Water Air Soil Pollut (2022) 233: 73
https://doi.org/10.1007/s11270-022-05553-5

Four-Month Assessment of Water Quality in a Channeled Urban Stream in São Paulo State, Brazil

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Received: 27 October 2021 / Accepted: 10 February 2022 / Published online: 19 February 2022

Abstract The Metropolitan Region of São Paulo (MRSP) faces an intense water crisis, which requires measures to guarantee water supply. However, it neglects urban water bodies, often using them as sewage receptors. To improve the quality of urban rivers, it is necessary to study and to mitigate the sources of pollutants. Thus, the objective of this study was to evaluate the Water Quality Index (WQI) of the Comprido stream, an urban freshwater ecosystem which flows into the Tamanduateí River and this to Tietê River, the most important river of São Paulo State, Brazil. Eight occasions over 4 months in 2017 of surface water were conducted at three sampling stations along the longitudinal axis of the stream. The following parameters were evaluated in triplicate: pH, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand (COD), temperature, apparent color, turbidity, total solids, total dissolved solids, total suspended solids, sedimentable solids, electrical conductivity (EC), ammonia nitrogen, total phosphorus, and coliforms. The water quality parameters and the WQI revealed an alarming scenario regarding the environmental and sanitary conditions of Comprido stream. COD (up to 1,000 mg L^{-1}) and EC (~500 µS cm^{-1}) presented very high values. The WQI was always between bad and very bad (20–40), which allows us to conclude that the waters of the Comprido stream are quite degraded. The pollution was associated with sewage discharges. The study points to the need to carry out the integrated management of urban micro-watersheds to preserve streams and, consequently, improve the quality of adjacent water bodies and the maintenance of ecosystem services to the population.

Keywords Anthropogenic impacts · Bad management · Micro-basin · Organic matter · Water Quality Index

1 Introduction

Urban streams have a very important role in the maintenance of ecosystem services to the population (e.g., biological diversity and habitat provision, prevent flooding and moderation of heavy rainfalls, water purification, pollutant retention, climate regulation, physical and mental recreation, water supply, and landscape harmony) (Haase, 2015; Ranta et al., 2021). However, the disordered urbanization causes pressures in streams, bringing some problems, such as occupation of banks,

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11270-022-05553-5.

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which affects flooding events; covering of streams and rivers, blocking photosynthesis and the ability to self-clean and landscape harmony; runoff pollution; and water contamination by sewage discharges and the disposal of solid waste. Domestic wastewater has a high biodegradable fraction and a low ratio of chemical oxygen demand (COD)/biological oxygen demand (BOD) (Von Sperling, 2007). Depending on the industrial process, the industrial wastewater can have contaminants such as potentially toxic metals, organic pollutants, and poorly biodegradable pollutants, with a high ratio of COD/BOD (Ahmed et al., 2021; Von Sperling, 2007), and high values of COD. When it is considered the COD and total suspended solids from the urban runoff, industrial areas have more pollutant loads followed by commercial and residential areas (Zhang et al., 2021). Presence of nutrients, favorable climate conditions, and degraded riparian vegetation are factors that cause proliferation of algal and macrophyte (Bareuther et al., 2020; Wiederkehr et al., 2020), especially in tropical streams (Wiederkehr et al., 2020). Thus, anthropogenic activities can negatively impact the quality of surface waters in urbanized regions (Inostroza et al., 2018; Liu et al., 2014; Markogianni et al., 2018; Miagostovich et al., 2020). The pollution of streams and rivers causes health issues, e.g., bathing and associated sanitary practices explain ~ 7.5% of diarrhea-related deaths annually in Indonesia (Garg et al., 2018). Yet, urban stream pollution decreases the price of buildings in the region, causing economic losses to the population (Chen & Li, 2018).

Identifying the causes of declining water quality and their geographical location is necessary for reducing the deterioration and implementing strategies for its improvement. The procedures for water quality management require a measurable definition of what constitutes water quality (Liu et al., 2018; Srebotnjak et al., 2012). Therefore, the pollution control and water resource management depend on the water quality assessment that permits identifying the contributors to spatial and temporal variations on its quality (Wu et al., 2018). Spatial and temporal variations in water quality are common and depend on the type of source of pollution and the effects of seasons; may occur dilution of contaminants during periods of higher rainfall (Barrenha et al., 2018; Qadir et al., 2008). However, data from freshwater pollution, especially to streams, frequently are unavailable (Excell & Moses, 2017; Garg et al., 2018).

A Water Quality Index (WQI) is important for the understanding and dissemination of a water ecosystem's health, since the concentration of individual pollutants has little meaning for the population in general (Von Sperling, 2007). Therefore, the WQI is a form of communication to citizens and policy makers about the conditions of a water body (Wertz & Shank, 2019). The WQI consists of the use of variables that correlate with changes (anthropogenic or natural origins), occurring in the micro-basin (Toledo & Nicolella, 2002) through physical, chemical, and biological parameters that are combined into a single score (Kavurmacı & Karakuş, 2020).

There are several types of WQI, such as Liebmann and Harkins, developed based on physical–chemical characteristics (Toledo & Nicolella, 2002). Water Quality Index diversity demonstrates that there is no single set of parameter values that summarize and define all possible parameters that define the water quality (Srebotnjak et al., 2012).

