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Performance of satellite precipitation products for streamflow simulation and water availability in the Cerrado[1]

Desempenho de produtos de precipitação por satélite para simulação de vazão e disponibilidade hídrica no Cerrado

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HIGHLIGHTS:

Global Precipitation Climatology Centre 7.0 outperformed four satellite and reanalysis products for streamflow simulation in a Cerrado watershed.
Satellite and reanalysis products with global coverage are viable alternatives for data-scarce Cerrado watersheds.
Flow duration curves showed statistical equivalence between observed and simulated streamflows for all products.

ABSTRACT: The Cerrado biome has high agricultural potential, but increasing water demand, driven by irrigation expansion and climate variability, has intensified disputes over water use. Strategic planning for sustainable development requires reliable information on water availability; however, there is a scarcity of hydrometeorological data, especially precipitation. In this context, computational modeling tools such as the Soil and Water Assessment Tool (SWAT) emerge as an alternative to process data from satellite precipitation products and reanalysis datasets(ERA5, GPCC 7.0, CHIRPS v2.0, PERSIANN-CDR, and MSWEP) in estimating water availability, although their accuracy must be evaluated. The objective of this study was to assess the precision of different satellite precipitation models and reanalysis in estimating water availability through hydrological modeling. It was verified that GPCC 7.0 achieved the best performance, with Nash–Sutcliffe efficiency (NSE) values of 0.76 in calibration and 0.80 in validation, classified as very good. ERA5 and CHIRPS v2.0 also performed good, with NSE values of 0.73 and 0.70 in calibration, and 0.75 and 0.62 in validation, respectively. PERSIANN-CDR ranged from satisfactory to good, while MSWEP was considered unsatisfactory. Percent bias (PBIAS) values indicated very good performance for most products, with ERA5 and CHIRPS v2.0 slightly underestimating streamflow and GPCC 7.0 slightly overestimating it. Flow duration curve analysis confirmed statistical equivalence between simulated and observed streamflows, with GPCC 7.0 standing out in quartile 95 estimation. The Mann-Whitney test reinforced these findings, validating the robustness of GPCC 7.0 for hydrological studies and water resource planning in the Cerrado.

Key words: hydrological modeling, water resources management, satellite precipitation models and reanalysis, SWAT

RESUMO: O bioma Cerrado possui elevado potencial agrícola, porém o aumento da demanda hídrica, impulsionado pela irrigação e pela variabilidade climática, intensifica disputas por água. O planejamento sustentável da região depende de informações sobre a disponibilidade hídrica; entretanto, há escassez de dados hidrometeorológicos, especialmente de precipitação. Assim, ferramentas de modelagem como o Soil and Water Assessment Tool (SWAT) surgem como alternativa para processar dados de precipitação por satélite e reanálise (ERA5, GPCC 7.0, CHIRPS v2.0, PERSIANN-CDR e MSWEP) na estimativa da disponibilidade hídrica, embora sua acurácia necessite avaliação. O objetivo deste estudo foi avaliar a precisão de diferentes modelos de precipitação por satélite e de reanálise na estimativa da disponibilidade hídrica por meio de modelagem hidrológica. Os resultados mostraram que o GPCC 7.0 obteve o melhor desempenho, com valores de eficiência de Nash–Sutcliffe (NSE) de 0,76 na calibração e 0,80 na validação, classificados como muito bons. ERA5 e CHIRPS v2.0 também apresentaram desempenho bom, com NSE de 0,73 e 0,70 na calibração, e 0,75 e 0,62 na validação. O PERSIANN-CDR variou entre satisfatório e bom, enquanto o MSWEP foi considerado insatisfatório. Os valores de viés percentual (PBIAS) indicaram desempenho muito bom para a maioria dos produtos, com ERA5 e CHIRPS v2.0 subestimando ligeiramente a vazão e GPCC 7.0 superestimando-a ligeiramente. A curva de permanência confirmou equivalência estatística entre vazões simuladas e observadas, com destaque para o GPCC 7.0 na estimativa do quartil 95. O teste de Mann-Whitney reforçou esses resultados, validando a robustez do GPCC 7.0 para estudos hidrológicos e planejamento de recursos hídricos no Cerrado.

Palavras-chave: modelagem hidrológica, gestão dos recursos hídricos, modelos de precipitação por satélite e reanálise, SWAT

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Introduction

The growing dispute over water use in some Cerrado watersheds can compromise the sustainable development of the region (Ferreira et al., 2026), so it is essential to adopt development strategies based on strategic planning and integrated multidisciplinary approaches across sectors (Ferreira et al., 2026).

Indicative scenarios of water availability are important for the strategic planning and sustainable development of a region. The use of mathematical models in this planning is essential, but has been hampered by the lack of hydroclimatic data (Gualdani & Araújo Sobrinho, 2023), especially precipitation.

Precipitation has a major influence on the hydrological behavior of watersheds, which makes its accurate estimation essential (Cunha Filho et al., 2022). Its spatial variability, however, poses a challenge for modeling and water resource management, especially in small watersheds located in regions such as the Cerrado (Gashaw et al., 2025). To overcome the limitation and scarcity of such data, satellite precipitation models and reanalysis are a promising alternative. These models have been widely used due to their near-global coverage and high spatiotemporal resolution (Ibrahim et al., 2024).

There are several satellite precipitation models and reanalysis available for estimating rainfall. Some of these products are derived from reanalysis data (Tan et al., 2021) (ECMWF Reanalysis v5 - ERA5, Modern-Era Retrospective Analysis for Research and Applications, v2 -MERRA-2, Japanese 55-year Reanalysis - JRA-55, Climate Forecast System Reanalysis - CFSR), others combine remote sensing data with rain gauge measurements (Climate CPC Merged Analysis of Precipitation - CMAP, Tropical Rainfall Measuring Mission - TRMM, Integrated Multi-satellite Retrievals for GPM - IMERG, Climate Hazards Group InfraRed Precipitation with Station data v2.0 - CHIRPS v2.0, Tropical Applications of Meteorology using satellite data - TAMSAT v3), and another group comes directly from satellites (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks – Climate Data Record - PERSIANN-CDR, Dual-frequency Precipitation Radar - GPM-DPR, Geostationary Operational Environmental Satellites - NOAA-GOES, and CPC Morphing Technique - CMORPH-RAW). These products provide coverage across the entire Brazilian territory and can contribute to improving simulations and scenarios developed for the sustainable growth of the Cerrado (Tan et al., 2018; Ahmed et al., 2022).

Guermazi et al. (2019) evaluated two satellite-based precipitation products (PERSIANN-CDR and CHIRPSv2) in the northwest region of Africa and observed good performance of CHIRPS v2.0 in the simulation of precipitation on a monthly scale. Belete et al. (2020) found that the CHIRPS v2.0 and TAMSAT v3 satellite precipitation models and reanalysis showed good accuracy in estimating precipitation in the Blue Nile River basin region. Amorim et al. (2020), Junqueira et al. (2022) and Ferraz et al. (2023) evaluated Tropical Rainfall Measuring Mission (TRMM), Global Precipitation Measurement (GPM), Tropical Rainfall Measuring Mission Multisatellite Precipitation Analysis (TMPA), and Integrated Multi-Satellite Retrievals for Global Precipitation Measurement (IMERG) in the hydrological modeling of the Cerrado biome and obtained promising results.

On the other hand, there are few studies that have evaluated the performance of satellite precipitation models and reanalysis in the Cerrado biome, especially regarding the possibility of using them in hydrological models to improve the estimation of water availability. It is therefore noted that there is a need to evaluate the quality of the data from these models and the possibility of improving the performance of hydrological models in estimating water availability.

In this context, the objective of this study was to evaluate the accuracy of different satellite precipitation models and reanalysis in the estimation of water availability through hydrological modeling.

Material and Methods

The accuracy of satellite precipitation data in the estimation of water availability was evaluated using streamflow data from the Porto Extrema stream gauge station (code 42690001), located in the municipality of Brasilândia de Minas, state of Minas Gerais, in the Paracatu River basin, Brazil (Figure 1). This station has a drainage area of approximately 29,913.0899 km².

The region of the Porto Extrema stream gauge station (PESGS) has a humid tropical climate, with a rainy season from October to March (Althoff et al., 2020). The average annual reference evapotranspiration is 1200 mm (Ribeiro et al., 2022), with an average temperature between 22 and 24 °C and annual rainfall of 1400 mm (Souza et al., 2023).

