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Spatio-temporal changes in water quality in the Guarapiranga reservoir (São Paulo, Brazil): insights from a long-term monitoring data series

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Abstract The provision of drinking water in metropolises is a challenge that requires programs for continuous monitoring of water quality and processes that impact the land cover of the watershed. In this work, we investigated through multivariate statistical analysis the temporal and spatial trends of several variables, not yet explored in a data series that includes 42 years (1978–2020) of monitoring in the hydrographic basin of the Guarapiranga reservoir, in the São Paulo Metropolitan Region—SPMR (Brazil). This reservoir is the source of drinking water for 3.8 million people and plays a strategic role in the social, environmental, and economic structure at SPMR. Our results point to the continuous degradation of water quality in the reservoir, although with different causes and spatio-temporal aspects. Between the 1970s and 1980s, variables associated with erosion/silting played a more critical role. From the 1990s, the introduction of N and P intensified, and the concentration of thermotolerant coliforms increased. The loss of quality is mainly associated with the progressive advance of urban settlements without planning combined with the inefficient initiatives to control domestic sewage pollution. If there is no rapid and comprehensive intervention, there is a risk that the Guarapiranga reservoir may become unsuitable for drinking water supply and other types of use in the future. This scenario will represent a critical obstacle to regional development and the quality of life of the population.

Keywords Water quality monitoring · Water pollution · Reservoir management · Watershed degradation

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Introduction

Brazil holds 12% of total freshwater in the world, for which it is called the “country of waters” (Tundisi, 2014). Nevertheless, the territorial availability of water to people is dramatically unequal. The North Region has 68.5% of the country's total water, but only 8% of national inhabitants. On the other hand, 42% of the Brazilian population lives in the Southeast Region, containing only 6% of the country's water (São Paulo, 2008). This scenario historically has been disregarded, and a squandering culture persisted for decades. However, in the largest Brazilian cities, especially the São Paulo Metropolitan Region (SPMR), this notion has been changing since 2013 due to the worst climatological water crisis to date, boosted by the rising quantitative/qualitative water scarcities combined with unplanned demographic growth, insufficient infrastructure, and unbalanced economic development for the last decades (Empinotti et al., 2019; Millington, 2018; Nobre et al., 2016). It is virtually impossible to calculate the extent of all economic, social, and environmental impacts of this crisis, but it is reasonable to infer that they reverberate beyond the metropolitan region's geographic edges.

Several social and economic activities (e.g., finance, industry, services, tourism) connect the SPMR with the national and international economy, which is, in part, reflected by the region's Gross Domestic Product (GDP) of around USD 250 billion in 2018, according to the Brazilian Institute of Geography and Statistics website (IBGE). Water quality plays a strategic role in sustaining all human activities in the SPMR. Deficient planning for managing water resources, in addition to inefficient control of land cover in the watershed, has caused severe risks of social security and may leave some sectors of society on the verge of collapse, even in a region where human development indicators reach high levels (Millington, 2018). Water security is not just guaranteeing water quantity, but also maintaining its quality at levels compatible for different types of use (van Vliet et al., 2017).

Long-term programs to monitor water quality (40 years or more) are relatively rare and often restricted to a few watersheds with greater population density. The Environmental Company of the State of São Paulo (CETESB) has been carrying out a comprehensive program to monitor surface water quality with hundreds of points distributed throughout the state, based on dozens of variables. This extensive monitoring network follows all recommendations for best laboratory practices and meets the main guidelines suggested by Strobl and Robillard (2008) to maximize their efficiency. Annually, Cetesb releases consolidated reports with the results of the variables and various water quality indexes. However, such results are not analyzed using multivariate statistical tools, which could help interpret underlying environmental patterns and trends not observed by analyzing the water variables in isolation (Ouyang, 2005).

One of the reservoirs monitored by CETESB is the Guarapiranga, which is regionally second larger source of drinking water supply 3.8 million people, or 20% of the inhabitants of the SPMR. The watershed comprises seven cities (São Paulo, Embu, Cotia, Embu-Guaçu, São Lourenço da Serra, Itapecerica da Serra, and Juquitiba), extending over an area of 639 km^2. Its construction aimed to generate hydroelectric power, but changed to include supplying drinking water in 1929 after a severe climatological water scarcity event during the 1920s (Araújo, 2017).

The Guarapiranga reservoir plays a strategic role in the economic and social structure of one of the most populous regions in the world. Thus, in this paper, we applied multivariate statistical analyzes to a long-term data series of water quality to understand the spatial and temporal variations over time and enhance the monitoring and controlling pollution programs in the watershed.

Material and methods

Study area

The reservoir stores up to 171 million m^3, and the water surface covers 26.6 km^2, outflowing 14–15 m^3/s (Fig. 1). Water column depth averages 4.9 m (maximum depth: 12 m), and residence time ranges from 87 to 121 days (Salas & Martino, 1991). The catchment comprises two regional climatic units: super-moist tropical (southern), with average annual rainfall between 1400 and 1800 mm, and wet tropical (reservoir), with average annual precipitation between 1250 and 1400 mm (Tarifa & Armani, 2001). The rainy season extends from October to March and the dry season from April to September.

