

# In-situ Treatment of the Polluted Pinheiros River in São Paulo, Brazil

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**Abstract.** Historically, Brazilian sanitation has been relatively undeveloped as compared to other emerging countries. This situation is considered to have significant negative effects on human health indicators. Until recently, less than half of Brazil's domestic sewage volume was effectively treated before being discharged to the environment, leaving large urban populations exposed to untreated sewage and degraded surface waters. To address these issues, Brazil enacted federal water legislation in June 2020 with the goal of providing over 90% of its population with access to sanitation services by 2033. Typically, the design, construction, and commissioning process for such infrastructure projects takes years before the benefits of these investments are realized. Within this context, we present the results of efforts to expedite the delivery of such investments by treating polluted water bodies in-situ. This study reports the results from an in situ environmental remediation project on the Pinheiros River in São Paulo, Brazil using a side stream supersaturated dissolved oxygen (SDOX<sup>®</sup>) system to maintain aerobic conditions, suppress odour, and accelerate natural biological treatment processes. The side-stream process draws river water into the SDOX's pressurized saturation chamber where oxygen is dissolved to produce a virtually bubble free, supersaturated liquid solution that is returned to the river. By moving oxygen transfer from the bulk flow and into the controlled, optimal environment of the pressurized saturation chamber, the side-stream system achieves near complete gas transfer efficiency virtually independent of the depth of the river or canal.

## 1. Introduction

### 1.1 Global Context

Historically, Brazilian sanitation has been relatively undeveloped as compared to other emerging countries. In 2018, sanitation across Brazil ranked 112th out of 200 high-income countries and was suspected of having a significant negative effect on human health indicators [1][2]. Specifically, the percentage of the Brazilian population with sewage collected was 53% with only 46% of the sewage volume effectively treated. Nationwide, approximately 100 million people lacked access to sewage collection services [1]. Moreover, Brazil had an estimated 11.25-to-13.6 million people living in slums (favelas) [3] with virtually all such settlements discharging sewage directly into local streams and rivers. In short, untreated sewage is a major cause of water pollution in Brazil that undermines quality of life, health, and economic development in large,



urban areas and increases the cost of water treatment for downstream users, having a disproportionate negative effect on the poor [2].

Brazil's situation is not unique. The global south in general is experiencing tremendous growth of urban environments, with secondary cities<sup>1</sup> experiencing massive expansions during the next few decades comparable to the growth experienced in Europe and North America since the industrial revolution [4]. Such secondary cities are the emerging engine of the world's rapid pace of urbanization [4]. The challenge is one of increased demand for sanitation services in the face of non-existent or physically constrained wastewater collection and treatment capacity designed for historic demands. All of which compounds the fouling of surface waters, places additional demands on infrastructure, and erodes the quality of life, health, and economic development.

### *1.2 The Pinheiros River*

Located in the São Paulo Metropolitan Region, the Pinheiros River is approximately two meters deep, runs approximately 25 kilometers through the city of São Paulo, and has changed dramatically during the 20th century. During the 1920s, the River was a recreational corridor, home to several watersport clubs and regularly hosted swimming and nautical regattas; however, its use soon shifted to flood control and power generation. By 1950, extensive civil works had altered the River's course and the construction of a pumping station to support hydroelectric power generation regularly changed the flow. Additional civil works converted the Pinheiros River into a channeled waterway with minimal current, further reducing the River's natural ability to sustain the dissolved oxygen required to maintain water quality and aquatic life. Meanwhile, São Paulo's rapid growth outpaced urban planning, resulting in unorganized settlements along the River's banks and extensive water contamination due to a lack of basic sanitation and the irresponsible disposal of domestic and industrial wastewater and garbage.

To address the increasingly poor water quality of the River, a variety of initiatives were undertaken to improve the River during the 1990's. However, the River – fouled from ongoing release of untreated domestic sewage and industrial waste – remained a septic waterway, putting the entire river ecosystem at risk well into the 21st Century. In 2021, the Pinheiros River faced one of the most significant environmental rehabilitation challenges due to this long-standing history of severe pollution.

In December 2021, the Pinheiros River revitalization project implemented the high-purity oxygen (HPO) technology commonly known as supersaturated dissolved oxygen (SDOX®) as an innovative solution to enhance water quality of the River and promote self-purification processes. A Dual SDOX® 600 containerized unit was commissioned in a section of the Pinheiros River, located within Bruno Covas Park, an area of high environmental and social relevance. Capable of delivering up to 4,500 kg of oxygen per day when treating typical domestic wastewater, the Dual SDOX® 600 was tasked with maintaining a dissolved oxygen level of at least 2.0 mg/L in the treated, five-kilometer section of the River to recover and accelerate the ecosystem's natural, self-purification aerobic processes, reduce organic matter, mitigate unpleasant odors, and improve

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<sup>1</sup> Secondary cities are those with 500,000 to three million inhabitants that play an important role as catalysts and secondary hubs in facilitating the localized production, transportation, transformation, or transfer of goods, people, trade, information, and services between sub-national, metropolitan, national, regional, and global systems of cities, yet are often unknown outside of their national or regional context. Secondary Cities often demonstrate the presence of: industry agglomeration and clusters; a system of well-developed, localized supply chains and networks; a diversified economic and employment base; and a broad housing mix.

overall water quality while fostering the development of socio-economic benefits to the immediate river corridor.

