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Comparison of two successive versions 6 and 7 of TMPA satellite precipitation products with rain gauge data over Swat Watershed, Hindukush Mountains, Pakistan

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Abstract

Swat watershed in Hindukush Mountains was selected for the evaluation of Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) Versions 6 and 7 using rain-gauge data. Agreement between the satellite and gauge estimates was good at monthly scale but poor at daily and seasonal (monsoon and westerlies, particularly for monsoon) scales. Over and underestimations were observed at foothills and high-altitude areas, respectively. Although, bias was still present, but overall performance of TMPA-V7 was improved compared with TMPA-V6. Bias corrected-TMPA-V7 estimates were better than corrected-TMPA-V6. Basin average bias-corrected precipitation estimates of TMPA-V7 were estimated at daily, monthly, westerlies, monsoon, and annual scales [means (mm) 1.60, 48, 190, 173 and 582, respectively] for the period 1998–2014. Results suggest that regional bias correction of satellite-precipitation products is critical and can yield to the substantial improvement in capturing the precipitation.

Keywords: Swat Watershed; Hindukush Mountains; satellite precipitation; bias correction

I. Introduction

Precipitation is the key parameter for various applications and disciplines related to water resources. Getting accurate precipitation data is thus crucial for local, regional and global hydrologic predictions. However, acquisition of precipitation data is often limited to ground-based observations, but usually this traditionally available information suffers from low spatial and/or temporal coverage, particularly in the Hindukush-Himalayan (HKH) mountainous region.

At present, availability of remotely sensed data provides the information of global precipitation distribution with high spatiotemporal resolution (Hu *et al.*, 2014). Several satellite-based precipitation products have been operationally available to the researchers. Among these products, Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) products are widely used for various hydrological studies. Owing to high orientation, the performance of these products is expected to vary from area to area (Prakash *et al.*, 2014). Thus, it is essential to evaluate the performance of these products using locally observed ground-data before their applications in a specific area.

The latest version 7 (V7) of TMPA products is available since 1998. In contrast to the previous version 6 (V6), algorithms of V7 have been improved and additional datasets are incorporated. For the broadest usage and applications of TMPA precipitation products, a number of studies have been made to evaluate these products at regional to global scales (e.g. Vernimmen et al., 2012; Mashingia et al., 2014; Liu, 2015). As for the HKH region, Nair et al. (2009) evaluated the TMPA-V6 product using gauge-based data in Western Ghats Mountains in India for the period of 1998-2004. They concluded that TMPA-V6 does not capture well the precipitation over the study area. Xue et al. (2013) evaluated TMPA-V6 and V7 products using rain-gauge data in the Wangchu Basin, Bhutan. They concluded that TMPA-V7 products have significant improvements compared with the TMPA-V6 in terms of accuracy. Some studies have enumerated the similarities and differences between TMPA-V6 and V7 (e.g. Chen et al., 2013; Prakash et al., 2014; Zulkafli et al., 2014). These studies showed that V7 agreed well with ground-based precipitation data than V6.

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Figure I. Location and the hydro-meteorological network of the Swat River Watershed in the northwest of Pakistan.

Nevertheless, no particular study has been conducted to evaluate the performance of TMPA products in the north-western mountainous region of Pakistan, which consists of diverse topography and precipitation distributions. Therefore, an attempt was made to evaluate the error characteristics of two widely used high-resolution TPMA products over Swat Watershed. There are two main rainy seasons in this region: summer precipitations due to monsoon currents during July-September, and winter precipitations due to disturbances in the mid-latitude westerlies during January-March (Wang et al., 2011). Accurate estimation of precipitation during these seasons is crucial for operational flood monitoring and prediction in northern areas, which are considered as most flood-prone areas of Pakistan. Thereby, the specific objectives of this study are to (i) evaluate the widely used and globally available TMPA products (V6-V7) and quantify the errors associated with these two successive versions in Hindukush Mountainous range with varying precipitation climatology; (ii) assess how much they differ during daily annual scales and also to assess the improvements in the upgraded version (V7) relative to its predecessor version (V6).

