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APPLYING THE SACRAMENTO MODEL FOR HYDROLOGICAL FORECASTING IN SELECTED WATERSHEDS OF PARANÁ STATE

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Abstract: In recent decades, hydrological extreme events have become increasingly frequent and intense across various regions of the globe, including Brazil. In the State of Paraná, this trend has raised concerns about public safety, infrastructure resilience, and water resource management. This study presents the implementation of a hydrological forecasting system based on the conceptual Sacramento – Soil Moisture Accounting (SAC-SMA) model, focusing on streamflow prediction in predefined monitoring areas. The system was developed to operate across multiple watersheds in Paraná, integrating meteorological and hydrological data to generate water level forecasts. Input data, preprocessing steps, model parameters, and spatial interpolation methods are thoroughly described. The SAC-SMA model, with its conceptual-deterministic approach and water storage zone structure, allows a relatively simplified representation of physical runoff processes. Results indicate that the model shows potential for rainfall-runoff simulation in some watersheds, although with variable performance. Limitations include data scarcity and uneven rain gauge distribution. Nevertheless, the system proves promising as a support tool for water resource management and hydrological risk reduction.

Resumo: Nas últimas décadas, eventos hidrológicos extremos tornaram-se mais frequentes e intensos em diversas regiões do mundo, incluindo o Brasil. No estado do Paraná, essa tendência tem gerado preocupações quanto à segurança da população e à gestão dos recursos hídricos. Neste contexto, este estudo apresenta a implementação de um sistema de previsão hidrológica baseado no modelo conceitual Sacramento – *Soil Moisture Accounting* (SAC-SMA), com foco na previsão de vazões em áreas previamente definidas para monitoramento. O sistema foi desenvolvido para operar em diversas bacias hidrográficas do Paraná, integrando dados meteorológicos e hidrológicos para gerar previsões de nível d'água. São detalhados os dados de entrada, o processo de pré-processamento, os parâmetros do modelo e os métodos de interpolação espacial utilizados. A escolha do modelo SAC-SMA, com sua abordagem conceitual-determinística e estrutura em zonas de armazenamento de água, permite representar de forma relativamente simplificada os processos físicos do escoamento. Os resultados indicaram que o modelo apresenta potencial para simulação chuva-vazão em algumas bacias, embora com desempenho variável. As limitações incluem a escassez de dados e a distribuição irregular de pluviômetros. Ainda assim, o sistema mostra-se promissor como ferramenta de apoio à gestão de recursos hídricos e à redução de riscos hidrológicos.

Palavras-Chave – SAC-SMA, Modelo Hidrológico, Sistema de Previsão.

INTRODUCTION

In recent decades, the frequency and intensity of hydrological extreme events have increased across several regions of the globe, including South America (IPCC, 2021). These changes highlight

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the urgent need for effective forecasting tools that support decision-making processes and help mitigate the impacts of such events.

The development of hydrological forecasting systems has emerged as a crucial response to this need. These systems integrate meteorological and hydrological data to provide timely and reliable predictions of river flow and water levels, thereby supporting early warning systems and improving preventive actions in vulnerable areas.

The system was built to operate across the State of Paraná (southern region of Brazil). Its implementation is particularly relevant, not only because Paraná is one of the most populous and economically important states in Brazil (Paraná, 2019), but also because extreme events have been occurring with significant frequency in the region over the past decade (Pittol, 2022)

Hydrological forecasting systems are powerful and essential tools to prevent extreme events and to assist in the safety of the population, in decision-making and in water management policies. They are widely used worldwide (e. g. Breda, 2008 and Piadeh et al., 2022). The operation of a forecast hydrologic system always includes collecting meteorological and hydrological data and data assimilation run, which corrects the simulation according to the latest observation and simulation. They can be used to predict mean flow, low flows and peaks, depending on the focus of each implementation.

In this study, we present the implementation of a lumped rainfall-runoff model, Sacramento – Soil Moisture Accounting, aimed at predicting flows in high-risk areas. This work explains how the model operates, its input data, the pre-processing steps, the final implementation used to predict water levels in these specific regions, and discusses possible future improvements.

