) had higher values during wet season, having a eutrophic classification which indicates that the limiting nutrient could be nitrogen (Beghelli *et al*. 2016) or another agent, as light. Other sampling sites in the reservoir were classified as mesotrophic.

The rivers Una and Sorocabuçu were classified as supereutrophic according to TSI(TP) in the wet and dry seasons. During the dry period they were classified as

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supereutrophic only the Una and Sorocabuçu, while the Sorocamirim river was classified as supereutrophic in the wet season and as mesotrophic during the dry season. The TSI for these inflows indicated higher concentration of TP in water compared to Chl-a. The TP concentration is related with input of sewage and the lower level of Chl-a was attributed to the high content of suspended particulate matter in the region of these rivers (see supplementary material).

Past studies carried out in the reservoir itself already indicated the increase in the trophic state, as described by Taniwaki *et al*. (2013), Pedrazzi *et al*. (2014), Frascareli *et al*. (2015) and Beghelli *et al*. (2016). However, our results suggest strong impacts from land use around the reservoir and along the main catchments (Una, Sorocabuçu and Sorocamirim) as the main driver for trophic state increase.

The ALI and MPPI indices were analysed only in the reservoir, because it is a lentic environment and therefore the sedimentation of metals that may be potentially toxic to the aquatic fauna occurs in a higher rate (Cardoso-Silva *et al*. 2018). The spatial distribution of the ALI was presented in Fig. 7.

Figure 7. Spatial distribution of the Aquatic Life Index (ALI)

The ALI results in the wet period indicated the influence of the tributary rivers on Res-1, with an improvement from Res-2 to Res-7, with values of 3.2 for the respective sampled points.

The results of the ALI in dry period indicated increasing values towards inflows, with a value of 5.2 classified as bad for Res-1, and for Res-2 to Res-4 these values were 4.2, classified as medium. In Res-5 there is an improvement (3.2 - good), decreasing to Res-6, again with a value of 4.2 (bad) and 3.2 for Res-7. Therefore, this index reveals

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the influence of diffuse pollution on water quality and the possible impacts on the aquatic life of the organisms present in the reservoir.

MPPI demonstrated that the elements Al, Cr and Fe were potential pollutants according to Fig. 8a (dry period) and b (wet period).

Figure 8. Metal pollution potential index (MPPI) of Itupararanga Reservoir

Among these elements, Al showed the highest MPPI values (≥1) in all sample points in the rainy season, while in the dry period the values were higher in the sample points Res-1, Res-2 and Res-5. Cr also presented results higher than 1 in the Res-3 and Res-5 samples in the dry season, whereas Fe had MPPI values next to 1 in the wet season, with decreasing values from Res-1 to Res-7, except for Res-3 (0.7). Other elements analysed presented no potential of pollution, since their MPPI were below 1. Moreover, Hg, Pb and Ni were not detected in all samples.

Tropical soils have naturally high amounts of Al and Fe due to the presence of clay minerals (Landajo *et al*. 2004), which supports the higher concentrations of these elements found in the sediments of the reservoir according to Frascareli *et al*. (2018). Therefore, the high concentrations in the water column probably has autochthonous origin. On the other hand, the higher pollution potential of Cr cannot be explained by the soils around the reservoir but usually it is associated with untreated wastewater (Yin *et al*. 2011).

It was analysed whether the chemical elements detected in the MPPI could come from soil formation, since erosive processes and weathering can carry particulate material to water resources (Ramalho *et al*. 2000, Cardoso-Silva *et al*. 2018). For this purpose, the EPA Itupararanga soils were mapped with geographic information system

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(GIS) using the pedological database provided by the Forestry Foundation of São Paulo State (Fig. 9).

Figure 9. Soil map of the EPA Itupararanga

The soils of the study area are predominated constituted by Acrisols in the sub-catchment of the reservoir, while in the Una sub-catchment there is predominance of Ferrasols, with small portions of Gleysols. In the Sorocabuçu sub-catchment are Ferralsols and Gleysols. The Sorocamirim sub-catchment includes the largest variety of soils, with Acrisols, Ferrasols and Cambisols being found.

The Acrisols constituting the sub-catchment of the reservoir are dystrophic, being poor in nutrients, that does not justify the high Cr and Zn values detected in the MPPI. Also, the Acrisols found in this sub-catchment have an association of Red Yellow Acrisols with high amount of aluminum which support the transport of Al to the reservoir when the permanent preservation areas (PPA) are not preserved. However, Simonetti *et al*. (2019) studies analysed the PPA of the EPA Itupararanga and showed that the EPA marginal areas have residences and agricultural activities that allow the transport of pollutants into the reservoir and can negatively impact it.

Therefore, the soils identified in the study area do not have characteristics that are suggestive to the high values found for the Cr and Zn metal elements, corroborating with the hypothesis that inappropriate land uses near the reservoir, such as agricultural areas, can carry elements from the use of pesticides and fertilizers containing Cr, Mn, Cu and Zn detected in the study, among other metallic elements that may be potentially toxic when present in large quantities in the water column. Urban occupation in the vicinity of the reservoir can also be a potential source of pollution due to the discharge

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of irregular domestic sewage (Ramalho *et al*. 2000, Cardoso-Silva *et al*. 2018, Ishchenko and Vasylkivskyi, 2019).

Statistical analyses

The ANOVA with the data of precipitation indicated significant difference between the periods ($p<0.005$) (Table 2-Sup.Material).