The predominant soils are Latossolos Vermelho-Amarelos (Oxisols) (37%) and Neossolos Litólicos (Entisols) (27%). The PESGS has an average altitude of 701 m and a gently undulating relief (41.68%) (Rodrigues, 2023). Land use for the year 2018 consists of 37% pasture, 23% natural savannah formations, 15% crops, 11% natural forest formations and 14% other uses (MAPBIOMAS, 2018).

The study aimed to assess the accuracy of precipitation and reanalysis models applied to hydrological modeling. Simulated streamflow values were compared with observed streamflow data and statistically evaluated using specific metrics, in order to determine the degree of approximation to the observed records. Thus, the analysis sought to identify whether the simulated streamflow values are underestimated or overestimated when compared with the observed values.

To ensure that the objectives are achieved, the study employed the hydrological model Soil and Water Assessment Tool (SWAT) to simulate water availability in the Paracatu River basin, using the Porto Extrema streamflow gauging station as a reference. For this purpose, spatial data (soil maps, relief, land use and cover, digital elevation model) and tabular data (climate, vegetation, aquifers, and observed streamflow) were integrated. Model calibration and validation were carried out

in distinct periods (1988–2008 for calibration and 2009–2018 for validation), ensuring robustness in the comparison between simulated and observed results. This process allowed verifying the ability of different satellite precipitation models and reanalysis to reproduce the hydrological dynamics of the region.

For calibration and validation, an automatic procedure was employed using the SWAT-CUP software, applying the Sequential Uncertainty Fitting algorithm (SUFI-2). The SUFI-2 algorithm has been widely applied in hydrological modeling studies in Brazil, as reported by Monteiro et al. (2016), Amorim et al. (2020), Gomes et al. (2021), and Junqueira et al. (2022), who conducted their experiments in watersheds located in the Brazilian Cerrado biome.

Based on the aforementioned studies, the Nash–Sutcliffe (NS) objective function was selected. Calibration was performed over ten iterations, each consisting of 500 simulations, while validation was conducted over five iterations, also with 500 simulations, following the methodology proposed by the aforementioned authors.

Based on the cited studies, eight parameters were selected: GWQMN, GW_REVAP, REVAPMN, CN2, ESCO, EPCO, SOL_K, and ALPHA_BF, which are described in Table 1.

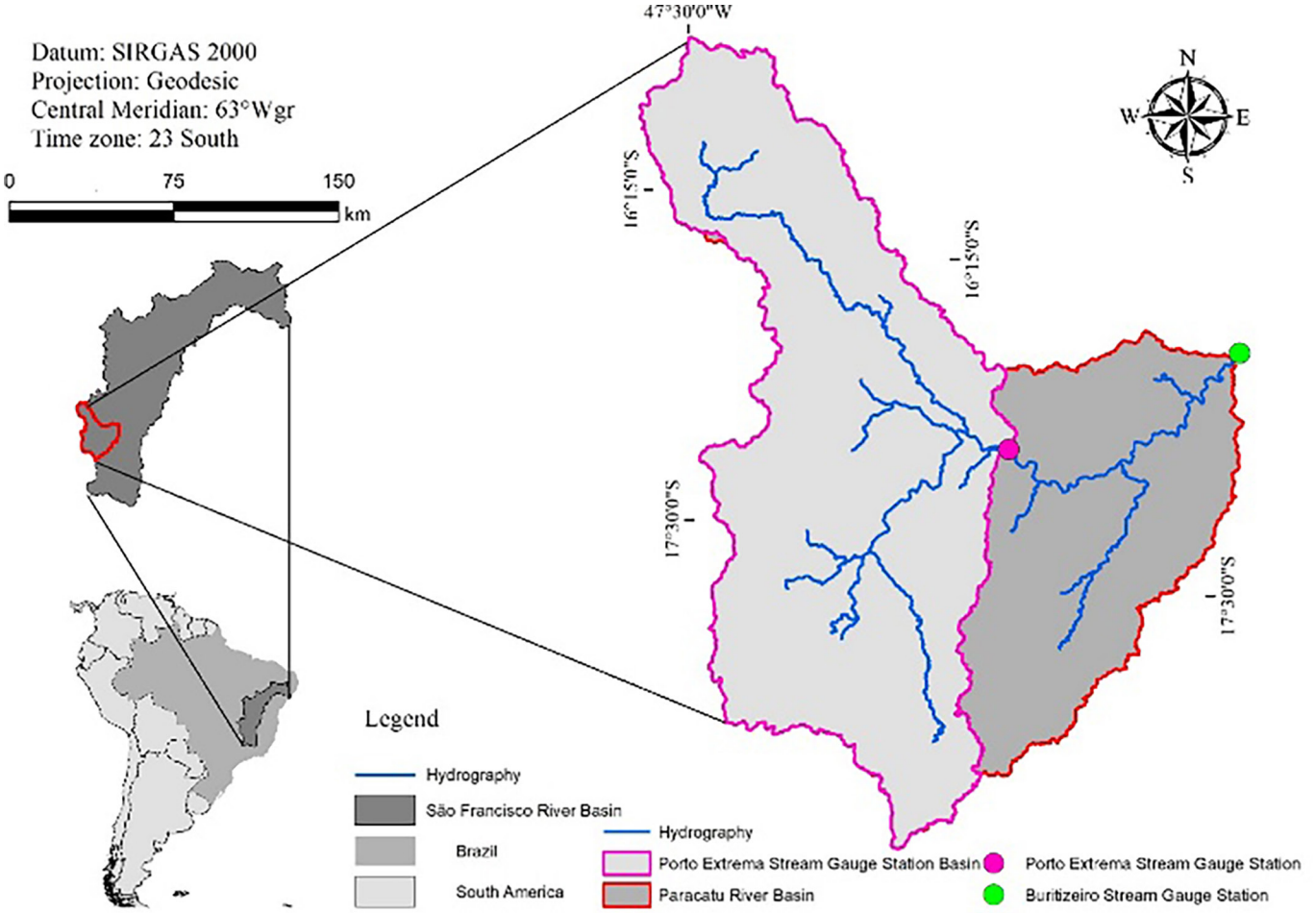


Figure 1. Paracatu River Basin in the context of Brazil and the São Francisco River Basin, highlighting the Porto Extrema stream gauge station

Table 1. Range of calibrated parameter values

Parameter	Range of Variation		Definition
	Minimum value	Maximum value	
GWQMN	0	5000	threshold depth of water in shallow aquifer for return flow (mm)
GW_REVAP	0.02	0.2	groundwater revap coefficient (dimensionless)
REVAPMN	0	500	threshold depth of water in shallow aquifer for revap (mm)
CN2	-0.2	0.2	SCS runoff curve number (dimensionless)
ESCO	0	1	soil evaporation compensation factor (dimensionless)
EPCO	0	1	plant uptake compensation factor (dimensionless)
SOL_K	0	2000	saturated hydraulic conductivity (mm h^{-1})
ALPHA_BF	0	1	baseflow alpha factor (day)

Next, five precipitation datasets from satellite and reanalysis models were evaluated: European Centre for Medium-Range Weather Forecasts, fifth generation reanalysis (ERA5), Global Precipitation Climatology Centre, version 7.0 (GPCC 7.0), Climate Hazards Group InfraRed Precipitation with Station data, version 2.0 (CHIRPS v2.0), Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks – Climate Data Record (PERSIANN-CDR), and Multi-Source Weighted-Ensemble Precipitation (MSWEP).

These products, obtained from international databases and made available through Google Earth Engine, were used as input variables in SWAT to simulate monthly streamflow in the study area. The analysis included comparison of the simulated series with the observed ones, using established statistical metrics such as the coefficient of determination (R^2), the Nash-Sutcliffe Efficiency index (NSE), and the percent bias (PBIAS). These indicators allowed classifying model performance into quality categories (very good, good, satisfactory, or unsatisfactory), according to guidelines established in the literature.

Finally, the Mann-Whitney statistical test was applied to verify the equivalence between the distributions of simulated and observed streamflows. This test provides evidence on the reliability of precipitation products in reproducing real hydrological conditions, especially regarding minimum flows, and is used as reference in water use rights, such as quartile 95 (Q95).

The analysis consisted of evaluating the products ECMWF Reanalysis 5th Generation (ERA5), Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks – Climate Data Record (PERSIANN-CDR), Multi-Source Weighted-Ensemble Precipitation (MSWEP), Global Precipitation Climatology Centre – Version 7.0 (GPCC 7.0) and Climate Hazards Group InfraRed Precipitation with Station data – Version 2.0 (CHIRPS v2.0) for the period from 1988 to 2018 (30 years of data). These datasets, presented in Table 2, were acquired from the Google Earth Engine (GEE) database (Rincón-Avalos et al., 2022; Google Earth Engine, 2024).