MATERIAL AND METHODS

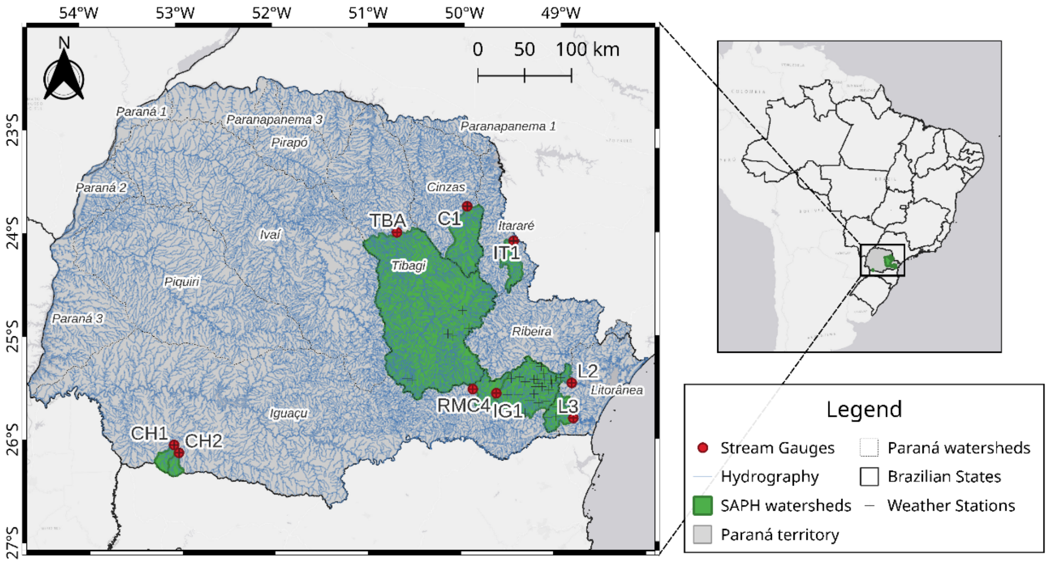
Study area description and data series

The State of Paraná has an area of approximately 200,000 km², making it the 15th largest state in Brazil. It ranks as the 5th most populous and has the 4th largest economy (IBGE, 2023). Paraná, along with the watersheds of the Sistema Autônomo de Previsão Hidrológica (SAPH), which are the focus of this study, experiences a range of climatic conditions, spanning Cfa, Cfb, and Af classifications in the Köppen-Geiger scale, which represent Humid Subtropical, Subtropical Highland, and Tropical Rainforest climates, respectively (Köppen & Geiger, 1928; IAT, 2014).

The SAPH watersheds and their respective outlets are depicted in Figure 1. Their implementation spans different parts of Paraná, covering the southwestern and eastern regions of the state. The latter holds greater importance, as it concentrates the majority of the state's economic and population activities (Paraná, 2019).

The telemetric stream gauges analyzed in this study are: C1 – Tomazina (23774995) on the Rio das Cinzas, CH1 – ETA Francisco Beltrão (26085307) on the Rio Marrecas, CH2 – ETA Marmeleiro (26155302) on the Rio Marmeleiro, IG1 – Porto Amazonas (25334953) on the Rio Iguaçu, RMC4 – Balsa Nova (25584963) also on the Rio Iguaçu, IT1 – Sengés (24104946) on the Rio Jaguaricatú, L2 – Morretes (25474883) on the Rio Nhundiaquara, L3 – Cubatão (25814881) on the Rio Cubatão, and TBA – Ribeirão das Antas (24035069) on the Rio Tibagi.

