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Applicability of TRMM Precipitation Product in Qinba Mountainous Area of Shaanxi Province

Chunpanha Khem[1,2], Baowen Yan[1*], Sereyrorth Ouk[1,2]

[1]College of Water Resources and Architectural Engineering, Northwest A&F University, Xianyang, China
[2]Faculty of Hydrology and Water Resources Engineering, Institute of Technology of Cambodia, Phnom Penh, Cambodia
Email: khemchunpanha@yahoo.com, *yanbaowen@nwsuaf.edu.cn

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Abstract

The applicability of Tropical Rainfall Measuring Mission (TRMM3B42V7) precipitation data in the region was evaluated using the measured daily precipitation data in 16 hydrological stations in Shaanxi Province from 1998 to 2014. The evaluation process with several statistical error metrics was applied to daily, monthly, and annual timescale. The results show that the satellite and gauge stations show good consistency for monthly and annual timescale, but rather worse accuracy of daily timescale. All timescales produced the overestimated result of average precipitation measurement. The spatially statistical distribution shows a slight correlation between the observation and satellite estimation, especially at the higher elevation area such as Taibai. The TRMM precipitation value is closer to the gauge station precipitation value at a place with lower elevation, whether the timescale is daily, monthly or annual. At the same time, the smaller timescale leads to closer relations between elevation and metrics. The research results are important value of the research study of meteorological process in the Qinba mountain area.

Keywords

TRMM, Applicability, Precipitation, Qinba Mountain Area

1. Introduction

Capturing accurate spatial and temporal patterns of precipitation is the key variable factor for supporting and analyzing the global water cycle system for water resources development, disaster prevention, and water security in tropical mountains [1] [2] [3]. In the topographically complex area, precipitation patterns are descended from nonlinear terms of geography, elevation gradient, and broad atmospheric circulations [4] [5]. Thus, to obtain reliable precipitation measurement, the traditional rain gauge observation is picked for measurement at the fine-point scale observation [6]. However, the traditional method tremendously depends on the availability of point measurements at a specific site which often comes up with limitations and budget obstacles [7]. Thus, satellite-based precipitation products have emerged as a significant alternative to the restriction of gauge station precipitation measurement, especially where rain gauges are impossible or unreliable [8] [9].

Plentiful experiences of NASA on launching the remotely sensed precipitation products claimed that TRMM (Tropical Rainfall Measuring Mission) has been matured enough for research study. The most noticeable satellite precipitation product, TMPA (TRMM multisatellite precipitation analysis products), which is an algorithm, providing precipitation with nearly zero bias of TRMM Combined Instrument precipitation, has been extensively applied in a variety of research studies because of its high accuracy and applicability [10] [11] [12]. In the northern region of the Himalayan mountain range, the validation of TRMM against observation found that climate and topographical condition are the main factors that affected the bias of precipitation estimation [13]. The comparison of two precipitation products (TRMM and GPM) in a mid-latitude Ganjiang River of China, both IMERG and TRMM revealed similar ability in seizing the precipitation trend, and TRMM has overestimation instead [14]. One study used monthly and seasonal timescale of TRMM 3B42V7 to validate over Columbia explained that error characteristics identified limitations of satellite precipitation products and compose a warning about complex and physiographic climatic pattern established on satellite precipitation missions [15]. In the study of extreme precipitation, TRMM 3B42 product was evaluated in southern IRAN, and the findings prove the ability of TRMM 3B42 product can capture the spatiotemporal interaction of many extreme indices. [16]. In Pakistan, GPM-IMERG and TRMM-3B42 were evaluated throughout 2014 to 2018, and the study shows that topography has effectiveness on satellite's performances. And, precipitation intensity and climatic condition are the variables on which error characteristics of satellite precipitation depend [17].

Spatial and temporal variation of precipitation exhibit great challenges for precipitation estimation, especially the fluctuation of topography area. This made satellite images difficult to precisely capture the precipitation. So far, many studies have performed evaluation satellite precipitation over various terrain complexities. Recently, Sara *et al.* [15] validated the TRMM at monthly and seasonal timescale from 1998 to 2015, and the results show that 3B42 had good performance in the low-lying area but less ability to catch light rainfall and very heavy rainfall. The spotting homogeneous spatial distribution study over the rugged topography of Lebanon using TRMM showed that spatial distribution of maximum rainfall didn't correlate between map and TRMM's map has different trend of Passard's rainfall distribution [18]. The study of evaluation of multiple satellite products with 256 gauge stations from 2014 to 2018 in the complex topography of Turkey showed that TMPA had the least bias but lower than IMERG in daily and monthly, and the overall performance of satellites indicates better in matching daily precipitation [19]. In another study in 2017 [20], GPM and TRMM 3B42V7 have examined the dependency of products in the Tibetan plateau. The results confirmed the precipitation is highly correlated to elevation and intensity.

Many studies try to validate TRMM in different scenarios to use this available dataset for further purposes in scientific research. This present study extensively evaluates TRMM 3B42V7 against the observation data at the transition zone between two different climate conditions of China, Qinba mountain area, over a spanning period of 1998 to 2014 corresponding to the availability of both datasets. The findings of the study will serve as valuable information to the researchers and algorithm developers in describing the efficiency of satellite products for capturing precipitation pattern and hydrological study for this area. This paper is constructed as follows: Section 2 presents the material and methodology of the whole study. Section 3 describes the results and explanations. Section 4 presents the conclusion part of the study.

