Evaluation of TRMM precipitation and its application to distributed hydrological model in Naqu River Basin of the Tibetan Plateau

Denghua Yan, Shaohua Liu, Tianling Qin, Baisha Weng, Chuanzhe Li, Yajing Lu and Jiajia Liu

ABSTRACT

The Tibetan Plateau (TP) is the roof of the world and water towers of Asia. However, research on hydrological processes is restricted by the sparse gauge network in the TP. The distributed hydrological model is an efficient tool to explore hydrological processes. Meanwhile, the spatial distribution of precipitation directly affects the precision of distributed hydrological modelling. The latest TRMM 3B42 (V7) precipitation was evaluated compared with gauge precipitation at station and basin scales in the Naqu River Basin of the TP. The results show that Tropical Rainfall Measuring Mission (TRMM) precipitation overestimated the precipitation with BIAS of 0.2; the intensity distributions of daily precipitation are consistent in the two precipitation data. TRMM precipitation was then corrected by the good linear relation between monthly areal TRMM precipitation and gauge precipitation, and applied into the Water and Energy Process model. The results indicate that the simulated streamflow using both precipitation data produce a good fit with observed streamflow, especially at monthly scale. Furthermore, the better relations between average slopes and runoff coefficients of sub-basins from the corrected TRMM precipitation-based model implies that the spatial distribution of TRMM precipitation is closer to the spatial distribution of actual precipitation, and has an advantage in driving distributed hydrological models.

Key words | distributed hydrological model, hydrological simulation, Naqu River Basin, precipitation, TRMM

INTRODUCTION

The Tibetan Plateau (TP), with an average altitude of over 4,000 m above sea level, is referred as the roof of the world (Royden \textit{et al.} 2008). With more than 36,000 glaciers having a total volume of over 4,000 km$^3$ located in the TP (Yao \textit{et al.} 2007), the TP is the headwater area of several major rivers (e.g. Nujiang-Salween, Yellow River, Yangtze River, and Lancang-Mekong River) in Asia. Nevertheless, research on hydrological processes of the region is rare, and limited by the sparse gauge network in the TP, especially around the source of Nujiang-Salween. On the one hand, the extremely high altitude and low population density result in a low density gauge network, which is a challenge for hydrological simulation due to the lack of accurate spatial distribution of meteorological elements (Wu \textit{et al.} 2015). On the other hand, the observed streamflow of Nujiang-Salween is scarce in the region. Therefore, hydrological research is seriously limited by the inadequate hydro-meteorological data and cannot support water resource management in Nujiang-Salween.

Distributed hydrological models have been used to investigate the hydrological processes and support water resource management due to the ability to describe spatial
heterogeneity, which consists of the underlying heterogeneity and meteorological heterogeneity (Li et al. 2012). The former can be represented by the spatial distribution of a digital elevation model (DEM), soil type, and land use. The latter includes the spatial distribution of precipitation, temperature, wind speed, and other meteorological elements. Nevertheless, the spatial distribution of meteorological elements is uncertain and inaccurate due to the influence of complex topography and the low density of the meteorological gauge network, especially the uneven spatial distribution of precipitation, which is the dominant meteorological element in driving distributed hydrological models (Gourley & Vieux 2006; Taesombat & Sriwongsitanon 2009) and usually obtained from rain gauges by spatial interpolation such as the Thiessen polygon method (Tabios & Salas 1985; Li et al. 2012).

A number of quasi-global satellite-based precipitation products have been developed and applied to improve the accuracy (ACC) of spatial precipitation distribution in hydrological modelling (Stisen & Sandholt 2010). Among them, the Tropical Rainfall Measuring Mission (TRMM) from the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency is an active instrument dedicated to the measurement of precipitation from a satellite platform conjointly with a radiometer (Kirstetter et al. 2013) that generates a series of widely used precipitation products with a near-global coverage and adequate spatial-temporal resolution from 1997 to present (Huffman et al. 2007, 2010). The most popular TRMM products are the post-real-time research products, which have been globally applied in driving hydrological models. The earlier post-real-time research product (TRMM 3B42V6) has already been used in hydrological simulation in Africa (Hughes et al. 2006; Li et al. 2012), Latin American (Colischonn et al. 2008; Su et al. 2008; Tobin & Bennett 2009), and South Asia (Finsen et al. 2014). With the upgrade of TRMM 3B42V6 to version 7 (TRMM 3B42V7) in May 2012, TRMM 3B42V7 has been compared with the TRMM 3B42V6 and gauge precipitation in hydrological simulation in South Asia (Xue et al. 2013), South American (Zulkafli et al. 2014), and Africa (Adjei et al. 2015). In contrast, researches on the application of TRMM products in driving hydrological models started late and advanced fast in China. TRMM 3B42V6 has been applied in driving hydrological modelling in the Xinjiang River, Poyang Lake Basin (Li et al. 2012), Laohahe Basin (Yong et al. 2012), the source of the Yellow River (Meng et al. 2014), and the Xiangjiang River Basin (Xu et al. 2015). Wang et al. (2015) compared TRMM 3B42V7 with other satellite-based precipitation products in hydrological modelling of the Lhasa and Gongbo Basins, two tributaries of the Yarlung Zangbo (Upper Brahmaputra) River. Zhang et al. (2016) investigated the reliability of satellite products, including TRMM 3B43V7, in the water balance of the Yangtze River Basin. The results of the aforementioned researches are generally consistent and suggest that TRMM products can be an efficient source of precipitation data for hydrological modelling, but need correction, and while unsuitable for daily streamflow simulation achieve better performance in monthly streamflow simulation (Xu et al. 2015). The performance of TRMM 3B43V7 in hydrological modelling produces a significant improvement on TRMM 3B43V6 (Xue et al. 2013; Zulkafli et al. 2014). However, the new TRMM 3B42V7 has rarely been applied to hydrological modelling in China. Besides, hydrological research on the source of the Nujiang-Salween River is scarce due to the low density of gauge station networks and the inadequate hydro-meteorological data. Therefore, the objectives of this paper are designed to: (1) evaluate TRMM 3B42V7 (TRMM precipitation henceafter) in comparison with gauge precipitation in the Naqu River Basin; and (2) compare the application of TRMM precipitation and gauge precipitation in driving distributed hydrological models in the Naqu River Basin.