Water availability at the Porto Extrema stream gauge station (PESGS) was simulated using the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998). The database required for hydrological simulation with the SWAT model consists of tabular and spatial data. The spatial data consist of maps of soil types, hydrographically conditioned digital elevation model, and land use and cover. The tabular data constitute the database with quantitative information on climate, vegetation, soils, aquifers, streamflow, management, etc.

Figure 2 presents maps of the PESGS drainage area, highlighting the rain gauge, stream gauge and climatological stations, pedology, relief, and land use.

Twenty-three rain gauge stations were identified in the National Water Agency (ANA) database (ANA, 2021). After analyzing the consistency of these data, which consisted of eliminating the stations with more than 10% of failures, four stations with historical series of precipitation from 1988 to 2018 were selected, Table 3.

For the observed streamflow, data from the Porto Extrema stream gauge station were used. A pre-treatment of the data was carried out, discarding, in the determination of annual total series, the years that showed failures greater than 10%, in order to avoid obtaining non-representative annual data (Amorim et al., 2020; Junqueira et al., 2022).

In addition to observed streamflow and precipitation data, daily records of maximum and minimum air temperature, relative humidity, wind speed, and solar radiation were used, obtained from four climatological stations for the period from 1988 to 2018 (30 years of data), as listed in Table 2. The data were acquired from the Meteorological Database for Teaching and Research (BDMET), a platform of the National Institute of Meteorology (INMET), which provides free access to historical series of daily and hourly meteorological data from conventional and automatic stations in Brazil (BDMEP, 2018).

The Hydrologically Conditioned Digital Elevation Model (HCDEM) was developed from NASADEM data (NASA, 2020). The soil map was obtained through GEOINFO (Embrapa's Spatial Data Infrastructure), in the vector shapefile format, with an exploratory scale of 1:5,000 (EMBRAPA, 2021).

The land use and occupation map, for the year 2018, with a resolution of 30 m, in geotiff format, was acquired from the Annual Map of Land Use and Land Cover in Brazil (MapBiomas) Project (MAPBIOMAS, 2018; Souza Jr. et al., 2020).

To evaluate the precipitation products, the following statistics were used: percent bias (PBIAS, Eq. 1), coefficient of determination (R^2, Eq. 2), and Nash–Sutcliffe Efficiency Index (NSE, Eq. 3) (Nash & Sutcliffe, 1970).

$$\text{PBIAS} = \left[\frac{\sum_{i=1}^{N}(\text{Obs,t} - \text{Sim,t})}{\sum_{i=1}^{N}(\text{Obs,t})}\right] \quad (1)$$

Where:

Table 2. Satellite precipitation models and reanalysis

ID	Satellite precipitation models and reanalysis	Resolution	Period	Source
1	ERA5	25 km	1983 to 2018	https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form
2	PERSIANN-CDR	27 km	1983 to 2018	https://chrsdata.eng.uci.edu/
3	MSWEP	11 km	1983 to 2018	https://www.gloh2o.org/MSWEP/
4	GPCC 7.0	111 km	1983 to 2018	https://opendata.dwd.de/climate_environment/GPCC/html/download_gate.html
5	CHIRPS v2.0	5.6 km	1983 to 2018	https://data.chc.ucsb.edu/products/CHIRPS-2.0/africa_daily/tifs/p05/

$O_{bs,t}$ - observed value at time t;
$S_{im,t}$ - simulated value at time t; and,
N - number of observations.

$$R^2 = \left(\frac{\sum_{i=1}^{n}(Obs_{,t} - \overline{Obs_{,t}})\,(Sim_{,t} - \overline{Sim_{,t}})}{\sqrt{\sum_{i}^{n}(Obs_{,t} - \overline{Obs_{,t}})^2}\sqrt{\sum_{i}^{n}(Sim_{,t} - \overline{Sim_{,t}})^2}}\right)^2 \quad (2)$$

Where:
$O_{bs,t}$ - observed value at time *t*;
$S_{im,t}$ - simulated or predicted value at time *t*;
$\overline{Obs_{,t}}$ - average of observed values;
$\overline{Sim_{,t}}$ - average of simulated values; and,
N - number of observations.

$$NSE = 1 - \frac{\sum_{i=1}^{N}(Q_{obs,t} - Q_{sim,t})^2}{\sum_{i=1}^{N}\left(Q_{obs,t} - Qmean_{obs}\right)^2} \quad (3)$$

Where:
Q_{obst} - observed value at time i;
$Q_{sim,t}$ - value simulated by the model at time i;
$Qmean_{obs}$ - average of observed values, and,
N - total number of observations.

The hydrological model simulated in SWAT was calibrated and validated for the Porto Extrema streamflow gauging station (code 42690001). The complete simulation

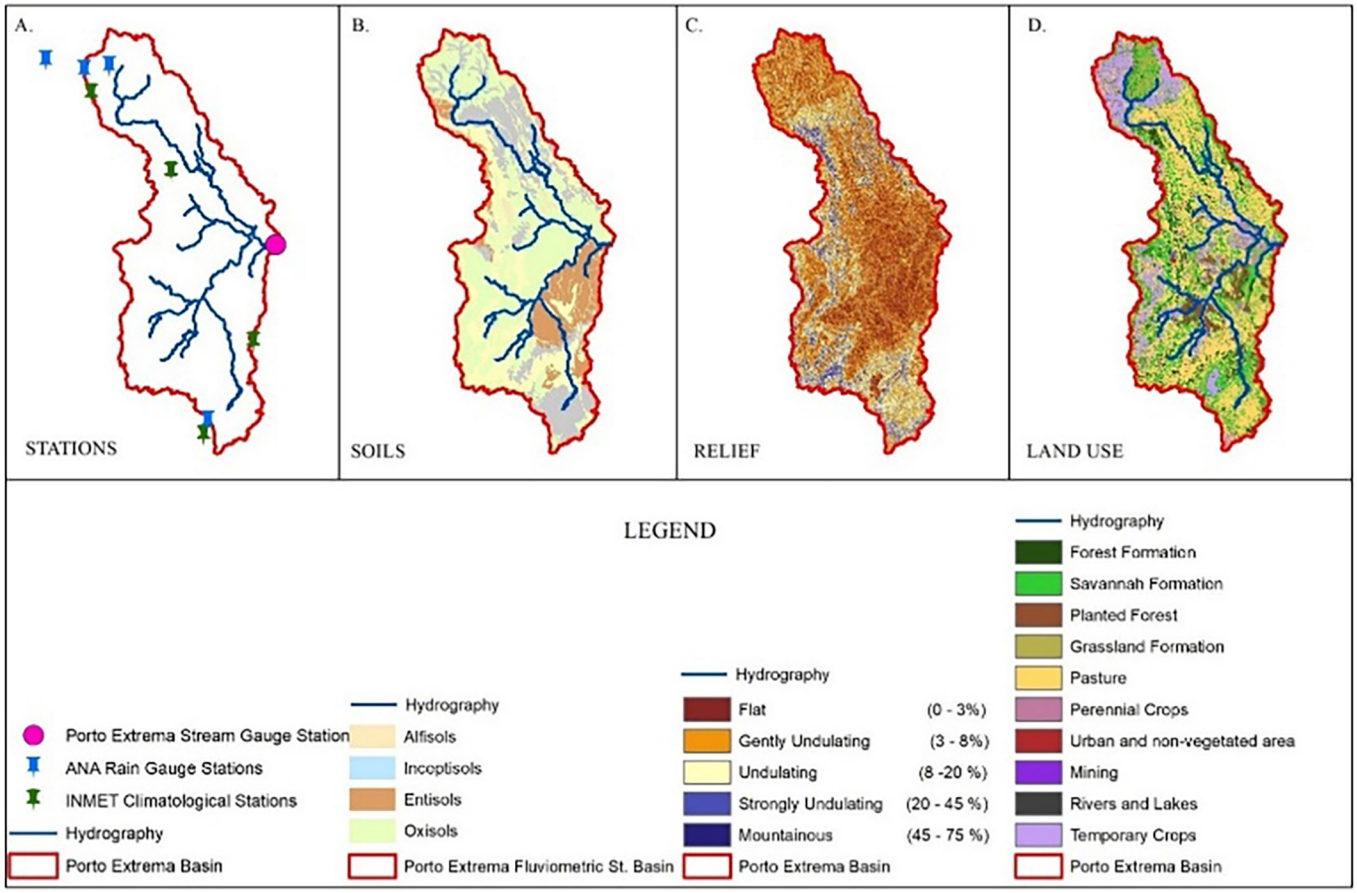


Figure 2. Map of the drainage area of the Porto Extrema stream gauge station, highlighting the rain gauge, stream gauge and climatological stations (A), pedology (B), relief (C) and land use (D)

Table 3. Rain gauge and climatological stations

Rain gauge station*	Name	Latitude	Longitude	Altitude
1547005	Brasília (Núcleo Bandeirante)	-15.78	-47.93	620
1547021	Barreiro DR-130	-15.84	-47.63	994
1547022	Rio Preto	-15.79	-47.43	928
1846005	Presidente Olegário	-18.41	-46.42	941
Climatological Station**	**Name**	**Latitude**	**Longitude**	**Altitude**
A047	Paranoá (COOPA-DF)	-16.01	-47.56	1043
A542	Unaí	-16.55	-46.88	641
A553	João Pinheiro	-17.78	-46.12	877
A562	Patos de Minas	-18.52	-46.44	950

*(https://www.snirh.gov.br/hidroweb/serieshistoricas), **(https://bdmep.inmet.gov.br/#)

period spanned from January 1983 to December 2018 (36 years). The first five years (1983–1987) were used as a model warm-up period to minimize the influence of initial conditions on the simulation results. It is important to note that the warm-up period was not included in the statistical analyses, as its purpose is solely to stabilize the model state variables.

