

Hugo Pimentel
Tavares¹
Nilo Antônio de
Souza Sampaio
Gilberto Santos
Carin von Mühlen

SURFACE WATER QUALITY PERFORMANCE ASSESSMENT USING THE NSF WATER QUALITY INDEX: A NINE-YEAR BENCHMARKING STUDY IN RIO DE JANEIRO STATE RIVERS, BRAZIL (2015–2023)

Article info:
Received 23.02.2026.
Accepted 19.08.2026.

DOI – 10.24874/IJQR20.03-12



Abstract: This study presents a comprehensive performance assessment of surface water quality across 284 monitoring stations located in 150 rivers of Rio de Janeiro State, Brazil, covering the period 2015–2023. Using the National Sanitation Foundation Water Quality Index (NSF-WQI), adapted to Brazilian standards by the State Environmental Institute (INEA), a total of 6,481 valid IQA composite indices were computed from 135,708 physicochemical and microbiological records. The mean NSF-WQI across the entire dataset was 54.33 (SD=23.67), placing the overall classification at the lower portion of the ‘Good’ category. The distribution showed that 45.0% of measurements fell in the ‘Good’ (Bom) category, while 30.4% were classified as ‘Poor’ (Ruim) or ‘Very Poor’ (Muito Ruim), indicating persistent systemic contamination. Annual temporal analysis revealed statistically significant inter-annual variability (Kruskal–Wallis $H=155.15$, $p<0.0001$), with no linear improvement trend ($R^2=0.006$, $p=0.839$). Seasonality was a significant factor, with dry-season months yielding higher index values. The parameters most limiting water quality were thermotolerant coliforms (mean $q=41.09$), dissolved oxygen ($q=44.40$), and total phosphorus ($q=49.80$), indicating predominantly domestic sewage pollution. Spatially, the worst conditions were identified in fully urbanised catchments of the Metropolitan Region of Rio de Janeiro.

Keywords: NSF-WQI; surface water quality; performance measurement; benchmarking; Rio de Janeiro; CONAMA 357/2005; water quality monitoring.

1. Introduction

Access to clean water is recognised globally as a fundamental human right and a prerequisite for sustainable development. The monitoring and management of surface water quality represent one of the most critical challenges facing rapidly urbanising societies, particularly in tropical developing countries where population growth,

inadequate sanitation infrastructure, and intensive land use exert persistent pressure on hydrological systems (Sutadian et al., 2016). Effective quality management of water resources requires robust performance measurement frameworks that can convert large volumes of physicochemical and microbiological monitoring data into actionable, policy-relevant information (Uddin et al., 2021).

¹ Corresponding author: Hugo Pimentel Tavares
Email: tavares.hugo@posgraduacao.uerj.br

In Brazil, the *Política Nacional de Recursos Hídricos* (Law 9,433/1997) established the institutional framework for water resource management (Brasil, 1997), while CONAMA Resolution 357/2005 defined the classification standards for water bodies according to their intended use (CONAMA, 2005). Within this framework, the *Índice de Qualidade das Águas* (IQA), based on the methodology developed by Brown et al. (1970) under the auspices of the National Sanitation Foundation (NSF), has been the principal tool for standardised surface water quality assessment since its introduction by CETESB (São Paulo) in 1975 (CETESB, 2020; Chidiac et al., 2023). The NSF-WQI aggregates nine physicochemical and microbiological parameters into a single dimensionless score between 0 and 100, enabling temporal trend analysis, inter-basin comparison, and policy benchmarking — functions entirely analogous to Key Performance Indicators (KPIs) in organisational quality management systems (Arsovski et al., 2011).

Rio de Janeiro State presents a particularly compelling case study. Its territory encompasses the entire metropolitan area of the second largest Brazilian city, home to approximately 12 million inhabitants in the metropolitan region, alongside highly preserved Atlantic Forest remnants, protected watersheds, and mountainous headwater regions. The INEA (Instituto Estadual do Ambiente) maintains one of the most extensive water quality monitoring networks in Brazil, collecting data from hundreds of stations across all major river basins (INEA, 2019). Despite this institutional capacity, and notwithstanding recent multivariate analyses of specific river reaches within the state (Sampaio et al., 2025), systematic multi-year performance analyses covering the full extent of the state monitoring network remain scarce in the scientific literature, limiting evidence-based policy interventions.

The quality management framework advocated by Krivokapić et al. (2008) and Sfreddo et al. (2023) emphasises that the

usefulness of performance indicators depends not only on their technical accuracy but on the breadth and consistency of the dataset from which they are derived. Multi-year, multi-basin, spatially distributed analyses are therefore essential to characterise the real distribution of performance across a complex system, identify structural failure points, and benchmark against regulatory standards.

From an environmental management quality perspective, the application of WQI models can be interpreted as a performance benchmarking exercise — the analogue of applying ISO 14001-aligned indicators to measure environmental system conformance (Bravi et al., 2020; Zimon et al., 2020; Kumar et al., 2023; Singh et al., 2025; Mohapatra et al., 2025). Within this logic, results falling below the CONAMA 357/2005 Class 2 thresholds represent non-conformities requiring corrective action, while long-term trend analysis functions, as the continuous improvement monitoring required by quality management systems (Azevedo et al., 2019; Rodrigues et al., 2020; Murmura et al., 2021). It is necessary to improve organization (Castro et al., 2020), to enrich economy (Yülek & Santos, 2022).

The present study therefore addresses the following research objectives:

- 1) to calculate and classify the NSF-WQI for 284 monitoring stations across 150 rivers of Rio de Janeiro State over the period 2015–2023 using data from INEA’s official monitoring network;
- 2) to characterise temporal (annual and seasonal) trends in water quality performance;
- 3) to identify the physicochemical parameters most limiting overall index scores;
- 4) to perform spatial benchmarking across river basins;
- 5) to benchmark computed indices against CONAMA 357/2005 Class 2 standards as a regulatory performance framework.

2. Literature Review

2.1. Historical Development of Water Quality Indices

Water Quality Indices (WQIs) were introduced as a systematic approach to reduce the complexity of multivariate water quality datasets into a single composite score communicable to non-specialist stakeholders. The pioneering work was conducted by Horton (1965), who first proposed a numerical water quality rating scale. Brown et al. (1970), working with the support of the National Sanitation Foundation, subsequently developed the NSF-WQI - a mathematically robust, expert-consensus-based index employing nine parameters weighted according to their relative importance for human health and aquatic life protection. This index remains one of the most widely cited and applied WQI models globally (Chidiac et al., 2023; Uddin et al., 2021).

