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Comparative Study of Satellite and Gauge-Based Rainfall Data by Using Advanced Rainfall Correction Methods

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Abstract. Rainfall data is the primary source for flood forecasting. Ungauged basins or the basin with limited ground-based observation need satellite rainfall products to compensate the scarcity. This problem becomes serious in the rugged terrain areas like the river Jhelum catchment, the area of interest for this research. The focus of this research is to evaluate the accuracy of satellite-based GSMaP_NRT rainfall products with gauge-based rainfall data. GSMaP_NRT-global satellite mapping of precipitation, near real time is a component of the GPM mission. The data for GSMaP_NRT is supplied by JAXA (Japan Aerospace Exploration Agency). GSMaP_NRT offers freely available rainfall datasets with 3 h and 24 h accumulated. These datasets are provided in two resolutions: 0.1 and 0.25 degrees. In this analysis, the rainfall dataset is used of 0.1 degree resolution. Applied correction methods in this research included, are regression method and GSMaP_NRT rainfall correction methods. It has been observed that the results provided by GSMaP_NRT (uncorrected) are not satisfactory. For this, bias correction methods GSMaP_IF2 (inter face-2) and IF3 (interface-3) have been applied. The result shows an under estimation of the precipitation at some specific locations and an over estimation where gauge-based rainfall is zero. Additionally, low-elevation areas give better results than high-elevated areas. The highest correlation coefficient is 0.90 using IF3. Spatially, IF2 follows the pattern of ground-based rainfall and IF3 follows the peak but deviates temporally and spatially at some points. Based on the conclusion of this research, the implementation of the correction methods, GSMaP_IF2 and IF3, resulted in improved estimations from GSMaP_NRT, bringing it closer to the ground-based data. This outcome aligns with the primary objective of the research, which aimed to improve the accuracy and alignment between GSMaP_NRT and ground-based rainfall data.

Keywords: GSMaP_NRT, GSMaP_IF, IF2, IF3, Jhelum, bias correction

Introduction

Rainfall is one of the most important meteorological phenomena that has a considerable impact on human life. Rainfall falls in the liquid category of precipitation, which is a natural cycle of water coming back to the earth from the sky (Wang *et al*., 2020; Levizzani and Cattani, 2019; Weldegerima *et al*., 2018). In terms of the water cycle, rainfall tends to be a key component as the water cycle is facing pressure due to the growth in population as well as continuous climate change. A very common source of rainfall data is the rain gauge. Generally, rainfall data is retrieved by rain gauges (Wang *et al*., 2023; Selase *et al*., 2015) which works well where the gauges are dense but it makes problems where there are no gauges like in remote areas (Satgé *et al*., 2018; Mlynski *et al*., 2018). International scientific society alerts that climate change can cause an abrupt temperature change which will directly affect water storage and evapotranspiration. This change then affects the rainfall as well (Wang *et al*., 2014; 2013; Middelkoop *et al*., 2001). The intensity of runoff also results in floods which are very damaging to human life and the country's economy (Sohayl *et al*., 2023; Zhu *et al*., 2018). The percentage of losses due to floods in the United States is 4.0 billion dollars. In 1843 and 1888, China also faces very large floods which caused the worst damage to China. Then there are several studies were conducted to enhance the flood prediction (Luo, 1987). The areas which are most dispose to floods are the areas of south Asia. Floods are frequent in developing countries where the population lives near the floodplain (Smith *et al*., 2019; Kirsch *et al*., 2012). In Cambodia, the climate change department and government panel suggest that there is a 50% increase in Tonle Sap Lake which causing high floods and intense spells of monsoon rainfall (ESCAP, 2011). The ower Mekong river basin recently faces high floods in the years of 2000, 2011, 2013 and 2016 (Pokhrel *et al*., 2020).

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In 2010, Pakistan faced a historically damaging flood. The westerly waves of monsoon resulted in intense rainfall which caused floods and the worst damage to a vast area of Pakistan. There was a series of floods that were occurring around the country. This devastating flood affect 18,000,000 people and more than 1700 people lost their lives (Mahmood *et al*., 2021; United Nations, 2010). Record rainfall was noted in 2010 and this is also a result of lacking rainfall prediction (Ushiyama *et al*., 2014). To avoid and control flooding in any area, flood forecasting is very important. Flood forecasting includes discharge from upstream based on flood routing. Kabul river is an upstream basin that requires rainfall data with systematic distribution and forecast of stream flow with the help of a rainfall runoff model. Now, the point raises that in a vast basin like the Kabul river, it is complicated to monitor the rainfall with an inadequate number of rainfall observatories. As Kabul basin has only 3 rain gauges in it (Ghulami *et al*., 2017; Sayama *et al*., 2012). Rainfall estimation is the primary key for the forecast system as sudden intense rainfall cause much damage to the country and human lives. The conventional methods of rainfall measurement include the most commonly used rainfall gauge. To get the most accurate rainfall values, it is necessary that the gauge network is dense and there are no vast areas that are ungauged (Xu *et al*., 2017). But a country like Pakistan does not have a dense network of gauges. To overcome this issue, remotely sensed data plays a vital role as this data continues without any gap. Obtaining information about an object without any physical touch or going there is called remote sensing (Gupta, 2017). This technique revolutionized the process of data collection as one can get data from any place in the world without going there like for flood analysis (Domeneghetti *et al*., 2019), the roads are blocked and the areas are damaged. Remote sensing helps in collecting data on an affected area in the form of images. The process of collecting Remote sensing images includes Airborne and Spaceborne methods. In an airborne method, images are: collected by using an aircraft and space-borne, images are collected by satellites (Tripathi and Tiwari, 2021; Luo *et al*., 2019). Remote sensing data for rainfall have been used for the last three decades with the enhancement of spatial and temporal resolution (Mugnai *et al*., 2013). The first-ever satellite rainfall product was:

- Tropical rainfall measuring mission (TRMM) (Huffman *et al*., 2007).
- Global precipitation measurement (GPM) (Hou *et al*., 2014).

