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Integrated modeling of quality and quantity for water resources management: case study in the Upper Paranapanema Basin

Modelagem integrada de qualidade e quantidade para gestão de recursos hídricos: estudo de caso na Bacia do Alto Paranapanema

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ABSTRACT

This study introduces an integrated model for water resources planning and management that accounts for both the quantity and quality of water in watersheds and reservoirs. Therefore, it provides a comprehensive approach for better understanding and assessing water systems. The model facilitates analyses of the spatial and temporal dynamics of hydrological processes, pollutant transport, and the behavior of rivers and reservoirs. The study evaluated pollutant load transport in the Upper Paranapanema Basin by applying the Soil Moisture Accounting Procedure (SMAP) model, Muskingum method, Streeter-Phelps buildup/washoff model, and zero-dimensional (0D) models to estimate inflows to the Jurumirim reservoir. A Python-based public library was developed to model all hydrological processes. The model calibration yielded a NSE, KGE, PBIAS and RMSE result of 0.746, 0.778, 6.5% and 73.3 m^3s^{-1}, respectively. Indicating a robust simulation that attests to the versatility and reliability of the proposed approach. The methodology outlined in this research enables comprehensive water quality simulation at basin scale, thereby serving as a tool for understanding water quantity and quality dynamics and support decision-making regarding water resource planning and management.

Keywords: Hydrological modeling; Integrated water management; Quality and quantity analysis; Jurumirim reservoir.

RESUMO

Este estudo apresenta um modelo integrado de planejamento e gestão de recursos hídricos que leva em conta tanto a quantidade quanto a qualidade da água em bacias hidrográficas e reservatórios. Portanto, fornece uma abordagem abrangente para uma melhor compreensão e avaliação dos sistemas hídricos. O modelo facilita análises da dinâmica espacial e temporal dos processos hidrológicos, do transporte de poluentes e do comportamento de rios e reservatórios. O estudo avaliou o transporte de cargas poluentes na Bacia do Alto Paranapanema aplicando o modelo Soil Moisture Accounting Procedure (SMAP), método Muskingum, modelos de acúmulo/lavagem, Streeter-Phelps e de dimensão zero (0D) para estimar afluências no reservatório de Jurumirim. Uma biblioteca pública baseada em Python foi desenvolvida para modelar processos hidrológicos. A calibração do modelo resultou em NSE, KGE, PBIAS e RMSE de 0,746; 0,778; 6,5% e 73,3 m^3s^{-1}, respectivamente. Indicando uma simulação robusta que atesta a versatilidade e confiabilidade da abordagem proposta. A metodologia delineada nesta pesquisa permite uma simulação abrangente da qualidade da água à nível de bacia, servindo assim como uma ferramenta para compreender a dinâmica da quantidade e qualidade da água e subsidiar a tomada de decisões relativamente ao planeamento e gestão dos recursos hídricos.

Palavras-chave: Modelagem hidrológica; Gestão integrada da água; Análise quantitativa e qualitativa; Reservatório de Jurumirim.

INTRODUCTION

Water, an essential resource for life with inestimable economic value due to its limited spatial and temporal availability, supports a diversity of essential human activities. In Brazil, hydroelectric power, accounting for over two-thirds of the country's energy matrix, exemplifies the strategic importance of water (Loucks & van Beek, 2017). This multifaceted resource, known as a water resource, requires efficient and sustainable management to harmonize its conflicting uses and ensure optimal functioning in society (Brasil, 1997).

The qualitative management of waters in water bodies is critical and requires continuous monitoring, study, and evaluation. In this context, mathematical modeling emerges as an indispensable tool, providing mathematical representations of natural systems through observation and understanding of physicochemical phenomena, allowing the creation of varied scenarios for future and hypothetical analyses (Bonnecarrere et al., 2018; Lopes et al., 2021; Lyra et al., 2021; Méllo Júnior et al., 2022; Silva et al., 2022; Tercini et al., 2021).

The effectiveness of modeling depends on a deep understanding of natural dynamics and the inherent limitations of models, considering the complexity of interconnected natural processes in water systems and the need for integration of different modeling tools. Lemaire et al. (2021) pioneered a system dynamics model adept at addressing the complexities of peri-urban stream systems. Concurrently, Zhou (2020) research applied a nuanced model to the intricate hydrological context of the Yellow River. In a similar vein, Xue et al. (2021) proposed a synergistic hydrological and water quality model, specifically tailored for agricultural watersheds. Furthering this discourse, Ma et al. (2019) adeptly employed the SWAT model to elucidate the dynamics within the Baihe River Basin.

In a forward-looking perspective, Copetti (2023) articulated the imperative of integrating hydrological quantity and quality modeling with socio-economic paradigms, highlighting the multidisciplinary nature of contemporary water resource management. Complementing these insights, Ejigu (2021) offered an expansive overview of water quality modeling methodologies, presenting a comprehensive synthesis of current practices. Additionally, Hwang et al. (2020) contributed to this body of knowledge with the development of an integrated river evaluation system, specifically catered to the hydrological conditions of the Republic of Korea.