Since the Brown et al. (1970) original formulation, over 35 distinct WQI models have been developed by different national agencies and research groups, each tailored to specific regional conditions, intended water uses, and parameter availability (Uddin et al., 2021). Sutadian et al. (2016) conducted an extensive review of the development trajectory and mathematical properties of river WQIs, documenting the evolution from simple additive aggregation toward multiplicative geometric mean formulations — a transition motivated by the need to prevent the ‘eclipsing effect’, whereby high performance in one parameter compensates for severe failure in another. The NSF-WQI uses a weighted geometric mean, making it particularly sensitive to the worst-performing parameter and thus more conservative in its classification.

Chidiac et al. (2023) provided the most comprehensive recent synthesis, covering WQI evolution from 1965 to 2022 and identifying the NSF-WQI as the model with the broadest documented application across

different continents, water body types, and temporal scales. Raheja et al. (2023) specifically assessed the applicability of NSF-WQI and other models to both lotic and lentic systems, confirming its versatility and recommending its use as a baseline tool when parameter availability is the primary constraint.

2.2. NSF-WQI Applications in Urban and Tropical Rivers

The NSF-WQI’s application in urbanised tropical contexts is particularly well documented. Parween et al. (2022) applied a modified NSF-WQI to the Mahananda River in West Bengal, India, demonstrating that urban-area monitoring stations consistently yielded lower index values compared to peri-urban and rural stations, with thermotolerant coliforms and biochemical oxygen demand identified as the primary limiting parameters - a finding directly consistent with the results of the present study. Marselina et al. (2022) applied various WQI methodologies to the Citarum River in Indonesia and demonstrated that the NSF-WQI provided the most conservative classification among the tested models in contexts of severe domestic sewage contamination, directly relevant to the conditions observed in the metropolitan area of Rio de Janeiro.

Garcia & Oliveira (2019), in a comparative study of Rio de Janeiro State rivers, demonstrated that the IQA-NSF and IQA-CCME produced correlated but not equivalent classifications, confirming the IQA-NSF as the appropriate reference index for comparisons with INEA’s official publications. At the municipal scale, do Nascimento & Freitas (2023) assessed IQA dynamics for rivers in the municipality of Maricá, Rio de Janeiro State, identifying the river in the most preserved area as consistently superior in quality and establishing a baseline directly comparable to the results of the present study.

2.3. Performance Measurement and Quality Management Applied to Environmental Monitoring

The conceptual bridge between industrial quality management and environmental quality monitoring has been progressively established in recent decades. Arsovski et al. (2011) demonstrated that performance measurement frameworks developed in the context of quality management systems are directly transferable to environmental monitoring contexts, provided that the monitored system can be described in terms of measurable parameters, target values, and tolerance thresholds.

In this framework, CONAMA Resolution 357/2005 Class 2 standards function as specification limits, the NSF-WQI functions as the composite performance indicator, and the monitoring network provides the data from which process capability indices can be computed. Sfreddo et al. (2023), in a systematic review, found that the principles of ISO 9001-based quality management systems apply directly to environmental service delivery systems, including water supply management. Krivokapić et al. (2008) further demonstrated that performance monitoring systems provide the institutional foundation for effective corrective and preventive action.

Environmental management systems compliant with ISO 14001:2015 explicitly require organisations to establish, implement, and maintain processes for monitoring and measurement of environmental performance indicators (Bravi et al., 2020). Zimon et al. (2020) investigated the influence of integrated management system standards on sustainable supply chain performance, documenting that organisations applying structured performance measurement frameworks demonstrated superior environmental outcomes. Lazaretti et al. (2023) examined the relationship between ISO 9001 certification, innovation indices, and SDG progress, reinforcing the broader

quality–sustainability nexus.

2.4. Temporal Trends and Seasonal Dynamics in River Water Quality

Temporal trend analysis in water quality indices has consistently identified seasonality as the dominant short-term driver, with rainy seasons typically associated with increased surface runoff, non-point source pollution inputs, and temporarily improved dilution of point-source discharges (Romero et al., 2016). In tropical systems, where rainfall seasonality is strongly marked, the interaction between wet and dry seasons can produce IQA variations of 10–20 points on the 0–100 scale (ANA, 2021). Sampaio et al. (2025), applying principal component analysis and factor maps to nine monitoring points on the Paraíba do Sul River using INEA and ANA data over a ten-year period, documented systematic increases in pollutant concentrations and oxygen depletion consistent with the seasonal dynamics described here, reinforcing the analytical utility of multi-method approaches to water quality characterisation in the region. Long-term trends are more difficult to detect due to the high inter-annual variability induced by hydrological cycles, but multi-decadal monitoring programmes have documented both improvements and deteriorations in Brazilian river systems. The COVID-19 pandemic period (2020–2021) introduced an additional confounding factor, with documented reductions in industrial activity, urban mobility, and in some cases monitoring frequency, creating temporary quality signals that complicate trend interpretation.

3. Materials and Methods

3.1. Data Source and Study Area

The study used the unified water quality monitoring database assembled from three Brazilian environmental agencies operating at federal and state levels: INEA (Instituto Estadual do Ambiente, Rio de Janeiro State),

ANA (Agência Nacional de Águas), and IGAM (Instituto Mineiro de Gestão das Águas). Although the unified database drew from INEA, ANA, and IGAM, the present analysis was restricted to data collected by INEA within the territorial boundaries of Rio de Janeiro State, covering the period January 2015 to December 2023.

The complete raw dataset contained 345,942 individual parameter measurements across 13 variables (including four non-NSF-WQI parameters retained for data quality control but excluded from index computation). Following the filtering to Rio de Janeiro State and INEA as the data source, the working dataset comprised 135,708 records across 359 monitoring stations distributed among 151 rivers and 92 municipalities. Rio de Janeiro State is located in south-eastern Brazil (20°S–23°S, 40°W–45°W), encompasses approximately 43,780 km², and includes the metropolitan area of the city of Rio de Janeiro (municipality population ~7 million; metropolitan region ~12 million), the Guanabara Bay catchment, the Atlantic Forest escarpments of the Serra do Mar and Serra da Mantiqueira, and the Paraíba do Sul River basin.