The comparison of ground-based and satellite rainfall shows a good correlation which gives a positive result regarding the use of satellite-based rainfall data (Ogbu *et al*., 2020; Brunetti *et al*., 2018). Remotely sensed data can give high temporal accuracy data for even a large basin (Karimi *et al*., 2015). Collecting spatial data, storing it in an organized way, editing and analyzing, and doing several analyses on it is called Geographical Information System (GIS). GIS allows users to do various types of analysis including historic rainfall data by using the interpolation technique. This technique allows users to see the rainfall trend over previous years and can use this data to determine different water-related problems (Bouaida *et al*., 2021; Arabeyyat *et al.,* 2018). The overall discussion leads to the need for an alternative of rainfall data that can be used where there are no gauge or minimum rain gauge stations. This scarcity of rain gauges can be filled by satellite rainfall products (Shamkhi *et al*., 2019). When using satellite rainfall, the first step is to analyze the accuracy of rainfall values. This can be done by comparing the satellite rainfall to gauge-based rainfall to check whether the values are matching or not. In Pakistan, the standard for rainfall data is rain gauges. This research is focusing on this comparison to give an alternative for ungauged areas. The main objectives of this research are: Comparison of Gauge-based and GSMaP_NRT (satellite-based) rainfall; Correction of GSMaP_NRT rainfall using three Bias-correction methods; Comparison of Bias-correction methods to find the most suitable (Saber and Yilmaz, 2018). The area of interest is the river Jhelum Catchment comprising 9 rainfall observatories.

Study area. Jhelum river catchment is located on the west side of the Himalayan and is the most vital part of the upper Indus basin ranging between 33°25′ N to 34°40′ N and 73°55′ E to 75°35′ E (Fig. 1). Two main types of precipitation dominates the whole climate of this catchment; Indian Monsoon (in summer; Precipitation in winter from the west (westerlies) reported by (Azmat *et al*., 2018). Different researchers determine the Himalayan and upper Indus basins as “Hotspots” for making changes in the climate of south Asia (Bajracharya *et al*., 2018; Lutz *et al*., 2016a).

Taking into consideration the importance of this basin, the Jhelum river catchment is therefore selected for this research. The total drainage area of the Jhelum river is

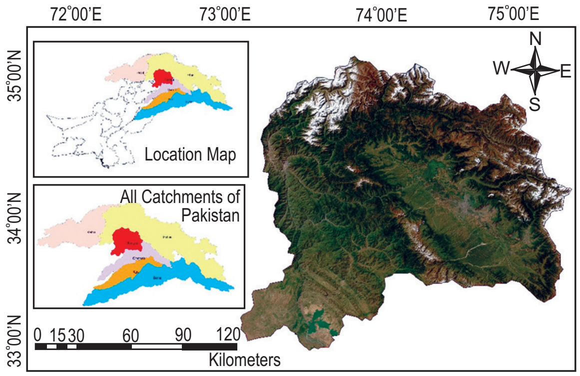


Fig. 1. Map of study area, Jehlum catchment.

33,867 km^2 and is controlled by Mangla reservoir which is Pakistan's second and seventh largest water storage reservoir in the world having a total storage capacity of 7.29 km^3. As a transboundary basin, 46% of Jhelum catchment falls in Pakistan and 56% in India (Umer *et al*., 2021; Azmat *et al*., 2018). This is the main reason for the scarcity of rain gauges in the Jhelum catchment. As more than half of the catchment's area is on the Indian side, the information on rainfall from rain gauges is not accessible resulting in an ungauged area (Nikolopoulos *et al*., 2015). Below is the (Table 1) and (Fig. 2) showing the location and names of all the rain gauges in Pakistan.

Material and Methods

Below is the flowchart of the work methodology used in this research (Fig. 3).

Global satellite mapping of precipitation, near real time (GSMaP_NRT). The satellite rainfall product used in this research is GSMaP_NRT-Global satellite mapping of precipitation, near real time is a GPM mission (Weng *et al*., 2023; Kubota *et al*., 2020; Shi *et al*., 2020). The data is being supplied by JAXA, Japan. GSMaP_NRT provides hourly, 3 h to 24 h accumulated rainfall datasets which are freely available with two resolutions of 0.1 degrees and 1.25 degrees (Darand and Siavashi, 2021; Veerakachen *et al*., 2014). In this analysis, the rainfall dataset of 0.1 degrees (11 km) resolution is used. Three h rainfall estimation makes the analysis more precise and the availability of

Table 1. Selected gauge stations with coordinates and elevation

Gauge stations	Latitude and longitude (DD)	Elevation (m)
Balakot	34.5397° N 73.3502° E	980
Garhi Dupatta	34.2256°N 73.6154°E	812
Kakul	34.1875° N, 73.2618° E	1308
Murree	33.9078° N, 73.3915° E	2167
Mangla	31.89306° N, 72.3816° E	283
Rawalakot	33.8536° N, 73.7507° E	1677
Muzafrabad	34.37002° N, 73.47082° E	701
Kotli	33.51836° N, 73.90220° E	613
Jhelum	32.9405° N, 73.7276° E	232

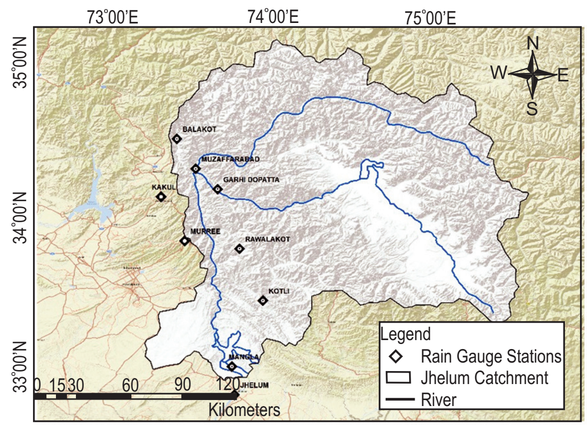


Fig. 2. Selected 9 gauge stations of Jehlum catchment.