STUDY AREA AND DATA PREPARATION

Study area

The Naqu River basin, with an area of about 76,000 km², is the upstream basin of Nujiang (upper Salween), ranging from 91°10' E to 96°20' E and 29°55' N to 32°50' N. It is a typical high altitude basin with an average altitude of about 4,800 m above sea level located in the east of TP (Figure 1). The basin is one of the most vulnerable and sensitive areas to climate change as a result of the high altitude and complicated monsoon climate. The average annual, minimum, and maximum daily temperatures during 1961–2013 were 1.47, −22.62, and 16.33 °C, respectively. Average annual precipitation is about 566 mm and it is unevenly distributed in temporal scale with
about 75% of annual precipitation concentrated in the flood season (June–September). The economic development of the Naqu River Basin is mainly dependent on animal husbandry and lags behind other regions in China, thus water resource management is necessary to improve pasture production and promote economic development. However, research on hydro-logical processes is restricted by the inadequate hydro-meteorological data, which is insufficient to support water resource management in the Naqu River Basin.

Data preparation

The meteorological data, including daily precipitation, temperature (average, maximum and minimum), sunshine duration, wind speed, and relative humidity of eight meteorological stations (Figure 1) from 1998 to 2013, were originally acquired from the China Meteorological Data Sharing Service System (http://cdc.nmic.cn/home.do). In order to extend the daily meteorological data of stations over the basin, particularly the precipitation that is the most spatially variable meteorological factor, it is vital to select suitable interpolation methods, which can be divided into two classes: geo-statistical methods and geometric methods. The geo-statistical methods (e.g. Kriging, co-Kriging) use the structure of spatial correlation from observed data to estimate the spatial distribution of precipitation (Tabios and Salas 1985; Das et al. 2008; Hofstra et al. 2008; Ashiq et al. 2010), and are widely and successfully used in spatial interpolation of monthly and annual precipitation (Lloyd 2005; Ninyerola et al. 2007). However, these methods are inadequate to be applied in spatial interpolation of daily precipitation, especially in sparsely gauged regions (Buytaert et al. 2006; Ly et al. 2011; Castro et al. 2015). The Inverse Distance Weighting (IDW) interpolation is the most popular geometric method and has been applied at different spatial-temporal scales due to its simplicity (Kurtzman et al. 2009; Chen et al. 2010; Hwang et al. 2012). IDW interpolation constructs the spatial distribution of precipitation based on the distance weighting relation between observed precipitation gauges and unknown points. Therefore, IDW interpolation is sensitive to the number of gauges used and the exponential function of distance; it is difficult to identify an optimal number of neighboring gauges to be used and the exponential function of distance in IDW interpolation (Babak and Deutsch 2009), not to mention in sparsely gauged regions. As a result, the simple and popular Thiessen polygon method was applied to extend the daily meteorological data of eight stations over the basin, which was divided into eight polygons controlled by eight stations. Then the polygons were converted into grids with a resolution of 1.0 km to match the resolution of the distributed hydrological model. Consequently, the daily meteorological data (gauge precipitation) of grids within the polygon are the same and equal to the daily meteorological data (gauge precipitation) of the controlling station.

TRMM 3B42V7 3-hourly temporal, 0.25° × 0.25° spatial scale product ranging between 50° N-50° S is applied in this study. It is a post-real-time and accessible online product from the Goddard Earth Sciences Data and Information Services Centre of NASA, and is dependent on two different types of sensors, namely microwave and infrared radiation.
(Huffman et al. 2007; Chen et al. 2013a, 2013b, 2013c). The sources of passive microwave satellite precipitation estimates include the TRMM Microwave Imager, Special Sensor Microwave Imager/Sounder, Advanced Microwave Scanning Radiometer-EOS, Advanced Microwave Scanning Sounding Unit-B, and the Microwave Humidity Sounder. In addition, the Global Precipitation Climatology Centre gauge analysis and Climate Assessment and Monitoring System are incorporated into the TRMM 3B42V7 (Chen et al. 2013a, 2013b, 2013c). Daily TRMM precipitation from 1998 to 2013 was accumulated from the original TRMM 3B42V7 in the Naqu River Basin. On the one hand, the current downscaling methods concentrate on the monthly and annual TRMM precipitation and are not suitable for downscaling of daily TRMM precipitation, on account of the temporal-spatial variation of daily precipitation (Jia et al. 2011; Duan & Bastiaanssen 2013; Mahmud et al. 2015). Therefore, in order to match the resolution of the distributed hydrological model, the daily TRMM precipitation with 0.25° × 0.25° resolution was resampled into grids at a 1.0 km resolution by nearest neighbor method, which will not change the values of original TRMM precipitation. On the other hand, in order to evaluate the TRMM precipitation in comparison with gauge precipitation at station and basin scales, the daily TRMM precipitation and gauge precipitation of eight stations were derived from the TRMM precipitation resampled grids and gauge precipitation grids from the Thiessen polygon method, which cover the corresponding station gauges with the same resolution of 1.0 km, and so the station scale represents the single grid scale with a resolution of 1.0 km in this study. The areal TRMM precipitation and gauge precipitation over the basin was averaged from the daily TRMM precipitation resampled grids and gauge precipitation grids in the Naqu River basin (basin scale), respectively. Then, monthly and annual TRMM precipitation and gauge precipitation at station and basin scales were accumulated by the daily TRMM precipitation and gauge precipitation, accordingly.