2. Material and Methodology

2.1. Study Area

The selected study domain, Qinba mountain, is situated in the southern part of Shaanxi Province, China, covering an area of about 77,000 square kilometers, accounting for about 35% of the total area of Shaanxi Province in **Figure 1**. The Qinba area has complex terrain, diverse topography, and is certified as a central-transitional zone of China with high ecological vulnerability and sensitivity [21]. The deep-cut terrain is recognized by steep-slop and impaired by floods, landslides, and other natural disasters such as mudslides [22]. The cold and warm air from north and south, respectively, were bounded by Qinba mountain, which was entitled as the climate frontier spot [23]. The altitude range of this area is 164 - 3748 m above sea level [24]. The area is drained by the Hanjiang River and its distributed streams. During periods of heavy rainfall, natural slopes may be prone to failure. Due to the various climatic characteristics in the area, the annual precipitation in this area varies from 500 mm in the north to 1300 mm in the south [25]. The Hanjiang River Basin has diverse geomorphic features and climate, and diverse hydrological conditions. A continental monsoon and transitional monsoon climate are observed as well as warm temperate and northern subtropical regions [21] [26].

2.2. Satellite TRMM Dataset and Gauge Station Dataset

The synergy of space mission between the National Aeronautics and Space Administration (NASA) and Japanese Aerospace Exploration Agency (JAXA) in 1997 has launched a Tropical Rainfall Measurement Mission (TRMM) to capture

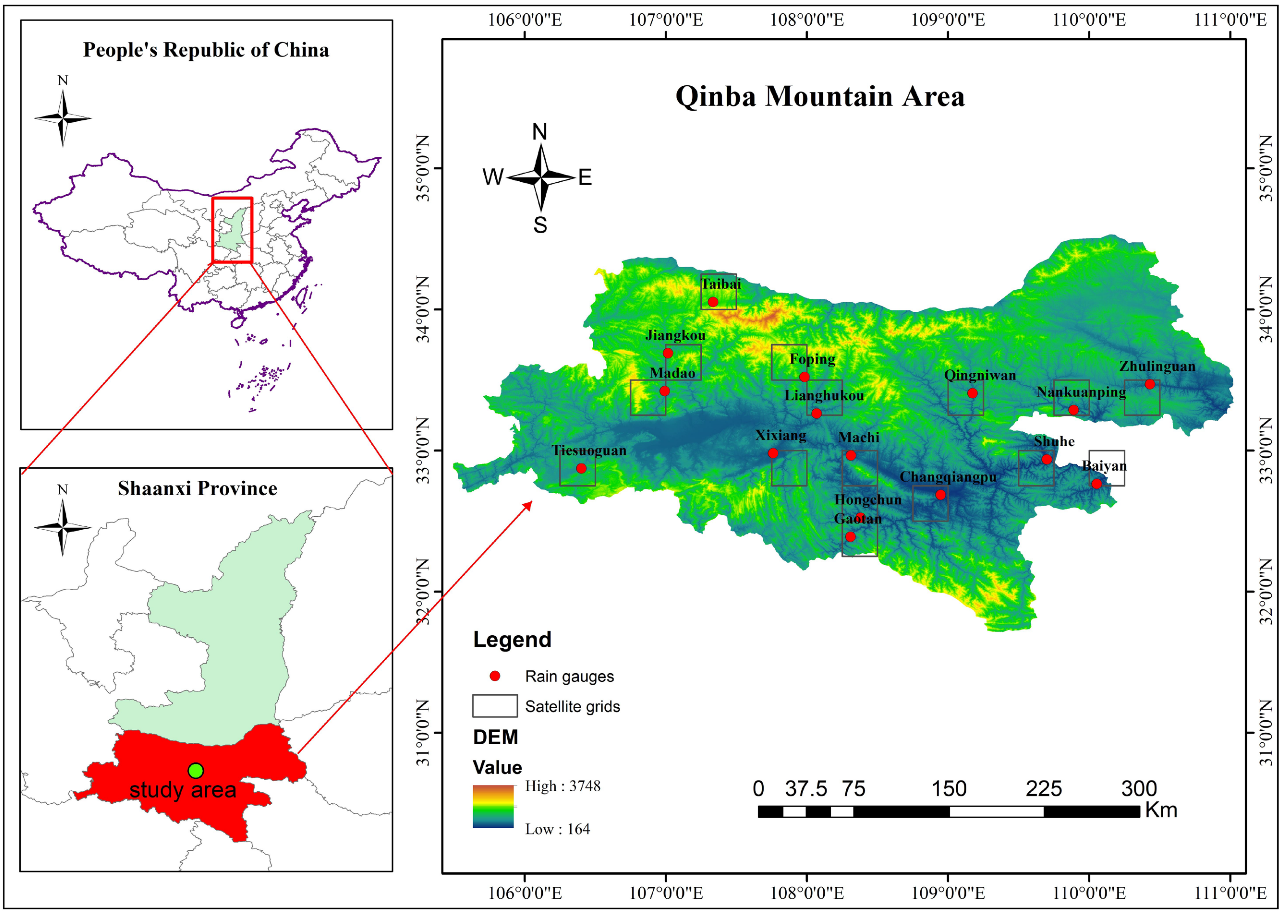

Figure 1. The spatial distribution of rain gauge network, and the geographical elevation pattern over the study area.

the intensity and the spatial coverage of global precipitation over the region, particularly the tropical and semi-tropical climate region. This product floats to the circular orbit clinging by several precipitation measuring instruments such as precipitation radar, Microwave imager, and visible infrared scanner (DISC 2017; [10]). An algorithm, TMPA (TRMM Multi-Satellite Precipitation Analysis) existing among the data product, estimates the 3B42 Version 7 and blends satellite rainfall estimates (S) with gauge data (G) for bias correction. Version 7 of TMPA algorithm was published with three temporal resolutions (3-hourly 3B42, daily 3B42, and monthly 3B43) and a high-temporal resolution of 0.25˚ × 0.25˚ between latitude 50˚N and latitude 50˚S of 3B42V7. Thus, this study selected TRMM3B42V7 for conduction evaluation.