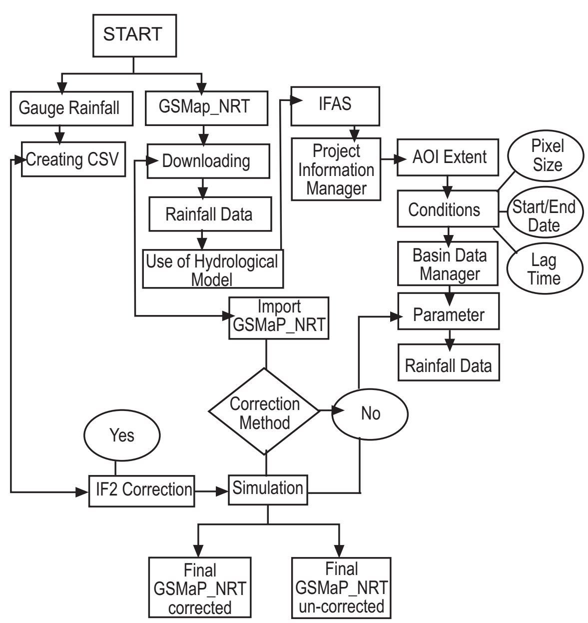


Fig. 3. Flowchart of Methodology.

these datasets by GSMaP_NRT is very beneficial (Yeh *et al*., 2019). In Pakistan, every year the rainy season starts in July and ends in September. This season is called Monsoon season in which the highest rainfall occurred. The rainfall measurement in this season has a strong influence on agriculture and irrigation network. For this research, the 3 h GSMaP_NRT data of September, 2017 is downloaded from the official website https://sharaku.eorc.jaxa.jp/GSMaP

Extracting GSMaP_NRT data is a complex procedure. After downloading, the data files are in . dat format which is not able to extract directly to the computer. For this, a hydrological model Integrated flood analysis system (IFAS) is used.

Integrated flood analysis system (IFAS). IFAS is developed by ICHARM, International Centre for Water Hazard and Risk Management. The main purpose of developing this model is to provide an efficient interface to overcome the lacking of hydrological data for better flood forecasting (Shahzad *et al*., 2018; Chow and Jamil, 2017). The capability of this model is that 3B42RT and GSMaP_NRT datasets can be imported into it and this is the reason behind using the model for this research. GSMaP_NRT data can be visualized globally by using this model. When GSMaP_NRT files are available in excel format, they have rows and columns in it (Chow, 2021). To find the rainfall data for desired location/gauge station, row and column address needs to be collected from IFAS. The methodology of collecting row and column addresses is: first enter the coordinates of the gauge station in which rainfall is needed. The software selects the pixel on a given location *i.e.* any gauge station location. Enter all the coordinates of gauge stations one by one and note down their row and column addresses (Fig. 4).

After that, the next step is to go to the output files that are generated by IFAS *i.e.* excel files. Find the desired row and column for each station and note down the complete address. This method gives a final excel file containing all the rainfall of desired gauge stations at once. After this, the next step is to compare the GSMaP_NRT rainfall to gauge stations. To compare both rainfall datasets, the first step is to use regression analysis to see the difference and similarities between both datasets. The following graph (Fig. 5) is showing an overall view of GSMaP_NRT and Gauge-based rainfall. It can be seen from the above graph that GSMaP_NRT is under estimating the rainfall data. It is continuously showing a low range of rain even at peak points. This uncorrected GSMaP_NRT dataset can be used where there is low rain or no rain but where rainfall values are high and peaks are present, there is much need to correct this rainfall. For this correction methods are applied to this dataset.

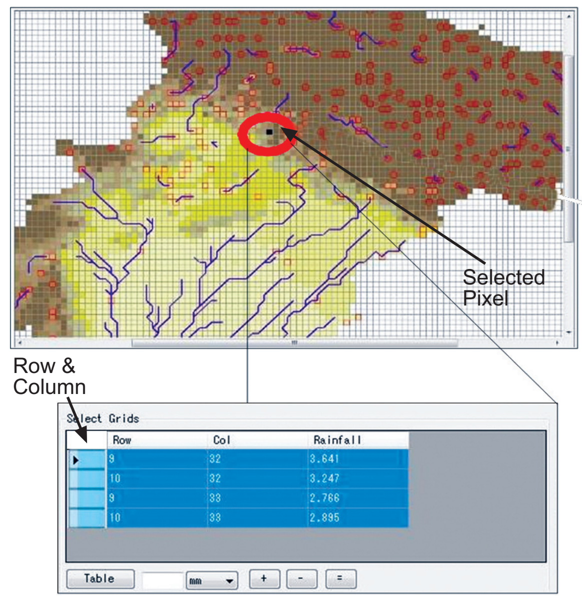


Fig. 4. Selecting row and coloumn address in IFAS by selecting the pixel according to gauge location.

