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Comparative analysis of rainfall data from remote sensing and surface stations in the Paracatu river basin, Brazilian Cerrado

Análisis comparativo de datos de precipitación de sensores remotos y estaciones de superficie en la cuenca del río Paracatu, Cerrado brasileño

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Abstract

Accurate precipitation estimation is essential for water resource management, especially in tropical regions where the spatial and temporal variability of rainfall presents significant challenges. In areas with limited terrestrial station coverage, satellite-based products such as the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) have become particularly valuable. This study compares CHIRPS data with surface station records in the Paracatu River Basin in the Brazilian Cerrado from 2010 to 2023, employing a "point-to-pixel" approach. Among the statistical analyses, we have used metrics commonly applied in precipitation studies, such as Pearson's correlation coefficient (CC), relative bias (BIAS), coefficient of determination (R^2), and root mean square error (RMSE). Monthly coefficients of determination (R^2) ranged from 0.77 to 0.89, reflecting CHIRPS' capability to capture rainfall patterns on this scale. However, its accuracy decreased when estimating total annual precipitation, highlighting some limitations. Despite these challenges, CHIRPS is a valuable tool for supplementing surface data on a monthly basis, although discrepancies are more pronounced during periods of intense rainfall and in annual aggregates. Future research should investigate the integration of additional remote sensing products and assess how changing climate conditions affect precipitation estimates.

Keywords: CHIRPS; performance assessment; water security; precipitation; environmental management; Brazil.

Resumen

La estimación precisa de la precipitación es esencial para la gestión de los recursos hídricos, especialmente en regiones tropicales donde la variabilidad espacial y temporal de las lluvias presenta desafíos significativos. En áreas con cobertura limitada de estaciones terrestres, los productos satelitales, como el Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), se han vuelto particularmente valiosos. Este estudio evaluó los datos de CHIRPS en comparación con los registros de estaciones de superficie en la cuenca del río Paracatu, en el Cerrado brasileño, durante el período de 2010 a 2023, empleando un enfoque de "punto a píxel". Entre los análisis estadísticos, utilizamos métricas comúnmente aplicadas en estudios de precipitación, como el coeficiente de correlación de Pearson (CC), el sesgo relativo (BIAS), el

coeficiente de determinación (R^2) y la raíz del error cuadrático medio (RMSE). Los coeficientes de determinación mensuales (R^2) variaron entre 0.77 y 0.89, lo que refleja la capacidad de CHIRPS para captar los patrones de precipitación en esta escala. Sin embargo, su precisión disminuyó al estimar la precipitación anual total, lo que pone en evidencia algunas limitaciones. A pesar de estos desafíos, CHIRPS sigue siendo una herramienta valiosa para complementar los datos de superficie a escala mensual, aunque las discrepancias son más pronunciadas durante los períodos de lluvias intensas y en los acumulados anuales. Investigaciones futuras deberían explorar la integración de productos adicionales de teledetección y evaluar cómo las condiciones climáticas cambiantes afectan las estimaciones de precipitación.

Palabras chave: CHIRPS; evaluación de desempeño; seguridad hídrica; precipitación; gestión ambiental; Brasil.

1. Introduction

In recent years, global warming has triggered a series of drastic transformations in global climate patterns, particularly the intensification of sudden droughts, whose impacts are becoming increasingly severe and widespread (Christian et al., 2023; Zeng et al., 2023). These extreme events affect the environment and pressure essential human activities such as agriculture and water management (Estrela-Segrelles et al., 2024).

The primary methods for acquiring precipitation data include measurements from terrestrial weather stations and meteorological radar observations, which are fundamental for research in agriculture and hydrology (Gu et al., 2024). In Brazil, the primary sources of climatological data, particularly precipitation-related, are federal institutions such as the National Institute of Meteorology (INMET) and the National Water Agency (ANA). While essential, these data present limitations, including errors, gaps in time series, and discontinuities, compromising their reliability (Júnior et al., 2023; Tórnio et al., 2024). Additionally, precipitation data obtained from ground stations are point-based and do not represent the entire surface, meaning that the distribution of the stations influences the precision of regional precipitation monitoring (Gu et al., 2024; Paredes-Trejo et al., 2021).

Given these limitations, advances in remote sensing technology have driven the development of satellite-based precipitation products at various scales (Zhu & Liang, 2024; Saldanha et al., 2015). These products have been widely used in various scientific fields such as meteorology, hydrometeorology, climatology, and water resource management (Boluwade, 2024; Wiwoho et al., 2021). However, despite their potential to provide comprehensive precipitation data coverage, satellite-based estimates exhibit a degree of error (Nadeem et al., 2022; Ye et al., 2022). Studies on error evaluation in these data indicate that inaccuracies may vary across regions. Geographic characteristics such as elevation, longitude, and latitude are among the main factors contributing to these inconsistencies (Nadeem et al., 2022; Yang & Luo, 2014). Therefore, it is essential to validate these data before using them in agricultural studies, enabling the estimation of water deficits, the detection of changes in crop cycles, and the support of management practices.

A promising tool to overcome these limitations is comparative analyses between remote sensing data and in situ observations. This approach allows for the calibration and validation of estimates, increasing their reliability (Zhang et al., 2018).

Among the precipitation products derived from remote sensing, the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) stands out, providing near-global precipitation estimates based on in situ observations and satellite data. Developed by scientists from the United States Geological Survey (USGS) and the Climate Hazards Center (CHC), CHIRPS offers data at three different temporal resolutions: daily, pentadal, and monthly (Funk et al., 2014). One of the advantages of CHIRPS is its relatively better performance in detecting precipitation with less bias during the dry season (Datti et al., 2024), making it widely used in precipitation studies (Ferreira et al., 2025; Alsumaiti et al., 2024). Studies such as that by Paredes-Trejo et al. (2017) compared monthly precipitation estimates from CHIRPS with rain gauge data in northeastern Brazil. The study by Hsu et al. (2021) evaluated the performance of CHIRPS in representing precipitation variation at various temporal scales in Taiwan. In addition, the study by Han et al. (2023) in the Upper Colorado River Basin where investigated the effects of topographic conditions on the quality of precipitation estimates provided by CHIRPS.

