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# Hydrological-hydraulic and water quality modeling of the Maceió Stream in Fortaleza/CE: a case study

## *Modelagem hidrológico-hidráulica e da qualidade da água do Riacho Maceió em Fortaleza/CE: um estudo de caso*

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## ABSTRACT

The Maceió Stream watershed, in Fortaleza, Ceará, Brazil, plays a vital role in the city's urban drainage system but suffers from urbanization, pollution, and environmental degradation. This study applies the Storm Water Management Model (SWMM) to develop hydrological-hydraulic and water quality models, assessing the impacts of impervious areas and diffuse pollution. The integrated model simulates flow rates, flood peaks, and pollutant concentrations, focusing on Biochemical Oxygen Demand (BOD), Total Nitrogen (TN), Total Phosphorus (TP), and Escherichia coli (E. coli). The watershed's relevance stems from its location across densely populated and socially vulnerable areas, making its management environmentally and socially critical. Model performance showed good reproduction of Maceió Stream hydrographs (NSE = 0.78, PBIAS = -9%), with excellent accuracy for BOD (NSE = 0.97, PBIAS = 2%), TN (NSE = 0.91, PBIAS = -3%), and TP (NSE = 0.98, PBIAS = -4%). Scenario analyses considering climate change and continued urbanization revealed the necessity of drainage interventions to mitigate extreme hydrological events and strategies to improve water quality. The study concludes that integrated modeling with SWMM is an effective tool for diagnosing water-related challenges and guiding sustainable management solutions for urban watersheds.

**Keywords:** Modeling; Water quality; SWMM; Urban drainage; Climate change.

## RESUMO

A bacia hidrográfica do Riacho Maceió, situada em Fortaleza, Ceará, é um componente essencial do sistema de drenagem urbana, mas sofre com urbanização intensa, poluição e degradação ambiental. Este estudo aplica o Storm Water Management Model (SWMM) para modelagem hidrológico-hidráulica e da qualidade da água, avaliando os efeitos da impermeabilização e da poluição difusa. O objetivo é desenvolver um modelo integrado capaz de simular vazões, picos de cheia e concentrações de poluentes como Demanda Bioquímica de Oxigênio (DBO), Nitrogênio Total (NT), Fósforo Total (PT) e Escherichia coli (E. coli). A relevância do trabalho decorre da importância ambiental e social do Riacho Maceió, que corta áreas densamente povoadas e de interesse social. Os resultados mostraram que o SWMM reproduz satisfatoriamente os hidrogramas do riacho (NSE=0,78; PBIAS=-9%), com excelente ajuste para DBO (NSE=0,97; PBIAS=2%), NT (NSE=0,91; PBIAS=-3%) e PT (NSE=0,98; PBIAS=-4%). As análises de cenários de mudanças climáticas e urbanização reforçam a necessidade de intervenções nos canais de drenagem para mitigar eventos extremos e de estratégias voltadas à melhoria da qualidade da água. Conclui-se que a modelagem integrada com o SWMM é uma ferramenta eficaz para diagnóstico e proposição de soluções em bacias urbanas.

**Palavras-chave:** Modelagem; Qualidade da água; SWMM; Drenagem urbana; Mudanças climáticas.

## INTRODUCTION

Water resource management in urban areas poses a growing challenge in the context of Brazilian cities, particularly in regions like the Northeast, where climate variability and rapid urbanization exacerbate issues related to water availability and quality (Araújo & Lima Neto, 2019; Araújo et al., 2019; Fraga et al., 2020; Freire et al., 2021; Mesquita & Lima Neto, 2022; Lima Neto, 2023; Rodrigues et al., 2025). In this scenario, the Maceió Stream, located in Fortaleza, the capital of Ceará State, emerges as a paradigmatic case. This watercourse, part of the Vertente Marítima Basin, plays a crucial role in the city's macro-drainage system but faces significant challenges stemming from urbanization, including pollution, flooding, and environmental degradation.

The environmental challenges of the Maceió Stream are worsened by disorganized occupation, including informal settlements such as Saporé, which intensify pollution through the irregular discharge of sewage and solid waste (Maia, 2010; Mesquita et al., 2020). Recent studies, such as those conducted by the Institute of Marine Sciences (Labomar) at the Federal University of Ceará (UFC), have reported high concentrations of *Enterococcus* bacteria at the stream's mouth, rendering Meireles Beach unsuitable for swimming. These issues underscore the need for management strategies that address both the quantity and quality of water, considering the impacts of urbanization and the region's climatic characteristics.

The present study proposes the application of hydrological-hydraulic and water quality models for the Maceió Stream using the SWMM (Storm Water Management Model) software (Rossman & Simon, 2022; Mesquita & Lima Neto, 2022), aiming to contribute to the integrated and sustainable management of this water resource. This effort supports the formulation of strategies to mitigate the impacts of urbanization and promote the environmental recovery of this vital water resource.

River water quality modeling has become a cornerstone of urban hydrology, enabling the simulation of pollutant dynamics, eutrophication risks, and restoration scenarios in increasingly impervious watersheds. A variety of models have been developed to address these complexities, each with distinct capabilities suited to specific scales and objectives. For instance, QUAL2K is a steady-state, one-dimensional model optimized for river reaches, excelling in simulating dissolved oxygen, nutrients, and temperature under baseflow conditions but limited in handling dynamic stormwater events due to its assumption of uniform flow (Chapra & Pelletier, 2003; Noor et al., 2025). In contrast, SWAT (Soil and Water Assessment Tool) operates at watershed scales, integrating land-use changes and agricultural non-point sources with riverine processes, making it ideal for large basins but computationally intensive for urban stormwater quality (Zhao et al., 2024).

WASP (Water Quality Analysis Simulation Program), a modular EPA model, supports one-, two-, and three-dimensional simulations of toxics, nutrients, and eutrophication, offering flexibility for linking with hydrodynamic models like HEC-RAS, though it requires extensive calibration for urban diffuse pollution (Ambrose & Wool, 2017). MIKE 11, developed by DHI, combines one-dimensional hydrodynamic routing with water quality kinetics, suitable for integrated urban-river systems with real-time forecasting capabilities, but demands high-resolution topographic data (DHI, 2021). HSPF (Hydrological Simulation Program - FORTRAN), part of BASINS, excels in continuous simulation of hydrology and non-point source pollution over extended periods, incorporating land-use scenarios, yet its complexity suits regional assessments rather than site-specific urban streams (Duda et al., 2012).

These models differ fundamentally in spatial-temporal resolution and process representation: QUAL2K prioritizes steady-state kinetics for short reaches, SWAT focuses on watershed-scale non-point sources, WASP emphasizes modular toxics modeling, MIKE 11 integrates hydraulics for dynamic flows, and HSPF handles continuous simulations for land management. Reviews emphasize that model selection hinges on data availability, computational resources, and objectives, e.g., QUAL2K for rapid assessments and SWAT for land-use sensitivity (Talukdar et al., 2023).

In urban contexts such as the Maceió Stream, the focus of the present study, the SWMM model stands out among the aforementioned approaches due to its integrated representation of hydrology, hydraulics, and stormwater quality. This integration enables comprehensive simulations of runoff and pollutant transport driven by impervious surfaces. Thus, the objective of this study is to advance the understanding of hydrological and water quality processes within the watershed, thereby contributing to the integrated and sustainable management of this and similar urban water resources.

## METHODOLOGY

### Study area

The study area focuses on the Maceió Stream watershed, which is part of the Vertente Marítima Basin, entirely located within the municipality of Fortaleza, as shown in Figure 1. The Maceió Stream watershed is characterized by predominantly urban occupation, featuring a mix of residential, commercial, and industrial land uses. The stream's banks are occupied by low-income housing and informal settlements, which contribute to pollution from domestic sewage and solid waste (Fechine, 2007; Maia, 2010). These vulnerable areas have been designated as Special Zones of Social Interest (ZEIS) under the Participatory Master Plan of Fortaleza, areas prioritized for urban and land regularization, as well as the development of social housing programs, as stipulated in Complementary Law No. 62/2009, Article 123 (Fortaleza, 2009).

According to data from the Fortaleza Municipal Government, in 2010, the sewage coverage rate in the Maceió Stream basin was above 80%. However, this value does not reflect the effective connection of properties to the sewage network, only indicating the availability of a collection network in the region.

The drainage system of the Maceió Stream, the subject of this study, is a complex system composed of preserved natural sections, sections in open artificial channels, and confined drainage galleries.