The discussion about the indices indicate which sub-catchment presented highest or lowest quality according to each classification index. However, the correlation among the response variables and land use was confirmed and according to PCA explain 55% of total variation of the data set (Fig. 10 - supl.material). The PC1 explained 34% and total coliforms (0.85), TN (0.75) forest (0.88) and unoccupied area (0.87) had strong positive correlation with Una, Sb and Sm catchments. and negative correlations with pH (-0.76), Chl-a (-0.85), herbaceous (-0.73) and bare soil (-0.93). For the Itupararanga reservoir pH, Chl-a, herbaceous and bare soil had positive correlations. The change of land cover around the reservoir to bare soil and herbaceous cover can cause an increase of particulate material and nutrients (Kellner and Hubbart, 2019, Lacher *et al*. 2019). The drained material can reduce the lifetime of the reservoir by reduction of volume capacity as well as an artificial eutrophication which infeasible the public supply of water (Zorzal-Almeida *et al*. 2018).

Indicators for PC2 are agricultural (-0.96), urban green area (0.94) and allotment (0.77). The percentage of forest but also the intense agriculture and urban activity is high in the Una and Sb catchments. These results suggest that diffuse sources are more pronounced in these sub-catchments surpassing the benefits of the preserved area; it is worth pointing out that the forest area include silviculture activities. The Sm catchment indicate a transitional area between the land uses urbanisation, allotment and unoccupied area, indicating that the Sm constitutes the most urbanized catchment of the

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study, with land uses that may increase the pollution potential of the catchment watercourses due to anthropogenic pressure, such as the discharge of domestic sewage.

The cluster analysis indicated three groups (Fig. 11- supl. material). The similarity between Sb: Una (group 1), Sb: Una and Sm (group 2) and reservoir (group 3). We attributed this result to the lowest quality water in Una: Sb, followed by Sm until the Itupararanga Reservoir.

Conclusions

The geoprocessing analysis showed that the reservoir has a significant area of forest in its northern part. However, its southern part has agricultural and urban uses that can endanger its water quality in the case that permanent preservation areas are not respected. The agricultural areas need special attention because poor management of soil practices can lead soils, fertilisers and pesticides to be washed into the reservoir as observed by the results of nutrients in water from agricultural soil use.

This study showed good results for WQI. On the other hand, TSI classified the reservoir as eutrophic and supereutrophic in both periods. ALI presented medium and very bad values, while MPPI revealed that the potential toxic elements were Al, Cr and Fe.

The statistical analyses suggested that pollution source has a pronounced negative impact in the Sorocabuçu and Una, followed by Sorocamirim. These analyses can explain the deterioration of water quality detected in Res-1 in the reservoir for all indices analysed. This study indicates that measures of pollution control in the cities in the influence zone of the reservoir are required.

The use of indices with GIS supports allows to obtain relevant and detailed information in the quality of the aquatic environments, being able to be adapted and

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replicated in different regions. Furthermore, water quality indexes combined with land use can be an important management tool to provide support for decision making.

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Classes	**Reservoir (Res)**		**Una**		**Sorocabuçu (Sb)**		**Sorocamirim (Sm)**	
	km²	**%**	**km²**	**%**	**km²**	**%**	**km²**	**%**
Agriculture	34.41	13.35	16.13	16.59	31.75	15.67	39.73	10.79
Urbanization	40.77	15.82	16.20	16.66	19.69	9.72	102.23	27.77
Wet area	0.32	0.13	0.00	0.00	0.08	0.04	0.81	0.22
Forest cover	84.19	32.67	37.34	38.41	114.09	56.31	157.51	42.78
Herbaceous cover	60.92	23.64	25.66	26.40	34.56	17.06	56.82	15.43
Water resources	25.23	9.79	0.61	0.63	0.45	0.22	1.35	0.37
Urban green area	0.17	0.07	0.00	0.00	0.09	0.05	0.35	0.10
Allotment	0.08	0.03	0.00	0.00	0.04	0.02	1.31	0.35
Bare soil	11.56	4.49	1.27	1.30	1.76	0.87	7.83	2.13
Unoccupied area	0.00	0.00	0.00	0.00	0.11	0.05	0.26	0.07

Table 1. Distribution of land use/cover classes in different sub-catchments of Itupararanga Reservoir