This study evaluates the relationship between CHIRPS precipitation estimates and surface station data in the Paracatu River Basin from 2010 to 2023. Studying precipitation in this region is particularly relevant due to its direct dependence on rainfall for sustaining agricultural activities and the local ecosystem. Furthermore, as a strategic biome, the Cerrado plays a crucial role in the country's water recharge.

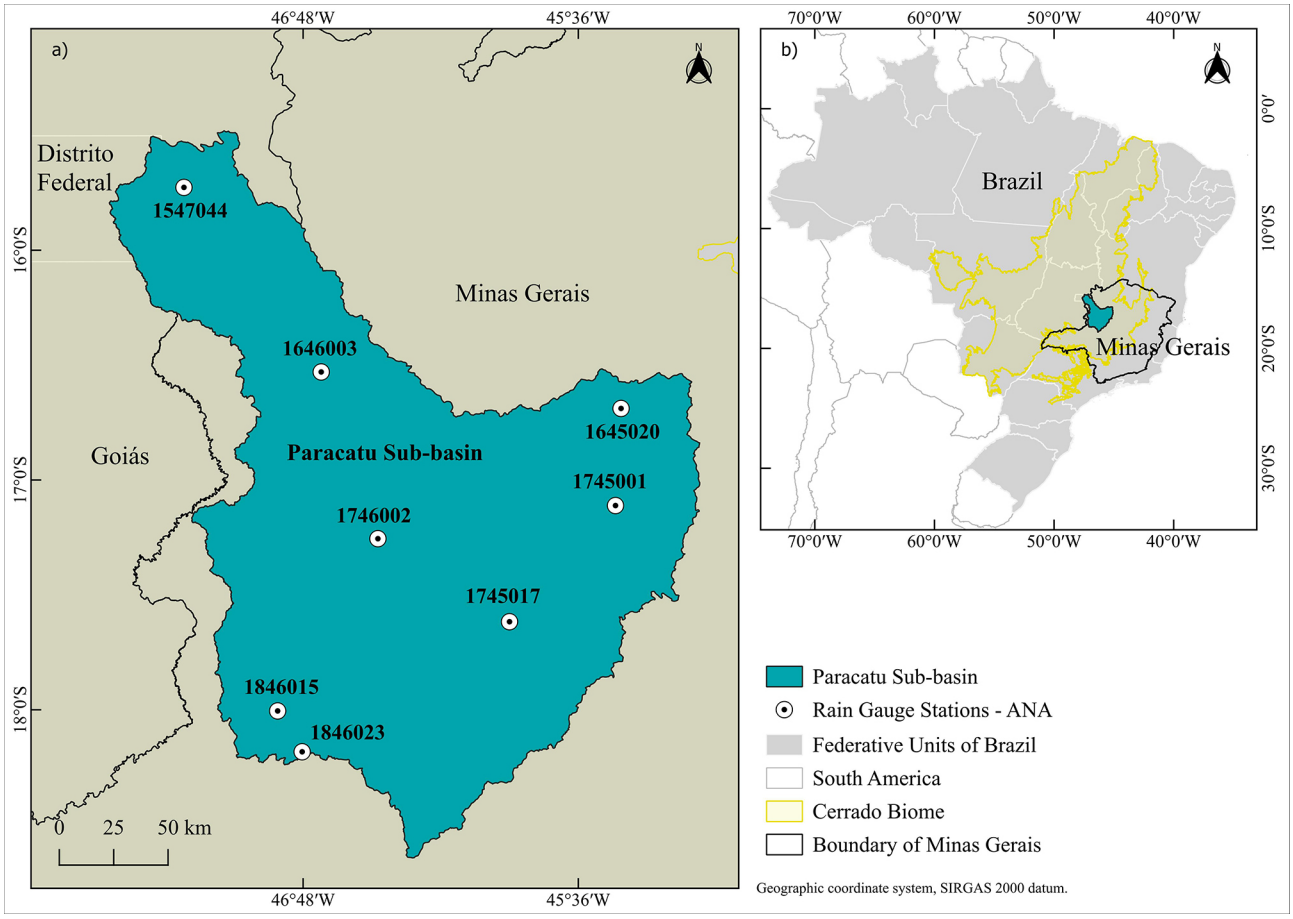
The results of this study will not only expand scientific knowledge in remote sensing, hydrology, and climatology but also provide crucial data to support decision-making in agricultural and water management, especially in the Cerrado region.

2. Methodology

2.1. Study area

The Paracatu River Basin (Figure 1) is located within the Brazilian Cerrado in the Middle São Francisco region. It spans an area of 45,600 km², making it the second-largest sub-basin of the São Francisco River. It is located almost entirely in the northwest region of Minas Gerais, with small areas extending into the states of Goiás and the Federal District (Lima et al., 2019).

Figure 1. Location map. a) Location of the Paracatu Basin. b) Paracatu Basin in Minas Gerais



Own elaboration

The basin region has a humid tropical climate (Aw) (Alvares et al., 2013), with rainfall concentrated between October and April and a dry period from May to September. The average annual precipitation is approximately 1,178.3 mm, with December being the wettest month, recording average values of up to 256 mm, and July the driest, with an average of 7 mm (Loures Ferreira et al., 2024). The altitude varies from 500 m to 1,050 m, and the predominantly flat and gently undulating topography favors the use of central pivot irrigation systems, giving the region great relevance for agricultural production in Brazil, especially for seasonal crops such as corn, beans, and soybeans (Ferreira et al., 2025).

2.2. Data collection

The rainfall data from remote sensing were obtained through CHIRPS and processed using the Google Earth Engine interface for monthly and annual scales covering 2010 to 2023. CHIRPS integrates orbital data with a

spatial resolution of 5.3 km (0.05°) and in situ meteorological station information to create precipitation time series on a grid, widely used in trend analysis and monitoring of seasonal droughts (Mianabadi et al., 2022).

