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# ENVIRONMENTAL RESEARCH
## LETTERS

**LETTER**

# Achieving sustainable water and land use systems in highly developed tropical landscapes

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## Abstract

Water quality degradation from human related activities has become a pressing global issue, putting water security at risk around the world. Land use decisions can severely degrade stream water quality, compromising water supply and increasing water treatment costs. Here we examine changes in water quality over 20 years and their association with land use, urbanization, and sewage treatment in the state of São Paulo, Brazil. We also consider how a severe drought in 2014–2015 affected water quality, uncovering the potential impacts of a changing climate on water treatment costs. We analyzed water quality data between 2000 and 2019 from 230 monitoring stations focusing on seven metrics: dissolved oxygen, biological oxygen demand, total nitrogen, total phosphorus, turbidity, total dissolved solids, and fecal coliforms. We first calculated the number of times that metrics exceeded the legal thresholds and then assessed if metrics were improving or deteriorating over time. Across all stations, a large proportion of stream water samples failed to comply to the legal standards for human consumption for at least one water quality metric. This proportion was highest for total dissolved solids (30.7%) and total phosphorus (42.8%), with fewer samples exceeding the threshold for turbidity and dissolved oxygen. Deteriorating water quality trends over time were prevalent for dissolved solids (33.33%) and total nitrogen (52.45%), while dissolved oxygen exhibited the highest percentage of improving trends across watersheds (43.63%). Moreover, we observed that four of the seven metrics analyzed deteriorated during the 2014–2015 drought. Urbanization and agricultural activity led to deterioration of water quality, while improvement in sewage treatment infrastructure improved water quality across watersheds. The decline in water quality observed in the region, especially during the recent drought, highlights the need to develop land use management strategies to protect water quality and reduce growing costs of water treatment in the state.

## 1. Introduction

One of today's most pressing challenges is ensuring an adequate supply of water in light of burgeoning and often conflicting human and ecosystem needs (Brauman *et al* 2007, Vörösmarty *et al* 2010). Declining water quality has become a global concern (Michalak 2016, Abbott *et al* 2019) and changes in land cover are one of the leading causes of water quality degradation worldwide (Giri and Qiu 2016). Land use decisions underlie important tradeoffs between

water use and quality (Malmer *et al* 2010). Many anthropogenic land uses have negative effects on water resources (Mello *et al* 2020). Point-source pollution via sewage discharge and increased runoff are major sources of water quality degradation in highly urbanized areas and a great concern for city managers worldwide (Walsh *et al* 2005, McGrane 2016). Degradation of water quality in urban catchments is further aggravated by deficiencies in sewage treatment infrastructure and inadequate disposal of untreated sewage (Salim Dantas *et al* 2021). Similarly,

intensive agriculture can significantly deteriorate water quality through widespread fertilizer addition to crop fields, soil erosion, and sediment and nutrient runoff (Schröder *et al* 2004, Ferreira *et al* 2012, Souza *et al* 2013, Taniwaki *et al* 2017). However, the diffuse nature of water pollution makes it difficult to assess and control and often reflects multiple interactions between the hydrological cycle and land use and land cover patterns (Mello *et al* 2020). Although the maintenance of native forests in human-modified watersheds offers a viable and efficient nature-based solution to protect or improve water quality (Keesstra *et al* 2018, Ferreira *et al* 2019, Piffer *et al* 2021), setting aside areas for watershed conservation often comes at the expense of arable and productive land. The challenges posed by developing sustainable water and land use systems have become a pressing global issue and a better understanding of these relationships is essential for efficient watershed management and land use planning targeted at protecting water quality (Mello *et al* 2020).

A changing climate adds further urgency to watershed management issues. Although the potential impact of climate change on water supply have received much attention (Whitehead *et al* 2009), less is known about its effects on water quality (Delpla *et al* 2009, Whitehead *et al* 2009). Increases in the number and frequency of extreme droughts and flooding presaged by a changing climate (Feng *et al* 2013, Mora *et al* 2013, Greve *et al* 2014) may compound the impacts of land use on water systems and jeopardizing future water provision (Grimm *et al* 2008). Floods and droughts directly affects dilution or concentration of different substances in streams and existing evidence suggests that extreme climate events often lead to degradation of water quality, placing a further burden on future water supply (Delpla *et al* 2009). For example, floods may dramatically increase pollutant loads due to higher surface runoff and sediment yields, while long drought periods may be accompanied by higher pollutant concentrations due to lower dilution, especially if the amount of effluents from point sources remains the same (Kundzewicz and Krysanova 2010). This emerging and complex issue will only intensify with the fast growing contributions of anthropogenic activities to climate change (Michalak 2016). Consequently, land managers must develop plans to minimize the pervasive impacts of human activities on water resources while also ensuring water provision under future climates (Piffer *et al* 2021), especially considering that the costs for water treatment are often exacerbated during extended periods of water shortage (Cunha *et al* 2016, Soriano *et al* 2016).