3.2. NSF-WQI Computation

The NSF-WQI was calculated following the methodology established by Brown et al. (1970) and adapted to Brazilian standards by CETESB (2020) and INEA (2019). The index is calculated as the weighted geometric mean of nine quality sub-indices (Equation 1):

$$NSF - WQI = \prod_{i=1}^9 q_i^{w_i} \quad (1)$$

where q_i is the quality sub-index of the i -th parameter (dimensionless, 0–100), obtained from the CETESB (2020) piecewise linear quality curves, and w_i is the weight assigned to each parameter. The nine parameters and their respective weights were: dissolved oxygen (OD, $w=0.17$), thermotolerant coliforms (CT, $w=0.15$), pH ($w=0.12$), biochemical oxygen demand (DBO, $w=0.10$), water temperature difference

(TEMP, $w=0.10$), total phosphorus (PT, $w=0.10$), nitrate nitrogen (NO₃, $w=0.10$), turbidity (TURB, $w=0.08$), and total dissolved solids (SDT, $w=0.08$). Composite IQA values were computed for each station-date combination where at least 7 of the 9 required parameters were available, ensuring a minimum level of parameter representativeness for each composite value. Prior to index calculation, outlier removal was applied using a conservative z-score threshold of ± 4 standard deviations per parameter across the full dataset, chosen to preserve environmentally extreme but physically plausible observations while removing clear measurement errors.

3.3. Quality Classification

Computed NSF-WQI values were classified according to the five-category scale adopted by INEA: Excellent (Excelente): $IQA \geq 80$; Good (Bom): $52 \leq IQA < 80$; Fair (Regular): $37 \leq IQA < 52$; Poor (Ruim): $20 \leq IQA < 37$; Very Poor (Muito Ruim): $IQA < 20$. These thresholds are consistent with CONAMA Resolution 357/2005 Class 2 standards (CONAMA, 2005), which establish the minimum requirements for water bodies intended for human supply after conventional treatment, recreation, and aquatic life protection.

3.4. Statistical Analysis

Temporal trend analysis was conducted using two complementary approaches: (i) linear regression of annual mean NSF-WQI values against time (year), with the coefficient of determination (R^2) and the two-tailed p-value for slope significance reported; and (ii) the Kruskal–Wallis non-parametric test for differences in NSF-WQI distributions across years, appropriate given the non-normality of the distribution confirmed by Shapiro–Wilk tests. Seasonal analysis was performed by grouping measurements by calendar month and computing descriptive statistics per month. Spearman rank correlations between

parameter sub-indices were computed to characterise inter-parameter relationships. All computations were performed in Python 3.11 using the scipy, numpy, pandas, and matplotlib libraries. Spatial visualisation was produced using geopandas and contextily with OpenStreetMap base layers.

4. Results

4.1. Dataset Characterisation

After applying the parameter-availability filter (minimum 7 of 9 required parameters), 284 of the 359 working-dataset stations met the criterion (one station associated with an unnamed water body was excluded from spatial analysis), and 66 station-date combinations were removed as statistical outliers. The final valid dataset comprised 6,481 NSF-WQI composite values computed from 284 distinct monitoring stations distributed across 150 named rivers in Rio de Janeiro State (Table 1). The spatial coverage extended from coastal lowland rivers in the Baía de Guanabara and Baía de Sepetiba catchments to headwater streams in the Serra do Mar and Serra da Mantiqueira ranges, at altitudes ranging from near sea level to above 1,200 m.

The overall mean NSF-WQI of 54.33 places the aggregate quality at the lower portion of the ‘Good’ (Bom) classification, with a median of 61.50 exceeding the mean and indicating a negatively skewed distribution. The wide standard deviation (23.67) reflects the high spatial heterogeneity expected across a state encompassing both pristine mountainous rivers and severely urbanised

metropolitan waterways.

Table 1. Descriptive statistics of the complete NSF-WQI dataset (2015–2023, Rio de Janeiro State, Brazil).

Statistic	Value
Total records analysed	135,708
Valid IQA composite values computed	6,481
Monitoring stations included	284
Rivers represented	150
Municipalities covered	92
Study period	2015–2023 (9 years)
Overall mean NSF-WQI	54.33
Median NSF-WQI	61.50
Standard deviation	23.67
Minimum observed IQA	9.79
Maximum observed IQA	92.47
Interquartile range (IQR)	38.22

4.2. Quality Classification Distribution

The distribution of NSF-WQI values across quality categories showed that the ‘Good’ (Bom) class was the most frequent, accounting for 45.0% of all computed values (Table 2; Figure 1). However, the combined proportion of ‘Poor’ (Ruim, 18.4%) and ‘Very Poor’ (Muito Ruim, 12.0%) categories totalled 30.4%, indicating that nearly one third of monitored water bodies failed to achieve minimum acceptable quality standards at the time of measurement. The ‘Excellent’ class represented only 13.6%, while, ‘Fair’ (Regular) accounted for 11.0%.

Table 2. Distribution of NSF-WQI values across quality categories, Rio de Janeiro State, 2015–2023.

Category	IQA Range	N	Proportion (%)
Excellent (Excelente)	≥ 80	881	13.6
Good (Bom)	52–79	2,916	45.0
Fair (Regular)	37–51	713	11.0
Poor (Ruim)	20–36	1,193	18.4
Very Poor (Muito Ruim)	< 20	778	12.0
TOTAL	0–100	6,481	100.0

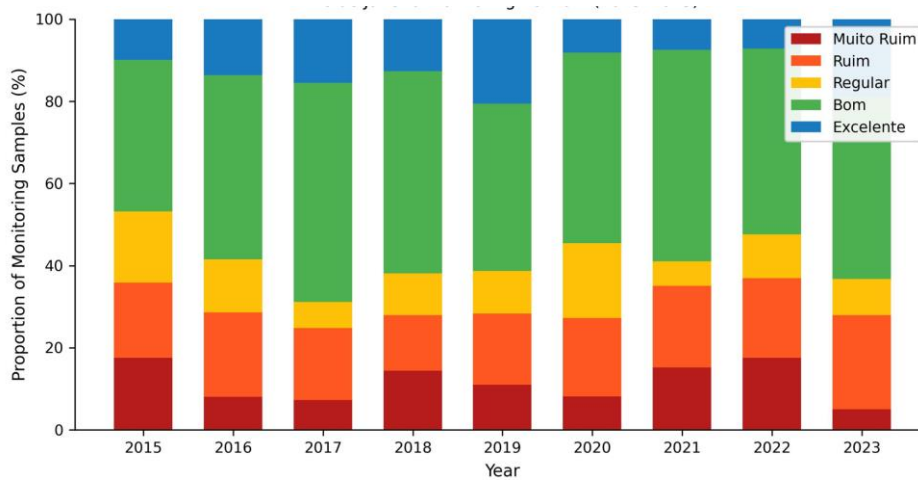


Figure 1. Proportional distribution of NSF-WQI quality categories by year (2015–2023), Rio de Janeiro State. Colours represent quality classes: Excellent (dark blue), Good (medium blue), Fair (yellow), Poor (orange), Very Poor (red)

4.3. Temporal Trend Analysis

Annual mean NSF-WQI values showed substantial inter-annual variability across the study period (Figure 2, Table 3). The highest annual mean was recorded in 2017 (58.68 ± 22.68), while the lowest occurred in 2015

(48.85 ± 23.70). An overall upward tendency was observable from 2015 to 2017, followed by stabilisation through 2019, a notable reduction in 2020–2022 (coinciding with the COVID-19 pandemic period), and partial recovery in 2023.