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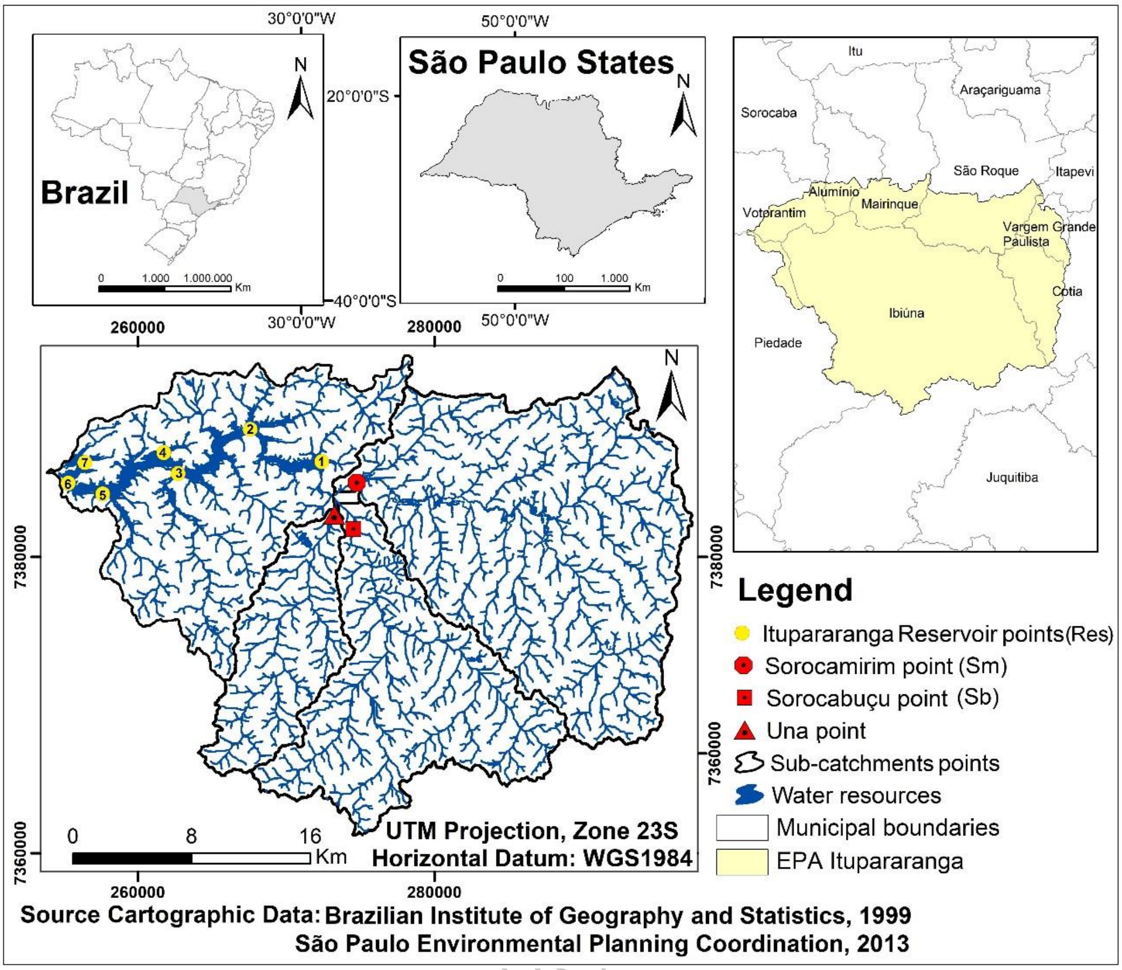