Here we use a comprehensive dataset from 230 sampling stations to examine changes in water quality between 2000 and 2019 and their association with land use and urbanization in the state of São Paulo in southeastern Brazil, a highly developed and densely populated tropical region. A major water crisis during a severe drought in 2014–2015 exposed the precariousness of the water supply system in the region (Nobre *et al* 2016, Soriano *et al* 2016, Empinotti *et al* 2019) and the growing costs of water treatment during drought (Cunha *et al* 2016), calling for the development of integrated water and land management plans. To assess temporal trends in water quality within our study period, we first calculated the proportion of samples for every monitoring station that exceeded the legal threshold for each metric and then determined if metrics were improving or deteriorating over time. We also investigated the effects of watershed landscape composition, urban population density, and sewage treatment on temporal trends in water quality. Finally, we examined if water quality deteriorated during a recent drought in the region.

## 2. Methods

### 2.1. Study area

Our study area includes the southern and eastern portions of the state of São Paulo (figure 1), a densely populated region with intense agricultural and industrial activity. Covering about 3% of the Brazilian territory, the state is home for 42 million people or 22% of the countrỳs population, including the São Paulo Metropolitan Area, with a population of 21 million. It is also the most economically developed region in the country, responsible for over 30% of the Brazilian Gross Domestic Product. The once-dominant forest cover has been drastically reduced to less than 14% of its original extent, following centuries of agricultural expansion followed by intense industrialization and urbanization in the early 20th century (Ribeiro *et al* 2009, Lira *et al* 2012) (figure 1). Today, the state's landscape can be considered of a mosaic of small forest fragments disperse in a matrix of anthropic land uses and most of the forest cover is conserved along a network of protected area along the coast (figure 1). Agricultural and industrial activities currently account for almost 80% of the water use in the state, with the remaining 20% allocated for household use (Dufek and Ambrizzi 2008).

The state of Sao Paulo is divided into 22 large watershed units (UGRHI or watershed management units) used for water resource planning and management (figure 1). These are classified into four different development categories according to the degree of economic activity: conservation, agricultural, under development and industrialized (São Paulo state Environmental Agency, CETESB 2020). For this study, we selected water sampling stations within eight of these planning units, which spanned three of these categories (conservation, under development, and industrialized) and contained sufficient data for robust parameter estimation. We excluded agricultural watersheds, largely in the north and west
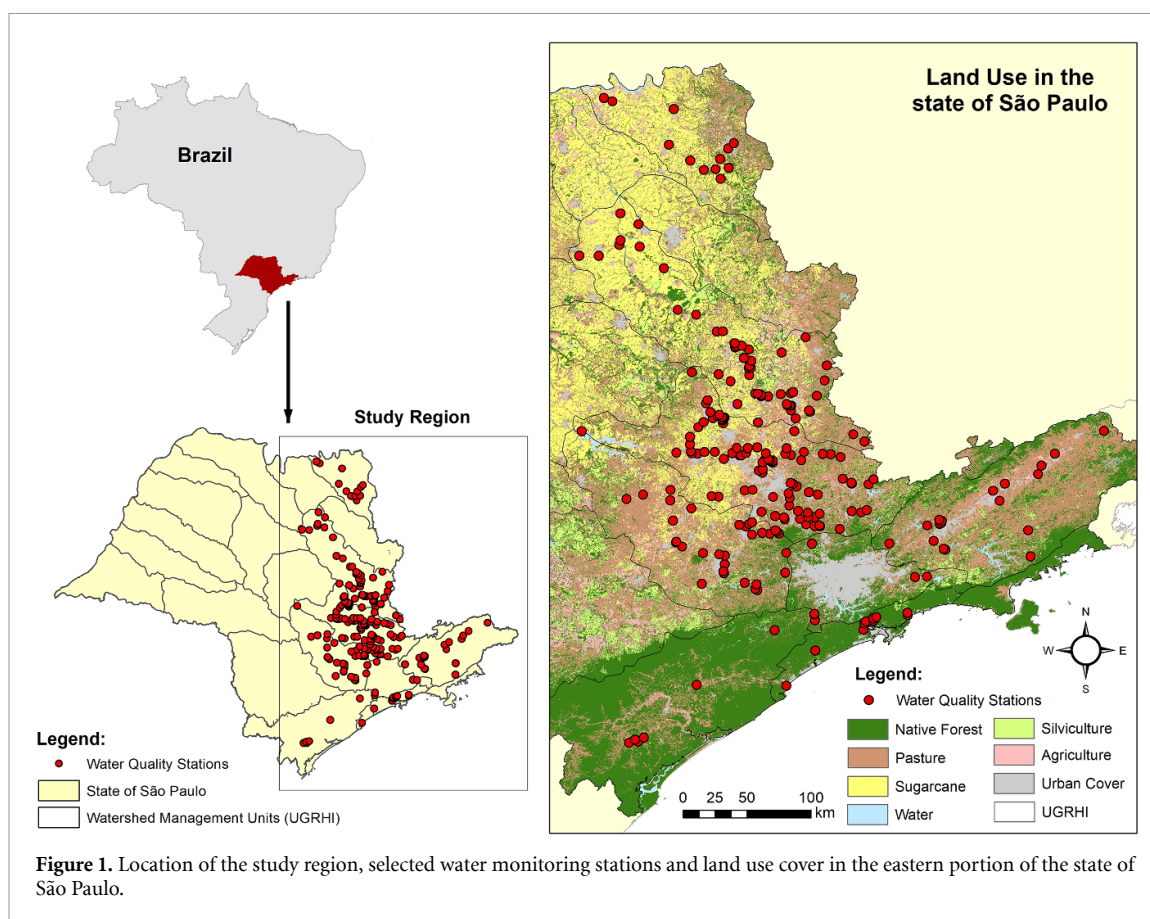
**Figure 1.** Location of the study region, selected water monitoring stations and land use cover in the eastern portion of the state of São Paulo.