Figure 1 – SAPH watersheds with their respective outlets



Classification and description of SAC-SMA

The Sacramento Soil Moisture Accounting (SAC-SMA) model is a conceptual-deterministic lumped rainfall-runoff model. Conceptual (or grey-box) models represent physical laws in a highly simplified form (Xu, 2002). These models are formulated as functions derived from the physical processes that influence input variables to produce output variables (Xu, 2002). In the case of SAC-SMA, the output variable is discharge. The model is considered deterministic because all variables are treated as free from random variation, meaning none are assumed to follow a probability distribution (Xu, 2002). It is classified as lumped since its parameters and variables vary only as functions of time, without accounting for spatial variability across the drainage area (Breda, 2008).

A rainfall-runoff model is defined as a set of equations that aid in estimating the portion of rainfall that becomes runoff based on various watershed parameters (Devia et al., 2015). As such, SAC-SMA uses mean areal rainfall (P) and potential evapotranspiration (PET) as inputs, with discharge (Q) as the output (Breda, 2008).

Inputs of SAC-SMA Model: Precipitation and Potential Evapotranspiration

To obtain precipitation values, the availability of telemetric stations within each watershed was considered. For the calibration process, a total of 41 weather stations, managed by Instituto Nacional de Meteorologia (INMET) or by Sistema de Tecnologia e Monitoramento Ambiental do Paraná (SIMEPAR), were used, as shown in Figure 1. It is important to note that for some watersheds (C1, CH1, CH2, IT1, and L2), only one telemetric station was available, which may limit the ability to capture spatial variability.

After collecting precipitation data, a spatial average was calculated using the Inverse Distance Weighted (IDW) Interpolation method, as described by Wei and McGuinness (1973). The method uses the distance between points to assign weights, giving more importance to closer stations. To avoid division by zero, the minimum distance is set to 1 meter.

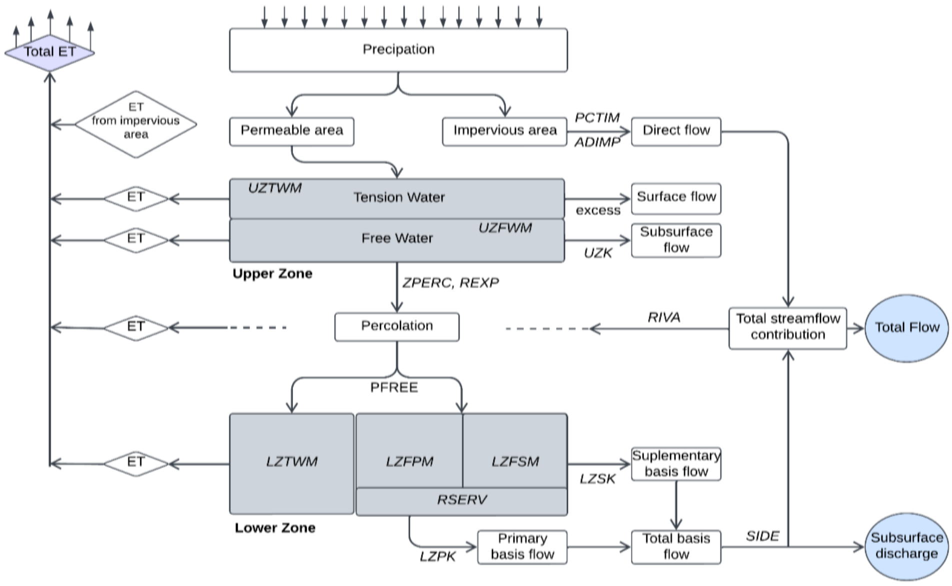
The PET values were estimated for each day of the year (366-day average) for each watershed using general climatology data. These values were then spread over the entire study area and accessed as needed for each time step. For SAPH, 6-hour accumulated PET values were used. PET was calculated using the Penman-Monteith equation based on climatological data from 54 SIMEPAR stations, spatialized over Paraná using the Angular Distance Weighting (ADW) interpolation method.

Parameters of SAC-SMA

The Sacramento model partitions the basin into upper and lower zones, each at different depths, to represent moisture distribution (Figure 2). It distinguishes between two water components: tension water (affected by evapotranspiration and diffusion) and free water (influenced by gravity) (Hogue et al., 2006). These are managed within the two zones through a defined set of parameters shown in Figure 2.