Urban land use has continuously increased in the last decades, impacting the water quality and the

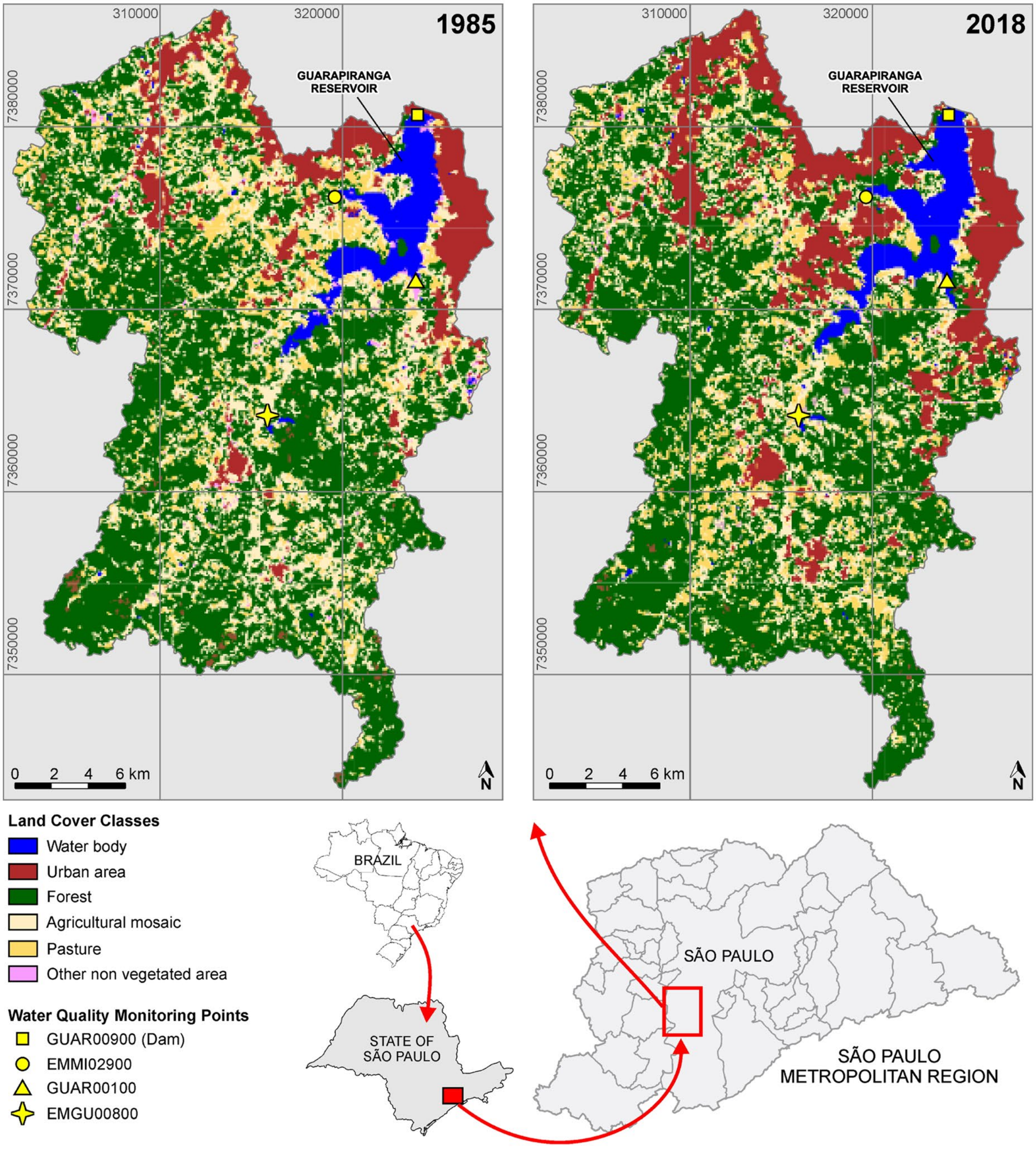

Fig. 1 Guarapiranga reservoir watershed with water quality monitoring points. Land cover classes (1985 and 2018—oldest and newest maps available to date, respectively) are based on MapBiomas Project (Souza et al., 2020). Source: MapBiomas Project Collection 4.1 of the annual series of land cover maps from Brazil, accessed in August/2020 through the link: https://mapbiomas.org/

ecosystem services provided by the reservoir (Adas et al., 2020; Andrade et al., 2015; Brito et al., 2018; Semensatto & Asami, 2017). The populational density reaches up to 100 inhabitants/ha in the northwest sector of the reservoir, where sewage collection and treatment systems serve only 53% of households

(Otomo et al., 2015; São Paulo, 2008, 2011). Thus, raw domestic sewage disposal is the main threat to water quality in the Guarapiranga reservoir (Fontana et al., 2014; Leal et al., 2017; Semensatto & Asami, 2017; Whately & Cunha, 2006).

Historical background: the first seven decades of the reservoir

Construction of the Guarapiranga dam began in 1906. Initially called the "Santo Amaro Dam" after a nearby agricultural settlement, the reservoir's initial purpose was to store additional water volume and regulate the flow of the Tietê River for the city of São Paulo's emergent hydroelectric complex. State officials offered highly favorable concessions to a Toronto-based utility company called the São Paulo Tramway, Light and Power (known locally as "Light and Power" or "Light"). The company, which also operated São Paulo's public transportation system, built a hydroelectric dam and power plant east of the city in 1899 (McDowall, 1988; Souza, 1989). The inaugural Light hydroelectric dam, located downstream from the capital at Santana de Parnaíba, sparked an important transformation in both the metropolitan hydrology and energy matrix of the capital of São Paulo. The construction of the Santo Amaro reservoir through the damming of the Guarapiranga River reflected public authorities' and private interests' willingness to channel the untapped hydrological resources of the Planalto Paulista to electrify and industrialize the city.

The Bureau of Water and Sewer pursued plans to locate pure and plentiful sources of water far outside the city limits in the hopes of avoiding contamination and relying on pumping and filtering water from the city's principal rivers. Projects to bring water from the Cotia and Claro Rivers (east and west of the city, respectively) faced hurdles to success. Cotia experienced technical problems and required multiple expansions, while the construction of the Rio Claro system proceeded slowly, in terms of winning approval and terminating construction. In the years 1924 and 1925, drought conditions in São Paulo led to water shortages, affecting hydroelectric capacity as well as public supply. The manager of Light's annual report noted: "1925 will figure in the annals of the history of the Company as the year of greatest tribulation owing to the unprecedented dry season and consequent shortage of power" (General Manager's Annual Report, 1963). Political unrest in 1924, including a general labor strike and a barracks uprising known as the Tenentes Revolt, also threatened social stability. One proposal to address the question of water supply was to divert water from the "Light Reservoir" for public supply. In 1927, state authorities negotiated a deal with Light to draw an initial 1 m^3/s from the reservoir. The Guarapiranga system was inaugurated in 1929, tapping a source that in 30 years would grow to supply nearly half of São Paulo's water (4 m^3/s).