**Table 1.** Number of samples collected for each water quality metric across 230 monitoring stations between 2000 and 2019. Legal thresholds indicate required values for streams to be considered suitable for human consumption after water treatment (classes 1–3). There are no established thresholds for total nitrogen and for coliforms, thresholds are based on the CONAMA resolution 357 of 2005. We also show the proportion of samples that did not meet this threshold and the percentage of stations with improving, deteriorating and no change trends for each metric.

| Metric | No. of samples | Legal threshold (units) | % Samples exceeding threshold | % Stations improving | % Stations deteriorating | % Stations with no change |
|---|---|---|---|---|---|---|
| Dissolved oxygen | 18 912 | 4 (mg $l^{-1}$ O$_2$) | 22.40 | 43.63 | 21.08 | 35.29 |
| Biological oxygen Demand | 18 847 | 10 (mg $l^{-1}$ O$_2$) | 14.04 | 29.90 | 24.50 | 45.60 |
| Total nitrogen | 12 499 | NA (mg $l^{-1}$) | NA | 6.87 | 52.45 | 40.68 |
| Total phosphorus | 16 949 | 0.15 (mg $l^{-1}$) | 42.80 | 29.90 | 20.10 | 50.00 |
| Turbidity | 18 396 | 100 (NTUs) | 9.24 | 10.30 | 7.35 | 82.35 |
| Total dissolved solids | 13 802 | 500 (mg $l^{-1}$) | 30.69 | 17.65 | 33.33 | 49.02 |
| Fecal coliforms | 10 493 | NA (units ml$^{-1}$) | NA | 24.03 | 9.80 | 66.17 |

of the state, due to the low the density of water monitoring stations.

### 2.2. Water quality and sewage treatment data

We used data from 230 water quality sampling stations monitored by the São Paulo State Environmental Agency (CETESB). Samples were collected once every two months from January 2000 through December 2019, including the 2014–2015 drought (table 1). For this analysis we selected seven commonly used metrics (Mello *et al* 2018b, Piffer *et al* 2021): dissolved oxygen (mg $l^{-1}$); biological oxygen demand (BOD) (mg $l^{-1}$); total nitrogen (mg $l^{-1}$); total phosphorus (mg $l^{-1}$); turbidity/ nephelometric turbidity units (NTUs); total dissolved solids (mg $l^{-1}$); and number of thermotolerant fecal coliforms (units ml$^{-1}$). Each of these metrics is associated with legal thresholds (table 1) that determine the allowable uses of water bodies which are: (a) suitable for human consumption after some level of treatment (classes 1–3); (b) navigation and scenic beauty (class 4); and (c) inadequate for human use (class 5)

(CONAMA resolution 357, 2005). For our analysis we established classes 1–3 as the minimum acceptable threshold for human consumption.

To investigate how differences in urban sewage treatment efficiency and urban population density between watersheds affected water quality, we obtained annual sewage treatment data at the municipality level from 2008 to 2019 for the entire state of São Paulo from CETESB, which included the percent of collected and treated sewage as well as the indicator of municipal urban population sewage collection and treatability (ICTEM) index. This index, developed by the agency, reflects the efficiency of the municipal urban sewage treatment system by incorporating parameters such as percent of sewage collection, efficiency of sewage treatment, appropriate destination of effluents, and disposal of untreated sewage. Due to higher data availability and reliability across the entire state (CETESB, personal communication) in the later years of the sewage treatment data and because we are interested in how differences in sewage treatment efficiency between watersheds affect water quality and not the temporal variation over time, we used the year 2019 as a reference for the analysis. Urban population data at the municipality scale was collected from the periodic demographic census conducted by the Brazilian Institute for Geography and Statistics for the years 2000, 2010 and 2016. Considering that urban population increased throughout the region during our study period and we our main interest is to analyze differences between watersheds, we used population density data the year 2010 as reference as it is the midpoint of our study period. We highlight that we did not investigate how changes in these socioeconomic variables over time affected water quality trends, but rather focused on the differences between watersheds, which can be considerable across the study region. Given that the socioeconomic data was collected at the municipality scale and many watersheds extended beyond the municipality boundaries, we calculated the area weighted mean for the sewage treatment and urban population density variables for each watershed to match the municipality scale data to the watershed scale. All calculations were done in Google Earth Engine.

### 2.3. Watershed delineation

We delineated the drainage area for each water sampling station based on 1:50 000 sub-watersheds maps (São Paulo, 2013) and adjusted the boundaries through visual interpretation of the digital elevation model ASTER GDEM 2 images (NASA, 2009). Watershed size for the water quality sampling stations ranged from 0.4 to 32 667 km$^2$ (Mean = 2141).

