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Hydrological modeling and water allocation in the Piranhas-Açu River Basin in the eastern axis of the São Francisco River integration project

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ABSTRACT

This study presents the integrated application of the lumped hydrological model SMAP and the optimization library Pywr to assess water allocation in the Piancó-Piranhas-Açu river basin, located in the Brazilian semi-arid region. We developed comparative scenarios with and without inflows from the São Francisco River Integration Project (PISF), based on historical monthly series of rainfall and streamflow, combined with sectoral demands obtained from the National Water Use Register. Results showed that the PISF inflow, which began in December 2021, improved flow regularity, reduced the frequency of critical storage levels in the reservoirs, and increased the reliability of demand supply. Public water supply was the most benefited sector, with a significant reduction in deficits and higher frequency of full demand satisfaction, while irrigation showed modest improvements due to the legal priority of human consumption. These findings underscore the strategic importance of the PISF in strengthening regional water security and demonstrate the potential of integrated modeling as a decision-support tool, providing technical evidence for water management policies in critical semi-arid basins.

Keywords: PISF, semi-arid, water allocation.

Modelagem hidrológica e alocação de água na bacia hidrográfica dos rios Piranhas e Açu, no eixo leste do Projeto de Integração do Rio São Francisco

RESUMO

Este trabalho apresenta a aplicação integrada do modelo hidrológico concentrado SMAP com a biblioteca de otimização Pywr para avaliar a alocação de água na bacia do rio Piancó-Piranhas-Açu, inserida no semiárido brasileiro. Foram gerados cenários comparativos com e sem aporte do Projeto de Integração do Rio São Francisco (PISF), considerando como base séries históricas mensais de precipitação e vazão, além das demandas setoriais obtidas no

Cadastro Nacional de Usuários de Recursos Hídricos. Os resultados evidenciaram que a entrada do PISF, iniciada em dezembro de 2021, conferiu maior regularidade às afluências, reduziu a permanência de volumes críticos nos reservatórios e ampliou a confiabilidade do atendimento às demandas. O abastecimento público foi o setor mais beneficiado, com redução significativa dos déficits e aumento da frequência de atendimento pleno, enquanto para a irrigação os ganhos foram modestos, devido à prioridade legal do consumo humano. Os achados reforçam o papel estratégico do PISF na segurança hídrica regional e demonstram o potencial da modelagem integrada como ferramenta de suporte à decisão, fornecendo subsídios técnicos para políticas públicas em bacias críticas do semiárido.

Palavras-chave: Alocação, PISF, semiárido.

1. INTRODUCTION

Adequate water availability—in terms of quantity, quality, timing, and location—is essential for human supply, agriculture, industry, and energy generation. The different characteristics of these demands, with their distinct requirements, combined with uncertainties in basin-scale water availability, are directly tied to water supply security. Increases in demand or decreases in availability heighten the potential for conflicts over water use, especially in basins with vulnerable aquatic and terrestrial ecosystems.

Much of Northeastern Brazil has low to very low annual per capita water availability, with values below 500 m³ per person per year, due to recurrent periods of low rainfall. This condition has plagued the region for decades, posing challenges to socioeconomic development (De Castro and Cerezini, 2022). The São Francisco River, one of Brazil's largest, is a major water source for this entire region. The São Francisco River Integration Project (PISF) aims to connect São Francisco to other river basins in the northern portion of the Northeast—Paraíba (PB), Pernambuco (PE), Rio Grande do Norte (RN), and Ceará (CE).

Assessing the balance between water demand and availability is fundamental for sustainable basin management. To make this feasible, representative hydro-meteorological data and efficient tools for integrated analysis of water allocation to multiple demands are required. In Brazil, many basins have hydrological time series of low quality, short and discontinuous records, and a sparse monitoring network. When data exist, they are often not released or are available online in a restricted and decentralized manner (Pereira *et al.*, 2020). The situation is no different in the basins of the northern Northeast.

Hydrological models are useful tools for reconstructing and extending historical streamflow series and for evaluating hydrological responses arising from interactions among processes, given basin physical characteristics, climatic conditions, and land cover (Dwarakish and Ganasri, 2015; Méllo Júnior *et al.*, 2022). Various rainfall–runoff transformation models can be applied to this end. From the standpoint of spatial representation, models are classified as lumped, semi-distributed, or fully distributed. Lumped (aggregated) models have greater difficulty representing heterogeneity because they do not simulate spatially explicit physical processes within the basin.

Lumped models exhibit limited performance in heterogeneous basins. Their accuracy decreases markedly in large watersheds with complex topography, varied soil types, non-uniform rainfall patterns, and changes in vegetation cover (Dwarakish and Ganasri, 2015; Okiria *et al.*, 2022). When watersheds are relatively homogeneous, data are limited, parameters capture differences in soil water storage, and the focus is on outlet response, lumped models can satisfactorily represent the rainfall–runoff relationship (Niel *et al.*, 2003). The lumped SMAP (Soil Moisture Accounting Procedure) model (Lopes *et al.*, 1982) has been used widely in Brazil, including for hydropower inflow forecasting (Bosa *et al.*, 2024), flow estimation in semi-arid and sub-humid basins (Nunes *et al.*, 2014; Silva and Luz, 2015; Chagas *et al.*, 2024; Lima *et al.*, 2024), and studies of the São Francisco River (Miranda *et al.*, 2017).