Applied researchers implemented a continuous monitoring plan combining field measurements and laboratory analysis. The study focused on dissolved oxygen (DO), biochemical oxygen demand (BOD), and sulfide as the main indicators used to assess oxygenation performance, organic matter degradation, and septic conditions in the study reach. Researchers used these datasets to support the modeling of oxygen plume dispersion and decay, as well as the reduction of organic matter and pollutants.

## 2. Objective

The objective of this article is to present the results of an in-situ environmental remediation project on the Pinheiros River in São Paulo, Brazil. Specifically, we present information demonstrating how a side-stream, supersaturated dissolved oxygen (SDOX®) system can expedite the delivery of environmental and public health benefits before long-term sanitation infrastructure is completed. We document the ability SDOX® technology to develop and sustain aerobic conditions in heavily polluted, shallow (~ 2 meters) urban waterway by decoupling oxygen transfer efficiency from river depth, suppressing unpleasant odors, and accelerating natural biological treatment and ecosystem biodegradation;.

## 3. Supporting Literature

Water resources provide several contributions to society, such as drinking water, power generation, flood mitigation, humidity and temperature control, recreation, and environmental conservation. Due to the variety of possible uses and their importance to society and the quality of life, it is essential to guarantee the quality of their water [5]. One's ability to manage the water resource to meet societal demands is aided by a collective understanding of hydrological studies of how water behaves in nature, hydraulic studies of how water moves through systems, how anthropogenic actions in the drainage basin influence sedimentological dynamics, and the physical-chemical properties of water – with mathematical modeling being the most suitable tool for understanding these complex relationships [6][7].

Scientific literature establishes advective transport and molecular dispersion as the main processes responsible for the mixing of constituents (e.g., DO) in river water and artificial channels [7]. Advective transport is associated with channel flow, responsible for the longitudinal transport of the constituents. Dispersion, in turn, is carried out by diffusive transport, linked to molecular agitation and flow turbulence [8]. Thus, the hydraulic conditions of the river exert an important influence on the dispersion of the oxygen plume. Higher flow velocities result in more significant advective transport and, therefore, greater longitudinal dispersion of the plume, which will extend over a longer stretch of the river channel. Low flow velocities, such as those found near dams, result in less longitudinal dispersion, with a predominance of molecular diffusive transport [8].

In parallel, the flow velocity also influences the channel reaeration process. The natural process of incorporating oxygen into water through the surface of the water body presents, in locations with higher flow velocities, a high reaeration coefficient and, thus, high concentrations of incorporated DO [7].

In the case of the Pinheiros River, the existence of hydraulic structures, including the São Paulo Hydroelectric Power Plant, and the Pedreira and Retiro Dams along the channel's length reduce

flow velocities, hindering the action of advective transport. In addition, the complex and irregular operational scenario of the channel, with flow reversals and interruptions for flood control, affects the river's hydraulic conditions, generating turbulence and the existence of a bidirectional flow, especially during the wet season.

Other processes are also relevant in altering DO concentrations in the river, notably exchanges with the atmosphere at the water-air interface, the decay of the constituent due to its consumption, and algal activity.

In the case of DO, much of its decay occurs due to its consumption by microorganisms responsible for the degradation of organic matter and/or by nitrification processes. The activity of algae, in turn, contributes both to the increase and decrease of concentrations in dissolved oxygen, causing seasonal and daily variations in the rates of oxygen consumption and production. During the photo period, the process of photosynthesis is triggered, in which oxygen is produced. Outside the photoperiod, photosynthesis is inhibited and the main process underway is respiration, which consumes the oxygen present in the environment, resulting in extreme diurnal drops in DO, creating an environment that is unsuitable for aerobic organisms.

Mathematical modeling of river dynamics is commonly used to support decision-making. Modelling enables technicians to perform diagnostic analyses and integrating the data from distant sampling and real-time monitoring stations to extrapolate data to locations without measurement, aiding in the understanding dynamic processes. As such, simulation modelling is a crucial tool in environmental licensing processes and in defining response, monitoring, and mitigation strategies.