### Urban drainage system

The delineation of the Maceió Stream watershed, including its sub-basins, and the inventory of both canalized and natural drainage networks, with their respective typology, materials,

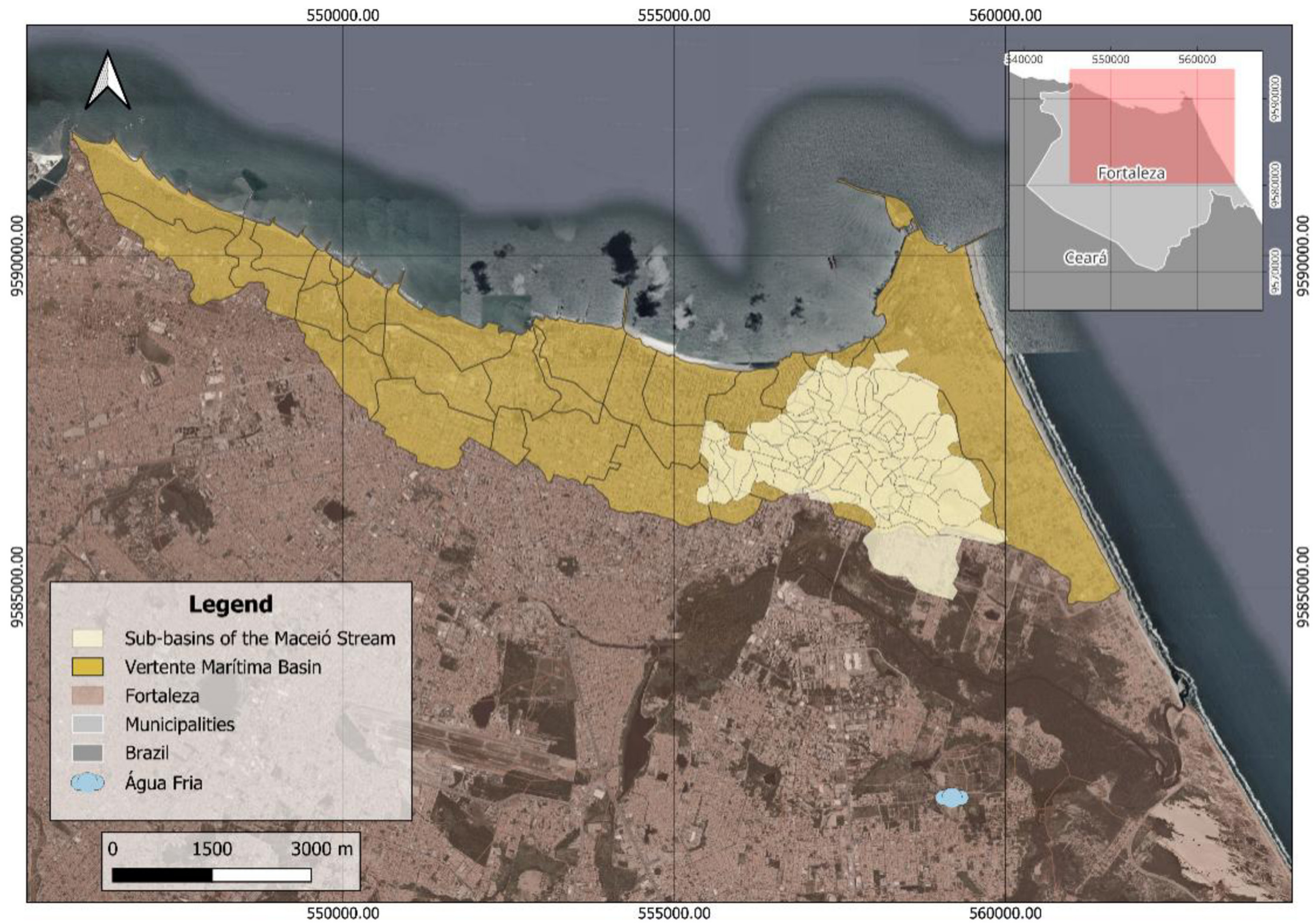


**Figure 1.** Location of the study area.

diameters, and bathymetries of natural sections, were provided by the Fortaleza Municipal Secretariat of Infrastructure (SEINF) and the Municipal Secretariat of Urbanism and Environment (SEUMA). The bathymetries of the natural sections were conducted in January 2024. The Maceió Stream drainage network consists of preserved natural sections and canalized segments in the urban zone, comprising 12,830 m of concrete-lined channels, 395 m of open channels, 3,344 m of natural sections, and 3,560 m of piped sections with diameters ranging from 0.6 to 1.5 m. The Papicu Stream serves as its primary tributary. See Figure 2.

## Hydraulic parameters for the model

The hydrological-hydraulic modeling was conducted using the Storm Water Management Model (Rossman & Simon, 2022), following adaptations of methodologies applied in hydrological modeling studies of urban watersheds, such as those by Mesquita (2018) and Silveira et al. (2022). The system was configured with 94 sub-basins, 95 reaches, 95 nodes, and a single outfall. Roughness coefficients of 0.015 were adopted for concrete structures, while 0.05 was used for natural sections. At the nodes receiving contributions from the sub-basins, a base dry-weather flow of 0.05 $L \cdot s^{-1}$ was incorporated.

Initial basin characteristics, including slope, Curve Number (CN), Manning's roughness coefficients for pervious and impervious areas, depression storage depths for pervious and impervious surfaces, and the percentage of impervious area, were derived from the validated study by Mesquita (2018), as well as values obtained from the literature and the minimum and maximum values established in the SWMM User's Manual (Rossman & Simon, 2022; Silveira et al., 2022). Subsequently, the morphological and land-use characteristics of the sub-basins were calibrated through a sensitivity analysis in which the parameters were modified by ±5 from the baseline values to achieve the best fit for flow rates at the monitored reach. As discussed earlier.

The flow path widths (Width) for each sub-basin were recalculated using the Equivalent Rectangle Method (Equations 1 and 2) (Rossman & Simon, 2022; Silveira et al., 2022).

$$W=\frac{k_C\sqrt{A}}{1.12}\left[1-\sqrt{1-\left(\frac{1.128}{k_C}\right)^2}\right] \tag{1}$$

$$k_C = 0.282\frac{P}{\sqrt{A}} \tag{2}$$

Where W is the width of the equivalent rectangle (m); A is the area of the sub-basin ($m^2$); $k_c$ is the compactness coefficient; P is the perimeter of the sub-basin (m).

## Rainfall data

The selected rain gauge station was Água Fria, identified by code 338038, chosen due to its proximity to the study area and the consistency of its data, which exhibited no gaps during the study period (January to June 2024), with daily precipitation readings. During this period, precipitation amounts typical of the city of Fortaleza were recorded (within ±20% of the historical mean), serving as a basis for modeling representative conditions of regional reality. The station is maintained and operated by the Ceará Foundation of Meteorology (FUNCEME), located at coordinates -3.7833 latitude and -38.4667 longitude. Historical data series were obtained from the HidroWeb Portal of the National Agency for Water and Basic Sanitation (ANA). Figure 3A presents the time series of precipitation, while Figure 3B displays the rainfall histogram.