Following the warm-up, the period from January 1988 to December 2018 (30 years) was used for model evaluation. This period was divided into calibration and validation phases. Calibration was performed from January 1988 to December 2008 (20 years), corresponding to approximately 67% of the observed discharge data, while validation was conducted from January 2009 to December 2018 (10 years), representing the remaining 33%.

This partitioning was adopted to ensure a sufficiently long calibration period to adequately constrain model parameters, while preserving an independent dataset for validation, following common practices in hydrological modeling studies.

To evaluate the performance of the simulated streamflow, the metrics PBIAS (Eq. 1), R^2 (Eq. 2), and NSE (Eq. 3) were applied, the same metrics used to assess the performance of simulated precipitation against observed precipitation.

Table 4 presents the values of the statistical limits considered as a guideline for interpreting the performance of the satellite precipitation data (Moriasi et al., 2007; Mararakanye et al., 2020).

The Mann-Whitney statistical test (Eq. 4) was applied to compare observed streamflows with those simulated from satellite precipitation models and reanalysis (CHIRPS v2.0, ERA5, GPCC 7.0, MSWEP, PERSIANN-CDR). This test compares the ranks of the observed and simulated streamflow series to assess whether their distributions differ significantly, generating two indicators: the statistic value (w), which represents the magnitude of the discrepancy, and the p-value, which quantifies the statistical significance of this difference.

$$U = n_1 \times n_2 + \frac{n_1(n_1+1)x^2}{2} - R_1 \quad (4)$$

Where:

n_1 and n_2 - are the sample sizes; and,

R_1 and R_2 - are the sums of ranks for each sample.

The results were presented in different stages of analysis. First, the annual precipitation estimated by satellite and reanalysis models were compared with the observed data from rain gauge stations. Reference evapotranspiration was estimated by the Penman-Monteith method (Monteith, 1965), using daily data on maximum and minimum air temperature, relative humidity, wind speed and solar radiation, referring to four climatological stations.

Next, simulated streamflows were compared with observed values, highlighting seasonal differences between dry and wet periods. Subsequently, scatter plots were analyzed to identify which precipitation products tend to overestimate or underestimate streamflows, thereby revealing their limitations in hydrological representation.

Finally, the flow duration curve was presented to assess which models most closely matched the observed streamflows and to discuss the relevance of the Q95 reference flow as a fundamental criterion for water rights allocation and water resource management planning.

Statistical metrics were calculated and the graphs were prepared using the integrated development environment (IDE) for the R programming language, known as RStudio (R Core Team, 2025). No bias correction or complex resampling procedures were applied; this study opted to use the precipitation products in their original form (raw data), as provided by the processing centers. This methodological choice is based on the objective of evaluating the intrinsic performance of each dataset and its direct applicability in hydrological modeling using SWAT.

Results and Discussion

Figure 3 shows the distribution of the total annual precipitation estimated by the satellite precipitation models and reanalysis for the PESGS in the form of a boxplot. By analyzing Figure 3, it is possible to observe that the annual rainfall data obtained from the various products were similar, except for the PERSIANN-CDR product, which showed greater variability.

When analyzing Figure 3, it is observed that the satellite precipitation models and reanalysis do not show large discrepancies in rainfall estimates for the PESGS region. This is relevant because rainfall has high spatial variability, and depending on the recording capacity of each sensor, the models could generate highly divergent estimates. In such cases, it would not be appropriate to validate models that show excessive discrepancies in precipitation estimates.

The CHIRPS v2.0 and ERA5 products showed results close to the average annual rainfall, with values of 1,337.6 and 1,334.9 mm, respectively (Figure 3). Both showed moderate amplitude, with lower limits of 862.8 and 899.7 mm, while reaching upper limits of 1,966.2 and 2,014.9 mm, respectively.

The average annual rainfall of MSWEP was 1,378.1 mm, with a minimum value of 859.9 mm and a maximum value of 1,893.3 mm, the lowest value compared to other products.

Table 4. Values of statistical limits for model performance interpretation

Performance statistics	R^2	NSE	PBIAS
Very good	> 0.7-1.0	> 0.75-1.0	< ± 10
Good	> 0.6-0.7	> 0.65-0.75	± 10 ± 15
Satisfactory	> 0.5-0.6	> 0.50-0.65	± 15 ± 25
Unsatisfactory	≤ 0.5	≤ 0.50	≥ ± 25

GPCC 7.0 had an average annual rainfall of 1,350.6 mm, about 0.21% lower than PERSIANN-CDR. The GPCC 7.0 product stood out with the highest lower limit of 916.8 mm when compared to PERSIANN-CDR, MSWEP, ERA5, and CHIRPS v.2.0 products. The upper limit of GPCC 7.0 was 1,967.8 mm, with a difference of 0.08% for the CHIRPS v2.0 product. On the other hand, the PERSIANN-CDR product had the largest range of values among the products analyzed, with an average annual rainfall of 1,353.4 mm, but with a minimum value of 578.4 mm and a maximum of 2,040.3 mm.

Figures 4 and 5 show the simulated monthly streamflow for the five precipitation products.

It can be observed that the PERSIANN-CDR product (Figure 5B) was classified as satisfactory in the calibration period with Nash–Sutcliffe Efficiency (NSE) of 0.6138. CHIRPS v.2.0 (Figure 4A) and ERA5 (Figure 4B) products were classified as good, with NSE values of 0.6952 and 0.7250, respectively. GPCC 7.0 product (Figure 4C) was classified as very good, with NSE of 0.7553. MSWEP product (Figure 5A), on the other hand, was considered unsatisfactory, with an NSE value of 0.3527.