Its data sources include (1) monthly climatological records (CHPClim); (2) infrared imagery from NOAA geostationary satellites; (3) rainfall estimates from TMPA 3B42 v7; (4) atmospheric models from the NOAA Climate Forecast System v2; and (5) precipitation measurements from global meteorological networks (Funk et al., 2015).

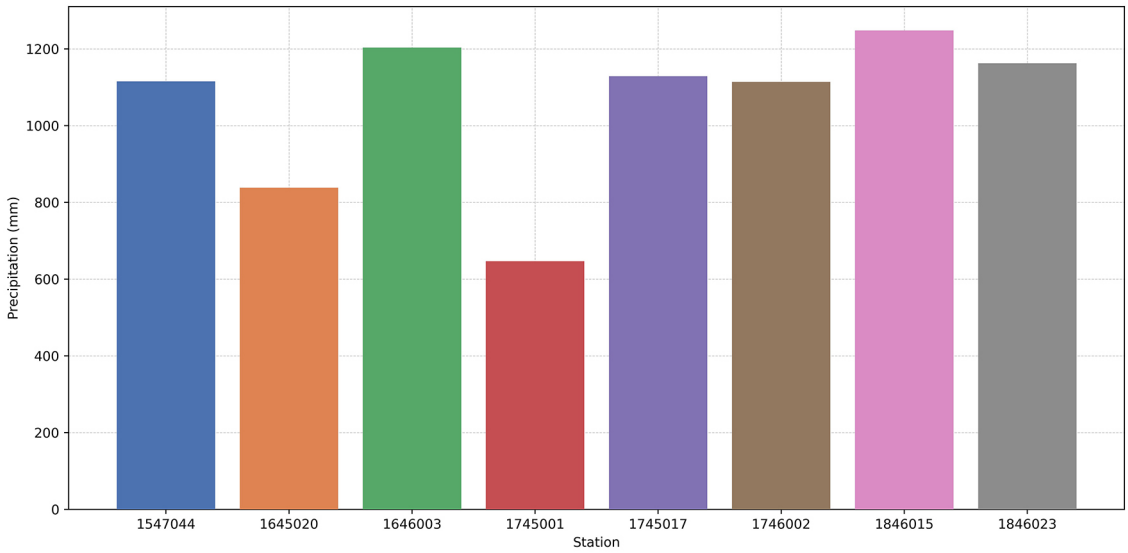
This dataset provides high-resolution estimates covering the period from 1981 to the present and is widely applied in climate research and disaster management (Mouafik et al., 2024; Nicholson & Klotter, 2021). Its selection was based on results from previous studies, demonstrating its effectiveness in climatological analyses, its broad validation in various scientific studies, and its suitability for estimating precipitation in areas with complex topography, such as the Cerrado.

Considering the accuracy, temporal coverage, spatial resolution, and integration with surface station data, CHIRPS emerges as the most suitable option for precipitation monitoring in the study area. These characteristics align with the specific needs of this study, which aims to compare satellite-derived precipitation data with surface observations.

The observed rainfall data were collected from stations in the Paracatu Basin and accessed through the HidroWeb portal of the National Water Agency (ANA)[1]. The distribution of stations is limited, but they cover strategic areas of the Paracatu River Basin. Some are located in regions with a high concentration of central pivot irrigation systems. On the other hand, others are located in areas with a low concentration of this irrigation method, ensuring diverse and representative basin coverage. Regarding data quality, only stations with high-quality data were selected, discarding those with errors exceeding 3% or that did not cover the entire period of interest (2010 to 2023), ensuring the reliability of the information used. This process resulted in eight measurement stations (Figure 1).

The average annual precipitation recorded by rain gauges from 2010 to 2023 varied significantly across the study area. For example, station 1745001 recorded approximately 646 mm, while station 1846015 recorded an average above 1,248 mm (Figure 2). The lowest precipitation values were observed in the eastern region of the study area (Figure 1). At the other stations, average precipitation ranged between 838 mm and 1,200 mm.

Figure 2. Average annual precipitation by station (period from 2010 to 2023)



Own elaboration

To complement this analysis, CHIRPS precipitation pixel values were extracted for the coordinates corresponding to each rain gauge station (point-to-pixel extraction) for the same period. This method assumes that rain gauge measurements represent the pixel values of the CHIRPS dataset, allowing direct comparisons between ground observations and satellite estimates (Baez-Villanueva et al., 2018; Alsilibe et

1 https://www.snirh.gov.br/hidroweb/serieshistoricas

al., 2023; Li et al., 2023; Datti et al., 2024). The application of this method eliminated the uncertainty inherent in pixel-to-pixel analysis, where the interpolation procedure can introduce considerable uncertainty (Xu et al., 2015). The study by Zhang et al. (2018) demonstrated that assessments using both the "point-to-pixel" and "pixel-to-pixel" methodologies produce statistically similar results. Thus, the distinction between these approaches may be unnecessary in assessing the accuracy of satellite precipitation estimates.

2.3. Data analysis

In terms of statistical indicators, this study employed commonly used metrics such as Pearson correlation coefficient (CC), Relative Bias (BIAS), Coefficient of Determination (R^2), Root Mean Square Error (RMSE), and average precipitation to quantitatively assess the correlation and degree of deviation of the CHIRPS precipitation products.