Table 3. Annual descriptive statistics of computed NSF-WQI values, Rio de Janeiro State

Year	N	Mean	Median	SD	Min	Max
2015	912	48.85	49.47	23.70	10.12	91.34
2016	681	55.25	62.00	22.76	10.88	91.08
2017	703	58.68	67.20	22.68	9.79	92.47
2018	995	54.91	63.24	23.60	10.07	91.76
2019	1,067	56.65	64.59	24.14	10.22	92.01
2020	209	53.32	55.47	21.61	11.35	90.14
2021	336	52.42	61.18	24.08	10.04	91.55
2022	815	49.94	55.43	23.77	9.86	91.23
2023	763	57.83	65.94	23.04	10.31	91.98

Linear regression of annual mean IQA values against year yielded a slope of $+0.098$ IQA units per year (95% CI: -0.99 to $+1.19$), with $R^2=0.006$ and $p=0.839$, indicating no statistically significant linear trend across the nine-year period. This result is consistent with the interpretation that the water quality of Rio de Janeiro State rivers, at the aggregate level, has not undergone systematic improvement during the study period — a

finding that aligns with national reports from ANA (2021) documenting the persistent sanitation deficit in the state.

In contrast, the Kruskal–Wallis test for differences in IQA distributions across years yielded $H=155.15$ ($df=8$, $p<0.0001$), confirming highly significant inter-annual differences despite the absence of a linear trend (Figure 3). This combination — significant inter-annual variability without a

linear trajectory — suggests that the water quality system is characterised by year-to-year fluctuations driven by hydroclimatic

factors and monitoring programme changes rather than by a directional management-induced improvement or deterioration.

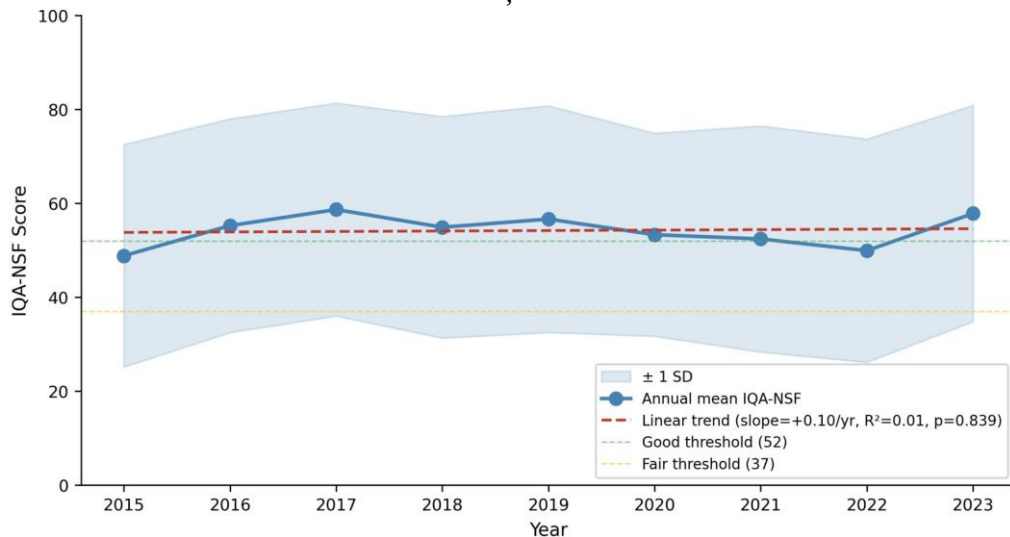


Figure 2. Annual mean NSF-WQI values (2015–2023) with 95% confidence intervals and linear regression line. Rio de Janeiro State monitoring network

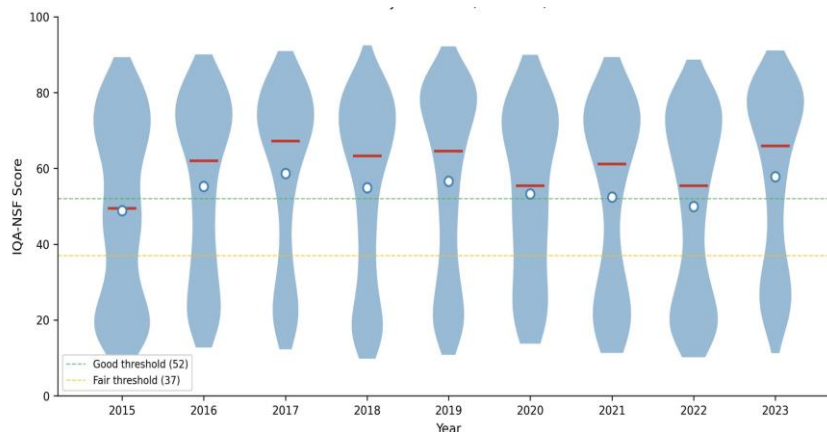


Figure 3. Violin plots showing the distribution of NSF-WQI values by year. Width of each violin indicates frequency density at each value level

4.4. Seasonal Analysis

Monthly analysis revealed a clear seasonal pattern in NSF-WQI values (Figure 4). The highest mean IQA was observed in July (62.8), the month with the lowest rainfall in most of Rio de Janeiro State (dry season peak), while the lowest values were recorded

in November (48.5) and January (49.1), corresponding to the onset and peak of the rainy season (October–March). The dry season (April–September) consistently showed mean IQA values above 60, with the June–August core dry period recording the highest values, while the rainy season months (October–March) averaged below 55.