Mathematical modeling may also be used to characterize the environment and create a digital representation of it, allowing for variations in environmental conditions and observation of different responses within the system, generating scenarios. For example, scenario modelling using Delft 3D model's hydrodynamic/morphological and water quality modules enables managers to better understand environmental systems and the synergistic relationships the affecting those systems to develop forecasts of possible outcomes, enabling society to better prepare and avoid greater harm, making this method a valuable tool in the decision-making process.

#### **4. Methods**

This article compares water quality of Pinheiros Rivers during the SDOX® operation using two monitoring datasets. The baseline dataset comprised measurements sampled from August 2021 to November 2021, representing pre-improvement conditions in the study reach. These data were compared with a second dataset collected from August 2023 to November 2023, to evaluate the operational indicators of the SDOX® system, the dispersion of the resulting dissolved oxygen plume, as well as reductions in BOD and sulfide. Monitoring was performed at four (4) monitoring points along the study reach, with an extension of approximately 4 km, and consisted of collecting surface water at each point for chemical analysis.

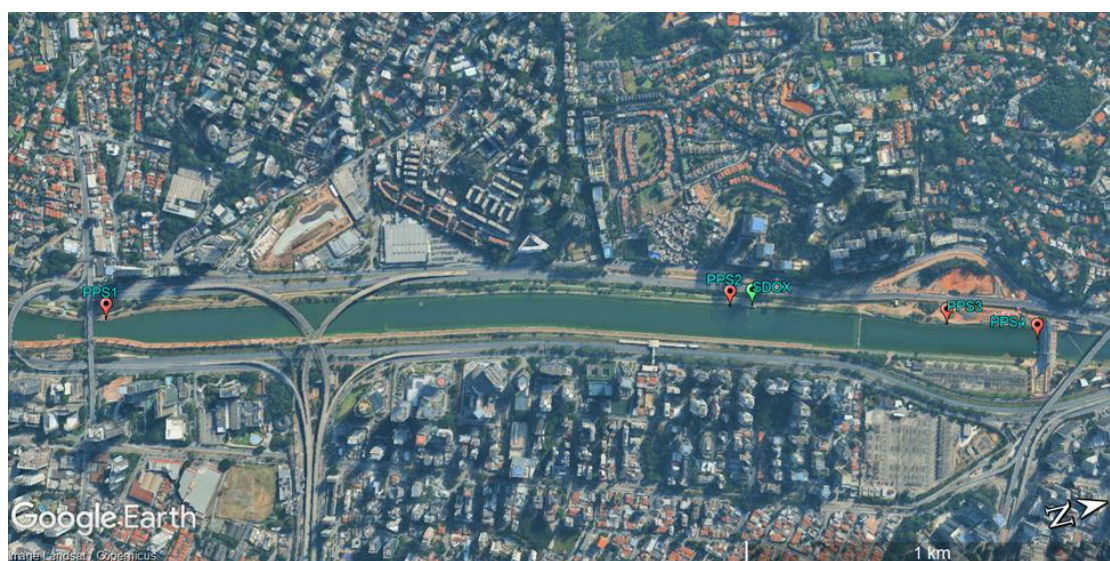
Monitoring campaigns were conducted at four monitoring points distributed along the study reach, with sampling frequency varying throughout the project duration. During 2021, surface water samples were collected three times per week, while 2023 the monitoring frequency was adjusted to two sampling campaigns per week.

Sampling activities were performed at all four monitoring points (PPS1 to PPS4), whose geographic coordinates and distances relative to the SDOX® outlet are presented in Table 1, below. Figure 1 shows the monitoring points in the Pinheiros river.

**Table 1.** Geographic coordinates\* of the monitoring points (PPS1-PPS4) and their respective distances from the SDOX® outlet.

| Monitoring Point | Eastings (mE) | Northings (mN) | Relative Position | Distance from SDOX® (m) |
|------------------|---------------|----------------|-------------------|-------------------------|
| PPS1             | 326.473       | 7.387.058      | Upstream          | 1,800                   |
| PPS2             | 326.854       | 7.388.783      | Upstream          | 50                      |
| PPS3             | 327.014       | 7.389.307      | Downstream        | 550                     |
| PPS4             | 327.113       | 7.389.541      | Downstream        | 800                     |

\*UTM Coordinates referenced to SIRGAS 2000 datum, Zone 23S.



**Figure 1.** Monitoring points along the Pinheiros River study reach, including SDOX® installation site and the dominant flow direction. Researchers collected data from two monitoring points upstream SDOX® and two monitoring points downstream.

It is important to note that due to operational and environmental constraints, sampling could not be performed during periods of extremely low river levels or under severe rainfall conditions, when safe field access and representative sample collection were not feasible.