SAC-SMA is a saturation-excess model with 16 parameters. When precipitation exceeds the percolation and interflow capacities, the upper zone overflows, generating overland flow (Hogue et al., 2006). Compared to other conceptual rainfall-runoff models, its relatively high number of parameters can make calibration more challenging (Gan et al., 1997; Breda, 2008).

Figure 2 – SAC-SMA representative scheme, with respective parameters. Adapted from: Breda (2008) and Uliana et al. (2019).



Calibration process

The automatic calibration process of the SAC-SMA model was performed using an algorithm implemented in Python 3, the Dynamically Dimensioned Search (DDS) (Tolson & Shoemaker, 2007). DDS is a global optimization algorithm designed for the automatic calibration of hydrological models. It optimizes one objective function (OF) at a time and operates without requiring extensive parameter tuning (Tiwari et al., 2023).

In this study, two distinct objective functions (OF) were employed: Nash–Sutcliffe Efficiency (NSE) and Root Mean Square Error (RMSE). NSE is commonly used to assess the predictive performance of hydrological models. It evaluates how well the variance of simulation errors, typically associated with flow data, aligns with the variance of observed time series data (Tiwari et al., 2023). RMSE measures the average magnitude of error between observed and simulated values.

Precipitation forecast (ECMWF)

The precipitation forecast for the hydrological modelling was obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). ECMWF provides global numerical weather predictions using advanced atmospheric models that assimilate various meteorological data sources, including satellite observations and ground-based measurements (ECMWF, 2020). These forecasts are essential for hydrological applications, as they offer high spatial and temporal resolution, allowing for better anticipation of extreme precipitation events that could lead to flooding or drought conditions.

One of ECMWF's key forecasting tools is the Ensemble Prediction System (EPS), which generates 51 ensemble members to account for uncertainties in atmospheric initial conditions and model physics. This probabilistic approach improves forecast reliability, particularly for medium-range and extreme event predictions, by providing a range of possible outcomes rather than a single deterministic forecast.

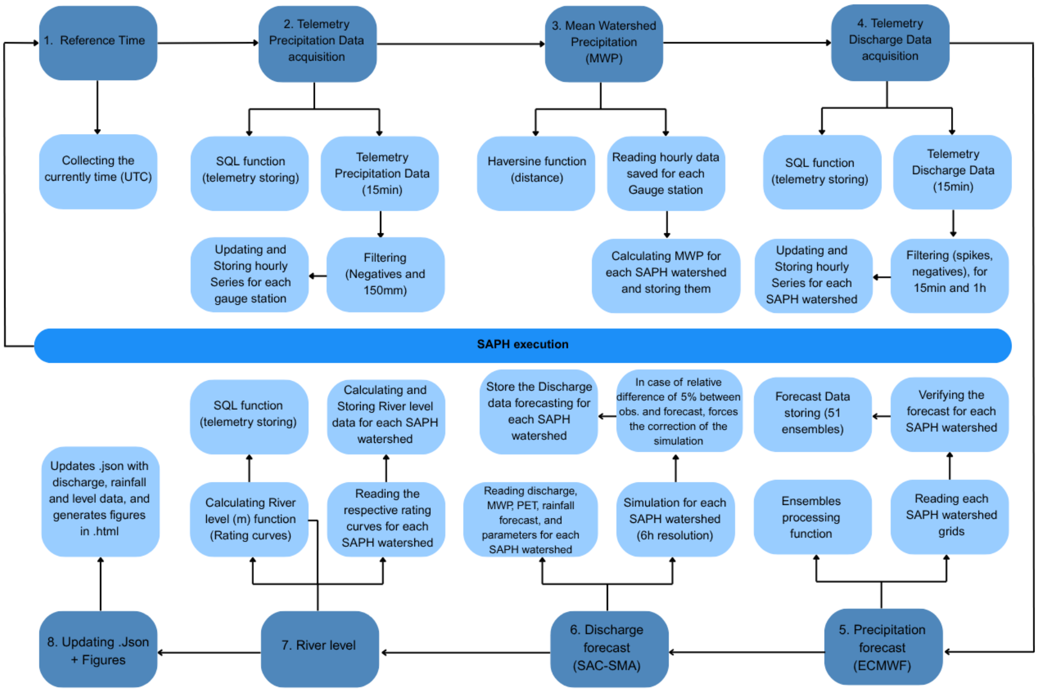
The use of ECMWF forecasts enhances the accuracy of hydrological models by providing updated meteorological inputs, which are crucial for real-time forecasting and early warning systems. Studies such as Haiden et al. (2021) highlight the reliability and continuous improvements of ECMWF's forecasting capabilities, making it one of the most widely used global forecasting systems in hydrology. For this reason, this forecasting model was selected to provide the meteorological data used in this study.