Brazil, the USA, and England use WQIs based on the model developed by NSF (National Sanitation Foundation), created through an opinion poll with several specialists, who selected the relevant physical, physical–chemical, and biological parameters of water quality, accompanied by a relative weight for each of them, according to their importance in the calculating of the WQI (Brown et al., 1970; Von Sperling, 2007).

In Brazil, the following instruments for water resources management have been implemented: (I) river basin plans, which define management actions, programs, projects, and investments that have priority for the basin; (II) classification of water bodies according to their preponderant use (Table 1); (III) water permits, water usage charges, with the revenue to be invested in the basin, and the water resources information system (Veiga & Magrini, 2013). In the classification of water bodies for each class, there are a set of conditions and water quality standards required for a preponderant use, which guaranteed the necessary quality to attend a predicted use (Brasil, 2005).

Thus, considering the importance of streams to the maintenance of water quality of adjacent rivers and other ecosystems services to population, the present study had as objective to assess the water quality

Table 1 Framing classes of surface freshwater ecosystems in Brazilian legislation (National Environmental Council, CONAMA)

Framing	Multiple uses
Special class	Water intended for human consumption after disinfection; preserving the natural balance of aquatic communities; preservation of aquatic environments in fully protected conservation units
Class 1	Waters intended for human consumption after simplified treatment; protection of aquatic communities; primary contact recreation, such as swimming, water skiing, and diving; irrigation of vegetables that are eaten raw and fruits that grow close to the ground and are eaten raw without film removal; protection of aquatic communities in Indigenous lands
Class 2	Waters intended for human consumption after conventional treatment; protection of aquatic communities; primary contact recreation, such as swimming, water skiing, and diving; irrigation of vegetables, fruit plants and parks, gardens, sports, and leisure fields, with which the public may come into direct contact; aquaculture and fishing activities
Class 3	Waters intended for human consumption after conventional or advanced treatment; irrigation of trees, cereal, and fodder crops; amateur fishing; secondary contact recreation; and animal watering
Class 4	Waters for navigation; and landscape harmony

Adapted from Brasil (2005)

of a tropical urban stream (Comprido stream) using the Water Quality Index (WQI). This ecosystem was chosen because it flows to Tamanduateí River and after to Tietê River, the most important river of São Paulo State, and represents a good example of what is happening with our streams in urbanized regions in Brazil. We emphasize that data from our streams are completely scarce.

Considering the area of the Comprido stream micro-basin of 1.95 km^2 (SEMASA, 2017), and the population density of the municipality of 3,952 inhabitants km^{-2} (SEADE, 2021), the micro-basin has an estimated population of ~ 7,706 inhabitants. Furthermore, Comprido stream is located behind residential and commercial lots, is a natural water course that has human intervention with complete canalization (concrete channel), and the region is susceptible to flooding in rainy periods (Rosseto, 2020) increasing the health and security risk to the local population.

2 Material and Methods

2.1 Study Area

The Comprido stream is one of several streams affluent to the Tamanduateí River, which is the main drainage channel of the industrial region called “ABC Paulista” (SAMA, 2004). The Tamanduateí River flows into the Tietê River, in the municipality of São Paulo, Brazil. The Comprido stream is classified as class 4 by the São Paulo State Basin Committee, according to CONAMA nº 357 (Brasil, 2005), having its multiple uses defined as waters intended for navigation and contribution to landscape harmony. The Comprido stream region is characterized by mixed land use, encompassing trades, public areas, squares, gas stations, and, predominantly, residences (Fig. 1). These have the most diverse construction patterns, which characterizes a disorderly urban occupation. There are no industries in this micro-basin (Rosseto, 2020).

The Comprido stream (Fig. 2) is about 2 km long, 4.23 m wide, average depth of 0.23 m, and average flow of 0.18 $m^3 s^{-1}$. Its bed is rectified and channeled (closed section upstream and open section downstream) to increase its flow capacity and to prevent flooding and erosion. In the field, it was noticed several effluent point sources, mostly from the residences and businesses around, as well as solid waste disposal, from small objects to tables and sofas. The water body is entirely channeled (concrete channel) (Rosseto, 2020) (Fig. 2) which reduces the possibility of groundwater infiltration.

2.2 Water Quality Monitoring

Eight sampling campaigns were conducted between September 2017 and December 2017 (wet period) in three sampling stations along the Comprido stream longitudinal axis, in the stretch with open section: station 1 (23° 38′ 29.2″ S 46° 31′ 19.3″ W), located approximately in the downstream of the Comprido stream, one of the first points accessible; station 2