The Water and Energy Transfer Processes (WEP) model (a distributed hydrological model) was driven by the daily gauge precipitation and TRMM precipitation from 1998 to 2013, yet daily TRMM precipitation underperforms monthly TRMM precipitation in hydrological simulation (Li et al. 2012; Meng et al. 2014; Xu et al. 2015). Moreover, the daily streamflow of Jiayuqiao station (the outlet of the Naqu River basin) in flood season (generally from early June to the end of September, but not a fixed duration) during 1998–2008 was sourced from the Water Conservancy Information Center in the Ministry of Water Resources of the People’s Republic of China. Meanwhile, the monthly streamflow of Jiayuqiao station from 1998 to 2008 was provided by the Water Conservancy Bureau of the Tibet Autonomous Region. Although the daily and the monthly streamflows were derived from different sources, they are consistent at monthly scale in flood season. As is seen, the daily observed streamflow is incomplete and only adequate in flood season (June to September) during 1998–2008, and the monthly observed streamflow is adequate from January 1998 to December 2008. Therefore, the monthly streamflow is used to calibrate and validate the empirical parameters in the distributed hydrological model, and the daily streamflow in flood season was also used to verify the performance of the WEP model at daily scale.

The basic geographic information was derived from a DEM (Figure 1) at a resolution of 1.0 km from the National Geomatics Centre of China (http://ngcc.sbsm.gov.cn/). The land use map in 2000 (Figure 2(a)) at scale of 1:250,000 was obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences. Vegetation parameters evolve with seasons; the vegetation parameters, including the vegetation coverage rate (Veg), leaf area index (LAI), vegetation height (hc), root depth (lr) and minimum stomatal resistance (rs) (Jia et al. 2009), are shown in Table 1. The soil-type map (Figure 2(b)) at a scale of 1:1,000,000 was provided by the National Natural Science Foundation of China (http://westdc.westgis.ac.cn), and the relative soil physical properties (Table 2) were calculated according to information from the China soil database (http://www.soil.csdb.cn). Finally, the maps of land use and soil type were converted into grids with a resolution of 1.0 km to match the resolution of the distributed hydrological model.

**METHODS**

**Hydrological model**

The WEP model is a distributed physically-based model that has been widely used in different river basins in Japan,
Korea and China (Jia et al. 2009). The WEP model selection in this study is attributed to its detailed energy transfer processes, which is meaningful for hydrological simulation in high latitude and intense radiation basins (Tanaka et al. 2003). In the WEP model, evapotranspiration and latent heat flux are computed by combining the Penman-Monteith equation (Monteith & Unsworth 2003) with the force-restore method (Hu & Islam 1998) instead of the potential value method. Infiltration during heavy rains is simulated by a generalized Green-Ampt model (Jia & Tamai 1998), whereas soil moisture movement during the remaining periods is obtained by the Richards model. Two-dimension groundwater flow is simulated to consider the interactions between grid cells, meanwhile river flow routing and overland flow routing are conducted using the kinematic wave method. Moreover, for the energy processes short-wave

<table>
<thead>
<tr>
<th>Type</th>
<th>Parameter</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood Veg</td>
<td>LAI</td>
<td>0.24</td>
<td>0.24</td>
<td>0.36</td>
<td>0.48</td>
<td>0.72</td>
<td>0.84</td>
<td>0.96</td>
<td>0.96</td>
<td>0.84</td>
<td>0.6</td>
<td>0.36</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>hc (m)</td>
<td>1.20</td>
<td>1.20</td>
<td>1.56</td>
<td>2.16</td>
<td>3.00</td>
<td>3.36</td>
<td>3.6</td>
<td>3.6</td>
<td>3.36</td>
<td>2.76</td>
<td>2.16</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>lr (m)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>rs (s/m)</td>
<td>10</td>
<td>1.5</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
</tbody>
</table>

| Grass Veg| LAI       | 0.12  | 0.12  | 0.24  | 0.36  | 0.60  | 0.84  | 0.96  | 0.96  | 0.72  | 0.48  | 0.24  | 0.12  |
|          | hc (m)    | 0.60  | 0.60  | 0.72  | 1.20  | 1.80  | 2.16  | 2.40  | 2.40  | 1.92  | 1.44  | 0.72  | 0.60  |
|          | lr (m)    | 0.1   | 0.1   | 0.1   | 0.2   | 0.2   | 0.2   | 0.2   | 0.2   | 0.2   | 0.1   | 0.1   | 0.1   |
|          | rs (s/m)  | 0.3   | 0.3   | 250   | 250   | 250   | 250   | 250   | 250   | 250   | 250   | 250   | 250   |

| Shrub Veg| LAI       | 0.24  | 0.24  | 0.36  | 0.48  | 0.72  | 0.84  | 0.96  | 0.96  | 0.84  | 0.60  | 0.36  | 0.24  |
|          | hc (m)    | 1.20  | 1.20  | 1.56  | 2.16  | 3.00  | 3.36  | 3.6   | 3.6   | 3.36  | 2.76  | 2.16  | 1.20  |
|          | lr (m)    | 0.01  | 0.01  | 0.12  | 0.12  | 0.36  | 0.60  | 0.84  | 0.96  | 0.12  | 0.12  | 0.01  | 0.01  |
|          | rs (s/m)  | 3     | 0.8   | 250   | 250   | 250   | 250   | 250   | 250   | 250   | 250   | 250   | 250   |