Vichete *et al.* (2023) showed potential conflicts among public supply, irrigation, and hydropower generation in the São Francisco River Basin and within the scope of the PISF. Despite the PISF's operational complexity, efficient water use is essential. The decision-making process for allocating water—aimed at minimizing conflicts and achieving sustainability—has proven challenging (Srdjevic *et al.*, 2019). According to Cardoso *et al.* (2023), water resources management should prioritize preventive planning, efficient operational management of transfers from the PISF North and East axes, water-allocation scenario planning, and the application of technologies that enhance understanding of water resources and enable assessment of ecosystem impacts and resilience.

The objective of this study is to propose a generic water-allocation model formulated in the Pywr library (Tomlinson *et al.*, 2020). The model is applied to the Piancó-Piranhas-Açu River Basin, which is characterized by scarce hydrological data, with inflows estimated using a lumped hydrological model. Rather than testing the effectiveness of the PISF itself, this study focuses on quantifying the reliability gains, deficit reduction, and allocation dynamics under legally defined priority rules, using an integrated hydrological and optimization-based allocation framework.

2. MATERIAL AND METHODS

The methodology was structured into three main stages: (i) generation of inflows using the rainfall–runoff SMAP model; (ii) characterization of water demands from the National Water Use Register (CNARH); and (iii) simulation of water allocation with the Pywr library, implementing comparative scenarios with and without the contribution of the PISF.

2.1. Study area

The study area corresponds to a portion of the Piancó-Piranhas-Açu River Basin, located in the Atlantic Northeast Oriental Hydrographic Region, with a total area of 43,683 km². Its extension covers the states of Paraíba (approximately 60% of the territory) and Rio Grande do Norte (40%). Inserted in a semi-arid region, the basin experiences rainfall concentrated in a few months of the year, characterized by high interannual variability. This pattern is marked by alternating periods of above-average and regular rainfall, interspersed with prolonged droughts that result in low water availability.

The Piancó-Piranhas-Açu River, like most watercourses in the basin, is naturally intermittent. However, its perennialization is maintained by two major regulation reservoirs built by the National Department of Works Against Droughts (DNOCS): Curema/Mae d'Água, in Paraíba, and Armando Ribeiro Gonçalves, in Rio Grande do Norte. The basin also receives external inflows from the São Francisco River Integration Project (PISF).

In addition to these large reservoirs, a widespread network of small dams serves the basin to meet diverse water demands. In this study, the basin outlet was defined at the boundary between the states of Paraíba and Rio Grande do Norte, covering approximately 21,000 km² within the Piranhas River Basin (Figure 1).

2.2. Generation of inflows with SMAP

Estimating natural flows in semi-arid regions with sparse monitoring remains a challenge for the input that rainfall–runoff models require. In this study the generation of natural inflows was performed using the lumped hydrological model SMAP (Soil Moisture Accounting Procedure), originally proposed by Lopes *et al.* (1982). The model operates at a monthly timestep and represents basin-scale hydrological processes through two conceptual mathematical reservoirs whose state variables are updated at each time step.

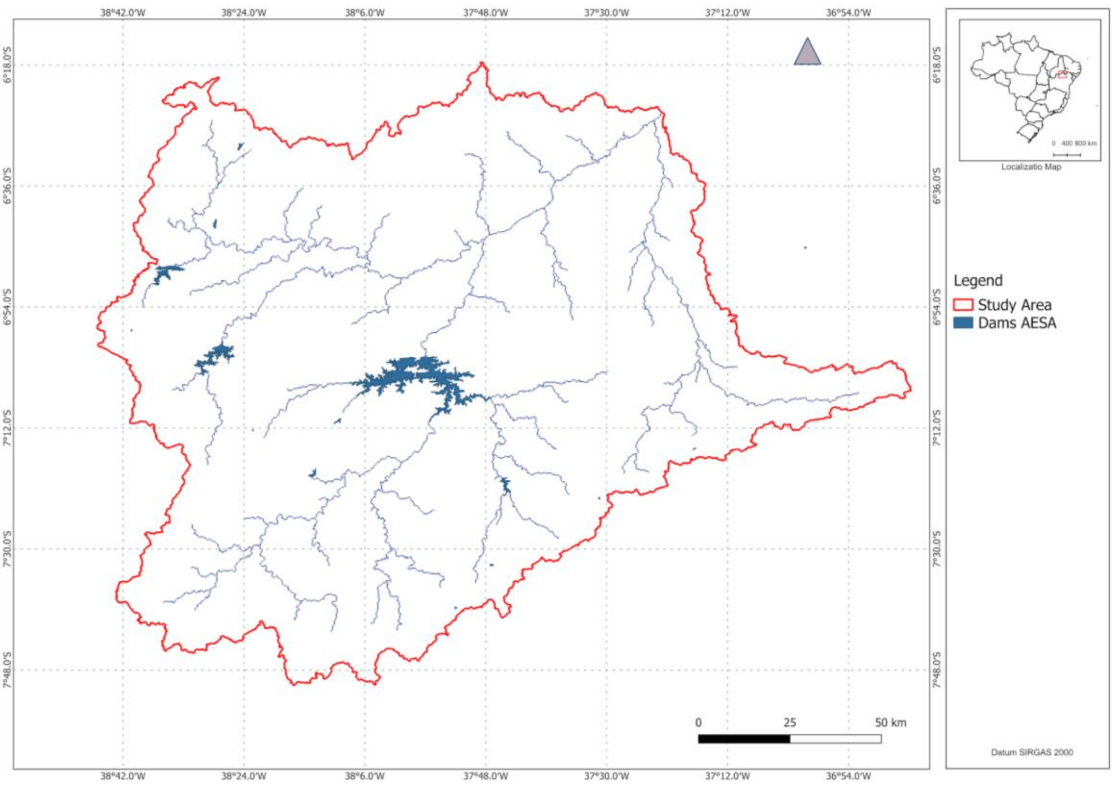

Figure 1. Study area, Upper Piranhas-Açu Basin.