### 2.4. Land use cover data

We obtained land use cover data from MapBiomas (Collection 5), a time series of annual land use and land cover maps from 1985 to 2019 derived from Landsat imagery using Google Earth Engine and Random Forests (Souza *et al* 2020). Global accuracy for land use and land cover maps is 90.7%. Within each the watershed, we calculated the percentage of the following land use cover classes of interest from 2000 to 2019 (study period): (a) native forest; (b) silviculture (mainly Eucalyptus); (c) agriculture (perennial and annual crops); (d) sugarcane; (e) pasture; and (f) urban cover (figure 1). We separated sugarcane from other agricultural crops due to its relevance for the context of the state of São Paulo, which is the biggest sugarcane producer in Brazil. We then calculated the mean percentage of each land cover class for each watershed over the entire study period (2000–2019) to use in the analysis.
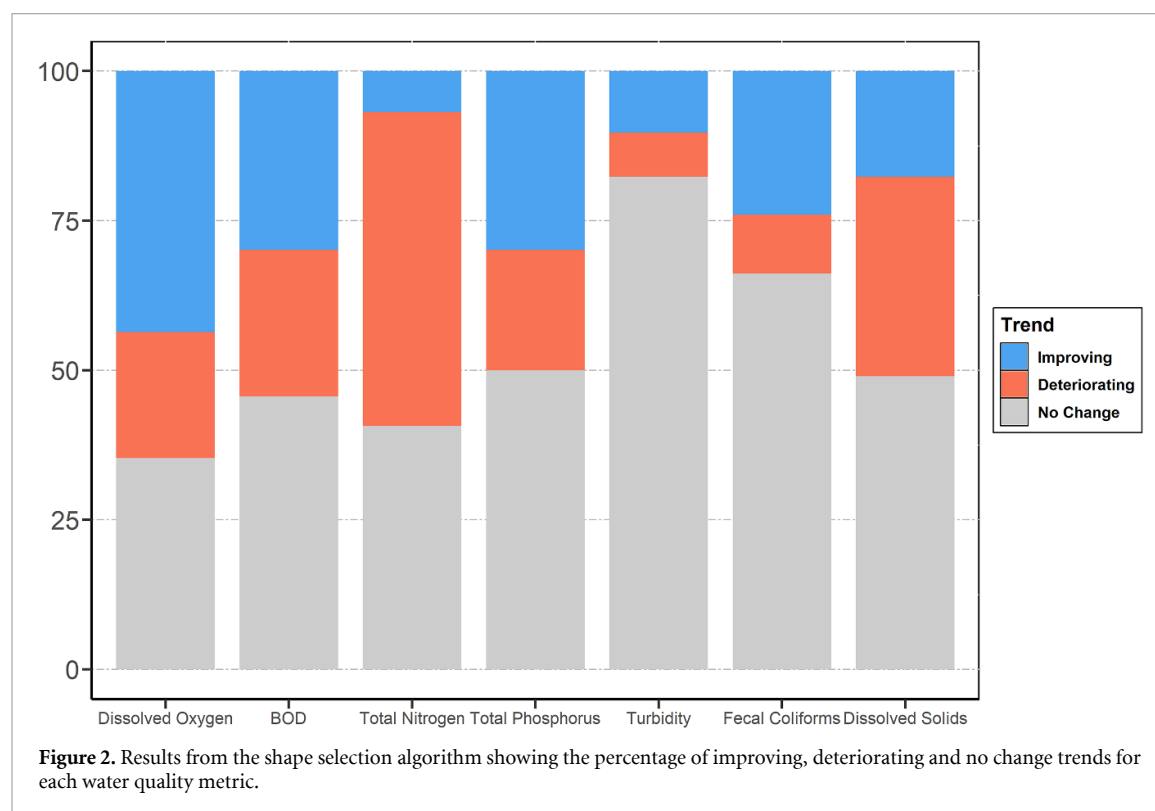
### 2.5. Statistical analyses

To assess temporal trends in water quality for each monitoring station, we first calculated the proportion of samples of each metric that exceeded the legal threshold between 2000 and 2019 (does not meet threshold for classes 1–3 for human consumption) (table 1). We then investigated if metrics were improving or deteriorating over time by using a shape selection algorithm designed for fitting trajectories to time series data (Moisen *et al* 2016). The algorithm uses non-parametric statistical methods to fit a set of discrete possible shapes or trajectories to a time series of data; it picks the optimal shape based on goodness of fit and a penalty for model complexity (Moisen *et al* 2016). We focused on three possible trajectories for our 20 year time series of water quality data: (a) flat (or no change over time); (b) decreasing; and (c) increasing. The best fit for each metric/time series was determined using Bayesian Information Criterion. With the exception of dissolved oxygen, an increasing trend over time indicate deterioration of the water quality metric within the watershed, while a decreasing trend have the opposite interpretation (decrease in the metric, therefore, an improving trend). We only analyzed the trends for those water quality stations that had more than 12 samples (>2 years of samples).

To investigate how differences in land use, sewage treatment efficiency and urban population density between watersheds affected trends in water quality, we correlated each predictor variable (six land cover classes, urban population density, ICTEM index and percent of treated sewage) with the proportion of samples that exceeded the legal thresholds over the study period, which was done separately for each metric.