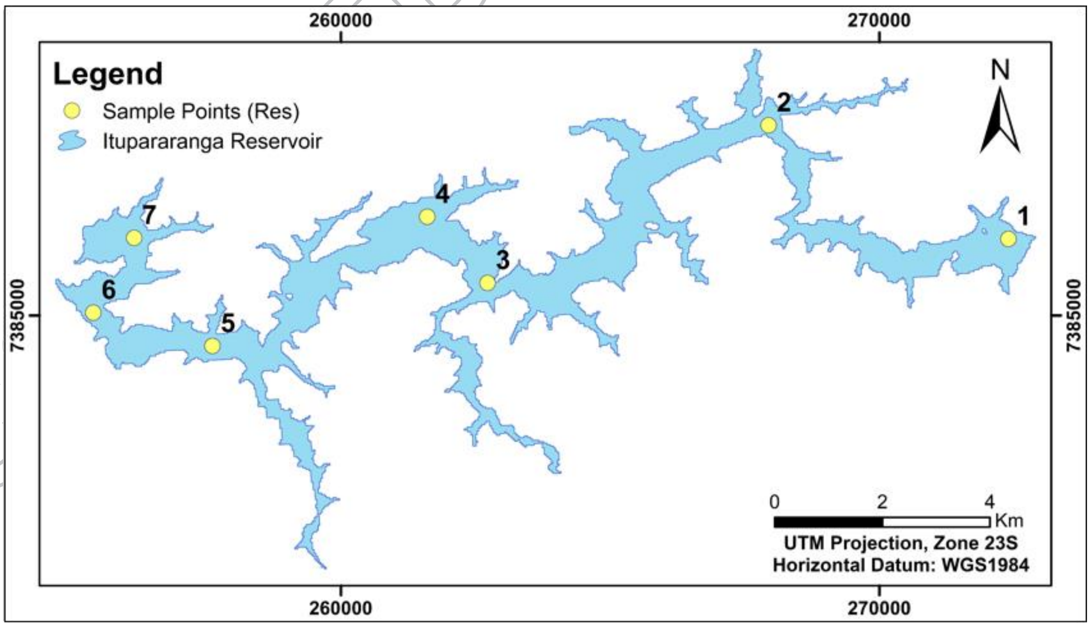

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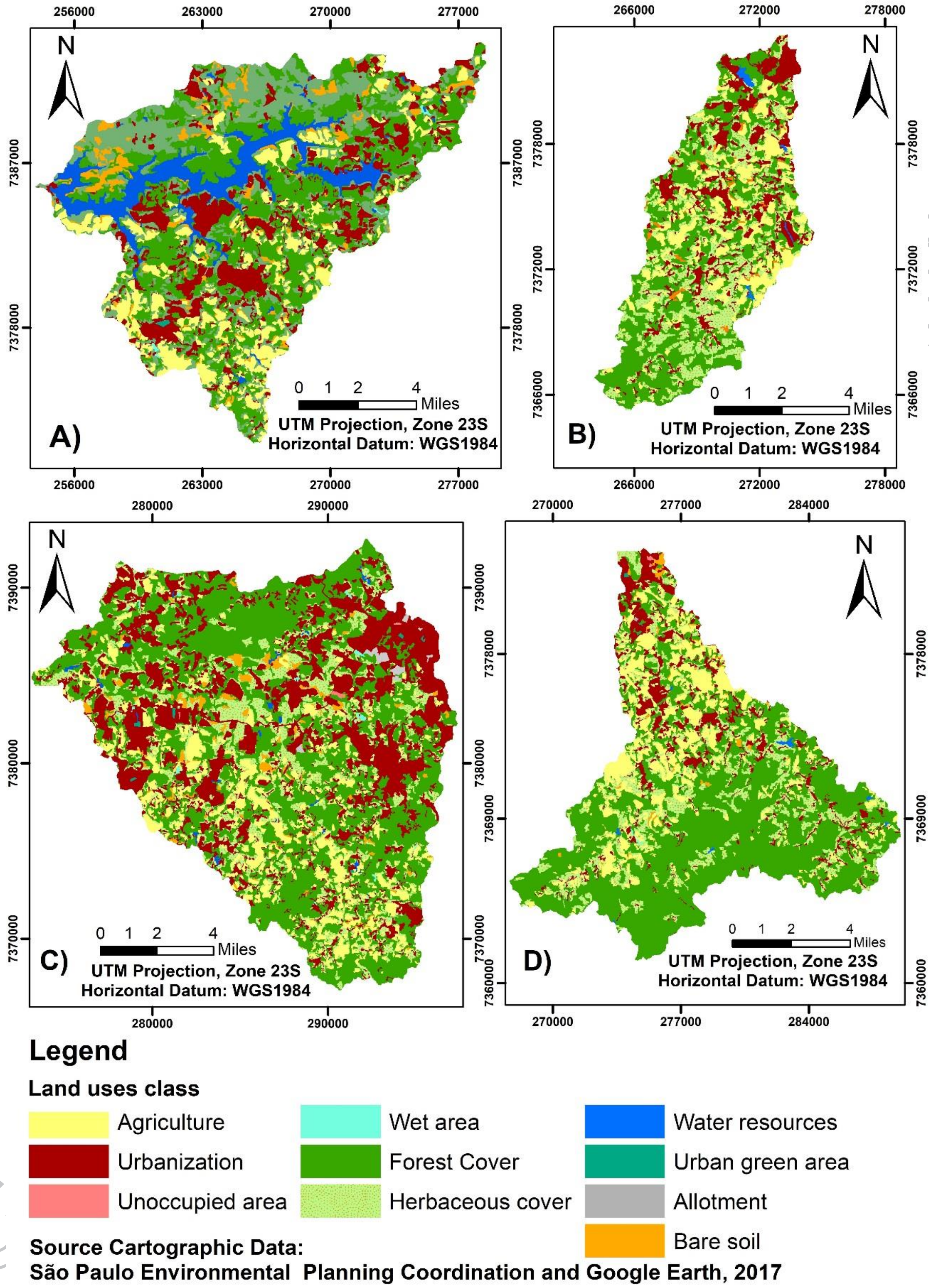

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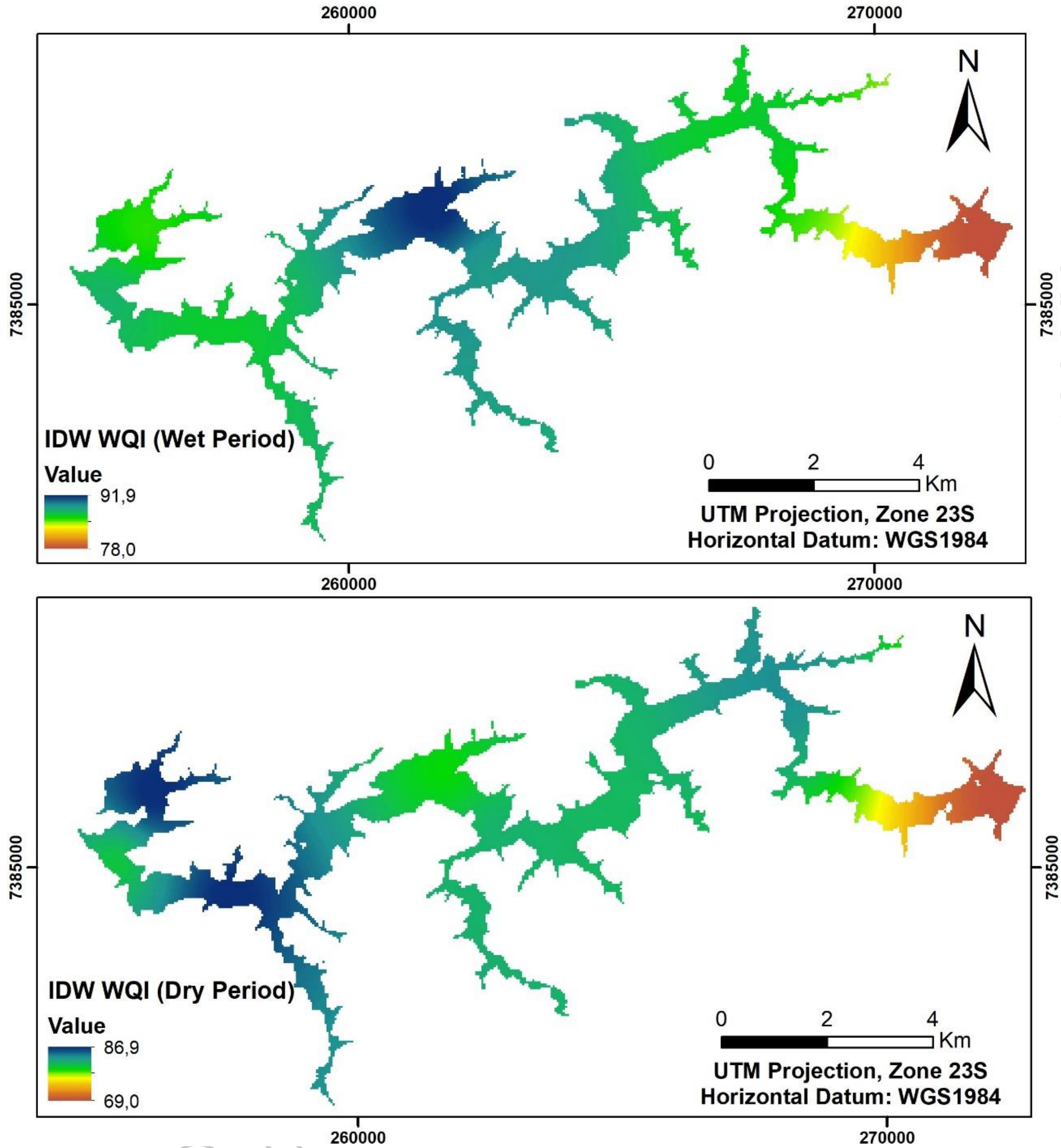