The SMAP model consists of two interconnected reservoirs:

- **Soil reservoir (Rsoil)**, representing the aerated zone, responsible for controlling infiltration, soil moisture storage, evapotranspiration, and groundwater recharge;
- **Groundwater reservoir (Rsub)**, representing the saturated zone, responsible for baseflow generation.

The state variables are updated monthly according to the following water balance Equations 1 and 2:

$$R_{soil}(i+1) = R_{soil}(i) + P - E_s - E_r - Rec \quad (1)$$

$$R_{sub}(i+1) = R_{sub}(i) + Rec - E_b \quad (2)$$

Where:

R_{soil}: Soil water storage (mm),

R_{sub}: Groundwater storage (mm),

P: precipitation (mm),

E_s: surface runoff (mm),

E_r: Actual evapotranspiration (mm),

Rec: Groundwater recharge (mm), and

E_b: Baseflow (mm).

The initial conditions of the reservoirs using Tu_{in} as the initial soil moisture content (dimensionless), Str as the soil saturation capacity (mm), E_{bin} as the initial baseflow ($m^3 s^{-1}$), and A_d the drainage area (km^2). The other parameters include Crec – groundwater recharge coefficient (%); Ai – initial abstraction (mm); Sat – field capacity ratio (% of Str) and Kkt – baseflow recession constant (month) and Pes – surface runoff parameter.

These parameters control soil water storage limits, runoff generation, recharge processes, and groundwater recession behavior. The transformation of precipitation into runoff, evapotranspiration, recharge, and baseflow is governed by four transfer functions as described by Lopes *et al.* (1982).

Despite its conceptual simplicity, SMAP has proven suitable for semi-arid basins with limited hydrological data, where lumped representations and reduced parameter sets are advantageous. The monthly time step and explicit representation of soil moisture dynamics allow the model to reproduce seasonal variability, drought persistence, and baseflow behavior, which are critical for water allocation studies in intermittent river systems.

2.2.1. Input data

Climatic data were obtained from remote sensing sources:

● Precipitation (**P**): monthly series from CHIRPS (Climate Hazards Group InfraRed Precipitation with Stations), which combines satellite data (0.05° resolution) with ground station observations (Funk *et al.*, 2015). Data extraction was automated via Google Earth Engine (GEE), generating drainage-area averages.

● Potential evapotranspiration (**Ep**): obtained from TerraClimate, which combines WorldClim climatologies with CRU Ts4.0 and JRA55 reanalysis time series (Abatzoglou *et al.*, 2018).

2.2.2. Calibration and validation

Model calibration was conducted for the period 2015–2023 at four gauging stations (Figure 2). Performance was evaluated using the coefficient of determination (R^2), Nash–Sutcliffe Efficiency (NSE), and Pearson correlation. Although the semi-arid context and intermittent flow regime limit model performance, NSE values between approximately 0.4 and 0.7 are considered acceptable for monthly simulations in data-scarce regions.

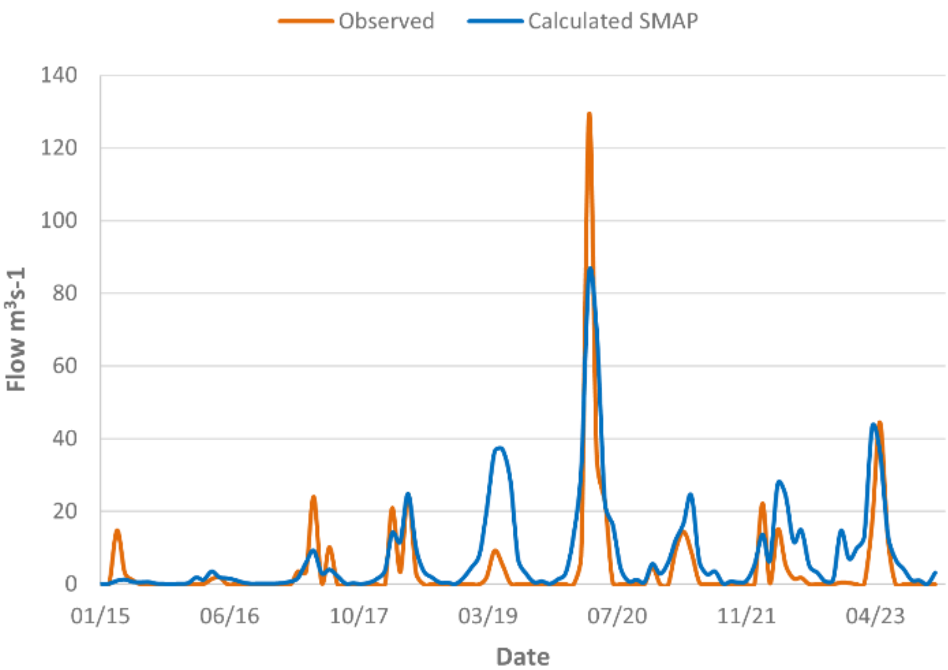

Figure 2. Simulated and observed flow at Piancó gauge.

With calibrated parameters, the model was applied to 16 discretized sub-basins (Figure 3), defined according to confluences, reservoir locations, and water quality monitoring points. This subdivision enabled generation of individualized inflow series for each section of the flow network.