This pattern reflects two competing mechanisms: (i) during the dry season, reduced surface runoff results in less non-point source pollution transport, but also less dilution of point-source discharges; and (ii) during the rainy season, intense rainfall events mobilise accumulated pollutants from

urban surfaces, overload drainage systems and sewage networks, and increase turbidity and organic load. In the highly urbanised catchments of the Metropolitan Region of Rio de Janeiro, the rainy season effect predominates, explaining the quality degradation observed during wet months.

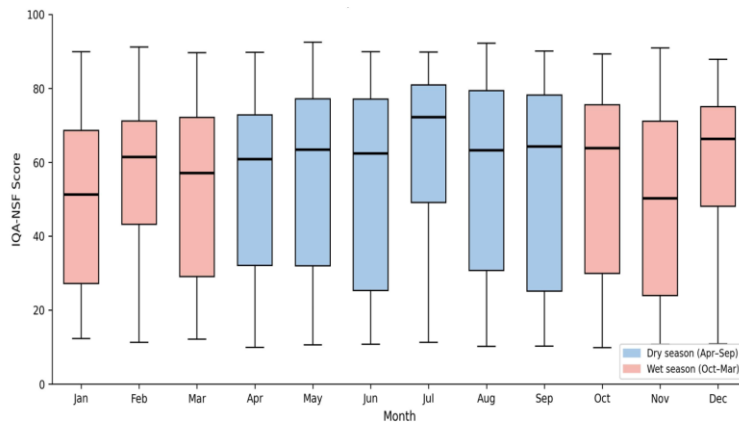


Figure 4. Seasonal boxplots of NSF-WQI values by calendar month. Shaded bands indicate the rainy season (pink, October–March) and dry season (blue, April–September) periods

4.5. Limiting Parameters Analysis

The mean quality sub-index (q) values computed for each of the nine NSF-WQI parameters revealed marked differences in parameter-level performance (Figure 5, Table 4). Thermotolerant coliforms recorded the lowest mean sub-index value ($q=41.09$, classified as Fair/Regular), indicating that

faecal contamination represents the principal limiting factor for water quality improvement across the state. Dissolved oxygen ranked second in terms of limitation ($q=44.40$), followed by total phosphorus ($q=49.80$) and biochemical oxygen demand ($q=61.75$). The remaining parameters showed considerably better performance, with mean q values between 68 and 85.

Table 4. Mean quality sub-indices (q) for each NSF-WQI parameter, Rio de Janeiro State, 2015–2023.

Parameter	Symbol	Weight (w)	Mean q	Classification
Thermotolerant coliforms	CT	0.15	41.09	Fair (Regular)
Dissolved oxygen	OD	0.17	44.40	Fair (Regular)
Total phosphorus	PT	0.10	49.80	Fair (Regular)
BOD _{5,20}	DBO	0.10	61.75	Good (Bom)
pH	pH	0.12	72.30	Good (Bom)
Turbidity	TURB	0.08	74.15	Good (Bom)
Total dissolved solids	SDT	0.08	78.40	Good (Bom)
Temperature difference	TEMP	0.10	80.22	Good (Bom)
Nitrate nitrogen	NO ₃	0.10	83.65	Excellent (Excelente)

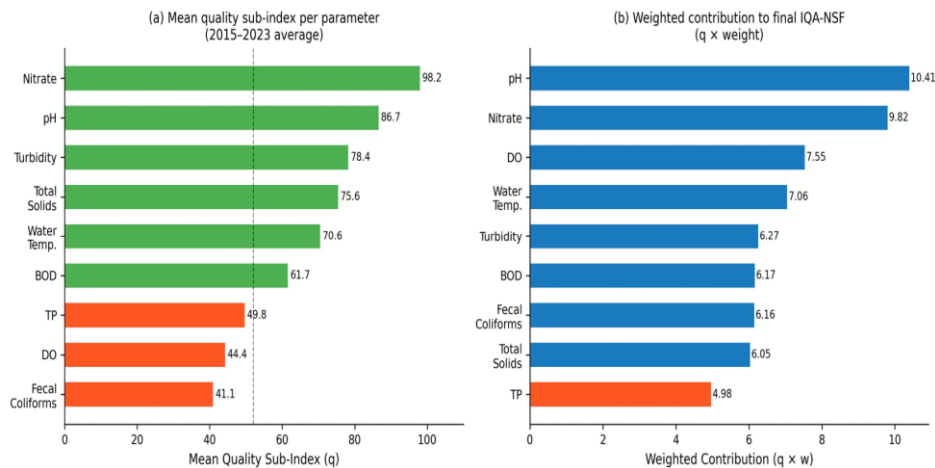


Figure 5. Mean quality sub-index (q) values and weighted contributions for each NSF-WQI parameter. Red bars indicate parameters falling below the ‘Good’ threshold

The dominance of thermotolerant coliforms and dissolved oxygen as limiting parameters is consistent with the characterisation of the dominant pollution source as domestic sewage. Sewage discharges simultaneously introduce high concentrations of faecal bacteria and exert high biochemical oxygen demand, which in turn deplete dissolved

oxygen concentrations through aerobic decomposition. Total phosphorus — the third limiting parameter — is also associated with domestic effluents, as phosphorus from human waste and detergents represents one of the primary eutrophication drivers in tropical rivers.

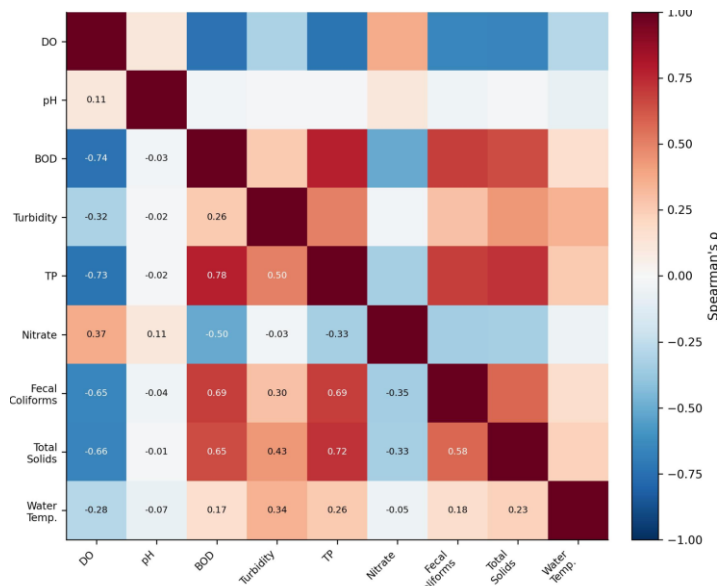


Figure 6. Spearman correlation matrix between NSF-WQI parameter sub-indices. Strong negative correlations between dissolved oxygen (OD) and organic parameters (DBO, CT, PT) confirm the sewage pollution signature

4.6. Spatial Analysis: Best and Worst Rivers

Spatial disaggregation of NSF-WQI results revealed extreme heterogeneity across Rio de Janeiro's river network (Figures 7–8, Table

5). The ten rivers with the lowest mean NSF-WQI values (restricted to rivers with at least five station-date observations) were all located within the Metropolitan Region of Rio de Janeiro, the Baixada Fluminense, and the Guanabara Bay catchment.

