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TECHNICAL REPORT

Development of Real-time Rainfall Quality Monitoring for the Highly-Dense AWS Network over Telangana

Upal Saha, V. S. Prasad, S. Indira Rani and John P. George

August 2023

National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
A-50, Sector-62, NOIDA-201309, INDIA

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Contents

Abstract

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Keywords: Rainfall; Automatic Weather Station (AWS); monsoon; Telangana; quality control.

1. Introduction

Accurate rainfall estimates are in high demand for real-time modelling as well as scientific study. Despite advances in remote sensing techniques for estimating rainfall, ground-based rain gauges remain the final reference for meteorological analysis. The installation of AWS networks has given a vital source of direct observations of instantaneous rainfall. These ground-based rainfall observation networks are critical for a variety of applications, including calibrating remote sensing quantitative precipitation estimation (QPE), producing national, regional, and location-specific rainfall maps, nowcasting and hydrological model validation (Saha et al., 2020, 2021; Ośródka et al., 2022). To meet the requirements of hydro-meteorological analysis, a well-designed rain gauge network is required to give rainfall data with high temporal and spatial resolution (Sunilkumar et al., 2022; Saha et al., 2023). In operational forecasting, the existence of low-quality observational rainfall records, such as abnormally high or false zero rainfall readings, can have a negative impact on model calibration and initialization, resulting in erroneous forecasts and misleading warnings (Borga et al., 2006; Szturc et al., 2022). Several variables, including power outages, server and internet connectivity issues, sensor failures, localised extreme weather events, and maintenance activities, might result in missing or erroneous rainfall data from AWS stations inside dense networks.

As a result, it is critical to ensure the accuracy of recorded rainfall data through a thorough quality checking (QC) procedure that includes both qualitative and quantitative corrections. To get trustworthy rainfall records, this stage must be completed before using the data as input for real-time hydrological modelling. Saha et al. (2021, 2023) previously developed real-time monitoring and quality control approaches for rainfall data. Saha et al. (2021) concentrated on the IMD-operated AWS/ARG network in India, giving Quality Flags to each station based on computed statistics from a 15-day time series of AWS/ARG rainfall, as well as comparisons with

WMO-SYNOP and gridded/satellite-merged gauge rainfall observations. Similarly, Saha et al. (2023) developed a real-time quality control module for the densely dispersed MESONET rain gauges in Mumbai by applying related techniques.

The Telangana State Development Planning Society (TSDPS), was established by the Planning Department, Govt. of Telangana, in order to build a strong, reliable and accurate data for real time acquisition and dissemination of weather related parameters, such as temperature, humidity, rainfall, wind speed and wind direction. The present work is based on the high-density AWS network, named as TSDPS-AWS, over Telangana state (15.5^0N-20.0^0N, 77.0^0E-81.5^0E) for developing a rainfall quality monitoring algorithm. The network started with 831 AWS sites in 2008, which increased to ~ 1043 sites in 2022. Telangana is located in south central India and shares borders with Andhra Pradesh, Chhattisgarh, Orissa, Maharashtra, and Karnataka. Telangana is located on the vast Deccan plateau, spanning 112,077 square kilometres with an average elevation of 500 metres. Its western section is hilly, with elevations ranging from 300 to 600 metres, while the state's highest mountain, at 949 metres is found in the east. Telangana State has witnessed instances of extreme rainfall, characterized by heavy downpours and intense precipitation events. The geographical location of the state, on the eastern seaboard of the Indian peninsula, exposes it to a variety of weather systems and atmospheric dynamics that might result in severe rainfall occurrences. The influence of monsoonal systems, geographical factors, and the convergence of moisture-laden winds make the state vulnerable to severe precipitation. These events have underlined the necessity for a robust and broad network of AWSs in the region to properly estimate and analyse extreme rainfall occurrences. The constant monitoring of rainfall via AWS enables the detection of quick changes in precipitation intensity, ensuring timely and accurate forecasts of extreme occurrences. AWS plays an important role in improving early warning systems, assessing flood risks, and developing effective measures to mitigate the impacts of heavy rainfall events by providing real-time data and permitting precise analysis of precipitation patterns. Thus, it is very much necessary to daily monitor and check the quality of rainfall data from this high-density TSDPS-AWS network.