2. Case study specifications and datasets

This experiment is performed using 8 years of available rain-gauge data (1999–2006) over Swat River Watershed (drainage area = 14039 km^2) located in the north-western Pakistan (Figure 1). Source of this river is in Hindukush Mountains, from where it flows

through the Kalam Valley and Swat District. The elevation within the watershed varies from 376 m a.s.l. to 5,917 m a.s.l. (south-north). The average annual precipitation over the watershed varies from 300 to 980 mm. This area falls in the monsoon and westerlies belt. Heavy precipitations occurred merely under the interaction of westerly wave and intensified monsoon trough. Considerably high precipitation occurs only during westerlies as well as in the monsoon season. Heavy isolated precipitations in summer are often caused by the orographic lifting of the monsoon air mass arriving from south to south-east direction (Wang et al., 2011). Hourly datasets from total 15 automatic rain-gauge stations were collected and accumulated for daily precipitation considering UTC because TMPA-estimates were available at UTC. Eight-years (1999–2006) precipitation data of nine stations, used for evaluation of satellite estimates, were selected after sensitivity analysis of observed precipitation records. Similarly precipitation data from two stations, 'Munda' for the period of 2000-2005 and 'Dir' for the period of 2002-2009, were selected for the validation of bias correctors. All selected automatic-gauging stations were located within, and around the study area and their datasets were considered as ground truth for evaluation of satellite-precipitation products. Pakistan Meteorological Department (PMD), Water and Power Development Authority (WAPDA), and Irrigation Department (ID) of Khyber Pakhtunkhwa (KPK), Pakistan, provided the observed datasets.

Satellite-based precipitation estimates of TMPA-3B42 (V6-V7) products were obtained from the website of Goddard Earth Sciences Data and

Information Services Centre (http://mirador.gfsc. nasa.gov) which are freely available. Detailed information about these products can be found in Huffman *et al.* (2007) and Xue *et al.* (2013). Daily TMPA-3B42 satellite-precipitation products (V6-V7) at 0.25°×0.25° resolutions were used in this study.

3. Methodology

The performance of TMPA-V6 and V7 was evaluated on point (gauging-station) and basin levels at daily, monthly, seasonal (monsoon and westerlies) and annual timescales. Precipitation time-series of January-March were considered for westerlies while July-September for monsoon season. Gauge-based basin average precipitation was estimated using the Thiessen polygons approach [with ArealRain extension in ArcView (Petras, 2001)]. Satellite-based basin average precipitations were estimated by averaging values of all pixels that lie within the watershed. Pearson's correlation coefficient (CC), mean error (ME), mean absolute error (MAE), root mean square error (RMSE) and relative bias (BIAS) were used to evaluate the precision of satellite-based precipitation products. Detailed information about statistical indices can be found in Mashingia et al. (2014). The formulas of statistical indices are given below:

$$CC = \frac{\sum_{i=1}^{n} (PG_i - P\overline{G}) (PS_i - P\overline{S})}{\sqrt{\sum_{i=1}^{n} (PG_i - P\overline{G})^2} \times \sqrt{\sum_{i=1}^{n} (PS_i - P\overline{S})^2}}$$
(1)
$$ME = \frac{1}{n} \sum_{i=1}^{n} (PS_i - PG_i)$$
(2)

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |PS_i - PG_i|$$
(3)

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(PS_i - PG_i \right)^2}$$
(4)

$$BIAS = \frac{\sum_{i=1}^{n} (PS_i - PG_i)}{\sum_{i=1}^{n} PG_i} \times 100$$
(5)

where *n* represents the total amount of rain-gauge or satellite precipitation data, PG_i and PS_i represent the *i*th values of gauge and satellite precipitation, respectively; and $P\overline{G}$ and $P\overline{S}$ are the mean values of gauge and satellite precipitation estimates, respectively.