The linear correlation coefficient (CC) (Equation 1) measures the strength of the linear relationship between the two compared products (Cattani et al., 2021).

$$\mathrm{CC} = \frac{\sum_{\mathrm{i}=1}^{n}(P_i - \bar{P}) \,.\, (S_i - \bar{S})}{\sqrt{\sum_{\mathrm{i}=1}^{n}(P_i - \bar{P})^2 \;.\; (S_i - \bar{S})^2}} \tag{1}$$

The RMSE (Equation 2) is a metric that evaluates the error level between the estimated and observed values (Zhu & Liang, 2024). The RMSE integrates the sizes of prediction mistakes for different times into a single indicator of predictive capacity (Rachidi et al., 2023).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - S_i)^2} \tag{2}$$

The BIAS (Equation 3) is used to characterize the biases and inaccuracies in satellite data compared to field-based rainfall data (Silva et al., 2023).

$$BIAS = \frac{\sum_{\mathrm{i}=1}^{n}(P_i - S_i)}{\sum_{\mathrm{i}=1}^{n} S_i} \,.\, 100 \tag{3}$$

The R^2 (Equation 4) is an essential measure for assessing the quality of a model's fit to the observed data (Araújo et al., 2020).

$$\mathrm{R}^2 = \left(\frac{\sum_{\mathrm{i}=1}^{n}(P_i - \bar{P}) \,.\, (S_i - \bar{S})}{\sqrt{\sum_{\mathrm{i}=1}^{n}(P_i - \bar{P})^2 \,.\, (S_i - \bar{S})^2}}\right)^2 \tag{4}$$

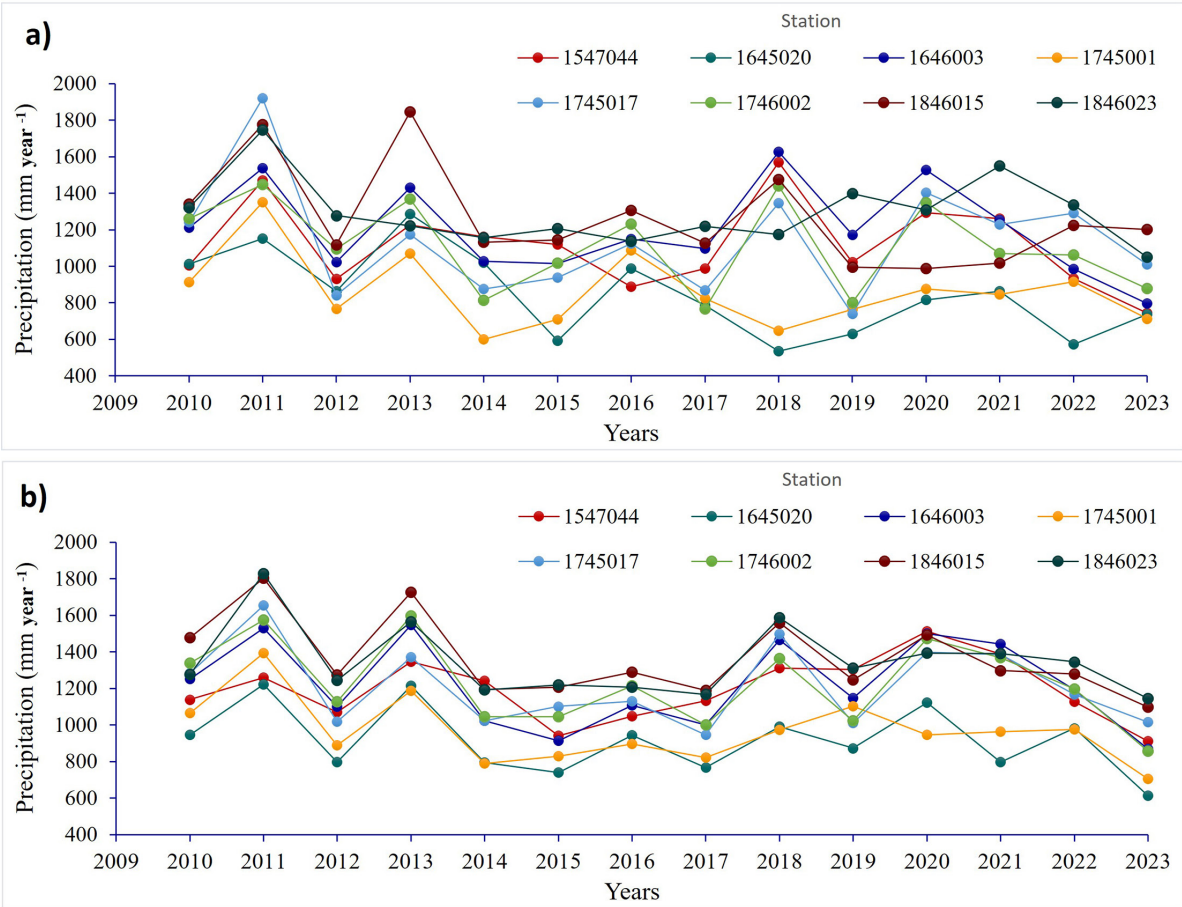
Where: $\mathrm{P_i}$ is the precipitation value from the CHIRPS products, $\overline{\mathrm{P}}$ is the mean of $\mathrm{P_i}$, $\mathrm{S_i}$ is the value from the rain gauge stations, $\overline{\mathrm{S}}$ is the mean of $\mathrm{S_i}$, and n is the total number of data records.

3. Results

Precipitation in the Paracatu River Basin shows temporal and spatial variability, consistent with the results of Freitas et al. (2022) and Ferreira et al. (2025) for the study area where the basin is located. The observed annual averages ranged from 540 to 1,845.6 mm year^{-1} (Figure 3). Regarding the averages obtained from CHIRPS, fluctuations ranged from 613.0 to 1,827.6 mm year^{-1}. The data show the annual mean variations within the basin for both data sources, with the lowest precipitation occurring in the eastern region, where stations 1645020 and 1745001 are located (Figure 1).

When evaluating the monthly precipitation averages between Rain Gauges and CHIRPS Precipitation, it was observed that both data sources exhibit variations throughout the months (Figure 4). Notably, February was the month that deviated the most from the proposed confidence interval in most of the studied locations, indicating a significant difference between the two datasets during the period from 2010 to 2023. It is observed that, despite showing spatial variations, the precipitation in the basin follows a well-defined pattern, with the driest months being from May to September. According to Reboita et al. (2015), this region experiences a wetter summer and drier winter, a pattern that, according to Reboita et al. (2010), is influenced by the South American monsoon precipitation regime.