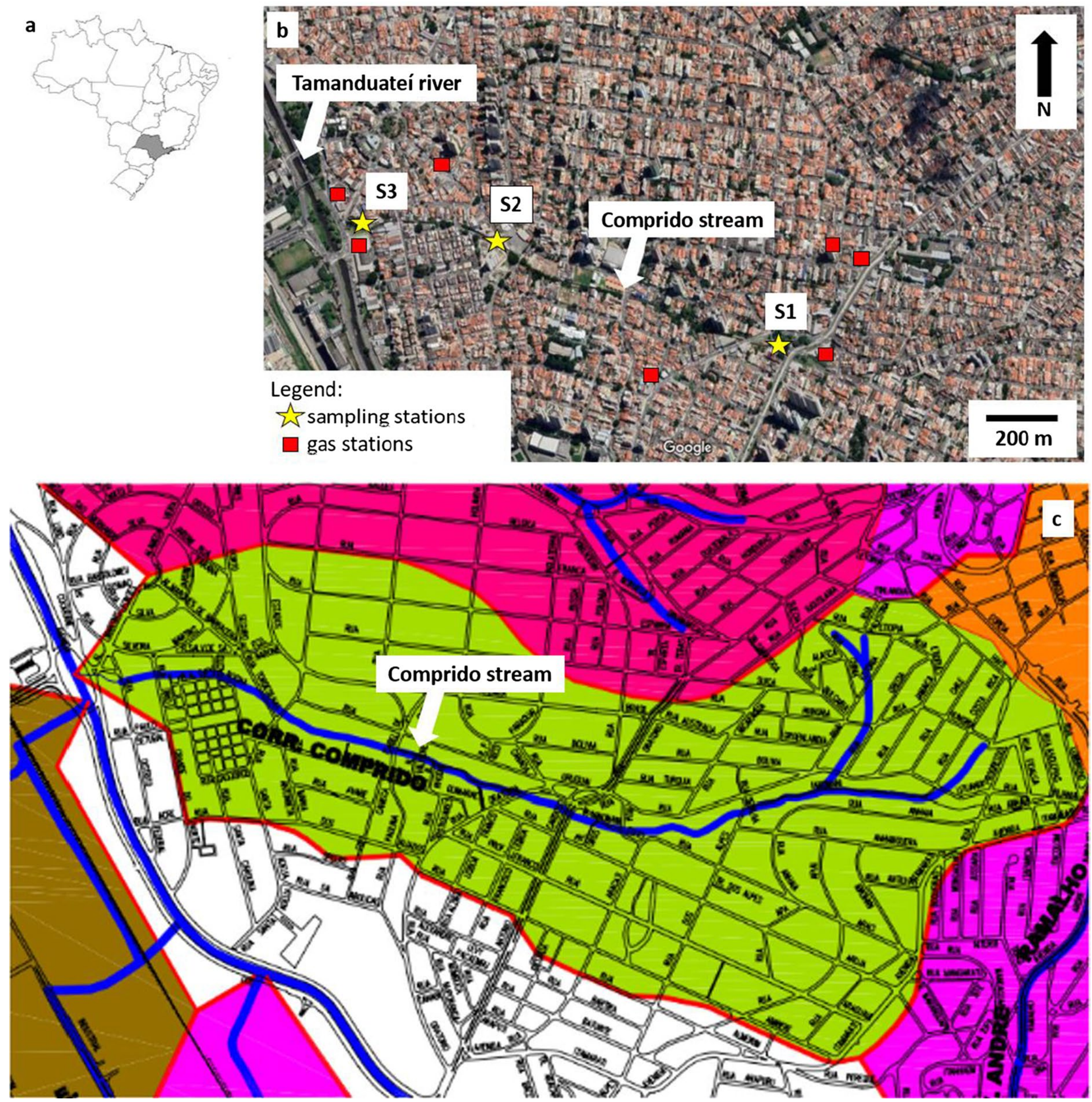

Fig. 1 Study area. **a** São Paulo State location (in gray) in Brazil; **b** sampling stations (S1, S2, and S3) at Comprido stream, which flows to Tamanduateí River, and gas stations; **c** Comprido stream micro-basin area (green). Sources: b adapted from Google (CNES/Airbus, Maxar Technologies 2021); c SEMASA, 2017

(23° 38′ 19.1″ S 46° 31′ 47.3″ W), central portion of the water body; and station 3 (23° 38′ 18.0″ S 46° 32′ 00.5″ W), location nearest the mouth of the Tamanduateí River (Fig. 1).

In this region of Brazil, the wet period is from September to March and the dry period is from April to August (Benassi et al., 2021; Coelho et al., 2020; Lima & Rueda, 2018; Valverde et al., 2020). Figure 3 shows the monthly precipitation (mm) in Santo André municipality in the year of the study (2017), as well as the comparison with historical data (1999–2016) to the region (Data from CEMADEN—National Center for Monitoring and Natural Disaster Alerts, previously published by Valverde et al., 2020). Regarding

Fig. 2 Current condition of Comprido stream: **a** channeled bed; **b**, **c**, and **d** examples of domestic sewage discharges along the water body; **e** example of building in the banks of the stream. Source: authors

the sampling period of the present study, it can be noticed that September presented low rainfall values, but October to December had typical values of a rainy period.

The samples were collected in areas without water stagnation, far from the curved internal margins and without water reflux. Sampling was simple and direct, performed on different days and times, to obtain the integrated characterization of the object of study (Von Sperling, 2007). The samples were packed in polyethylene and amber glass bottles, as suggested by their methodologies, properly decontaminated. The transfer to the laboratory was performed in an ice cooler to preserve the natural conditions of the samples. Table 2 summarizes the methods used to determine the physicochemical parameters required to calculate the Water Quality Index (WQI).