For more detailed evaluation and to estimate correspondence between the TMPA-based and gauge-based precipitation observations, four additional categorical statistical measures were adopted: false alarm ratio (FAR), probability of detection (POD), critical success index (CSI) and equitable threat score (ETS), details of categorical statistical measures are given in Mashingia *et al.* (2014). Thresholds of 0.5-25 mm were adopted to measure the ability of both TMPA products to capture precipitation occurrences at different intensities. Perfect values were considered as 1 for FAR, and 0 for each of POD, CSI and ETS. Formulas of categorical statistics are given by:

$$FAR = \frac{F}{H+F}$$
(6)

$$POD = \frac{H}{H+M}$$
(7)

$$CSI = \frac{H}{H + M + F}$$
(8)

$$ETS = \frac{H - Ar}{H + M + F - Ar}$$
(9)

Ar, represents the random hits that could occur by chance and is given by:

$$Ar = \frac{(H+M)(H+F)}{H+M+F+Z}$$
(10)

where H represents the hits (event forecast to occur, and did occur), F shows false alarms (event forecast to occur, but did not occur), M represents misses (event forecast not to occur, but did occur), and Z stands for correct negatives (event forecast not to occur, and did not occur).

4. Results and discussions

4.1. Evaluation results

Table 1 shows the statistical error characteristics of both TMPA products. At daily scale, both TMPA (V6 and V7) products did not show a good agreement with the rain-gauge data on point and basin level. The correlation coefficients (CC) were low (0.25-0.30 for V6-V7, respectively, on basin level and the best values of 0.18-0.26 on point level for V6-V7, respectively) and values of statistical errors were high [ME = 0.28 - 0.19; MAE = 2.31 - 2.23; RMSE = 5.19 - 5.29 for V6-V7, respectively, on basin level and the best values of ME= -0.21-(-0.03); MAE=1.90-1.73; RMSE=6.12-6.24 for V6-V7, respectively, on point level]. Both products showed a significant bias compared with the gauge data (18.5-12.9% for V6-V7, respectively, on basin level and the best values of -11.14% - (-1.66%)for V6-V7, respectively, on point level). At monthly timescale, both products showed a good correlation with the gauge data. Monthly data comparison exhibited the best values of CC as 0.66-0.71 for V6-V7, respectively, on point level and 0.71-0.73 for V6-V7, respectively, on basin level. But at seasonal (monsoon and westerlies) scale, both products (V6–V7) did not show a good agreement with the gauge data both on