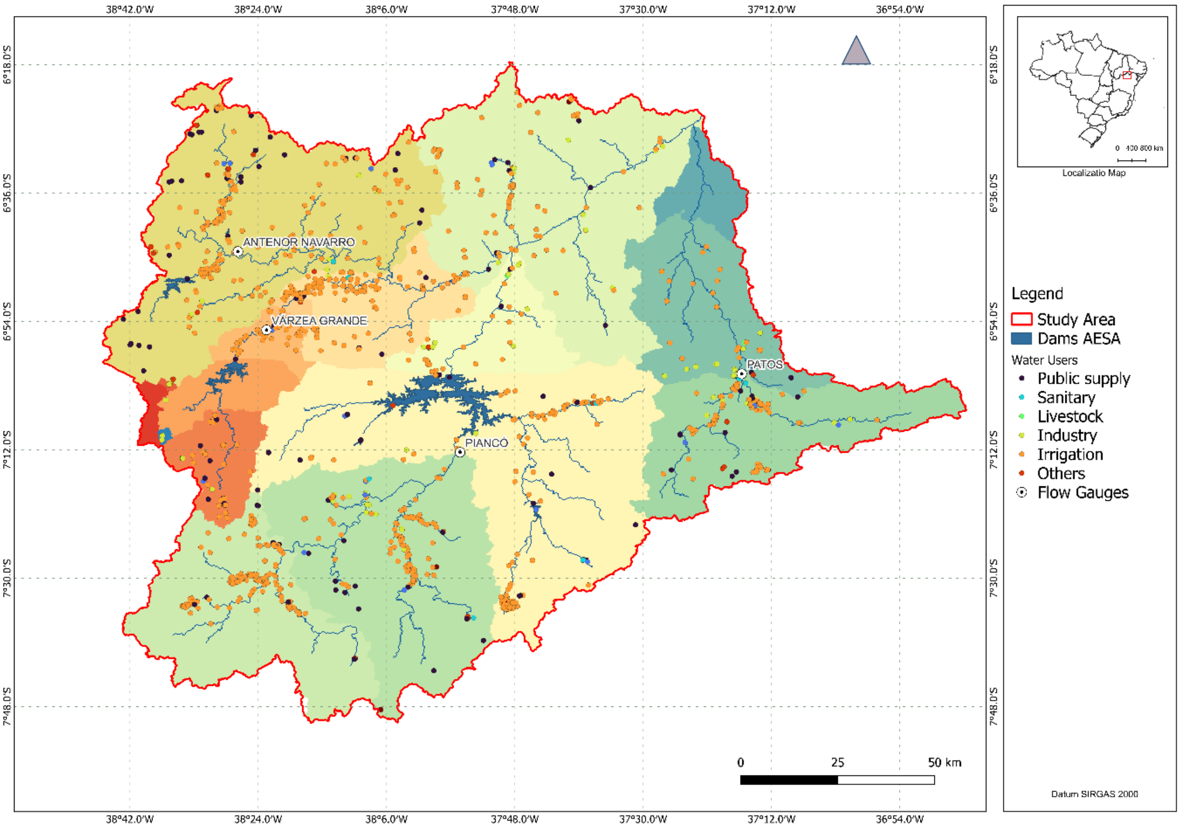

Figure 3. Sub-basin discretization, flow gauges and demand locations in CNARH.

Figure 2 presents observed versus simulated flows for the calibration period for Piancó gauge, illustrating the model's ability to reproduce seasonal variability and drought periods.

2.3. Characterization of water demands

Water demands were characterized using CNARH, the official register maintained by the National Water and Sanitation Agency (ANA).

The demands were classified as follows: public supply (77% of total abstractions), irrigation (19%), and other uses (approximately 4%), including livestock, industry, and aquaculture. This pattern confirms public supply as the priority use, followed by irrigated agriculture, an important regional economic activity.

The CNARH records are declaratory, reporting licensed flows in L s^{-1} or m^3 s^{-1}. To make them compatible with the monthly modeling scale, they were converted into monthly volumes (m^3 $month^{-1}$), aggregated by sector and sub-basin, and inserted as demand nodes in the Pywr network. Figure 3, shows the locations of the water abstractions registered in CNARH by purpose and sub-basin, totaling approximately 12 m^3 s^{-1}.

2.4. Allocation modeling with Pywr

The final step consisted of representing the water system as a network using the Pywr library, a Python-based water resources modeling framework (Tomlinson *et al.*, 2020), which formulates the allocation problem as a linear programming model solved independently at each monthly time step.

In Pywr, the system is represented by four types of elements:

- **Input nodes:** natural inflows generated by SMAP and external inflows from PISF;
- **Storage nodes:** the main reservoirs of the basin, with elevation–volume–capacity curves;

- **Output nodes:** sectoral demands (e.g., public supply, irrigation);
- **Links:** connections establishing flows between nodes, subject to capacity constraints.

The objective function minimizes the total weighted cost of flows throughout the network:
Minimize (Equation 3)**:**

$$\sum_t \sum_{l \in L} c_l \ Q_{l,t} \tag{3}$$

Where $Q_{l,t}$ is the flow through link or node l at time t, and c_l is the associated cost. Negative costs represent priority uses, encouraging allocation, while higher (less negative) costs represent lower-priority demands.

Subject to:

- mass balance constraints at each node,
- capacity limits for links and reservoirs,
- minimum and maximum storage bounds,
- demand upper bounds defined by monthly profiles.