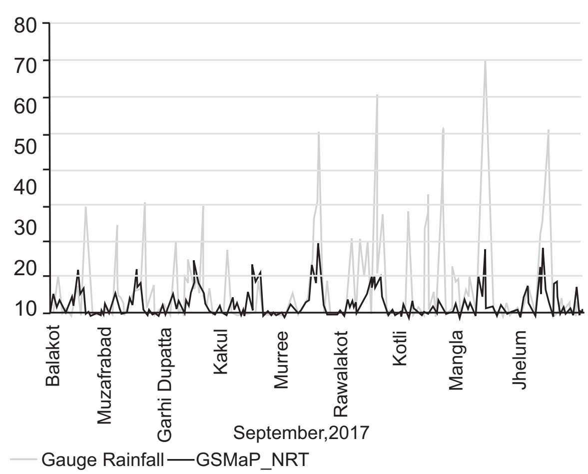


Fig. 5. Comparison of GSMaP_NRT uncorrected with gauge based rainfall by using a line graph.

Correction method. As GSMaP_NRT is under estimating the ground rainfall, the next step is to use a correction method. In this research, two correction methods are used:

(a). IF2 (Interface-2), (b). IF3 (Interface-3)

Both correction methods are developed by JAXA, Japan Aerospace Exploration Agency and in April, 2015 are fully functioned as the National research and development agency.

Methodology of correction method. The correction method IF2 is added in IFAS interface from which satellite rainfall can be corrected. The second method IF3 is not added in IFAS, the rainfall correction is done outside the IFAS interface. For a real-time correction or calibration, three datasets are required:

GSMaP_NRT rainfall; Gauge rainfall; Digital elevation model.

In this procedure, GSMaP_NRT is the object on which all the correction is applied. The second dataset which is ground rainfall works as ground truthing. In the ground rainfall file, the date and time of the rainfall are listed which also helps in calibration.

The rainfall correction method continues by following five steps.

- The first step is to set the time span same for both GSMaP_NRT and gauge rainfall.
- The second step is to correct the geographic errors which are corrected by comparing both GSMaP and gauge-based rainfall. GSMaP rainfall pattern is corrected according to the ground-based rainfall.
- The weight of the calibration coefficient is adjusted with the help of elevation and distance.

$$\text{Weight} = \frac{1}{\text{distance}} \times \frac{1}{\text{elevation}}$$

- The amount of rainfall is corrected with the use of offset and scaling at each gauge location. After offsetting and scaling, the final corrected rainfall is merged into a final file based on the weighted mean (Fig. 6).
- In last, the final corrected files are converted to hourly GSMaP_NRT format.

The final formula for correcting GSMaP_NRT rainfall according to the gauge-based is:

High rainfall: (corrected rainfall) = (original rainfall) × (scale factor) × (weight)
Small rainfall: (corrected rainfall) = (original rainfall) + (offset factor) × (weight)

GSMaP_IF corrects the rainfall by combining the weighted mean of (distance and topography) only at each observatory, while in IF2 correction methods, the weight coefficient decreases depending on the distance from the ground rain gauge. In the case of IF3, this correction method has two ways together to determine the coefficient outside of the defined distance: fixed weight coefficient within the user-defined distance and decreasing coefficient outside of the defined distance.

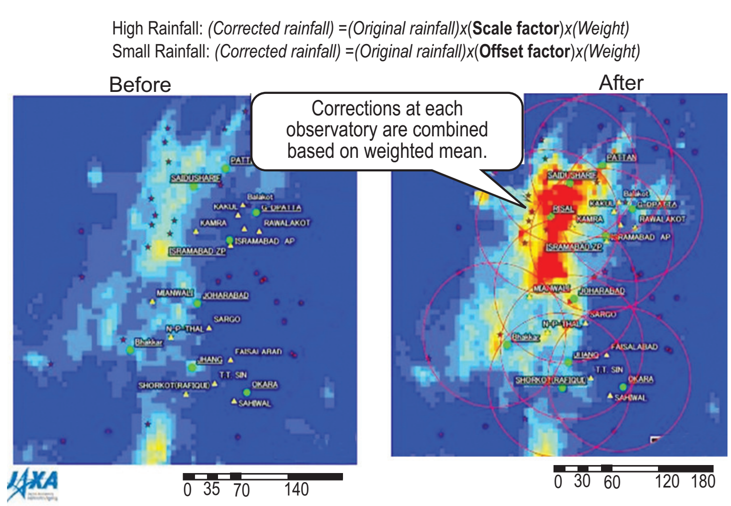


Fig. 6. Rainfall correction by using scale and offset (GSMaP-IF3 User Manual, 2014).

GSMaP_NRT (uncorrected) data. The first dataset when applying the correction method is GSMaP_NRT raw data (without correction). The pixel size of this dataset is 11 Km. The first analysis is done by comparing the GSMaP_NRT raw data with ground-based rainfall data. The initial results of this study are not satisfactory as GSMaP_NRT is underestimating the rainfall. So, there was a need to apply a correction method to find suitable results.

GSMaP-IF2 correction method. GSMaP_IF2 works within the IFAS interface. There is an option of "GSMaP_IF2 (real-time correction)" that needs to be checked in for using the IF2 correction method. First, a .csv file of ground-based data is needed for this correction. The .csv file should be in the pre-defined format of IFAS. If the format is not the same, the correction method will not work properly. When raw data of GSMaP_NRT is not giving good results. The correction method IF2 is applied to raw data which is uncorrected GSMaP files. After the correction of raw data, the corrected data is compared with ground-based rainfall to check the reliability of the corrected files.

GSMaP-IF3 correction method. GSMaP-IF3 after IF2 focuses on the short-term (hour/daily) rainfall correction. GSMaP-IF corrects GSMaP rainfall by using ground-based rainfall data taken in synchronization with GSMaP. Version 3.1 has been improved on correction accuracy by a rain-cloud object-based algorithm and has a function to support IFAS format of ground rainfall observation data. IF3 is not built-in in IFAS, the whole working of IF3 is a manual based on the concerned files. The main three files need to be prepared for running IF3 *i.e*. Correction area; IFAS settings and Subset area.