Figure 3. Average annual precipitation in the study area. (a) represents the average of the measuring stations, (b) corresponds to the average of the CHIRPS data



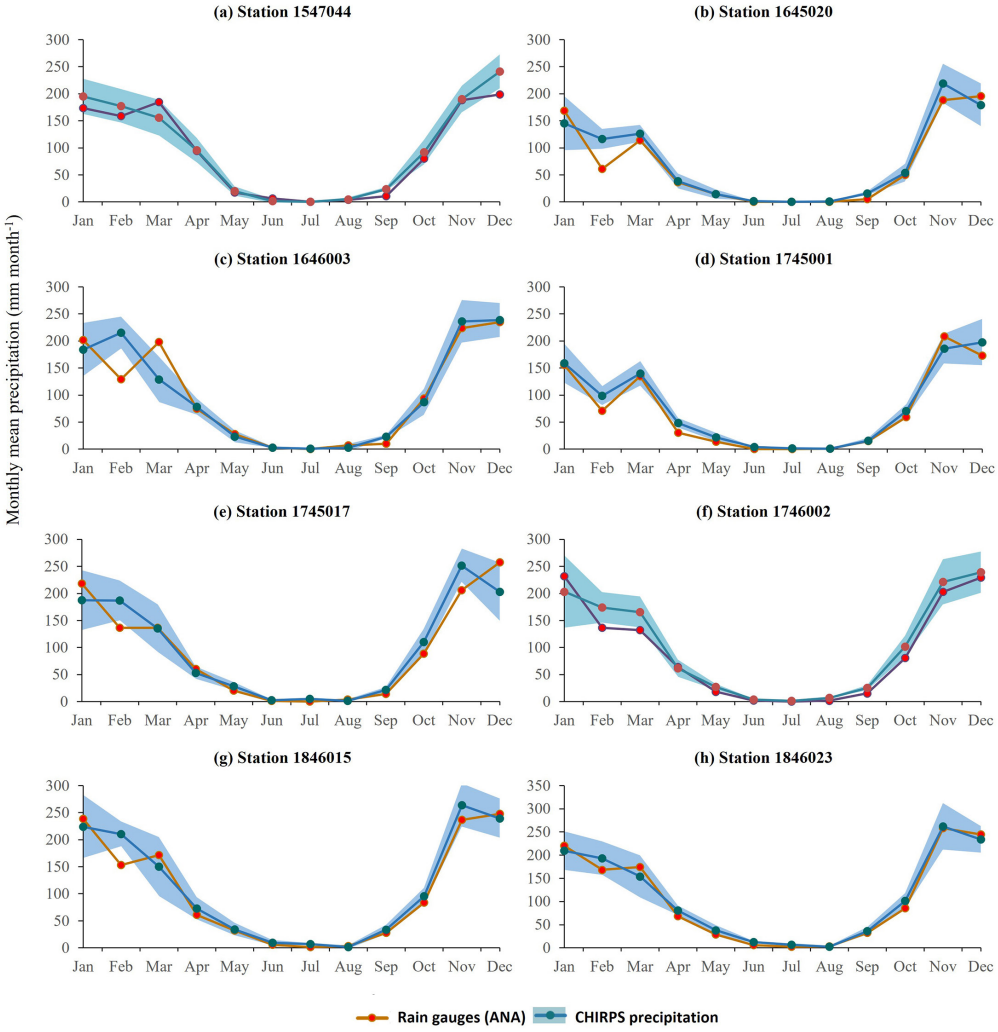
Own elaboration

The difference between precipitation estimated by CHIRPS and observed by ANA (Figure 5) reveals seasonal and regional discrepancies. In general, CHIRPS tends to overestimate precipitation during wet months and underestimate it during dry months. However, station variations may be associated with factors such as topography and local climatic patterns, which influence the satellite's ability to capture the spatial variability of precipitation.

Figure 6 illustrates the comparative analysis between the precipitation data obtained from surface stations (ANA) and those estimated by the remote sensing product CHIRPS for eight rain gauge stations on a monthly scale. The R^2 values ranged from 0.77 to 0.89, demonstrating CHIRPS' ability to explain the variability of the observed data. Among the analyzed stations, station 1846023 presented the highest R^2 value (0.89), indicating an excellent fit between the satellite-derived estimates and the observed data.

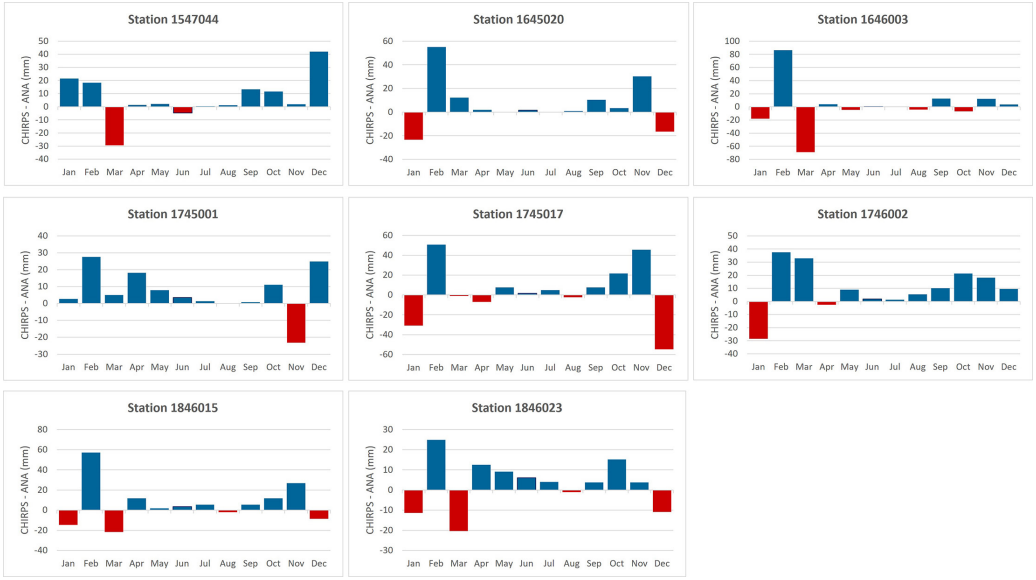
This strong correlation across most stations reinforces the reliability of CHIRPS as a tool for monitoring precipitation in regions with limited rain gauge coverage. By integrating surface observations with satellite-derived estimates, this study underscores the potential of remote sensing to enhance hydrological studies and support water resource management, particularly in areas with complex topography, such as the Paracatu Basin.