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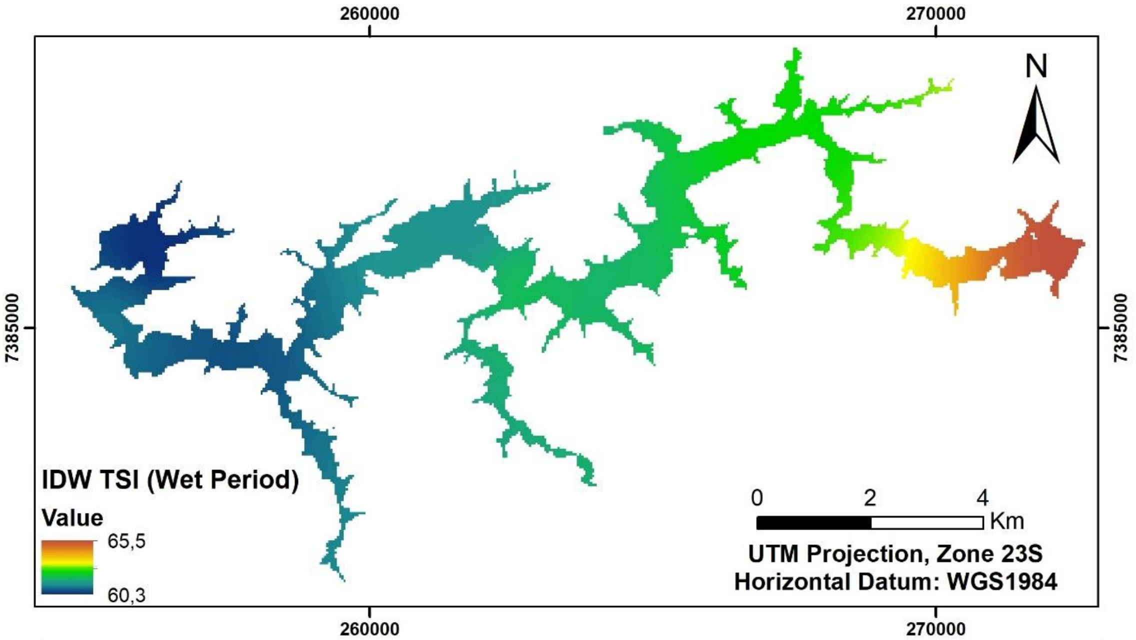
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7385000
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2
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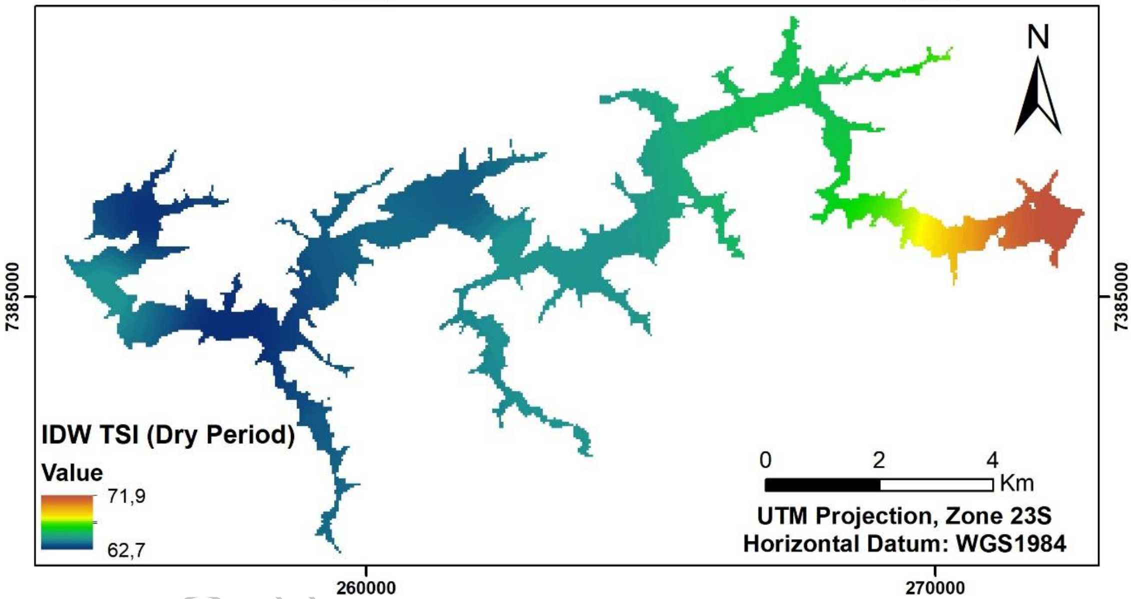
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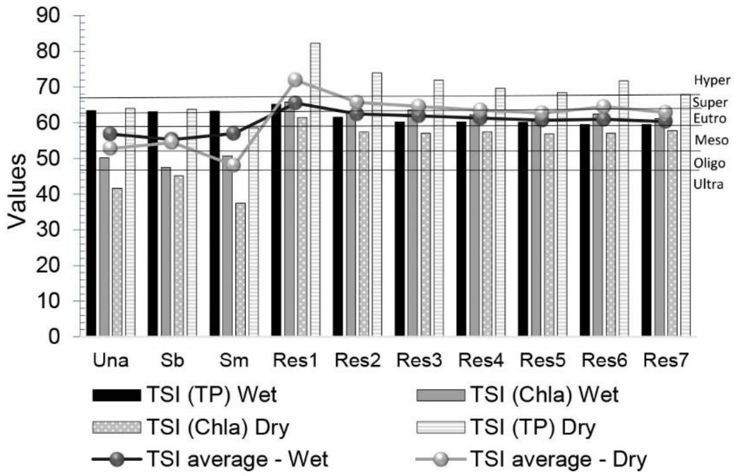