The original dataset of precipitation provided by the Shaanxi Water Resource Exploration Bureau was recorded as daily data (mm/day). According to the basis dataset, we primarily select 16 hydrological stations with daily historical precipitation recording from 1st January 1998 to 31st December 2014 as the gauge station benchmark for study. The selection period of study was considered by corresponding to the availability of TRMM 3B42-V7 (3-hourly 3B42, with the high-temporal resolution of 0.25˚ × 0.25˚ between latitude 50˚N and latitude 50˚S). As an easy way to manage the dataset, the initial dataset was subjected to filling the missing non-precipitation days. For validation purposes, the 16 stations were clipped by the pixel, where it's located. Each station individually stands in a single TRMM pixel as in **Figure 1**. The accuracy evaluation of TRMM-3B42V7 was carried through monthly and annual aggregated timescale based on the daily precipitation. Detailed information of meteorological stations was used in this study listed below in **Table 1**.

2.3. Methodology

The present study adopted the point-to-pixel evaluation method [27] to induce a series of data observed by the rain gauge to be compared with the corresponding satellite pixel of each rain gauge for the whole region. To quantify and evaluate the accuracy of the satellite dataset against the gauge station, three basic statistical metrics were adopted for evaluation in three long-term timescales, daily, monthly, and annual. The correlation coefficient (CC) represents the linear correlation level, measuring the goodness of fit between the satellite datasets and rain gauge datasets [28]. Mean Bias Error (MBE) reflects the actual good measure of model bias and is simply the average of all differences in the datasets [29]. Root Mean Square Error (RMSE) is the measurement of the average error magnitude between datasets. The mathematical equations for statistical metrics are described as below:

Table 1. Detailed information of geography and precipitation of rain gauge.

Station	Longitude (˚E)	Latitude (˚N)	Altitude (m)	Annual precipitation (mm)
Baiyan	110.053997	32.764663	234	670.86
Foping	107.983932	33.520746	831	876.71
Gaotan	108.309166	32.388483	369	1170.98
Hongchun	108.380910	32.524691	349	1147.48
Jiangkou	107.016062	33.690025	889	753.13
Lianghekou	108.069339	33.261934	1336	840.72
Machi	108.311982	32.964445	397	892.90
Madao	106.993274	33.421676	672	871.29
Nankuanping	109.889856	33.287855	584	787.21
Qingniwan	109.174519	33.405550	585	760.40
Shuhe	109.700095	32.937781	207	762.71
Taibai	107.335352	34.053153	1558	738.59
Tiesuoguan	106.402770	32.872456	741	1036.61
Xixiang	107.761191	32.980324	433	863.41
Changqiangpu	108.948267	32.686345	253	870.79
Zhulinguan	110.430847	33.469768	420	754.06

$$\text{CC} = \frac{\sum_{i=1}^{n}\left(S_i - \bar{S}\right)\left(G_i - \bar{G}\right)}{(n-1)\sigma_S \cdot \sigma_G} \tag{1}$$

$$\text{MBE} = \frac{1}{n}\sum_{i}^{n}\left(S_i - G_i\right) \tag{2}$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i}^{n}\left(S_i - G_i\right)^2} \tag{3}$$

where n: number of pair samples; S_i: the estimated values; G_i: the reference gauge values; σ_S: standard deviations of satellite value; σ_G standard deviations of gauge value.

These statistical indices indicate the accuracy of satellite only when the result of MBE and RMSE approach to 0 (perfect) and CC close to 1 (perfect). In this study, the rainfall threshold is 0.1 mm, and it is considered as a no-rain day for daily precipitation less than 0.1 mm/day.

3. Result and Discussion

3.1. Accuracy of TRMM at Different Timescale

Using statistical metrics to analyze the relationship between satellite product and gauge station dataset, the performance's result 3B42V7 against observed data over the whole region are presented in Table 2. The average gauge precipitation of the entire study area is 2.36 mm/day, 71.86 mm/month and 862.37 mm/year, while the mean satellite precipitation of the entire region is 2.45 mm/day, 74.42 mm/day, 893.07 mm/day. In general, the satellite and gauge station show good consistency with correlation coefficient (CC) of 0.91 and 0.79 for monthly and annual timescale, respectively. For daily timescale, the average correlation result between TRMM-3B42 and rain-gauge (CC = 0.18) is shown. Mean bias error (MBE) of TRMM shows error values of 0.21 mm, 6.40 mm, and 76.81 mm for both daily, monthly and annual. Meanwhile, both timescales produced the over-estimated result of average precipitation measurement which confirms by RMSE value of 9.97 mm, 33.63 mm for daily, monthly, and 134.44 for annual timescale.

Figure 2 shows that the TRMM-3B42 has the highest correlation coefficient value (0.59) and the smallest RMSE (6.04 mm) at the station of Baiyan station, while Nankuanping station has the smallest MBE (−0.01 mm). For the daily-based dataset, nearly all of the stations reveal relatively weak correlation coefficient (0.11≤ CC ≤ 0.22), except for the Baiyan station (CC = 0.59) that passes the

Table 2. Statistical results between rain gauge and satellite over the study area.

Statistical Indicators	Index	Daily (mm)	Monthly (mm)	Annual (mm)
Mean (rain gauge, 3B42V7)	Mean	(2.36, 2.45)	(71.86, 74.42)	(862.37, 893.07)
Correlation Coefficient	CC	0.18	0.91	0.79
Mean Bias Error	MBE	0.21	6.40	76.81
Root Mean Square Error	RMSE	9.97	33.63	134.44