Water quantity and quality considerations in hydrological modeling, thereby enriching the decision-making processes in water resource management with robust, data-driven insights. Employing a streamlined steady-state modeling methodology, Tercini & Méllo Júnior (2016) demonstrated that the distribution of organic matter within reservoirs can be directly correlated to the input loads and the specific operating regulations governing these systems in Tietê River, Brazil.

Given the specific Brazilian scenario and the need for appropriate methodologies for effective water resource management, this study aims to propose an integrated model for the management of watersheds, addressing both the quantity and quality of water. This model will allow detailed spatial and temporal analyses, considering hydrological processes and pollutant load transport in basins, transport phenomena in river stretches, and dynamics in reservoirs.

Our goal was to evaluate the hydrological variables that most influence the transport of pollutant load in the Upper Paranapanema Basin. A Python-based public library (Hossoda, 2024) has been developed to model water quality and quantity, allowing simultaneous simulation of basins, rivers, and reservoirs, thereby providing versatility in terms of spatial and temporal variables. This study introduces an integrated model designed to address the management and planning of water resources by considering both water quantity and quality within watersheds and reservoirs. This approach offers a comprehensive framework aimed at enhancing the understanding and evaluation of water systems. The model enables the examination of spatial and temporal variations in hydrological processes, pollutant transport, and the behavior of rivers and reservoirs. The case study allowed the analysis of the applicability of integrated models in simulating the quantity and quality of water for water resource management.

CASE STUDY

The Upper Paranapanema Basin (Figure 1) is situated on the border of São Paulo and Paraná states in Brazil. The river stretch under consideration has a length of around 160 km leading to the Jurumirim reservoir. The land use land cover map is presented in Figure 2.

The sub-catchments in his study were obtained using the Otto Pfafstetter Coding System, which is employed by the National Water Agency (Agência Nacional de Águas e Saneamento Básico, 2017).

MATERIAL AND METHODS

Measured data

The National Water Agency (ANA) offers public access to its tool, HidroWeb. The platform provides data from over 4,611 stations in Brazil, allowing users to view information on river levels, flow, water quality and rainfall.

The region under study has previously undergone an analysis of its water bodies in a study developed by Agência Nacional de Águas e Saneamento Básico (2022). Which included the assessment of source point and non-source point pollution in the upper Paranapanema through a GIS-based application (Acosta et al., 2023) using the MoRE model (Fuchs et al., 2017) for the watershed area, resulting in a shapefile with pollutant loads for the sub-catchments in the study area. The condensed daily average BOD values in the study area are presented in Table 1.

Table 1. BOD data for the study area.

Watershed Code	BOD (kg/day)
86492	11116.1
86493	6539.0
86494	2291.4
86495	2577.5
86496	5099.6
86497	266.9
86498	9742.2
86499	5471.5

Adapted from Agência Nacional de Águas e Saneamento Básico (2022).

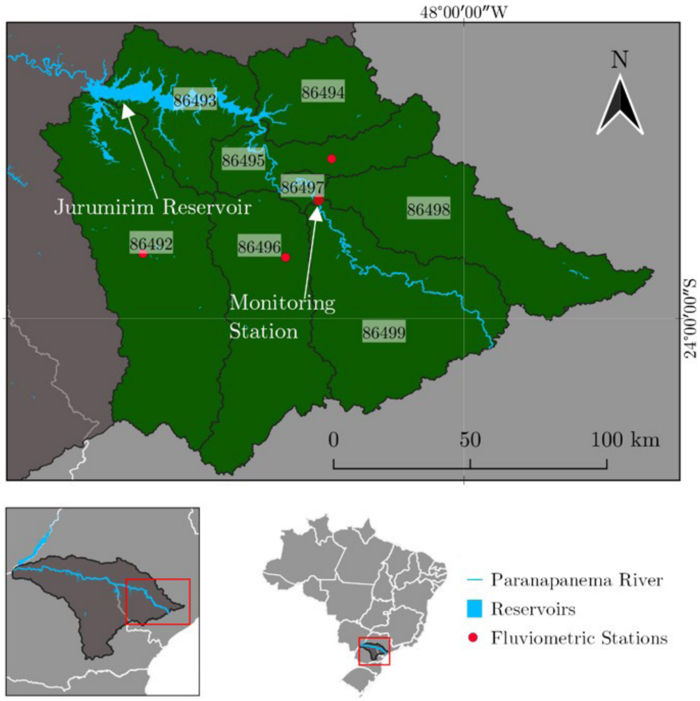

Figure 1. Upper Paranapanema Watershed.

