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Artigo

Applicability of TRMM Precipitation for Hydrologic Modeling in a Basin in the Northeast Brazilian *Agreste*

Marcus Aurélio Soares Cruz[1], Leonardo Teixeira Rocha[2], Ricardo de Aragão[3], André Quintão de Almeida[2]

[1]*Embrapa Tabuleiros Costeiros, Aracaju, SE, Brazil.*
[2]*Programa de Pós-Graduação em Recursos Hídricos, Universidade Federal de Sergipe, São Cristóvão, SE, Brazil.*
[3]*Universidade Federal de Campina Grande, Campina Grande, PB, Brazil.*

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Abstract

Determining precipitation using remote sensing is gaining space in hydrologic studies, helping make up for the lack of data in many regions of Brazil. The products from satellite TRMM (Tropical Rainfall Measuring Mission) are widely applied in studies in Brazil, but there are still few results about their applicability for hydrologic modeling in the Northeast Region, which is characterized by an irregular precipitation regime. The objective of this study is to evaluate the feasibility of using the TRMM 3B42 V7 data for hydrologic modeling in the Japaratuba river basin in Sergipe at three timescales: daily, every ten days, and monthly. The comparative analysis between the rainfall data from rain gauges and TRMM did not indicate satisfactory adequacy at these studied scales, since the TRMM data underestimated the total rainfall for all stations used in the study. However, for the hydrologic modeling, acceptable values were obtained for the efficiency coefficients evaluated only for the ten-day and monthly scales.
Keywords: TRMM, hydrological modeling, Japaratuba river basin.

Aplicabilidade da Precipitação TRMM para Modelagem Hidrológica em uma Bacia no Agreste do Nordeste Brasileiro

Resumo

A determinação da precipitação por sensoriamento remoto está ganhando espaço nos estudos hidrológicos, ajudando a compensar a falta de dados em muitas regiões do Brasil. Os produtos do satélite TRMM são amplamente aplicados em estudos no Brasil, mas ainda há poucos resultados sobre sua aplicabilidade para a modelagem hidrológica na região Nordeste, caracterizada por um regime irregular de precipitação. O objetivo deste estudo é avaliar a viabilidade de utilizar os dados TRMM 3B42 V7 para modelagem hidrológica na bacia do rio Japaratuba, em Sergipe, em três escalas temporais: diária, a cada dez dias e mensal. A análise comparativa entre os dados de pluviômetros e TRMM não indicou adequação satisfatória nessas escalas estudadas, uma vez que os dados TRMM subestimaram a precipitação total para todas as estações utilizadas no estudo. No entanto, para a modelagem hidrológica, foram obtidos valores aceitáveis para os coeficientes de eficiência avaliados apenas para as escalas de dez dias e mensal.
Palavras-chave: TRMM, modelagem hidrológica, Bacia do Rio Japaratuba.

1. Introduction

Rainfall is one of the most important variables in the hydrologic cycle, and is indispensable in climatological studies (Zhan *et al.*, 2015). The understanding of its spatial and seasonal variability in each region is essential for agriculture and for various sectors of the economy (FAO, 2015). Within this context, the reliability of the estimates of precipitation is of paramount importance (Silva *et al.*, 2012).

Countries with continental dimensions and low investment capacity, such as Brazil, have problems of meteo-

Autor de correspondência: Marcus Aurélio Soares Cruz, marcus.cruz@embrapa.br.

rological station coverage (Basso *et al.*, 2015). Thus, hydrologists have sought alternatives to estimate precipitation values, such as remote sensing (Collischonn *et al.*, 2007).

Rainfall estimates from remote sensors have been obtained through various projects around the globe and the products available are constantly improving as new techniques of production and correction of the final information emerge (Tapiador *et al.*, 2012; Liu, 2015). Precipitation data at different temporal and spatial scales are available via an Internet, such as: PERSIANN-CDR (Ashouri *et al.*, 2015), CMORPH (Jiang *et al.*, 2012), NCEP (Philbin & Jun, 2015) and TRMM/TMPA (Liu, 2015), CHIRPS (Paredes *et al.*, 2017).