Finally, to explore the potential effects of the 2014–2015 drought on water quality in the state of São Paulo, we used t-tests to compare values for each metric during drought versus non-drought years. For the drought years, we selected all samples collected in 2014 and 2015 (total of 2069 samples), while the non-drought years encompassed the remaining

**Table 2.** Number of stations with different proportion of samples that did not meet legal threshold required for human consumption for each metric (see section 2 for details and table 1 for legal thresholds).

| % Samples above legal threshold | Dissolved oxygen | Biological oxygen demand | Total phosphorus | Turbidity | Total dissolved solids |
|---|---|---|---|---|---|
| 0%–20% | 141 | 170 | 78 | 180 | 137 |
| 20%–40% | 22 | 11 | 40 | 25 | 20 |
| 40%–60% | 10 | 9 | 13 | 1 | 12 |
| 60%–80% | 17 | 8 | 20 | 0 | 10 |
| 80%–100% | 19 | 11 | 56 | 2 | 31 |



**Figure 2.** Results from the shape selection algorithm showing the percentage of improving, deteriorating and no change trends for each water quality metric.

of our study period, from 2000 to 2013 and from 2016 to 2019 (total of 17 135 samples) (appendix table 2). We opted to use t-tests instead of a one-way ANOVA due to very unbalanced sample sizes. All analyses were conducted using R Statistical software (R Development Core Team 2008).

## 3. Results

### 3.1. Temporal trends in water quality in the state of São Paulo

Our analysis of water quality data from 230 monitoring stations in the state of São Paulo uncovered a large variation in water quality compliance for different metrics (table 1; appendix table 1). Across all stations, a large proportion of stream water samples exceeded legal thresholds for total phosphorus and to a lesser degree, total dissolved solids, with fewer samples doing so for turbidity, dissolved oxygen and BOD (tables 1 and 2; appendix figure 1). For example, in 89 out of 230 stations, total phosphorus concentrations exceeded the legal threshold for more than 40% of the samples and for 56 stations, more than 80% of

the samples exceeded the threshold (table 2). On the other hand, only three stations had more than 40% of the samples exceeding the legal threshold for turbidity (table 2). A large proportion of the samples exceeded the legal threshold for at least one metric (table 2; appendix figures 2–4). However, we were not able to identify clear and discernible spatial patterns across the sampling stations (appendix figures 2–4).

Failure to meet water quality standards does not indicate whether water quality is deteriorating or improving over time. Deteriorating trends prevailed for dissolved solids and total nitrogen, while dissolved oxygen mostly exhibited improving trends (table 1; figure 2; appendix figures 5–8). Total phosphorus, BOD, turbidity and fecal coliforms presented a balance between stations with improving and deteriorating trends, with a slight predominance of improving trends (table 1; figure 2; appendix figures 5–8). However, we also detected no change for a large number of stations and metrics (table 1) with only a handful of stations had either significant improving or deteriorating trends for several water quality metrics (figure 3).
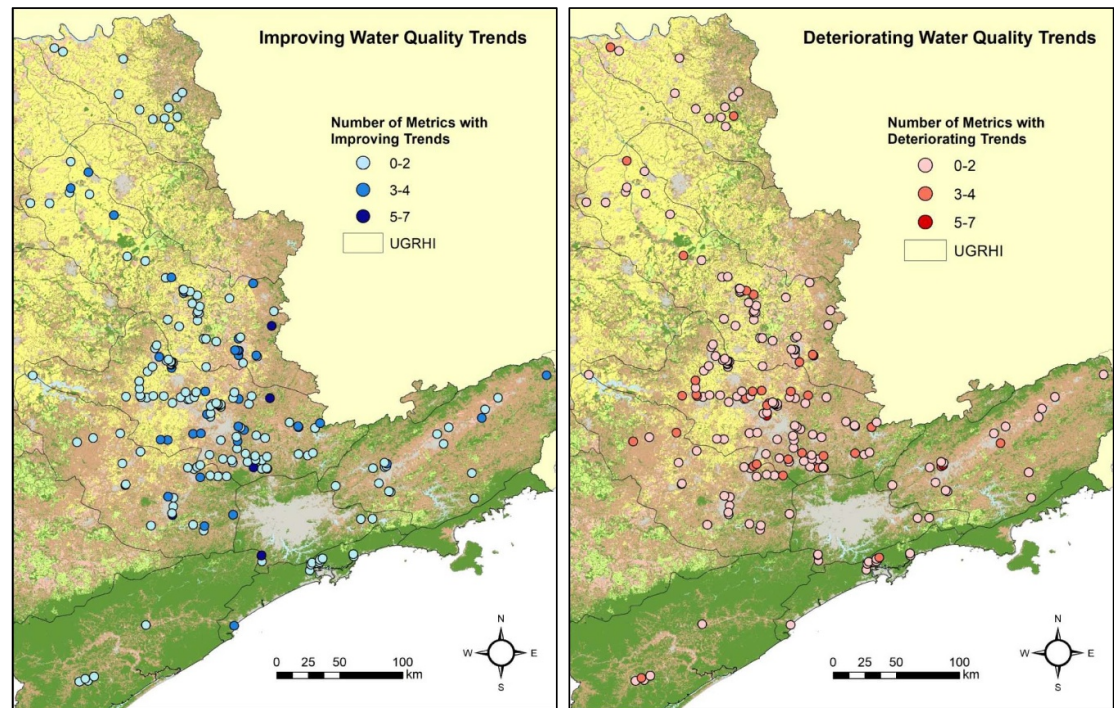
**Figure 3.** Number of metrics with significant improving (left) or deteriorating (right) trends for each of the 230 water monitoring stations in our study region.