| Crop Veg | LAI       | 0.01  | 0.01  | 0.12  | 0.12  | 0.36  | 0.60  | 0.84  | 0.96  | 0.12  | 0.12  | 0.01  | 0.01  |
|          | hc (m)    | 0.1   | 0.1   | 0.1   | 0.2   | 0.2   | 0.2   | 0.2   | 0.2   | 0.1   | 0.1   | 0.1   | 0.1   |
|          | lr (m)    | 0.01  | 0.01  | 0.12  | 0.12  | 0.36  | 0.60  | 0.84  | 0.96  | 0.12  | 0.12  | 0.01  | 0.01  |
|          | rs (s/m)  | 0.3   | 0.3   | 250   | 250   | 250   | 250   | 250   | 250   | 250   | 250   | 250   | 250   |

Figure 2 | Distribution of (a) land use and (b) soil type in the Naqu River Basin.
radiation is based on observation or deduced from sunshine duration, long-wave radiation is calculated according to temperatures, latent and sensible fluxes computed by the aerodynamic method, and surface temperature is solved by the force-restore method. Much more information about WEP models can been seen in previous publications (Jia & Tamai 1998; Jia et al. 2001, 2009).

Statistical analysis methods

Contingency table indices

The contingency table (Table 3) is a key tool to evaluate the occurrence of precipitation events in a binary manner (Yes/No): ‘Yes’ represents that the precipitation event occurs and ‘No’ depicts that the precipitation event does not happen. The threshold to separate the ‘Yes’ and ‘No’ precipitation event is 1 mm/day (Conti et al. 2014; Mantas et al. 2015). Therefore, there are four categories defined in the contingency table: ‘Hits’ presents a precipitation event that is observed by gauge precipitation and estimated by TRMM precipitation; ‘Misses’ presents a precipitation event that is observed by gauge precipitation, but not estimated by TRMM precipitation; ‘False alarms’ presents a precipitation event that is not observed by gauge precipitation, but estimated by TRMM precipitation; ‘Correct negatives’ presents a precipitation event that is not observed by gauge precipitation and not estimated by TRMM precipitation. As a result, the contingency table indices including probability of detection (POD), false alarm ratio (FAR), ACC, and critical success index (CSI) were used to verify the capability of TRMM precipitation to correctly estimate precipitation events at daily scale in this study. The indices are briefly described as follows:

\[
POD = \frac{\text{Hits}}{\text{Hits} + \text{Misses}}
\]

\[
FAR = \frac{\text{False Alarms}}{\text{Hits} + \text{False Alarms}}
\]

\[
ACC = \frac{\text{Hits} + \text{Correct negatives}}{\text{Hits} + \text{Misses} + \text{False Alarms} + \text{Correct negatives}}
\]

\[
CSI = \frac{\text{False Alarms}}{\text{Hits} + \text{Misses} + \text{False Alarms}}
\]

Statistic indices

The Pearson Correlation Coefficient (PCC) was employed to analyze the relation between gauge precipitation and TRMM precipitation at daily and monthly scales. Furthermore, Root Mean Square Error (RMSE) and BIAS were also applied to validate the TRMM precipitation, expressed as follows:

\[
PCC = \frac{\text{Cov}(P_{\text{TRMM}}, P_{\text{Gauge}})}{\sqrt{\text{Var}(P_{\text{TRMM}})} \sqrt{\text{Var}(P_{\text{Gauge}})}}
\]

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_{i\text{TRMM}} - P_{i\text{Gauge}})^2}{n}}
\]

\[
BIAS = \sum_{i}^{n} \frac{P_{i\text{TRMM}}}{P_{i\text{Gauge}}} - 1
\]

where the \(P_{i\text{TRMM}}, P_{i\text{Gauge}}\) are the TRMM precipitation and gauge precipitation of the \(i\) th day/month, respectively, and \(n\) is the total number of days/months.

| Soil moisture characteristics parameters
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sandy soil</th>
<th>Silty loam</th>
<th>Clay loam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturated moisture content (\theta_s)</td>
<td>0.396</td>
<td>0.412</td>
<td>0.44</td>
</tr>
<tr>
<td>Residual moisture content (\theta_r)</td>
<td>0.083</td>
<td>0.129</td>
<td>0.135</td>
</tr>
<tr>
<td>Single molecule moisture content (\theta_m)</td>
<td>0.015</td>
<td>0.05</td>
<td>0.111</td>
</tr>
<tr>
<td>Field capacity (\theta_f)</td>
<td>0.177</td>
<td>0.284</td>
<td>0.319</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity (k_s) (m/s)</td>
<td>(3.0 \times 10^{-5})</td>
<td>(6.5 \times 10^{-6})</td>
<td>(2.5 \times 10^{-6})</td>
</tr>
</tbody>
</table>

| Contingency table
<table>
<thead>
<tr>
<th>Contingency Table</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRMM precipitation</td>
<td>Hits</td>
<td>False alarms</td>
</tr>
<tr>
<td>No</td>
<td>Misses</td>
<td>Correct negatives</td>
</tr>
</tbody>
</table>
Linear regression model