Many studies that evaluate the quality and applicability of the data have been developed and applied in various regions, demonstrating which products have the greatest potential for use in different environments (Collischonn *et al.*, 2007; Sapiano & Arkin, 2009, Leivas *et al.*, 2014; Liu *et al.*, 2015; Melo *et al.*, 2015; Prat & Nelson, 2015; Paredes *et al.*, 2017).

The Tropical Rainfall Measuring Mission (TRMM) was developed as a joint between NASA and National Space Development Agency of Japan mission to study tropical rainfall and its implications for climate (Shepherd *et al.*, 2002). The products supplied by the radar on the TRMM satellite have been widely applied in studies in Brazil (Collischonn *et al.*, 2007; Pereira *et al.*, 2013; Leivas *et al.*, 2014); however, there are still only a few reports on their applicability for hydrologic modeling in medium-sized basins located in the northeast region of the country, which is characterized by an irregular temporal and spatial rainfall regime (Silva *et al.*, 2011).

The Japaratuba river basin, in the state of Sergipe, Northeast of Brazil, is characterized by climate variability, presenting three climatic zones: semiarid in headwaters, agreste in the most part of the basin and humid coastline in the lowest portion. This basin has a low density of pluviometers, which implies uncertainties in the estimates of precipitation, which is also apparent due to the water flow in regions where water is necessary to meet the demand for irrigation. Thus, the overall objective of this study is to assess the quality of the precipitation data of algorithm 3B42_V7 from the TRMM satellite within the context of hydrologic modeling of the Japaratuba river basin.

2. Materials and Methods

The Japaratuba river basin in Sergipe is located within the geographic coordinates (10°13'00'' to 10°47'00'' S and 36°48'00'' to 37°19'00'' W) (Fig. 1). Its main river is 135 km long and the basin has an area of 1685 km^2 (Aragão *et al.*, 2011). Twenty municipalities in Sergipe are drained by the Japaratuba river basin, of which only five are fully within it (Capela, Carmópolis, Cumbe, General Maynard and Rosário do Catete). The population of about 200,000 people is divided between 62.4% in the urban area and 37.6% in the rural area (Aragão *et al.*, 2013).

Three climatic zones are present in the basin: humid coastline (near the river mouth, with 1000 to 1400 mm of annual rainfall, concentrated in the period from April to August), *agreste* (the middle portion, 700 to 900 mm on rainfall concentrated between April and August), and semi-arid (the headwaters, 400 to 700 mm of rainfall concentrated between January and May). The average annual temperature is 25 °C. The relative air humidity is 74%. Of the total area of the basin, 9.63% belongs to the semi-arid region, 30.18% to the humid coastline and 60.17% is located in *agreste* (Aragão *et al.*, 2013).

In the Japaratuba river basin, Acrisol type soils predominate (about 75% of the area of the basin), followed by Latosols, fluvic Neosols and Vertisols. The presence of agricultural activities characterizes the use and coverage of the soil, with emphasis on pasture (about 50% of the basin area) and agricultural crops (sugar cane, corn and fruit plants, which accounts for about 25% of the area). In addition to these, there are also mining activities (oil and potassium), exposed soils and urban areas. Consequently, the native vegetation is gradually being reduced, totaling 15% of the area of the basin. The water potential is low and has been greatly affected by the various uses of the land (Aragão *et al.*, 2013).

The analysis performed in this study used the following data: observed daily precipitation (*OP*) at three rain gauges installed in the basin; observed daily flow (*OQ*) at a fluviometric station in the main river; estimated daily precipitation (*EP*) from the TRMM satellite; physical parameters of the adjacent basin (area, length and declivity) for the mathematical simulation of flows (estimated flow, EQ).

OP values were obtained from the Capela (Code 1037078), Fazenda Cajueiro (Code 1036063) (ANA, 2014) and Aquidabã (Code 31782) (INPE, 2014) stations (Fig. 1). These were compared with the *EP* (TRMM) on three temporal scales: daily, every ten days and monthly. For Capela and Fazenda Cajueiro the period from 1998 to 2013 was used, and for Aquidabã the periods from 2004 to 2013 was used. The TRMM 3B42 data (*EP*) is available from 1998 until 2013, and it is available in the NASA homepage.