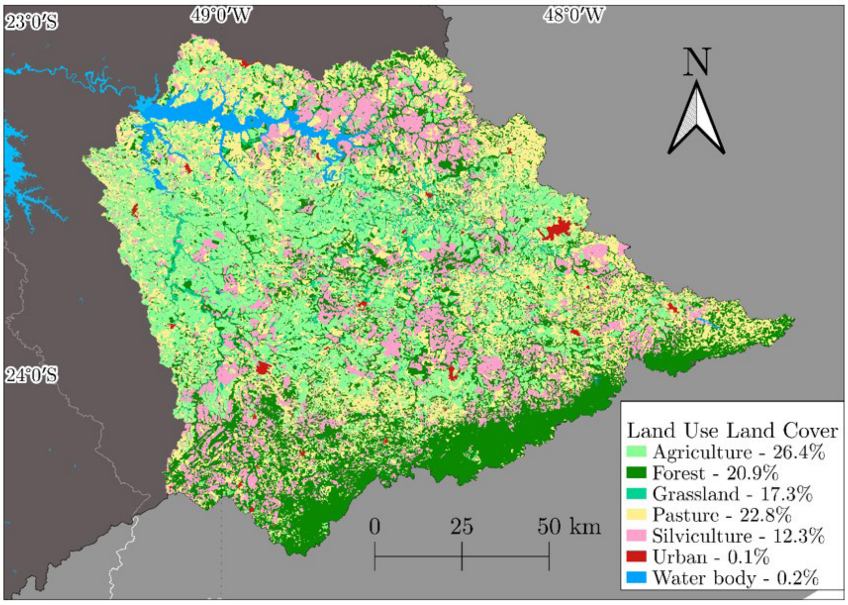

Figure 2. Land Use and Land Cover Map.

This data was compiled for the 2012 base year chosen for this study as it provided the best data availability in the region while considering all the necessary parameters for the case study area.

Quantity modeling

This study utilizes the Soil Moisture Accounting Procedure (SMAP) model, developed by Lopes et al. (1982) and it has effectively been utilized in Brazil (Raulino et al., 2021; Tercini & Mello Júnior, 2023), as the rainfall-runoff model for estimating inflows to the Jurumirim reservoir, accounting for the sub-catchments.

The SMAP model (Figure 3) is made of conceptual reservoirs with transfer functions (Equations 1, 2,3, 4, 5 and 6).

$$Rsolo(0) = Tu_{in} \cdot Str \tag{1}$$

$$Rsup(0) = 0 \tag{2}$$

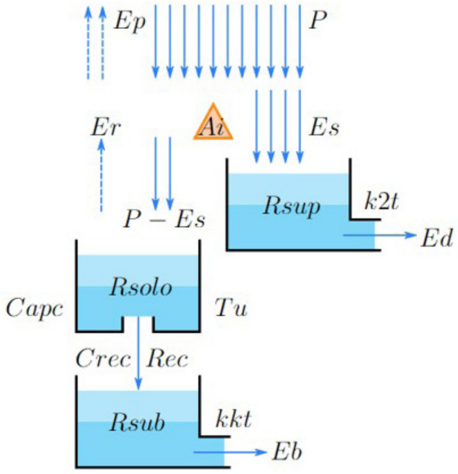

Figure 3. SMAP structure for conceptual reservoirs.

$$Rsub(0) = \frac{Eb_{in}}{1 - \frac{1}{2}^{1/kkt}} \cdot \frac{1}{Ad} \tag{3}$$

$$Rsolo(i+1) = Rsolo(i) + P - Es - Er - Rec \tag{4}$$

$$Rsup(i+1) = Rsup(i) + Es - Ed \tag{5}$$

$$Rsub(i+1) = Rsub(i) + Rec - Eb \tag{6}$$

With *Rsolo* being the soil reservoir, *Rsup* the watershed surface reservoir and *Rsub* the underground reservoir. *P* is the rainfall, *Es* the surface runoff, *Ed* the direct runoff, *Er* is the real evapotranspiration and *Eb* is the base flow, while Tu_{in} and Eb_{in} are initial values for humidity content and base flow, finally, *Rec* is recharge to the underground reservoir, all units are in mm.

The transfer functions are show in Equations 7, 8, 9, 10 and 11:

$$Es = \begin{cases} \dfrac{(P - Ai)^2}{P - Ai + Str - Rsolo}, & \text{if } P > Ai \\ 0\text{ , otherwise} \end{cases} \tag{7}$$

$$Er = \begin{cases} Ep, & \text{if} (P - Es) > Ep \\ (P - Es) + (Ep - (P - Es)) \cdot Tu\text{ , otherwise} \end{cases} \tag{8}$$

$$Rec = \begin{cases} Crec \cdot Tu \cdot (Rsolo - Capc \cdot Str), \text{ if } Rsolo > Capc \cdot Str \\ 0\text{ , otherwise} \end{cases} \tag{9}$$

$$Ed = Rsup \cdot (1 - 0.5)^{1/k2t} \tag{10}$$

$$Tu = Rsolo / Str \tag{11}$$

Ep is the potential evapotranspiration in millimeters and *Tu* is the humidity content also in mm. The SMAP model is calibrated with the following parameters: soil saturation capacity (*Str*) in mm, surface runoff recession coefficient (*k2t*) in days, underground recharge parameter (*Crec*) in %, initial abstraction (*Ai*) in mm, field capacity (*Capc*) in %, and base flow recession coefficient (*kkt*) in days.

