EVALUATION AND USE OF THE PERSIANN-CDR PRECIPITATION PRODUCT IN A NORTHERN PORTUGAL WATERSHED

Mahdi Alemi [a,b], Vanessa Ramos [b,c] and Rodrigo Maia [a,b]

[a] Departamento de Engenharia Civil, Faculdade de Engenharia, Universidade do Porto, Porto, Portugal.
[b] Centro Interdisciplinar de Investigação Marinha e Ambiental, Universidade do Porto, Porto, Portugal.
[c] proMetheus, Instituto Politécnico de Viana do Castelo, Viana do Castelo, Portugal.
malemi@fe.up.pt & ramosvanessa@esa.ipvc.pt & rmaia@fe.up.pt

ABSTRACT:

This study evaluates the performance of a gridded satellite-based precipitation product, the PERSIANN-CDR, over a river basin in northern Portugal (about 1600 km^2) with a limited number of rain-gauge data. The evaluation was performed (*i*) by considering a direct comparison between two precipitation datasets for the period 1988-2018 and (*ii*) by estimating the corresponding streamflow values during 1992-1998 at a relatively small sub-basin (about 100 km^2) and comparing those with the reference data. For the precipitation comparison, a simple procedure was used to obtain the average precipitation from the rain-gauge data over each grid cell (0.25^o × 0.25^o). Concerning the streamflow values, estimations were performed using the SWAT model. The corresponding comparisons were performed at a monthly time scale. A detailed description of the corresponding comparison procedures is presented. Although PERSIANN-CDR data is adjusted using a 2.5^o monthly global precipitation data, the present results show some differences between the monthly PERSIANN-CDR data and corresponding rain-gauge data at some 0.25^o grid cells over the study area. Concerning the streamflow modeling, although the sub-basin area is smaller than the area of a 0.25^o grid cell, the performance of PERSIANN-CDR is very good and confirms the good agreement between the two precipitation datasets on the corresponding grid cell.

KEYWORDS: Precipitation**;** PERSIANN-CDR; Hydrological Modeling; SWAT; Portugal.

INTRODUCTION

This study focuses on the problem of common and relevant precipitation data gaps, namely in Portugal. Typically, a missing value in a rain-gauge station is estimated based on (i) corresponding data from neighboring stations (sample data) or (ii) available time-series of data for the estimated point. In the former approach (i), the estimation is usually done by spatial interpolation from the sampled points. Therefore, apart from the accuracy of the interpolation techniques, the success of the approach at each estimated point depends on the quality of the corresponding sample data (i.e., in terms of the number of available data and distances to the estimated point). In other words, using poor sample data results in an inaccurate estimation. The latter approach (ii) is based on fitting a probability distribution to each station's data. Thus, a large amount of data at the target station (estimated point) is needed to generalize the corresponding statistical parameters required for the estimations. Overall, besides the accuracy issues, the above-mentioned approaches may not be applicable in the areas with limited rain-gauge precipitation data.

Compared to the rain-gauge data, satellite observations may overcome the deficiency by providing data which are more spatially homogeneous and temporally complete (Sun et al., 2018). Nevertheless, the satellite products are just estimations which have various sources of uncertainty (Bui et al., 2019). A bibliography survey on related works shows that PERSIANN-CDR product, introduced by Ashouri et al. (2015), has attracted the attention of many researchers and several studies have been done to assess its accuracy over different global zones. It is noteworthy to mention that the abbreviation stands for Climate Data Record (CDR) of Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN). In short, the above-referred dataset is adjusted by using monthly 2.5° precipitation data from the Global Precipitation Climatology Project. It provides relatively long-term daily records from January 1983 to the near-present. Moreover, the product makes available the precipitation estimates at 0.25° spatial resolution. Analysis of the previous studies on the product indicates that its performance varies in different global zones. Some of the related works are presented here.

As an early work on the PERSIANN-CDR data, Miao et al. (2015) evaluated the corresponding daily precipitation estimates over China during the period 1983–2006. The results show that the PERSIANN-CDR dataset presents similar precipitation behavior as the ground-based gridded daily dataset in the regions with heavy rainfall events (mostly east of China), whereas the agreement between the two datasets in the dry regions (mostly west of China) is not high. Duan et al. (2016) evaluated the accuracy of the PERSIANN-CDR gridded-data in the Adige River basin, located in Italy, at different temporal (daily, monthly and yearly) and spatial (grid and watershed) scales considering the rain-gauge data from 2000 to 2010. The corresponding results show a poor correlation between the daily PERSIANN-CDR and rain-gauge data at both grid and watershed scales, but a relatively good correlation for the monthly and yearly accumulated precipitation data (derived from, respectively, daily and monthly data). Moreover, the results indicate that the PERSIANN-CDR data are overestimated in the Adige River basin. Alijanian et al. (2017) assessed the performance of the PERSIANN-CDR data over Iran for a ten-year period (2003–2012). The best correlation between daily PERSIANN-CDR data and ground data was observed in the south of Iran (shore of the Persian Gulf) with a very hot and humid climate, while the low correlation corresponded to the moderate and rainy regions (shore of the Caspian Sea in the north of Iran). Further, the monthly rainfall patterns were captured well by the PERSIANN-CDR data in different climate zones of the country. Baez-Villanueva et al. (2018) analyzed the PERSIANN-CDR daily-data from 2001 to 2015 over three different basins in Latin America (i.e., Brazil, Chile and Colombia). The analysis was based on comparing the time series of the rain-gauge data with the corresponding grid-cell satellite data (point to grid-cell analysis). The results show a better performance of the PERSIANN-CDR data, in terms of the modified Kling-Gupta Efficiency index, at the Chilean river basin than that at two other river basins considered.