Figure 4. Mean monthly precipitation for Rain Gauges and CHIRPS Precipitation in the study area. The shaded region represents the CHIRPS Precipitation series's mean confidence interval (α = 0.05). Rain Gauge means that falls outside this shaded area are statistically distinct at this confidence level



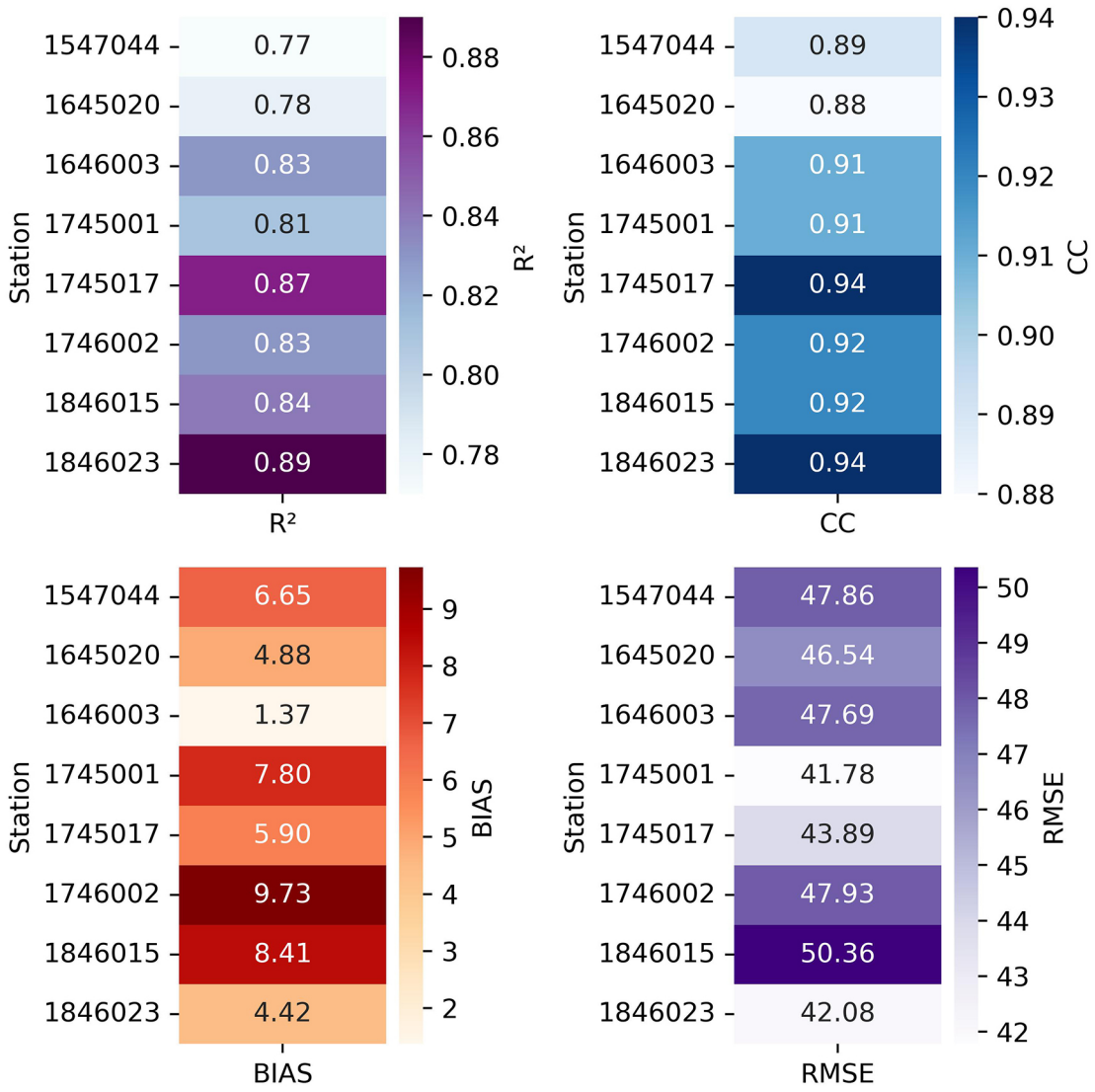
Own elaboration

Figure 5. Calculation of the difference between precipitation estimated by CHIRPS and observed by ANA



Own elaboration

Figure 6. Heatmap showing the statistical summary of the performance metrics of CHIRPS precipitation data compared to field data (monthly scale)