Correction area file specifically based on the extent of the study area. The IFAS setting file contains all the basic settings of IFAS like project name, start/end date and rainfall lag time and subset area file is almost the same as the correction area but in this file, some extra area is included so that the corrected area will be covered fully with no missing place.

Input/output files. The input and output files are also manually placed under IF3 folder. When all the required files are completed. There is a file for running the IF3 correction method. After running this file, the final corrected files are available in the output folder.

GSMaP_NRT correction method results. The defined methodology is applied to GSMaP_NRT rainfall to obtain the final results. Both correction methods IF2 and IF3 are applied to this dataset to calibrate the rain to get the desired values according to the gauge-based rainfall. The correction methods are applied on each gauge station and calibrated rain is compared with gauge-based rain. There are several corrected files for each day that is why the corrected maps are showing only for 2 dates *i.e*. 18th and 20th September (Fig. 7).

This map is also showing the same comparison of uncorrected and corrected GSMaP_NRT rainfall for the same date and same location. The pixels in the middle of the catchment showing no rain in the uncorrected file but the corrected file is showing rain at the same location. This correction is further checked by comparing the values to gauge-based rainfall.

Results and Discussions

The below graph shows the rainfall distribution for the month of September based on 4 datasets for Balakot station. GSMaP_NRT uncorrected, IF2 and IF3 corrected

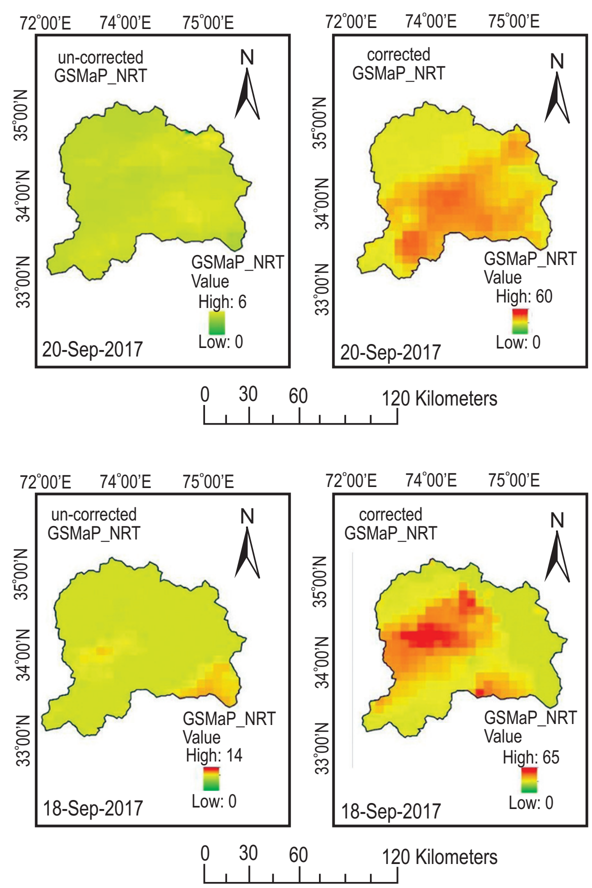
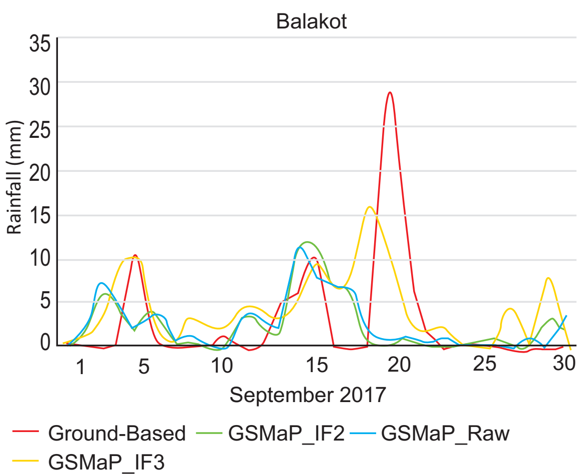


Fig. 7. Corrected and un-corrected GSMaP.

rainfall is compared with gauge-based rainfall. It can be seen that GSMaP is uncorrected and IF2 is almost showing the same result in a lower range. The range between these two datasets are showing results is 0 to 11 mm. Whereas IF3 is showing better results than these two datasets. The noticeable thing is IF3 is following the peaks, however, the amount of rainfall is less but the peaks are almost according to the gauge-based rain (Fig. 8). The highest correlation is found between gauge-based and IF3 corrected rainfall which is 0.40 (Table 2). In case of Muzaffarabad, again it can be seen that IF3 is following the peaks but over-estimating the rainfall.

A peak point where gauge rainfall is 30 mm, IF3 is showing 64 mm. The time of the rainfall peak is the same but the total amount is different. The highest correlation is 0.79 using IF3. The peak rainfall at Garhi Dupatta is 25 mm and the nearest value of 21 mm is showing as the result of IF3 corrected rainfall. The second peak at this station is 20 mm and IF3 is showing 10 mm. Another point where IF3 is giving good results is where gauge rainfall is 14 mm and IF3 is giving 11 mm which is also a good result. IF2 is also following peak at one location where gauge rainfall is 10 mm and IF2 is giving 13 mm. The highest correlation coefficient is 0.78 using IF3. Rainfall recorded at Kakul station is much less which is 28 mm for the whole month having mostly no rain days with zero values (Table 2). This is the reason that among all methods, no method shows a good result and gives over-estimating rain values. The only similar point for this station is where gauge rainfall is 17 mm and IF3 is showing 10 mm of rain after correction. There are negative correlation values for both uncorrected and IF2 correction methods as both datasets are showing completely opposite rain values than the gauge-based values (Fig. 9). The correlation value for IF3 is 0.16 which shows a very weak linear relationship because IF3 shows similarity with gauge based rainfall only at one point.