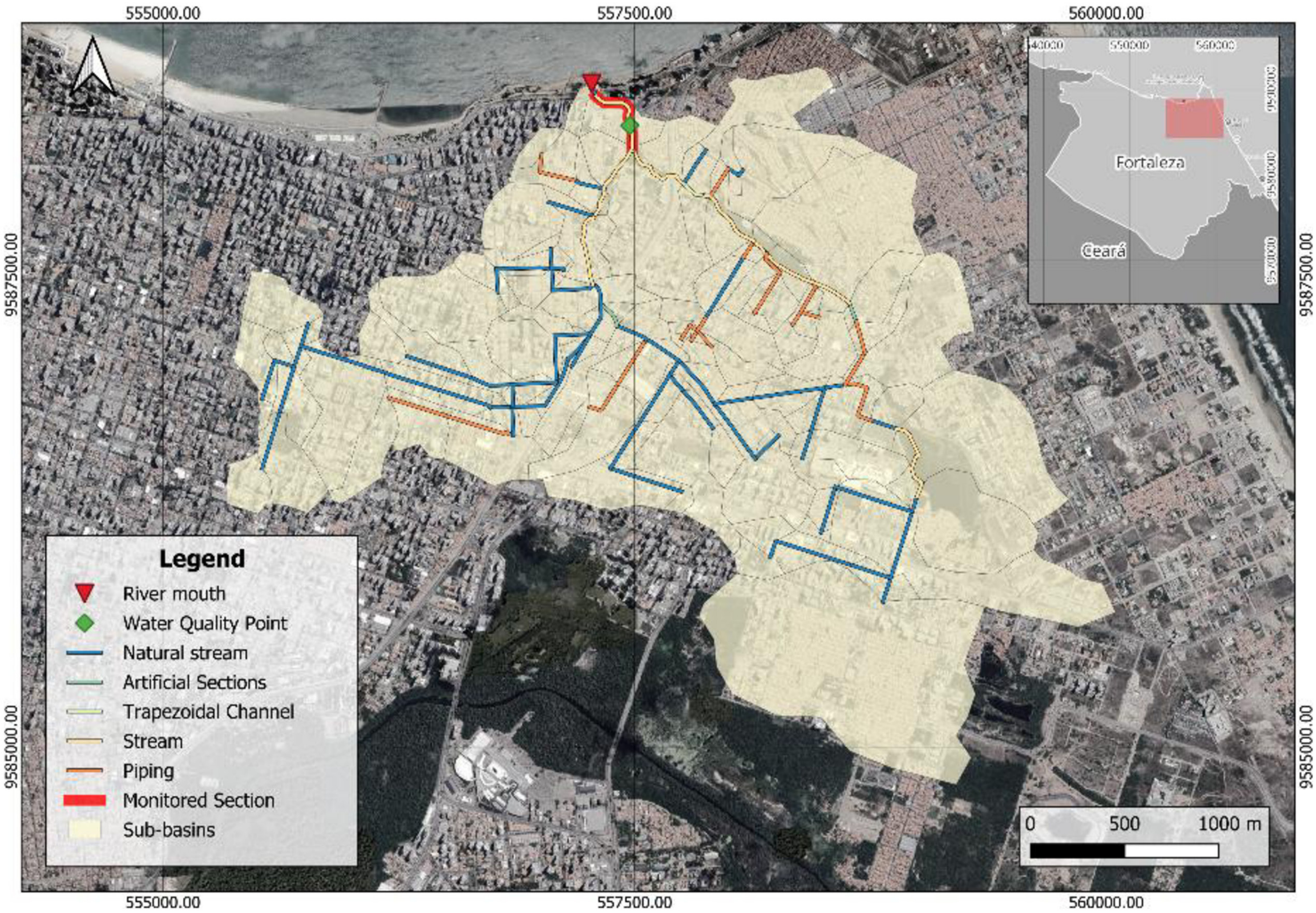


**Figure 2.** Modeled Maceió Stream Watershed.

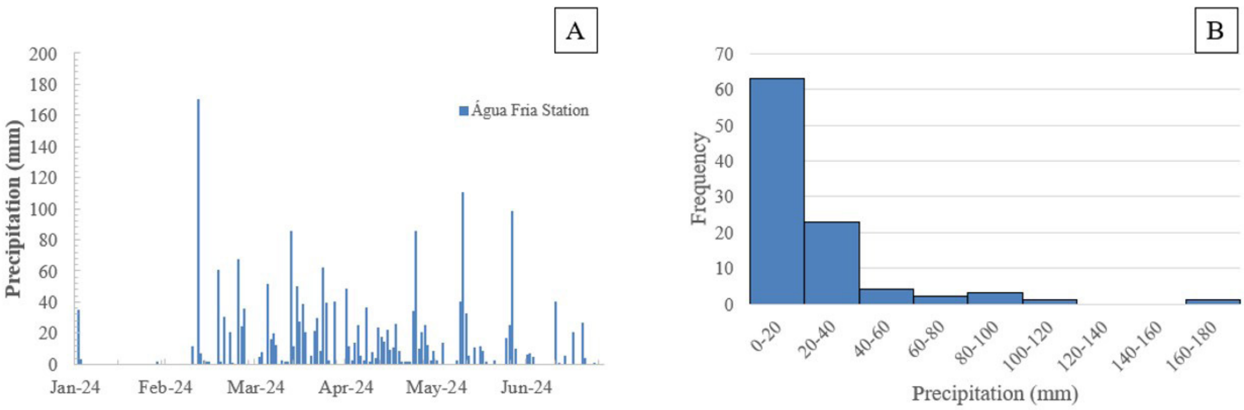


**Figure 3.** Time Series of Precipitation (mm) from the Água Fria Station (A), Precipitation Histogram (mm) from the Água Fria Station (B).

## Calibration

The calibration of the hydrological-hydraulic and water quality models was statistically evaluated using the Nash-Sutcliffe Efficiency (NSE) coefficient and the percent bias (PBIAS), as described by Equations 3 and 4, respectively. These metrics quantify the correspondence between simulated and observed flow rates, as outlined in the equations below (Moriasi et al., 2015). The individual calibration of the hydrological-hydraulic characterization coefficients and water quality parameters will be addressed in the following sections.

Nash-Sutcliffe Efficiency (NSE):

$$NSE=1-\frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \quad (3)$$

Percent BIAS (PBIAS):

$$PBIAS=\frac{\sum_{i=1}^{n}(O_i-P_i)}{\sum_{i=1}^{n}O_i}\times 100 \quad (4)$$

Where $O_i$ is the observed value at point i, $P_i$ is the simulated value at point i, and $\bar{O}$ is the mean of the observed values. Table 1 summarizes the reference values for NSE and PBIAS.

### Flow rates

In the initial phase, the flow rates within the system were calibrated using measurements taken at the monitored point. These measurements were conducted indirectly using a high-precision flow velocity meter (MiniAir20, Omni Instruments), similarly to the studies of Araújo et al. (2019) and Fraga et al. (2020). To facilitate the measurement process, a 4.5-meter-long graduated PVC guide tube was fabricated to stabilize the probe during velocity calibration, ensure access to the sampling location, and measure the water depth at that point. The procedure involved measuring the velocity at five points across the stream's cross-section, located at the two extremes, the center, and the two intermediate positions. The probe was inserted to approximately two-thirds of the water depth from the surface and held until the equipment reading stabilized. This process was repeated to obtain four readings at each point. The flow rate was then calculated by weighting the average velocities from the four readings against the wetted areas of influence for each point, based on the corresponding water depths.

The flow measurement campaigns in the Maceió Stream were conducted on six days at 10 a.m. during the months of February, March, and April 2024. Due to equipment limitations that prevented continuous monitoring, point measurements were collected at the same location as the Water Quality monitoring site identified in Figure 2. The measurements carried out in February preceded the first rains of the season; however, a small perennial flow was observed, estimated to originate from irregular sewage discharges and subsurface drainage from buildings and developments requiring groundwater table lowering.

The hydraulic model's flow rates were calibrated through manual iterations. The parameters with the greatest influence on flow generation were adjusted by increasing or decrementing their current values by 5%. The simulations were then run again in SWMM, and the performance indicators NSE and PBIAS were quantified. This procedure was repeated until the best fit was achieved.

### Water quality

Water quality was also modeled using the Storm Water Management Model (SWMM), employing buildup and washoff equations. For all pollutants, the POW (power function) was adopted to model the accumulation of contaminants on urban surfaces prior to rainfall events, with normalization based on the sub-basin area. For the washoff process, the EXP (exponential function) was employed to describe how contaminants are transported during rainfall, with coefficients and exponents adjusted to reflect sensitivity to precipitation intensity (Rossman & Simon, 2022).

The water quality data used for model calibration were sourced from bimonthly pollution control reports of the Fortaleza/CE Water Resources Monitoring Program, available up to the preparation of this study, covering the months of February, April, and June 2024. These reports were compiled by the Fortaleza Secretariat of Urbanism and Environment (SEUMA). It is emphasized that all analyses were performed by accredited laboratory, strictly following the procedures outlined in the Standard Methods for the Examination of Water and Wastewater specific to each pollutant. Given that the Fortaleza Water Resources Monitoring Program is in its initial phase, sufficient data with adequate frequency were not available to perform a typical characterization of the stream under study.

Among the available parameters, four were selected: Biochemical Oxygen Demand (BOD), *Escherichia coli* (E. coli), Total Nitrogen (TN), and Total Phosphorus (TP). These were chosen as direct indicators of organic matter load, bacteriological pollution, sewage presence, and eutrophication potential of the water body, while also serving as indirect indicators of impacts on coastal ecosystems and economic activities such as swimming, tourism, and fishing. This selection reflects environmental, sanitary, and social perspectives.

**Table 1.** Performance classification based on statistical metrics.

| Performance Classification | NSE | PBIAS (%) |
|---|---|---|
| Very Good | NSE > 0.80 | PBIAS < ±5 |
| Good | 0.70 < NSE ≤ 0.80 | ±5 ≤ PBIAS < ±10 |
| Satisfactory | 0.50 < NSE ≤ 0.70 | ±10 ≤ PBIAS < ±15 |
| Unsatisfactory | NSE ≤ 0.50 | PBIAS ≥ ±15 |

For the implementation of contaminants in the SWMM, it was necessary to characterize them in terms of dry-weather concentration, initial basin concentration, and the coefficients of the buildup and washoff equations (Equations 5 and 6). In this study, a simplification was introduced to the model by disregarding the decay coefficient for contaminants, based on hydraulic results. This decision was justified by the high transport velocities and low residence times within the watershed, rendering decay negligible. This hypothesis aligns with the findings of Pereira et al. (2015), which demonstrated that canalization limits natural self-purification processes due to increased transport velocities.

Buildup:

$$\mathrm{Min}\left(\mathrm{C1},\ \mathrm{C2}^{*}t^{\mathrm{C3}}\right) \tag{5}$$

Washoff:

$$\mathrm{C1}(\mathrm{runoff})^{\mathrm{C2}}(\mathrm{buildup}) \tag{6}$$

For the dry-weather concentrations and initial concentrations, typical values for domestic sewage were initially adopted, along with the average values from water quality reports provided by SEUMA, respectively (Table 2). In the SWMM, the concentration of E. coli is expressed in units of $\#\cdot L^{-1}$, which corresponds to $10^{-4}$ $MPN\cdot 100\ mL^{-1}$.

The calibration process followed a methodology analogous to that used for flow rates. Iterative adjustments were made to the coefficients of the buildup and washoff equations, with NSE and PBIAS coefficients calculated after each iteration. This procedure was repeated to achieve the best model performance. A summary of the adopted parameters is available in Table 3 and Table 4.

Where Max. Buildup (C1) is given in $kg\cdot ha^{-1}\cdot day^{-1}$ and represents the accumulation rate per hectare; Rate Constant (C2) and Power/Sat Constant are dimensionless; Normalizer defines the parameterization method for accumulation within the basin based on the area extent; and Coefficient (C3) and Exponent (C4) are also dimensionless

## Scenario simulation

Three scenarios were evaluated, involving changes in the rainfall regime due to climate change and watershed interventions, thereby demonstrating the application of modeling as a tool for water resources planning and management. At this stage, the results for *E. coli* were not assessed, since the model was unable to reproduce the behavior of this parameter.