The Pywr implementations use the GLPK (GNU Linear Programming Kit) solver, with the simplex and interior-point methods as the main solution approaches.

Demand priorities were defined through differentiated costs, following Brazil's Water Law (Law 9.433/97). Lower costs were assigned to human supply, intermediate costs to livestock watering, and higher costs to irrigation. Under scarcity conditions, the model thus ensures legal priority for human consumption. Table 1 summarizes the cost structure adopted.

Table 1. Cost values for net water users in pywr.

Water Use	Node Type	Cost
Public Water Supply / Human Consumption	Output	-999
Livestock	Output	-999
Irrigation	Output	-900
Aquaculture	Output	-900
Industry	Output	-800
Other Uses	Output	-700

3. RESULTS AND DISCUSSION

Table 2 presents the correlation indicators and R^2 values obtained in the calibration of the SMAP model for each gauging station.

Table 2. Calibrated parameters and adjustment coefficients of the SMAP model for the selected stations.

			Spatial characteristics			**Initial Condition**		**Model Parameters**			
Station	**Corre**	**R^2**	**AD**	**Pcoef**	**Ecoef**	**TUin**	**EBin**	**sat**	**pes**	**crec**	**Kkt**
			km²	**-**	**-**	**%**	**$m^3\ s^{-1}$**	**mm**	**-**	**%**	**Month**
Antenor Navarro	0.521	0.3456	1,519	1.0	1.0	0.0	1.5	4,000	8.4	0.1	1.0
Várzea Grande	0.526	0.3973	4,754	1.0	1.0	0.0	0.64	5,000	8.3	1.0	6.0
Piancó	0.782	0.6315	4,558	1.0	1.0	9.53	0.0	2,735	3.7	0.0	3.0
Patos	0.732	0.5776	1,629	1.0	1.0	0.0	1.5	1,616	9.0	0.0	1.0

Although models such as HBV, Sacramento, and the Tank Model allow greater detail of hydrological processes, SMAP has the advantages of simplicity, reduced number of parameters, and rapid calibration. Previous studies confirm its suitability for semi-arid conditions: Nunes *et al.* (2014) applied SMAP to the Piancó River Basin, obtaining good monthly fits, and Miranda *et al.* (2017) used SMAP to simulate headwaters of the São Francisco River. The results showed R^2 values between 0.52 and 0.78, which are considered satisfactory in semi-arid environments, where natural river intermittency makes continuous simulation difficult.

Figure 4 shows the flow network built to evaluate the system. Gray nodes represent inflows calculated for each sub-basin, orange nodes represent abstractions disaggregated by use sector (allowing differentiated optimization costs), blue nodes represent reservoirs, and the red circle highlights the PISF inflow node.

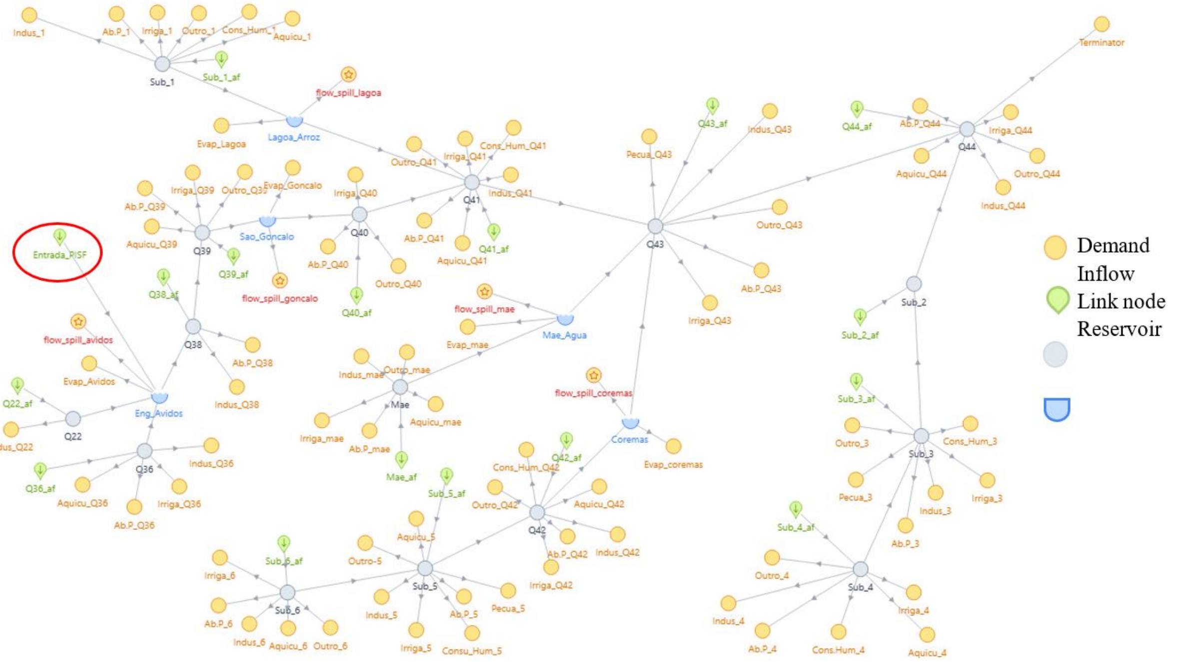

Figure 4. Flow network of the Upper Piranhas-Açu Basin.

The application of the Pywr water allocation model enabled evaluation of reservoir behavior under two scenarios: (i) with PISF inflows and (ii) without PISF inflows.