Evaluation of TMPA-3B4 2	2 versions 6 and 7	over Swat	Watershed,	Pakistan
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Table	I. Statistical	error cha	Iracteris	tics of TI	MPA (V6	and V7) p	orecipitat	ion estir	nates at	differen	t tempoi	al and s	oatial sc	ales.							
Statior	n name	Amb	ahar	Chai	rsada	Dro	sh	Kal	am	Mar	dan	Risa	pur	Thalo	mozo	Toor (Camp	Zulam	Bridge	Basin	ave.
TMPA	product	77	۷6	77	٧6	77	۷6	77	۷6	77	٧6	77	۷6	77	٧6	77	٧6	77	۷6	77	٧6
S	Daily	0.06	0.10	0.14	0.10	0.16	0.15	0.26	0.18	0.18	0.13	0.17	0.12	0.14	0.10	0.13	0.09	0.21	0.15	0.30	0.25
	Monthly	0.52	0.64	0.58	0.66	0.50	0.55	0.72	0.53	0.68	0.59	0.54	0.51	0.66	0.60	0.61	0.50	0.71	0.64	0.73	0.71
	Monsoon	0.06	0.05	0.21	0.11	0.02	0.07	0.12	0.13	0.21	0.18	0.21	0.11	-0.0	-0.05	0.24	0.12	0.12	0.10	0.24	0.16
	Westerlies	0.06	0.12	0.12	0.14	0.17	0.13	0.23	0.23	0.24	0.12	0.17	0.19	0.18	0.15	0.12	0.12	0.25	0.24	0.34	0.31
ΔE	Daily	0.33	0.66	-0.03	0.38	0.61	0.84	-0.93	- . 3	0.06	-0.26	0.12	-0.21	-0.05	-0.21	0.46	0.60	0.69	0.77	0.19	0.28
	Monthly	9.99	19.7	-0.76	9.11	18.6	25.2	-28.2	-34.3	1.99	-8.58	3.64	-7.04	-1.56	-6.85	13.9	17.8	21.0	22.6	6.11	8.63
	Monsoon	0.96	.18	-0.96	-0.13	1.63	1.79	0.59	0.72	-0.69	- . 8	0.02	-0.68	1.12	1.03	1.45	1.68	1.17	.18	1.15	1.28
	Westerlies	-0.49	0.08	-0.10	0.02	0.05	0.34	-2.26	-2.78	-0.14	-0.92	-0.48	- . 8	-1.10	-1.50	-0.34	-0.54	0.07	0.18	-0.64	-0.66
MAE	Daily	1.73	1.90	2.45	2.89	2.42	2.59	3.4	3.39	2.83	2.75	2.61	2.50	3.07	3.08	2.09	2.28	2.51	2.66	2.23	2.31
	Monthly	25.5	26.1	22.8	23.7	34.5	36.4	42.8	53.8	31.6	36.4	35.6	34.1	30.8	33.9	27.2	32.6	31.5	31.6	22.9	24.6
	Monsoon	1.33	1.46	3.99	4.81	06.1	2.06	2.21	2.32	5.05	4.91	4.10	3.98	2.17	2.19	2.25	2.54	3.79	3.89	2.07	2.18
	Westerlies	2.98	3.22	3.05	3.12	3.45	3.69	5.47	5.22	3.14	2.88	3.52	3.06	4.84	4.85	3.26	3.14	3.29	3.41	3.34	3.36
RMSE	Daily	6.24	6.12	8.48	8.77	6.49	6.65	8.72	8.63	9.63	9.43	9.17	8.87	9.77	9.73	7.17	7.35	8.17	8.45	5.29	5.19
	Monthly	34.1	32.6	43.8	42.4	46.2	47.0	60.8	72.2	47.7	53.3	52.5	52.8	43.4	46.5	36.5	42.2	42.9	42.2	31.5	31.8
	Monsoon	3.92	4.10	10.85		3.27	3.78	4.21	4.58	12.95	12.9	11.15		4.06	4.24	6.35	6.95	10.38	10.4	3.81	3.94
	Westerlies	8.43	8.37	9.42	9.07	8.83	8.96	12.80	12.07	9.85	9.32	11.69	10.84	13.58	13.42	9.64	9.43	9.41	9.55	7.56	7.4
BIAS	Daily	40	80.64	-1.66	25.39	52.1	71.88	-34.6	-42.3	3.75	-14.6	7.6	-13.2	-2.74	. 	45.1	59.1	56.3	62.5	12.5	17.9
	Monthly	40	79.90	-1.66	25.45	52.1	71.69	-34.6	-42.1	3.75	-14.2	7.59	-13.7	-2.74	0.11-	45.1	59.2	56.3	60.5	13.1	18.7
	Monsoon	370	453	-31.3	-13.0	711	783	50.8	62.5	-19.4	-33.2	0.64	-25.4	9	44	226	262	71.1	71.4	132.6	147.3
	Westerlies	-24.7	4.06	-5.16	1.22	2.53	15.83	-48.3	-59.3	-6.30	-42.3	-19.3	-46.8	-30.9	-41.9	-15.9	-25.1	2.94	7.99	-22.4	-23.3

point and basin levels. As shown by CC, the precision of both products during monsoon season was reduced (0.16–0.24 for V6–V7, respectively, on basin level and the best values of 0.11–0.21 for V6–V7, respectively, on point level). During this season, both products overestimated the precipitation at most of the stations and basin level. However, the performance of both versions was slightly improved during westerlies compared with the monsoon season (shown by improved values of CC). Both TMPA products underestimated the precipitation compared with the gauge observations during westerlies precipitations. Results indicate that about 10% overestimations during monsoon and about 4% underestimations during westerlies precipitations were reduced in TMPA-V7.