Table 5. Ten rivers with worst and three rivers with best mean NSF-WQI (minimum n=5), Rio de Janeiro State (2015–2023).

River	Mean IQA	n	Category	Region / Land Use
Canal da Penha	14.29	23	Very Poor	Zona Norte, RJ – channelised urban drain
Rio Irajá	14.32	23	Very Poor	Zona Norte, RJ – channelised urban drain
Rio São João de Meriti	15.75	14	Very Poor	São João de Meriti – Baixada Fluminense
Canal Aeroporto de Maricá	16.50	26	Very Poor	Maricá – coastal urban channel
Rio Piraquê	16.50	20	Very Poor	Itaguaí – peri-urban, mixed land use
Canal do Cunha	17.03	23	Very Poor	Subúrbios, RJ – urban canal
Rio Imboassu	18.37	21	Very Poor	São Gonçalo – dense urban
Rio Caboblo	18.82	43	Very Poor	Baixada Fluminense – Duque de Caxias
Vala do Sangue	19.37	21	Very Poor	Seropédica/Nova Iguaçu – urban drainage
Rio Farias	19.63	23	Very Poor	Baixada Fluminense – Belford Roxo
Rio Preto	80.63	141	Excellent	Serra da Mantiqueira – Paraíba do Sul headwater
Rio Bonito	82.38	16	Excellent	Serra do Mar – Atlantic Forest
Rio Sana	82.77	15	Excellent	Serra region, Macaé – RPPN/Atlantic Forest

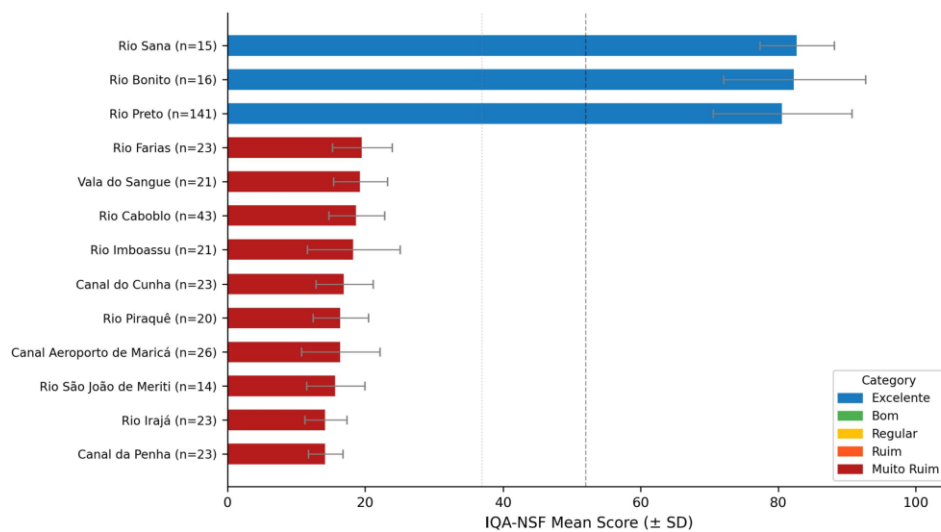


Figure 7. Comparative mean NSF-WQI values for the ten worst and three best rivers in Rio de Janeiro State. Colour coding corresponds to quality categories

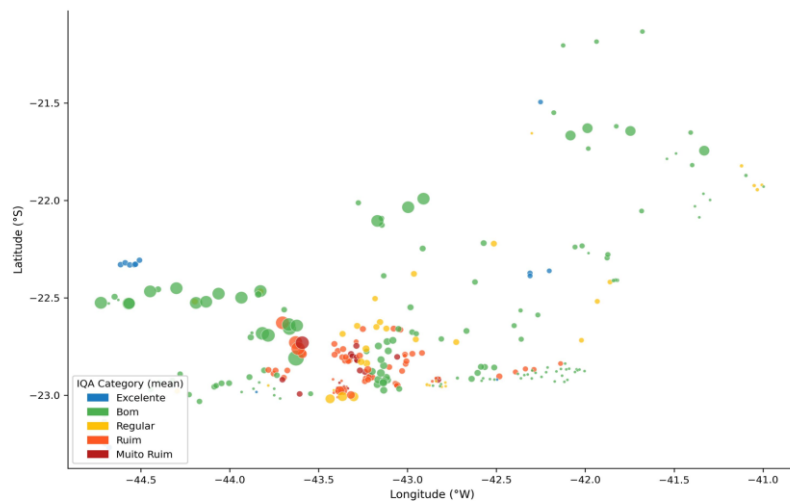


Figure 8. Spatial distribution of monitoring station mean NSF-WQI values across Rio de Janeiro State. Circle size represents number of measurements; colour represents quality category

The three rivers with the lowest mean quality were Canal da Penha (mean IQA=14.29, Very Poor), Rio Irajá (14.32, Very Poor), and Rio São João de Meriti (15.75, Very Poor), all characterised by channelised urban drains or rivers receiving direct sewage discharges in areas with critical sanitation deficits.

At the opposite end of the quality spectrum, rivers in the montane Atlantic Forest zones and protected area watersheds consistently achieved Good-to-Excellent classifications. The three highest-quality rivers were Rio Sana (mean IQA=82.77, Excellent), Rio Bonito (82.38, Excellent), and Rio Preto

(80.63, Excellent). These rivers serve as important ecological reference points, demonstrating the quality achievable in the absence of significant anthropogenic pressure.

4.7. Annual Quality Dynamics (Heatmap Analysis)

The temporal heatmap of mean parameter sub-indices per year (Figure 9) provides a multi-dimensional view of quality evolution that complements the single-index trend analysis.