2.3 WQI Calculation

The WQI, described in Von Sperling (2014), was developed by the National Sanitation Foundation (Brown et al., 1970). This index involves nine relevant variables to assess water quality. It is noteworthy

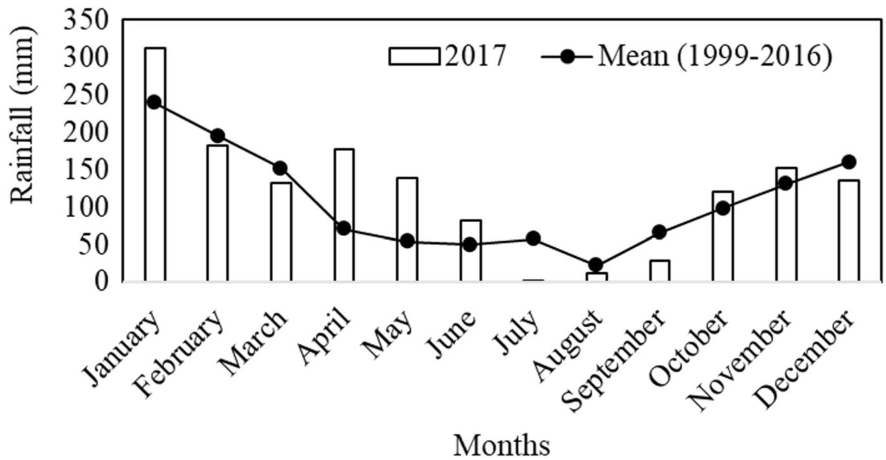

Fig. 3 Monthly rainfall (mm) in Santo André municipality in the year of the study (2017), as well as the comparison with historical data (1999–2016) to the region. Source: elaborated by the authors using CEMADEN data

Table 2 Physicochemical, physical, and biological variables and their analytical methods

Parameters	Analysis location	Analysis period	Replicates	Sample preservation	Methods	Equipment	Reference
Ammonia nitrogen, $N\text{-}NH_4$	Laboratory	Posterior	3	Plastic bottle under refrigeration (< 10 °C)	4500NH3B and 4500NH3C — distillation and titrimetric	Nitrogen distiller and automatic titrator	APHA (2012)
Biochemical demand of oxygen, BOD_5	Laboratory	Sampling date	3	1% dilution	Potentiometric	Oxygen probe	-
Chemical oxygen demand, COD	Laboratory	Sampling date	3	-	5220 D — closed reflux	Block digester and spectrophotometer	APHA (2012)
Dissolved oxygen, DO	In situ	Sampling date	3	-	Potentiometric	Oxygen probe	-
pH	In situ	Sampling date	3	-	Potentiometric	Multiparameter probe	-
Temperature	In situ	Sampling date	3	-	Potentiometric	Multiparameter probe	-
Thermotolerant coliforms	Laboratory	Sampling date	3	-	Presence or absence	Vertical autoclave, incubator, and analytical balance	FUNASA (2013)
Total phosphorus, TP	Laboratory	Posterior	3	Plastic bottle under refrigeration (< 10 °C)	Persulfate digestion and 4500P E — ascorbic acid	Vertical autoclave and spectrophotometer	APHA (2012)
Total solids, TS	In situ	Sampling date	3	-	Potentiometric	Multiparameter probe	-
Turbidity	Laboratory	Sampling date	3	-	Potentiometric	Turbidimeter	-

Authors

Table 3 Water Quality Index (WQI) classification by National Sanitation Foundation

Classification	Color	WQI range
Excellent	Blue	$90 < WQI \leq 100$
Good	Green	$70 < WQI \leq 90$
Medium	Yellow	$50 < WQI \leq 70$
Bad	Orange	$25 < WQI \leq 50$
Very bad	Red	$0 < WQI \leq 25$

that the calculation methodology for the determination of the WQI, proposed by Von Sperling (2014), was adapted according to the availability of laboratory equipment. Thus, the total nitrogen analysis could not be performed, thus adopting the ammonia nitrogen instead. The WQI was calculated as a product of the individual scores of each parameter, raised to their respective weights (Eq. 1). The water quality classification was performed according to Table 3, considering the NSF ranges (Von Sperling, 2014).

$$WQI = \prod_{i=1}^{n} q_i^{w_i} \quad (1)$$

where q_i = quality of the ith parameter calculated based on the equations in Table S1 (Supplementary Material); w_i = weight corresponding to the ith parameter (between 0 and 1) depending on its importance; i = number of WQI parameters.

2.4 Statistical Analysis

Differences between the three sampling stations were evaluated using the analysis of variance (ANOVA) ($p < 0.05$), followed by Tukey's test ($p < 0.05$), using the software Minitab Release 14®. The Pearson correlation matrix was used to evaluate the correlations among the results of water quality variables. The interpretation was performed considering the scale (Mukaka, 2012): $\rho > 0.9$: very strong correlation; ρ: 0.7 to 0.9 = strong correlation; ρ: 0.5 to 0.7 = moderate correlation; ρ: 0.3 to 0.5 = weak correlation; ρ: 0 to 0.3 = negligible correlation.