Figure 2(a–i) shows the spatial distribution [adopting inverse distance weighting (IDW) interpolation] of average annual, westerlies and monsoon precipitation estimates of gauge and TMPA products. Gauge-based maps of average annual and westerlies precipitation showed as increasing pattern towards to north-east but monsoon map indicated an increasing pattern towards the south to south-east of the watershed (Figure 2(a-c)). From seasonal to annual scale, both TMPA products failed to capture the spatial patterns and magnitudes of precipitation over the watershed (Figure 2(d-i)). Compared with TMPA-V6, somewhat of these spatial precipitation patterns were captured by TMPA-V7. Figure 2(j-q) shows the results of evaluations conducted to estimate the occurrence of precipitation at different intensities. Results show that the precipitation detection skill of both satellite-precipitation products, on point and basin levels, decreases with the increase of precipitation intensity. Values of FAR were increased, while the scores of POD, ETS and CSI decreased with the increase of thresholds. This means that both TMPA products are less skilful to detect the occurrence and magnitude of intense precipitation events.

Figure 3(a) shows the comparison of average annual gauge and TMPA-based precipitation estimates at all stations. It is clear from this comparison that in lower altitude areas agreement between the TMPA-V7 and gauge observations are higher than that of the TMPA-V6. Nevertheless, both satellite products overestimated (69.6% by TMPA-V6 and 48.4% by TMPA-V7) the precipitation at stations on altitudes between 500 and 1500 m a.s.l. and underestimated (26.73% by TMPA-V6 and 19% by TMPA-V7) at stations above an altitude of 2000 m a.s.l. This error variability shows a significant geo-topographical dependent distribution of both satellite precipitation products. In low altitude areas, the overestimation by TMPA products was mainly ascribed to evaporation of precipitation, because of the warm atmosphere in lower areas. While the underestimation of precipitation over high-altitude areas (cooled atmosphere) was mainly ascribed to topology and orographic effects. Overall, the TMPA-V7 performed well as compared with TMPA-V6. Our results are consistent with the already published findings of Chen et al. (2013).

4.2. Correction of satellite-precipitation estimates

Results showed that the upgraded TMPA-V7 product performed slightly better than TMPA-V6. Nevertheless, significant bias was still present in TMPA-V7. Based on the findings, an effort was made to remove the bias of both TMPA products, to compare both versions after bias adjustment. In this regard, several time scales (daily, monthly, and seasonal) were considered for bias correction. Still high correlations between gauge data and TMPA products were found at the monthly scale, so bias correction factors at monthly timescale were developed within the study area. Previously, many researchers have adopted a monthly bias correction factor for the adjustment of satellite-based precipitation data (Vernimmen et al., 2012; Arias-Hidalgo et al., 2013). In this study, we adopted the methodology of Arias-Hidalgo et al. (2013) for the estimation of bias correctors. For that objective, the average monthly precipitation values of both TMPA products were compared with gauge-based observations. Equation (11) shows the developed relationship between rain gauge observations and their corresponding satellite-based precipitation estimates at the monthly timescale.

$$GP_{i,m} = f_{i,m} \times TMPA_{i,m} \tag{11}$$

where $f_{i,m}$ is monthly bias factor at the *i*th rain-gauge. TPMA_{*i,m*} is original satellite-based monthly precipitation (mm/month) at the *i*th rain-gauge during the month *m*, GP_{*i,m*} is total precipitation at the *i*th rain-gauge and the month *m*.

In order to assess the validity of corrected satellite-precipitation estimates over Swat Watershed, RMSE and relative bias of corrected data were calculated. Table 2(a) shows the bias correction factors, estimated RMSE, and relative BIAS of adjusted data. Results showed that the bias-adjusted TMPA-V7 product was quite comparable with gauge-based data. Therefore, by adopting IDW approach, the bias correction factors for TMPA-V7 were spatially distributed across the whole watershed resulting in a distributed map of bias correctors. The corresponding bias correction factors for 'Munda' and 'Dir' gauging stations were estimated from that map. Before bias correction, statistical error characteristics of both validation stations were also calculated. The calculated values were CC = 0.17 - 0.17; ME = 0.74 - 0.93; MAE = 2.41 - 2.39; RMSE = 7.87 - 7.06, and bias =66-94% for Munda and Dir stations, respectively. As expected, significant bias (90% at Munda and 105% at Dir station) was reduced after correction. Thus, the developed correction factors are considered valid for whole watershed and adjacent similar watersheds.