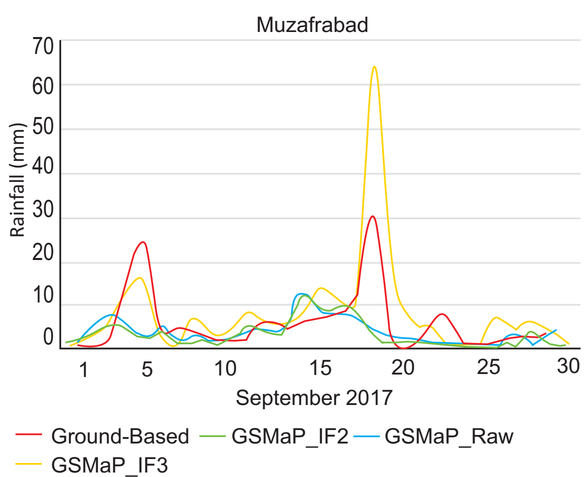


Fig. 8. Comparison of GSMaP un-corrected, IF2, IF3 and gauge based rainfall for Garhi Dupatta and Kakul station.

The result at Murree station shows a peak rain value of 49 mm which is gauge rainfall. At that point, correction method IF3 is following the peak but shows a lesser amount of rainfall which is 29 mm. But the overall distribution of IF3 correction is well with gauge-based rain. The other two datasets, uncorrected and IF2-corrected rainfall again show similar results with each other. The correlation between gauge-based and IF3 correction method is 0.72 which shows a good linear relationship between these two datasets. It can be seen from the above graph that IF3 is again showing a good trend with gauge-based rainfall. The peak rainfall of gauge based is 60 mm, where IF3 is showing 47 mm rainfall (Fig. 10). With the correlation of 0.83, the IF3 correction method is again dominating (Table 2). The reason is the same that it is following the rain according to the days of the gauge based rain.

The peak rainfall recorded at Kotli is 51 mm and IF3 is giving 49 mm of rain at that point which is nearest to the gauge-based rain. There are another two peaks with the values of 32 and 28 mm gauge rainfall and at both peaks IF3 is showing 26 and 22 mm rainfall which is also a very good representation of the ground-based rainfall. Not only at peaks but also at lower values, IF3

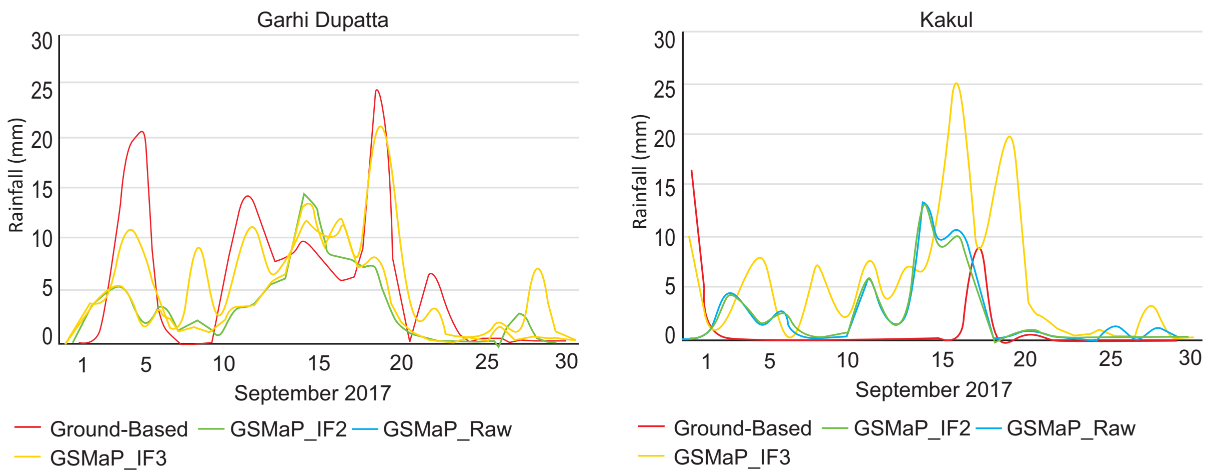


Fig. 9. Comparison of GSMaP un-corrected, IF2, IF3 and gauge based rainfall for Garhi Dupatta and Kakul station.

Table 2. Statistical results of corrected and uncorrected rainfall of all stations

Station	Methods	Valid N	Mean	Minimum	Maximum	Std.Dev.	Correlation
	Ground based	30	2.655	0.000	30	6.286	
	Raw	30	2.428	0.000	11.521	3.186	0.08
Balakot	IF2	30	2.507	0.000	11.428	2.951	0.05
	IF3	30	4.087	0.000	15.885	4.003	0.40
	Ground based	30	4.655	0	30	7.097	
	Raw	30	2.508	0	11.627	3.132	0.18
Muzaffarabad	IF2	30	2.745	0	12.445	3.020	0.23
	IF3	30	7.355	0	64.151	11.809	0.79
	Ground based	30	5.310	0	25	6.819	
	Raw	30	3.180	0	14.595	3.568	0.48
Garhi Dupatta	IF2	30	3.304	0	13.601	3.789	0.52
	IF3	30	5.772	0	21.604	5.353	0.78
	Ground based	30	7.027	0	49	12.091	
	Raw	30	2.934	0	18.455	4.261	0.52
Murree	IF2	30	2.883	0	18.822	4.195	0.51
	IF3	30	6.332	0	28.990	7.744	0.72
	Ground based	30	9	0	60	13.344	
	Raw	30	3.249	0	10.41	3.193	0.55
Rawalakot	IF2	30	3.295	0	10.577	3.240	0.46
	IF3	30	6.896	0	47.343	9.165	0.83
	Ground based	30	9.162	0	51	14.728	
	Raw	30	1.006	0	3.509	1.168	0.001
Kotli	IF2	30	0.896	0	4.085	1.209	0.17
	IF3	30	7.914	0	48.365	11.519	0.94
	Ground based	30	10.1	0	70	17.087	
	Raw	30	2.507	0	17.115	3.916	0.79
Mangla	IF2	30	2.324	0	17.706	3.994	0.78
	IF3	30	9.904	0	62.711	14.482	0.94
	Ground based	30	7.152	0.000	49.4	12.096	
	Raw	30	4.351	0.000	18.718	4.535	0.52
Jhelum	IF2	30	2.795	0.000	16.317	4.294	0.39
	IF3	30	10.812	0.00	62.399	15.461	0.88