Finally, the total flow (*Q*) is calculated as the sum of the base flow (*Eb*) and the surface runoff (*Es*) according to Equation 12.

$$Q = (Es + Eb) \cdot Ad / 86.4 \tag{12}$$

Coefficients for the precipitation (P_{cof}) and potential evapotranspiration (E_{cof}) can improve the representation of climatological data in the watershed.

Considering the watershed area and river characteristics, such as slope and length, the impact of downstream storage, and flood routing phenomenon cannot be disregarded (Koussis, 2009). Thus, the Muskingum hydrological method (Equation 13) is employed in this study.

$$Q_{t+1} = C_1 I_{t+1} + C_2 I_t + C_3 Q_t \tag{13}$$

The downstream flow (Q_{t+1}) calculated considering storage and routing have coefficients C_1, C_2 and C_3 represented by the Equations 14, 15 and 16:

$$C_1 = \frac{T - (2KX)}{2K(1 - X) + T} \tag{14}$$

$$C_2 = \frac{T + (2KX)}{2K(1 - X) + T} \tag{15}$$

$$C_3 = \frac{2K(1 - X) - T}{2K(1 - X) + T} \tag{16}$$

The quantity results are needed to model the quality of the water given the pollutants are carried through rivers.

Quality modeling

The simulated pollutant present in this study is the biochemical oxygen demand (BOD) and it is often used to measure water quality.

The model used to simulate BOD is based on the Buildup/Washoff exponential functions from SWMM (U.S. Environmental Protection Agency, 2016) (Equations 17, 18, 19 and 20).

$$b_u = B_{max}\left(1 - e^{K_B \cdot t}\right) \tag{17}$$

b_u is the buildup specific mass in $\text{kg} \cdot \text{d}^{-1} \cdot \text{m}^{-2}$ or $\text{ton} \cdot \text{d}^{-1} \cdot \text{m}^{-2}$ and K_B is the buildup rate constant, t is the simulated time.

$$m_B = b_u \cdot A \tag{18}$$

m_B is the buildup mass in $\text{kg} \cdot \text{d}^{-1}$ or $\text{ton} \cdot \text{d}^{-1}$ and A is the watershed area.

$$w = K_W \cdot \left(\frac{Q}{A}\right)^{N_W} \tag{19}$$

w is the washoff rate in $\text{kg}\cdot\text{d}^{-1}$ or $\text{ton}\cdot\text{d}^{-1}$, K_W and N_W area coefficients used to define the exponential function.

$$m_W = w\Delta t \tag{20}$$

m_W is the washoff mass in kg or ton and Δt is the buildup/washoff time step.

To convert the mass into pollutant concentration the Equation 21 is used:

$$c = \frac{m_W}{Q}\cdot\frac{1}{86.4} \tag{21}$$

c being the pollutant concentration in $\text{mg}\cdot\text{L}^{-1}$.

In addition to the Streeter-Phelps method (Equation 22), which is commonly utilized to model the decay of organic matter that enters the reservoir.

$$L = L_0 \cdot e^{-k_d \cdot t} \tag{22}$$

L is the BOD concentration, L_0 is the initial BOD concentration, both in $\text{mg}\cdot\text{L}^{-1}$ and k_d is the oxygen consumption to decay the organic matter (d^{-1}).

Within the reservoir environment, the zero-dimensional model for continually stirred tank reactor proposed by Becker et al. (2023) was used as a single reactor (Equation 23).

$$c_{out}^{i+1} = \frac{c_{out}^{i} + \frac{\Delta t}{V^{i+1}}\left(Q_{in}^{i+1} c_{in}^{i+1}\right)}{1 + \frac{\Delta t}{V^{i+1}} Q_{out}^{i+1} + kV^{i+1} + vA_s^{i+1} + \frac{\Delta V}{\Delta t}} \tag{23}$$

The resulting concentration (c_{out}) results from the inflow concentration (c_{in}) both in $\text{mg}\cdot\text{L}^{-1}$, requiring the time step (Δt) in seconds, volume series (V) in m^3 and consequently the volume variation (ΔV), inflow series (Q) in m^3s^{-1} and estimation of the k (s^{-1}) and v ($\text{m}\cdot\text{s}^{-1}$) parameters.

Within the outlined methodology, the quantity and quality models detailed enable the generation of outcomes within reservoir settings.

Model structure

The structure of the study case is depicted in Figure 4, illustrating the sub-catchments taken into account that contribute to the inflow of the Jurumirim reservoir. The model structure has 3 levels for sub-catchments, in which 86492, 86494, 86496, 86498 and 86499 are headwaters, 86495 and 86497 receive inflows originally from these headwaters and lastly the sub-catchment 86493 where the reservoir is located.