Thus, the current research focuses on monitoring the high-density TSDPS-AWS network and implementing a Quality Checking (QC) mechanism during the monsoon months (June to September) from 2020 to 2022. The study aims to validate rainfall observations from the high-density AWS network against a variety of sources, including the high-resolution Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (IMERG) rainfall product, gridded observations from the India Meteorological Department (IMD), the IMD-NCMRWF merged satellite-gauge rainfall product, and data from collocated AWS sites within 3 km radius. The validation results are used to create a mechanism for identifying reliable AWS rainfall observations throughout the network. These observations can be used efficiently in real-time operational tasks, weather monitoring, and model verification. This rainfall data is critical for meteorologists, researchers, policymakers, urban planners, and those involved in Telangana State's water resource management, flood control, and infrastructure development. The present report is structured as follows: Following the Introduction in Section 1, Section 2 describes the in-situ (TSDPS AWS rainfall data) and gridded rainfall observations as well as the methodology applied for daily monitoring and QC; Sections 3 and 4 present the coverage and availability of rainfall observations from AWS sites during JJAS 2020-2022; Section 5 deciphers the methodology and its application for the assignment of QC Flags to each AWS sites within TSDPS-AWS during monsoon along with the overall status of the performance of these stations over different districts; Section 6 comprises of some case studies for extreme rainfall events over Telangana state and finally the report has been wrapped up with Summary and Conclusions in Section 7.

2. Data and Methodology

Daily rainfall observations (24 hourly accumulated from previous day 08:30 AM to present day 08:30 AM, i.e. 04Z-03Z) of stations from the “TSDPS-AWS network” has been validated against neighbouring AWS sites and three gridded (one in-situ, one satellite and other satellite-gauge merged) rainfall datasets over Telangana state during June-September for 2020 to 2022.

2.1 In-situ rainfall observations

The study utilizes hourly cumulative rainfall observations obtained from the TSDPS data center, accessed through a dedicated FTP server. These observations are stored in comma-separated value (.csv) format on the NCMRWF server. Specifically, the study focuses on the daily accumulated rainfall data reported at 03:15Z during the monsoon months spanning from 2020 to 2022. Prior to analysis, the data undergoes pre-processing procedures, including checks for missing values, identification of neighbouring collocated stations, and categorization of rainfall observations based on the responsible agency overseeing the data collection and maintenance.

2.2 Gridded rainfall observations

To validate the rainfall observations acquired from the TSDPS AWS stations, this research study uses three gridded rainfall datasets, namely i) gauge-only, ii) satellite-based gridded and iii) satellite-gauge merged dataset. The gauge-only dataset at 25 km spatial resolution is derived from daily rainfall observations gathered from roughly 2600 sites per year across India, with a maximum of 6955 stations (Rajeevan et al., 2006, 2008; Pai et al., 2014). This daily IMD-gridded gauge-only rainfall data is freely available at the website of IMD, Pune: https://imdpune.gov.in/cmpg/Realtimedata/Rainfall/Rain_Download.html.

The research incorporates the use of the Integrated Multi-satellitE Retrievals for GPM (IMERG) satellite rainfall product, a high-resolution (0.1° x 0.1°) dataset derived from ten microwave imaging and sounding satellites within the GPM constellation (Huffman et al., 2019). This half-hourly IMERG satellite rainfall product is further processed to obtain 24-hourly daily (04Z-03Z) accumulated rainfall data specifically for the monsoon season (JJAS) spanning from 2020 to 2022. These processed IMERG data are subsequently employed to validate the densely observed rainfall data from the TSDPS AWS network.

The research incorporates the NCMRWF merged satellite gauge (MSG) rainfall product, developed collaboratively by NCMRWF and IMD (Mitra et al., 2003, 2009), as an additional dataset for validation purposes. The daily blended satellite-gauge rainfall data is sourced from the IMD Pune website (https://imdpune.gov.in/cmpg/Realtimedata/gpm/Rain_Download.html). This dataset has been widely used in numerous research studies (Prasad et al., 2016; Sharma et al., 2017; Sridevi et al., 2020; Saha et al., 2021, 2023, etc.) to validate model forecasts specifically for the Indian region. The merged satellite-gauge gridded rainfall data serves as supplementary information for verifying and ensuring the quality of rainfall measurements from the TSDPS-AWS stations in Telangana during the monsoon season (JJAS) of 2020-2022.