The *OQ* values were taken from the Japaratuba fluviometric station (Code 50040000, 735 km^2 area) (ANA, 2014) for the period between February 10, 2004 and January 31, 2007. These data were compared with those simulated (*EQ*) by the WIN_IPH2 rain-flow model (Bravo *et al.*, 2009) after the calibration of its parameters, also for the three timescales, and considering the specific and average rainfall over the basin. Evapotranspiration data were estimated based on Sousa *et al.* (2010). The WIN_IPH2 model can be requested to Climate and Water Resources Section in the Hydraulic Research Institute (IPH) homepage.

The TRMM satellite has an oblique non sun-synchronous orbit located at about 403 km. It allows daily sam-

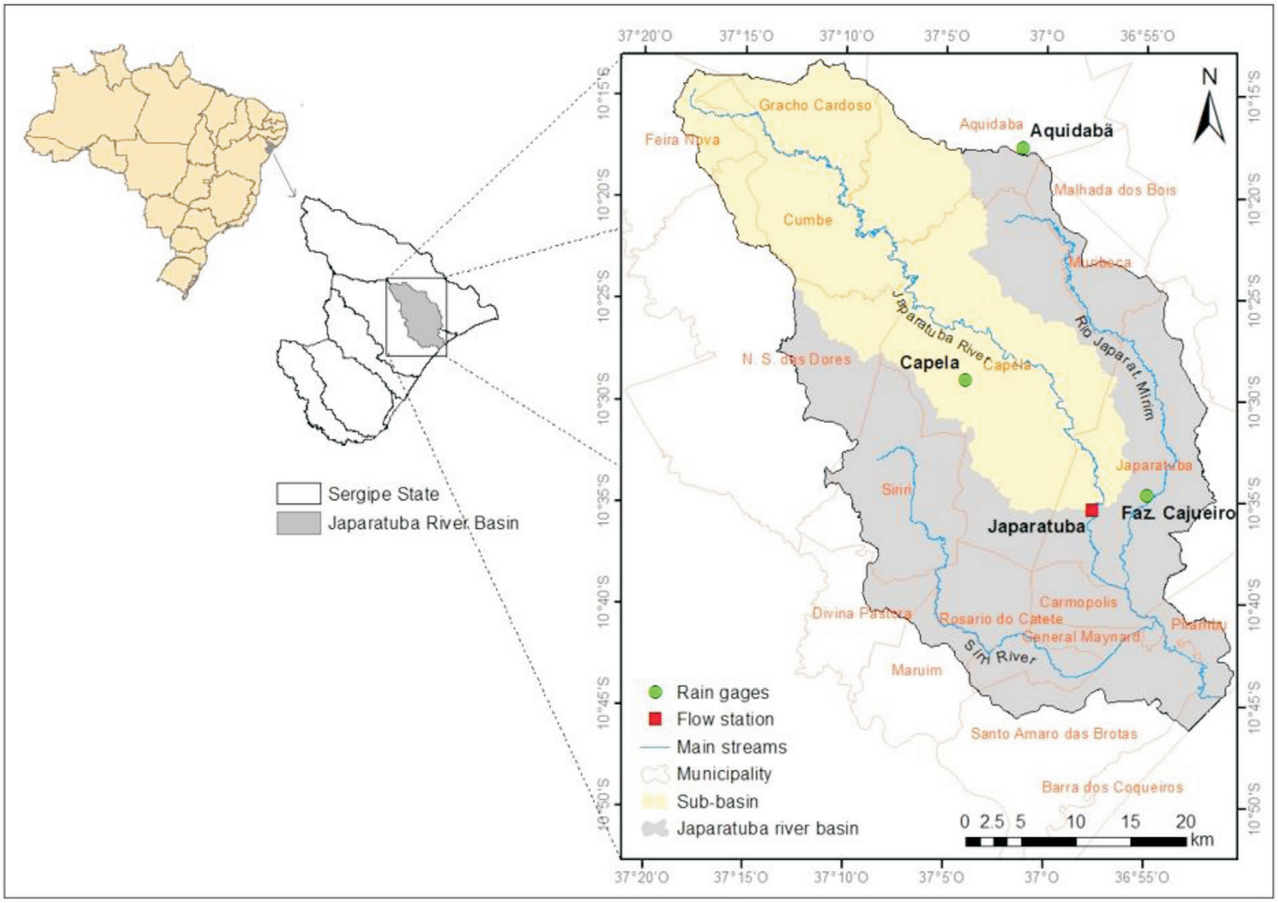

Figura 1 - Geographical location of the Japaratuba river basin and its hydrological monitoring system. The Japaratuba fluviometric station and its contributing area are highlighted.

pling, with data estimated every three hours and a spatial resolution of 0.25° between 50° N and 50° S (NASA, 2014). More information about formats and means of obtaining the data can be obtained from NASA (2014). To encompass the entire area of study, 16 points of the TRMM grid were selected.