The SMAP model is applied to every sub-catchment, while concurrently executing the buildup/washoff model to calculate the loads in each area. Subsequently, the outcome of the rainfall-runoff model is processed through the Muskingum method.

Point-source pollution fractions from previous studies were incorporated as mass pollutants in the total pollution, along with the non-point source pollution for each area. Finally, they were transformed into pollutant concentrations within the river reach that feeds the Jurumirim reservoir.

A BOD simulation can be conducted using the concentration series, inflow, and other required data for the zero-dimensional model.

Result evaluation

The following efficiency coefficients and evaluation functions were utilized to assess the outcomes generated through modeling with observed values and to adjust the model parameters.

The root of the mean square error (RMSE) is a measure of dispersion about the evaluated data (Equation 24).

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(P_i - O_i\right)^2} \tag{24}$$

The percent bias (PBIAS) compares the average amount in which the predicted values are in relation to the observed data (Equation 25).

$$\text{PBIAS} = 100\frac{\sum_{i=1}^{n}\left(O_i - P_i\right)}{\sum_{i=1}^{n} O_i} \tag{25}$$

The Nash-Sutcliffe efficiency coefficient (Equation 26) scores the predicted values in comparison to the observed data and is often used to evaluate hydrological models.

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(O_i - P_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2} \tag{26}$$

With O_i being the observed values, P_i the predicted values, $\bar{O}$ the mean of the observed values.

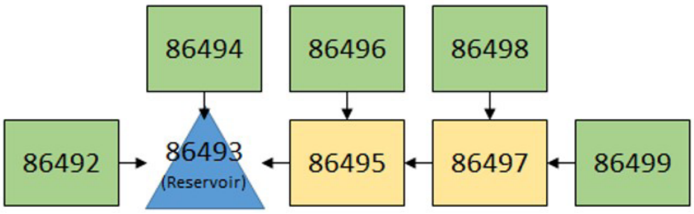

Figure 4. Model Structure for the Study Case.

Another goodness-of-fit indicator often used to evaluate hydrological models is the Kling-Gupta efficiency (Equation 27).

$$\text{KGE} = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2} \tag{27}$$

The r, β and γ represents the Pearson correlation coefficient, the variability of prediction errors and bias from the observed values to the prediction, respectively.

RESULTS AND DISCUSSIONS

Theoretical load generation model analysis

A buildup/washoff model theoretical analysis was produced to verify its application to non-urban basins. The model was used along with a theoretical watershed of 2 km^2, adopted and an observed rainfall.

The observed rainfall was the source for different cases with the same total volume but different temporal spacing ("blocks") in a period of 365 days (Figure 5). At first, blocks of 4, 8 and 15 days were simulated and through the examination of varied storm patterns throughout the year, an assessment is conducted on the model's response to diverse temporal dynamics in non-urban settings. The objective is to contribute insights into the model's applicability and robustness, thereby informing effective water resources management in varied environments.

Figure 5 shows the observed rainfall series through an average year and the cumulated sum during this period was used to produce the different precipitation blocks with the same annual cumulated volume but different frequencies along the period, indicated by Δt. In this regard, the higher the frequency of precipitation events, the lower the value of its volume per rain event. The objective is to understand how the precipitation can influence the load generation model under study.

With these rainfall series, the SMAP model was used to produce the surface runoff to use as input data to the load generation model.

Figure 6 presents the surface runoff for each precipitation block and the observed rainfall. In all cases the SMAP model was utilized with the same set of parameters, including the evapotranspiration, which explains the temporal variability along the simulated year, however the runoff remained proportional to the precipitation blocks. This surface runoff is the input data for the load generation model, changing the buildup mass produced and washoff in the catchment.

From Equations 17 and 19 with coefficients $B_{max} = 1$, $K_B = 0.01$, for the buildup and $N_W = 0.9$ and $K_W = 0.02$ For the washoff equations the Figure 7 was produced with the different rainfall discretization. These values were select to illustrate a fictional watershed with smooth pollutant buildup and washoff curves with close values to Bonhomme & Petrucci (2017). Additional cases were added to verify the model behavior regarding the buildup and the washoff cumulative sums, including the blocks $\Delta t = 4$ to 15, 30 and 60 days.

The relationship between cumulative buildup and cumulative washoff presented in Figure 7a) reveals this phenomenon of optimization of load generation for pollutants in a watershed for a set of parameters. The 45° line indicates the boundary that limits washoff, given it is impossible to have a washoff mass bigger than the buildup mass. Figure 7b) displays the cumulative washoff mass in relation to the simulated rainfall blocks. The graph indicates that longer dry periods result in less total washoff, even with larger surface runoff and total buildup. This can be attributed to the buildup curve reaching saturation after extended periods of time, limiting the amount of washoff that can occur after this point.