Of these, two scenarios focused on changes in the rainfall regime. In the first, the situation of reduced precipitation volume (dry regime) was evaluated; in the second, the increase in rainfall volume and peak precipitation (wet regime) was considered. Studies such as Costa et al. (2025) have examined variations in precipitation because of atmospheric temperature changes, leading to extreme climate events such as intense storms. To this end, precipitation data were classified by quartiles for each month, and reduction or amplification factors were applied to these intervals. Finally, the monthly totals were normalized to match, in scenario one, 80% of the baseline precipitation for the corresponding month, and in scenario two, 120%, thus maintaining the consistency of the generated series and the seasonal characteristics of rainfall. The tables below present the quartile limits, the accumulated monthly precipitation (Table 5), and the factors used for generating the new rainfall series (Table 6).

**Table 2.** Pollutant input concentrations in SWMM.

| Pollutant | Dry-Weather Concentration | Initial Concentration |
|---|---|---|
| BOD ($mg\cdot L^{-1}$) | 100.0 | 63.5 |
| *E. Coli* ($\#\cdot L^{-1}$) | $3.5\times10^{7}$ | $8.0\times10^{7}$ |
| TN ($mg\cdot L^{-1}$) | 10.0 | 1.0 |
| TP ($mg\cdot L^{-1}$) | 0.9 | 0.2 |

$\#\cdot L^{-1}$ is used to represent direct counting per liter in SWMM.

**Table 3.** Configuration applied to the buildup function.

| Pollutant | Function | *Max. Buildup* | *Rate Constant* | *Power/Sat. Constant* | *Normalizer* |
|---|---|---|---|---|---|
| BOD ($mg\cdot L^{-1}$) | POW | 80 | 0.4 | 0.2 | AREA |
| *E. Coli* ($\#\cdot L^{-1}$) | POW | $1.0\times10^{11}$ | 0.1 | 0.1 | AREA |
| TN ($mg\cdot L^{-1}$) | POW | 12 | 0.4 | 0.4 | AREA |
| TP ($mg\cdot L^{-1}$) | POW | 10 | 0.4 | 0.4 | AREA |

$\#\cdot L^{-1}$ is used to represent direct counting per liter in SWMM.

**Table 4.** Configuration applied to the washoff function.

| Pollutant | Function | *Coefficient* | *Exponent* |
|---|---|---|---|
| BOD ($mg\cdot L^{-1}$) | EXP | 0.0004 | 0.185 |
| *E. Coli* ($\#\cdot L^{-1}$) | EXP | 0.5 | 1.8 |
| TN ($mg\cdot L^{-1}$) | EXP | 0.5 | 1.3 |
| TP ($mg\cdot L^{-1}$) | EXP | 0.0005 | 0.17 |

$\#\cdot L^{-1}$ is used to represent direct counting per liter in SWMM.

The third scenario simulated an increase in the watershed's impervious area, caused by urbanization, to assess the conveyance capacity of the existing drainage system and to verify the impacts on water quality. For this purpose, a Curve Number value of 85 was applied to all sub-basins, corresponding to residential areas with approximately 65% impervious surface (Rossman & Simon, 2022).

## RESULTS AND DISCUSSION

### Hydrological and hydraulic results

Figure 4 presents box plots that illustrate the variability of characterization parameters across the 94 modeled sub-basins following the calibration process. This figure allows for the identification of the ranges of adopted values and the mean values obtained after sensitivity analysis of the model and calibration through manual iteration methods, starting from baseline values derived from the literature, as outlined in the methodology.

Where CN is the Curve Number, N-Imperv is the Manning's roughness coefficient for impervious areas, and N-Perv is for pervious areas, with all three parameters being dimensionless; S-Imperv is the surface storage for impervious areas, and S-Perv is for pervious areas, both in millimeters; %Imperv is the percentage of impervious area; Width is the characteristic width of the sub-basin based on its shape, in meters; and %Slope is the average percentage slope of the basin.

The average CN was approximately 67, indicating soils with moderate infiltration capacity (SCS Group B/C) and partial urbanization. The minimum CN adopted was 56, in the sub-basins surrounding the Papicu Lagoon, which are less urbanized. Low CN values such as this may overestimate infiltration processes, contributing to errors during dry periods. The values adopted for Manning's coefficients in impervious and pervious areas are consistent with the findings of Mendes & Andrade (2021), who used N-Imperv = 0.011 for asphalt and N-Perv = 0.15 for grass-covered areas.

**Table 5.** Quartile limits and accumulated precipitation of the baseline series.

| Month | 1st Quartile (Q1) | 3rd Quartile (Q3) | Accumulated Precipitation (mm) |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 39.2 |
| 2 | 0.00 | 11.00 | 431.0 |
| 3 | 0.50 | 28.10 | 553.0 |
| 4 | 1.85 | 22.75 | 462.2 |
| 5 | 0.00 | 11.50 | 408.8 |
| 6 | 0.00 | 3.20 | 114.6 |

**Table 6.** Factors for generating rainfall series.

| Interval | Scenario 01 – Dry regime | Scenario 02 – Wet regime |
|---|---|---|
| ≤ Q1 | 0.6 | 1.5 |
| Q1 < p ≤ Q3 | 0.4 | 2.2 |
| > Q3 | 0.1 | 3.0 |

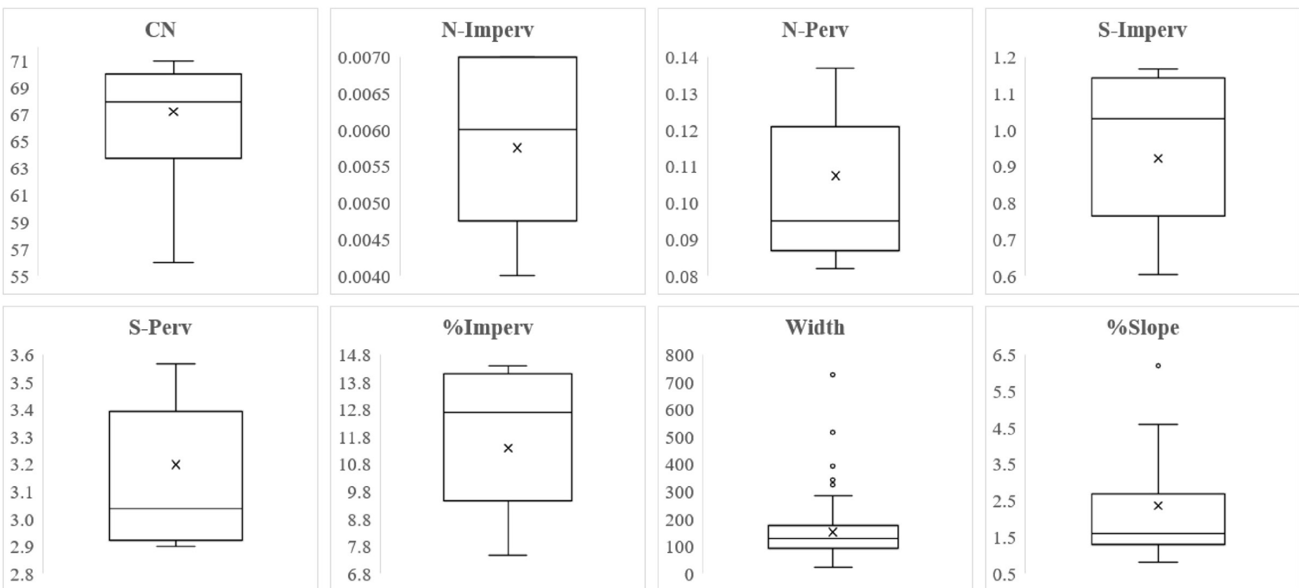


**Figure 4.** Box plot of the input parameters of the sub-basins in SWMM.

In the sensitivity analysis, the percentage of impervious area (%Imperv) was identified as the most significant parameter in the developed hydrodynamic model, consistent with the findings of Zakizadeh et al. (2022). In urban watersheds, imperviousness rates above 60% have been reported, as shown by Mendes & Andrade (2021). However, in the Maceió Stream watershed, the average value obtained was 11.6%, indicating either internal losses in runoff or an overestimation of the watershed boundaries contributing to the tributaries of the drainage network. This corresponds to 30% of the %Imperv value adopted by Mesquita (2018). Manning's roughness coefficients of 0.015 were adopted for concrete channels and 0.05 for natural channels (Rossman & Simon, 2022).

The simulation was performed for the period from January 1 to June 30, 2024, covering field observations and including both the pre-rainy season and the end of the rainy season, with a calculation time step of 30 minutes for both dry and wet periods. The simulated series exhibits periods of low and stable discharge (generally $< 3\ m^3 \cdot s^{-1}$), with an average flow of $0.89\ m^3 \cdot s^{-1}$ and flood events with significant peaks at the monitored reach. Rocha et al. (2021) reported an average discharge of $2.35\ m^3 \cdot s^{-1}$ and a mean flow of $0.33\ m^3 \cdot s^{-1}$ for a coastal river in Fortaleza, with slightly lower flows due to its transitional watershed between rural and urban zones, characterized by a lower urbanization rate. These peaks are associated with intense rainfall events, as illustrated in Figure 5. The abrupt increase in flow within less than 24 hours indicates high imperviousness and reduced time of concentration. Strong agreement can be observed between the measured and modeled values, as reflected in the statistical metrics presented below.