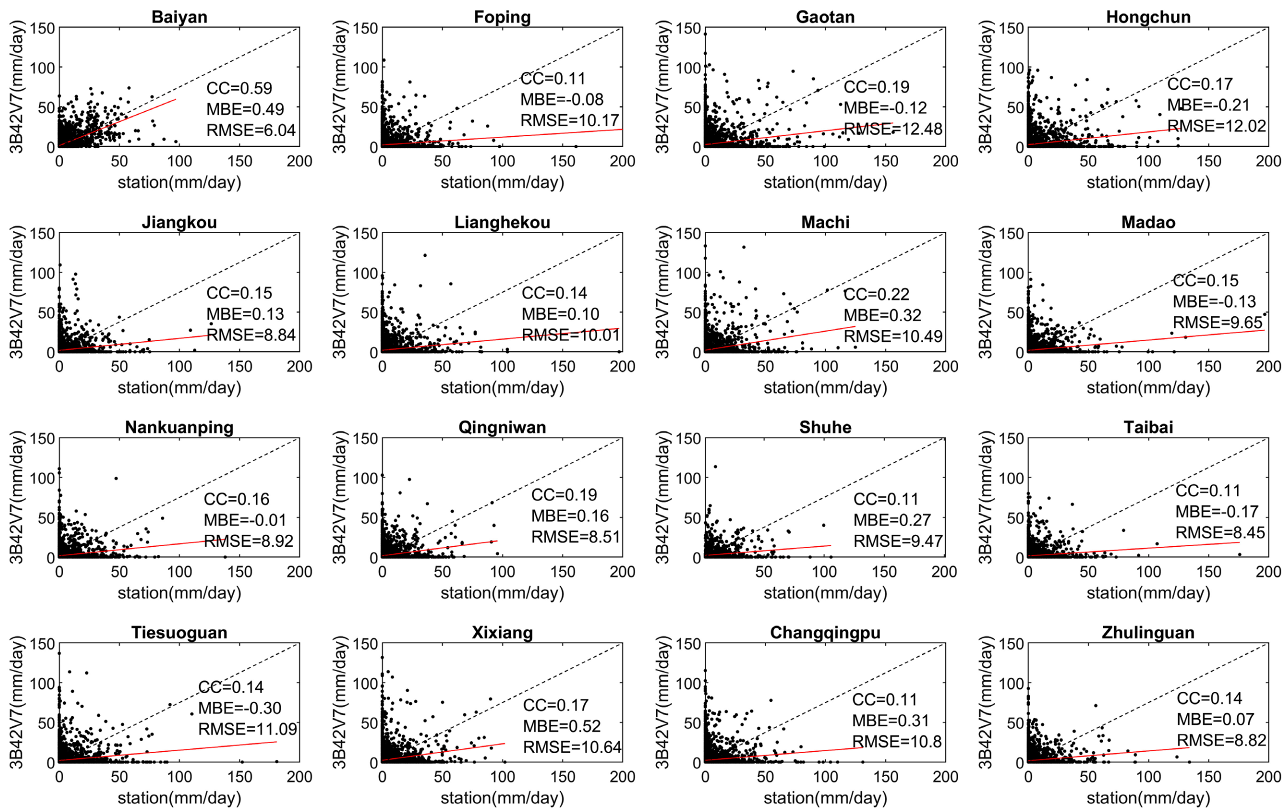

Figure 2. Scatter plots of precipitation between satellite data (TRMM-3B42) and corresponding gauge data at daily timescale, during 1998-2014. The black dot spot represents point data; the dashed line is the 1:1 line; and the red solid one indicates the linear fitting line.

good rank of the correlation coefficient. The MBE matrice indicated both overestimation and underestimation. The MBE shows underestimated value of MBE (−0.3 to −0.01), for most stations with an elevation up to 580 m such as Foping, Madao, Nankuanping, Taibai, Tiesuoguan, except for Gaotan, Hongchun, whereas others show overestimated (0.07 to 0.49). The RMSE reflected the highest value at Gaotan (12.48) and the lowest value at Baiyan (6.04).

The scatter plots of the dataset at different timescales are brought to discuss. Figure 3 and Figure 4 illustrate the scatter plots of monthly and annual timescale datasets from TRMM-3B42V7 against with gauge dataset for every single station over Qinba mountain area, respectively. Based on the plots in Figure 3, it is evident that there is a close relationship between the TRMM-3B42V7 and rain gauge, and it proved that the satellite dataset can depict the precipitation distribution in the study area. The correlation coefficient is considerably high on each station. Among them, the least correlation is found in Foping station, while the highest correlation appears in Changqingpu, with a value ranging from 0.87 to 0.94, respectively. As for numerical differences, the satellite precipitation values appear to be overestimated with MBE of 2.04 mm in Zhulinguan station to 15.71 mm in Xixiang station, while underestimation is found −9.15 mm in Tiesuoguan station to −0.42 mm in Nankuanping station. In terms of error magnitude, RMSE shows overestimation which ranges from 24.55 mm (Jiangkou) to 43.44 mm (Xixiang).