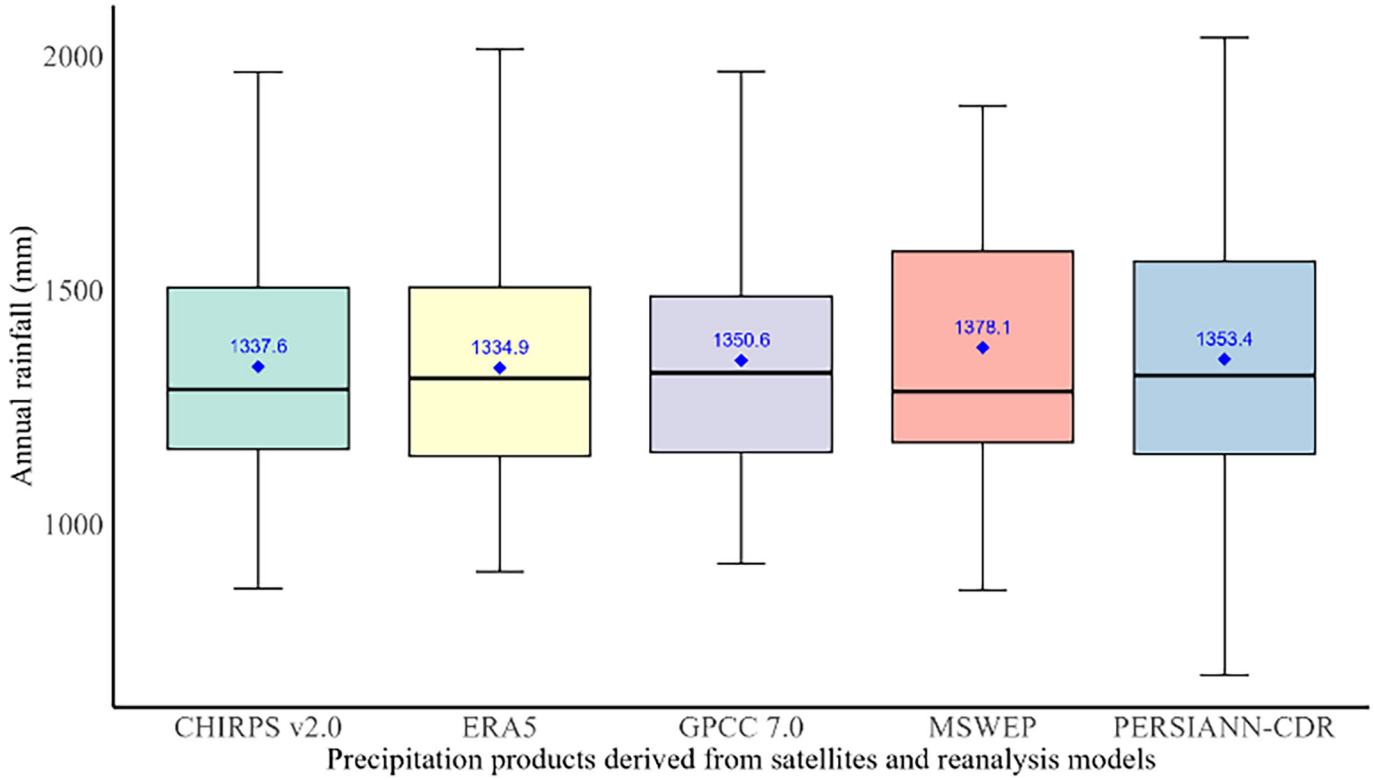
During the validation period, all models, with the exception of the CHIRPS v.2.0 product, showed superior performance compared to the calibration period. GPCC 7.0 was classified as very good, with an NSE value of 0.8049. CHIRPS v.2.0, ERA5, and PERSIANN-CDR products were classified as good, with NSE values of 0.6180, 0.7496, and 0.7113, respectively. MSWEP, however, reached an NSE value of 0.0507, being classified as unsatisfactory.

Considering the Percent Bias (PBIAS) values, in calibration, all precipitation products (Figures 4 and 5) were classified as very good according to Moriasi et al. (2007) and Mararakanye et al. (2020). CHIRPS v.2.0 (Figure 4A), ERA5 (Figure 4B), and MSWEP (Figure 5A) products showed PBIAS of -4.4, -7.0, and -2.5, respectively, underestimating the streamflow. GPCC 7.0 (Figures 4C) and PERSIANN-CDR (Figure 5B) products overestimated the streamflow, with PBIAS values of 3.2 and 9.9, respectively. In validation, MSWEP was classified as good (PBIAS of 11.3), while CHIRPS v.2.0, ERA5, GPCC 7.0, and PERSIANN-CDR were classified as very good, with PBIAS values of 3.1, 0.1, 2.4, and -9.4, respectively. The PERSIANN-CDR product underestimated the modeled streamflow, while the other products overestimated it.

Among the five precipitation products analyzed, GPCC 7.0 was the one that had the highest accuracy to estimate water availability in the PESGS, standing out for its robustness in capturing hydrological trends, low dispersion and high correlation with observed data, being an ideal choice for studies of management and planning of water resources in the region.

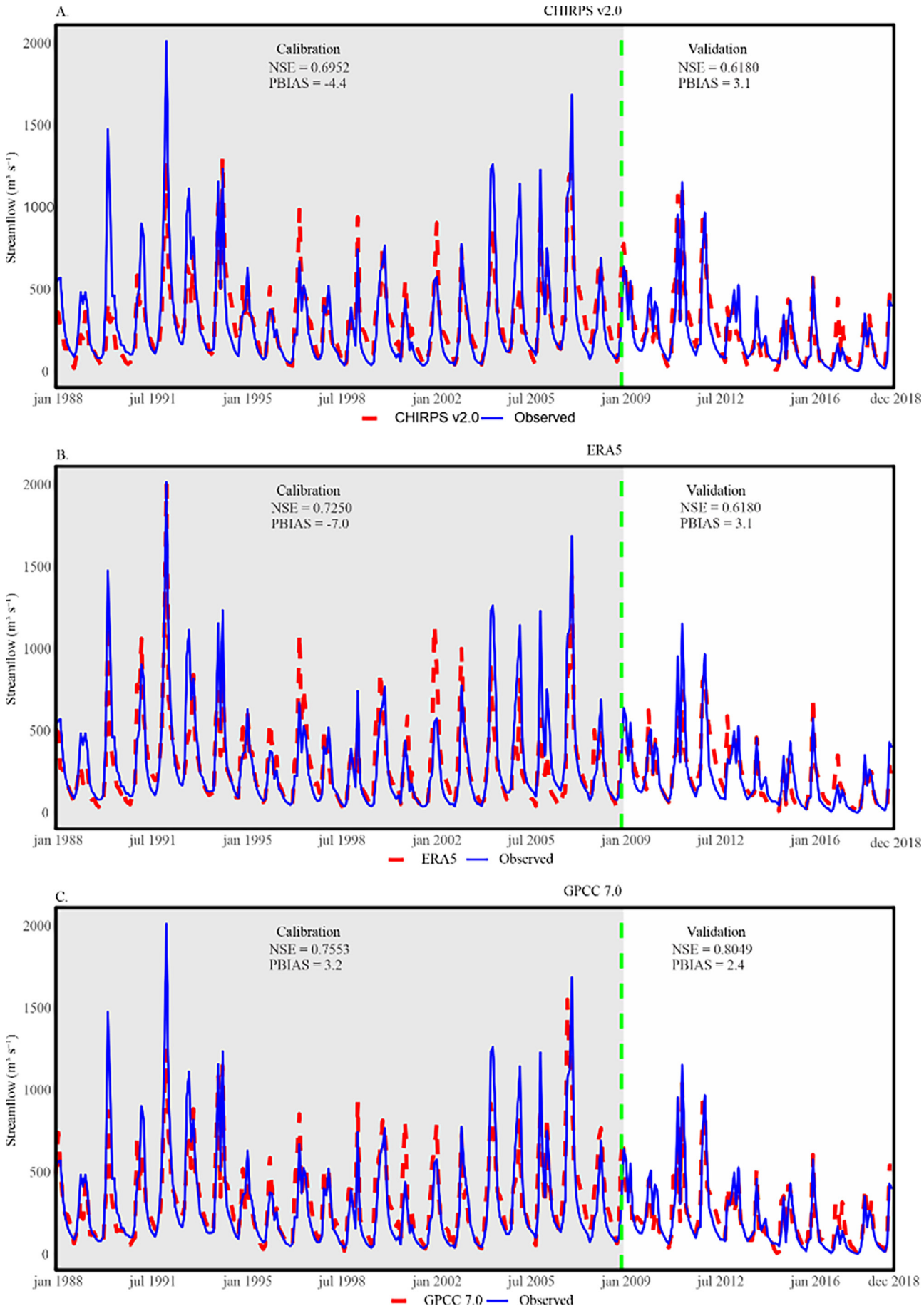
Studies conducted by Hajihosseini et al. (2016) and Gunathilake et al. (2021) corroborate these results, confirming the effectiveness of GPCC 7.0 as an input precipitation product in the SWAT model.

The second best performing product was ERA5. This result corroborates the study conducted by Monteiro et al. (2016), who tested several products in the Usina do Pandeiros - Montante basin, in the Cerrado biome, and found ERA5 as



Rhombus in blue indicates the average annual precipitation. Box: Represents the range between the first quartile (Q1, 25%) and the third quartile (Q3, 75%) of the data. Line inside the box: Indicates the median (Q2, 50%), that is, the central value of the distribution. Whiskers: Represent the minimum and maximum values within a range considered "normal" (usually up to 1.5 times the interquartile range – IQR). Diamond or blue point: Indicates the mean of the annual precipitation*

Figure 3. Boxplot graph of the simulated total annual rainfall of the PESGS precipitation products



NSE (Nash–Sutcliffe Efficiency): measures the efficiency of the model in reproducing observed data. PBIAS (Percent Bias): indicates whether the model tends to overestimate or underestimate simulated values compared to observed ones*