2.3. Methodology

Validation of the 24-hourly (8:30 AM previous day to 8:30 AM next day) accumulated rainfall from TSDPS-AWS network is carried out against neighbouring AWS sites as well as GPM, IMD and MSG gridded rainfall data following the steps discussed below:

1. Rainfall Database Preparation: Since the daily receiving of AWS rainfall observations is highly variable, only stations with at least 50% (61 days) of reported observations in the season (i.e. June to September, 122 days) are considered for validation. These stations are termed "Regular Stations". Those stations reported rainfall data less than 61 days during the season are marked "Irregular Stations".

2. Handling Missing Data: The produced rainfall database is thoroughly checked to find missing dates and incomplete data, which are then filled with 'NaN' or '-99' values for each station.

3. Neighbouring Station Selection: A search is conducted for nearby stations within a range of 3 km radius of each AWS site.

4. Outlier Data Removal: To eliminate potential outliers or erroneous data, the rainfall values from each station undergo outlier detection using the 2-Sigma Rule (Median ± 2 sigma). This process helps maintain data integrity and reliability. Additionally, the mean of rainfall measurements from the neighbouring stations is calculated, providing valuable contextual information for further analysis.

5. Rainfall Time-series Preparation: After the outlier data removal step, the rainfall data from AWS, GPM, IMD, and MSG sources is processed to generate time-series data during monsoon season. This time-series data forms the basis for subsequent statistical analysis and comparison.

6. Statistical Analysis: Various statistical measures, including Pearson's correlation coefficient, root mean square error (RMSE), standard deviation, BIAS, and mean of rainfall observations, are computed for each AWS site. These measures are then compared to the corresponding data from collocated neighbouring sites, GPM, IMD, and MSG rainfall datasets. Such analysis provides insights into the performance and accuracy of the TSDPS-AWS network in capturing rainfall events.

7. Quality Flagging: Each AWS station in the network is issued a quality flag ranging from 0 to 9, with 0 representing the highest quality. Flag 0-5 are termed as "Regular and Usable Stations", while Flag 6 is termed as "Regular but Non-Usable Stations" and Flag 7-9 are designated as "Irregular Stations". The details of quality flagging criteria is described in Section 5.

8. Coverage and Time-series Analysis: Coverage plots are generated to visualise the extent of reported rainfall measurements by various datasets over a certain time period, together with associated statistical measures. Furthermore, rainfall time series plots are created for each AWS site, comparing the recorded rainfall to data from GPM, IMD, MSG, and the mean of collocated neighbouring stations (NHBR).

3. Spatial coverage of AWS stations during monsoon over Telangana

TSDPS-AWS network is the first-ever so highly dense in-situ network that been deployed over entire Telangana, having inter-gauge distance between ~1-5 km. This section describes the coverage and statistics of AWS stations within the network over Telangana based on (a) daily accumulated rainfall observations reported over 33 districts and (b) actual reported days of rainfall observations, sub-divided into categories during JJAS-2020 to JJAS-2022.

3.1. Based on daily accumulated rainfall observations

During monsoon (JJAS) seasons of 2020, 2021 and 2022, an average of 1043, 1043, and 1044 AWS stations over Telangana reported daily rainfall data (Figure 1). The Govt. of Telangana recognizes the importance of accurate rainfall information and is actively enhancing the rain gauge infrastructure throughout the state to acquire detailed data on rainfall patterns in every districts and mandals. This expansion seeks to improve preparedness and response to extreme rainfall occurrences by examining the overall distribution and identifying locations prone to intense or prolonged rainfall.