In addition to the direct comparison between the two precipitation datasets, as mentioned above, several studies were also performed to evaluate the PERSIANN-CDR data for the streamflow modeling. For example, Liu et al. (2017) assessed the PERSIANN-CDR data over the Yangtze River and upper Yellow River basins (with a total drainage area of about 130000 km^2) on the northern Tibetan Plateau using the so-called "Hydroinformatic Modeling System rainfall–runoff model". The calibration of the model was done for the period from 1983 to 1997 and validation of the model for 1998 to 2012. In this study, the Nash–Sutcliffe efficiency (NSE) was obtained by considering the simulated and observed daily streamflow values for both river basins. The obtained results show a "very good" performance of the PERSIANN-CDR data in terms of NSE ($0.77 \leq NSE \leq 0.80$) in both calibration and validation periods. Liu et al. (2018) evaluated the PERSIANN-CDR data over the Lhasa River basin in China (contributing area of about 32000 km^2) by considering the corresponding streamflow values obtained using the so-called "IHACRES rainfall-runoff model", in which the calibration and verification periods were, respectively, 2009–2011 and 2012–2014. The simulated daily streamflow values (in the verification period) were largely overestimated compared to the observed data (PBIAS = -135%, where PBIAS denotes the percent bias). The performance of the model was greatly increased (NSE = 0.7 and PBIAS = -23%) when the PERSIANN-CDR data were corrected using an iterative method, in which a weighting factor was used to reduce the bias between two precipitation datasets. It is noteworthy to note here that the adjustment of the satellite-based precipitation data can be done in different ways. For example, Tobin and Bennett (2010) developed a methodology that adjusts the satellite precipitation data at the grid scale to obtain accurate daily streamflow. The method uses a filter that acts as a mechanism to screen for false alarms and missing precipitation events. Moreover, in this method, the bias correction is based on the transformation of the probability distribution function (PDF) of the satellite product into the PDF of the ground-based precipitation data. Ajaaj et al. (2019) investigated the PERSIANN-CDR product for hydrological modeling of Tigris River basin (with an area of about 450000 km^2), using the Soil and Water Assessment Tool (SWAT). Overall, 10 stream-gauge stations were selected for the comparison study during 1983-1997 (calibration and validation period). The draining areas of the selected stations vary from about 200 km^2 to 150000 km^2. The results show that the performance of the model changes from one station to another. For example, the correlation coefficient between the simulated monthly streamflow and observed data ranges from 0.11 to 0.61. In terms of the NSE, the performance of the model was "unsatisfactory" in 4 stations (i.e., $NSE < 0.5$), but it was mostly "good" in the other stations. Recently, Alnahit et al. (2020) also used the SWAT model to evaluate the 13 years of PERSIANN-CDR data (2001-2014) over two small watersheds (126 and 274 km^2) in the Seneca River basin in the USA. The corresponding results were compared with monthly observed streamflow values by considering NSE, PBIAS and coefficient of determination (R^2). The obtained results ($0.66 \leq NSE \leq 0.75$, $|PBIAS| \leq 18$ and $0.7 \leq R^2 \leq 0.78$) indicate that the model achieved at least a "good" performance in the evaluation period.

The present study was aimed to assess if the PERSIANN-CDR data can be used as a surrogate or supplementary source of the observational data over a river basin with poorly gauged data in Portugal (a common issue in hydrological studies). However, the approach can be applied to any satellite-based precipitation data and over any study area around the world. The main objectives of the present study are then: (i) finding the relationship between the rain-gauge data and the monthly PERSIANN-CDR data over all the grid cells ($0.25^o \times 0.25^o$) representing a northern Portugal river basin selected for this presentation; and (ii) using PERSIANN-CDR data to estimate the corresponding monthly streamflow values at a small sub-basin and comparing those values with referenced data. This last evaluation helps to clarify the accuracy of the PERSIANN-CDR data required for accurate rainfall-runoff transformation.

In this study, the Soil & Water Assessment Tool (SWAT) was used for the rainfall-runoff transformation. A detailed description of the SWAT model has been presented by Arnold et al. (2012). Therefore, the governing equations and model parameters are not repeated here.