The construction of the Guarapiranga Reservoir had several implications for urban growth beyond its official purpose of regulating the flow of the Tietê River for the Parnaíba plant. News reports at the time claimed that the Santo Amaro lake would be surrounded by a vast park. Appropriation of land in the Guarapiranga River basin in the municipality of Santo Amaro also demonstrated the relative power of the company versus local jurisdictions (Jorge, 2014). Light's ability to expropriate land in the municipality of Santo Amaro led to conflicts with local landowners. Evidence exists that during a period of heavy rainfall and flooding, Light released water from the Guarapiranga reservoir to inundate the floodplains of the Pinheiros River, facilitating their expropriation for the expansion of hydroelectrical energy (Seabra, 2015). A complex relationship thus emerged between local municipal government, the Water and Sewer Bureau (under control of state government), and Light, as all sought to control flows of water for different purposes.

When it was inaugurated, Guarapiranga system was a significant addition to São Paulo's water supply system, in terms of both additional volume and technical sophistication. A notable component of the system was its treatment station, which purified water via rapid filtration and chlorination. Less than a decade after its incorporation into public water supply, Guarapiranga already showed signs of degradation. The Treatment Section of the Water and Sewer Bureau began to note higher levels of pollution in the reservoir, due to an uptick in leisure properties, including yacht clubs and retreat villas (Paranhos, 1937). These leisure properties did not treat any of their effluence, and despite the fact that citywide sewage treatment was at best embryonic, the Water and Sewer Bureau resolved to install interceptors and treatment. The Bureau's technical journals contain no quantitative data on the degree of pollution from these structures, yet it is clear from these publications that growing population density potentially threatened the water quality of Guarapiranga.

Guarapiranga continued to be a popular spot for recreation, and not just for elites. Aquatic activities and small-scale fishing were promoted by state government (Azevedo, 1952). The reservoirs became alternative sites for these activities as the city's rivers were heavily modified and subsequently polluted in service to industrialization and the proliferation of the automobile. After 1953, the newly formed State Board for Control of Water Pollution issued decrees on acceptable levels of water quality in Guarapiranga. Decrees set coliform levels and prohibited the dumping of sanitary sewage and industrial waste in the Guarapiranga watershed officially designated for "public water." The establishment of a 1-year grace period in 1954 for those currently sinking wastewater into Guarapiranga indicated that such regulations intended to address rather than prevent contamination (Correio Paulistano, 1954). In 1957, the state governor authorized the construction of sewer interceptors in the neighborhoods of Interlagos and Cidade Dutra with the express purpose of protecting Guarapiranga (Diário da Noite, 1957). Industrial waste continued to be a concern, particularly in the South Zone of São Paulo, which had developed a significant industrial belt. The reservoir zone, which also included the neighboring Billings reservoir built to provide hydroelectric volume for the Cubatão Plant, continued to be the patrimony of Light, and thus, some maintenance responsibility fell on the company. In addition to the runoff from property owners, the company reported mud, sand, and kaolin accumulations from construction that required intervention and removal (General Manager's Annual Report, 1963).

In the 1970s, the state of São Paulo passed watershed protection legislation that officially prohibited urban settlement in designated reservoir zones. Much of the north and eastern shores of Guarapiranga (the latter of which contained the Interlagos and Cidade Dutra neighborhoods) had already experienced rapid urbanization and would continue to see expansion into the present (Meyer et al., 2003). Environmental legislation passed 3 years later attempted to prevent urban settlement in the reservoir zone, yet the Guarapiranga had already become a significant frontier for urbanization by the industrial, migrant working class. Weak enforcement of a law shaped more by ideas about land occupation than environmental protection along with a severe housing shortage made the protected watershed zone ripe for illegal speculation (Marcondes, 1999). By the 1970s, unauthorized subdivisions, often with non-existent sanitary infrastructure, had proliferated. The presence of these called "loteamentos" spoke to wider failures in urban planning and environmental protection, yet these settlements received much of the blame for polluting one of the city's principal water sources.

Water quality in the Guarapiranga reservoir has been a long-standing concern for the city, most notably after its incorporation into public water supply. Guarapiranga became an early field site for early hydrobiological studies in Brazil (Kleerekoper, 1937) as well as the site of one of Brazil's most sophisticated water purification plants. The rural character of the surrounding basin made it ideal for providing pure and plentiful water to the growing city. Yet almost immediately, authorities sough to ameliorate pollution particularly from structures built to support recreational activities by constructing sewer infrastructure. Subsequent urban growth and ineffective efforts to prevent urbanization along with streams industrial waste management all increasingly threatened water quality. The present threats to water quality are an accumulation of close to a century of varying degrees of environmental pollution in the reservoir.

Water quality data series

Since 1978, CETESB has been monitoring the water quality of the Guarapiranga reservoir and some tributaries. Results are available in annual compiled reports and online by accessing the system InfoÁguas (https://cetesb.sp.gov.br/infoaguas/), the current dataset source. CETESB monitors bimonthly at four sampling sites (Fig. 1): EMGU00800, EMMI02900, GUAR00100, and GUAR00900. Nine variables used to compute the Water Quality Index (WQI) were selected from the 42-year data series (1978–2020): pH, turbidity (Turb), dissolved oxygen (DO), total solids (TS), biochemical oxygen demand (BOD), total phosphorus (TP), total nitrogen (TN), water temperature (Temp), and thermotolerant coliforms (TC), precisely *Escherichia coli*.

CETESB modified the WQI from the index created by the National Sanitation Foundation (NSF, USA), which summarizes in a single number the water quality condition used to drinking water supply based on the weighted product of those nine variables mentioned in the last paragraph (CETESB, 1978). WQI encompasses five categories: Excellent ($79 < \text{WQI} \leq 100$), Good ($51 < \text{WQI} \leq 79$), Medium ($36 < \text{WQI} \leq 51$), Bad ($19 < \text{WQI} \leq 36$), and Very Bad ($\text{WQI} \leq 19$).