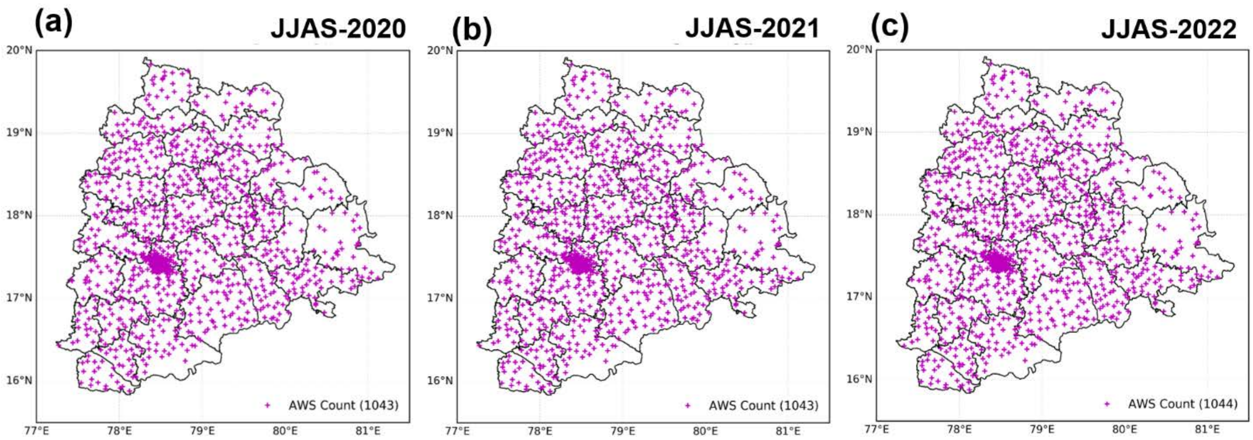

Fig. 1. *Coverage of AWS stations maintained by TSDPS during monsoon (June-September, JJAS) months of (a) 2020, (b) 2021 and (c) 2022.*

3.2 Based on actual reported days of rainfall observations

The daily recorded rainfall observations over Telangana are divided into six groups based on the number of days with observations out of 122 JJAS days. The categories are as follows: i) 90% and above (>=110 days), ii) 80-89% (98-109 days), iii) 70-79% (85-97 days), iv) 60-69% (73-84 days), v) 50-59% (61-72 days), and vi) less than 50% (< 61 days). Analysing Figure 2, it is clear that the top category (90% and above), indicated by green stars, has the largest coverage. In 2020, 1042 stations received rainfall measurements for 90% or more of the JJAS days, increasing to 1043 and 1044 stations in 2021 and 2022, respectively. These numbers reflect the TSDPS-AWS site's outstanding availability of rainfall observations. The availability of extensive rainfall observations from the TSDPS-AWS site is a significant advantage for Telangana. The consistently high number of stations reporting in the first category (90% and above) indicates a robust and reliable network capturing rainfall data across the region. This comprehensive temporal coverage enables a more accurate assessment of rainfall patterns and their variations over time. The second category (80-89%), denoted by blue stars, comprises of only 1 station in JJAS-2020, and no stations in 2021 and 2022 respectively.