CASE STUDY

The selected study area is the hydrological basin of the Cávado River, an area of about 1600 km^2, located in northern Portugal as shown in Figure 1. In summary, the river basin has a relatively high rainfall average (approximately 2000 mm/year). The main watercourse (129 km in length) springs in the Larouco mountain range (in Portugal) at a relatively high altitude and ends up in the Atlantic Ocean. The Cávado River has two main tributaries, namely the Homem River (45 km) on the right bank and the Rabagão River (37 km) on the left bank. Overall, 35 rain-gauge stations (see Figure 1) may directly represent the precipitation over this mountainous basin. However, as seen in Figure 2, the analysis of the corresponding available daily precipitation data for 30 years (from 1988 to 2018) indicates that the number of missing values is significant, justifying the evaluation of a satellite precipitation product for this basin.

It should be mentioned that the study area contains seven dams, which belong to one of the most important hydroelectric systems in Portugal (i.e., Cávado-Rabagão-Homem hydroelectric system). One of those dams is located at the outlet of the Alto-Cávado catchment (about 100 km^2), the upstream part of the Cávado River basin (see Figure 1). The Alto-Cávado catchment was selected in this study for the rainfall-runoff analysis due to the availability of the corresponding natural flow data (inflow to dam).

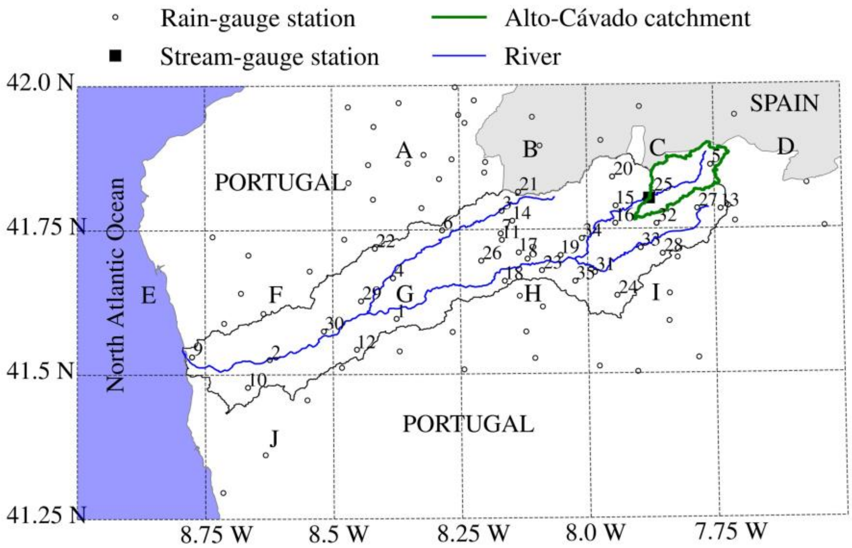

Figure 1.- Cávado River basin and distribution of rain gauges over the PERSIANN-CDR overlapping grid cells (inside and adjacent to the basin)

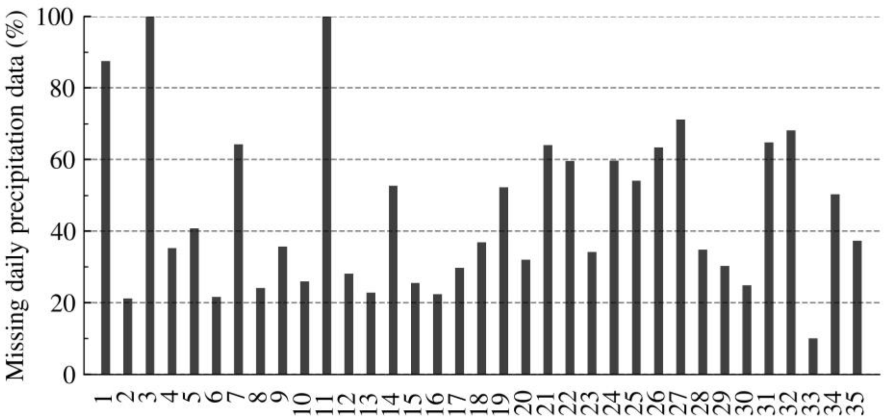

Figure 2.- Percentage of the missing daily precipitation data at the (35) rain-gauge stations located inside the Cávado River basin (for the period 1/10/1988 - 30/9/2018).

MATERIALS

The satellite grid cells considered (identified by letters A to J) and the location of the corresponding 85 rain-gauge stations can be seen in Figure 1. However, the stations with no daily data in the time period of 1/10/1988 to 30/9/2018 (6 stations) were excluded from the calculations. Most of the stations are located in the territory of mainland Portugal and the corresponding data are available at https://snirh.apambiente.pt/, provided by the Portuguese Environmental Agency (APA: Agência Portuguesa do Ambiente). Moreover, 5 Spanish rain-gauge stations (managed by the regional meteorological agency of Galicia, called MeteoGalicia, http://www.meteogalicia.gal/) were also selected for the present study, covering parts of the cells which are not supported by the Portuguese rain-gauge stations. Concerning the satellite-based precipitation data, the corresponding gridded PERSIANN-CDR daily-data were extracted from https://chrsdata.eng.uci.edu/.