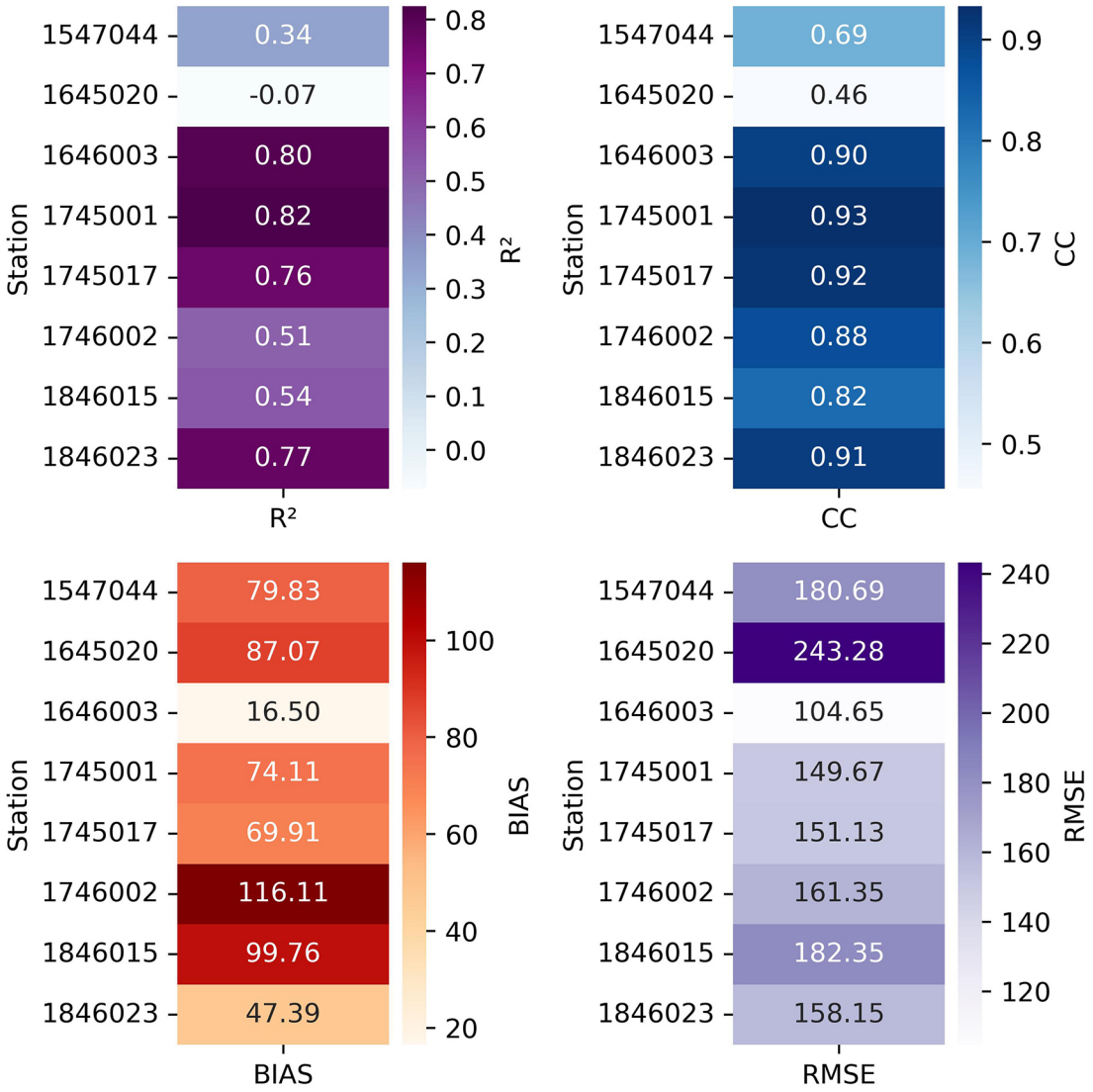
Own elaboration

The correlation coefficients (CC) further confirmed the substantial agreement between CHIRPS estimates and field data, ranging from 0.88 to 0.94. Station 1745017 achieved the highest CC value (0.94), emphasizing the accuracy of CHIRPS data. Bias (BIAS) analysis revealed values ranging from 1.37 to 9.73, with station 1646003 showing the lowest bias (1.37), indicating that CHIRPS estimates were relatively close to the observed data. Conversely, station 1746002 recorded the highest bias (9.73), reflecting a significant overestimation of precipitation at this location.

The RMSE values ranged from 41.78 mm to 50.36 mm, highlighting discrepancies between CHIRPS estimates and observed data. Station 1745001 demonstrated the lowest RMSE (41.78 mm), indicating greater accuracy in the forecast for this location.

On an annual scale, as shown in Figure 7, the analysis revealed notable variability in the fit quality between ANA and CHIRPS data across stations. While some stations exhibited satisfactory R^2 values, others showed poor results. Station 1646003 stood out with an R^2 of 0.80 and a CC of 0.90, indicating a strong correlation and high reliability of CHIRPS estimates for this location. In contrast, station 1645020 exhibited a negative R^2 value of -0.07, reflecting a lack of correlation between ANA and CHIRPS data, which limits the usability of these estimates for analysis or water management decisions.

Figure 7. Heatmap showing the statistical summary of performance metrics for CHIRPS precipitation data compared to field data (annual scale)



Own elaboration

The BIAS, on an annual scale, also varied significantly between stations. Station 1646003 exhibited the lowest bias value (16.50), while station 1746002 recorded the highest bias (116.11), indicating substantial overestimation. Similarly, the RMSE ranged widely, with station 1646003 displaying the lowest RMSE (104.65), confirming the higher precision of CHIRPS estimates for this location. These results highlight the variability in CHIRPS performance across the study area and emphasize caution when applying satellite-derived precipitation data for specific stations, particularly those with weaker correlations.

4. Discussion

The results of the comparative analysis between the precipitation data from ANA and the CHIRPS estimates highlight relevant aspects regarding the reliability and limitations of satellite precipitation products in the Brazilian Cerrado region. Our findings indicate that CHIRPS performs satisfactorily as a complementary tool to in situ observations, especially for monthly precipitation estimates at most Paracatu River basin stations, with R^2 values ranging from 0.77 to 0.89. Similarly, Bhattarai and Talchabhadel (2024) identified CHIRPS as the most accurate product in estimating monthly precipitation totals in their comparative analysis.

The analyzed data show that CHIRPS maintains good performance on the monthly scale, with bias (BIAS) values ranging from 1.37% to 9.73%. Similarly, the correlation coefficients varied from 0.88 to 0.94, indicating

a strong association between CHIRPS estimates and observed data, with most stations showing results within acceptable limits. According to Nadeem et al. (2022), for monthly hydrological studies, the acceptable limits are ±10.0% for bias and ≥0.7 for the correlation coefficient.

The root mean square error (RMSE) ranged from 41.78 mm to 50.36 mm, reflecting the discrepancy between CHIRPS estimates and observed data. The lowest RMSE was recorded at station 1745001 (41.78 mm), indicating higher estimation accuracy at this location. RMSE variation is common in tropical and subtropical regions, where the spatial distribution of rainfall is highly irregular. Values near 40 mm indicate higher accuracy in estimates, while values around 50 mm suggest wider error margins, as discussed by Bhattarai and Talchabhadel (2024). This variation reflects the challenges in capturing local rainfall fluctuations, particularly in areas with high spatial and temporal rainfall variability. Similar studies conducted in other tropical regions, such as Ye et al. (2022) in Sub-Saharan Africa, also reported significant variations in RMSE, particularly in areas with high rainfall variability and complex topography, reinforcing the influence of these factors on satellite estimate accuracy.