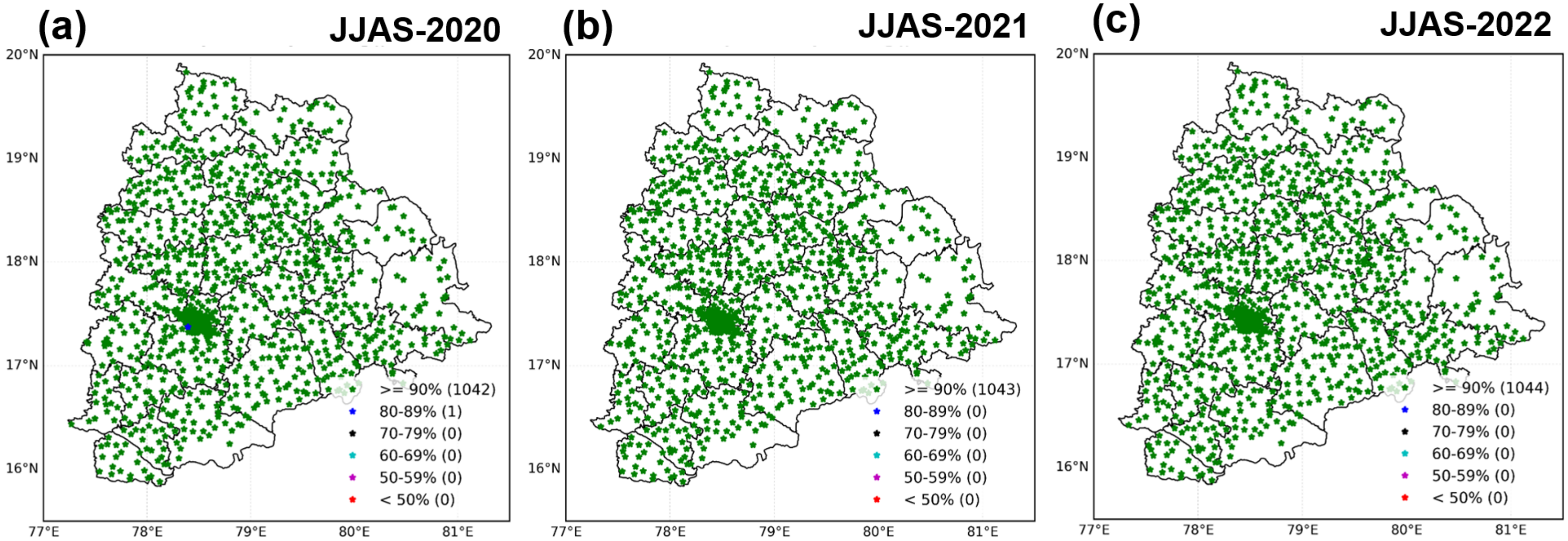

Fig. 2. *Coverage and categorization of TSDPS-AWS stations based on the actual reported days of rainfall observations during monsoon (June-September, JJAS) months of (a) 2020, (b) 2021 and (c) 2022.*

The stations reporting in other remaining categories are none which highlights the effectiveness of the TSDPS-AWS network in capturing rainfall data throughout the monsoon season. This comprehensive dataset supports informed decision-making, enables effective disaster preparedness and response, and enhances the state's ability to mitigate the impacts of extreme weather conditions.

4. Districtwise distribution of AWS stations during monsoon over Telangana

Telangana encompasses a total of 33 districts, and among these districts, Bhadradri Kothagudem holds the distinction of being the largest, while Hyderabad stands as the smallest. Understanding the districtwise distribution of AWS stations in Telangana during the monsoon season is crucial for accurate weather monitoring and forecasting, as well as for assessing the spatial representation of rainfall observations across the state. The district-wise count of TSDPS-AWS stations serves as a valuable tool for evaluating the coverage and representativeness of the observational network. By analyzing this count, we can gain valuable insights into the distribution and frequency of rainfall events within each district, using the daily accumulated rainfall observations. Table 1 provides a tabular representation of the district-wise distribution of all TSDPS-AWS stations across Telangana during the monsoon months of 2020 to 2022. During the monsoon season of 2020 (JJAS-2020), the district of Rangareddy reported the highest number of AWS stations, with a count of 83, which accounted for more than 7% of the total AWS stations in the state (1043 in count). Following Rangareddy, the districts of Medchal-Malkajgiri, Hyderabad, and Nalgonda held the second, third, and fourth positions, respectively, in terms of active AWS station reporting. Notably, even though Hyderabad is the smallest district among all 33 districts, it had 64 actively reporting AWS stations in 2020, representing more than 6% of the total active AWS stations in the state. Similarly, in JJAS-2021 and JJAS-2022, Rangareddy, Medchal-Malkajgiri, Hyderabad, and Nalgonda remained the top four districts with the highest number of actively reporting AWS stations, based on daily accumulated rainfall observations. It is worth mentioning that Warangal was subdivided into Warangal-Rural and Warangal-Urban in 2020 but became a single district in 2022, while Hanumakonda emerged as a new district in 2022. By examining the district-wise count of TSDPS-AWS stations and their reporting patterns, we can enhance our understanding of the spatial distribution of rainfall events within Telangana.

Table 1. *Districtwise count of AWS Counts over Telangana during JJAS 2020 to 2022:* (*NA indicates AWS Data 'Not Available' for that particular year*)