3 Results and Discussion

3.1 Water Quality Variables in Comprido Stream

Table 4 presents the results of the water quality variables used for WQI calculation. COD presented extremely high values (up to 1,000 mg L^{-1}). High COD values and high COD/BOD ratio are typical of

Table 4 Average values ($n = 24$) and standard deviation of quality water parameters evaluated for three sampling stations along Comprido stream between September and December of 2017 (8 samplings). Different letters on the same line indicate statistically significantly different means ($p < 0.05$)

Parameter	Sampling station		
	S1	S2	S3
Biochemical oxygen demand, BOD_5 (mg L^{-1})	106.9 ± 35.6^a	147.6 ± 26.4^a	122.38 ± 31.2^a
Chemical oxygen demand, COD (mg L^{-1})	$1,087.1 \pm 606.8^a$	$1,304.0 \pm 522.2^a$	$1,436.3 \pm 840.7^a$
Total phosphorus, TP (µg P-PO_4 L^{-1})	174.7 ± 134.1^a	244.53 ± 71.4^a	256.0 ± 121.6^a
Total solids, TS (mg L^{-1})	331.2 ± 121.5^a	354.8 ± 123.8^a	338.7 ± 308.8^a
Suspended solids, SS (mL L^{-1})	0.9 ± 1.3^a	2.94 ± 3.2^a	0.33 ± 0.4^a
Apparent color, AC (uC)	144.7 ± 84.1^a	204.1 ± 34.1^a	187.5 ± 42.7^a
Turbidity (NTU)	29.6 ± 20.7^a	42.2 ± 11.6^a	34.4 ± 14.2^a
Total dissolved solids, TDS (mg L^{-1})	222.2 ± 30.2^a	251.6 ± 42.1^a	264.0 ± 32.2^a
Dissolved oxygen, DO (mg L^{-1})	3.6 ± 1.9^a	3.1 ± 1.6^a	2.3 ± 1.6^a
Electric conductivity, EC (µS cm^{-1})	483.4 ± 106.8^a	518.7 ± 89.7^a	537.0 ± 68.9^a
pH	7.2 ± 0.5^a	7.4 ± 0.4^a	7.4 ± 0.4^a
Temperature (°C)	22.4 ± 0.9^a	22.9 ± 1.2^a	23.2 ± 1.7^a
Ammoniacal nitrogen, N-NH_4 (mg L^{-1})	7.7 ± 2.3^a	12.6 ± 3.1^a	12.6 ± 5.4^a
Thermotolerant coliforms (MPN 100 mL^{-1})	767.7 ± 664.1^a	380.8 ± 496.0^a	552.8 ± 624.0^a

industrial effluents (Von Sperling, 2017; Ahmed et al., 2021). However, since there are no industrial activities within the Comprido stream micro-basin (Rosseto, 2020), the high COD/BOD ratio obtained (~tenfold) could be related with the gas stations. However, it could not be proved by our data. In fact, in the micro-basin, there are records of groundwater contamination within properties, mainly gas stations, by aromatic solvents, phenols, polycyclic aromatic hydrocarbons, metals, and automotive fuels (CETESB, 2017c).

Electrical conductivity (EC) also presented high values (~500 μS cm^{-1}), denoting the anthropogenic impact in the Comprido stream. In fact, during the sampling, it was noticed several sewage discharges into the ecosystem. The point sources will be presented and discussed later. The Environmental Agency of the State of São Paulo monitors the Tamanduateí River (3.2 km downstream of Comprido stream — 23° 36′ 38″ S 46° 32′ 39″ W) (CETESB, 2017a). In the months of January, March, May, July, September, and November of 2017, except for BOD_5 (89.7 mg $L^{-1} \pm 51.7$), the water quality in the Tamanduateí River was lower than that observed for the Comprido stream (total phosphorus = 2,425.0 μg $L^{-1} \pm 1{,}038.0$; total solids = 489.3 mg $L^{-1} \pm 87.2$; turbidity = 95.6 NTU ± 32.3; total dissolved solids = 398.0 mg $L^{-1} \pm 90.4$; dissolved oxygen = 1.2 mg $L^{-1} \pm 1.4$; electrical conductivity = 756.7 μS $cm^{-1} \pm 190.5$; pH = 7.42 ± 2.1; and ammoniacal nitrogen = 17.0 mg $L^{-1} \pm 5.5$) (CETESB, 2017b).

Strong and very strong Pearson correlations were obtained among the studied variables (Table 5), suggesting the same origin. For example, EC, that is a sewage tracer (Chalupová et al., 2012; Thompson et al., 2012), showed very strong correlations with COD, TP, TDS, pH, temperature, and $N\text{-}NH_4$. Coelho et al. (2020) obtained high correlations between EC and TP in two polluted streams also in São Paulo State, Brazil. Our EC values are higher than the ones reported by Coelho et al. (2020) and Medeiros et al. (2017) to polluted streams and twice those reported to the inlet tanks by Baldovi et al. (2021) treating the effluent of an activated sludge system. Yet, our results of turbidity, AC, and DO are comparable to the inlet tanks of Baldovi et al. (2021).

3.2 WQI in Comprido Stream

The WQI for Comprido stream during the evaluated period varied between bad and very bad (20 to 40), with a predominance of the bad classification (Fig. 4). As several parameters presented high levels throughout the monitoring period, the "eclipse effect" may have occurred, an effect resulting from the process of aggregating several variables into a single number, which may produce attenuation of the negative or positive impact of one or more variables against the behavior of the others (Silva & Jardim, 2006; Wertz & Shank, 2019). For the mean values, there were no significant differences between the three stations (station 1 in relation to station 2 ($p = 0.9644$), and between station 3 ($p = 0.9986$) and station 2 in relation to station 3 ($p = 0.9495$)).

After our sampling campaigns, the Comprido stream was monitored by a Brazilian Non-Governmental Organization "SOS Mata Atlântica" (between 2018 and 2019, $n = 10$). Unfortunately, the WQI remained poor (SOS Mata Atlântica, 2021). So, the necessity of a better management of this micro-basin remains.