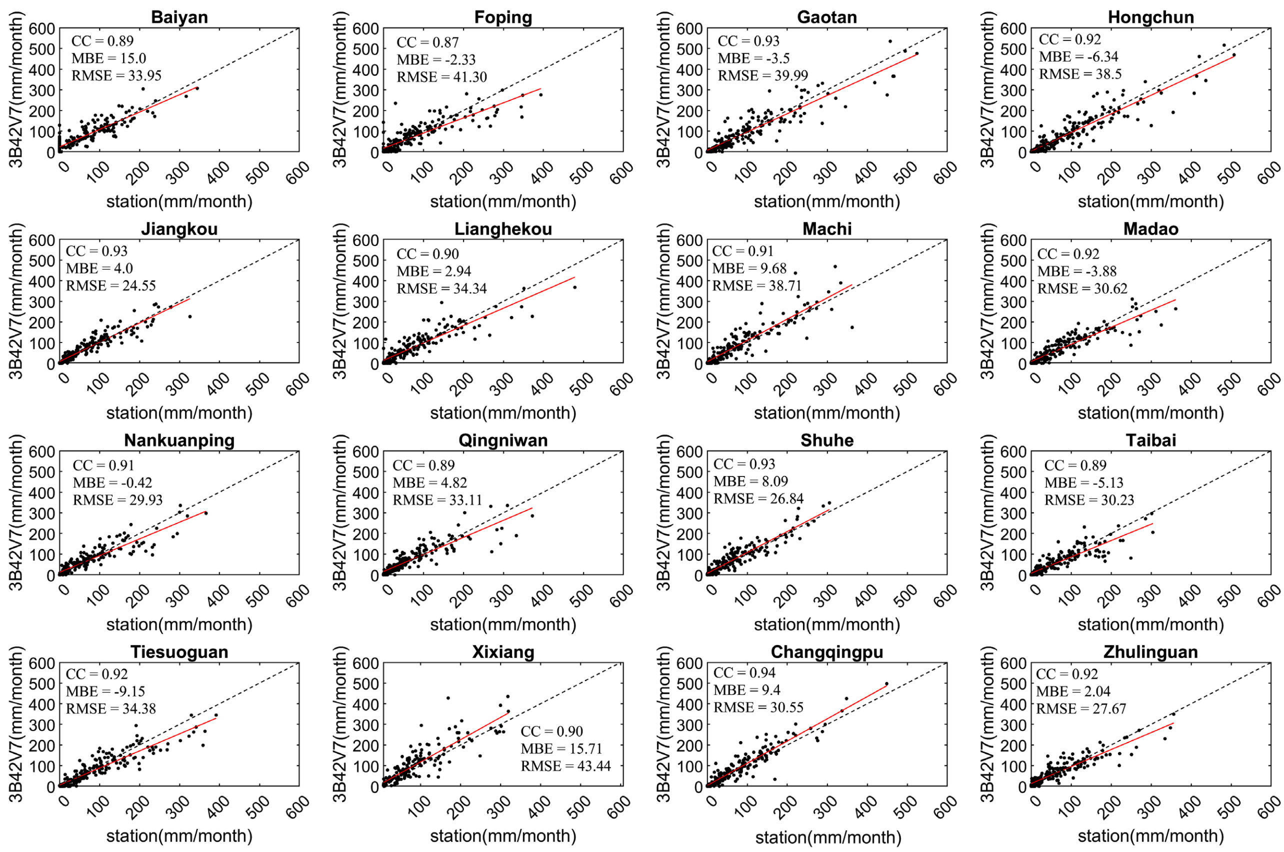

Figure 3. Scatter plots of precipitation measured by satellite data (TRMM-3B42) and corresponding gauge data at monthly timescale, during 1998-2014. The black dot spot represents point data; the dashed line is the 1:1 line; and the red solid one indicates the linear fitting line.

According to **Figure 4**, the ability to depict the annual precipitation of TRMM-3B42 shows lower consistency in comparison to monthly timescale. The result shows that the correlation coefficient for all stations is between 0.61 (Taibai) to 0.93 (Changqingpu), except for the inconsistent correlation of station Foping with CC of 0.36 (**Figure 4**). For MBE, the maximum underestimation is found in the Tiesouguan station (−109.74 mm), whereas the maximum overestimation is observed in the Xixiang station (188.48 mm). Similar to the monthly timescale, RMSE results show overestimation, the least overestimation is Nankuanping (66.65 mm) and the largest overestimation is Baiyan (219.59 mm).

The application of remote-sensing precipitation data has addressed the further comprehension of hydrological variation patterns in the area where the difficulty of collecting fine-scale data has existed. The evaluation of the satellite dataset with the corresponding gauge dataset brought the determination of the ability, reliability, and limitation of satellite performance in the region. The present study reveals the results of different timescale evaluations that annual and monthly timescale have better results as compared to daily timescale. This corresponding pattern has been found in the study of different satellite precipitation evaluations over Pakistan and Hexi region of China [17] [28]. In addition, this observation was also found in other satellite precipitation datasets such as CHIRPS,