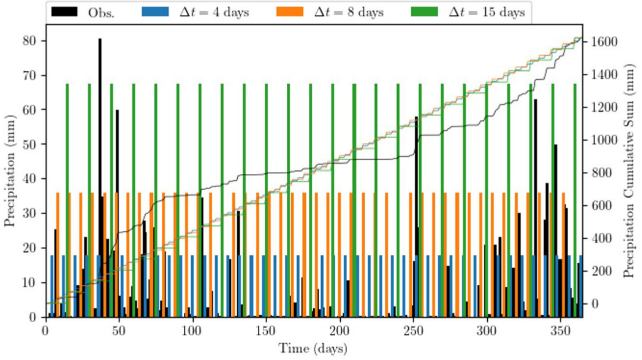

Figure 5. Precipitation scenario blocks.

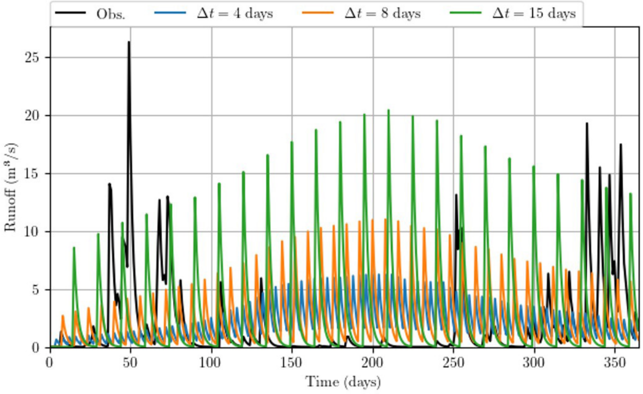

Figure 6. Theoretical surface runoff produced.

Case study results

The results are shown for the monitoring station and the Jurumirim reservoir, the monitoring station was chosen to show the results because the data allows model calibration using simulations from other studies and observed data. Due to the lack of all necessary concurrent data, only the year of 2012 was simulated and calibrated. In contrast to the conventional method, there was no specific timeframe chosen for model validation, as recommended by Shen et al. (2022).

Quantity results

The monitoring station is located at the outlet of sub-catchments 86499 and 86498, these two areas were combined and simulated using the SMAP model, the resulting runoff is represented in Figure 8a). Due to sub-catchment 86497 being small (approximately 163 km^2) compared to the entire watershed, and next to the monitoring station the calibrated parameters for the aggregated sub-catchment were also used for this area, as no other station could be used.

The remaining sub-catchments were calibrated individually with flow data at each area. Since all the observed data was inside the sub-catchment the resulting runoff was pondered with the contribution area to the station. For the sub-catchments 86494 and 86493, no data was available for the individual calibration, therefore the total inflow to the Jurumirim reservoir was used to calibrate the remaining areas. The SMAP parameters optimal values were obtained by optimizing the KGE value between the simulation and observed data.

With all sub-catchments calibrated, the Muskingum method was applied using $K = 1$ and $X = 0.25$, resulting in Figure 8b) that presents the inflow at Jurumirim reservoir, producing the best fit between observed values and simulated ones.

The final SMAP parameters obtained are presented in Table 2.

Table 3 contains the evaluation of the calibrated values for each sub-catchment for the quantity module.

Quality results

For the quality simulation, since point source pollution was added, sub-catchments 86499, 86498, 86497 and 86495 were designated as the "main course" and aggregated, since the

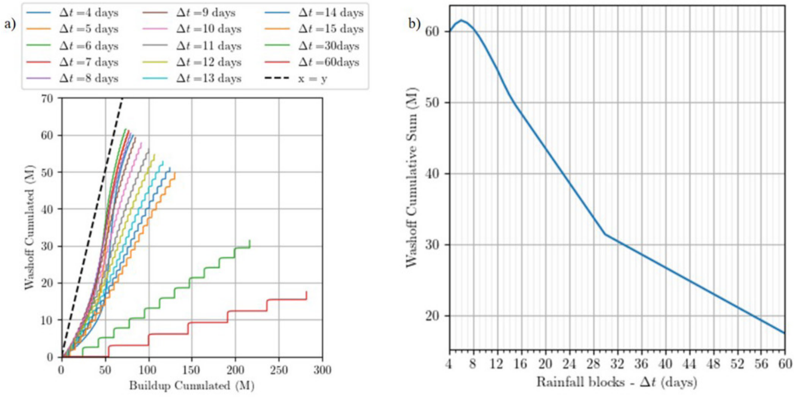

Figure 7. Theoretical scenarios results. a) Cumulated Washoff versus Cumulated Buildup. b) Cumulated Washoff versus rainfall.

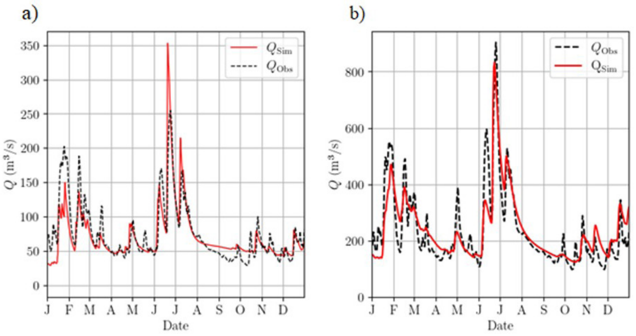

Figure 8. Calibration results. a) Monitoring station discharge. b) Jurumirim reservoir inflow.