3.3 Comparison with Other Studies

The results of WQI obtained at present and other studies and factors that influenced these results are presented in Table 6. Water ecosystems influenced by agricultural activities and the discharge of wastewater present results of WQI between Bad and Regular, in addition to low DO values and high concentrations of total solids and turbidity (Alves et al., 2012). In a region influenced by urbanization, the main parameters that influenced the WQI were DO, fecal coliforms, BOD_5, and TP (Strieder et al., 2006). Also, the greater influence of the BOD_5 and coliform on the WQI indicate signs of anthropogenic pollution and environmental degradation (Silveira et al., 2021; Siqueira et al., 2012). In water bodies with low degradation (Santos et al., 2018), with the presence of riparian forest (Leitão et al., 2015), native forest, or in regeneration and even pasture (Pinto et al., 2009), and in situations with factors that favor the dilution of evictions (Piratoba et al., 2017), good and excellent ratings were found. Considering that environments with good preservation conditions tend to have good WQI, while the presence of urbanized stretches induces a considerable reduction in this index (Table 6), the results obtained for Comprido stream are consistent with the reality of the water body, located in an urbanized area. In 2017, the

Table 5 Pearson correlation matrix among water quality parameters evaluated to sampling stations of Comprido stream. Very strong correlations (> 0.90): bold and italic; strong correlation (0.70–0.90): bold

	BOD	COD	TP	TS	SS	AC	Turbidity	TDS	DO	EC	pH	TEMP	N-NH_4	Coliforms
BOD	-	0.50	**0.70**	***1.00***	**0.83**	***0.93***	***0.93***	0.58	***0.91***	0.54	**0.79**	0.51	**0.79**	***−0.98***
COD	0.50	-	***0.97***	0.44	−0.07	**0.79**	0.50	***1.00***	0.10	***1.00***	***0.93***	***1.00***	***0.93***	−0.66
TP	**0.70**	***0.97***	-	0.18	0.18	***0.92***	**0.70**	***0.99***	0.35	***0.98***	***0.99***	***0.97***	***0.99***	**−0.83**
TS	***1.00***	0.44	0.65	-	**0.87**	***0.90***	***1.00***	0.52	***0.94***	0.48	**0.74**	0.44	**0.74**	***−0.96***
SS	**0.83**	−0.07	0.18	**0.87**	-	0.56	**0.83**	0.02	***0.99***	−0.03	0.31	−0.07	0.31	−0.70
AC	***0.93***	**0.79**	***0.92***	***0.90***	0.56	-	***0.93***	**0.84**	0.69	**0.82**	***0.96***	**0.79**	***0.96***	***−0.98***
Turbidity	***1.00***	0.50	**0.70**	***1.00***	**0.83**	***0.93***	-	0.58	**0.91**	0.54	0.79	0.51	**0.79**	***−0.98***
TDS	0.58	***1.00***	***0.99***	0.52	0.02	**0.84**	0.58	-	0.19	***1.00***	***0.96***	***1.00***	***0.96***	**−0.73**
DO	***0.91***	0.10	0.35	***0.94***	***0.99***	0.69	***0.91***	0.19	-	0.14	0.46	0.10	0.46	**−0.81**
EC	0.54	***1.00***	***0.98***	0.48	−0.03	**0.82**	0.54	***1.00***	0.14	-	***0.94***	***1.00***	***0.94***	**−0.70**
pH	**0.79**	***0.93***	***0.99***	**0.74**	0.31	***0.96***	**0.79**	***0.96***	0.46	***0.94***	-	***0.93***	***1.00***	***−0.90***
TEMP	0.51	***1.00***	***0.97***	0.44	−0.07	**0.79**	0.51	***1.00***	0.10	***1.00***	***0.93***	-	***0.929***	−0.67
N-NH_4	**0.79**	***0.93***	***0.99***	**0.74**	0.31	***0.96***	**0.79**	***0.96***	0.46	***0.94***	***1.00***	***0.93***	-	***−0.90***
Coliforms	***−0.98***	−0.66	**−0.83**	***−0.96***	**−0.70**	***−0.98***	***−0.98***	**−0.73**	**−0.81**	**−0.70**	***−0.90***	−0.67	***−0.90***	-

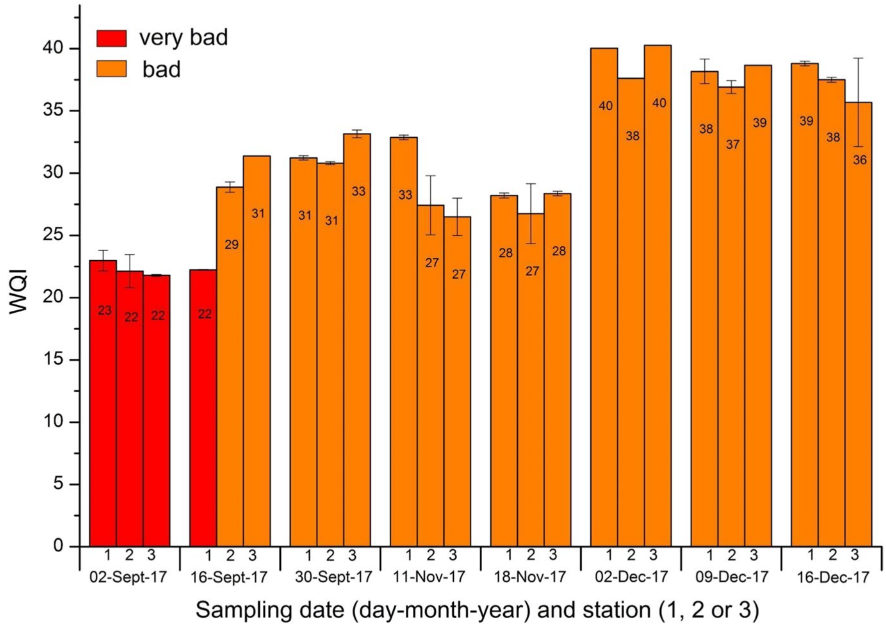

Fig. 4 Water Quality Index (WQI) variation by sampling date and station and National Sanitation Foundation classification