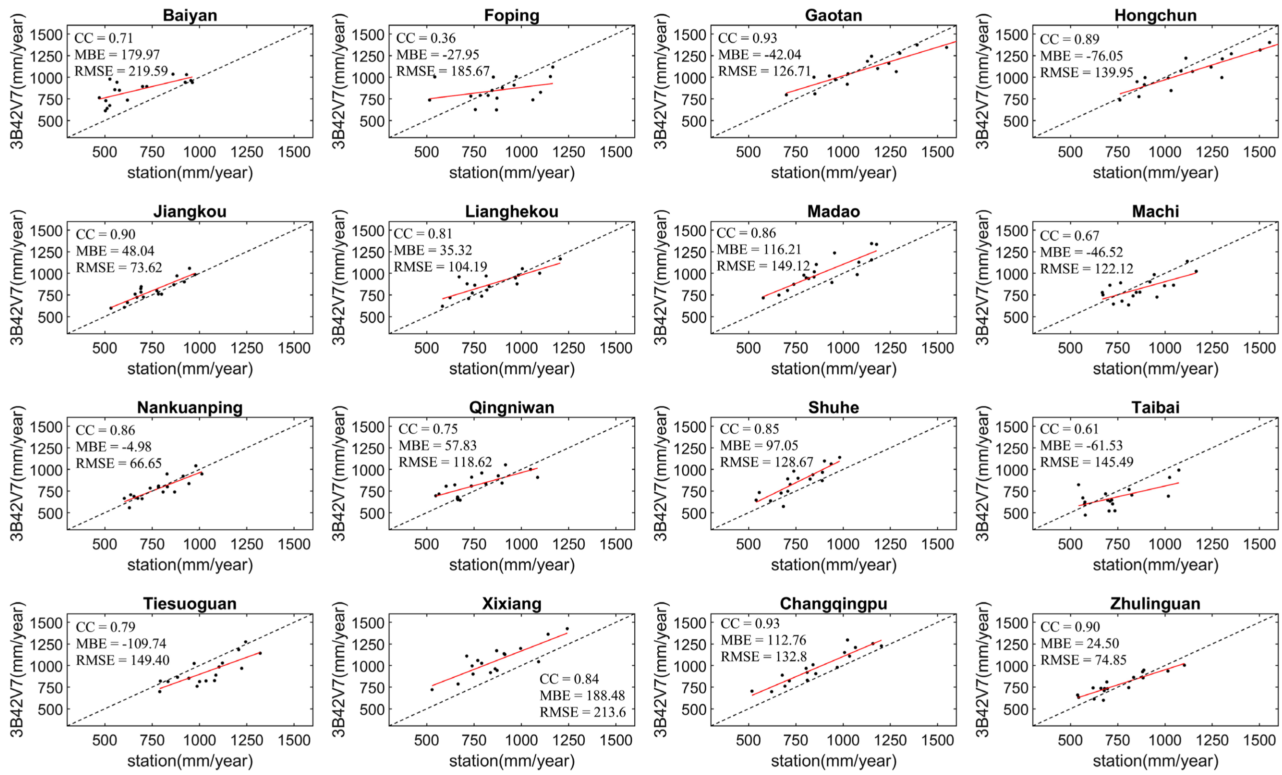

Figure 4. Scatter plots of precipitation measured by satellite data (TRMM-3B42) and corresponding gauge data at annual timescale, during 1998-2014. The black dot spot represents point data; the dashed line is the 1:1 line; and the red solid one indicates the linear fitting line.

GPM, and PERSIANN which was applied for validation of satellite precipitation products in Indonesia and Malaysia [30] [31]. For the overall accuracy of the TRMM3B42 satellite in Qinba area (Table 2), the above results reveal lower accuracy in comparison to the validation study in the southeastern part of China [32] [33] [34]. This discrepancy of TRMM due to a few significant factors affected the ability detection of satellite products such as geographical location, atmosphere condition, and surface coverage [35] [36]. Plus, the TRMM3B42V7 combined with extra satellite data and global precipitation data to conduct bias correction, thus, satellite products will be influenced by gauge factors [37] [38].

3.2. Spatial Distribution of Statistical Index at Different Timescale

The value of statistical indices, spatially distributed over the study region, illustrates the trend pattern of reliability between satellite product and observation measurement. To analyze the error indices of 3B42 product and topography features over the study period, the three statistical indices include CC, MBE, RMSE are adopted for calculation and spatially plot over the Qinba region for daily (A-C), monthly (D-F), and annual (G-I) in Figure 5. As observed in Figures 5(A)-(C), the spatially statistical distribution shows a slight correlation between the observation and satellite estimation, especially at the higher elevation such as Taibai. The mean bias error appears with the high range at the southeast

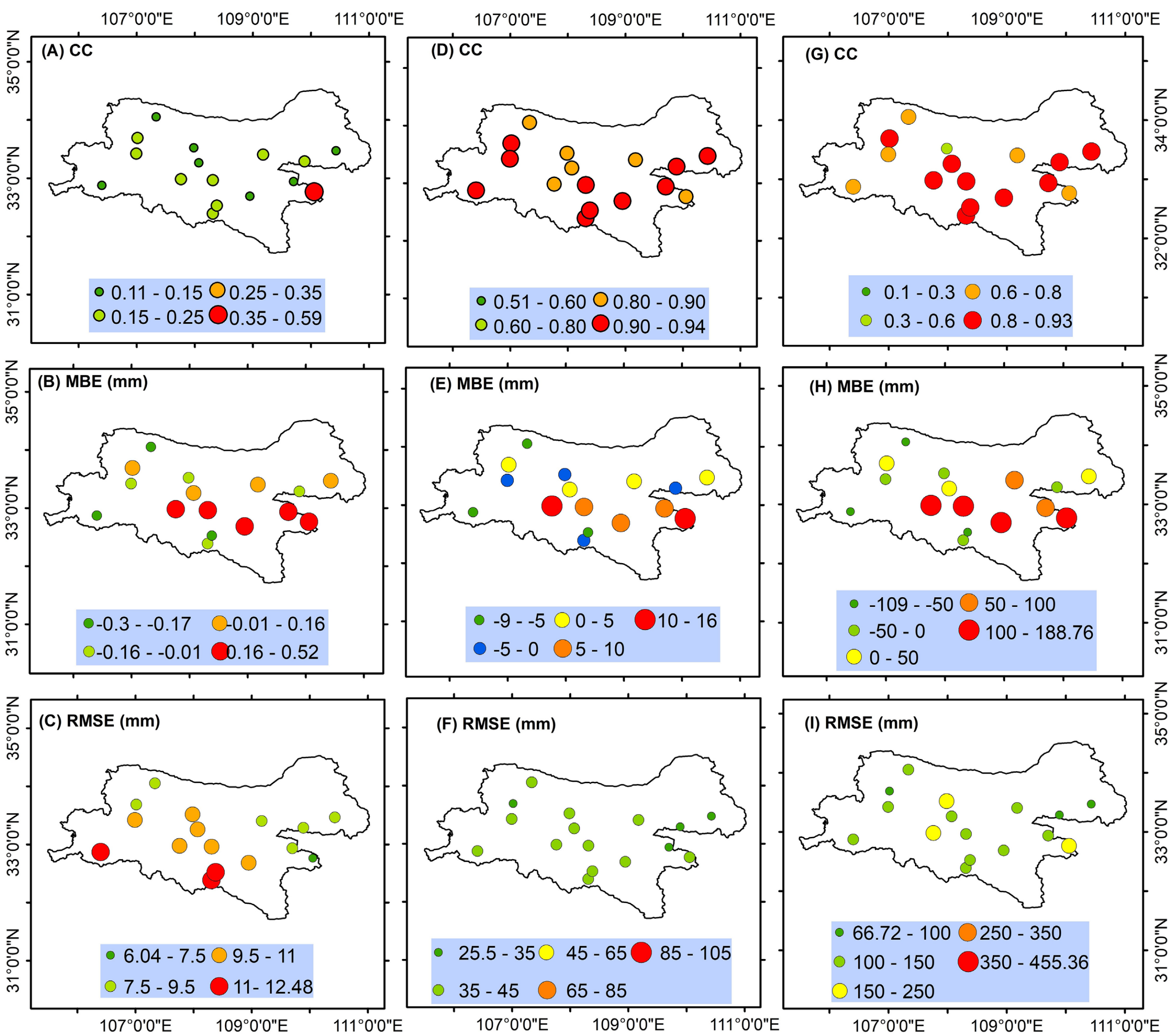

Figure 5. Spatial distribution of statistical indices based on daily precipitation (A-C), monthly precipitation (D-F), and annual precipitation (G-I)) from 1998 to 2014.

part of the region. Plus, the noticeable value of RMSE indicates at the south and the southwest of Qinba, while the less extreme value of RMSE is at the east side and upper part.