A total of 328 samples were collected throughout the monitoring program – 82 samples each point. All sampling procedures, handling, preservation, and analytical activities were conducted in accordance with the Brazilian Laboratory Accreditation Standard ABNT NBR ISO/IEC 17025. To assess water quality and the results obtained with the application of SDOX® technology, the researchers used the hydrodynamic/morphological and water quality modules of the Delft 3D

model to evaluate the dispersion, decay, and impact of the dissolved oxygen plume released into the river, as well the reduction in BOD and Sulfide.

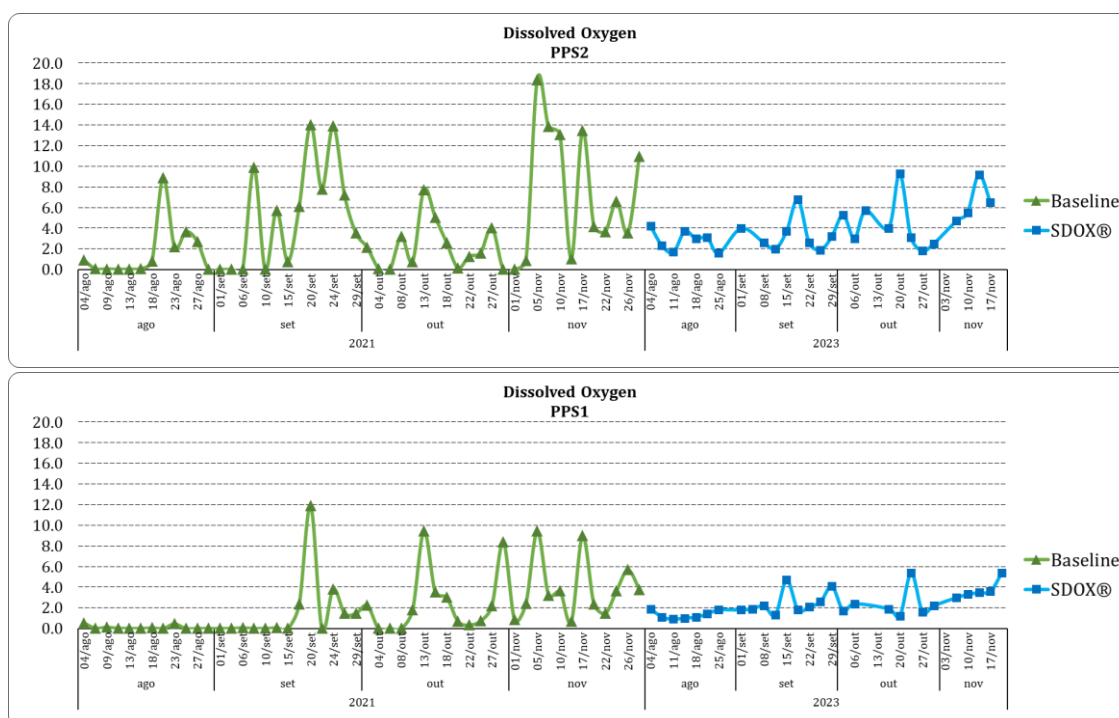
Delft3D is a world-leading 3D modeling suite to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments. To maintain aerobic zones and mitigate anaerobic hotspots associated with sewage inputs and low hydraulic retention, the operational strategy adopted for SDOX<sup>®</sup> was continuous injection of 2.000-to-4.000 kg of Oxygen per day depending on the volume of flow in the river.

## 5. Results

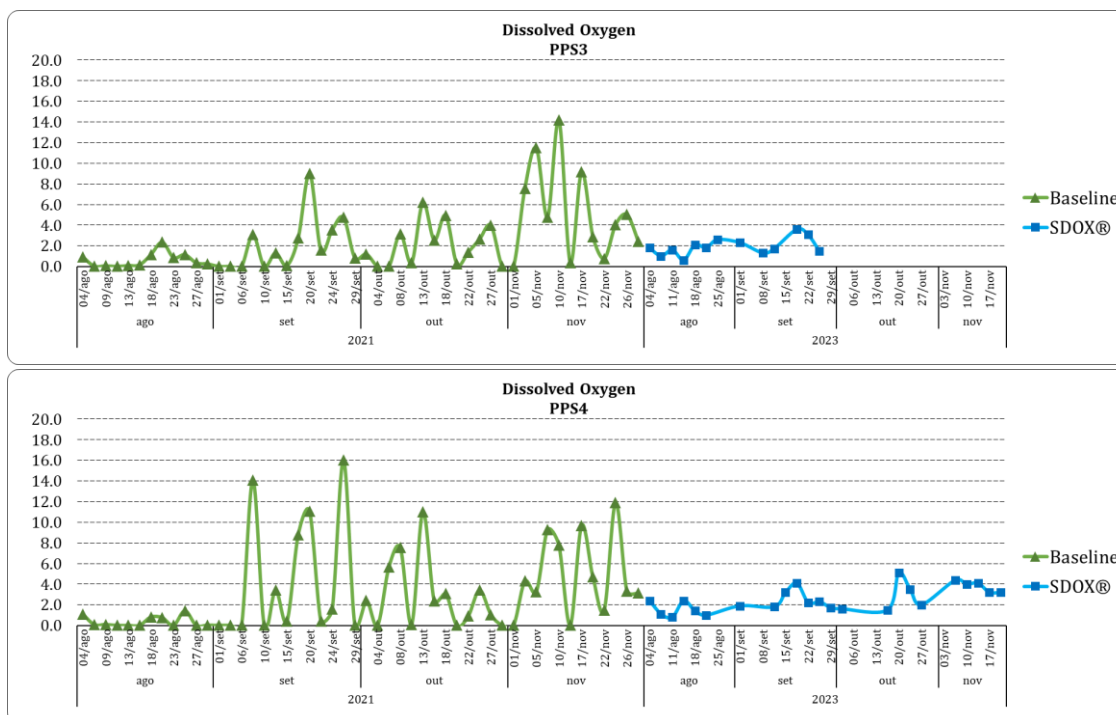
This section compares water quality conditions in the Pinheiros River between the baseline period (August to November 2021) and the optimized operational monitoring period (August to November 2023).