Figure 1 also shows the location of the stream-gauge station at the outlet of the Alto-Cávado catchment. The measured streamflow data were obtained from https://snirh.apambiente.pt/, provided by APA. Other weather data (such as temperature, relative humidity, solar radiation, and wind speed) over the Alto-Cávado catchment, required for the rainfall-runoff transformation by SWAT, were obtained from the Climate Forecast System Reanalysis (CFRS) - World weather database (https://swat.tamu.edu/data/cfsr). Besides the weather data, the SWAT model also requires information about the topography, land uses and soil types for simulation. In this study, a Digital Elevation Model (DEM) with a spatial resolution of 25 m was used to quantify the geometric characteristics of the land surface. The DEM is available online at https://land.copernicus.eu/, provided by European Environment Agency. The land use/cover map was obtained from the Corine Land Cover datasets (https://land.copernicus.eu/pan-european/corine-land-cover), and the corresponding land use classes were translated into the SWAT model classification. The soil type over the catchment was obtained from the FAO-UNESCO Soil Map of the World (https://data.apps.fao.org/map/catalog/srv/eng/catalog.search?id=14116#/home).

DATA ANALYSIS

Although both APA and PERSIANN-CDR are daily precipitation datasets, the 24h period for APA begins at 09:00 AM of each day whereas daily PERSIANN-CDR provides accumulated precipitation from 00:00. Therefore, for this study, the comparison was done at a monthly scale (using the daily records) which minimizes the error that arises from the above-mentioned difference in the time origin.

In the present approach, rain-gauge stations were separated into groups based on the grid cells (A - J) they fall within . Then, the corresponding Thiessen polygons were created for each grid cell except for cell E, because this cell contains only one station. Following, spatially-averaged daily precipitation was calculated for each cell using the corresponding available rain-gauge data. It should be noted that any station with a missing daily value was neglected from the averaging. In this case, the precipitation record at each station is given a weight corresponding to the ratio of the area of the corresponding polygon to the total area of the polygons with available data. Moreover, a nominal criterion was defined in which the mean daily precipitation is computed if the area corresponding to the available rain-gauge data is at least 50% of the grid-cell area. Finally, the complete monthly precipitation values (accumulation of the spatially-averaged daily values) were obtained for each cell and compared with monthly values from the daily PERSIANN-CDR gridded-data. A month is considered complete if no day is missing from the estimations. The incomplete months were neglected from the comparison. For this presentation, several evaluation indicators were then calculated to determine the relationship between two monthly datasets. It is noteworthy to mention that a Python script was developed for the above-mentioned data analysis, taking into account that any satellite gridded-data can be evaluated considering the corresponding point rain-gauge records.

It is recalled here that the performance of PERSIANN-CDR data is also evaluated by rainfall-runoff modeling over a small catchment located mostly in the grid cell C. To achieve the goal, the simulated streamflow values (using rain-gauge and PERSIANN-CDR data) are compared with the corresponding observed values. The comparison is done by considering the criteria suggested by Moriasi et al. (2007), based on three statistical metrics to evaluate the model performance for simulation of the streamflow at the monthly time step. The corresponding performance ratings are presented in Table 1. The statistical parameters are described in the next section.

Table 1.- Model evaluation guideline, established by Moriasi et al. (2007), for streamflow simulation at monthly time step.

Performance Rating	NSE	PBIAS (%)	RSR
“Very good”	0.75 < NSE ≤ 1.00	|PBIAS| < 10	0.00 ≤ RSR ≤ 0.50
“Good”	0.65 < NSE ≤ 0.75	10 ≤ |PBIAS| < 15	0.50 < RSR ≤ 0.60
“Satisfactory”	0.50 < NSE ≤ 0.65	15 ≤ |PBIAS| < 25	0.60 < RSR ≤ 0.70
“Unsatisfactory”	NSE ≤ 0.50	|PBIAS| ≥ 25	RSR > 0.70

EVALUATION INDICATORS

The correlation between the two series of monthly precipitation (or streamflow) data was computed using Eq. (1). It has a value between -1 and +1, where +1 indicates a perfect positive linear correlation, 0 means no linear correlation, and −1 is a total negative linear correlation. The Nash-Sutcliffe efficiency (NSE) index was computed through Eq. (2). The index indicates how well the plot of two data series fits the 1:1 line. The index ranges from −∞ to 1, in which the value of 1 corresponds to a perfect match of the model’s results (i.e., PERSIANN-CDR precipitation data or the corresponding simulated streamflow values) to the reference data (observed data). Moreover, values between 0 and 1 are considered acceptable levels of the performance, whereas values ≤ 0 indicate unacceptable performance. The percent bias (PBIAS) was obtained using Eq. (3). It represents the average tendency of the model’s results to the reference data, being optimum with PBIAS=0. Positive values indicate underestimation by the PERSIANN-CDR data, whereas negative values indicate overestimation. Finally, root-mean-square error (RMSE) was calculated to quantify the difference between the two series of data. For this presentation, the ratio of RMSE to the standard deviation of the reference data is reported. The ratio, denoted by RSR in Eq. (4), varies from the optimal value of 0 to a large positive value.