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Super
Eutro
Meso
Oligo
Ultra
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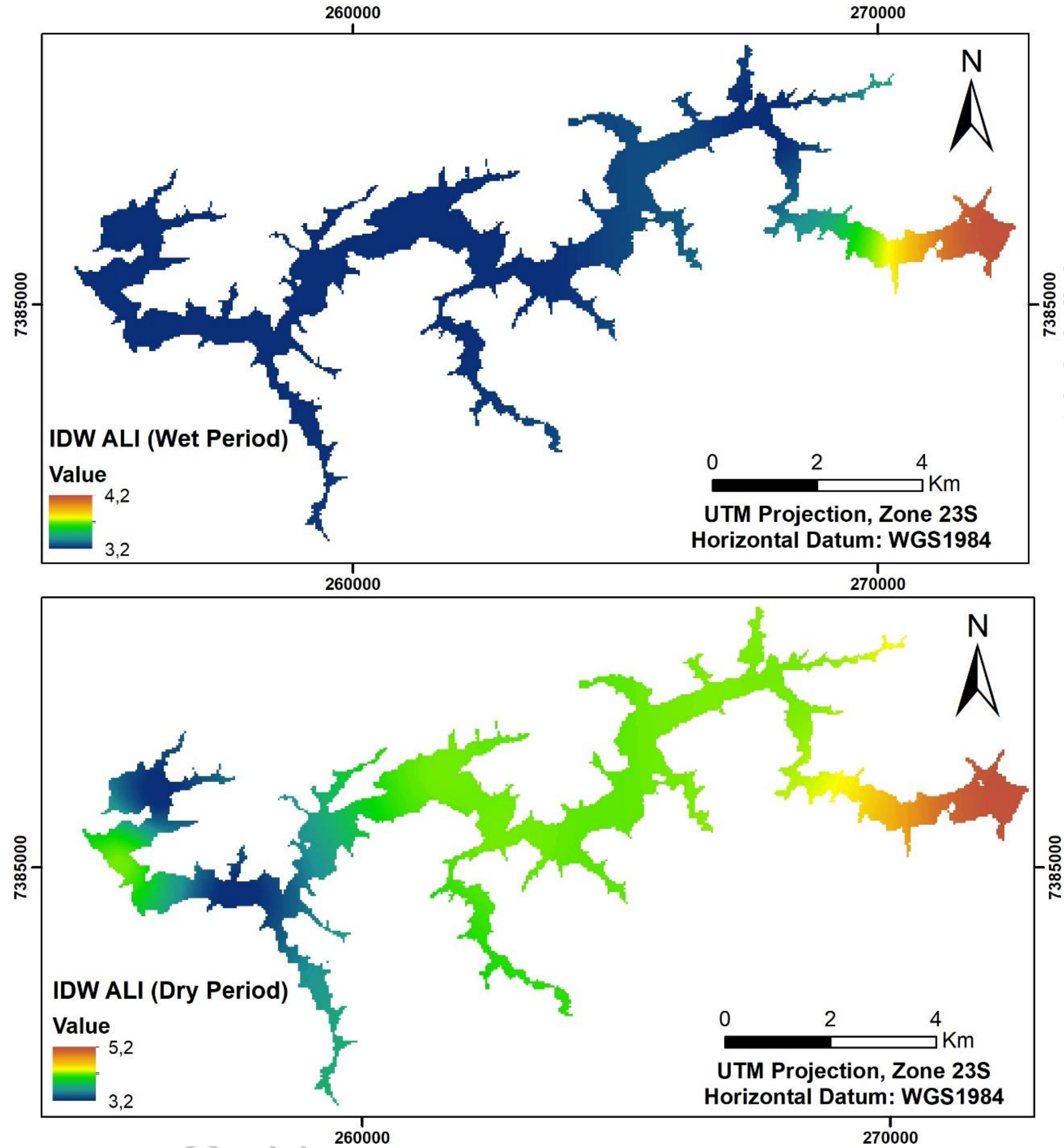
Sb
Sm
Res1
Res2
Res3
Res4
Res5
Res6
Res7
TSI (TP) Wet
TSI (Chla) Wet
TSI (Chla) Dry
TSI (TP) Dry
TSI average - Wet
TSI average - Dry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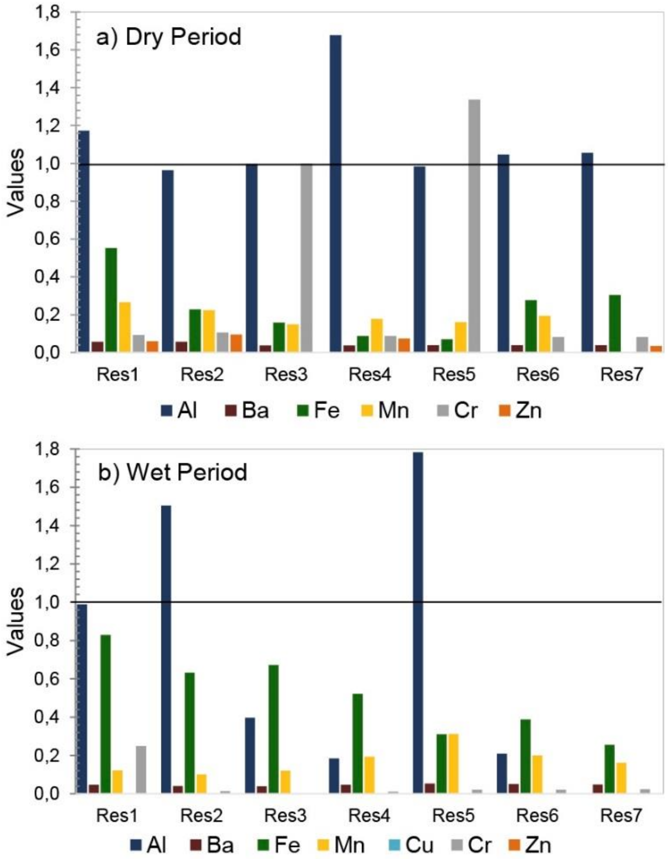