As various hydrological models use only daily precipitation data, thus monthly corrected precipitation estimates were disaggregated to daily scale, to make them available at daily time-scale for various hydrological modelling studies. For that, temporal disaggregation



Figure 2. Spatial patterns of average annual, westerlies and monsoon precipitations of gauge based (a-c), TMPA-V6 (d-f), and TMPA-V7 (g-i), respectively. Binary analysis (j-q) of both products for precipitation occurrence using ETS, POD, FAR, and CSI for a range of thresholds.

coefficients (k_i) were derived from gauge-based daily precipitation time series as follows:

$$k_{i,d,m} = \frac{P_{i,d,m}}{TP_{i,m}} \tag{12}$$

where $k_{i,d,m}$ is temporal disaggregation coefficient at the *i*th rain-gauge, for the day *d* of month *m*. $P_{i,d,m}$ is cumulative precipitation at the *i*th rain-gauge on the day *d* of month *m* (mm day⁻¹), and TP_{*i*,m} is cumulative precipitation at *i*th rain-gauge during the month *m*

precipitation e	stimates.														
(a)	Gauge data.	Origir	nal TMP.	A (V7)	Origi	al TMP/	A (V6)	Mont	hlv	Correct	ted TMF	A (V7)	Corrected T	MPA (V	()
Validation	annual rainfall	Annual rainfall	rBias	RMSE	Annual rainfall	rBias	RMSE	bias corre	ctor	Annual rainfall	rBias	RMSE	Annual rainfall	rBias	RMSE
station name	(mm year ⁻¹)	(mm year ⁻¹)	(%)	(mm year ⁻¹)	(mm year ⁻¹)	(%)	(mm year ⁻¹)	(77)	(7 6)	(mm year ⁻¹)	(%)	(mm year ⁻¹)	(mm year ⁻¹)	(%)	(mm year ⁻¹)
Ambahar	300	420	40	22.3	536	78.9	26.7	0.74	0.59	309	3.3	20	318	6.1	17.9
Charsada	633	537	-15.3	28.2	685	8.07	32.8	1.22	0.93	653	3.2	26.1	634	0.1	32.4
Drosh	428	650	52.1	31	730	70.7	34.1	0.65	0.6	426	-0.5	23.7	439	2.6	22.7
Kalam	679	640	-34.6	48.7	567	-42.	60.2	9.1	1.62	988	_	37	918	-6.3	51.2
Mardan	637	661	3.8	22.7	534	-16.2	30.5	1.17	Ľ.	692	8.6	22.5	695	9.1	26.9
Risalpur	575	619	7.6	21.4	491	-14.7	27.3	0.96	1.24	592	m	21.3	609	5.8	25.2
Thalozom	683	664	-2.7	30.5	109	-12	35.9	1.06	1.13	707	3.5	30.2	679	-0.6	35.2
Toor Camp	370	537	45.1	26.2	584	57.9	32.5	0.67	0.58	361	-2.4	20.7	341	-7.9	24
Zulam Bridge	448	700	56.3	26.4	719	60.5	26.9	0.68	0.67	476	6.3	16.7	479	4	15.7
(q)															
					Means over th	ie period	l of 1999–2006				I	Means o	ver the period	l of I 998	-2014
				TMPA-V6 (I	mm)		μT	PA-V7 ((mm)		ļ		TMPA-V7 (I	(uu	
Resolution	(mr	n)	Origir	nal	Corrected		Original		Corr	ected.	0	riginal		Corre	cted
Daily	-	51	1.7	78	1.54		1.69			1.52		1.77		_	60
Monthly	46		55		47		52		4	9		54		48	
Westerlies	262		201		170		204		<u>00</u>	2		213		190	
Monsoon	80		198		168		186		9	2		194		173	
Annual	552		656		564		625		55	9		650		582	

Table 2. (a) Bias correction based on monthly correction, gauge measurements vs. TMPA (V6 and V7) precipitation estimates. (b) Basin wide mean daily-annual values of gauge and TMPA

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Figure 3. (a) Average annual precipitation of the rain-gauges and TMPA (V6 and V7) estimates. (b-c) Accumulative precipitation of gauge observations against the original and corrected daily TMPA (V7) precipitation estimates at both validation stations. (d-f) Spatial patterns of corrected TMPA-V7 average annual, westerlies and monsoon precipitations, respectively.