Water temperature is used to compute how much a given variable deviates from the equilibrium. Nevertheless, CETESB assumed this deviation always equals 0 because there were no warm effluents in the reservoir that could change the equilibrium temperature (CETESB, 2019). Thermotolerant coliforms values are derived from applying a correction factor of 1.25 to *E. coli* concentrations (Sato et al., 2008). In the case of a missing value of any variable in a given sampling campaign, we could not calculate the WQI and dismissed the entire observation.

Numerical analysis

Data were grouped into five decadal intervals to highlight temporal trends: 1978–1979 (d1970), 1980–1989 (d1980), 1990–1999 (d1990), 2000–2009 (d2000), and 2010–2020 (d2010). We calculated basic descriptive statistics for each variable and sampling site within the decadal groups and performed two-way ANOVA with post hoc Tukey tests ($p < 0.05$) to verify environmental changes throughout the decades. The results were also evaluated in light of the National Environmental Council (CONAMA) Resolution 357/2005 (Class Special: GUAR0900, GUAR0100, EMGU0800; Class 2: EMMI02900), which provides the Brazilian national guidelines for water bodies classification and monitoring (CONAMA, 2005). We performed linear regressions of WQI throughout the complete timeline and segmented by decade to determine water quality decadal trends in each sampling site. Principal component analysis (PCA), considering the correlation matrix and variation between groups, was performed using the water quality value correspondent to each variable. Data were standardized ($\log x + 1$), and the centroids of the site's scores for each decade per sampling site were calculated to create a temporal path in PCA. All calculations were performed using the R Program (R Core Team, 2020), and *agricolae* (Mendiburu, 2020), and *vegan* packages (Oksanen et al., 2019).

Results

Water quality dropped throughout the decades, but in a heterogeneous degree, spatially and temporally (Table 1). In general, the reservoir underwent two tipping points: d1990 and d2010, when water degradation intensified. TC and BOD concentrations had risen in the whole reservoir, whereas the progressive depletion of DO and the increasing TP concentration were more intense in the northwestern tributary (EMMI02900). Considering only the decadal means, TC and TP exceeded the national water quality guidelines (CONAMA Resolution, 357/2005) since d1970, whereas BOD and DO do not meet the guidelines since d1990. Even in the cases that the decadal mean is according to the guidelines, the high variability (standard deviation) indicates that some variables sometimes exceeded the guidelines.

The WQI declined in the whole period in all sampling sites (Fig. 2). The site EMMI02900 was more irregular over time and exhibited the highest negative inclination among the regressions, whereas GUAR00900 stabilized the WQI at a high level, mainly in the last decade. The WQI ranged from medium to excellent in EMGU00800, poor to excellent in EMMI02900, poor to excellent in GUAR00100, and good to excellent in GUAR00900 (Fig. 3). Except for GUAR00100, where the monitoring program started at d1990, it is possible to observe that the water quality median rose from d1970 to d1980. After these decades, the median dropped, especially for EMMI02900, which drifted from predominantly "good" before the d1990 to "medium" in the last two decades and occasionally "bad." In GUAR00900, where Sabesp (Basic Sanitation Company of the State of São Paulo) captures drinking water to treat and distribute, water quality median moved from "excellent" to "good" in the last two decades and then stabilized. The water is still suitable for human consumption after conventional treatment, but as the reservoir is progressively degrading, GUAR00900 may drop in quality in the next years and raise the treatment costs.

The PCA explained 53.1% of the dataset variation, based on the correlation among the variables used to calculate the WQI (Fig. 4; Table 2). The first axis (PC1) is strongly correlated with the WQI, TC, BOD,

Table 1 Mean and standard deviation of variables used to calculate WQI (by decade for each sampling station in Guarapiranga reservoir). Bold numbers indicate the decades in which the mean values of the variable exceed the limits established by CONAMA Resolution 357/2005 (Guidelines for EMGU00800, GUAR00100, GUAR00900: Class Special; EMMI02900: Class 2). Same letters indicate no significant difference between decades within the sampling station (ANOVA/Tukey test, $p < 0.05$)