Table 2. SMAP parameters.

Basin	*Ad* (km^2)	*Str* (mm)	*Ai* (mm)	*Capc* (%)	*Crec* (%)	*k2t* (days)	*kkt* (days)	*Tuin* (mm)	*Ebin* (mm)
86492	4512.526	250.0	2.5	40.0	20.0	10.0	70.0	1.0	20.0
86493	1772.085	200.0	2.5	30.0	10.0	7.0	120.0	0.5	1.0
86494	1374.887	200.0	2.5	30.0	10.0	7.0	120.0	0.5	1.0
86495	1290.321	616.4	3.0	48.1	1.4	2.8	133.2	0.7	1.1
86496	2845.984	100.0	2.5	32.3	16.5	10.0	77.7	1.0	15.0
86497	163.593	500.0	2.0	30.0	0.6	5.0	115.0	9.0	0.1
86498	2609.573	500.0	2.0	30.0	0.6	5.0	115.0	9.0	0.1
89499	3201.243	500.0	2.0	30.0	0.6	5.0	115.0	9.0	0.1

Table 3. Evaluation results.

Basin	KGE	NSE	PBIAS	RMSE
86492	0.550	0.155	−1.6%	12.3
86495	0.297	0.297	−0.1%	24.2
86496	0.730	0.522	−16.1%	9.6
86498 89499	0.812	0.650	−4.8%	25.4
Jurumirim Inflow	0.778	0.746	6.5%	73.3

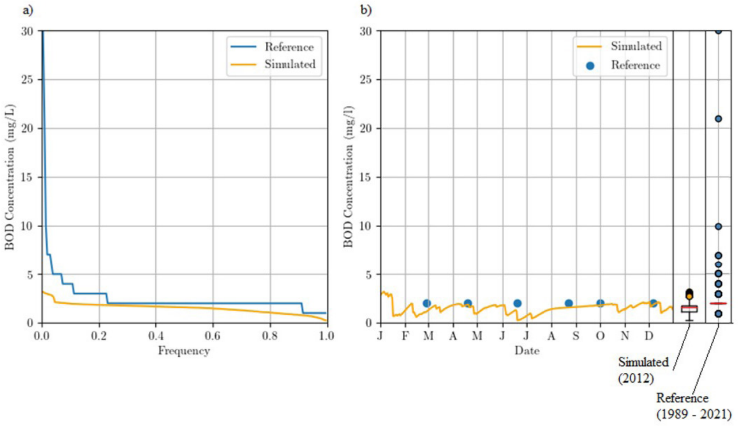

Figure 9. BOD simulated at the monitoring station. a) BOD duration curve. b) BOD over simulated period.

Paranapanema River flows through these areas. The monitoring station at the 86497 basin was used to adjust the Streeter-Phelps equation and estimate the whole study area through the estimation of the $Kd \cdot t$ parameter, which resulted in 0.8.

As presented in Figure 9a the BOD concentration duration curve considering the simulated period (2012) along with historical data, ranging from 1989 to 2021 and Figure 9b displays the BOD series for the same station along the study period with a box-plot representation of the same series.

For each sub-catchment the buildup and washoff were adjusted using the data from the results obtained by Acosta et al. (2023) and Agência Nacional de Águas e Saneamento Básico (2022) making the total annual load correspond to the reference values. The strategy to use the buildup/washoff with known load is to find the parameter B_{max} that makes the pollutant washoff with set parameters to correspond the average event load discharge (Table 4). The total BOD is shown in Figure 10.

The K_B, N_B and K_W values for all sub-catchments are 0.01, 2.0 and 1.0, respectively.

The 86494 sub-catchment has very little point source pollution releases in which the buildup/washoff model can represent the seasonal effects of load generation (Figure 11).

Figure 11 shows the cumulative sum of BOD during the simulation period, corresponding to the reference value. The adopted model introduces a noticeable difference in the BOD behavior just before March and from the end of August until the end of October, due to rainfall seasonal consideration taken into account. The Streeter-Phelps equation was applied to the resulting BOD concentration in the Jurumirim reservoir upstream, and using this result with the reservoir data, the zero-dimensional model was also applied. Using estimated values for the parameters $k = 1 \times 10^{-7} s^{-1}$ and $v = 1.15 \times 10^{-7} m \cdot s^{-1}$. The results shown in Figure 12 represent the effects of a continuous stirred tank reactor (CSTR) in which the BOD concentration decreases (Zero-dimensional) compared to the initial condition (Upstream Concentration).