$$r = \frac{\sum_{i=1}^{n}(R_i - \bar{R})\,(M_i - \bar{M})}{\sqrt{\sum_{i=1}^{n}(R_i - \bar{R})^2}\,\sqrt{\sum_{i=1}^{n}(M_i - \bar{M})^2}} \qquad [1]$$

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(R_i - M_i)^2}{\sum_{i=1}^{n}(R_i - \bar{R})^2} \qquad [2]$$

$$\text{PBIAS} = 100 \times \frac{\sum_{i=1}^{n}(R_i - M_i)}{\sum_{i=1}^{n} R_i} \qquad [3]$$

$$\text{RSR} = \frac{\text{RMSE}}{\text{STDEV}_{Ref}} = \frac{\sqrt{\sum_{i=1}^{n}(R_i - M_i)^2}}{\sqrt{\sum_{i=1}^{n}(R_i - \bar{R})^2}} \qquad [4]$$

where *R* and *M* represent, respectively, reference data and model’s results; *n* denotes the number of data pairs; and the overbar indicates mean quantities.

RESULTS

Scatterplots of monthly precipitation datasets at the studied grid cells A-J are shown in Figure 3. Since the calculations were performed for 30 years (1988-2018), ideally, there should be 360 (30×12=360) monthly precipitation values for each dataset. But, from Figure 3, one can see that the number of data pairs (n) is less than 360 because of the missing daily values in both datasets. It is noteworthy to mention that analysis of the PERSIANN-CDR daily-data (not shown here) indicates missing data over the study area for about 150 days, mostly before 2000. Figure 3 also presents a set of equations (obtained from the linear regression analysis), indicating the relationship between the rain-gauge and PERSIANN-CDR datasets at each studied grid cell.

Overall, according to the present results, the two datasets are in good correlation on the monthly time scale. For all the studied cells (except cell E), the lowest level of the correlation was obtained for cell C (r = 0.85), that possibly related to the relatively low number of data pairs (n = 71) at the cell. In fact, higher correlations ($r \geq 0.9$) were obtained when the number of data pairs increased. Concerning cell E, although a relatively good correlation between the two datasets is observed (r = 0.82), the PERSIANN-CDR monthly-data are clearly larger than those obtained from the rain gauges (blue circles are mostly below the bisector line), that attributed to the PERSIANN-CDR data over cell E mostly representing the precipitation over a large part of the ocean that is not in correspondence with mainland rain gauge (see also Figure 1).

Concerning the Nash-Sutcliffe efficiency (NSE), an efficiency of 1 corresponds to a perfect match of the PERSIANN-CDR data to the rain-gauge data. For the studied cells, the NSE ranges from 0.49 to 0.86 (except for cell E discussed before). The lowest NSE value (0.49) was obtained for cell D where the corresponding rain gauges are not well distributed over the grid cell. Overall, as is evident from Figure 3, the blue circles are close to the 45-degree line ($y = x$) at the cells with high NS efficiency. In accordance, the difference between the two datasets (presented by the RSR index) decreases by increasing the NSE. It is recalled that the RSR stands for the ratio of the root-mean-square error to the standard deviation of the observed data.

Analysis of the PBIAS values indicates that the monthly precipitation derived from the daily PERSIANN-CDR data is generally underestimated (positive PBIAS values) in the study area. Exceptions to that are cell D and cell J (see also Figure 1), where the present results show an overestimation of the PERSIANN-CDR. That might be due to the smaller number of rain gauges at those peripheric cells (compared to the other cells), affecting the results of the statistical parameters.

The quality of the monthly PERSIANN-CDR data was also investigated by hydrological modeling of the Alto-Cávado catchment, to evaluate the performance of the data on the rainfall-runoff modeling. The catchment is mostly located in cell C, where the corresponding analysis on the precipitation data showed a good agreement between the two monthly datasets. For a further evaluation on cell C, the corresponding average monthly precipitation values are presented in Figure 4. In other words, the two monthly datasets are now compared at each month. The average value for each month is the mean of the corresponding monthly values available during the study period. The obtained results indicate that both datasets are fairly in agreement at each month (except in November and March), confirming the general proposed equation (y=1.03x) for the relationship between the two datasets at the cell C.