	Decade	EMGU00800	EMMI02900	GUAR00100	GUAR00900
	Guideline	< 120	< 1250	< 120	< 120
Thermotolerant coliforms (number 100 mL^{-1})	1970	22,840 ± 101,848 a	5515 ± 7162 ab	-	164 ± 292 a
	1980	1483 ± 4015 b	1807 ± 4461 b	-	61 ± 272 a
	1990	7685 ± 19,940 ab	27,950 ± 50,164 ab	6716 ± 8314 ab	240 ± 632 a
	2000	3358 ± 6052 ab	19,190 ± 27,751 ab	3246 ± 7415 b	748 ± 2768 a
	2010	9560 ± 18,430 ab	101,792 ± 404,151 a	25,847 ± 60,327 a	69,327 ± 499,216 a
	Guideline	> 6.00	> 5.00	> 6.00	> 6.00
Dissolved oxygen (mg L^{-1})	1970	6.45 ± 2.09 a	7.26 ± 1.24 a	-	7.56 ± 0.75 a
	1980	6.82 ± 1.18 a	6.66 ± 1.23 a	-	7.69 ± 0.99 a
	1990	6.48 ± 1.47 a	5.60 ± 1.35 b	5.55 ± 1.99 a	7.45 ± 1.52 a
	2000	6.28 ± 1.15 a	4.58 ± 1.41 c	5.01 ± 3.16 a	7.50 ± 2.42 a
	2010	6.57 ± 1.00 a	3.24 ± 1.40 d	5.03 ± 2.92 a	7.46 ± 1.63 a
	Guideline	< 3.00	< 5.00	< 3.00	< 3.00
Biological oxygen demand (mg L^{-1})	1970	1.69 ± 1.10 b	1.63 ± 1.10 b	-	1.34 ± 0.93 c
	1980	1.96 ± 1.72 b	2.08 ± 1.79 b	-	1.70 ± 1.77 c
	1990	3.71 ± 4.62 a	5.91 ± 7.90 a	8.50 ± 6.25 a	3.20 ± 2.76 b
	2000	3.23 ± 0.81 a	4.28 ± 1.52 a	4.54 ± 1.63 b	4.03 ± 1.38 ab
	2010	3.34 ± 1.04 a	5.57 ± 1.86 a	6.70 ± 3.48 a	4.56 ± 1.53 a
Total nitrogen (mg L^{-1})	1970	0.79 ± 0.76 a	1.08 ± 0.98 a	-	0.64 ± 0.44 c
	1980	0.80 ± 0.48 a	2.86 ± 15.4 a	-	0.86 ± 0.42 c
	1990	0.93 ± 0.60 a	2.41 ± 1.26 a	2.42 ± 1.55 a	1.36 ± 0.75 ab
	2000	1.13 ± 1.36 a	4.95 ± 3.15 a	2.43 ± 2.14 a	1.69 ± 1.03 a
	2010	1.03 ± 1.16 a	4.64 ± 2.46 a	2.45 ± 1.17 a	1.20 ± 0.48 b
	Guideline	< 0.02	< 0.03	< 0.02	< 0.02
Total phosphorous (mg L^{-1})	1970	0.05 ± 0.09 a	0.09 ± 0.13 a	-	0.05 ± 0.07 a
	1980	0.06 ± 0.05 a	0.09 ± 0.12 a	-	0.06 ± 0.05 a
	1990	0.13 ± 0.44 a	0.30 ± 1.28 a	0.13 ± 0.10 a	0.06 ± 0.07 a
	2000	0.07 ± 0.05 a	0.20 ± 0.10 a	0.19 ± 0.43 a	0.06 ± 0.05 a
	2010	0.06 ± 0.09 a	0.37 ± 0.26 a	0.17 ± 0.12 a	0.08 ± 0.15 a
	Guideline	< 40	< 100	< 40	< 40
Turbidity (NTU)	1970	17.9 ± 8.1 ab	42.6 ± 34.9 a	-	26.2 ± 11.6 a
	1980	25.6 ± 23.9 a	28.5 ± 28.8 a	-	19.1 ± 15.8 b
	1990	18.3 ± 12.7 ab	15.5 ± 14.2 b	7.3 ± 5.4 ab	2.75 ± 1.54 c
	2000	18.9 ± 22.7 ab	14.5 ± 16.0 b	5.8 ± 5.8 b	3.2 ± 3.2 c
	2010	15.6 ± 14.4 b	16.3 ± 17.5 b	10.1 ± 9.4 a	4.5 ± 2.3 c
	Guideline	< 500	< 500	< 500	< 500
Total solids (mg L^{-1})	1970	51.3 ± 13.2 b	102.0 ± 36.2 bc	-	65.0 ± 14.0 b
	1980	66.6 ± 50.1 b	99.1 ± 40.9 c	-	60.1 ± 14.1 b
	1990	65.9 ± 34.0 b	118.9 ± 34.0 b	73.2 ± 25.0 b	60.1 ± 16.8 b
	2000	89.6 ± 58.2 a	137.9 ± 29.8 a	125.9 ± 31.7 a	99.1 ± 18.7 a
	2010	106.7 ± 22.5 a	140.6 ± 33.0 a	119.6 ± 23.1 a	105.3 ± 9.7 a
	Guideline	6.0–9.0	6.0–9.0	6.0–9.0	6.0–9.0

Table 1 (continued)

	Decade	EMGU00800	EMMI02900	GUAR00100	GUAR00900
pH	1970	6.19 ± 0.50 b	6.54 ± 0.42 b	-	6.77 ± 0.29 c
	1980	6.22 ± 0.44 b	6.62 ± 0.37 b	-	6.79 ± 0.43 c
	1990	6.60 ± 0.50 a	6.80 ± 0.44 a	7.23 ± 0.23 a	7.19 ± 0.50 b
	2000	6.42 ± 0.29 ab	6.91 ± 0.19 a	7.26 ± 0.48 a	7.84 ± 0.79 a
	2010	6.60 ± 0.41 a	6.94 ± 0.17 a	7.22 ± 0.61 a	7.65 ± 0.65 a

TN, TP, and DO, whereas the second axis (PC2) correlated with pH and turbidity. Therefore, the more the decades' centroids moved from the left to right and from top to bottom of the axes, the more degraded is the sampling site. The PCA highlights that EMMI02900 degraded more intensely and faster than