The average time of concentration from the onset of rainfall to the peak flow was 15 hours, generally occurring during the early hours of the day. This suggests that the most intense rainfall events may occur during the night or early morning, a pattern commonly observed in Fortaleza during the rainy season.

It is worth noting that, due to the monthly spacing of the calibration data and the limited data availability, less discretized precipitation data (daily precipitation) were used. Nevertheless, the results indicate that the developed model was capable of adequately representing the watershed dynamics. The statistical performance metrics, NSE and PBIAS, were evaluated for the monitored reach, yielding values of 0.78 and -9%, respectively. According to Moriasi et al. (2015), these results indicate good model performance, reasonably capturing the variability of observed flows. The negative PBIAS value indicates that the model tends to overestimate the flow, which may be related to the calibration data, which were collected in the field at the beginning of rainfall events or after flood peaks. Thus, it better represents the behavior for low flows.

## Water quality results

The simulation results for water quality demonstrated excellent model reproducibility (NSE > 0.9 and PBIAS < 5%) for BOD, Total Nitrogen, and Total Phosphorus, according to the ranges defined by Moriasi et al. (2015). Studies such as Li et al. (2016) have already demonstrated the SWMM's capability to simulate these pollutants. Figures 6 and 7 clearly show an increase in pollutant concentrations, especially during rainfall events, when accumulated contaminants are transported to the stream, corroborating the findings of Mesquita & Lima Neto (2022).

The temporal behavior of *E. coli* could not be adequately represented by the model. This poor performance for *E. coli* suggests the presence of fecal contamination sources that are not properly represented, due to the lack of detailed data on sewage discharges, variations in bacterial decay influenced by solar radiation, and other environmental factors (Pereira et al., 2015). The low number of observations used in the calibration stage also influenced model adjustment.

It is worth noting that the concentration of E. coli in a water body is a key parameter in monitoring, as it is one of the primary pollutants limiting the characterization of water uses, whether for recreational water quality or drinking water supply. In the Maceió Stream, the quality of its water directly reflects on the quality of its estuary, located at Mucuripe Beach, a prominent area of the Ceará state capital.

Based on the simulation results, the water body classification was evaluated according to CONAMA Resolution 357 of 2005 (Brasil, 2005). To this end, the average simulated concentrations were calculated, which represent the typical water quality characteristics of the Maceió Stream. These included concentrations of $54.6\ mg \cdot L^{-1}$ for BOD, $6.69\ mg \cdot L^{-1}$ for TN, $1.00\ mg \cdot L^{-1}$ for TP, and $9.0 \times 10^4$ MPN·100 $mL^{-1}$ for E. coli.

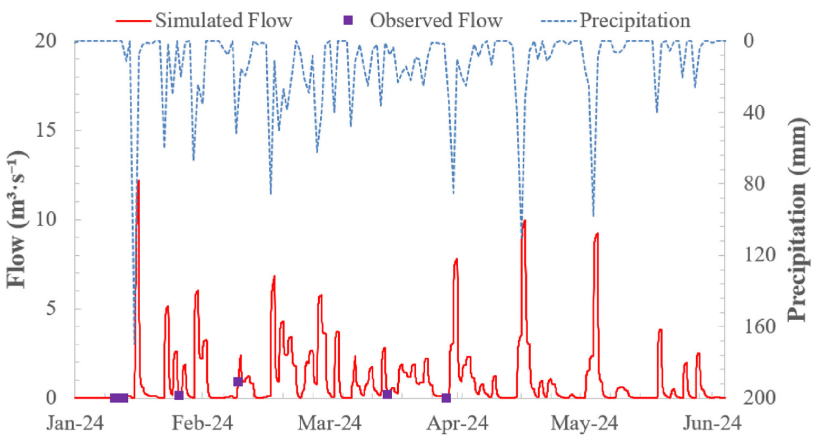


**Figure 5.** Simulated and observed flows at the monitored point.

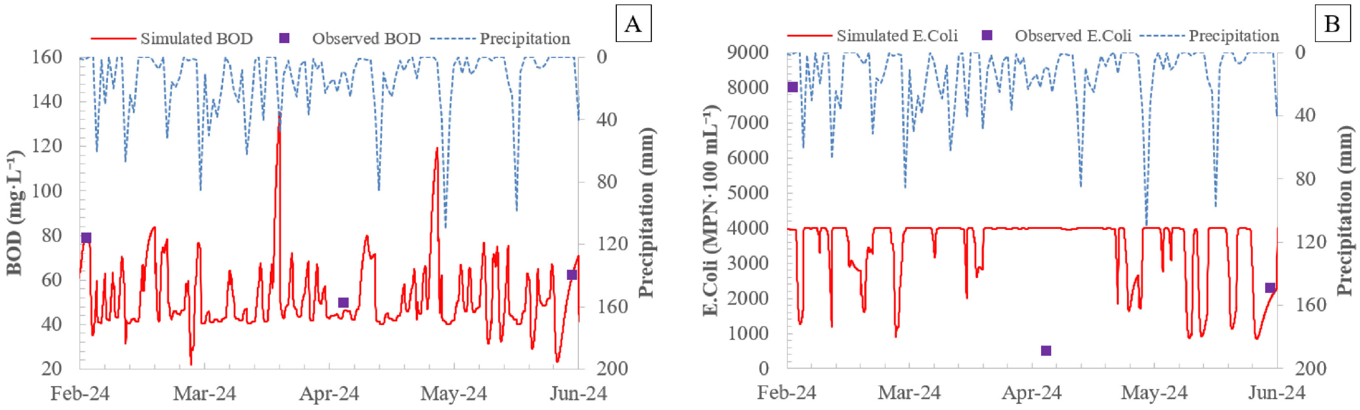


**Figure 6.** Time series of simulated and observed BOD (NSE = 0.97, PBIAS = 2%) (A); time series of simulated and observed *E. coli* (NSE = 0.07, PBIAS = 8%) (B).

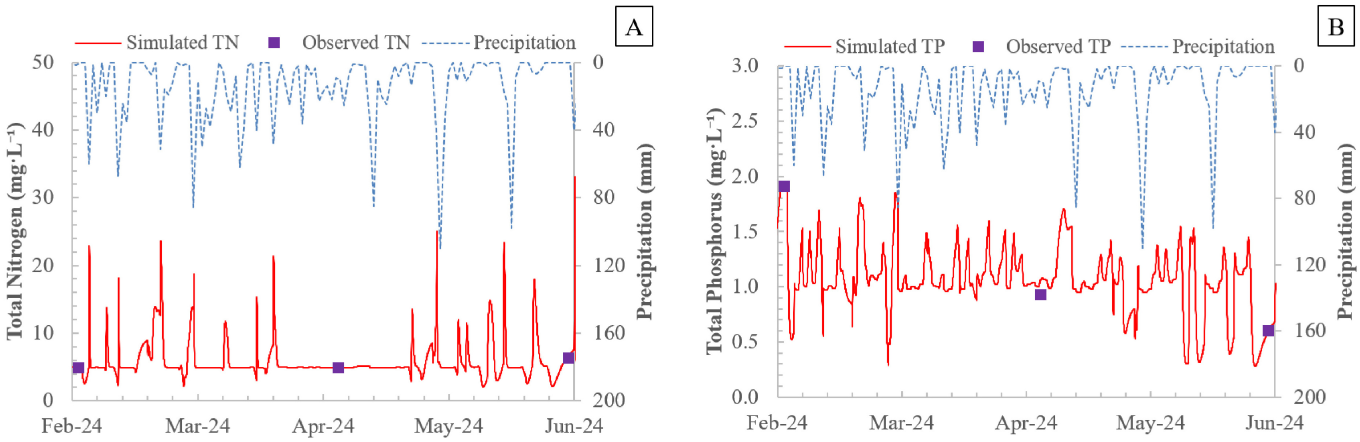


**Figure 7.** Time series of simulated and observed Total Nitrogen (NSE = 0.91, PBIAS = -3%) (A); time series of simulated and observed Total Phosphorus (NSE = 0.98, PBIAS = -4%) (B).

The resulting concentrations classify the Maceió Stream as Class 4, applicable to freshwater bodies designated exclusively for navigation and landscape harmony. The high concentration of organic matter, coupled with elevated bacteriological load, primarily reflects the effects of inadequate sewage disposal.

## Scenario simulation results

### Assessment of climate change effects on the maceió stream watershed

With a 20% reduction in rainfall volume, peak discharges decreased compared to those of the calibrated model, as seen in the flattened hydrograph in Figure 8A (short dashed line). Conversely, with increased precipitation, more intense runoff peaks occurred over shorter time intervals.