On the monthly timescale, a good agreement with gauge station data has been found in Figures 5(D)-(F). The CC values of all stations are higher than or equal to 0.86, and more than 10 rain gauges consist of CC values that are higher than 0.90 as shown in the figure. As appeared in the figure, the variation of correlation varied from lower elevation less than 600 m (better correlation value) to higher elevation above 600 m (slightly lower correlation value). The systematic bias (MBE) of 3B42-V7 appeared to be overestimated at the southeast part of the study area while underestimation existed in the northwest region. However, the bias of satellite performance compared to rain gauge is relatively small and it can be assumed that satellite performance is acceptable for representing the rain gauge. The error magnitude of satellite product measured by RMSE ranges shows a significant decreasing trend from west to east, north to south in **Figure 5(C)**. The distribution of statistical indices based on the annual scale is shown in **Figures 5(G)-(I)**. The CC value shows a great trend over the area, except for the west side slightly lower respected to the middle area. The error magnitude of TRMM measured by RMSE increases in quantity and this similar trend is found on the monthly scale.

The spatial pattern of correlation coefficient values is found better for the site at lower elevation, while lower correlation values are found to be located at higher elevation for all timescale in **Figure 5**. Similar conditions are consistent with the study of drought monitoring in Malaysia and the lower correlation coefficient was observed at the mountainous zone [39]. However, [37] [40] found different observations in the study that the higher elevation, mountain area, has superior correlation for both gauge station and satellite dataset. The consequences from these studies expressed that different geographical location and precipitation pattern are the main cause of different consequences.

3.3. Reliability of Satellite Performance on Elevation/Rainfall Intensity

To analyze the relationship between statistical metrics and elevation, scatter plots of three statistical indicators for each station against its elevation were shown in **Figure 6**. All three-evaluation metrics show a similar trend for both daily based,

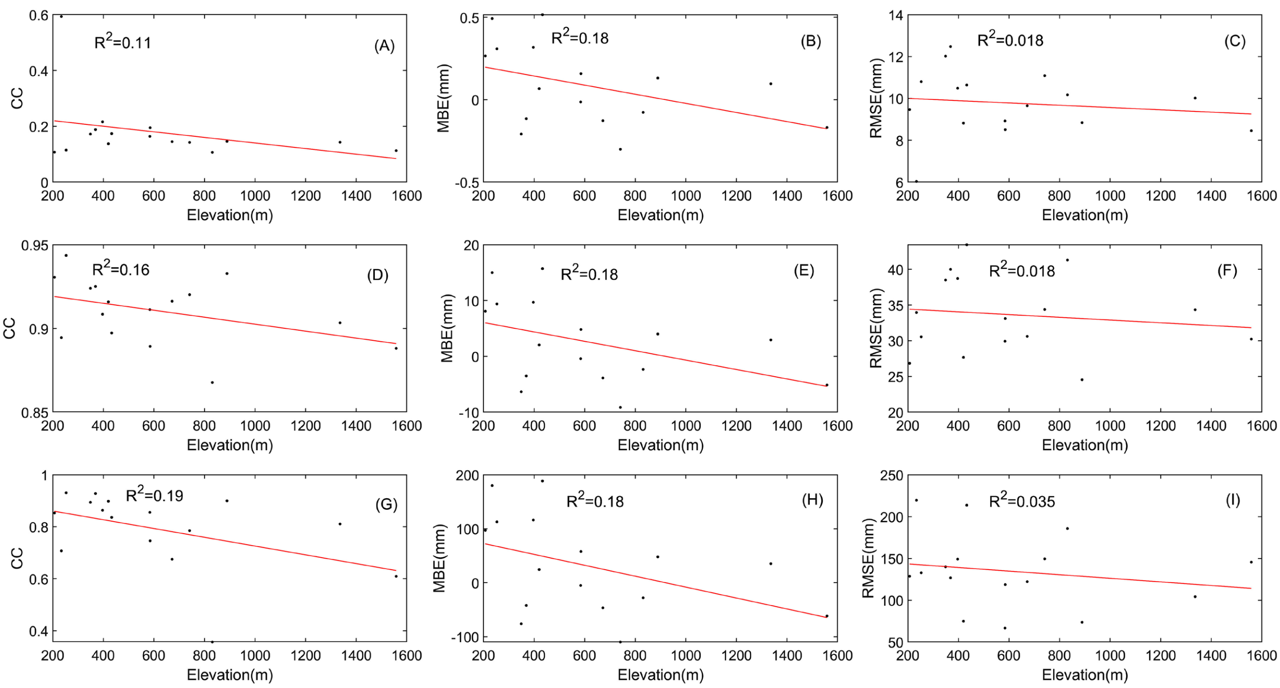

Figure 6. Relationship between statistical metrics and elevation for TRMM_3B42V7 based on daily data (A, B, C), monthly data (D, E, F), and annual data (G, H, I). Each point stands for the rain gauge. The straight red line indicates the linear fitting line.

monthly based, and annual based. With the increase of elevation, CC, MBE, and RMSE decrease. These characteristics can be observed on the linear regression line of the scatter plots. Among three of them, RMSE shows a little different slope. Among the three timescales, the better linear relationship of metrics and the elevation is the relationship based on the annual data (Figures 6(G)-(I)). This indicated that the metrics of annual precipitation are relatively related to the elevation. In addition, the value R^2 of CC, MBE, RMSE, belong to the annual timescale, also further confirmed that the smaller timescale leads to the larger relations between elevation and metrics.