RESULTS AND DISCUSSION

SAPH structure

The current workflow of SAPH is shown in Figure 3. The final execution routine consists of eight main Python 3 programs, each with a specific purpose. The first four handle pre-processing (data acquisition), the fifth and sixth focus on forecasting (precipitation and streamflow), the seventh converts discharge (m^3/s) to level (m), and the eighth updates JSON objects.

Figure 3 – SAPH workflow scheme.



The first program retrieves the current UTC time. The second and fourth collect and filter precipitation and discharge data, respectively. The third calculates Mean Watershed Precipitation (MWP) for each SAPH watershed. The fifth obtains 15-day Forecast Precipitation (FP) (51 ensembles), accumulated every 6 hours. The sixth reads all inputs needed for the SAC-SMA model

(MWP, PET, FP) plus watershed parameters to simulate streamflow for the next 15 days. The seventh converts simulated streamflow (m^3/s) into water levels (m) using watershed rating curves. Finally, the eighth compiles all predicted data (levels, discharge, precipitation) into a single JSON file and updates the HTML files.

SAC-SMA calibration and data validation

To assess calibration and validation, the Nash–Sutcliffe Efficiency Coefficient was used as the main performance metric. Table 1 presents the calibration results along with the Nash–Sutcliffe coefficients for each watershed. The table also details the objective function used to calibrate the parameters of each SAPH watershed.

Table 1 – Calibration and Validation performance in the SAPH watersheds

ID	Warm-up period	Calibration period	NSE	Validation period	NSE	OF
C1	10 months	2022/08/01 – 2023/09/03	0.65	-	-	RMSE
CH1	1 year	2016/08/09 – 2018/08/09	0.73	2022/03/18 – 2023/09/18	0.63	RMSE
CH2	11 months	2017/08/09 – 2018/11/09	0.71	-	-	RMSE
IG1	9 months	2021/05/01 – 2023/09/30	0.78	2018/01/01 – 2020/01/01	0.76	RMSE
IT1	9 months	2021/10/01 – 2022/10/01	0.65	2023/04/15 – 2023/09/30	0.77	RMSE
L2	1 year	2021/07/01 – 2023/03/01	0.60	2017/01/01 – 2019/01/01	0.60	RMSE
L3	1 year	2021/08/01 – 2023/08/01	0.78	2019/08/01 – 2021/08/01	0.74	NSE
RMC4	9 months	2022/05/01 – 2023/09/30	0.83	2021/08/02 – 2022/05/01	0.71	NSE
TBA	1 year	2015/02/01 – 2017/07/01	0.45	2014/01/01 – 2015/01/01	0.40	RMSE

The NSE values obtained were considered good and satisfactory. According to Motovilov et al. (1999), NSE values ≥ 0.75 indicate good simulation results, values between 0.75 and 0.36 are satisfactory, and values below 0.36 are unsatisfactory (Van Liew et al., 2007).