BOD and TP showed a significant reduction in concentrations under reduced precipitation conditions and only a slight effect under increased runoff, as shown in Figures 8B and 9B. This behavior is attributed to the saturation limit in pollutant accumulation within the watershed, which restricts the maximum load generated during wash-off events. Furthermore, higher runoff flow promotes dilution of contaminant concentrations. Total Nitrogen, on the other hand, did not undergo significant changes across the simulated scenarios, indicating that it is more closely related to diffuse loads from tributaries than to watershed accumulation and wash-off processes (Figure 9A).

### Assessment of imperviousness effects on the maceió stream watershed

In this scenario, an increase in peak flows was observed at the monitored reach, consistent with the results obtained by Li et al. (2016), reflecting the greater volume of rainfall converted into runoff within the watershed (Figure 10A). This increases vulnerability to flooding during extreme precipitation events (Rosenberger et al., 2021). Regarding water quality, a slight reduction was observed in the maximum concentration values of all pollutants during rainfall events, indicating possible dilution of contaminants and effective wash-off of accumulated loads in the sub-basins during dry periods (Figure 10B, Figure 11A, and Figure 11B).

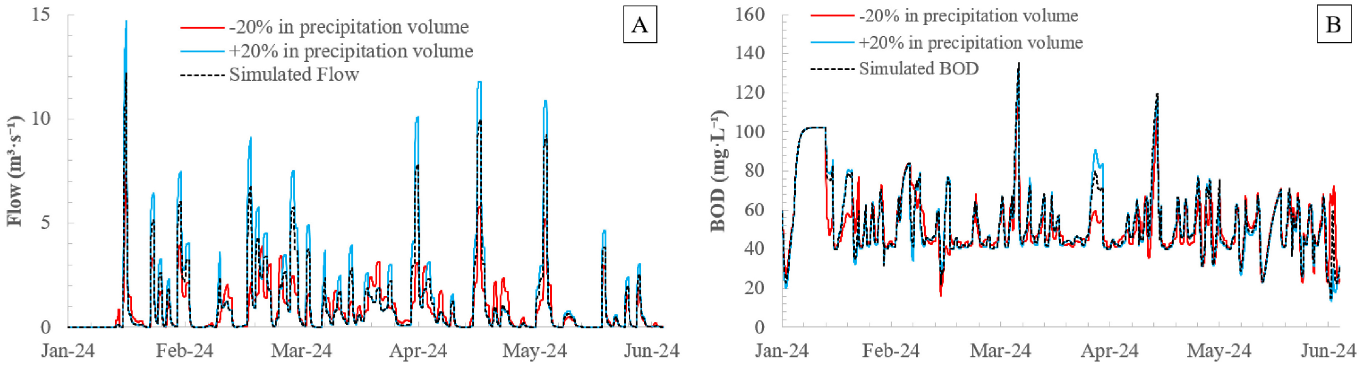


**Figure 8.** Effect of rainfall variation on runoff at the monitored reach (A); effect of rainfall variation on BOD concentration at the monitored reach (B).

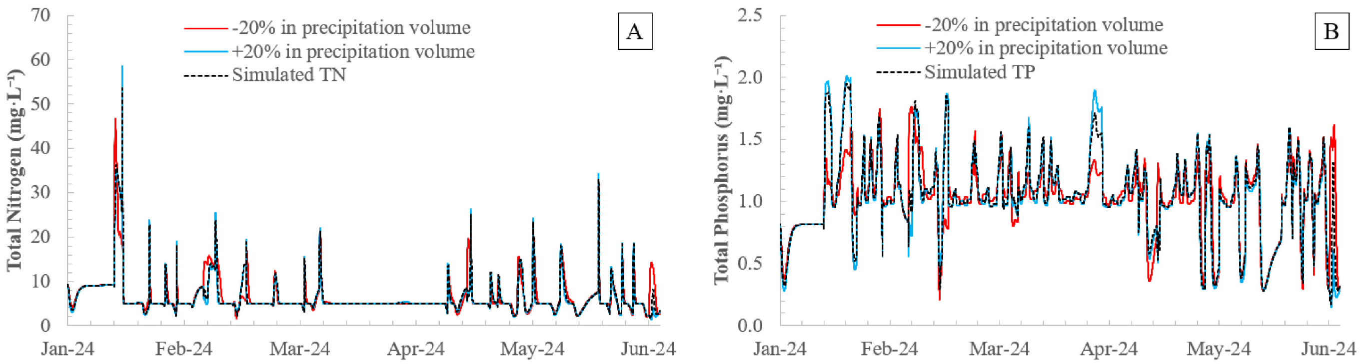


**Figure 9.** Effect of rainfall variation on Total Nitrogen concentration at the monitored reach (A); effect of rainfall variation on Total Phosphorus concentration at the monitored reach (B).

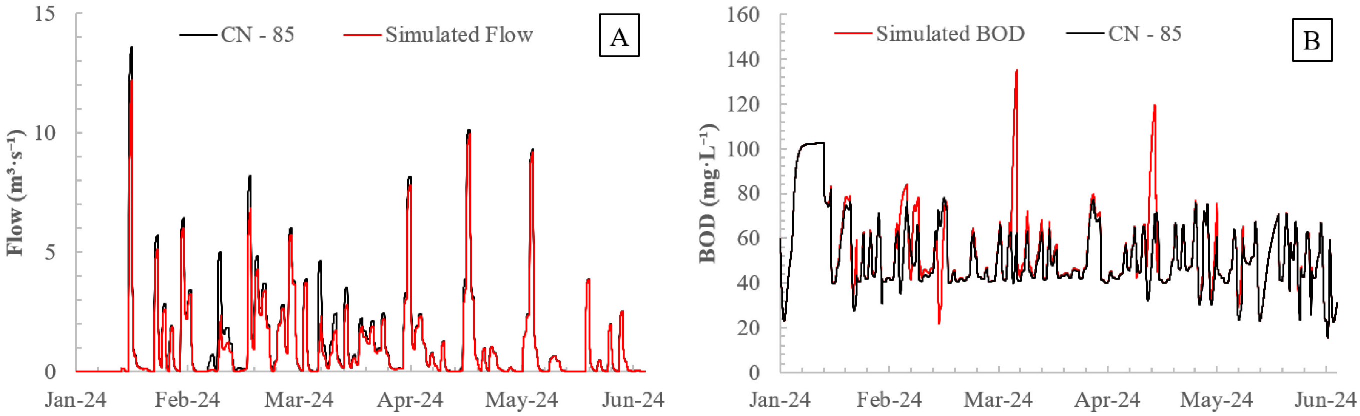


**Figure 10.** Flow series under the CN = 85 scenario (A); BOD series under the CN = 85 scenario (B).

## Cross-analysis of scenario results

With the consolidated results presented in Table 7 and Table 8, it is possible to visualize the variations in flow, BOD, TN, and TP relative to the calibrated model simulation. The effects on mean flows were close to a one-to-one relationship; that is, with a 20% reduction in precipitation, there was approximately a 20% decrease in the mean flow of the calibrated model. Similarly, with a 20% increase, the same increment was observed in the mean flow of the wet scenario. Maximum flows were limited to a 20% increase in the wet scenario and showed a sharper reduction under the dry scenario (-34.5%). This pattern was not observed in the imperviousness increase scenario, where precipitation was kept constant. In this case, mean flows increased by 16.3% and peak flow by 11.4%.

Furthermore, it was found that contaminants do not exhibit a straightforward response to precipitation variations.

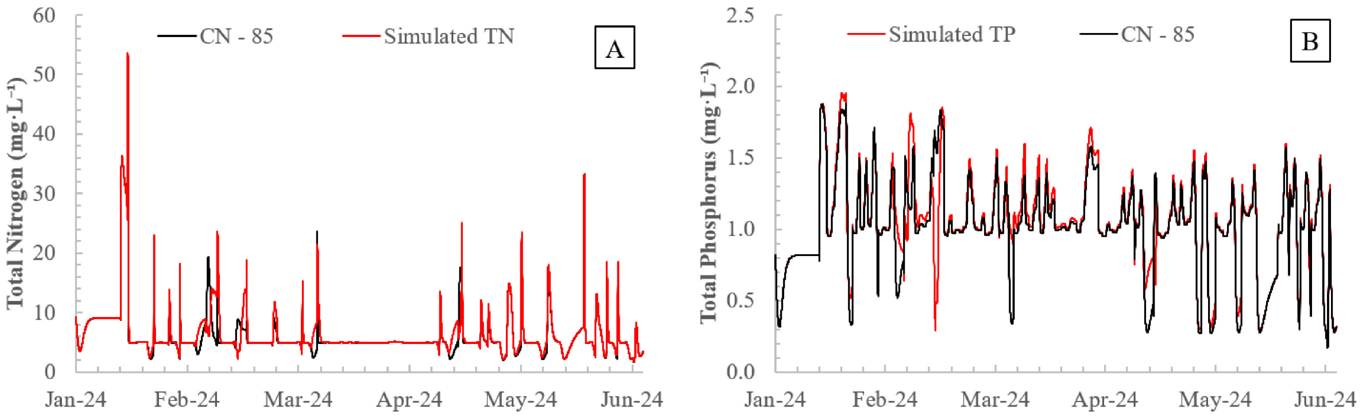


**Figure 11.** Total Nitrogen series under the CN = 85 scenario; Total Phosphorus series under the CN = 85 scenario.

**Table 7.** Variation in overall mean relative to the calibrated model.

| | Flow | BOD | Total Nitrogen | Total Phosphorus |
|---|---|---|---|---|
| **Dry Scenario** | -20.8% | -1.9% | 2.3% | -1.5% |
| **Wet Scenario** | 22.4% | -0.7% | -2.0% | -0.6% |
| **CN=85 Scenario** | 16.3% | -3.7% | -4.2% | -2.4% |

**Table 8.** Variation in the maximum value in the series relative to the calibrated model.

| | Flow | BOD | Total Nitrogen | Total Phosphorus |
|---|---|---|---|---|
| **Dry Scenario** | -34.5% | -3.3% | -12.8% | -9.7% |
| **Wet Scenario** | 20.4% | -0.8% | 9.2% | 3.1% |
| **CN=85 Scenario** | 11.4% | -24.3% | -0.4% | -3.6% |

In other words, while some parameters become diluted, others become more concentrated due to the nonlinearities of buildup and washoff processes. As shown in Table 7, BOD and TP concentrations decreased under both reduced and increased flow scenarios, whereas TN accumulated during low-precipitation periods and was diluted during flood events.