The linear regression model (LRM, Equation (8)) was applied to correct the TRMM precipitation based on the good linear relation between monthly TRMM precipitation and gauge precipitation. It should be noticed that the corrected TRMM precipitation can be negative, when the offset parameter \( a \) is negative and the TRMM precipitation is small. Therefore, the offset parameter \( a \) was set to 0 in order to avoid negative corrected TRMM precipitation. Then scale parameter \( b \) can be estimated by the ordinary least-squares methods, Equation (9), and the corrected TRMM precipitation can be obtained by Equation (10).

\[
P_{\text{Gauge}} = a + bP_{\text{TRMM}} \tag{8}
\]

\[
\hat{b} = \frac{\sum_{i=1}^{n} (P_{i}^{\text{Gauge}} \times P_{i}^{\text{TRMM}})}{\sum_{i=1}^{n} (P_{i}^{\text{TRMM}})^2}, \quad (a = 0) \tag{9}
\]

\[
P_{\text{corrected TRMM}} = \hat{b}P_{\text{TRMM}} \tag{10}
\]

Model assessment indices

The automatic parameter estimation optimization tool (PEST, http://pesthomepage.org/Home.php) is an efficient model-independent parameter estimation platform and is widely used for hydrological model calibration (Keating et al. 2003; Li et al. 2012). PEST with shuffled complex evolution algorithm was applied to calibrate the WEP model with statistic criteria including the Nash-Sutcliffe Coefficient of Efficiency (NSCE) (Duan et al. 1992), the relative bias ratio (Schneider et al. 2008), and the coefficient of determination (\( R^2 \)), which is also used to assess the regression equation between monthly TRMM precipitation and gauge precipitation. The NSCE is one of the favorite indexes for evaluating the goodness-of-fit of hydrological models, and the BIAS is the systematic errors of the simulated streamflow (Madsen 2000). They are expressed as:

\[
\text{NSCE} = 1 - \frac{\sum_{i=1}^{n} (Q_{\text{obs},i} - Q_{\text{sim},i})^2}{\sum_{i=1}^{n} (Q_{\text{obs},i} - \bar{Q}_{\text{obs}})^2} \tag{11}
\]

\[
\text{BIAS} = \frac{\sum_{i=1}^{n} (Q_{\text{sim},i} - Q_{\text{obs},i})}{\sum_{i=1}^{n} (Q_{\text{obs},i})} \tag{12}
\]

where the \( Q_{\text{obs},i} \) is the observed streamflow of the \( i \) th day/month, \( \bar{Q}_{\text{obs}} \) is the average value of the observed streamflow during the calibrated period, and \( Q_{\text{sim},i} \) is the simulated streamflow corresponding to \( Q_{\text{obs},i} \).

RESULTS AND DISCUSSION

Evaluation of TRMM precipitation – daily scale

Statistical results of daily TRMM precipitation and gauge precipitation at station and basin scales during 1998–2013 are listed in Table 4. As can be seen, the mean daily TRMM precipitation is more than the mean daily gauge precipitation in most stations, except for stations No. 55293 and No. 56018. As a result, daily areal mean precipitation derived from

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Summary of statistical results in comparison of daily TRMM precipitation with gauge precipitation at station and basin scales during 1998–2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge No./Basin</td>
<td>55294</td>
</tr>
<tr>
<td>Mean (mm)</td>
<td></td>
</tr>
<tr>
<td>Gauge</td>
<td>1.34</td>
</tr>
<tr>
<td>TRMM</td>
<td>1.20</td>
</tr>
<tr>
<td>Maximum (mm)</td>
<td></td>
</tr>
<tr>
<td>Gauge</td>
<td>33.70</td>
</tr>
<tr>
<td>TRMM</td>
<td>78.75</td>
</tr>
<tr>
<td>RMSE (mm)</td>
<td>4.36</td>
</tr>
<tr>
<td>BIAS</td>
<td>-0.10</td>
</tr>
</tbody>
</table>
TRMM precipitation is slightly more than that from gauge precipitation over the basin. This implies that TRMM precipitation overestimates precipitation in the Naqu River Basin, which is consistent with the findings from another study in the TP (Chen et al. 2013a, 2013b, 2013c). Meanwhile, maximum daily TRMM precipitation is noticeably more than maximum daily gauge precipitation, particularly at station scale. The possible reason is that as the gauge precipitation merely refers to a specific point it is more random and uncertain, and could easily miss the rainstorm center in comparison with TRMM precipitation, which is derived from the average value of the region with a range of 0.25° × 0.25°. Moreover, the RMSE and BIAS corroborate that there is a clear difference between daily gauge precipitation and TRMM precipitation at station and basin scales.

Contingency table indices were calculated based on the daily TRMM precipitation and gauge precipitation of eight station gauges and the entire basin from 1998 to 2013. As is seen in Figure 3, less than 60% of precipitation events were detected (PODs) and more than 40% of precipitation events were falsely predicted (FARs) in most of the stations, except for station No. 56223. Although the ACCs was greater than 70%, the CSIs and PCCs were less than 40% in all stations. The results are generally consistent with previous research in the TP (Chen et al. 2013a, 2013b, 2013c). In contrast, the daily areal TRMM precipitation performs better than the daily TRMM precipitation of stations with increasing POD and decreasing FAR. Nevertheless, the CSI and PCC of daily areal TRMM precipitation are still less than 60%. Consequently, it can be inferred that there is an obvious mismatch between daily gauge precipitation and TRMM precipitation in the Naqu River Basin.