The analysis was developed through the comparison between precipitations (*OP* and *EP*) and flows (*OQ* and *EQ*). *EP* was evaluated considering specific and average values. For the specific values, in the same geographical coordinates of the rain gauge stations, interpolation through the inverse-square-distance was applied considering the influence of four points from the TRMM grid. The inverse-square-distance was evaluated by cross-validation technique in TRMM grid and show it adequate to interpolate precipitation data in this basin. For the average weighting of the EP in the basin, a method similar to Thiessen polygons was used. To do so, the areas of influence in the basin for the 16 centroids selected from the TRMM grid, were determined and the proportion between each centroid influence area and the total area of the basin was used as weight for the average rainfall calculation.

Due to the number of variables involved in the process of rainfall-runoff modeling and considering that the objective of this work is to evaluate the possibility of using the TRMM-estimated precipitation in hydrologic modeling, a simple model with few parameters that could be calibrated automatically or semi-automatically was applied, thereby reducing the condition of uncertainty through parsimony. Thus, the historical series of estimated flow rates (*EQ*) were generated from *OP* and *EP* through the calibration of the WIN_IPH2 rainfall-runoff model for the continuous series (Tucci, 1997; Bravo *et al.*, 2009).

The IPH2 model, in its version for OS Windows, is widely applied in medium-sized basins in Brazil, mainly due to its simplicity and open source nature. In the model, among the existing parameters, seven parameters are related with the rain-flow transformation processes: *Io* = maximum infiltration capacity of the soil (mm/Δt); *lb* = minimum infiltration capacity of the soil (mm/Δt); *h* = parameter of decay of infiltration in the soil (dimensionless); *Ks* = parameter of propagation of surface runoff (δt); *Ksub* = parameter of propagation of underground runoff (δt); *Rmax* = maximum capacity of the reservoir of interception and depression (mm); and *Alpha* = dimensionless parameter for simulation of continuous series (Tucci, 1997; Bravo *et al.*, 2009; Bravo *et al.*, 2012).

In this study, we used the automatic calibration method for genetic algorithms (Shuffled Complex Evolution - SCE-UA), which already comes with the WIN_IPH2 model (Bravo *et al.*, 2012). Calibration adjusts the seven parameters within a pre-defined variation interval, ensuring their physical representability. It was chosen to optimize the parameters so that the Nash-Sutcliffe (*NS*) parameter, which is widely applied in efficiency tests for various types of hydrological models (Sharad & Sudheer, 2008), reached values greater than 0.5, which according to Moriasi *et al.* (2007) is the most suitable for this type of modeling. Five hundred iterations were used in all the calibrations to ensure global optimization.

Calibration was performed in four ways for each timescale, thereby totaling 12 procedures. The four steps were carried out using as input data: punctual precipitations (C1 - Capela rain gauge data, and C2 - ISD from TRMM in Capela rain gauge geographic coordinates) and average precipitations (C3 - three rain gauges, and C4 - TRMM grid over all basin area), contrasting with the flows recorded (*OQ*) at the Japaratuba fluviometric station. The Capela rain gauge was selected for C1 because of its location, close to the center of the sub-basin and adjacent to the fluviometric station.

Evaluation of the quality of the estimates of *EP* and *EQ* used the following efficiency indicators: Pearson correlation index (*r*), Nash-Sutcliffe coefficient (*NS*) and average percentage error of volume (*EV*), as indicated by Moriasi *et al.* (2007).