Figure 5 shows the flow duration curves with and without the PISF contribution. From December 2021, when PISF inflows began, the hydrographs showed improved regularity. Without PISF, flows remained below 21.0 $m^3 s^{-1}$ about 60% of the time. With PISF, this threshold was reduced to 65% of the time, indicating improved frequency of higher flows. In 70% of the period, inflows with PISF exceeded those without PISF. These results confirm that the external water transfer helped smooth the typical variability of the semi-arid, reducing the incidence of critical drought periods.

For the Engenheiro Ávidos Reservoir (the PISF inflow point), permanence curves of storage volumes (Figure 6) and time series of stored volumes compared to historical data (Figure 7) were constructed.

The permanence curves indicate that, in the scenario without PISF, the reservoir more often remained at low storage levels, revealing higher vulnerability. In this case, volumes remained below 50 hm^3 for 80% of the time, compromising regular demand supply. In the scenario with PISF, the frequency of critical low volumes was reduced to 67%, and the reservoir remained full for 20% of the period.

The temporal analysis (Figure 7) reinforces this result. While the historical series shows marked oscillations and recurrent partial depletion, the simulation with PISF demonstrated greater storage stability (with inflows starting in December 2021). Without the transfer, the reservoir reproduced depletion trends observed in drought periods, with greater difficulty recovering after critical events. In contrast, with PISF, the reservoir reached near-full capacity in several simulated periods, ensuring greater reliability in meeting supply and multi-use demands.

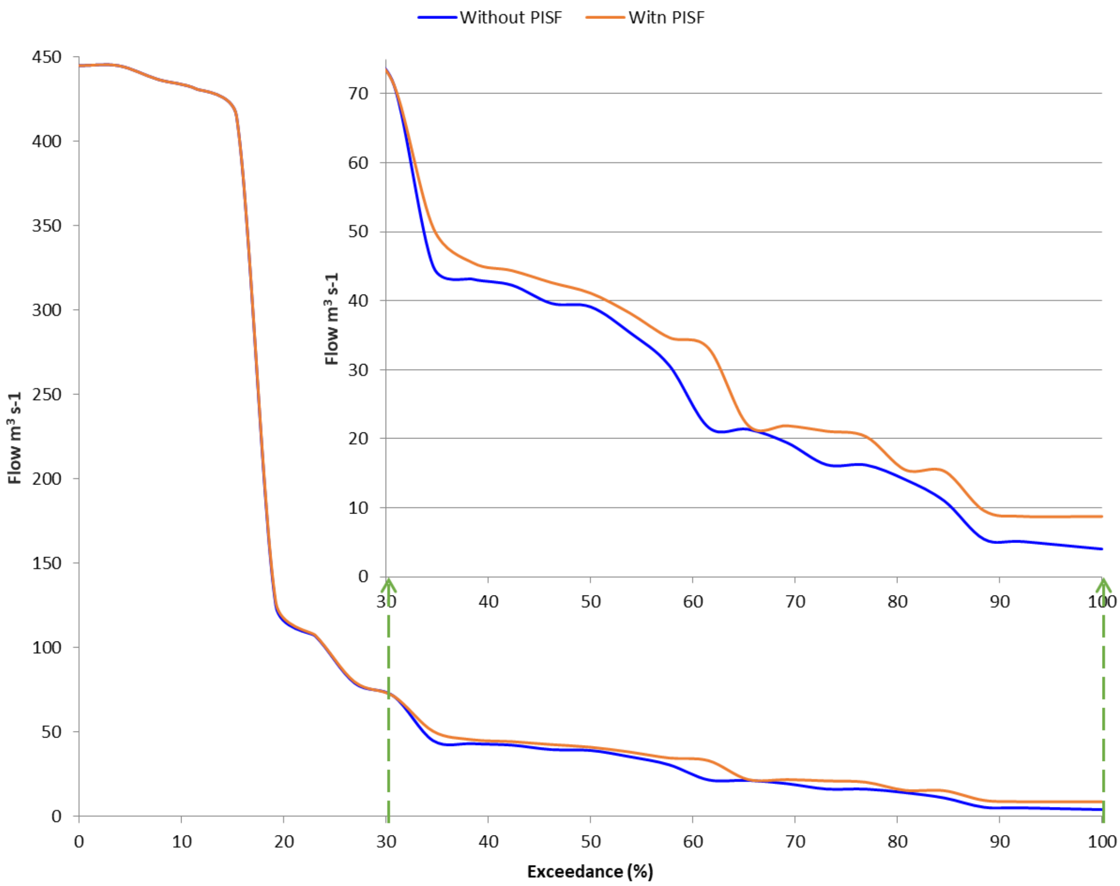

Figure 5. Flow duration curves with and without PISF inflows (highlighted range 30–100%).