According to daily precipitation intensity, daily precipitation is classified into five classes: no-rain (precipitation = 0 mm), mild precipitation (0 mm < precipitation ≤ 3 mm), moderate precipitation (3 mm < precipitation ≤ 10 mm), heavy precipitation (10 mm < precipitation ≤ 30 mm), and severe precipitation (30 mm < precipitation) (Schlünzen et al. 2010; Li et al. 2012). The intensity distribution of daily precipitation in different classes and their contributions to the total amount of precipitation from 1998 to 2013 at station and basin scales are shown in Figure 4. Based on the statistics of eight station gauges (Figure 4(a)–4(h)), it is seen that for gauge precipitation, the no-rain category has the largest occurrence and occurs on about 60% of the total days, followed by mild precipitation, moderate precipitation, heavy precipitation, and severe precipitation, respectively. Meanwhile, the intensity distribution of TRMM precipitation is overall consistent with that of gauge precipitation at station scale, yet the no-rain days and mild precipitation days of TRMM precipitation are separately slightly less and more than that of gauge precipitation, respectively. The possible reason is that slight precipitations (<0.1 mm) were omitted from the rain gauge record of meteorological stations in China. Moreover, it is worthy to note that the moderate precipitation days and heavy precipitation days occur on about 20% of the total days, but contribute nearly 80% of the total precipitation amount for both gauge precipitation and TRMM precipitation.
The contribution of severe precipitation of TRMM precipitation is obviously larger than that of gauge precipitation, which is attributed to the overestimation of extreme precipitation in TRMM precipitation. However, the differences at basin scale are manifest (Figure 4(i)). The mild rain days are obviously increasing along with the decrease in no-rain days, and have the largest precipitation occurrence in both gauge precipitation and TRMM precipitation. The reason is that daily precipitation is spatially averaged over the basin, which results in a decrease of daily areal precipitation and no-rain days, particularly for TRMM precipitation, with more uneven spatial distribution of daily precipitation. Meanwhile, the contribution of moderate precipitation is more than 50% of the total precipitation amount, which takes account of the largest proportion of both gauge precipitation and TRMM precipitation. The distribution of contributions of different precipitation classes in gauge precipitation are approximately in agreement with that of TRMM precipitation at basin scale.

**Evaluation of TRMM precipitation – monthly scale**

Statistical results for monthly TRMM precipitation and gauge precipitation during 1998–2013 are shown in Table 5. The mean precipitation, RMSEs and BIAS of monthly precipitation are consistent with those of daily precipitation. Meanwhile, PCCs show an obvious increase ranging from 0.86 to 0.98, and present a good linear relation between monthly TRMM precipitation and gauge precipitation, especially at basin scale. Moreover, Figure 5 shows the relation between monthly gauge precipitation and
TRMM precipitation from 1998 to 2013 at station and basin scales. It is seen that monthly TRMM precipitation is highly consistent with the monthly gauge precipitation with $R^2$ ranging between 0.74 and 0.96, which verifies that there is a good linear relation between monthly TRMM precipitation and gauge precipitation. Therefore, although areal TRMM precipitation overestimates the precipitation with a BIAS of 0.2 over the basin, there is a good linear relation between monthly TRMM precipitation and gauge precipitation.

According to the previous research, Xu et al. (2013) had proved that linear regression is an efficient method to correct monthly TRMM precipitation for hydrological simulation, and monthly TRMM precipitation had been corrected through the LRM grid-by-grid over a basin with a high-density gauge network in their study. However, an extremely low-density gauge network makes the spatial distribution of gauge precipitation by the Thiessen polygon method discontinuous and inaccurate, and the spatial distribution of TRMM precipitation is possibly more efficient and authentic in a sparse gauge region. Thus, the grid-by-grid corrected method is meaningless and will impact the spatial distribution of TRMM precipitation in the Naqu River Basin. Hence, monthly areal TRMM precipitation over the basin was corrected by LRM derived from the linear relation between monthly areal gauge precipitation and TRMM precipitation (monthly corrected TRMM precipitation = $0.84 \times$ original monthly TRMM precipitation, Figure 5(i)). Meanwhile, the monthly TRMM precipitation is obtained from the accumulation of the daily TRMM precipitation, which is directly proportional to the monthly TRMM precipitation. Therefore, the daily TRMM precipitation can also be corrected via the same LRM model (daily corrected TRMM precipitation = $0.84 \times$ original daily TRMM precipitation), and it can satisfy the conservation of precipitation amount (accumulated daily corrected TRMM precipitation equals the corresponding monthly corrected TRMM precipitation). Then, the TRMM precipitation (original and corrected) and gauge precipitation are illustrated in Figure 6, and their statistical results are also listed in Table 5. It is seen that monthly corrected TRMM precipitation shows an evident improvement with decreased RMSE and BIAS and approximately equals gauge precipitation. Therefore, the difference between total areal gauge precipitation and corrected TRMM precipitation over the basin is small, which can highlight the difference between the spatial distribution of gauge precipitation and corrected TRMM precipitation in hydrological simulation.

### Hydrological processes simulation

As a distributed physically-based model, most of the physical parameters of the WEP model can be obtained from the physical inputs including the DEM, land use and soil database. But there are still several empirical parameters such as Manning roughness for the overland flow routing calculation, Manning roughness for the river flow routing calculation, the hydraulic conductivity between the surface river and