3. Results and Discussion

Considering the precipitation data and daily time scale, the efficiency coefficients demonstrate a very low correlation for all pluviograph stations (Table 1). Figure 2 (A) shows the scatter plots of *EP vs. OP* at this timescale. The three efficiency indicators confirm the visual analysis and have non-satisfactory values, as shown in Table 1. The Aquidabã rain gauge has the best results, especially for *r* (0,32); however, the EV value has underestimated values, at near 50%, for all stations.

Considering the values determined over ten days, the efficiency indexes had improved, though are still not yet satisfactory (Fig. 2 (B) and Table 1). On this scale, the Aquidabã station still has the highest *r* value (0.65), followed by Fazenda Cajueiro (0,51); the best value for *NS* is still very low (< 0.50). The *r* value for Aquidabã approached that which Moriasi *et al.* (2007) considered to be acceptable ($r = 0.7$). *EV* is still the same, for dealing with the accumulated data only. Compared with the ten-day scale, the monthly scale shows improvement in some of the indicators: at Aquidabã there is improvement in *r* (0.71), and at Fazenda Cajueiro ($r = 0.62$); however, there are still not satisfactory values for *NS* and *EV* (Table 1).

Tabela 1 - Efficiency indicators for estimate of *EP vs. OP* in each station and the average of stations in the Japaratuba river basin considering the time scales: daily, ten days and monthly.

Time scale	Indicator	Rainfall stations			
		Capela	Faz. Cajueiro	Aquidabã	Average
Daily	r	0.09	0.12	0.32	0.27
	NS	-1.05	-0.63	-0.18	-1.00
	EV	-55.57	-48.64	-50.29	-43.54
Ten days	r	0.37	0.51	0.65	0.54
	NS	-0.33	-0.02	-0.22	0.03
	EV	-55.57	-48.64	-50.29	-43.54
Monthly	r	0.47	0.62	0.71	0.63
	NS	-0.04	-0.05	-0.16	0.11
	EV	-55 57	-48.64	-50 29	-43 54

r -Pearson Correlation Coef.; NS - Nash-Sutcliffe Coef.; EV - Percent Volume Error.

For average precipitation (Fig. 2 (C) and Table 1), the efficiency indicators show improved values in relation to the analysis of data for the Capela and Fazenda Cajueiro stations, and near for Aquidabã station coefficients. It is noted that *EV* decreased, but is still high and underestimated. The *r* values also improved, indicating a possible compensation error for studies in larger areas. Silva *et al.* (2012) presented similar results for the Northeast Region of Brazil.

In general the coefficients are not fully satisfactory on any temporal scale, however, an improvement in the results was observed proportional to the increase in temporal scale. Such behavior was also observed in other studies developed in Brazil (Pereira *et al.*, 2013; Oliveira *et al.*, 2014; Almeida *et al.*, 2015).

Unlike what was reported by Collischonn *et al.* (2007) and Pereira *et al.* (2013), this study detected the underestimation of precipitation by the TRMM. Such behavior may be associated with the characteristics of the precipitation in the region of study, with high concentrations in a few months and predominance of long-term frontal rainfall of medium intensity, and of convective rainfall, with higher intensity in the periods of less rain. Recently, Paredes *et al.* (2017) reported similar underestimation of rainfall, considering CHIRPS data (product calibrated with TRMM 3B42 V7) over entire Brazilian Northeast region.

In the evaluation of the *EQ* (Estimated Flow) resulting from the calibration of WIN_IPH2, rain gauges rainfall (C1 and C2) and average rainfall (C3 and C4) scenarios, considering the daily scale, values of the efficiency indicators *r* and *NS* are still below the ideal (Table 2), but show significant improvement compared with the previous analysis related only to precipitation. *EV* on the other hand is within acceptable limits (± 25%). These results corroborate the assertion that the remote precipitation data holds potential for hydrological studies, although they do not show excellent correspondence with the field data, since it may better represent the spatial distribution of rain to larger areas (Collischonn *et al.*, 2007; Nóbrega *et al.*, 2008; Pereira *et al.*, 2013). Thus, the performance of the satellite data (C2) surpassed the rain gauges data on the daily scale: *NS* =