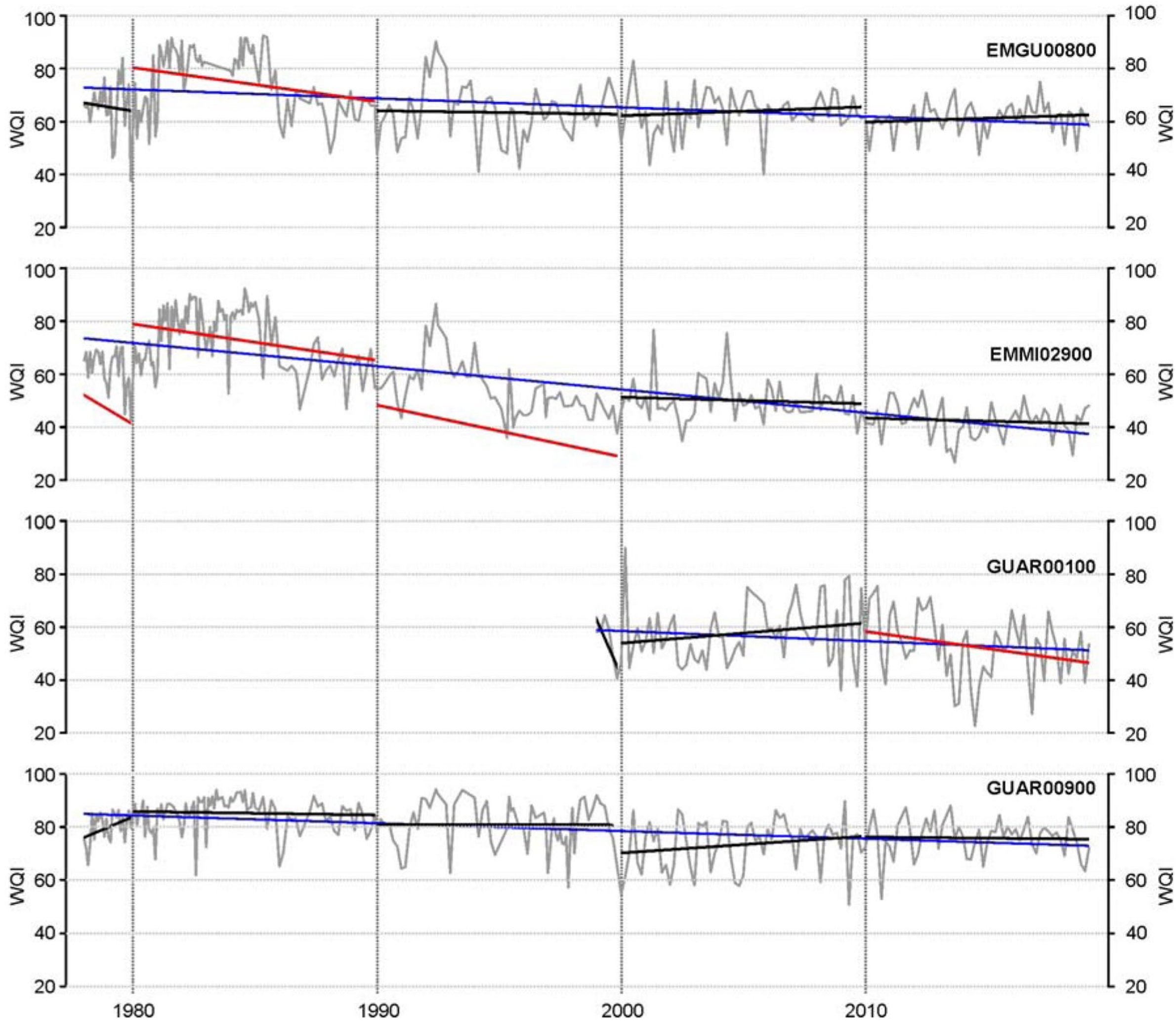

Fig. 2 Temporal evolution of Water Quality Index (WQI) in sampling sites of the Guarapiranga reservoir. The blue line represents the regression of the temporal evolution throughout the entire monitoring program (all regressions significant, $p < 0.05$). Red and black lines represent decadal significant and no-significant regressions, respectively

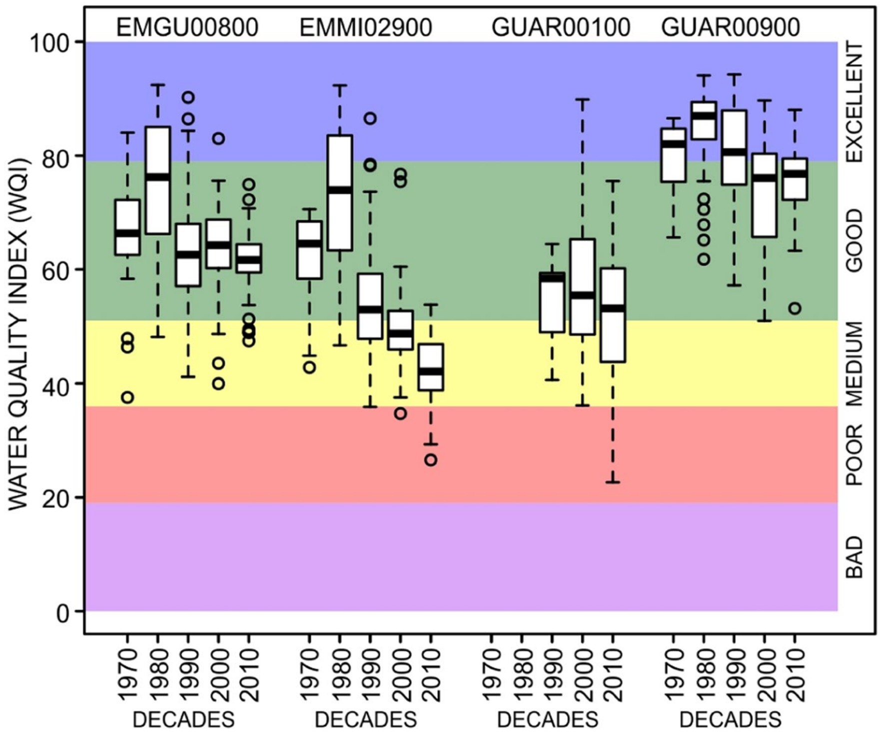

Fig. 3 Boxplot of the Water Quality Index (WQI) by decade in the sampling sites of the Guarapiranga reservoir. Colors represent the levels of water quality

other sampling sites. In d1970 and d1980, the pH and turbidity drifted more, but then variables associated with sewage pollution (PC1) exerted stronger influence in the last three decades, putting this sampling site in the worst condition.

On the other hand, EMMGU00800 has undergone a relatively lower degradation and prevailed as the sampling site with the reservoir's best water quality. Even though GUAR00900 remained in the WQI "excellent" to "good" quality most of the time, PCA's overall trend indicates that this site is moving towards progressive degradation. Lastly, in GUAR00100, the variables related to sewage pollution (PC1) have remained almost at the same level, but the sampling point position in the PCA denotes that it moved towards the degradation condition observed in EMMI002900.