The months that showed significant variation above the average confidence interval (α = 0.05) (Figure 4) coincided with the period of highest precipitation in the region (October to April). These results align with the findings of Datti et al. (2024), which indicate that CHIRPS performs better in detecting precipitation during the dry season. Generally, this product tends to overestimate precipitation in wet months and underestimate it in dry months, a behavior previously reported in studies evaluating its accuracy in different climatic contexts (Bhattarai & Talchabhadel, 2024; Ogbu et al., 2020).

On the annual scale, CHIRPS' performance is not uniform across the basin, with some stations showing more significant errors, possibly due to factors such as topography and local climate patterns. Only four of the eight stations analyzed showed a satisfactory R^2 above 0.7 (Figure 7). Station 1645020, which recorded a negative R^2 (-0.07), indicates the need for caution and further analysis. According to Bhattarai and Talchabhadelet (2024), CHIRPS has limitations in accurately estimating annual precipitation totals, which was also observed by Upadhyay et al. (2022), where the annual R^2 was 35.6% lower than that obtained on the monthly scale. This difference occurs because accumulated annual data tends to be associated with more significant errors, directly impacting the analysis (Ghorbanian et al., 2022).

The statistical data on monthly and annual scales revealed seasonal variations, even within the same watershed, for both data sources (Figures 3 and 4). The literature supports these findings, suggesting local climatic and topographic factors influence precipitation, especially satellite estimates. In mountainous regions, Hsu et al. (2021) argue that CHIRPS' accuracy can be compromised due to difficulties in capturing rainfall variations associated with local orography. Similarly, Nadeem et al. (2022) highlight that specific climatic zones and geographical features play a crucial role in the accuracy of satellite estimates. These topographic influences can result in discrepancies between precipitation estimates and observed data, particularly in areas with variations in relief and microclimates. Additionally, in the Cerrado, the well-defined seasons may affect the accuracy of CHIRPS, especially during the transition periods between dry and wet seasons.

One of the main limitations of this study is the low density of rainfall stations in the study area, with only eight stations distributed over approximately 45,600 km², resulting in limited spatial coverage. Furthermore, the sparse distribution of these stations makes it difficult to identify local patterns and detect extreme events, such as heavy rains concentrated in specific areas (Bai et al., 2018). This limitation is not restricted to CHIRPS data but is a common challenge for most satellite-based precipitation products (Sakib et al., 2021; Bhattarai & Talchabhadelet, 2024).

However, the results indicate that CHIRPS can be a valuable complementary tool for hydrological and agricultural studies in the Paracatu River basin. In regions lacking rainfall stations, CHIRPS data can provide relevant information for agricultural applications, considering that land-based precipitation measurements are also point-based and do not fully represent the study area (Gu et al., 2024; Caparoci Nogueira et al., 2018). This is particularly relevant for agricultural planning and water resource management, where accurate monthly estimates are essential for evaluating crop water requirements, scheduling irrigation, and managing reservoirs.

This study can contribute significantly to management in the Paracatu River basin, an important region for irrigated agricultural production. The basin plays a strategic role in grain production, particularly in the municipalities of Paracatu (72,726 hectares) and Unaí (71,573 hectares), which are among the areas with the most significant irrigated pivots in Brazil (Guimarães & Landau, 2020). In this context, relying on other sources of information on precipitation in the region can provide valuable insights for decision-making in the agricultural

sector, promoting more efficient and sustainable water management, encouraging agriculture, contributing to water security, and optimizing resources allocated to irrigation.

5. Conclusions

This study evaluated the performance of the CHIRPS product in estimating precipitation in the Paracatu River basin, located in the Brazilian Cerrado, by comparing its data with surface station observations from 2010 to 2023. The results demonstrate that CHIRPS shows a good correlation with observed data at a monthly scale, with coefficients of determination (R^2) ranging from 0.77 to 0.89 and correlation coefficients (CC) between 0.88 and 0.94, indicating a satisfactory representation of intra-annual precipitation variability. The monthly relative bias (BIAS) remained within an acceptable range (1.37% to 9.73%), with root mean square errors (RMSE) between 41.78 mm and 50.36 mm, reinforcing its usefulness as a complement to rain gauge stations.

However, at an annual scale, the performance of CHIRPS showed limitations, with greater discrepancies in total precipitation. While the stations recorded annual averages between 540 mm and 1,845.6 mm, CHIRPS ranged from 613.0 mm to 1,827.6 mm, presenting both underestimations and overestimations depending on the region and year analyzed. Some stations exhibited unsatisfactory results, notably station 1645020, which showed negative R^2 values (-0.07), highlighting the need for more detailed validations in such cases.

These results emphasize the importance of integrating data from different sources and conducting robust validation analyses to enhance the reliability of satellite data for agricultural and hydrological studies. The variation in results also suggests that local factors, such as topographical features and the distribution of meteorological stations, may influence the accuracy of precipitation estimates.

Therefore, CHIRPS precipitation estimates, when adequately validated, can serve as a valuable alternative to conventional rain gauge data, offering broader coverage and an effective tool for climate monitoring and water resources management in the Paracatu basin and other regions with similar characteristics. This approach is crucial for decision-making in sectors such as agriculture, where the accuracy of climate data directly impacts risk management and irrigation planning.

Future studies could explore the integration of other remote sensing products and analyze how changing climatic conditions impact precipitation estimates. Such analyses are crucial for increasing the resilience of human activities and protecting biodiversity in vulnerable regions, such as the Brazilian Cerrado.

Authorship contribution

Maycow Douglas de Oliveira Silva: Conceptualization, Writing - original draft, and formal analysis.
Paulo Sérgio Cardoso Batista: Validation and Visualization.
Sharrine Omari D. de Oliveira Marra: Project administration, Supervision, and Validation.
Marinaldo Loures Ferreira: Formal analysis and Writing - review & editing.

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