Figure 9. Heatmap of mean NSF-WQI parameter sub-indices (q-values) by year. Darker shades indicate higher quality sub-indices. Parameters ordered from most to least limiting (top to bottom)

The heatmap shows that thermotolerant coliforms maintained consistently low q-values throughout the study period, with no discernible improving trend. Dissolved oxygen showed the greatest year-to-year variation, with notably lower values in 2020 and 2021 — years coinciding with the COVID-19 pandemic period, during which reduced monitoring frequency (n=209 in 2020 vs n=995 in 2018) may have introduced sampling bias toward lower-quality stations. The nitrate sub-index remained stable and well-performing, throughout, while turbidity

showed some improvement from 2020 onward.

4.8. CONAMA 357/2005 Class 2 Regulatory Benchmarking

Compliance analysis of the raw parameter measurements against CONAMA Resolution 357/2005 Class 2 limits (CONAMA, 2005) — the regulatory standard for water bodies intended for human supply after conventional treatment — revealed stark contrasts across parameters (Table 6).

Table 6. Compliance rates of individual parameters against CONAMA 357/2005 Class 2 limits, Rio de Janeiro State (2015–2023).

Parameter	CONAMA Class 2 limit	n	Compliant	Rate (%)
Thermotolerant coliforms (CT)	≤1,000 NMP/100 mL	5,109	1,686	29.7
Total phosphorus (PT)	≤0.1 mg/L	7,296	3,298	45.2
BOD _{5,20} (DBO)	≤5 mg/L	7,289	4,322	59.3
Dissolved oxygen (OD)	≥5 mg/L	7,285	4,486	61.6
Total dissolved solids (SDT)	≤500 mg/L	6,126	5,575	91.0
Turbidity (TURB)	≤100 UNT	7,326	7,016	95.8
pH	6.0–9.0	7,225	7,131	98.7
Nitrate nitrogen (NO ₃)	≤10 mg/L	4,946	4,928	99.6
All parameters (overall)	All above	7,329	1,677	22.9

Thermotolerant coliforms showed the most severe non-compliance, with only 29.7% of measurements (1,686 of 5,109 observations) meeting the Class 2 limit of 1,000 NMP/100 mL. Biochemical oxygen demand compliance was 59.3% (limit: 5 mg/L), and dissolved oxygen compliance was 61.6% (limit: ≥5 mg/L), consistent with the identification of these parameters as the principal quality-limiting factors in the NSF-WQI analysis.

Total phosphorus compliance reached only 45.2% (limit: 0.1 mg/L). In contrast, physical parameters showed high compliance: turbidity 95.8% (limit: 100 UNT), total dissolved solids 91.0% (limit: 500 mg/L), pH 98.7% (range: 6–9), and nitrate nitrogen 99.6% (limit: 10 mg/L). Overall, only 22.9% of station-date combinations met all available Class 2 limits simultaneously, confirming that the majority of monitored water bodies in Rio

de Janeiro State fail to achieve the minimum standards required for Class 2 use (CONAMA, 2005).

5. Discussion

The results of this nine-year, multi-basin assessment of surface water quality in Rio de Janeiro State using the NSF-WQI are consistent with, and provide important quantitative reinforcement for, several findings reported in the prior literature. The overall mean IQA of 54.33 and the polarised quality distribution — with a dominant Good cluster (45.0%) and a substantial combined Poor/Very Poor tail (30.4%) — closely mirror patterns documented by Garcia & Oliveira (2019) for a shorter time window and a subset of the current stations, and are further consistent with multivariate analyses conducted for the Paraíba do Sul sub-basin

using the same institutional data sources (Sampaio et al., 2025). The persistent classification of heavily urbanised metropolitan rivers as Very Poor, documented across 150 rivers and nine consecutive years with formal statistical testing, represents a significant advance in the evidence base supporting targeted policy intervention.

The identification of thermotolerant coliforms and dissolved oxygen as the primary limiting parameters (mean $q=41.09$ and 44.40 , respectively) aligns with findings from comparable tropical urban river studies. Parween et al. (2022) reported a consistent dominant parameter for the Mahananda River system in India, with thermotolerant coliforms ranked first in both studies, while Marselina et al. (2022) documented the same dominant pollution signature in the Citarum River in Indonesia. Across vastly different geographic and institutional contexts, the NSF-WQI consistently flags faecal contamination as the primary barrier to water quality improvement in urbanising developing countries. This finding has direct implications for investment prioritisation: improvements in basic sanitation (sewage collection and treatment) would address simultaneously the two most limiting parameters, producing the highest marginal improvement in aggregate water quality.

The absence of a statistically significant linear improvement trend ($R^2=0.006$, $p=0.839$) over the 2015–2023 period is a particularly important management finding. While the Kruskal–Wallis test confirmed significant inter-annual variability ($H=155.15$, $p<0.0001$), the lack of a directional trend indicates that Rio de Janeiro State’s water quality, considered in aggregate, has neither improved nor deteriorated systematically during the study decade. This stagnation occurs against the backdrop of the Federal Government’s sanitation targets under Law 14,026/2020 (Marco Legal do Saneamento) (Brasil, 2020), which mandated 99% potable water coverage and 90% sewage collection and treatment by

2033. The data presented here suggest that the trajectory towards these targets is not yet reflected in measurable IQA improvements at the river basin scale.

The seasonal pattern observed — with best quality in July (mean IQA=62.8) and worst in November (48.5) and January (49.1) — is consistent with the hydrological cycle of south-eastern Brazil. These seasonal dynamics are more pronounced in urbanised catchments, where impervious surfaces amplify surface runoff and combined sewer overflows during rainfall events. From a quality management perspective (Vujović et al., 2011), this seasonal pattern constitutes a predictable, cyclical non-conformity that should trigger pre-emptive management actions during the transition to the rainy season in October–November each year.

The spatial polarity between the metropolitan area rivers (systematic Very Poor and Poor classification) and the conservation-area headwater rivers (consistent Excellent classification) reflects the classical urban–rural quality gradient documented across tropical river systems worldwide (Romero et al., 2016). The extreme magnitude of this gradient — with some metropolitan rivers averaging below IQA 15 while protected-area rivers exceed IQA 80 — underscores the extent of environmental degradation in Rio de Janeiro’s urban hydrological system. From a benchmarking perspective, the reference rivers (Sana, Bonito, Preto) can be used to establish realistic quality targets for degraded watersheds undergoing remediation.