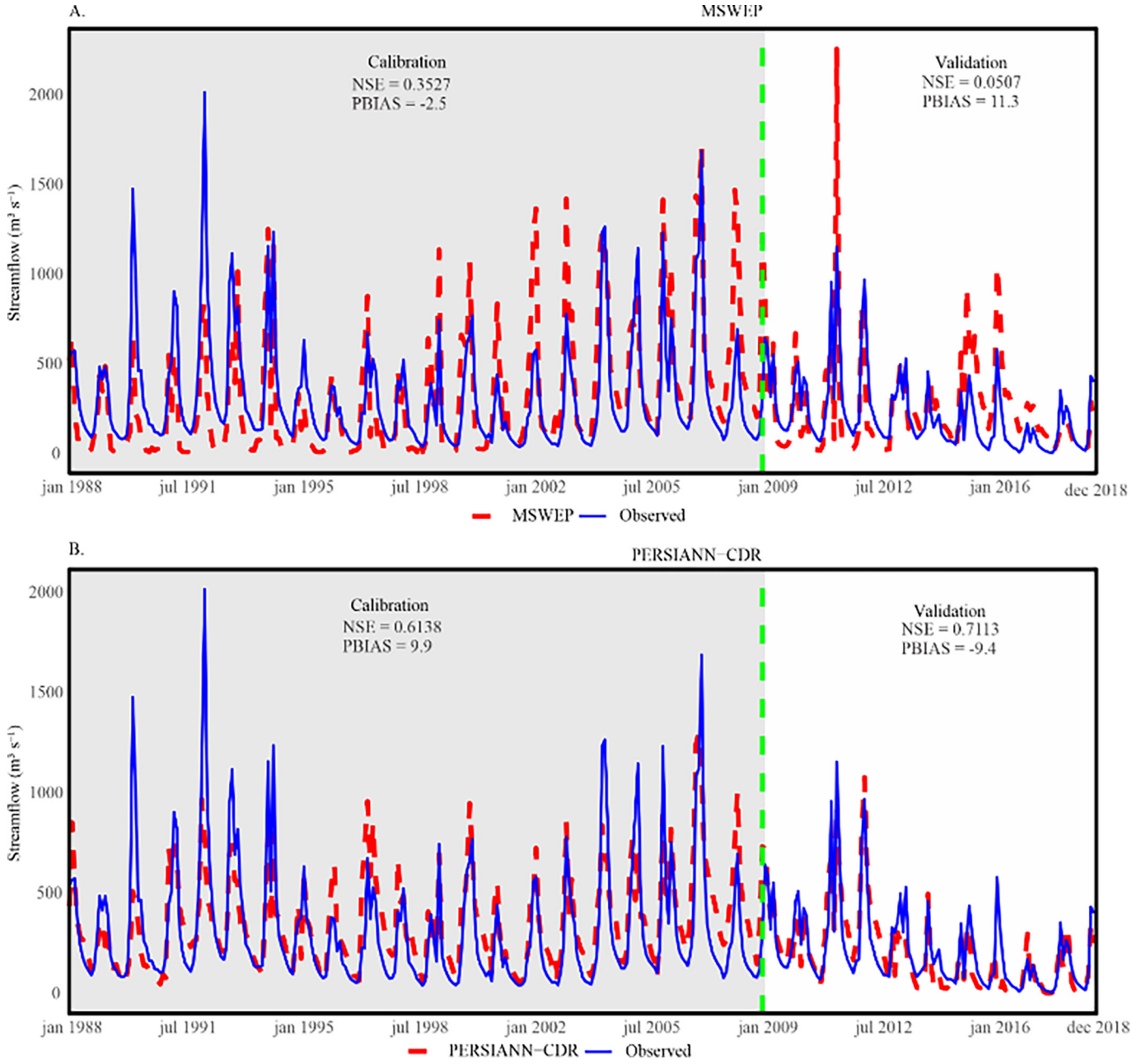
Figure 4. Observed and simulated streamflows of CHIRPS v.2.0 (A), ERA 5 (B), and GPCC 7.0 (C) products for the years 1988 to 2018

the only one with satisfactory results. Jahanshahi et al. (2024) also concluded that ERA5 performed best in hydrological modeling with SWAT in semi-arid regions of Iran, where there is a scarcity of observed rainfall data.

In this study, CHIRPS v.2.0 ranked third among the five datasets evaluated, showing a good performance, with NSE of 0.6952 in calibration and 0.6180 in validation. According to Dhanesh et al. (2020) and Du et al. (2024), CHIRPS v.2.0 is not always the best product, but it is an adequate product for capturing the dynamics of monthly precipitation.

PERSIANN-CDR ranked fourth in performance among the products evaluated, with good performance. Jimeno-Sáez et al. (2021) concluded that PERSIANN-CDR was the most suitable and stable product to simulate streamflow in the Grande de San Miguel River Basin in El Salvador. Tan et al. (2021) conducted a literature review and found that PERSIANN-CDR, along with APHRODITE, CHIRPS v.2.0 and CMADS, are the most used products and were applied in 10 to 18% of the publications investigated.

MSWEP showed an unsatisfactory performance in calibration and satisfactory performance in validation, with the worst statistical indices among the five products evaluated. Jimeno-Sáez et al. (2021) analyzed five precipitation products and found that PERSIAN and CHIRPS v.2.0 performed better than MSWEP. Swalih & Kahya (2022) and Aryal et al. (2023) also found that MSWEP was not effective in simulating maximum streamflows. MSWEP uses different algorithms and data sources, and its performance varies depending on the region, period, and specific weather conditions (Abbas et al., 2024).



NSE (Nash–Sutcliffe Efficiency): measures the efficiency of the model in reproducing observed data. PBIAS (Percent Bias): indicates whether the model tends to overestimate or underestimate simulated values compared to observed ones*

Figure 5. Observed and simulated streamflow of MSWEP (A) and PERSIANN-CDR (B) products for the years 1988 to 2018

Figure 6 shows the simulated monthly streamflows using different satellite precipitation models and reanalysis and the observed streamflow. In general, it is observed that the streamflows simulated with the different products show similar behavior, although they have different magnitudes.

The product GPCC 7.0 had the largest differences compared to the observed streamflow in the months of June (36.4%), July (43.4%), and August (28.4%). However, these differences decreased in September (13.8%) and October (15.1%), indicating a greater adherence to the conditions observed at the end of the dry period.

Simulations based on CHIRPS v.2.0 revealed differences above the observed values, in June (41.9%), July (45.3%), and August (26.4%). However, in September (7.43%) and October (13.5%), the product showed a performance closer to the observed reality, highlighting a reduction in these differences within this interval.

ERA5 stood out for showing moderate differences in the initial dry months, with values of 40.8, 46.8, and 31.2% in June, July, and August, respectively. In the months of September (12.8%) and October (7.6%), the differences were further reduced, which may indicate a more consistent performance of this product in the transition to the rainy season.

The streamflow estimates with MSWEP were the ones that came closest to the streamflows observed in the dry season, with percentage differences of 16.9, 11.6, 7.75, 3.59, and 4.00% in June, July, August, September, and October, respectively.

On the other hand, the estimates with PERSIANN-CDR were the ones that had the greatest differences in comparison to the observed streamflows, with differences of 51.9, 61.3, 50.0, 39.6, and 35.9% June, July, August, September, and October, respectively.

Figure 7 presents five scatter plots of the simulated monthly streamflow for the five satellite precipitation models and reanalysis, comparing with the observed streamflow data.

With a coefficient of determination (R^2) of 0.73, CHIRPS v.2.0 (Figure 7A) performed well, especially for values lower than 1000 $m^3 s^{-1}$. Dhanesh et al. (2020) corroborate these results, highlighting the robustness of CHIRPS v.2.0 in integrating data from weather stations and satellites with a resolution of 5.6 km. Luo et al. (2019), when simulating the streamflow of the Lancang-Mekong River, also observed a good performance of CHIRPS v.2.0, highlighting its long time series as an advantage for long-term analyses.

Figure 7B presents the results of the simulations with the ERA5 product. Despite the less detailed spatial resolution (25 km), ERA5 stood out with the third best fit, behind GPCC 7.0 and CHIRPS v2.0. Studies conducted by Kolluru et al. (2020) and Jahanshahi et al. (2024) corroborate the effectiveness of ERA5 in different climatic contexts, showing its potential for hydrological analyses, especially in regions with limited observational data.