According to the results, average concentrations decreased with increased watershed imperviousness. This behavior can be explained by the fact that higher surface runoff during the initial rainfall events promotes a more effective wash-off within the watershed, resulting in smaller pollutant accumulations in subsequent rainfall intervals. This was particularly evident for TN, which experienced the greatest dilution with increased runoff, a result consistent with those obtained by Porto et al. (2025, under review), who identified TN as the parameter most sensitive to seasonal variations, with higher concentrations during the wet season.

Cumulative frequency graphs were developed to analyze the flow rates and pollutant concentrations over the simulated period, providing a comprehensive comparison across the simulated scenarios. The graphs are presented in Figure 12A to 12D. Initial observations indicate that all parameters converge to a common baseline across scenarios: flow rates of up to 0.025 $m^3 \cdot s^{-1}$ in approximately 34% of the period (Figure 12A), BOD around 60 $mg \cdot L^{-1}$ in 12% of the period (Figure 12B), TN around 4.90 $mg \cdot L^{-1}$ in 37% of the time (Figure 12C), and TP around 0.82 $mg \cdot L^{-1}$ in 15% of the period (Figure 12D). Deviations from these baseline values reflect the dynamics of pollutant buildup and washoff within the watershed, as well as the influence of rainfall events of varying intensities. In Figures 12B and 12D, convergence is observed between the increased precipitation scenario and the calibrated base model for BOD and TP, respectively. This behavior suggests that these constituents are less sensitive to dilution from higher rainfall volumes and are more strongly influenced by physical transport mechanisms, particularly evident in the CN-85 scenario (increased imperviousness). Notably, BOD exhibited greater amplitude in oscillations compared to TP. Figure 12C provides a novel perspective on the behavior of TN, which, in contrast to BOD and TP, reached higher concentrations for longer durations in the reduced runoff scenario. This pattern reinforces the greater sensitivity of TN to variations in the rainfall regime, as evidenced by the CN-85 scenario (increased imperviousness with calibrated baseline precipitation), where enhanced TN leaching occurred within the watershed.

These simulated conditions served to evaluate the modeling approach applied as a tool for management and planning. Based on these findings, it is possible to identify key points within the watershed for implementing strategic interventions aimed at restoring and maintaining the health of this urban drainage system. The behavior of the simulated TN concentration observed in this study highlights the need to consider the specific characteristics of each contaminant during urban water quality modeling, avoiding generalizations based on typical patterns, such as those of domestic sewage. This is because conversions between pollutant forms can lead to responses of greater or lesser magnitude, as observed with TN, compared to other modeled contaminants, such as TP or BOD.

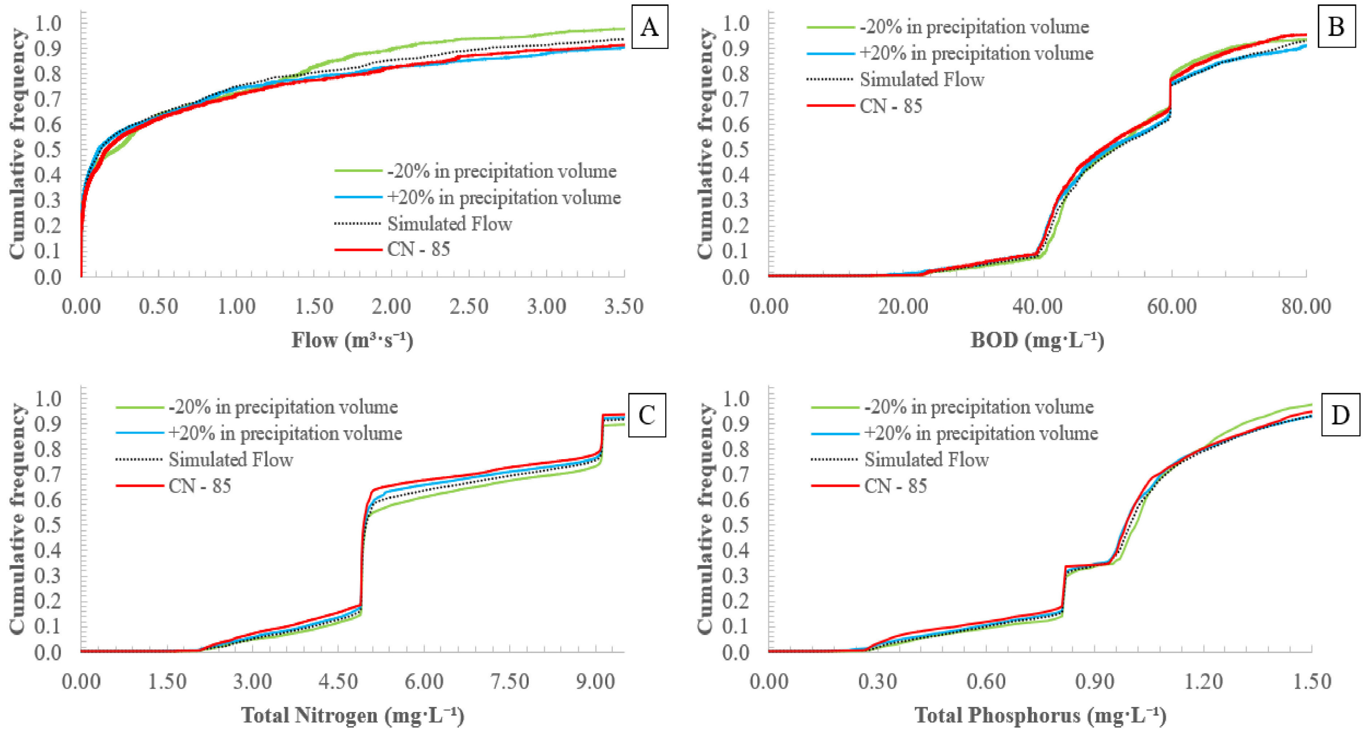


**Figure 12.** Cumulative frequency distributions of (A) flow rate, (B) BOD, (C) Total Nitrogen, and (D) Total Phosphorus in the Maceió Stream over the simulated period, comparing baseline (black dotted line), increased precipitation (blue line), reduced precipitation (green line), and CN-85 (high imperviousness, red line) scenarios.

## CONCLUSIONS

The SWMM model applied to the Maceió Stream proved effective in representing runoff through the rainfall–runoff approach (NSE = 0.78, PBIAS = -9%) and highly effective in water quality modeling for BOD (NSE = 0.97, PBIAS = 2%), TN (NSE = 0.91, PBIAS = -3%), and TP (NSE = 0.98, PBIAS = -4%). However, the adjustments made to the model were not sufficient to adequately represent the bacteriological load in the water body, resulting in unsatisfactory performance for *E. coli* modeling. The simplification of disregarding first-order decay for pollutants did not affect model accuracy, reinforcing the hypothesis that residence time is insufficient to promote contaminant removal.

Interventions in sanitation infrastructure and implementation of nature-based solutions, combined with socio-environmental awareness initiatives within the communities along the Maceió Stream watershed to connect households to the sewage network and minimize solid waste discharges, are essential for mitigating diffuse pollutant loads in the macrodrainage system. For future research in this study area, it is recommended to conduct additional flow rate and water quality measurements, preferably through continuous monitoring, covering both dry and wet seasons. Additionally, it is suggested to investigate the influence of tidal effects on drainage and incorporate this phenomenon into the model.

With the simulated scenarios of changes in rainfall regime and increased watershed imperviousness, it was possible to evaluate how the existing drainage system responds to extreme events and urbanization, respectively. It was inferred that, although soil imperviousness generates higher-magnitude flow peaks in the drainage network, it can either promote more effective wash-off of pollutants from the watershed or dilution of their concentrations. Long-term and high-frequency monitoring of flow rate and water quality would help elucidate this nonlinear behavior, specially for *E. coli* modeling.

## DATA AVAILABILITY STATEMENT

Research data is only available upon request

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## REFERENCES

Ambrose, R. B., & Wool, T. A. (2017). *WASP8 Stream Transport – Model Theory and User's Guide: Supplement to Water Quality Analysis Simulation Program (WASP) User Documentation.* Washinton: U.S. Environmental Protection Agency, Office of Research and Development.