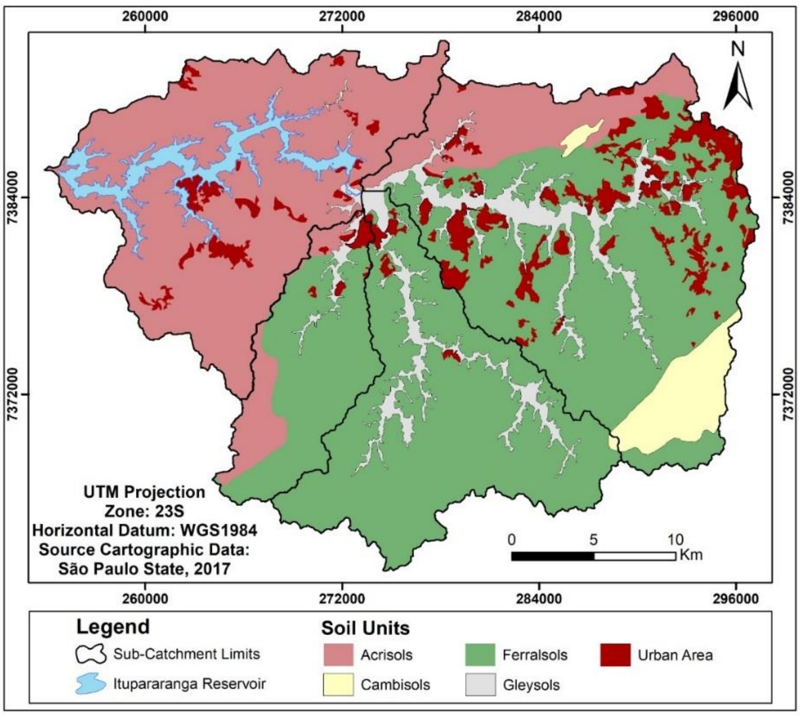

Supplementary Material

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Table 2- Data from rainfall of region of Itupararanga Reservoir

Points	Dry Season	Wet Season	Coordinate	Period	Source
Una	38,95	179,98	Ibiuna	1939-2017	DAEE
Sorocabuçu	34,0	188,5	Ibiuna	1996-2011	CIIAGRO
Sorocamirim	25,8	202,4	São Roque	2000-2013	CIIAGRO
Sorocaba	61.25	151.3	Sorocaba	2016-2018	DAEE
Piedade	75.5	120.6	Piedade	2016-2018	DAEE
Mairinque	92.9	175.35	Mairinque	2016-2018	DAEE
Mairinque II	77.15	239.1	Mairinque II	2016-2018	DAEE

Table 3 - Data set of variables that compose the indices. S: Dry period

Points	DO	Temp	pH	Cond	Turb	TDS	TR	Total Coliforms	TC	BOD	Chl-a	TP	TN	Surfac
Una	6.600	21.000	6.600	93.000	25.600	40.000	0.014	1601.000	1601.000	1.033	0.0014500	0.204	8.400	0.050

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Sb	6.800	21.700	5.930	51.000	77.000	33.000	0.013	1601.000	350.000	0.933	0.0010550	0.192	3.800	0.100
Sm	7.930	22.800	6.520	98.000	18.800	64.000	0.011	920.000	79.000	0.783	0.0015500	0.197	5.400	0.075
Res-1	5.770	27.600	8.380	82.000	22.900	53.000	0.012	130.000	17.000	2.585	0.0213800	0.044	0.688	0.110
Res-2	6.160	27.300	8.100	77.000	16.900	50.000	0.010	7.800	2.000	1.060	0.0127000	0.024	0.403	0.105
Res-3	5.860	27.300	7.400	74.000	17.600	48.000	0.010	2.000	1.790	0.380	0.0136300	0.019	0.364	0.085
Res-4	8.000	26.500	7.300	72.000	13.300	47.000	0.011	11.000	1.790	0.845	0.0104200	0.019	0.622	0.200
Res-5	6.700	23.500	7.340	72.000	16.100	47.000	0.009	49.000	4.500	0.100	0.0082900	0.019	0.745	0.260
Res-6	6.590	23.900	7.040	74.000	19.600	47.000	0.009	11.000	2.000	0.400	0.0106900	0.017	0.416	0.100