S. No.	Districts	AWS Count			% Count of AWS Coverage		
		2020	2021	2022	2020	2021	2022
1.	Adilabad	23	23	23	2.21	2.21	2.20
2.	Bhadradri Kothagudem	29	29	29	2.78	2.78	2.78
3.	Hyderabad	64	60	60	6.14	5.75	5.75
4.	Jagtial	30	30	30	2.88	2.88	2.87
5.	Jangaon	19	20	20	1.82	1.92	1.92
6.	Jayashankar	17	17	17	1.63	1.63	1.63
7.	Jogulamba Gadwal	20	22	22	1.92	2.11	2.11
8.	Kamareddy	30	31	31	2.88	2.98	2.97
9.	Karimnagar	27	27	27	2.59	2.59	2.59
10.	Khammam	40	40	40	3.84	3.84	3.83
11.	Kumuram Bheem	20	20	20	1.92	1.92	1.92
12.	Mahabubabad	23	23	23	2.21	2.21	2.20
13.	Mahabubnagar	24	24	24	2.30	2.30	2.30
14.	Mancherial	26	26	26	2.49	2.50	2.49
15.	Medak	35	36	36	3.36	3.45	3.45
16.	Medchal Malkajgiri	66	59	59	6.33	5.66	5.65
17.	Mulugu	18	18	18	1.73	1.73	1.72
18.	Nagarkurnool	35	35	35	3.36	3.36	3.35
19.	Nalgonda	58	58	58	5.56	5.56	5.56
20.	Narayanpet	17	17	18	1.63	1.63	1.72
21.	Nirmal	29	29	30	2.78	2.78	2.87
22.	Nizamabad	43	46	46	4.12	4.41	4.41
23.	Pedapalli	21	21	21	2.01	2.01	2.01
24.	Rajanna Sircilla	21	21	21	2.01	2.01	2.01
25.	Rangareddy	83	78	77	7.96	7.48	7.38
26.	Sangareddy	39	43	43	3.74	4.12	4.12
27.	Siddipet	38	39	39	3.64	3.74	3.74
28.	Suryapet	34	36	36	3.26	3.45	3.45
29.	Vikarabad	29	29	29	2.78	2.78	2.78
30.	Wanaparthy	19	20	20	1.82	1.92	1.92
31.	Yadadri Bhuvanagiri	28	28	28	2.68	2.68	2.68
32.	Warangal Rural	22	22	NA	2.11	2.11	NA
33.	Warangal Urban	16	16	NA	1.53	1.53	NA
32.	Hanumakonda	NA	NA	19	NA	NA	1.82
33.	Warangal	NA	NA	19	NA	NA	1.82

4.1 Based on actual reported days of rainfall observations

Figure 3 illustrates the cumulative statistics of rainfall observations reported by AWS stations across each district in Telangana during the monsoon seasons of 2020 to 2022, represented as a Heatmap. The figure presents the count of reported rainfall observations by AWS stations within each district, annotated within respective cells. Each cell corresponds to a specific category (as discussed in Section 3.2) based on the reported data within the district. The background color of each cell indicates the percentage count of AWS station coverage for the corresponding category. In Figure 3a to Figure 3c, it is observed that all AWS stations in the TSDPS network within each district reported rainfall observations for more than 90% of the monsoon days (i.e., greater than equal to 110 days out of the 122 JJAS days) during 2020 to 2022.