Discussion

Rapid urban growth and insufficient sanitation infrastructure are the main factors that explain the variation in water quality in the Guarapiranga reservoir over the past four decades. Within the first decades of its construction, sanitary engineers from the Water and Sewer Bureau noticed contamination of Guarapiranga's water. The construction of tramway lines by Light and the annexation of the municipality of Santo Amaro in 1935 by the city of São Paulo facilitated closer connections to the urban population. Unlike the other water systems in operation, Guarapiranga lay within the municipal jurisdiction of São Paulo and subsequently on the frontier of the Paulista capital's midcentury expansion. Sanitary engineers recognized that the proximity of the city to the reservoir required laws to protect water quality, as well as infrastructure to capture and treat infrastructure. The Guarapiranga water supply system when built also benefited from modern water treatment facilities; increased pollution implied greater treatment costs. Ultimately, though, these measures to curb contamination faced increasing challenge as unauthorized subdivisions proliferated in the city's reservoir zone.

Pollution by several types of contaminants as well as eutrophication and algal blooms has been observed since the 1980s (Beyruth, 2000; Caleffi et al., 1994; Fontana et al., 2014; López-Doval et al., 2017; Shihomatsu et al., 2017). Part of the high variability

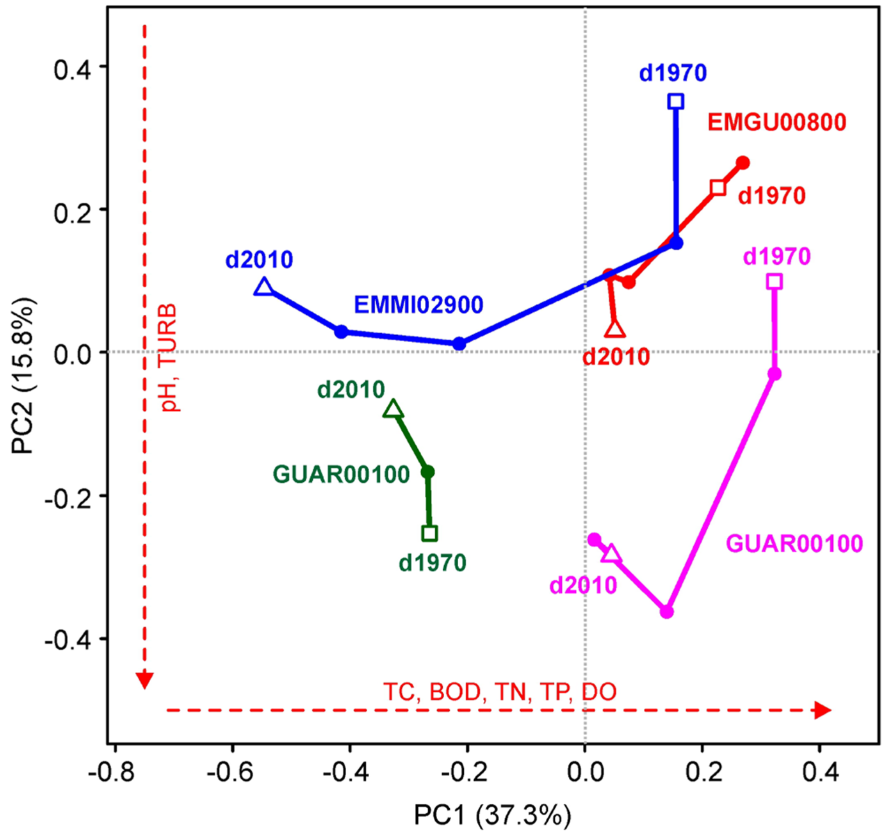

Fig. 4 Decadal centroids from Principal Component Analysis (PCA) using the WQI calculated for each variable. Colors represent the sampling sites, and each point represents a centroid of the PCA score samples for each decade. Open squares represent the first decade of sampling and open triangle, the last one in the temporal series. The gradients of WQI variables are represented by a red arrow showing the most correlated variables with the axis ($r > 0.5$ or $r < -0.5$; see Table 2). Arrows direction expresses the trend to the better water quality standards

within decades and sampling sites is probably related to annual climate variability, which can alter the aquatic ecosystems (Oliver & Ribeiro, 2014). Climatic projections for the SPMR indicate that rainfall and heavy precipitation may increase in intensity and frequency in the next decades with more extended dry periods between days of intense rain (Lima & Magaña-Rueda, 2018; Lyra et al., 2018; Marengo et al., 2013). These conditions will influence the operational routines applied to retain the water and the reservoir's storage capacity, which will affect the residence time and associated variables.

Table 2 Eigenvalues, proportion explained, and Pearson correlation of variables with PC1 and PC2, respectively. All correlations were significant ($p < 0.01$)

	PC1	PC2
Eigenvalues	2.981	1.266
Proportion explained (%)	37.3	15.8
Thermotolerant coliforms	0.63	−0.14
pH	−0.29	−0.54
BOD	0.73	0.16
TN	0.80	0.11
TP	0.75	−0.18
Turb	−0.15	−0.85
TS	0.45	−0.39
DO	0.74	−0.12

Vegetation cover loss due to urban growth, mainly in the reservoir's riparian zone, negatively impacted the local ecosystem services that regulate hydrological components (Adas et al., 2020; Brito et al., 2018; Romero et al., 2018). Brito et al. (2018) estimated that the watershed lost US$ 6.6 million in ecosystem services related to water quality from 1995 to 2010 due to vegetation cover loss. In addition, Adas et al. (2020) inferred that between 2011 and 2030, US$ 318 million will be lost in ecosystem services for water quality regulation, if the rate of loss of vegetation cover observed between 1986 and 2010 is maintained. This situation points to a worrisome scenario for maintaining water quality in the Guarapiranga reservoir in the future, for which the PCA illustrates different spatio-temporal rates and intensities of degradation. Operational routines on the reservoir to maintain water quality for public supply could become very complex (Chaves et al., 2003), which may raise their costs unless water conservation directives are put in practice. Hutton et al. (2007) estimated that in developing countries, the return on a US$ 1 investment in water supply and sanitation improvement was in the range US$ 5 to US$ 46, depending on the intervention.