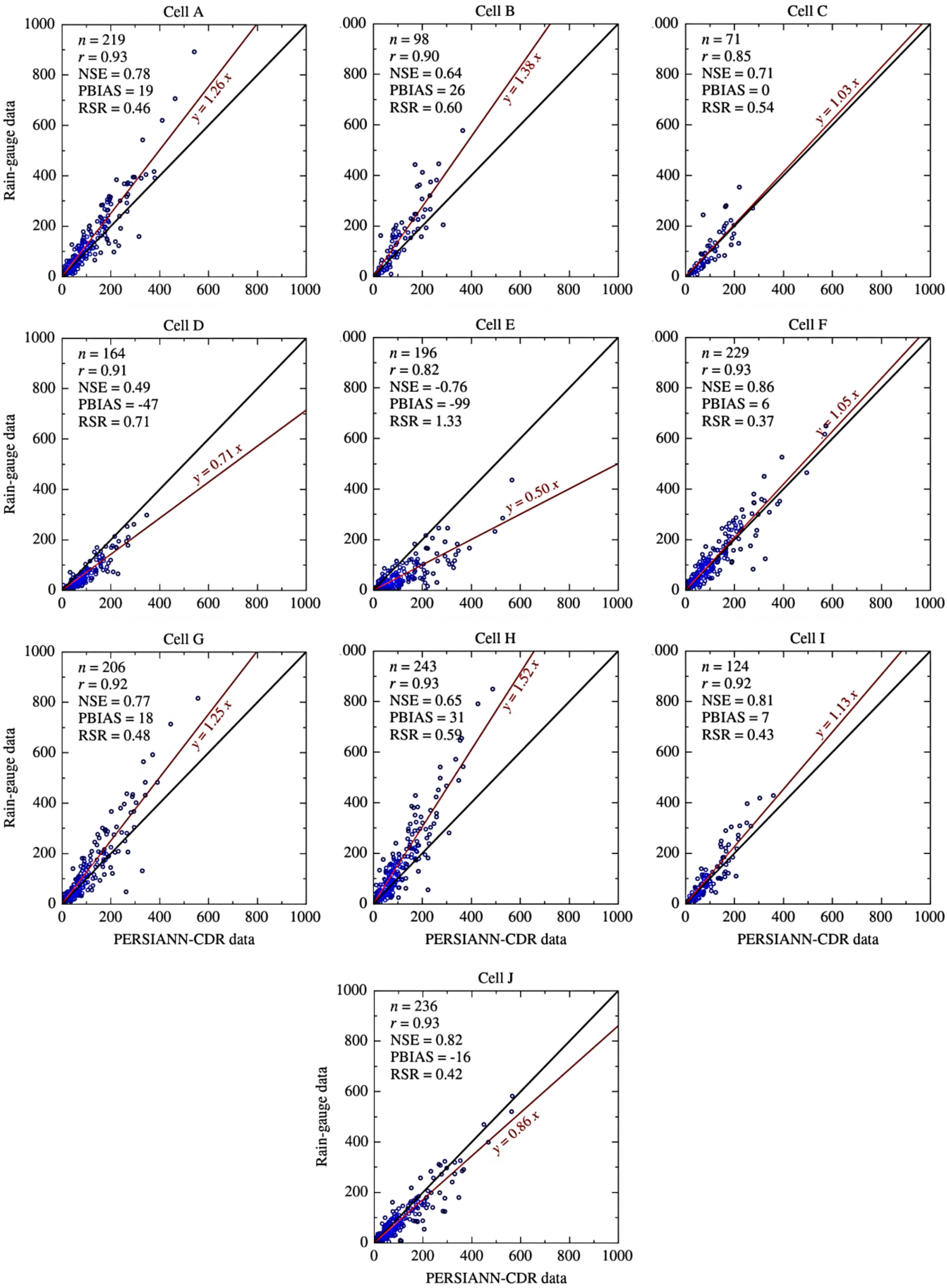

Figure 3.- Scatterplots of the monthly PERSIANN-CDR data vs rain-gauge data, derived from the corresponding daily data, at different grid cells over the study area (study period: 1988-2018).

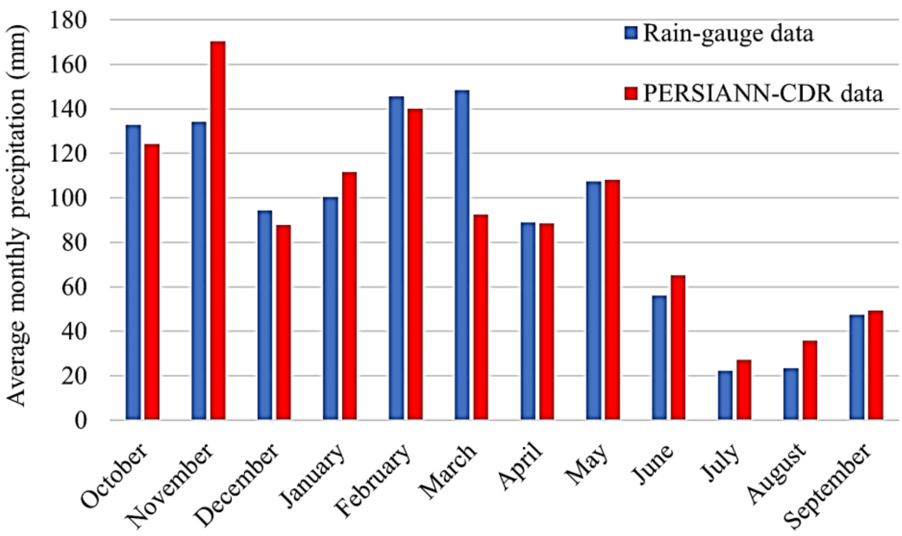

Figure 4.- Comparison of average monthly precipitation (rain-gauge and PERSIANN-CDR datasets) for each month over cell C (study period: 1988–2018).