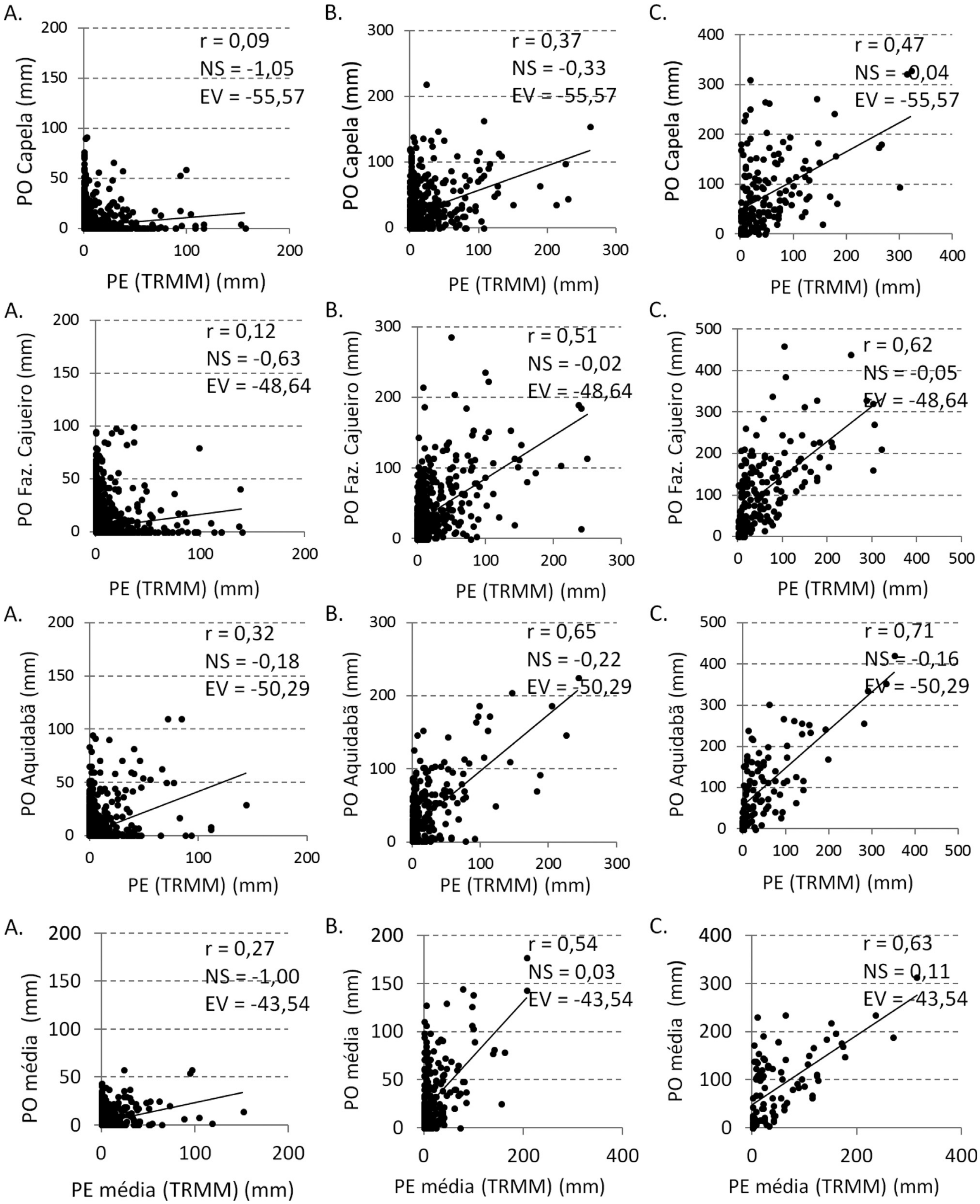

Figura 2 - Scatter plots and best fit line with efficiency indicators obtained for *OP vs. EP* at different time scales (daily (A), 10 days (B) and monthly (C)).

0.40; r = 0.65 and EV = 6.86, all of which are better than those obtained for C1 (Table 2).

As in the analysis of precipitation data accumulated during 10 days, here the efficiency indicators were better than those obtained on the daily scale (Table 2). It is observed, however, on this 10-day time scale, that the precipitation used in C1 had better performance than in C2, for both *NS* (0,78) and r (0.89), only for the indicator *EV* the simulation with the satellite data was better, however the value for C1 may also be considered very good (-2.94%).