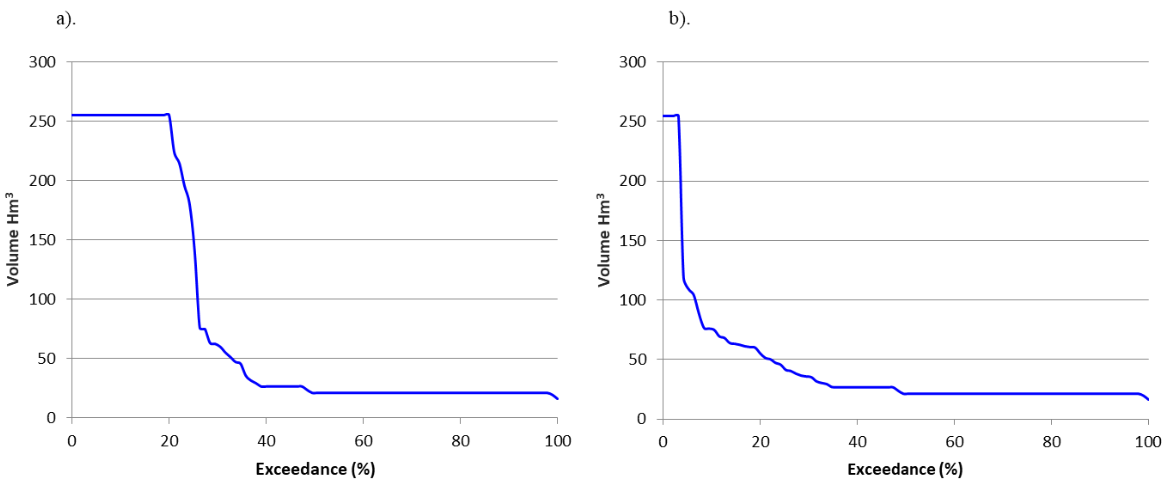

Figure 6. Storage permanence curves of Engenheiro Ávidos Reservoir with (a) and without (b) PISF inflows.

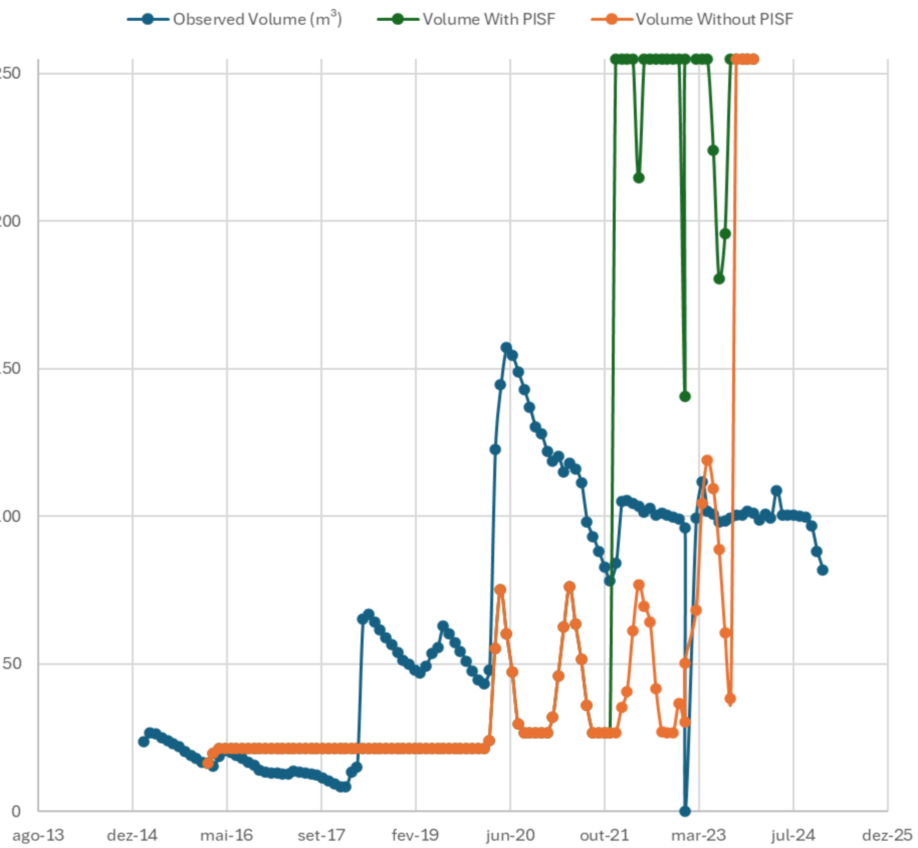

Figure 7. Time series of Engenheiro Ávidos Reservoir volumes during the simulation period.

Demand-satisfaction permanence curves were disaggregated by sector, focusing on public supply and irrigation, which together account for 96% of abstractions registered in CNARH.

For public supply (Figure 8), neither scenario achieved full demand satisfaction, but with the transfer the volume supplied at the 50% exceedance probability was double that without PISF. In terms of deficits, the gains were even clearer. Without PISF, deficits exceeded 1.0 hm³ in about 80% of the time, while with PISF deficits remained below 1.0 hm³ in more than 50% of the period. Thus, PISF not only increased the frequency of full demand coverage but also substantially reduced deficits under critical conditions, reinforcing its role in safeguarding water security for the population.

a). b).

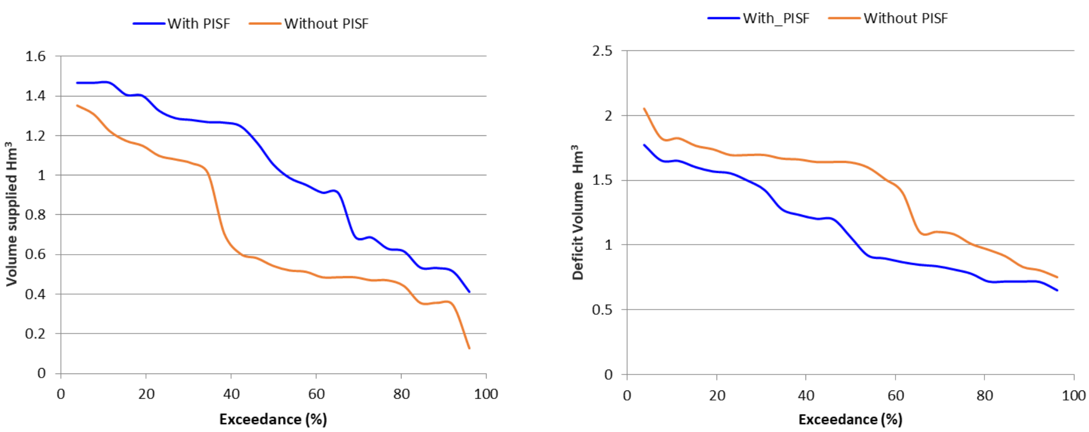

Figure 8. Permanence curves of public supply demand coverage with and without PISF: (a) volume supplied; (b) deficit.