The use of multivariate statistical techniques to assess the spatio-temporal changes of water quality in reservoirs makes it possible to draw conclusions that are more refined than those inferred from the analysis of a few variables (Baykal et al., 2000; Gu et al., 2016; Varol, 2020). In the Guarapiranga reservoir, the loss of water quality was linked to variables related to the first axis of the PCA (Fig. 4), indicating the negative effect of domestic sewage input. Since the first axis corresponds to the higher proportion to explain the data variation (Table 2), their correlated variables should have stronger effects. Romero et al. (2016) observed a similar situation during the 1970s and 1980s in the Seine River, downstream from Paris (France). The degradation trend reversed with the reinforcement of water quality directives and control of punctual sources after the 1990s. However, controlling the input of N and P from diffuse sources remains a challenge as in the Guarapiranga reservoir watershed.

The EMMI02900 monitoring point showed a faster and more intense loss of quality. Between d1970 and d1980 decades, degradation was more related to pH and turbidity, and in the latter decades mostly related to TC, BOD, TN, TP, and DO. Dense unplanned urban settlements began to be established around the reservoir in d1970, when erosive processes in the tributaries intensified, increasing the turbidity in the water column and speeding up the sedimentation rate in the reservoir (Fontana et al., 2014). In fact, the sub-catchment that flows to EMMI02900 shows the highest erosive potential and is the most responsible for silting up the reservoir (Queiroz et al., 2015). Later, from d1990, water quality dropped even more because a significant part of the households were not connected to sanitation services and directly dispose of domestic sewage in tributaries. This factor became a stressor more critical than those caused by erosion and silting. The residence time in this reservoir is relatively short (87–121 days), which may reduce nitrogen removal efficiency from water (Tong et al., 2019). Mozeto et al. (2001) estimated the burial fluxes of N and P near the Guarapiranga's dam in 30.54% and 76.89%, respectively. Therefore, N and P accumulation in the reservoir throughout the decades may result from the unbalanced input *versus* removal processes, where the short residence time may play an important role. Water quality slightly decreased at EMGU00800 but was less evident than at EMMI02900 because vegetation cover loss and urban growth upstream were more moderate throughout the decades. This point is located in a small river flowing to the reservoir, where the lotic conditions are different from the lentic points in the reservoir.

The EMGU00800 monitoring site started in 2000 when urban settlements had been present upstream for several years. Therefore, the centroid's behavior in the PCA was different from the other points because the pollution by domestic sewage was present since the beginning of the series and remained constant. At this point, pH and turbidity were the most changed variables, probably due to cyanobacteria blooms induced by eutrophication and transposition of supereutrophic waters from the Billings reservoir (Matsuzaki, 2007).

The GUAR00900 point is close to the reservoir's dam. Therefore, the water quality is influenced not only by its surroundings but also to some extent by other points. In the 1970s, the increase in turbidity and pH probably reflects the acceleration of urbanization and the sediment input to EMMI02900. From the 1980s onwards, the degradation caused by domestic sewage became more relevant, although it was not so intense, probably due to the phenomenon of self-purification of the water column that flows from the other points (Beyruth et al., 1997). Nevertheless, the decadal averages of CT and BOD indicate that domestic sewage effects must be controlled.

The results show that pollution from domestic sewage has always exerted the greatest impact on the Guarapiranga reservoir, as the decadal averages of CT and PT concentrations exceeded the legal limits at all points and decades. One of the consequences was cyanobacteria blooms, which were more frequent (Beyruth, 2000; Fontana et al., 2014). For a long time, the solution for local management of the reservoir quality was preventing these blooms with algaecides (copper sulfate pentahydrate), resulting in the massive accumulation of copper in the sediments (Leal et al., 2017). Another outcome is the increased risk of waterborne diseases, mainly due to the presence of strains of pathogens with great potential for impact on public health (Orsi et al., 2007).

The watershed was the focus of local directives (state laws and decrees) that aimed to limit the activities taking place on the banks of the reservoir in order to improve environmental conservation. These directives built on earlier regulations intended to prevent further degradation of the reservoir, most significantly the 1975 Watershed Law (Marcondes, 1999). On a broader scale, the government of the state of São Paulo implemented the Guarapiranga Program in the 1990s with funding from the World Bank, aiming to control diffuse sewage pollution across the watershed (Baltrusis & Ancona, 2006; Whately & Cunha, 2006). These efforts slowed down the water quality degradation, as seen in the shortest distances between the centroids of the most recent decades in the PCA. However, the program should go further to revert the degradation trend and recover the water quality to the previous condition.

Conclusions

The application of multivariate statistics to a long-term data series of the monitoring program made it possible to refine the understanding of which were the most relevant variables for the spatio-temporal variation of water quality. In the Guarapiranga reservoir, water quality degradation took place at all monitoring points, although at different intensities and rates. At the beginning of the series, pH and turbidity prevailed, which should reflect the changes caused by the replacement of vegetated areas by dense and unplanned urban settlements, with associated erosion/silting processes. Later, diffuse pollution by sewage had become a major impact on water quality.

Despite the control of massive algae blooms and the Guarapiranga Program's implementation to control diffuse pollution in the watershed, water quality loss continued over time. If we suppose that basic sanitation infrastructure is not installed in the next few years, and households are not adequately connected to the system, water quality may reach a level of unavailability for supplying drinking water, due to the combination of local changes in land use and occupation, climate changes in progress, and the difficulty in controlling diffuse pollution in a very complex watershed.

Author Contribution DS conceived the project. DS and SZA collected the data. DM contributed the historical background and revised the text. DS, GL, and SZA interpreted the data and wrote the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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Availability of data and material All the data analyzed in this paper are freely available on Infoáguas System (https://cetesb.sp.gov.br/infoaguas/) and can be sent in consolidated form by the authors by request.

Declarations

Conflict of interest The authors declare no competing interests.

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