(mm month⁻¹). $k_{i,d,m}$ were then applied back to the corrected TMPA-V7 data to estimate the daily corrected precipitation estimates. Equation (13) shows the final expression.

$$TMPA_{corr,i,d} = k_{i,d,m} \times TMPA_{corr,i,m}$$
(13)

where TMPA_{corr,*i*,*d*} is the disaggregated, corrected daily TMPA-V7 precipitation data at location *i* (mm day⁻¹) for month *m*.

Daily synthetic and gauge-based precipitation datasets were quite comparable with each other. To check the effectiveness of corrected daily TMPA-V7 precipitation values, double mass curves at both validation stations were developed between the gauge-based and the original and corrected daily satellite-based precipitation estimates. Synthetic daily data agreed well with observed data, as shown in Figure 3(b–c). By considering the validity of correction factors, corresponding correction factors for each grid centre of TMPA-V7 was estimated to calculate the corrected basin-wide precipitation estimates (mean values are given in Table 2b) over the Swat Watershed, for the period of 1998–2014. Spatial patterns of corrected basin average annual and seasonal precipitation estimates were plotted as shown in Figure 3(d-f). The spatial patterns of corrected average annual and westerlies TMPA-V7 precipitation estimates (Figure 3(d-e)) were quite comparable with the gauge-based patterns. But the corrected monsoon estimates were still unable to capture spatial pattern of precipitation over Swat Watershed (Figure 3(f)).

5. Summary and conclusions

This study was conducted to evaluate the performance of TMPA-V6 and V7 precipitation products over Swat River Watershed in Hindukush Region. Both satellite-based products have been evaluated by using rain-gauge network on point and basin levels. Daily, monthly, seasonal (westerlies and monsoon) and annual precipitation time-series were analysed. Findings of this study are summarized and concluded as following:

- 1. Both TMPA-V6 and V7 failed to capture the spatial pattern of precipitation on annual and seasonal scale in the Swat Watershed.
- 2. Daily and seasonal time series of both TMPA products showed very low correlation (CC < 0.35 for daily and seasonal precipitations both on point and basin levels) with the observed precipitations. However, agreement between satellite and gauge precipitations was good at monthly scale with CC > 0.70 for basin and CC > 0.50 for point level.
- 3. Both TMPA products tend to overestimate precipitation events over 500–1500 m a.s.l. altitude areas, particularly overestimations were quite significant during monsoon season. On the other hand, underestimations were observed over high-altitude (above 2000 m a.s.l.) areas.
- 4. Skill of satellite-based products to detect the intense precipitation events decreases with the increase of precipitation intensity. Overall, the performance of TMPA-V7 was better than TMPA-V6 product. Basin average estimates show that biases were improved by 4% and 10% in TMPA-V7 during westerlies and monsoon precipitation, respectively.
- 5. The adjusted monthly TMPA-V7 precipitation estimates showed better agreement with gauge data compared with adjusted monthly TMPA-V6 estimates. Also, the synthetic daily precipitation estimates were quite comparable with rain gauge observations.

By using the developed areal bias-correction factor, the corrected daily, monthly, westerlies, monsoon and annual time-series (with mean (mm) values of 1.60, 48, 190, 173 and 582, respectively) of TMPA-V7 products were estimated for the period of 16-years (1998–2014).

The spatial pattern of corrected-TMPA-V7 product on annual scale was quite comparable with gauge observed spatial pattern. Although the spatial pattern of precipitation was captured well by the corrected-TMPA-V7 westerlies estimates but still the precipitation magnitudes were not captured well. Unfortunately, both the magnitudes and spatial patterns were not captured well by the corrected-TMPA-V7 monsoon estimates.

Findings of this study suggest that direct utilizations of both TMPA-V6 and V7 products are unreliable at daily-annual scales. However, bias corrected monthly, annual and synthetic daily TMPA-V7 estimates have a good potential for hydrological applications. Future research may focus on the evaluation of V7 for other seasons and also the application of adjusted data within a distributed hydrological modelling framework for precipitation-runoff simulations.

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