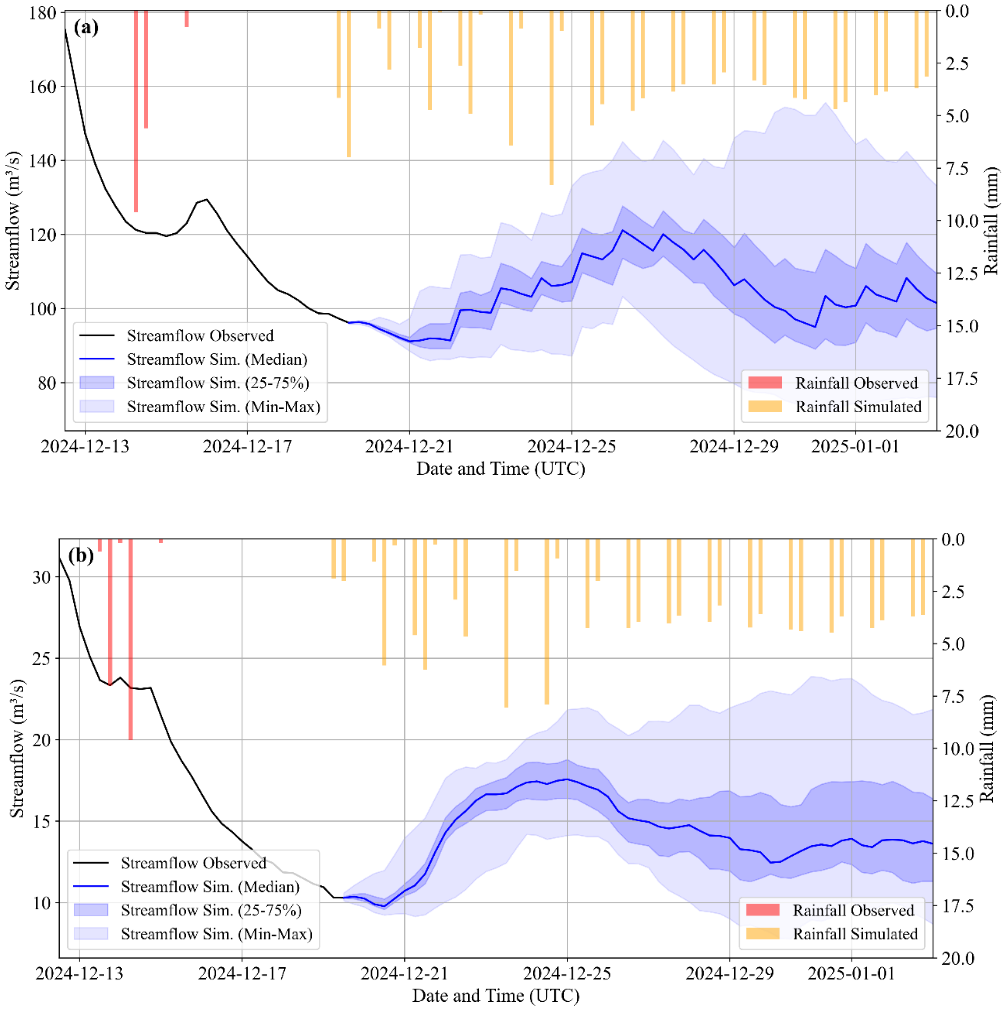
Model warm-up is an adjustment process that allows the model to reach an "optimal" state, where internal stores (e.g., soil moisture) stabilize from initial estimates to more representative conditions (Kim et al., 2018). Although no consensus exists on defining this equilibrium or ideal warm-up period, SAPH watersheds used a 9-month to 1-year warm-up.

Two key points from Table 1 are: (i) using the RMSE coefficient as the objective function in the DDS algorithm often improves capturing peaks and recessions; and (ii) validation was sometimes impossible due to missing or low-quality data, as seen for watersheds C1 (Tomazina) and CH2 (ETA Maringá).

SAPH results and future steps

The respective simulated streamflow values for two different stations (C1 and CH1) are shown in Figure 4.