### 5.1 Dissolved Oxygen (DO)

The comparison between the 2021 baseline dataset and the 2023 operational dataset showed an important change in the temporal behavior of dissolved oxygen along the monitored points. In 2021, DO concentrations were highly variable, with repeated oscillations between near-zero values and sharp peaks, indicating presence of algae and unstable oxygen conditions throughout the study reach. In contrast, the 2023 dataset showed a more consistent DO profile, with fewer extreme fluctuations and a greater concentration of values within a moderate range. Although maximum DO peaks were higher in 2021 (algae blooms), the 2023 monitoring period was characterized by more stable and sustained aerobic conditions, which is environmentally more relevant than isolated, high-value events. Overall, the results suggest that the main improvement observed in 2023 was not an increase in peak DO values, but rather a reduction in temporal variability and a more continuous presence of dissolved oxygen in the river, as shown in the Figure 2 below.



**Figure 2.** Comparison of dissolved oxygen (DO) concentrations before and during SDOX<sup>®</sup> operation in the Pinheiros River.



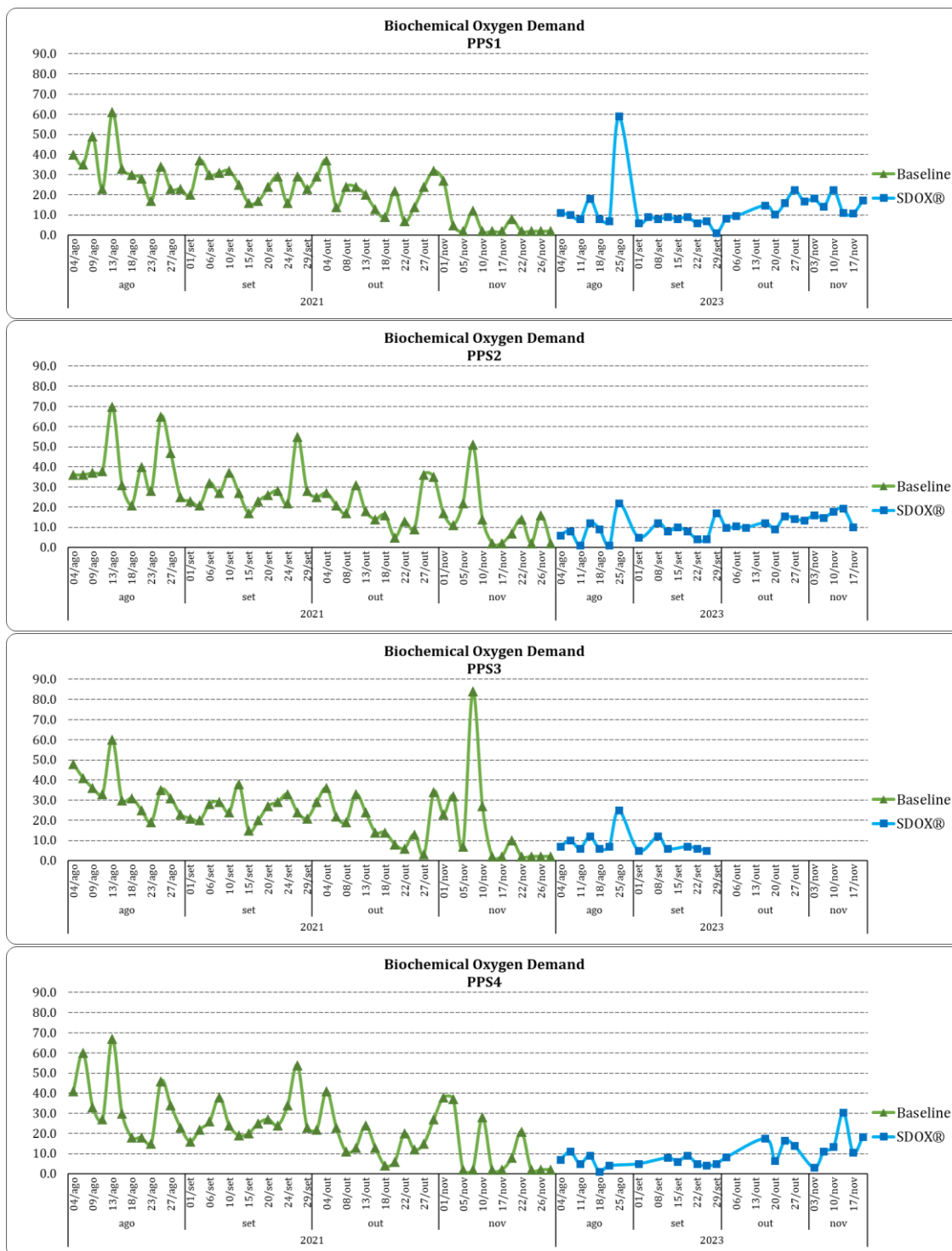
**Figure 2 (continued).** Comparison of dissolved oxygen (DO) concentrations before and during SDOX® operation in the Pinheiros River.