Regarding the available streamflow and the precipitation data, the hydrological model of the Alto-Cávado catchment was calibrated for the period 1982-1988 and it was validated for 1992-1998. It is to be noted that the model calibration was performed using the rain-gauge data, whereas the model validation was done considering rain-gauge and PERSIANN-CDR monthly datasets individually. Moreover, in this study, a calibration tool (SUFI-2, Sequential Uncertainty Fitting Algorithm) in SWATCUP-2012 (https://swat.tamu.edu/software/swat-cup/) was employed to minimize the difference between observed and simulated monthly flows in the calibration process.

The monthly simulated flow is shown in Figure 5 together with the corresponding observed flow for both calibration and validation periods. According to the obtained results, in the validation period the NSE value driven by rain-gauge data is 0.73, whereas it is 0.81 by PERSIANN-CDR data. Both precipitation datasets underestimate the monthly streamflow in the validation period. The corresponding PBIAS is 22.7% for the rain-gauge data and 11.3% for the PERSIANN-CDR. In terms of RSR, the overall difference between the simulated flow hydrograph using rain-gauge data and observed flow (RSR=0.52) is higher than that between the result for PERSIANN-CDR and reference data (RSR=0.44). Overall, the obtained results for the model validation show a "very good" performance (NSE=0.81, PBIAS=11.3% and RSR=0.44) of the PERSIANN-CDR data (slightly better than that with the rain-gauge data) at the Alto-Cávado catchment when comparing the corresponding simulated streamflow values with those directly measured at the stream-gauge station. It means that the PERSIANN-CDR data are a very good surrogate of in-situ data for this catchment.

CONCLUSIONS

This study assessed the performance of gridded PERSIANN-CDR product over the hydrological basin of the Cávado River located in northern Portugal. For that, the product was compared with rain-gauge data at the grid cell scale ($0.25^{o} \times 0.25^{o}$). The study area has a considerable missing rain-gauge data and that indicates the importance of evaluating an alternative precipitation source for the corresponding hydrological studies. In this study, the comparison between two precipitation datasets was performed at the monthly time. According to the obtained results, although two datasets are fairly in agreements in some regions, the PERSIANN-CDR data are generally underestimated over the study area. The difference between two datasets changes from one grid cell to another, indicating that local adjustments (at the grid scale) might be required to minimize the differences.

The performance of the PERSIANN-CDR data was also evaluated by estimating the corresponding river flow time series at Alto-Cávado catchment in the Cávado River basin. The evaluation was also performed at the monthly time scale. The obtained results show a “very good” performance of the PERSIANN-CDR data at the catchment. In other words, using PERSIANN-CDR data, the hydrological model was able to generate streamflow that agrees well with stream-gauge data. This is following the results of the precipitation data analysis that indicates that the PERSIANN-CDR data agree with the rain-gauge data at the grid cell C, which includes the Alto-Cávado catchment.