Table 6 Comparison of Water Quality Index (WQI), environment type, and factors of influence from present study and data from other studies

WQI	Classification	Environment type	Factors of influence	Reference
22–40	Bad–very bad	Lotic; urban stream	Domestic sewage discharge	Present study
25–50	Bad–acceptable	Lotic; Amazon region, partially urbanized	Natural characteristics of Amazonian rivers (low pH), farms, crops, and domestic sewage discharges	Alves et al. (2012)
27–63	Bad–good	Lotic; under the influence of urbanization and tanning	Industrial and domestic sewage	Strieder et al. (2006)
40	Acceptable	Lotic; Amazon region, partially urbanized	Riparian forest deforestation, sewage pollution, sediment exploration	Siqueira et al. (2012)
41–55*	Acceptable–good	Lentic; semi-arid region, partially urbanized	Discharges of untreated domestic sewage, agricultural exploitation	Ferreira et al. (2015)
50–95	Acceptable–great	River basin, rural region	Native forest, regenerating forest, pasture	Pinto et al. (2009)
54–91	Good–great	Lotic; partially urbanized	Pará River dilution capacity, enhanced by tidal effect	Piratoba et al. (2017)
57–77	Good	Lotic; under the influence of the farm industry	Agricultural activities and waste generated	Zanini et al. (2010)
65–78	Good	Lotic; semi-arid region	Low degradation	Santos et al. (2018)
66–81	Good–great	Lotic; Cerrado region	Presence of riparian forest with low degradation index	Leitão et al. (2015)
12–30	Bad–very bad	Lotic; urban river	High anthropic pressure, domestic sewage, and industrial discharges	CETESB (2017a,b)

*Adapted

Elaborated by the authors

Tamanduateí River, which has the Comprido stream as a tributary, had the worst WQI in the state of São Paulo (annual average of 14.55), in a scenario of high vulnerability due to impacts from the great human pressure (Cetesb, 2017a).

About the season in which the sampling campaigns were performed, Strieder et al. (2006) recorded lower WQI values in the hottest period of the year in Rio Grande do Sul state (South of Brazil), a region with rains well distributed along the year. On the other hand, Silveira et al. (2021) identified variation in the quality parameters because of rainfall events (Mirin Lago, South of Brazil), and Alves et al. (2012) noticed that the quality of the WQI decreased in the wet period in Marajó Island (North of Brazil), a very hot region of the country. Carvalho et al. (2000) indicate that in São Carlos (São Paulo State, Southern of Brazil) had a worsening in the WQI during the summer, when it rains more, while Zanini et al. (2010) found that there was no influence of the wet season on their data in Jaboticabal (São Paulo State, Southern of Brazil). Thus, in addition to the rainy season, a more careful assessment of the climate zone and the hydrographic basin in which the studied environment is located is required, considering for example factors such as agricultural activity (Silveira et al., 2021) and characteristics of the sanitary sewage systems (Aguilera et al., 2019) and rainwater drainage systems. We emphasize that our study has limitations, since we just monitored the stream for 4 months.

3.4 Comparison with Brazilian Legislation for Water Quality

In compliance with Brazilian legislation (São Paulo State Decree nº 10.755, of November 22 of 1977 (São Paulo, 1977), and National Council for the Environment "CONAMA" Resolution nº 357/2005 (Brasil, 2005)), the Comprido stream is currently classified as class 4. Thus, floating materials, including unnatural foams, must be virtually absent; odor and appearance must be non-objectionable; oils and greases tolerate iridescence; easily sedimentable substances that contribute to the siltation of shipping channels should be virtually absent; total phenols (substances that react with 4-aminoantipyrine) in concentrations of up to 1.0 mg L^{-1} of C_6H_5OH; DO greater than 2.0 mg L^{-1} in any sample; and pH between 6.0 and 9.0 (Brasil, 2005).

Among all the variables evaluated to Comprido stream, easily sedimentable substances that contribute to the siltation of navigation channels, odor, appearance, and DO did not meet the proposed legislation. Only the pH complied with the provisions of legislation. This scenario shows that Comprido stream does not meet its classification, even though this is the least restrictive class.

Yet, considering that the Comprido stream framework dates back to 1977 and that there are more recent guidelines, such as Resolution nº 91/2008 of the Brazilian Water Resources Council, which considers that the framework must include quality objectives to be achieved through quality goals of water and the existence of programs for the maintenance of the class (Brasil, 2008), it is noted that in Brazil there is a mismatch between legal instruments for the management of water resources and even the non-compliance with the existing ones. It is sad in the twenty-first century that our law allows such low values for some parameters, such as 2 mg L^{-1} of DO in aquatic environments. Furthermore, we often find even lower OD values in our rivers.