The distributions of three timescales of the relationship between indices and precipitation are shown in Figure 7. The trend of the relation of metrics and precipitation is similar for all metrics at all timescale. It can be observed that the increase of precipitation (mm) shows the increment of metrics values. Based on the linear line in Figure 7(C), the RMSE (daily data) has better relation with increase of precipitation than that of monthly and annual. More importantly, the CC of daily data seems no relation with precipitation ($R^2 = 0.002$), compared to monthly and annual.

The increasing trend of the three indices with precipitation intensity shows increasing indices values corresponding with increasing intensity levels. This study results found identical answers with the study from [20]. The consistency of these results can be due to the approximate amount of average precipitation in the study area, in which the average precipitation is about 2.36 mm/day and 2.42 mm/day in Qinba and southern Tibetan plateau, respectively.

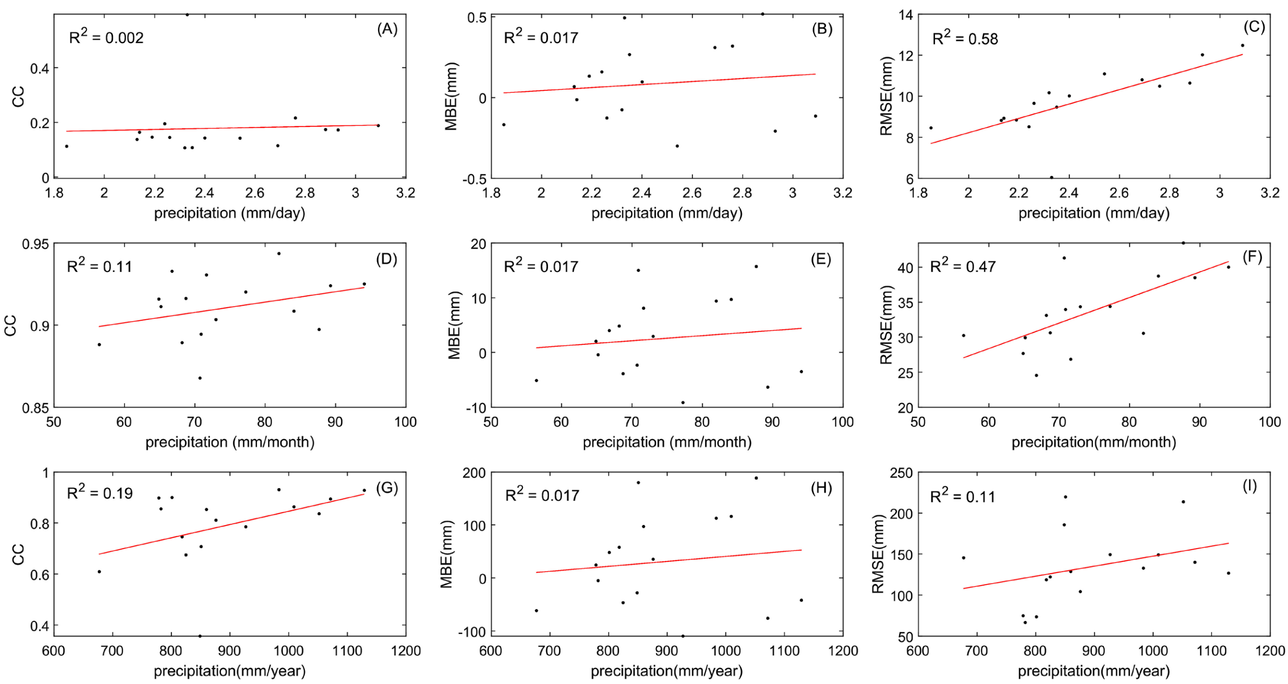

Figure 7. Relationship between statistical indices with average precipitation based on daily data (A, B, C), monthly data (D, E, F), and annual data (G, H, I). The straight red line indicates the linear fitting line.

4. Conclusions

Accuracy of satellite precipitation products acts as the crucial implementation of the hydrological study, especially the region with complex geographical terrain. This study evaluates the TRMM3B42V7 from 1998 to 2014 over Qinba mountain, using gauge station datasets as reference. The statistical metrics were adopted for point to pixel evaluation. The ability of the satellite to depict the rainfall in the area was notified as below:

1) In the Qinba mountain area of Shaanxi, precipitation from the satellite and gauge station show good consistency with correlation coefficient (CC) of 0.91 and 0.79 for monthly and annual timescale, respectively. The average correlation result between TRMM-3B42 and rain-gauge is lower, just 0.18 for the daily timescale. Mean bias error (MBE) of TRMM shows slight errors with values of 0.21 mm, 6.40 mm, and 76.81 mm for both daily, monthly and annual. Meanwhile, both timescales produced the overestimated result of average precipitation measurement which confirms by RMSE value of 9.97 mm, 33.63 mm for daily, monthly, and 134.44 for annual timescale.

2) Spatially statistical distribution shows a slight correlation between the observation and satellite estimation, especially at the higher elevation such as Taibai. The mean bias error appears with the high range at the southeast part of the region. The value of RMSE indicates at the south and the southwest of Qinba, while the less extreme value of RMSE is at the east side and upper part.

3) With increasing elevation, CC, MBE, and RMSE decrease mean that TRMM precipitation value slightly correlates to gauge station precipitation value at a place with higher elevation, whether the timescale is daily, monthly or annual. At the same time, the smaller timescale tends to larger relations between elevation and metrics.

The conclusion of this study recommends that whether the TRMM3B42V7 can capture the spatial-temporal precipitation in Qinba mountain, the error of satellite still exists and needs further improvement. In addition to the ability to capture precipitation in monthly and annual timescale, the daily precipitation should be more accurate and data correction procedure for long-term timescale should be done for further study.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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