<table>
<thead>
<tr>
<th>Gauge No./Basin</th>
<th>SS294</th>
<th>SS299</th>
<th>S6018</th>
<th>S6106</th>
<th>S6109</th>
<th>S6116</th>
<th>S6202</th>
<th>S6223</th>
<th>Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean (mm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gauge</td>
<td>40.72</td>
<td>39.53</td>
<td>45.67</td>
<td>52.83</td>
<td>52.92</td>
<td>56.42</td>
<td>62.59</td>
<td>35.31</td>
<td>47.18</td>
</tr>
<tr>
<td>Original TRMM</td>
<td>36.52</td>
<td>48.44</td>
<td>43.58</td>
<td>62.76</td>
<td>69.32</td>
<td>59.80</td>
<td>73.71</td>
<td>62.84</td>
<td>56.77</td>
</tr>
<tr>
<td>Corrected TRMM</td>
<td>30.68</td>
<td>40.69</td>
<td>36.61</td>
<td>52.72</td>
<td>58.23</td>
<td>50.24</td>
<td>61.91</td>
<td>52.79</td>
<td>47.69</td>
</tr>
<tr>
<td><strong>RMSE (mm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original TRMM</td>
<td>20.86</td>
<td>20.19</td>
<td>13.64</td>
<td>26.36</td>
<td>32.47</td>
<td>17.72</td>
<td>29.76</td>
<td>40.51</td>
<td>15.98</td>
</tr>
<tr>
<td>Corrected TRMM</td>
<td>24.67</td>
<td>13.94</td>
<td>18.78</td>
<td>20.10</td>
<td>21.46</td>
<td>18.64</td>
<td>22.59</td>
<td>29.12</td>
<td>9.66</td>
</tr>
<tr>
<td><strong>Bias</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original TRMM</td>
<td>−0.10</td>
<td>0.23</td>
<td>−0.05</td>
<td>0.19</td>
<td>0.31</td>
<td>0.06</td>
<td>0.18</td>
<td>0.78</td>
<td>0.20</td>
</tr>
<tr>
<td>Corrected TRMM</td>
<td>−0.25</td>
<td>0.03</td>
<td>−0.20</td>
<td>0.00</td>
<td>0.10</td>
<td>−0.11</td>
<td>−0.01</td>
<td>0.49</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>PCC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gauge &amp; original TRMM/gauge &amp; corrected TRMM</td>
<td>0.92</td>
<td>0.95</td>
<td>0.96</td>
<td>0.93</td>
<td>0.94</td>
<td>0.96</td>
<td>0.93</td>
<td>0.86</td>
<td>0.98</td>
</tr>
</tbody>
</table>
groundwater, and hydraulic conductivity in the groundwater aquifer, which need to be calibrated by observed streamflow. Therefore, the empirical parameters (Table 6) of the WEP model were automatically optimized by the PEST with the monthly streamflow during 1998–2003, and the monthly streamflow in 2004–2008 was used to validate the model.

Then, the performance of daily streamflow driven by gauge precipitation and corrected TRMM precipitation were evaluated (Table 7), and the results display that the NSCE and $R^2$ of daily simulated streamflow in flood season range between 0.58 and 0.77. The daily streamflow hydrograph (Figure 7) shows that simulated streamflow driven by the two precipitation data are consistent with the observed streamflow and to an acceptable extent in the flood season. Although daily streamflow driven by gauge precipitation produces a better fit to the observed streamflow than that driven by corrected TRMM precipitation, the performance of the two models is not very good with...
The reason is that daily gauge precipitation better matches the actual precipitation than daily corrected TRMM precipitation, and empirical parameters calibrated by monthly streamflow are possibly not suitable for the daily streamflow simulation.

Subsequently, the performance of monthly streamflow driven by gauge precipitation and corrected TRMM precipitation were evaluated (Table 8), and the results show that the NSCE and $R^2$ range between 0.86 and 0.91. Meanwhile the BIAS ranges from −4.7 to 5.71%, that is to say the monthly simulated streamflow driven by the two precipitation data agreed well with the observed streamflow in both calibrated and validated periods. Furthermore, the monthly streamflow driven by corrected TRMM precipitation performs slightly better than that driven by gauge precipitation according to the higher NSCE. In addition, the hydrograph of monthly streamflow (Figure 8) illustrates that the monthly simulated streamflow driven by the two precipitation data fit very well with the observed streamflow, which indicates that the WEP model is suitable for monthly streamflow simulation and corrected TRMM precipitation is adequate to force the model in the Naqu River Basin.

Additionally, Figure 9 displays the monthly BIAS of streamflow driven by the gauge precipitation-based model and corrected TRMM precipitation-based model. It can be seen that both gauge precipitation and corrected TRMM precipitation perform well in hydrological simulation in the...
Naqu River Basin with a total |BIAS| < 0.1. Nevertheless, it should be noted that monthly streamflow BIASs from the gauge precipitation-based model exhibit regular fluctuations. The BIASs are more than 0.1 during March–May and less than −0.1 from September to the following January, which results in a small total streamflow BIAS. In contrast, monthly streamflow BIASs from the corrected TRMM precipitation-based model are more than 0.1 only during February–May. The possible reason is that the gauge precipitation overestimates and underestimates the actual precipitation during March–May and September–following January, respectively, in the Naqu River Basin. Accordingly, the overestimation (underestimation) of gauge precipitation at station scale will result in an overestimation (underestimation) of regional (polygon) gauge precipitation by the Thiessen polygon method, which will amplify the streamflow BIAS of the gauge precipitation-based model. Therefore, although the algorithms of TRMM precipitation estimation need to be improved to eliminate the overestimation of TRMM precipitation in the TP, the areal corrected TRMM precipitation is more accurate and stable in different months than the gauge precipitation due to its authentic spatial distribution.