Araújo, G. M., & Lima Neto, I. E. (2019). Removal of organic matter in stormwater ponds: a plug-flow model generalisation from waste stabilisation ponds to shallow rivers. *Urban Water Journal*, *15*(9), 918-924. https://doi.org/10.1080/1573062X.2019.1581231.

Araújo, G. M., Lima Neto, I. E., & Becker, H. (2019). Phosphorus dynamics in a highly polluted urban drainage channel-shallow reservoir system in the Brazilian semiarid. *Anais da Academia Brasileira de Ciências*, *91*(3), e20180441. PMid:31432901. https://doi.org/10.1590/0001-3765201920180441.

Brasil. Conselho Nacional do Meio Ambiente - CONAMA. (2005). Resolução nº 357, de 17 de março de 2005. Dispõe sobre a classificação dos corpos de água e diretrizes ambientais para o seu enquadramento, bem como estabelece as condições e padrões de lançamento de efluentes, e dá outras providências. *Diário Oficial [da] República Federativa do Brasil*, Brasília.

Chapra, S. C., & Pelletier, G. J. (2003). *QUAL2K: a modeling framework for simulating river and stream water quality: documentation and users manual.* Medford: Civil and Environmental Engineering Dept., Tufts University.

Costa, J. M. F., Silveira, C. S., & Costa, A. C., Marcos Junior, A. D., & Gonçalves, S. T. N. (2025). Trend analysis of precipitation extremes in Brazil: the role of atmospheric temperature. *Revista Brasileira de Ciências Ambientais*, *60*, e2123.

DHI. (2021). *MIKE 11: a modelling system for rivers and channels: user guide*. DHI.

Duda, P. B., Hummel, P. R., Donigian, A. S., & Imhoff, J. C. (2012). BASINS/HSPF: model use, calibration, and validation. *Transactions of the ASABE*, *55*, 1523-1547. https://doi.org/10.13031/2013.42261.

Fechine, J. A. L. (2007). *Alterações no perfil natural da zona costeira da cidade de Fortaleza, Ceará, ao longo do Século XX* (Dissertação de mestrado). Centro de Ciências, Universidade Federal do Ceará, Fortaleza.

Fortaleza. Câmara Municipal. (2009, 13 de março). Lei Complementar n° 62, de 2 de fevereiro de 2009. Institui o Plano Diretor Participativo do Município de Fortaleza e dá outras providências. *Diário Oficial do Município de Fortaleza*, Fortaleza, DOM n. 14.020.

Fraga, R. F., Rocha, S. M. G., & Lima Neto, I. E. (2020). Impact of flow conditions on coliform dynamics in an urban lake in the Brazilian semiarid. *Urban Water Journal*, *17*(1), 43-53. https://doi.org/10.1080/1573062X.2020.1734948.

Freire, L. L., Costa, A. C., & Lima Neto, I. E. (2021). Spatio-temporal patterns of river water quality in the semiarid Northeastern Brazil. *Water, Air, and Soil Pollution*, *232*(11), 452. https://doi.org/10.1007/s11270-021-05406-7.

Li, C., Liu, M., Hu, Y., Gong, J., & Xu, Y. (2016). Modeling the quality and quantity of runoff in a highly urbanized catchment using storm water management model. *Polish Journal of Environmental Studies*, *25*(4), 1573-1581. https://doi.org/10.15244/pjoes/60721.

Lima Neto, I. E. (2023). Modeling water quality in a tropical reservoir using CE-QUAL-W2: handling data scarcity, urban pollution and hydroclimatic seasonality. *RBRH*, *28*, e8. https://doi.org/10.1590/2318-0331.282320230003.

Maia, E. B. (2010). *Dinâmica Geoambiental do Sistema Hídrico Maceió/Papicu* (Dissertação de mestrado). Pró-Reitoria de Pesquisa e Pós-Graduação, Programa Regional de Pós-Graduação em Desenvolvimento e Meio Ambiente, Universidade Federal do Ceará, Fortaleza.

Mendes, F. C., & Andrade, R. D. A. S. (2021). Scenarios for urban drainage on a Legal Amazon planned city: a case study in Palmas, Brazil. *Engenharia Sanitária e Ambiental*, *26*(3), 461-470. https://doi.org/10.1590/s1413-415220190019.

Mesquita, J. B. F. (2018). *Modelagem da drenagem urbana e avaliação das cargas bacteriológicas na vertente marítima de Fortaleza, Ceará* (Dissertação de mestrado). Centro de Tecnologia, Programa de Pós-Graduação em Engenharia Civil: Saneamento Ambiental, Universidade Federal do Ceará, Fortaleza.

Mesquita, J. B. F., & Lima Neto, I. E. (2022). Coupling hydrological and hydrodynamic models for assessing the impact of water pollution on lake evaporation. *Sustainability (Basel)*, *14*(20), 13465. https://doi.org/10.3390/su142013465.

Mesquita, J. B. F., Pereira, S. P., & Lima Neto, I. E. (2020). Modelagem da drenagem urbana e avaliação das cargas bacteriológicas na Vertente Marítima de Fortaleza, Ceará. *Engenharia Sanitária e Ambiental*, *25*(1), 205-216. https://doi.org/10.1590/s1413-41522020189161.

Moriasi, D. N., Gitau, M. W., Pai, N., & Daggupati, P. (2015). Hydrologic and water quality models: performance measures and evaluation criteria. *Transactions of the ASABE*, *58*(6), 1763-1785. https://doi.org/10.13031/trans.58.10715.

Noor, S. S. M., Saad, N. A., Akhir, M. F. M., & Rahim, M. S. A. (2025). QUAL2K water quality model: a comprehensive review of its applications, and limitations. *Environmental Modelling & Software*, *184*, 106284. https://doi.org/10.1016/j.envsoft.2024.106284.

Pereira, S. P., Rosman, P. C. C., Alvarez, C., Schetini, C. A. F., Souza, R. O., & Vieira, R. H. S. F. (2015). Modelling of Coastal Water Contamination in Fortaleza (Northeast of Brazil). *Water Science and Technology*, *72*(6), 928-936. PMid:26360752. https://doi.org/10.2166/wst.2015.292.

Porto, B. C., Fernandes, M. M. L., & Lima Neto, I. E. (2025). Impacts of hydroclimatic and land use/cover variability on water quality parameters in densely populated urban tropical basins. *Water, Air, & Soil Pollution*. Unpublished manuscript.

Rocha, M. J. D., Pereira, S. P., & Lima Neto, I. E. (2021). Integração do SWMM e ferramentas SIG para modelagem hidrológico-hidráulica de bacia complexa. *Engenharia Sanitária e Ambiental*, *26*(3), 451-459. https://doi.org/10.1590/s1413-415220190328.

Rodrigues, I. S., Costa, C. A. G., Teixeira, A. S., Lima Neto, I. E., Lopes, F. B., & Araújo, J. C. (2025). Effects of floating macrophytes on open-water evaporation in a Brazilian tropical reservoir. *Journal of South American Earth Sciences*, *164*, 105683. https://doi.org/10.1016/j.jsames.2025.105683.

Rosenberger, L., Leandro, J., Pauleit, S., & Erlwein, S. (2021). Sustainable stormwater management under the impact of climate change and urban densification. *Journal of Hydrology (Amsterdam)*, *596*, 126137. https://doi.org/10.1016/j.jhydrol.2021.126137.

Rossman, L. A., & Simon, M. A. (2022). *Storm Water Management Model User's Manual Version 5.2*. USA: U.S. Environmental Protection Agency.

Silveira, A., Cavalcanti, A. A., Menezes Filho, F. C. M., & Severino, M. F. (2022). Calibração do modelo hidrológico SWMM para a bacia do ribeirão vai e volta: poços de Caldas, Minas Gerais. *Engenharia Sanitária e Ambiental*, *27*(1), 55-65. https://doi.org/10.1590/s1413-415220200300.

Talukdar, P., Kumar, B., & Kulkarni, V. V. (2023). A review of water quality models and monitoring methods for capabilities of pollutant source identification, classification, and transport simulation. *Reviews in Environmental Science and Biotechnology*, *22*(3), 653-677. https://doi.org/10.1007/s11157-023-09658-z.

Zakizadeh, F., Moghaddam Nia, A., Salajegheh, A., Sañudo-Fontaneda, L. A., & Alamdari, N. (2022). Efficient urban runoff quantity and quality modelling using SWMM Model and Field Data in an Urban Watershed of Tehran Metropolis. *Sustainability (Basel)*, *14*(3), 1086. https://doi.org/10.3390/su14031086.

Zhao, J., Zhang, N., Liu, Z., Zhang, Q., & Shang, C. (2024). SWAT model applications: from hydrological processes to ecosystem services. *The Science of the Total Environment*, *931*, 172605. PMid:38663632. https://doi.org/10.1016/j.scitotenv.2024.172605.

## Author's contribution

João da Silva Cavalcante was responsible for data processing and information modeling for incorporation into the SWMM hydrological, hydraulic, and water quality model, as well as for the preparation of figures, maps, and graphs, and for the primary drafting of the manuscript.

Iran Eduardo Lima Neto was responsible for supervising the entire research process, validating the partial results, and providing support in the discussion of the results obtained in this study.

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