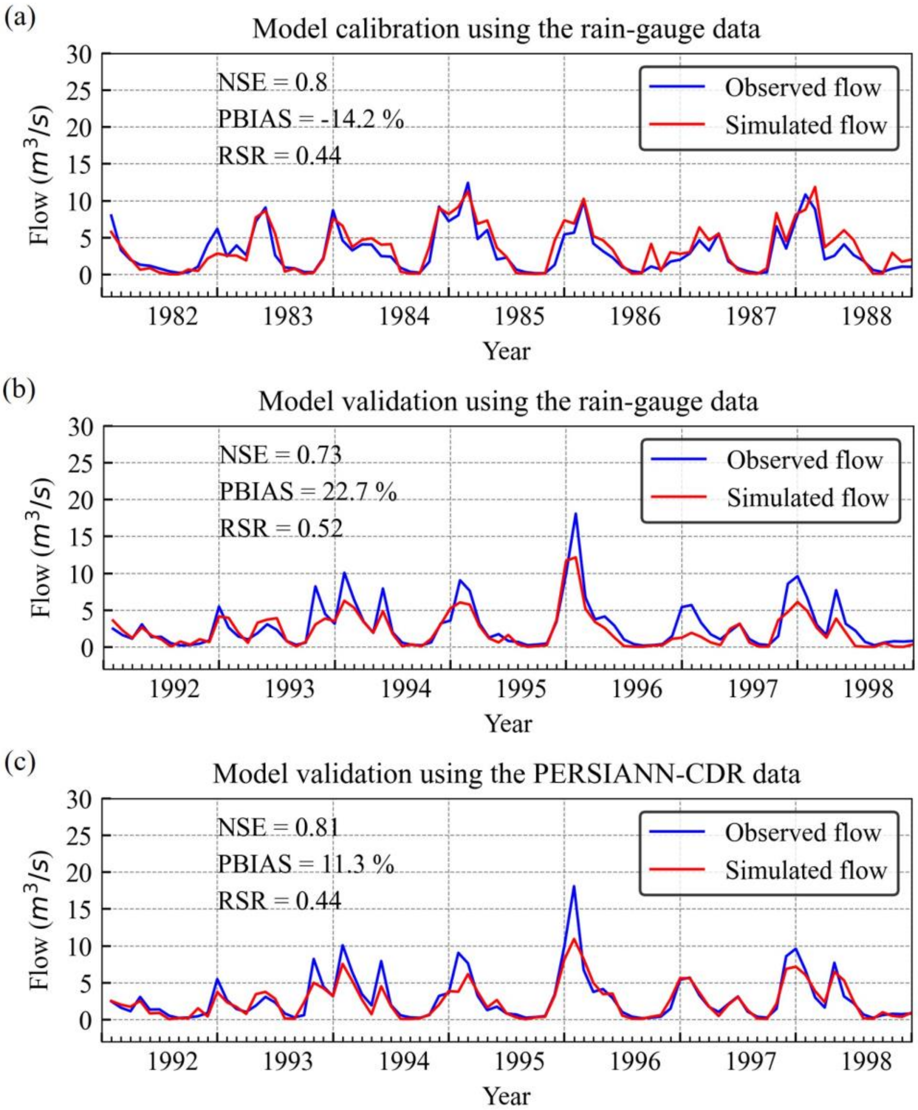

Figure 5.- Model calibration (a); and validation (b, c): comparison between observed and simulated monthly flow hydrograph.

REFERENCES

Ajaaj, A.A., Mishra, A.K., Khan, A.A. (2019). "Evaluation of Satellite and Gauge-Based Precipitation Products through Hydrologic Simulation in Tigris River Basin under Data-Scarce Environment". *J. Hydrol. Eng.* 24, 05018033. doi:10.1061/(asce)he.1943-5584.0001737

Alijanian, M., Rakhshandehroo, G.R., Mishra, A.K., Dehghani, M. (2017). "Evaluation of satellite rainfall climatology using CMORPH, PERSIANN-CDR, PERSIANN, TRMM, MSWEP over Iran". I*nt. J. Climatol.* 37, 4896–4914. doi:10.1002/joc.5131

Alnahit, A.O., Mishra, A.K., Khan, A.A. (2020). "Evaluation of high-resolution satellite products for streamflow and water quality assessment in a Southeastern US watershed". *J. Hydrol. Reg. Stud.* 27, 100660. doi:10.1016/j.ejrh.2019.100660

Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B., Neitsch, S.L. (2012). *Soil Water Assessment Tool, Input/Output Documentation, Version 2012*.

Ashouri, H., Hsu, K.L., Sorooshian, S., Braithwaite, D.K., Knapp, K.R., Cecil, L.D., Nelson, B.R., Prat, O.P. (2015). "PERSIANN-CDR: Daily precipitation climate data record from multisatellite observations for hydrological and climate studies". *Bull. Am. Meteorol. Soc.* 96, 69–83. doi:10.1175/BAMS-D-13-00068.1

Baez-Villanueva, O.M., Zambrano-Bigiarini, M., Ribbe, L., Nauditt, A., Giraldo-Osorio, J.D., Thinh, N.X. (2018). "Temporal and spatial evaluation of satellite rainfall estimates over different regions in Latin-America." *Atmos. Res.* 213, 34–50. doi:10.1016/j.atmosres.2018.05.011

Bui, H.T., Ishidaira, H., Shaowei, N. (2019). "Evaluation of the use of global satellite–gauge and satellite-only precipitation products in stream flow simulations". *Appl. Water Sci.* 9, 1–15. doi:10.1007/s13201-019-0931-y

Duan, Z., Liu, J., Tuo, Y., Chiogna, G., Disse, M. (2016). "Evaluation of eight high spatial resolution gridded precipitation products in Adige Basin (Italy) at multiple temporal and spatial scales". *Sci. Total Environ.* 573, 1536–1553. doi:10.1016/j.scitotenv.2016.08.213

Liu, J., Xu, Z., Bai, J., Peng, D., Ren, M. (2018). "Assessment and correction of the PERSIANN-CDR product in the Yarlung Zangbo River basin, China". *Remote Sens.* 10, 1–18. doi:10.3390/rs10122031

Liu, X., Yang, T., Hsu, K., Liu, C., Sorooshian, S. (2017). "Evaluating the streamflow simulation capability of PERSIANN-CDR daily rainfall products in two river basins on the Tibetan Plateau". *Hydrol. Earth Syst. Sci.* 21, 169–181. doi:10.5194/hess-21-169-2017

Miao, C., Ashouri, H., Hsu, K.L., Sorooshian, S., Duan, Q. (2015). "Evaluation of the PERSIANN-CDR daily rainfall estimates in capturing the behavior of extreme precipitation events over China". *J. Hydrometeorol.* 16, 1387–1396. doi:10.1175/JHM-D-14-0174.1

Sun, Q., Miao, C., Duan, Q., Ashouri, H., Sorooshian, S., Hsu, K.L. (2018). "A Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons". *Rev. Geophys.* 56, 79–107. doi:10.1002/2017RG000574

Tobin, K.J. and Bennett, M.E. (2010). "Adjusting satellite precipitation data to facilitate hydrologic modeling". *J. Hydrometeorol.* 11, 966–978. doi:10.1175/2010JHM1206.1