**Water balance analysis**

The water balance component is an important indicator to test the validity of precipitation data (Li et al. 2012), and the water balance components of the Naqu River Basin derived from the gauge precipitation-based model and corrected TRMM precipitation-based model are illustrated in Table 9. The results show that the average annual precipitation over all of the Naqu river basin obtained from corrected TRMM precipitation is slightly larger than that from gauge precipitation during 1998–2013. As a result, the areal runoff derived from the TRMM precipitation-based model is larger than that derived from the gauge precipitation-based model.
A precipitation-based model, especially for surface runoff. However, the total areal precipitation of gauge precipitation is approximated to corrected TRMM precipitation, and the two models were calibrated by the same observed streamflow. Although the different empirical parameters also have an influence on the simulated streamflow, the difference in empirical parameters is originally derived from the difference in precipitation data. Consequently, it can be inferred that the difference in water balance components in the two models is essentially due to the difference between the spatial distribution of gauge precipitation and corrected TRMM precipitation at spatial scale.

Furthermore, mean annual precipitation and runoff coefficients (runoff/precipitation) of 132 sub-basins were calculated based on their water balance components (Figure 10). This illustrates that the distribution of corrected TRMM precipitation is more authentic than that of gauge precipitation by the Thiessen polygon method. Yet, the distribution of runoff coefficients derived from the two models is consistent overall. The runoff coefficients are an integrated index for the effect of underlying conditions on the precipitation-runoff process and is directly influenced by the slope of the sub-basin, which impacts on the distribution and redistribution of precipitation in distributed hydrological processes (Beven & Kirkby 1979). The relations between runoff coefficients and the average slope of sub-basins are shown in Figure 11. It is seen that the relation from the corrected TRMM precipitation-based model is better than that from the gauge precipitation-based model, which implies that the runoff coefficients obtained from the TRMM precipitation-based model are more reasonable to represent the influence of geography on the rainfall-runoff process. The possible reason is that the empirical parameters in the gauge precipitation-based model were excessively calibrated due to the inaccurate distribution of gauge precipitation, thus the relation between slope and runoff coefficients have been impacted accordingly. Consequently, it can be concluded that the spatial distribution of TRMM precipitation is closer to the spatial distribution of actual precipitation than that of gauge precipitation by the Thiessen polygon method in the Naqu River Basin.

**CONCLUSIONS**

This paper compares daily and monthly TRMM precipitation with the corresponding gauge precipitation from 1998 to 2013 at station and basin scales in the Naqu River Basin. The statistic results show that TRMM precipitation overestimates the precipitation with a BIAS of 0.2 over the basin, and the poor performance of contingency table indices displays a mismatch between the daily TRMM

![Figure 9](https://iwaponline.com/hr/article-pdf/48/3/822/366378/nh0480822.pdf)

**Figure 9** Comparison of the BIAS of monthly streamflows driven by gauge precipitation and corrected TRMM precipitation.

**Table 9** Comparison of the water balance components using gauge precipitation and corrected TRMM precipitation

<table>
<thead>
<tr>
<th>Components</th>
<th>Gauge precipitation based model</th>
<th>Corrected TRMM precipitation based model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value (mm)</td>
<td>Percentage of precipitation (%)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>566.15</td>
<td>572.28</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>218.74</td>
<td>38.6</td>
</tr>
<tr>
<td>Runoff</td>
<td>347.42</td>
<td>61.4</td>
</tr>
<tr>
<td>Surface runoff</td>
<td>308.68</td>
<td>88.8</td>
</tr>
<tr>
<td>Groundwater runoff</td>
<td>38.74</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Note: Evapotranspiration includes soil evapotranspiration, vegetation evapotranspiration, and canopy interception.
precipitation and gauge precipitation. However, the percentage distribution of daily TRMM precipitation in different classes and their contributions are generally consistent with that of daily gauge precipitation. Moreover, the scatter plots of monthly TRMM precipitation and gauge precipitation show a good linear relation, especially at basin scale. Based on the good linear relation, the daily areal TRMM precipitation is corrected and applied to driving the WEP
model in comparison with daily gauge precipitation. The models driven by the two precipitation data were calibrated and validated by monthly streamflow from 1998 to 2008. The daily hydrological simulations show that daily simulated streamflow driven by gauge precipitation and corrected TRMM precipitation are generally consistent with the observed streamflow in flood season, and daily gauge precipitation outperforms daily corrected TRMM precipitation. Furthermore, both gauge precipitation and corrected TRMM precipitation perform well in monthly hydrological simulation with NSCE larger than 0.85. The streamflow BIASs derived from gauge precipitation display regular fluctuations and are inconsistent in different months. Additionally, the water balance component of sub-basins from the corrected TRMM precipitation-based model is more reasonably distributed than that from the gauge precipitation-based model at spatial scale.

As mentioned above, the distributed hydrological model driven by corrected TRMM precipitation presents a better understanding of the hydrological cycle in the Naqu River Basin, which is meaningful in supporting water resource management and economic development there. Furthermore, it can be concluded that TRMM precipitation is a potential and effective input for the distributed hydrological model, attributed to its advantage of spatial distribution of precipitation in sparse gauge regions, where the spatial interpolation method is limited by the extremely low density gauge network. Therefore, TRMM precipitation provides an important approach to simulating the hydrological cycle and reducing the hydrological uncertainty caused by the spatial heterogeneity of precipitation in ungauged or poorly gauged basins such as the Naqu River Basin. Nevertheless, there is still a demand for the algorithms of TRMM precipitation estimation in ACC and spatial-temporal resolution (Li et al. 2009). Moreover, hydrologists should focus on the suitable method to correct TRMM precipitation according to regional precipitation characteristics, given the variable effects of climatic and underlying conditions on the spatial distribution of precipitation.

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REFERENCES


Su, F., Hong, Y. & Lettenmaier, D. P. 2015 Evaluation of TRMM multisatellite precipitation analysis (TMPA) and its utility in hydrologic prediction in the La Plata basin. J. Hydrometeorol. 9, 622–640.