Finally, we found that water quality was significantly lower during the 2014–2015 drought in the state of São Paulo, as four of the seven metrics analyzed deteriorated during that period. Overall, dissolved oxygen levels were 2.34% lower (mean values) during the drought while stream concentrations of BOD (8.16%), total nitrogen (120%) and phosphorus (40.5%) increased substantially during that period (figure 4; appendix table 2). Not surprisingly, the only metric that improved in 2014–2015 was turbidity, which had significant lower values (24.8%) during the drought when compared to the remaining years (figure 4; appendix table 2). We did not find a significant difference for dissolved solids and could not investigate the effect of the drought on fecal coliforms, as the temporal series for that metric ended in 2014.

**3.2. Links between use coverland, urbanization, sewage treatment and water quality compliance**
Across the entire dataset, we detected significant relationships between the proportion of water quality metrics falling outside legal thresholds and watershed land cover, urbanization and sewage treatment (table 3). The percentage of treated sewage is negatively associated with the number of samples falling outside of the legal limits for dissolved oxygen and turbidity, while urban population density is positively associated with the proportion for dissolved oxygen, BOD and total phosphorus (table 3). High urban cover within the watershed also had a pervasive negative effect on water quality compliance, having a positive association with the number of samples

outside the legal threshold for four of the five analyzed metrics. On the other hand, high proportions of native vegetation, silviculture and pasture cover in watersheds increased compliance across all metrics (table 3). Finally, watersheds with a high proportion of agriculture had low compliance for dissolved oxygen, BOD and dissolved solids.

## 4. Discussion

Our analyses of 20 years of water quality data in the state of São Paulo identified significant issues for water resources management in the region. Across all stations, a large proportion of stream water samples failed to comply with the legal standards, albeit with considerable variation between metrics. Although we found marked deterioration trends over time for total nitrogen and dissolved solids, other metrics such as dissolved oxygen had a relatively high number of stations with improving trends. Our results suggest that water quality deterioration is a significant problem in the region, especially for some metrics, and costs for water treatment for human consumption could increase significantly in the near future, putting water provision at risk due to contamination. This scenario could be further aggravated under increasing drought frequency in the region, as water quality in the state of São Paulo was significantly lower during the 2014–2015 drought.

Nevertheless, it is important to highlight that legal compliance and prevalence of improving or deteriorating trends differed considerably across the seven
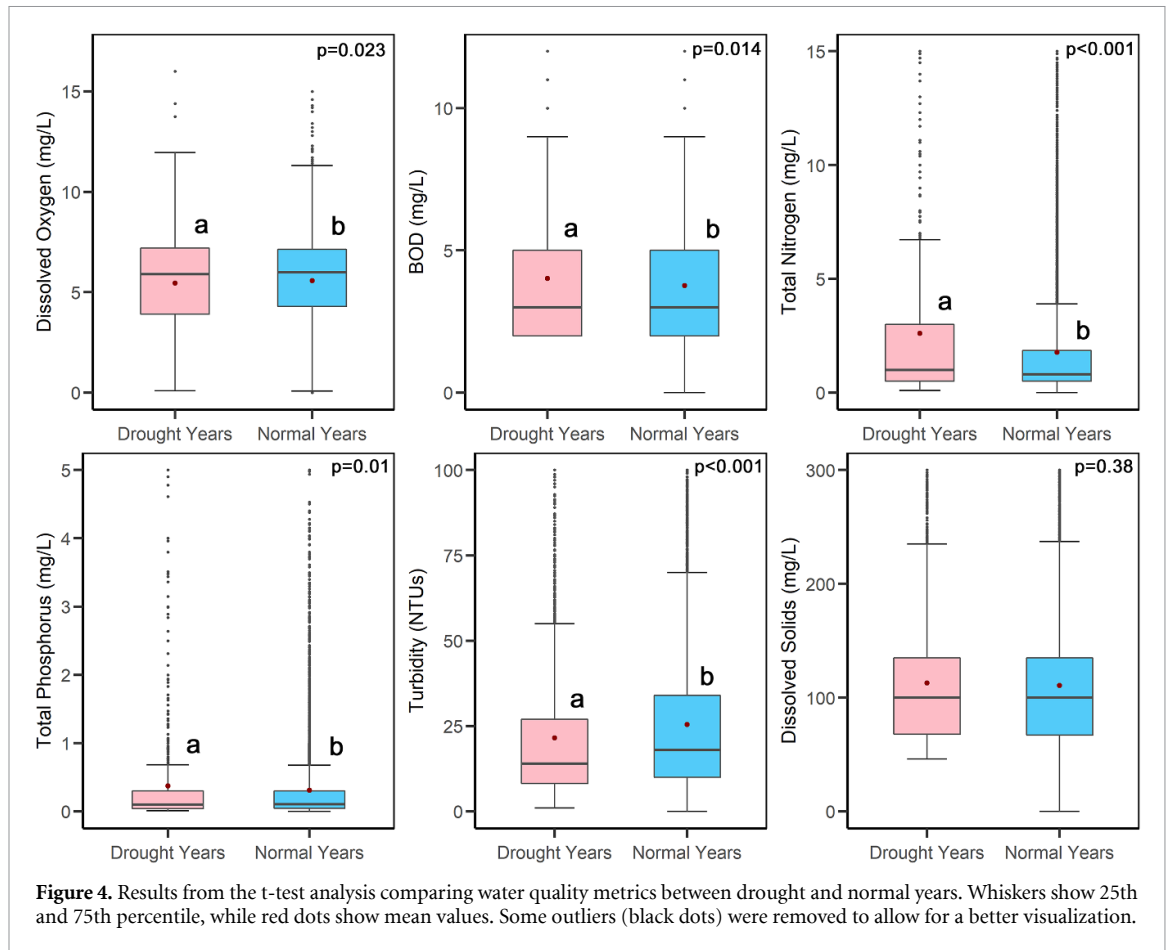
**Figure 4.** Results from the t-test analysis comparing water quality metrics between drought and normal years. Whiskers show 25th and 75th percentile, while red dots show mean values. Some outliers (black dots) were removed to allow for a better visualization.