Figure 7C shows the results of the simulations with GPCC 7.0, which had a R^2 of 0.77. This model, despite the lowest spatial resolution (111 km), showed the best performance in the representation of the observed streamflows. These results demonstrate that GPCC 7.0 not only captures the overall trend of the data, but also minimizes systematic over- or

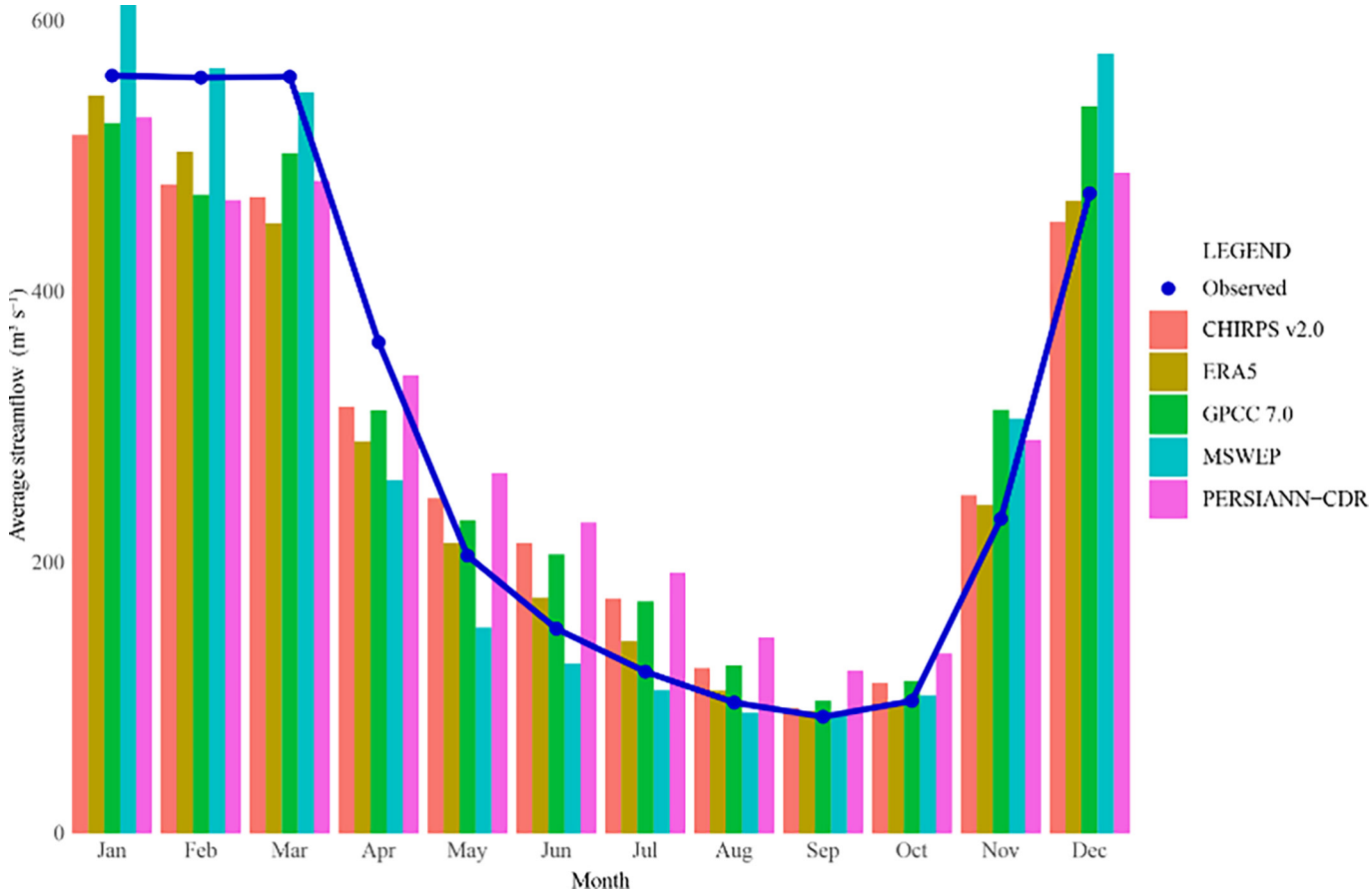


Figure 6. Monthly streamflow for the five satellite precipitation models and reanalysis at the Porto Extrema stream gauge station, identified by code 42690001

under-estimation errors, even under varying hydrological conditions. The robustness of this product becomes clear when observing the minimal dispersion of the points around the regression line, even for high streamflows above 1000 $m^3 s^{-1}$.

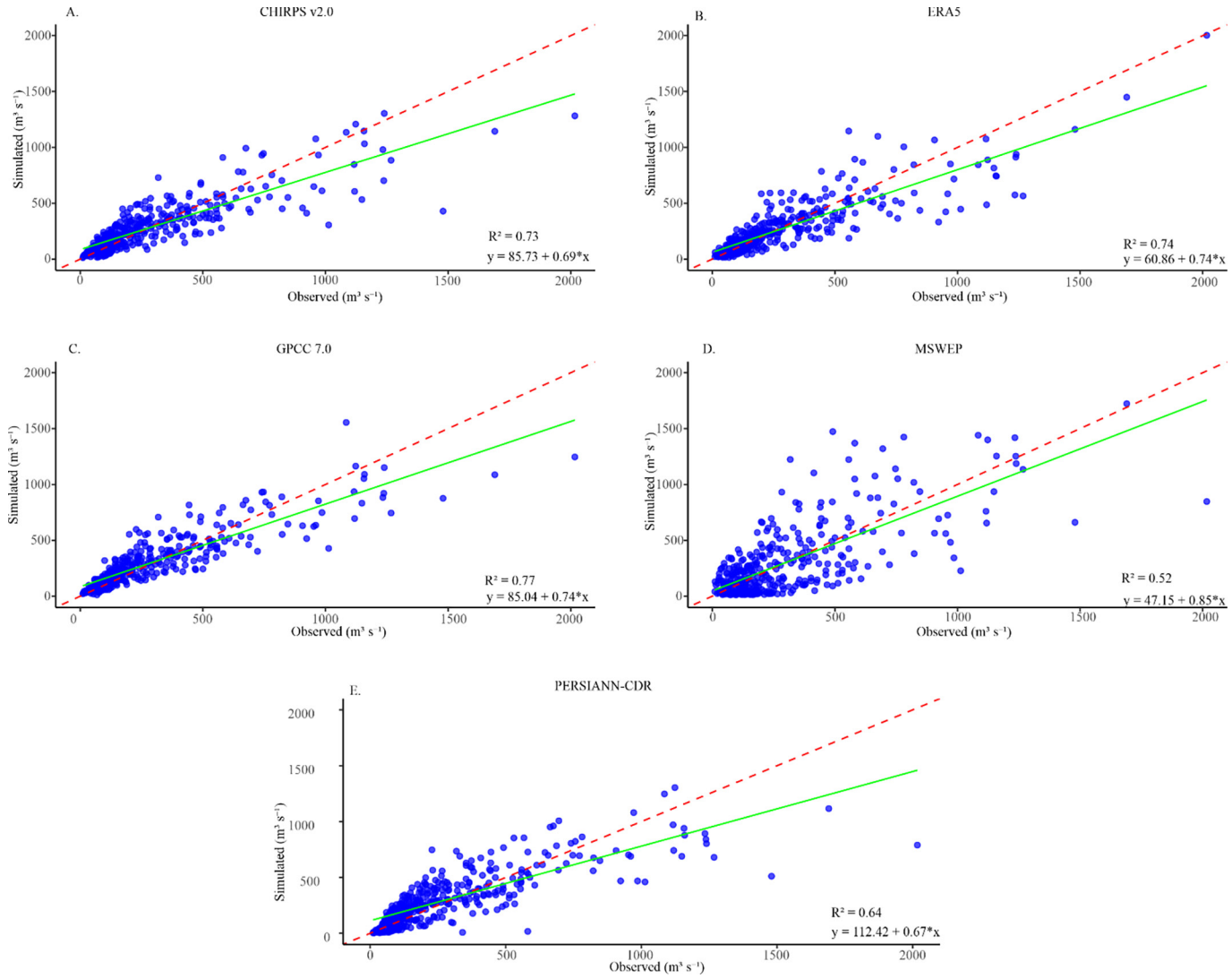
This is due to the global network of 126,000 calibrated rain gauge stations and robust data processing and fitting methods, as well as strict quality control. Fu et al. (2016) and Eini et al. (2021) corroborate these results, highlighting the effectiveness of GPCC 7.0 in hydrological modeling in different basins, such as the ten major river basins in China and the Dong Nai River Basin in Vietnam.

Figure 7D shows that MSWEP had the lowest R^2, equal to 0.52. Swalih & Kahya (2022) analyzed the performance of MSWEP with the CFSR, ERA5 and APHRODITE products, in Turkey, and observed problems of under- and overestimation, with R^2 of 0.61, the lowest value among the products analyzed. Beck et al. (2018) and Qi et al. (2024) highlighted that, despite the high resolution and large global coverage, this product has limitations in the accuracy and lack of quality control of its data.

PERSIANN-CDR, with a R^2 of 0.65 (Figure 7E), was the fourth product with the best performance among the products analyzed.