3.5 Identification of Pollution Sources

Twenty discharge points directly from houses to the water body were identified along the water body by visual identification (e.g., Fig. 2c, d), which contributes to the degradation of the ecosystem. The point sources identified are untreated sewage releases and have compliance issues. In addition, three affluents were identified that may also be undergoing changes in their natural characteristics through inadequate connection of sewage networks (Table S2 — Supplementary Material).

The rapid economic development and substantial increase of population, without increase in capacity of wastewater treatment, are factors that cause decrease of water quality (Liu et al., 2014). Urban expansion in the São Paulo megalopolis, which includes the Comprido stream region, was not accompanied by infrastructure networks, resulting in the maintenance of the degradation of water bodies (Denaldi & Ferrara, 2018), mainly in streams where the sewer loading can be elevated considering the natural flow (Namour et al., 2015). In addition, the occupation process did not consider the protection of water bodies, making it possible to identify buildings located on the banks of the ecosystem (Fig. 2e).

In 2017, the municipality of Santo André treated 41% of the collected sewage (Santo André, 2019). This percentage rose to 46% in 2019 (Brasil, 2019), with the remainder being discharged into water bodies or untreated rainwater galleries (Santo André, 2019). Direct discharge of untreated domestic sewage is the main factor of degradation of water quality in urban streams (Liu et al., 2014).

Even with the proximity of a huge Wastewater Treatment Plant (ABC WWTP), about 15 km distant, in 2019 the Comprido stream micro-basin did not have a trunk sewer in its entirety yet and there were records of sewage discharge into stormwater galleries. This situation is verified for other basins in the municipality (Santo André, 2019), and it is possible to infer that the quality of water bodies in the municipality may not differ from that observed for Comprido stream.

Although the municipality of Santo André has had a program to reorganize the sewage system since 1996, including actions in the Comprido stream micro-basin to combat irregular connections, in 2014 a depollution program in this micro-basin started (Santo André, 2014). In 2020, the works were still being carried out for this purpose (São Paulo, 2020), being completed in 2021 (Diário Grande do ABC, 2021). It demonstrates the slowness in the performance of those responsible for sanitary sewage services. For the rainwater drainage systems, the current municipal plan dates to 1999 and for the Comprido stream micro-basin measures are not provided for preserving the floodplain and land use control, as the region is fully urbanized (SEMASA, 1999).

The scenario presented confirms the diagnosis found from the calculation of the WQI, as well as the direct discharge points of effluents and polluted affluents in Comprido stream. The recovery of urban streams depends on effective management measures, continuously and rigorously enforced to be sustainable (Liu et al., 2014). The development of public policies that consider housing and environmental aspects and the performance of the government are essential to revert the situation in the region and to prevent new occurrences of irregular connections of sewage in the area. In addition, measures that use principles from the science of restoration and ecological engineering can prevent impacts from polluting stormwater loads, e.g., ensuring restoration of ecosystem services (Angela et al., 2015; Palmer et al., 2014). Also, the recovery of polluted streams can add value to the buildings in the region, bringing economic advantages to the population, since in urbanized areas natural environments are very scarce (Chen & Li, 2018).

The requalification and revitalization of the Comprido stream will contribute with the improvement of the water quality of the Tamanduateí River, one of the most important tributaries of the Tietê River, which has its quality extremely affected by the high urbanization of the Metropolitan Region of São Paulo (MRSP), but which in recent years, because of investments in sanitation and infrastructure works, has been showing a trend of stabilization and improvement (Abdala, 2019). We reinforce that the Comprido stream is an example of what is happening with our urban streams in Brazil. Yet, this environment is in the most developed state of Brazil with a reasonable sanitation infrastructure, and it can be worse in other less developed states.

4 Conclusions

The water quality parameters and the WQI revealed an alarming scenario regarding the environmental and sanitary conditions of Comprido stream between September and December of 2017. The WQI was always between bad and very bad (20 to 40), which allows us to conclude that the waters of the Comprido stream are quite degraded. Parameters that indicate anthropogenic interference such as high electrical conductivity, low dissolved oxygen concentration, BOD_5 with values approximately 10 times greater than those determined by Brazilian legislation, and alarming values for COD (mean 1,275.80 mg L^{-1}) demonstrate the environmental mismanagement of the Comprido stream micro-basin. The lack of public infrastructure for the proper removal and treatment of sewage highlights the need for public policies that integrate housing, environmental, and sanitary issues. The study points to the need to carry out the integrated management of urban micro-watersheds to preserve streams and, consequently, improve the quality of adjacent water bodies and the maintenance of ecosystem services to the population. The recent information shows that sanitary sewage works were completed in the micro-basin, but for rainwater drainage systems there are no current plans for preserving the floodplain and land use control. It is urgent to improve the monitoring of streams in the municipality and to monitor and to control the discharge of sewage into rainwater drainage systems. As a future work, it could be interesting to consider a complete year of monitoring, as well as to analyze other variables, such as flux, caffeine as a sewage tracer, and BTEX (benzene, toluene, ethylbenzene, and xylenes) to evaluate the influence of gas stations.

Acknowledgements The authors are thankful to CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) by the Scientific Initiation fellowship do B.N.R. Also, the authors are grateful to UFABC for the laboratory facilities, and Dr. María Cleofé Valverde for the rainfall data.

Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interests The authors declare no competing interests.

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