**Table 3.** Relationship between the proportion of samples that fail to meet water quality standards and the percentage of each land use cover class within the watershed, urban population density and sewage treatment.

| % Samples above threshold | ICTEM | % Treated sewage | Urban pop density | % Urban cover | % Native forest | % Silviculture | % Pasture | % Agriculture | % Sugarcane |
|---|---|---|---|---|---|---|---|---|---|
| Dissolved oxygen | −1.94 | **−0.23** | **0.006** | **0.51** | **−0.25** | −1.00 | **−0.41** | **1.90** | 0.06 |
| | ($p = 0.10$) | (***p* = 0.01**) | (***p* = 0.03**) | (***p* < 0.001**) | (***p* = 0.01**) | ($p = 0.21$) | (***p* = 0.005**) | (***p* < 0.001**) | ($p = 0.61$) |
| BOD | 0.18 | −0.06 | **0.01** | **0.85** | **−0.16** | **−2.37** | **−0.54** | **0.76** | −0.04 |
| | ($p = 0.85$) | ($p = 0.44$) | (***p* < 0.001**) | (***p* < 0.001**) | (***p* = 0.04**) | (***p* < 0.001**) | (***p* < 0.001**) | (***p* = 0.04**) | ($p = 0.66$) |
| Total phosphorous | 1.73 | 0.10 | **0.01** | **0.85** | **−0.29** | **−2.21** | −0.25 | 0.61 | −0.17 |
| | ($p = 0.22$) | ($p = 0.35$) | (***p* = 0.003**) | (***p* < 0.001**) | (***p* = 0.01**) | (***p* = 0.02**) | ($p = 0.16$) | ($p = 0.25$) | ($p = 0.21$) |
| Turbidity | −0.33 | **−0.08** | −0.0004 | 0.016 | **−0.12** | −0.19 | 0.07 | 0.09 | 0.02 |
| | ($p = 0.48$) | (***p* = 0.03**) | ($p = 0.72$) | ($p = 0.79$) | (***p* = 0.001**) | ($p = 0.55$) | ($p = 0.24$) | ($p = 0.60$) | ($p = 0.61$) |
| Dissolved solids | −1.56 | −0.22 | 0.009 | **0.90** | −0.27 | **−2.71** | **−0.61** | **1.84** | 0.01 |
| | ($p = 0.44$) | ($p = 0.15$) | ($p = 0.07$) | (***p* < 0.001**) | ($p = 0.11$) | (***p* = 0.05**) | (***p* = 0.01**) | (***p* = 0.01**) | ($p = 0.93$) |

water quality metrics. Some metrics such as dissolved oxygen, turbidity and fecal coliforms had a higher number of stations with improving or no change trends and a relatively low percentage of samples exceeding the legal thresholds. This could potentially be related to improvements in sewage collection and treatment in the state, although infrastructure investment remains a key issue for water governance in the region (Empinotti *et al* 2019). On the other hand, metrics such as total phosphorus, total nitrogen and dissolved solids had either high percentages of samples above the legal limits or a predominance of deteriorating trends over time, which may indicate either lack of compliance with environmental guidelines or insufficient treatment for these

metrics. These results provide pivotal information for future infrastructure investments targeted at improving water quality in the region.