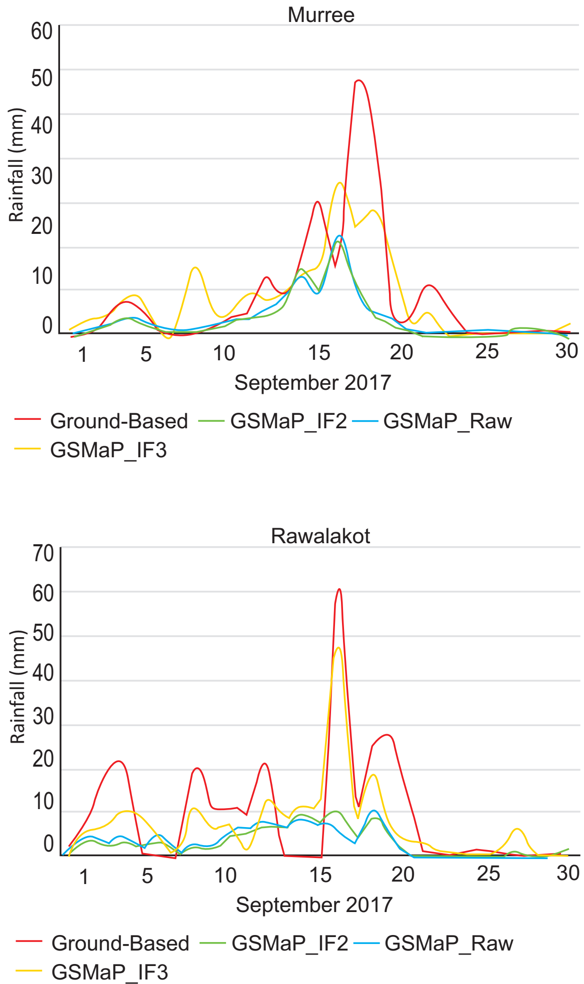


Fig. 10. Comparison of GSMaP un-corrected, IF2, IF3 and gauge based rainfall for Murree and Rawalakot station.

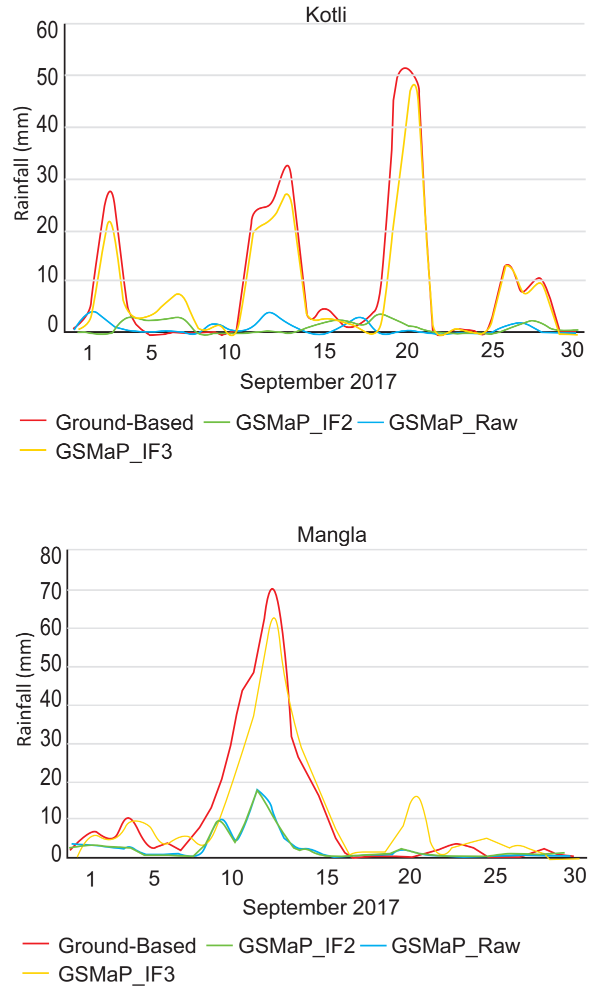


Fig. 11. Comparison of GSMaP uncorrected, IF2, IF3 and Gauge based rainfall for Kotli and Mangla station.

is giving far better results (Fig. 11). The statistical analysis for Kotli shows a very clear picture that IF3 is dominating with the correlation value of 0.94 (Table 2). This value represents a strong linear positive relationship with actual rainfall. It can be clearly seen that IF3 is following the peak by the amount and by time as well. The highest peak at Mangla is 70 mm of rain recorded by the gauge station. IF3 is giving 62 mm rain at that point which is pretty much satisfactory in terms of the correction method. The correlation coefficient is 0.94 which again shows a strong linear relationship between both datasets (Table 2).