The transition from highly volatile DO values with extreme peaks in 2021 to a stable, consistent aerobic profile in 2023 represents an important ecological breakthrough. The sharp peaks and near-zero values observed in the 2021 baseline of 2021 are classic indicators of eutrophication-driven algal blooms. In hypereutrophic urban rivers, high nutrient availability fuels uncontrolled daytime algal photosynthesis, causing artificial oxygen supersaturation [8]. At night, heavy community respiration combined with the decay of dead biomass collapses DO levels to zero, triggering mass aquatic mortality.

The 2023 dataset proves that continuous, controlled injection via SDOX® outpaces the erratic, sun-dependent oxygen generation of algae. Maintaining a steady baseline of dissolved oxygen suppresses the catastrophic nocturnal anoxia typical of urban streams. Literature in limnology confirms that a stable, continuous aerobic baseline is far superior for supporting complex aquatic macroinvertebrates and stabilizing biological pathways than erratic, isolated peak-value events.

### 5.2 Biochemical Oxygen Demand (BOD)

BOD data showed a clearer improvement than DO when comparing the historical and operational periods. The overall average BOD decreased from 23,3 mg/L in 2021 to 10,8 mg/L in 2023, corresponding to a reduction of approximately 54%. This decrease was observed at all monitoring points, indicating that the improvement was spatially consistent along the study reach. The most pronounced reduction occurred in September, when average values dropped from approximately 27,1 mg/L in 2021 to 6,0-8,5 mg/L in 2023. These results suggest a substantial reduction in biodegradable organic load and, consequently, a lower oxygen demand in the river during the operational period, as shown in the Figure 3.



**Figure 3.** Comparison of Biochemical Oxygen Demand (BOD) concentrations before and during SDOX® operation in the Pinheiros River.

Although the overall pattern indicates improvement, the 2023 dataset still showed occasional high BOD events, particularly in late August and during part of November, indicating that localized

or episodic organic load inputs were still present. Even so, the general reduction in BOD supports the interpretation that river conditions in 2023 were more favorable for maintaining aerobic processes. In this sense, BOD provides stronger comparative evidence of water quality improvement than DO peak values alone, because it more directly reflects the reduction in oxygen-consuming organic matter.

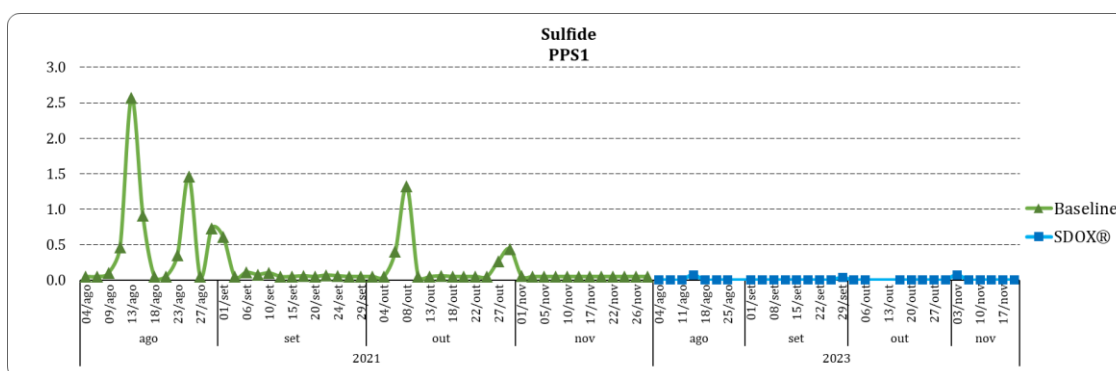
The 54% reduction in overall average BOD (dropping from 23,3 mg/L to 10,8 mg/L) provides clear evidence of accelerated carbonaceous matter mineralization. In heavily polluted waterways, the rate of organic matter breakdown by heterotrophic bacteria is often bottlenecked by oxygen availability. When DO drops near zero, microbial metabolism shifts to anaerobic pathways, which are slower and less efficient [8]. By injecting high rates of dissolved oxygen (up to 4.500 kg /day), the SDOX® system removes this kinetic barrier. It keeps native aerobic heterotrophs operating at peak metabolic velocity, accelerating ecosystem self-purification (autodepuration).