Our results highlight the pervasive negative effects of urbanization on water quality (Cunha *et al* 2011, 2016, Uriarte *et al* 2011, Mello *et al* 2018a, Piffer *et al* 2021). Urban population density and higher percentages of urban cover within the watersheds had a positive correlation with the number of samples not meeting the legal thresholds for four of the five metrics with established limits. Urban areas exert a disproportionately large influence on water quality despite usually comprising only a small portion of the catchment areas (Mello *et al* 2020, Piffer *et al* 2021) and the lower water quality compliance in urbanized watersheds

underscores the pervasiveness of domestic and industrial discharge as major sources of pollutants (Allan 2004, Walsh *et al* 2005, McGrane 2016). The fact that high sewage treatment levels (ICTEM index and percentage of treated sewage) elevated compliance for dissolved oxygen and turbidity highlights the importance of appropriate collection, treatment and disposal of domestic and industrial effluents in protecting water quality (Martinelli *et al* 2002, Cunha *et al* 2016). Our findings further reinforce previous studies conducted in the state of São Paulo and suggest that insufficient and/or inadequate sewage treatment and inappropriate wastewater disposal may be largely responsible for the poor quality of surface waters in urban catchments (Martinelli *et al* 2002, Cunha *et al* 2011, Mello *et al* 2020, Piffer *et al* 2021).

Higher percentages of less intensive land uses, such as native forest cover, silviculture (mostly eucalyptus) and pasture, were generally associated with higher compliance in water quality. Native forest cover had a negative association with the percentages of samples not meeting the legal thresholds for dissolved oxygen, BOD, total phosphorus and turbidity. Native forest cover has been associated with better overall water quality in previous studies conducted in the region (Mello *et al* 2018a, 2018b, Piffer *et al* 2021) and the presence of riparian forested buffers is particularly important for maintaining stream water quality (Ferreira *et al* 2012, 2019, Souza *et al* 2013, Tanaka *et al* 2016, Mello *et al* 2017, Piffer *et al* 2021). Similarly, silviculture increased compliance for BOD, total phosphorus and dissolved solids. This was already expected as non-native tree cover, namely eucalyptus plantations, usually have little effect on water quality and contribute to less contamination from fertilizers and erosion when compared to other cultures (Piffer *et al* 2021). A recent review suggests that the lower impact of plantation forestry than other crops on water quality could be attributed to recent improvements in management practices (Mello *et al* 2020). A high proportion of pasture lands in watersheds also had a negative association with the number of samples outside the legal limits for dissolved oxygen, BOD and dissolved solids.

On the other hand, agriculture, both permanent and perennial crops, had a positive association with the number of samples outside the legal thresholds for dissolved oxygen, BOD and dissolved solids, reinforcing that agricultural practices are a major cause of water quality degradation in Brazil (Mello *et al* 2020). Fertilizer runoff from agriculture is a significant sources of pollutants and nutrients to streams, which can lead to eutrophication of water bodies (Mori *et al* 2015, Taniwaki *et al* 2017). Finally, sugarcane had no significant correlations with water quality compliance. We expected sugarcane to have a stronger effect on water quality compliance, especially

considering that it has been identified as a significant source of stream nitrogen and a major issue for water quality in the state of São Paulo (Filoso *et al* 2015, Mori *et al* 2015, Taniwaki *et al* 2017, Piffer *et al* 2021).

The significant decline in water quality observed during the drought years is a key result of our analysis. Recent studies suggest an increase in floods and droughts in the state of São Paulo, which can severely increase water insecurity in the region (Gesualdo *et al* 2019). Stream total nitrogen and phosphorus levels were higher during the drought years, showing that lower dilution under reduced water availability can lead to higher nutrient concentrations (Delpla *et al* 2009, Kundzewicz and Krysanova 2010). These increases in nitrogen and phosphorus concentration could explain the lower dissolved oxygen and higher BOD levels, as both nutrients are major causes of eutrophication of water bodies (Schröder *et al* 2004, Taniwaki *et al* 2017). The lower turbidity values observed during the drought when compared to the remaining years can be explained by the reduced surface runoff and sediment input to streams during this low rainfall period.

Our findings highlight the need to incorporate land use decisions and management strategies in order to reduce contamination, safeguard water quality, and guarantee future water provision in the state of São Paulo. The development of sustainable water and land use systems become even more important under unpredictable future climates, where guaranteeing the quality and quantity of surface waters is crucial to secure water provision for both human and ecosystem use during extended dry periods (Gesualdo *et al* 2019). Our analysis showed that four out of the seven water quality metrics deteriorated during the 2014–2015 drought and the poor quality of surface waters further aggravated the water crisis during that period (Soriano *et al* 2016, Empinotti *et al* 2019). Potential land use solutions should include watershed restoration with native vegetation, especially riparian areas (Ferreira *et al* 2019, Piffer *et al* 2021), as well as better management practices in intensive land uses such as agriculture (Mello *et al* 2020). These are efficient and cost-effective nature-based solution to secure water resources in highly developed locations and can lead to systems with higher resilience to anthropogenic or climatic changes (Lafortezza *et al* 2018). Besides land use decisions, investment in sewage treatment infrastructure is also essential considering the high rates of samples exceeding legal limits and deteriorating water quality trends (Empinotti *et al* 2019). Our analysis allowed us to identify significant trends in water quality over a large number of watersheds in the last 20 years that could support watershed management and policy making not only in the state of Sao Paulo but also in other highly developed regions.

## Data availability statement

## Acknowledgments

## Author contributions

P R P, L R T and M U conceptualized the paper. P R P, L R T and M U developed analyses methods. P R P conducted the formal analysis. P R P and M U wrote the first draft and all authors contributed to the final draft.

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