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Res-7	10.900	23.300	6.860	76.000	13.000	48.000	0.007	11.000	4.000	0.450	0.008290	0.017	0.166	0.280
Una-s	7.200	14.210	6.700	206.000	9.700	134.000	0.007	2200.000	2200.000	1.600	0.001	0.230	1.300	0.080
Sb-S	7.800	15.000	6.600	49.000	10.500	32.000	0.038	3500.000	540.000	1.000	0.001	0.219	0.600	0.090
Sm-S	7.300	15.200	6.900	106.000	11.700	69.000	0.002	3500.000	920.000	0.367	0.000	0.080	1.500	0.045
Res-1-S	6.710	18.000	8.300	207.000	9.500	52.000	0.004	130.000	23.000	1.687	0.009	0.744	1.350	0.085
Res-2-S	7.270	19.210	7.900	69.000	8.500	45.000	0.005	6.800	4.000	0.723	0.009	0.186	0.500	0.090
Res-3-S	6.320	18.030	7.700	62.000	11.200	40.000	0.005	4.500	4.500	1.490	0.008	0.134	0.500	0.080
Res-4-S	7.010	19.700	7.630	66.000	7.500	43.000	0.004	7.800	1.790	1.940	0.009	0.091	0.300	0.090

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Res-5-S	6.630	18.500	7.680	67.000	8.500	44.000	0.004	1.790	1.790	1.837	0.008	0.075	0.300	0.090
Res-6-S	5.530	18.200	7.800	67.000	8.200	44.000	0.001	2.000	2.000	1.750	0.008	0.130	0.300	0.070
Res-7-S	7.320	18.400	6.400	73.000	7.700	46.000	0.004	1.790	1.790	2.143	0.010	0.068	0.300	0.090
Soro-S	7.850	17.900	7.400	79.000	4.500	51.000	0.001	170.000	79.000	1.383	0.001	0.044	0.250	0.115

Figure 10 - PCA with data set which compose the indices standardized with global mean to remove the seasonality effect.

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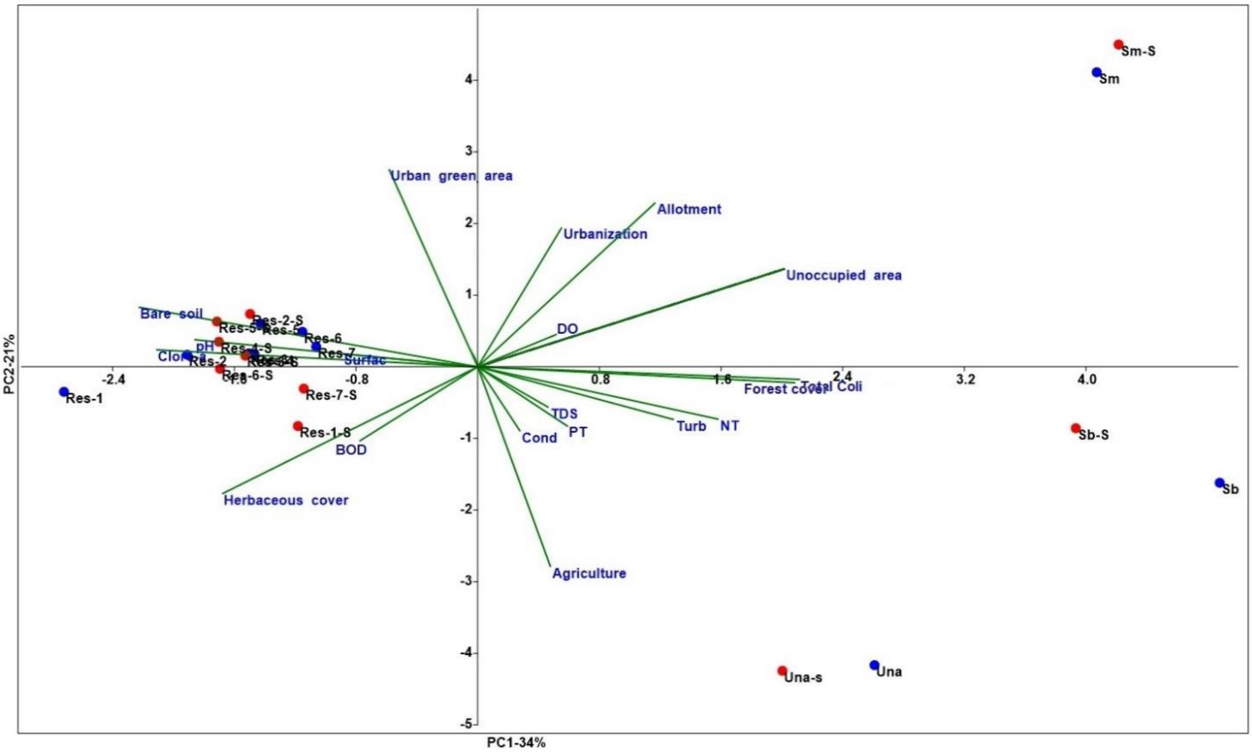

Figure 11 - Cluster analysis with indexes data