Following (Table 2) is showing the overall statistical results of all 9 stations analyzed in this research. The highest correlation coefficient is 0.94 in the case of Kotli and Mangla using the IF3 correction method. Another correlation value at Jhelum is 0.88 showing a strong positive relationship by using IF3. All these three stations have low elevation values. It can be seen that the values of standard deviation are relatively high as compared to the overall results. This is because of the sudden change in values of the datasets, like there are sudden jumps in high and low values which increases the standard deviation value.

Conclusion

The purpose of this research was to analyze two types of rainfall correction methods of GSMaP_NRT for the Jhelum Catchment in Pakistan. The main reason was to propose a suitable alternative for the ungauged areas in the Jhelum catchment due to the scarcity of gauge stations. The proposed alternative is GSMaP_NRT corrected rainfall by using two correction methods. This research revealed that the uncorrected rainfall and correction method IF2 is underestimating the rainfall where there are high rain values but at high values, IF3 is giving better results. However, it can be seen that where rainfall values are low, IF3 sometimes over-estimates the rain at these points. Although based on temporal scale, GSMaP IF2 and IF3 both corrected rainfall datasets showing good results. It is established that both correction methods follow the time and day of the rain according to the gauge-based. One important point outcome in this research is related to elevation as it can be seen from the results that the performance of both correction methods are better at the gauge stations with low elevation especially the performance of the IF3 correction method. Like Mangla has an elevation of 283 meters, Jhelum at 233 meters and Kotli at 613 meters, showing very significant results specifically by using IF3. The correlation values at these stations are 0.94 and 0.88 which shows a strong positive linear relationship between gauge-based and IF3-corrected rainfall. IF2 correction method at various points gives the result the same as uncorrected rainfall except for the few good results like at Mangla, it also shows a good correlation with the value of 0.78. It is concluded that the GSMaP_NRT IF3 correction method is giving better results as compared to the IF2 correction method and uncorrected rainfall. IF2 and IF3 are both correction algorithms used in the context of precipitation data. However, they differ in terms of their coefficient determination methods. The correction algorithm used by IF2 operates by assigning weight coefficients that decrease as the distance from the gauge station increases. This means that the influence of gauge stations decreases as the distance between them and the target location increases. In the case of IF3, the correction method incorporates two approaches to determine the coefficients for precipitation correction. Within the user-defined distance, a fixed weight coefficient is applied, while outside of the defined distance, a decreasing coefficient is employed. This means that gauge stations within this range have a consistent influence on the correction. Outside of the defined distance, IF3 applies a decreasing coefficient. This indicates that the impact of gauge stations gradually decreases as the distance from the target location increases beyond the user-defined distance. In summary, IF2 relies solely on distance-based weight coefficients, whereas IF3 incorporates a combination of fixed weight coefficients within a user-defined distance and decreasing coefficients outside of that distance. Therefore, IF3 has proven to be a suitable alternative for estimating rainfall in areas where gauge stations are not available. By incorporating a combination of fixed and decreasing weight coefficients, IF3 can utilize both nearby and more distant gauge stations to provide reliable precipitation estimates. This makes it a valuable tool for areas lacking gauge stations, enabling the estimation of rainfall with reasonable accuracy.

Limitations. The GSMaP_NRT is a valuable tool for near-real-time rainfall estimation, it does have certain limitations. Some of the limitations of GSMaP_NRT include:

Spatial and temporal resolution. GSMaP_NRT data is available at a relatively coarse spatial resolution, typically around 0.1 to 0.25 degrees (~10 to 25 km). This resolution may not capture local-scale variations in precipitation accurately. Additionally, the temporal resolution of the data may not capture rapid changes in rainfall patterns due to its near-real-time nature.

Satellite limitations. GSMaP_NRT relies on satellite-based observations, which can be affected by various factors such as cloud cover, sensor limitations, and signal attenuation. These factors can introduce errors and uncertainties in the rainfall estimates, particularly in regions with persistent cloud cover or complex terrain.

Validation challenges. Validating the accuracy of GSMaP_NRT data can be challenging due to the limited availability of ground-based observations over large areas, especially in remote or sparsely populated regions. Validation against ground-based rain gauge data is crucial but may be limited, leading to uncertainties in the evaluation of the data's accuracy.

Bias correction. The GSMaP_NRT incorporates bias correction methods such as IF2 and IF3, as mentioned earlier, these methods may not always yield optimal results. Overestimation of rainfall in areas with zero ground observations and the persistence of unchanged rainfall results even after applying corrections have been identified as potential issues that need further investigation and improvement.

It is important to consider these limitations when using GSMaP_NRT for various applications. Understanding the strengths and weaknesses of the data can help researchers and users make informed decisions and apply appropriate caution when interpreting the results.

Suggestions. To enhance the performance of bias correction methods, several suggestions can be considered. While the IF3 correction method generally provides more favorable results, it tends to overestimate rainfall in areas where the ground observations indicate zero rainfall. Similarly, the IF2 correction method may sometimes yield unchanged rainfall results even after applying the correction. Both of these issues require further investigation to improve the efficiency of the GSMaP_NRT correction methods.

Here are some steps that can be taken to address these challenges:

Refine the zero-rainfall handling. Investigate and develop techniques to handle zero rainfall situations more effectively in the IF3 correction method. This could involve incorporating additional information or modifying the weighting scheme to better account for areas with no observed rainfall.

Evaluate and enhance the correction algorithms. Analyze the underlying algorithms of both IF2 and IF3 to identify any potential limitations or areas for improvement. Explore modifications to the algorithms to enhance their performance, ensuring they provide more accurate and consistent results.

Incorporate additional data sources. Consider integrating other data sources, such as radar observations or satellite-based measurements, to complement the gauge-based correction methods. This can help fill in gaps and provide more comprehensive rainfall estimates.

Conflict of Interest. The authors declare that they have no conflict of interest.

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