On the monthly scale, the values of *NS* and r are better than those found for the 10-day scale. It should be stressed that the coefficients obtained on this scale were very good both for C1 (*NS* = 0.84 and r = 0.93) and C2 (*NS* = 0.60 and r = 0.79). This indicates the potential for using remote data on the 10-day and monthly scales. *EV* increased for both, and C1 had a higher value (undervalued in 15.29%) than C2 (overvalued in 14.43%). This result indicates the need of better evaluation concerning the objective function in the process of automatic optimization for calibration and assessment, for example, the use of multi-objective analysis techniques, once it was selected only Nash-Sutcliffe efficiency index to hydrological model calibration in this study (Bravo *et al.*, 2009).

Observing Fig. 3 as an example of calibration for 10-day time scale, it is possible to see that the model has a good representation of the seasonality in the basin, mainly for C1. In C2, despite also having good visual adjustment, there is divergence for low flow peaks (*OQ*) due to rains not detected by the TRMM satellite (C2).

For the scenarios with average of precipitation data (C3 and C4) were found coefficients near to values for C1 and C2 scenarios on the daily time scale (Table 2). Thus, there was improved performance of satellite data (C4) compared with the rain gauges (C3) in all the coefficients at this scale. An example of hydrographs for the 10-day scale is presented in Fig. 4 and these do not show significant variation in relation to the punctual modeling (Fig. 3).

Considering the daily simulation of punctual and average precipitations (Table 2) it is observed that there was improvement in the efficiency indicators; however, *NS* remains below 0.50. In this case, C4 was very close to the satisfactory limits.

For the values accumulated over 10 days, C4 showed better results than the average of the rain gauges (C3) for *NS* and r (0.50 and 0.76, respectively). For *EV*, a diverse behavior was noted, with overestimation in C3 (11.37) and underestimation in C4 (11.06). It should be emphasized that the objective function selected for calibration was maximizing *NS*, which may have interfered in the values of the other coefficients evaluated.

On the monthly scale, for the average values, the coefficients were similar for C3 and C4, with slight superiority for C4, with the exception of *EV* (-12.10) (Table 2). The values in C3 and C4 showed improvements in comparison with the values accumulated during 10 days, most notice-

Tabela 2 - Efficiency indicators to *EQ* (Estimated Flow) *vs. OQ* (Observed Flow) for different precipitation scenarios in the Japaratuba river basin considering the time scales: daily, ten days and monthly.

Time scale	Indicator	Precipitation scenarios applied to hydrological modeling			
		C1	C2	C3	C4
Daily	r	0.55	0.65	0.54	0.69
	NS	0.29	0.40	0.29	0.47
	EV	-10.99	-6.86	-7.61	-4.45
Ten days	r	0.89	0.75	0.62	0.76
	NS	0.78	0.56	0.35	0.50
	EV	-2.94	-0.65	11.37	-11.06
Monthly	r	0.93	0.79	0.83	0.84
	NS	0.84	0.60	0.69	0.70
	EV	-15.29	14.43	8.62	-12.10

r -Pearson Correlation Coef.; NS - Nash-Sutcliffe Coef.; EV - Percent Volume Error.