The Spearman correlation matrix (Figure 6) revealed strong negative correlations between dissolved oxygen sub-indices and organic pollution indicators (DBO, CT, PT), confirming the biochemical oxygen demand pathway as the mechanistic link between faecal sewage inputs and dissolved oxygen depletion. The relative independence of physical parameters (pH, turbidity, TDS) from the organic pollution cluster suggests that these parameters contribute independently to quality variation and should

not be considered redundant in the composite index.

The CONAMA 357/2005 Class 2 compliance analysis (Section 4.8, Table 6) provides a complementary regulatory perspective that reinforces the NSF-WQI findings. The 29.7% compliance rate for thermotolerant coliforms — the most severely non-conforming parameter — directly corresponds to the lowest mean quality sub-index ($q=41.09$) in the NSF-WQI analysis, confirming faecal contamination as the defining regulatory failure of the state's water bodies. The 45.2% compliance rate for total phosphorus and the 59.3% rate for BOD₅ further corroborate the sewage-dominated pollution profile. Taken together, the finding that only 22.9% of station-date combinations met all available Class 2 limits simultaneously underscores the severity of the quality deficit: the regulatory standards intended to protect human health and aquatic life are met in fewer than one in four monitoring events. This dual-framework result — both composite WQI scoring and direct regulatory benchmarking — provides a stronger evidentiary basis for targeted sanitation investment than either approach in isolation.

6. Conclusion

This study presented a comprehensive nine-year performance assessment of surface water quality in 150 rivers of Rio de Janeiro State, Brazil, through the computation of 6,481 NSF-WQI composite indices derived from 135,708 physicochemical and microbiological measurements collected by INEA's official monitoring network (2015–2023). The following principal conclusions are drawn:

1. The aggregate water quality of Rio de Janeiro State rivers falls at the lower portion of the 'Good' category (mean NSF-WQI=54.33), with 30.4% of measurements classified as Poor or Very Poor — indicating a persistent systemic quality deficit driven primarily by domestic sewage contamination.

2. No statistically significant linear improvement trend was observed across the nine-year period (slope=+0.098 IQA units/year, $R^2=0.006$, $p=0.839$), suggesting that current levels of sanitation investment are insufficient to produce measurable aggregate river quality improvement. This finding constitutes a critical indicator for policy makers monitoring progress toward the Marco Legal do Saneamento (Law 14,026/2020; Brasil, 2020) targets.

3. Thermotolerant coliforms (mean $q=41.09$), dissolved oxygen ($q=44.40$), and total phosphorus ($q=49.80$) were the three principal limiting parameters, identifying domestic sewage as the dominant pollution source. Addressing these parameters through expanded sewage treatment infrastructure represents the highest-return investment in water quality improvement.

4. Clear seasonality was documented, with dry-season months (April–September) consistently yielding higher IQA values, with July peak=62.8, compared to rainy-season months (October–March, nadir November=48.5). This seasonal non-conformity pattern is predictable and should be incorporated into adaptive management protocols.

5. Extreme spatial heterogeneity was confirmed, with the most degraded rivers in the Metropolitan Region and Baixada Fluminense — including Canal da Penha (14.29), Rio Irajá (14.32), and Rio São João de Meriti (15.75) — consistently classified as Very Poor, while conservation-area rivers (Rio Sana, IQA=82.77; Rio Bonito, 82.38; Rio Preto, 80.63) consistently achieved Excellent mean classification.

The NSF-WQI, applied to a large-scale, long-duration monitoring dataset, demonstrated robust utility as a performance management tool for river water quality - functioning as an environmental KPI directly analogous to quality indicators in ISO 14001-aligned management systems. Future work should investigate whether the expansion of sanitation infrastructure under Law

14,026/2020 (Brasil, 2020) produces detectable IQA improvements post-2023, and should explore the application of machine-learning-enhanced WQI models to improve predictive capability for water quality forecasting.

7. Study Limitations

Several limitations should be acknowledged, when interpreting the results of this study. First, the temporal trend analysis was performed on $n=9$ annual mean values, which provides limited statistical power for detecting moderate trends; the non-significant slope ($p=0.839$) is therefore indicative but cannot be considered conclusive in the absence of a longer time series. The Kruskal–Wallis test, which operates on the full distribution ($n=6,481$), is more statistically robust and its result is the primary basis for conclusions about inter-annual variability. Second, monitoring frequency dropped markedly in 2020 ($n=209$, compared to $n=995$ in 2018), likely reflecting pandemic-period operational constraints at INEA; this creates the possibility of spatial sampling bias in those years, as not all stations were visited with equal frequency. Third, the minimum parameter-availability criterion of 7 of 9 required parameters, while pragmatic, is not standardised in the WQI literature and may introduce a minor selection bias toward stations with more complete monitoring records. Fourth, the CONAMA 357/2005

Class 2 compliance analysis (Section 4.8) was conducted on raw parameter measurements prior to IQA computation and therefore reflects direct exceedance of regulatory limits rather than composite index performance; the two analyses are complementary but not directly comparable. These limitations do not affect the principal conclusions but should be considered in future comparative studies.

Acknowledgment: The authors acknowledge INEA (Instituto Estadual do Ambiente, Rio de Janeiro) for providing access to the official water quality-monitoring database used in this study.

The author Gilberto Santos acknowledge Fundação para a Ciência e a Tecnologia (FCT) for its financial support to LAETA via project- UID/50022/2025. (DOI: <https://doi.org/10.54499/UID/50022/2025>).

Data Availability Statement: The water quality monitoring data used in this study are publicly available from INEA (Instituto Estadual do Ambiente, Rio de Janeiro) and from the Brazilian National Water Agency (ANA) via the HidroWeb platform (hidroweb.ana.gov.br). The unified dataset and analysis scripts are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest. The data providers had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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Hugo Pimentel Tavares

UERJ-DEAMB,
Rio de Janeiro, Brazil
tavares.hugo@posgraduacao.uerj.br
ORCID 0009-0008-8137-9054

**Nilo Antônio de Souza
Sampaio**

UERJ-DEAMB,
Rio de Janeiro, Brazil
nilo.samp@terra.com.br
ORCID 0000-0002-6168-785X

Gilberto Santos

Associate Laboratory for
Energy, Transports and
Aerospace (LAETA-
INEGI), Porto, Portugal,
santos@inegi.up.pt
ORCID 0000-0001-9268 3272

Carin von Mühlen

UERJ-DEAMB,
Rio de Janeiro,
Brazil
carin@fat.uerj.br
ORCID 0000-0003-0876-1237