The dramatic BOD drop in September (from 27.1 mg/L down to 6.0–8.5 mg/L) is highly significant. In the state of São Paulo, September typically marks the transition into the dry season, characterized by low river flows and concentrated pollution. Bringing BOD down below 10 mg/L under these challenging conditions shifts the stream reach toward water quality standards typical of less degraded water bodies, satisfying the kinetic requirements of advanced self-purification models like Streeter-Phelps.

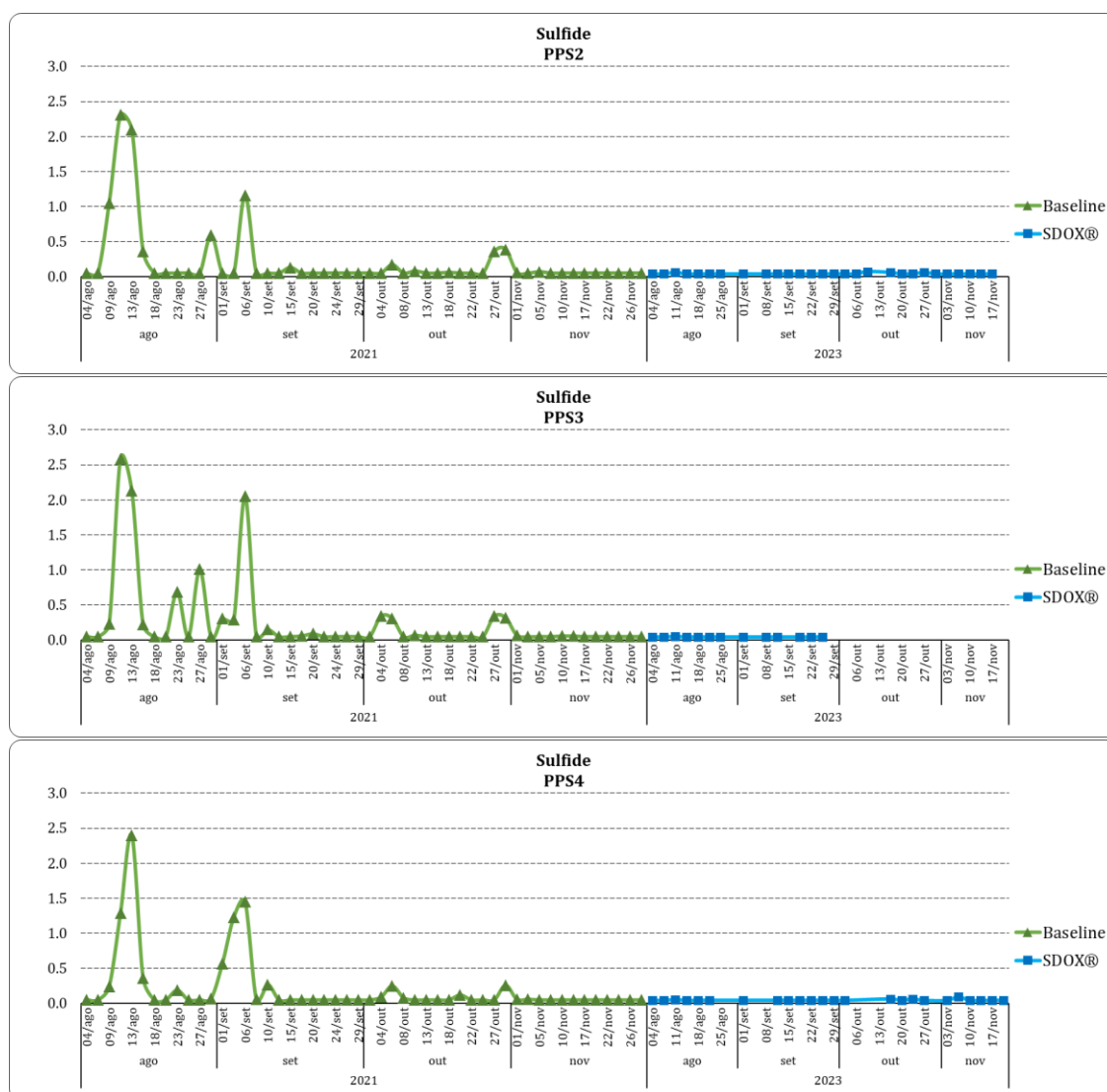
### 5.3 Sulfide

Sulfide data showed a marked reduction between the baseline and operational periods, providing strong evidence of improved control of septic conditions in the study reach. In 2021, measurable sulfide concentrations were recorded repeatedly, especially during August, with several peak values above 1,0 mg/L, and maximum values reaching 2,6 mg/L. In contrast, the 2023 dataset was characterized almost entirely by zero values, with only occasional isolated measurements of 0,1 mg/L. The overall average decreased from 0,2 mg/L in 2021 to approximately 0 in 2023.

This result, as shown in Figure 4, suggests a substantial reduction in anaerobic or strongly reducing conditions along the monitored reach. From an environmental perspective, the near elimination of sulfide is particularly relevant since this parameter is associated with septic conditions, odor generation, and the persistence of oxygen-depleted zones. Therefore, among the parameters evaluated, sulfide provides one of the clearest indications that water quality conditions in 2023 were more favorable than those observed during the baseline period.



**Figure 4.** Comparison of sulfide concentrations before and during SDOX® operation in the Pinheiros River.



**Figure 4 (continued).** Comparison of sulfide concentrations before and during SDOX® operation in the Pinheiros River.

The near-total elimination of measurable sulfide concentrations in 2023 (averaging close to 0 mg/L compared to 2021 peaks of 2.6 mg/L) is a direct consequence of shifting the river's redox potential.

**Inhibition of Sulfate-Reducing Bacteria (SRB):** Hydrogen sulfide is generated exclusively under strongly reducing, strictly anaerobic conditions. In these environments, specialized anaerobic microorganisms (Sulfate-Reducing Bacteria, or SRB) use sulfate as an electron acceptor to degrade organic matter, producing toxic, foul-smelling sulfides [5].

In environmental biotechnology, molecular oxygen is the thermodynamically preferred electron acceptor. Maintaining sustained aerobic conditions throughout 2023 raised the redox potential of the river water, effectively shutting down SRB metabolic pathways. This confirms that the SDOX® system does not merely mask foul urban odors; rather, it fundamentally blocks the chemical and biological pathways that generate them, removing septic zones from the shallow waterway.