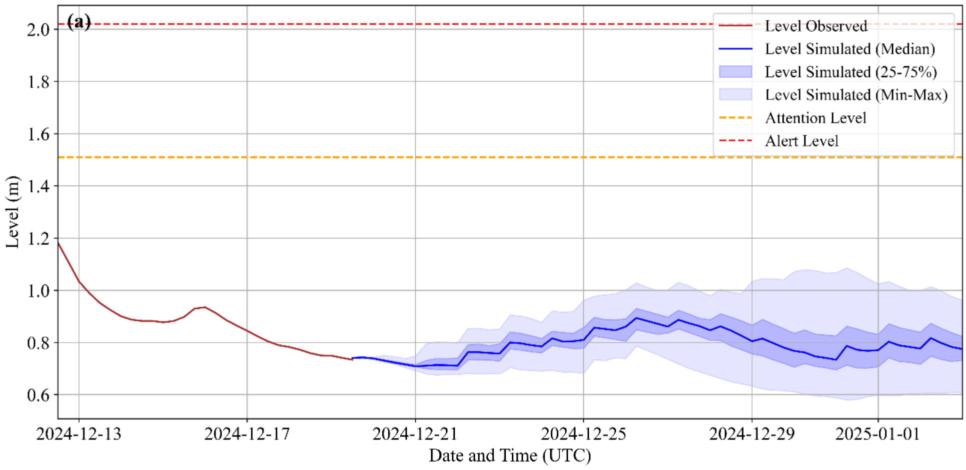
Figure 4 – Simulated streamflow for two different SAPH stations: a) C1 and b) CH1. The simulated Rainfall represents the median of the 51 ensemble members from ECMWF.



These results, as depicted in Figure 4, illustrate the streamflow simulations generated by the SAPH system for two monitoring stations (C1 and CH1), covering different parts of Paraná. The ensemble-based approach provides a range of possible outcomes, with the darker blue shading representing the interquartile range (25–75%) and the lighter blue shading encompassing the full ensemble spread. The median of the simulations serves as the system's reference value for streamflow estimation. This output highlights the capability of SAPH to provide continuous hydrological monitoring, integrating ensemble precipitation forecasts into real-time streamflow predictions.

To estimate the water level (m) at each station, the respective rating curve is applied to the simulated values. For clarity, Figure 5 presents these results only for station C1. The Attention and Alert Levels shown in Figure 5 were established by the Instituto Água e Terra (IAT), serving as reference thresholds for monitoring water levels at this station.

Figure 5 – Simulated Levels for one SAPH station C1.



Although SAPH already provides operational monitoring, as illustrated in Figures 4 and 5, several improvements can be incorporated to enhance its accuracy and coverage:

I. Expansion and maintenance of the hydrometric network: data gaps in many stations hinder calibration and forecast reliability. Expanding and maintaining this network is essential for continuous, reliable time series;
II. Improvement of the meteorological database: currently based on stations within monitored watersheds, integrating more stations across Paraná and applying spatial interpolation (e.g., IDW, Kriging) would better represent rainfall patterns;
III. Inclusion of new watersheds: adding watersheds, especially in areas prone to extremes, would extend coverage and improve response to adverse conditions, strengthening SAPH's role in hydrological monitoring and water resource management.

CONCLUSIONS

This study investigated the application of the Sacramento hydrological model (SAC-SMA) for implementing the SAPH Forecast System in Paraná watersheds. Preliminary results indicate that the model has potential to represent rainfall-runoff processes, but its performance varies considerably across different regions. The Dynamically Dimensioned Search (DDS) algorithm efficiently optimized model parameters, reducing errors between simulated and observed streamflow. However, the accuracy is affected by the availability and spatial distribution of rain gauge stations, especially in basins with sparse data.

As next steps, the system's representation will be improved by incorporating a larger number of rain gauge stations and structuring a grid that enables the interpolation of precipitation within the watersheds. Additionally, implementing a simpler model like GR4J — with fewer parameters and shorter calibration time — could expand SAPH's applicability to more watersheds, enhancing its accessibility and use across Paraná. Future studies may also test alternative performance metrics and calibration strategies to improve the model evaluation process.

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