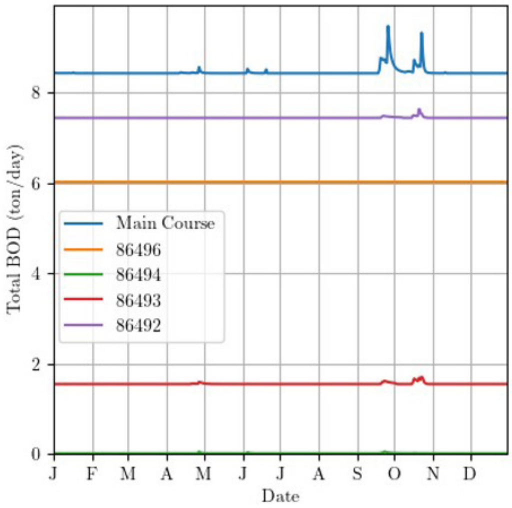

Figure 10. Total BOD produced.

Table 4. Buildup/Washoff B_{max} parameters.

Basin	B_{max}
86492	1.261
86493	2.167
86494	0.575
86495	0.591
86496	0.402
86497	4.192
86498	2.059
86499	4.979

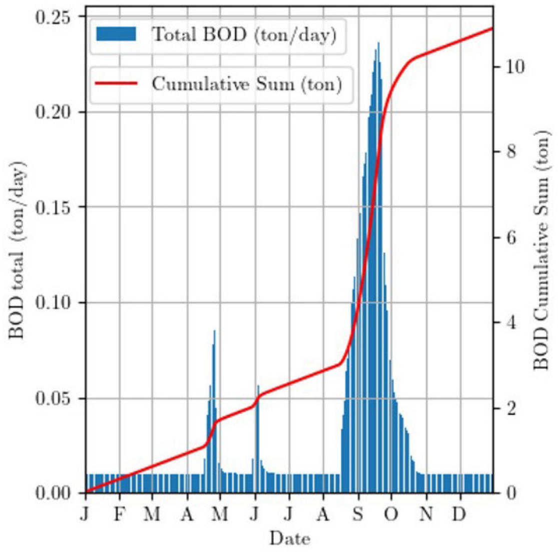

Figure 11. BOD produced at sub-catchment 86494.

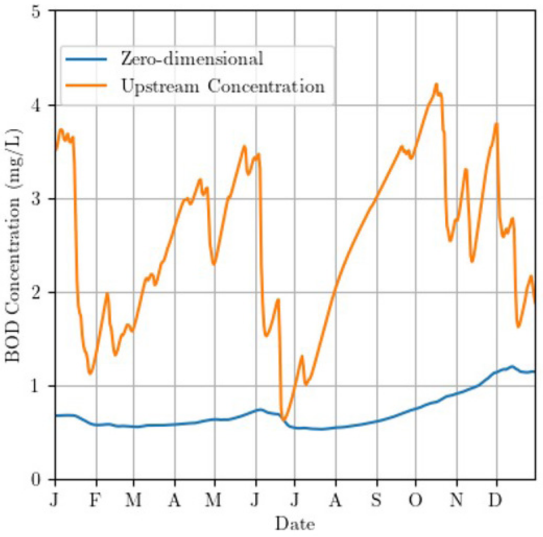

Figure 12. Jurumirim reservoir BOD simulation results.

The simulation using the zero-dimensional model utilized a period range greater than the study period because of the model lag and the results from the model-heating period were discarded. The result indicates that the zero-dimensional model can represent the considered pollutant decay in a simplified manner in a reservoir as a CSTR environment. Multiple reactors can be modeled to better represent this environment (Becker et al., 2023).

CONCLUSIONS

The management of water resources is based on the planning of hydrological basins and to achieve the proposed objectives it is supported by scenarios that allow proposals considering the reality in which the basin is inserted and to achieve this, analyses through models are a necessity. There are models which can represent natural phenomena such as the relationship between rainfall and runoff, flood routing, storage in rivers, pollutant production, transport and decay, and many others, thus making an integrated model has such an important role for water resources management.

Although certain monitoring stations had data gaps, the quantity model was calibrated with remarkable efficiency. The model's successful calibration, despite limited data availability, demonstrates its robustness and ability to adapt to real-world monitoring constraints. This resilience contributes to the model's reliability in providing precise assessments, even in less-than-ideal data scenarios.

The methodology detailed in this research enables a full-scale quality simulation, providing a significant resource for comprehending water quality dynamics. By integrating specific techniques, our methodology allows for a refined representation of water quality parameters. This simulation capability improves our ability to predict and regulate water quality fluctuations, furthering informed decision-making in water resource planning and management.

In summary, this study's results firmly establish the employed models and methodology's practicality and effectiveness. The theoretical model's applicability in water resources management, efficient calibration of the quantity model despite data limitations, and conducting a robust quality simulation all attest to the proposed approach's versatility and reliability. These insights advance our understanding of water quality dynamics and offer valuable implications for informed and adaptive water resources management strategies.

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