In general, the results of SDOX® installation on the Pinheiros River demonstrate a consistent ability to dissolve and entrain sufficient oxygen to produce measurable improvements in DO, maintain an aerobic environment, mitigate odour, and enhance natural ecosystem biodegradation in the heavily polluted, shallow urban waterway. The results demonstrated the ability SDOX® to significantly improve the water quality of the Pinheiros River, with notable increases in dissolved oxygen levels and reductions in Biochemical Oxygen Demand (BOD).

During the period explored in this report, the data for dissolved oxygen (DO) and BOD indicate an inverse relationship between variables, as described in the literature: higher BOD concentrations reduce DO concentrations, since they consume this oxygen available for organic matter stabilization reactions.

The fact that average DO concentrations are currently higher, a condition provided by the injection of DO into the river, allows for greater degradation of the organic matter present in the river, reducing average BOD concentrations compared to local historical data with average BOD ~ 43 mg/L, according to CETESB- Environmental Agency, 2018, thus demonstrating the improvement in quality parameters in the stretch.

## 6. Conclusion

Comparison between the baseline dataset (August 2021 to November 2022) and the 2023 operational dataset indicates that the principal benefit of SDOX® was not simply higher isolated DO peaks, but a more sustained oxygen regime over time. Historical DO data were highly irregular, with alternating near-zero values and sharp peaks, whereas the 2023 dataset showed more consistent moderate DO concentrations along the monitored reach. This more stable oxygen regime coincided with a substantial reduction in average BOD, from 23,3 mg/L to 10,8 mg/L, and with sulfide concentrations that were nearly eliminated in 2023 compared with the repeated sulfide events observed in the baseline period.

These findings underscore the system's ability to significantly enhance water quality, favor aerobic organisms, and mitigate hypoxia in critical sections of the river. The SDOX® system also directly contributed to reducing BOD, a key indicator of organic pollution. Since BOD reflects the oxygen consumption required for organic material degradation, this significant reduction highlights the SDOX® system's efficiency in enhancing aerobic degradation processes within the river.

The SDOX® system has demonstrated its ability to be an efficient, flexible, and replicable solution, with potential applications in bioremediation processes for other heavily polluted water bodies, establishing a foundation for environmental recovery.

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