For irrigation (Figure 9), no significant differences were observed between the scenarios, reflecting the priority legally assigned to human consumption, which represents the lowest cost in the optimization network. Thus, inflows are allocated first to supply demands before other uses. In both scenarios, irrigation demands were not fully satisfied, with only a small increase (about 0.5%) in coverage under the PISF scenario.

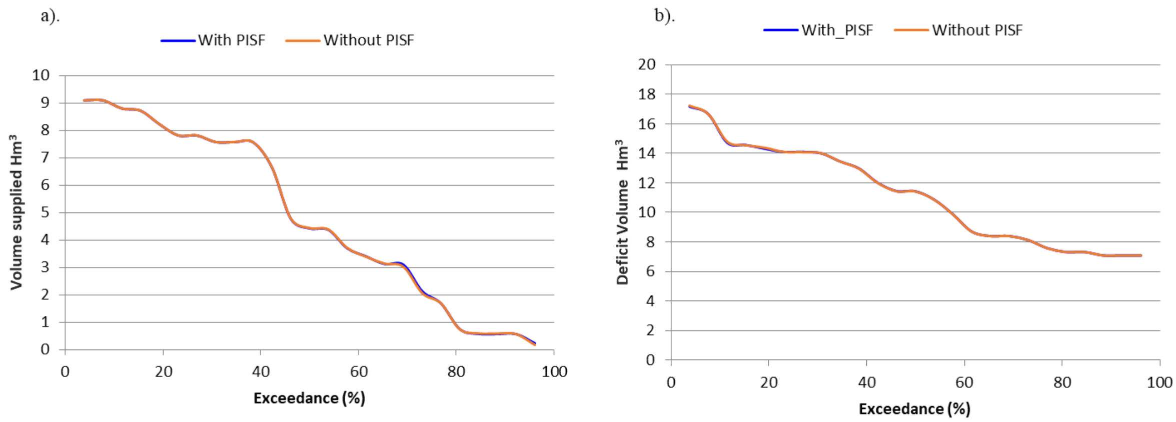

Figure 9. Permanence curves of irrigation demand coverage with and without PISF: (a) volume supplied; (b) deficit.

Overall, the results demonstrate that PISF plays a decisive role in strengthening water security in the basin, primarily for public supply, but with additional benefits for irrigated agriculture. The external transfer not only increased availability but also improved system resilience to climatic variability, reducing the severity of failures and ensuring greater stability in meeting priority demands.

These findings confirm that the inclusion of the transfer in the basin's water balance increases the reliability of supply for multiple demands, particularly during drought periods. The additional inflows from the São Francisco River reduce system vulnerability, guaranteeing greater continuity in human supply and greater stability for irrigated agriculture.

The flow network also provides a fundamental basis for evaluating management scenarios, supporting decision-making, and proposing solutions that foster sustainable water use in the basin. Furthermore, it enables the integration of climatic, hydrological, and socioeconomic aspects, broadening understanding of water dynamics and their implications for regional development.

This study focuses exclusively on allocation dynamics within the receiving basin. Inter-basin transfers such as the PISF inherently involve trade-offs, including environmental, financial, and opportunity costs at the donor basin. A comprehensive assessment of impacts on the São Francisco River Basin would require coupled hydrological and allocation modeling across both basins, which is beyond the scope of this work.

Nevertheless, the modeling framework presented here is fully compatible with such extensions and may support future integrated assessments of inter-basin transfer policies

4. CONCLUSION

The integrated modeling of inflow generation (SMAP) and water allocation (Pywr) applied to the Piancó-Piranhas-Açu River Basin demonstrated that inflows from the São Francisco River Integration Project (PISF) play a critical role to ensure water security in the semi-arid region of Northeastern Brazil.

The results for the Piancó-Piranhas-Açu Basin showed that the PISF contribution is decisive in reducing system vulnerability by providing greater regularity to inflows, lowering the frequency of critical volumes in the Engenheiro Ávidos Reservoir, and significantly improving the coverage of priority demands. Public supply showed the greatest benefits from the transfer, with substantial reductions in deficits and increased reliability in meeting population needs. For irrigation, although the improvements were more modest due to the legal priority of human consumption, greater stability in supply was also observed. These findings confirm the importance of PISF as a strategic measure for regional water security and demonstrate that allocation models based on optimization can serve as a valuable tool for informing public policy and decision-making in critical semi-arid basins.

In addition to ensuring greater reliability, the proposed approach has the potential to be replicated in other basins with similar characteristics, integrating hydrological and network allocation models. Future research should incorporate water quality modules, enabling the evaluation of diffuse pollution impacts and their influence on water allocation.

5. DATA AVAILABILITY STATEMENT

Data availability not informed.

6. ACKNOWLEDGEMENTS

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