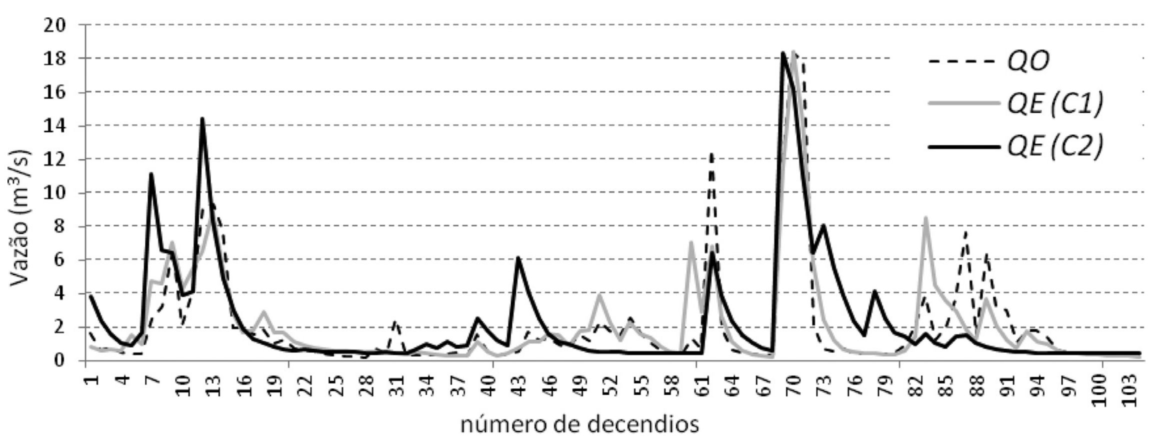

Figura 3 - Observed (*OQ*) and simulated hydrographs (*EQ*) considering punctual precipitations data (scenarios C1 and C2) at the Japaratuba fluviometric station for 10-day time scale, beginning in February 10, 2004 until January 31, 2007.

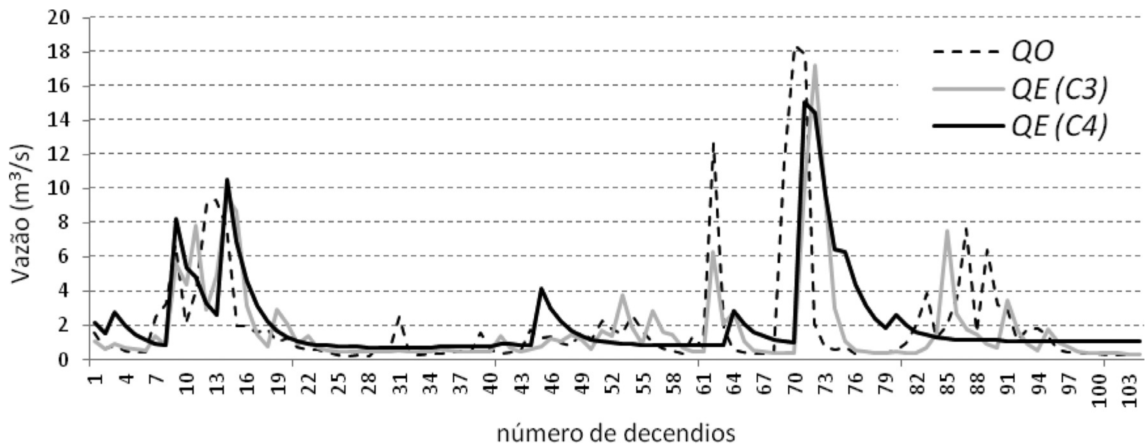

Figura 4 - Observed (*OQ*) and simulated hydrographs (*EQ*) considering the average of precipitations data (scenarios C3 and C4) at the Japaratuba fluviometric station for 10-day time scale, beginning in February 10, 2004 until January 31, 2007.

ably in C3. Like the punctual precipitation data, the average values on a monthly scale had satisfactory efficiency coefficients, which implies that they could be used for modeling purposes.

Still analyzing Table 2, it can be noted that overall the results for average TRMM (C4) had better *NS* and *r* coefficients at all timescales compared with punctual TRMM (C2), with the single except of *NS* at the 10-day scale. Regarding the field data (C1 and C3), contrary to the TRMM, the coefficients were better for punctual precipitation than for average rainfall in almost all cases, with daily and monthly *EV* being the only exception. This may indicate that the chosen pluviograph station is spatially and temporally representative of the precipitation that occurs in the monitored sub-basin, once losses having been noted when performing the weighted average within other rain gauges.

4. Conclusions

1. The direct comparative analysis between the field and satellite precipitation did not indicate the suitability of the TRMM data for any of the selected indicators in the Japaratuba river basin, but does indicate great improvement in the correlation coefficient (*r*) for monthly scale average precipitation, as compared to other temporal scales;

2. The precipitations derived from the TRMM underestimated the precipitation values for all rain gauges used in the study;

3. The analysis on the estimate of flows showed better values for the efficiency indicators on all temporal scales compared with the direct comparison between precipitations;

4. For hydrologic modeling, acceptable values were only obtained for the efficiency coefficients evaluated for the TRMM scenarios on the 10-day and monthly time scales.

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