Eini et al. (2021), when studying the accuracy of the PERSIANN-CDR precipitation database (Figure 7E), obtained the same R^2 of 0.65 in the Lake Maharloo basin, Iran, highlighting difficulties in predicting maximum streamflows. Barezaei & Jalali (2023), when applying PERSIANN-CDR in the Chelgerd basin, Iran, obtained R^2 of 0.79, a value close to rain gauge data (R^2 of 0.82), indicating good accuracy. Sadeghi et al. (2021) highlighted that PERSIANN-CDR is a suitable product to simulate extreme events, but still with limitations in the representation of maximum streamflows.

For the purpose of analyzing water availability, the permanence curve is a valuable instrument, as it allows, among other things, visualizing the natural potential of the river, highlighting the minimum streamflow and the degree of permanence of any streamflow in time. Figure 8 shows the permanence curve obtained based on the five satellite precipitation models and reanalysis for the Porto Extrema stream gauge station, located in the Paracatu river basin.



Dashed line represents the 1:1 ratio and solid line represents the regression line*

Figure 7. Comparison between the monthly water availability at the Porto Extrema stream gauge station, simulated by the SWAT model, obtained with the five precipitation products and with the observed precipitation data

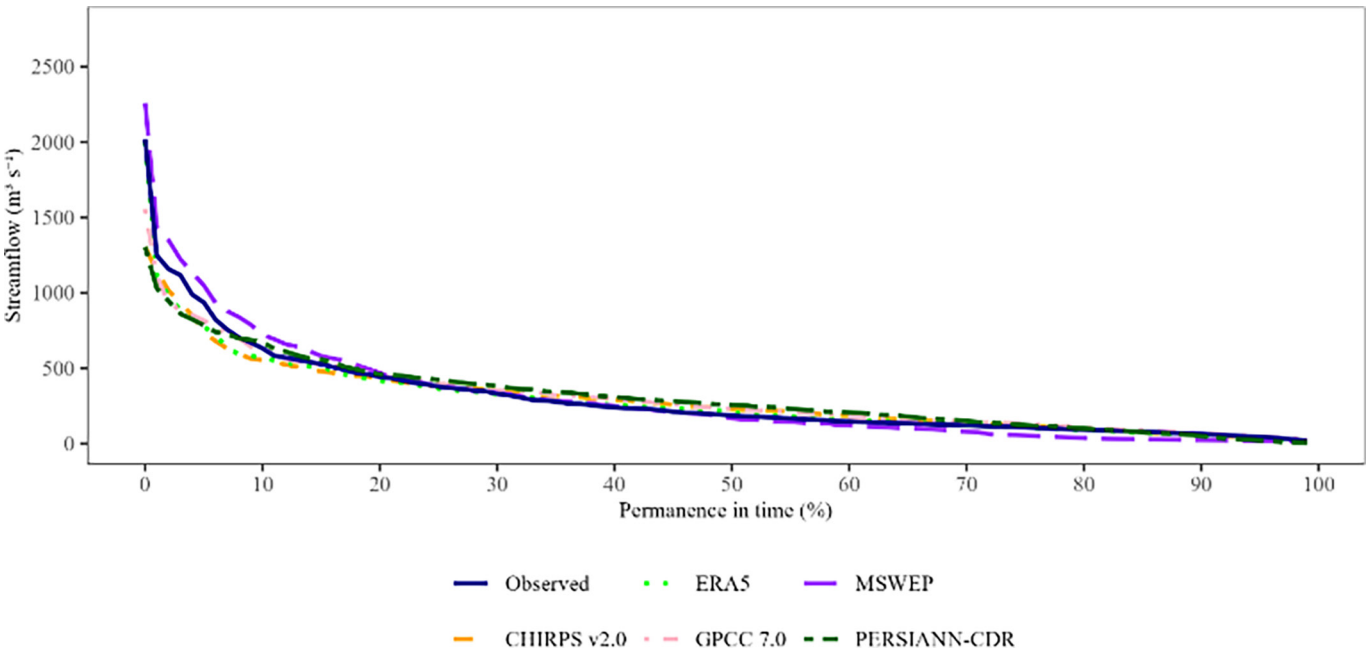


Figure 8. Simulated streamflow permanence curve based on the five satellite precipitation models and reanalysis, for the Porto Extrema stream gauge station, located in the Paracatu River basin

Estimates of minimum streamflows are essential in the management of water resources. Reference streamflows, such as Q95, are used as a criterion for granting water-use permits. The Mann-Whitney statistical test was performed to evaluate the accuracy of the streamflows simulated using the different satellite precipitation models and reanalysis (Table 5). This statistical test compares the observed streamflows with the simulated streamflows of the satellite precipitation models and reanalysis (CHIRPS v2.0, ERA5, GPCC 7.0, MSWEP, PERSIANN-CDR). This test evaluates the largest absolute difference between the accumulated distributions of the observed and simulated streamflow series, generating two indicators: the value of the statistic (w), which represents the magnitude of the discrepancy, and the (p-value), which quantifies the statistical significance of this difference.

Table 5 indicates that, for all satellite precipitation models and reanalysis evaluated, the p-value obtained were higher than 0.05. This result indicates that the streamflows simulated by the satellite precipitation models and reanalysis are statistically equivalent to the observed streamflows, that is, there was no statistical difference between the data. Thus, the differences between the accumulated distributions of the observed and simulated data are not relevant to compromise the equivalence between the series.

When analyzing the results in terms of absolute difference, it was observed that the GPCC 7.0 product, represented by the dashed pink line, showed the best performance. The simulated value of the reference streamflow Q95 was equal to 47.0 $m^3 s^{-1}$, which is 2% higher than the value calculated with the observed data. MSWEP showed the worst performance among the products analyzed, with a value equal to 18.9 $m^3 s^{-1}$, which is 26.2 $m^3 s^{-1}$ less than the value calculated with the observed data.

Table 5. Values of the Mann-Whitney statistical test

Database	W	p-value
Observed/CHIRPS v2.0	1339	0.5418
Observed/ERA5	1334	0.5649
Observed/GPCC 7.0	1379	0.3757
Observed/MSWEP	1158	0.5282
Observed/PERSIANN-CDR	1104	0.3158

Conclusions

1. The product from the Global Precipitation Climatology Centre version 7.0 (GPCC 7.0) showed the best overall performance in reproducing monthly streamflow at the Porto Extrema streamflow gauging station, considering the Nash-Sutcliffe efficiency, percent bias, and coefficient of determination. The fifth-generation atmospheric reanalysis from the European Centre for Medium-Range Weather Forecasts (ERA 5) and the Climate Hazards Group InfraRed Precipitation with Station data version 2.0 (CHIRPS v2.0) also showed adequate performance, while the Multi-Source Weighted-Ensemble Precipitation (MSWEP) product showed unsatisfactory performance in reproducing the monthly hydrograph.

2. During the dry season, the MSWEP product simulated streamflow estimates closer to the observed values between June and October. However, this better performance in low-flow months did not compensate for its weak overall performance in the calibration and validation periods.

3. The flow duration curve analysis showed that all precipitation products generated streamflow distributions statistically similar to the observed streamflow series according to the Mann-Whitney test. For the streamflow

equaled or exceeded ninety-five percent of the time, the GPCC 7.0 produced the closest estimate to the observed value, while the MSWEP product showed the largest discrepancy.

4. The results indicate that satellite and reanalysis precipitation products can support streamflow simulation and water resources planning in Cerrado basins with limited rainfall observations.

Contribution of authors: The authors have relevant contributions to the manuscript. Preparation of the material and data collection and processing were carried out by all authors, and Caio Henrique Patrício Pagani performed the analysis. The first version was written by Caio Henrique Patrício Pagani. Lineu Neiva Rodrigues contributed significantly to conducting the study. All authors have read and approved the final manuscript.

Data Availability Statement: The datasets supporting the results of this study are publicly available from the following sources: The original precipitation products were obtained from their respective public repositories: CHIRPS v2.0 (https://data.chc.ucsb.edu/products/CHIRPS-2.0/), ERA5 (https://cds.climate.copernicus.eu/), GPCC 7.0 (https://opendata.dwd.de/climate_environment/GPCC/), MSWEP (https://www.gloh2o.org/MSWEP/), and PERSIANN-CDR (https://chrsdata.eng.uci.edu/). Land-use data were obtained from MAPBIOMAS Collection 7 (https://mapbiomas.org/), soil properties from EMBRAPA (https://geoinfo.cnpm.embrapa.br/), DEM from NASADEM (https://lpdaac.usgs.gov/products/nasadem_hgtv001/), and meteorological data from INMET (https://bdmep.inmet.gov.br/).

Conflict of Interest: The authors declare that they have no conflicts of interest.

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