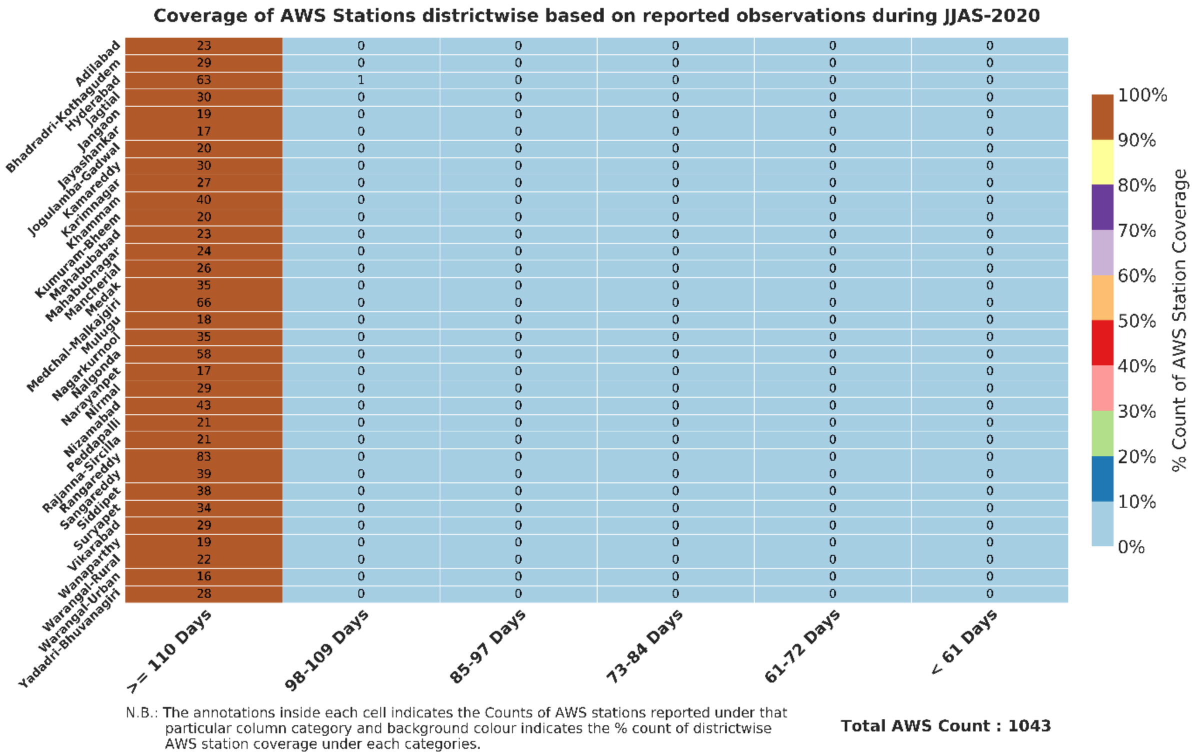

Fig. 3a. *Coverage and categorization of TSDPS-AWS stations in each of the districts based on the actual reported days of rainfall observations during monsoon (June-September, JJAS) months of 2020.*

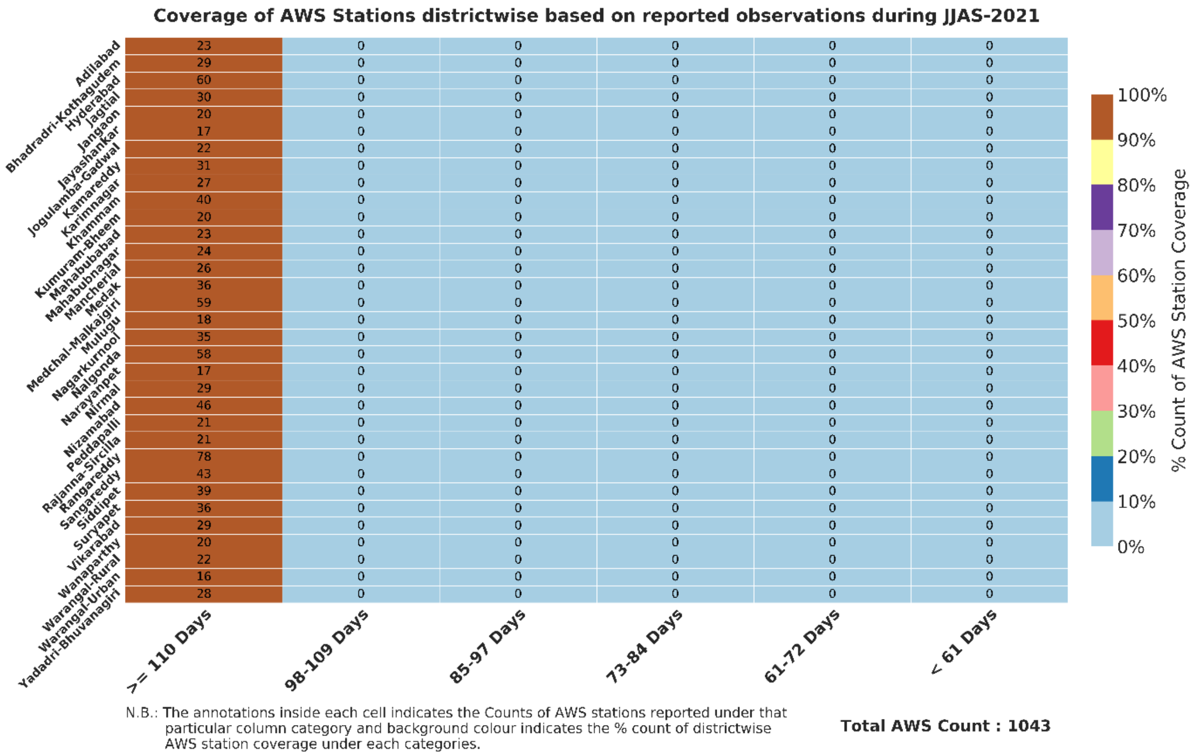

Fig. 3b. *Same as Figure 3a but for JJAS-2021.*

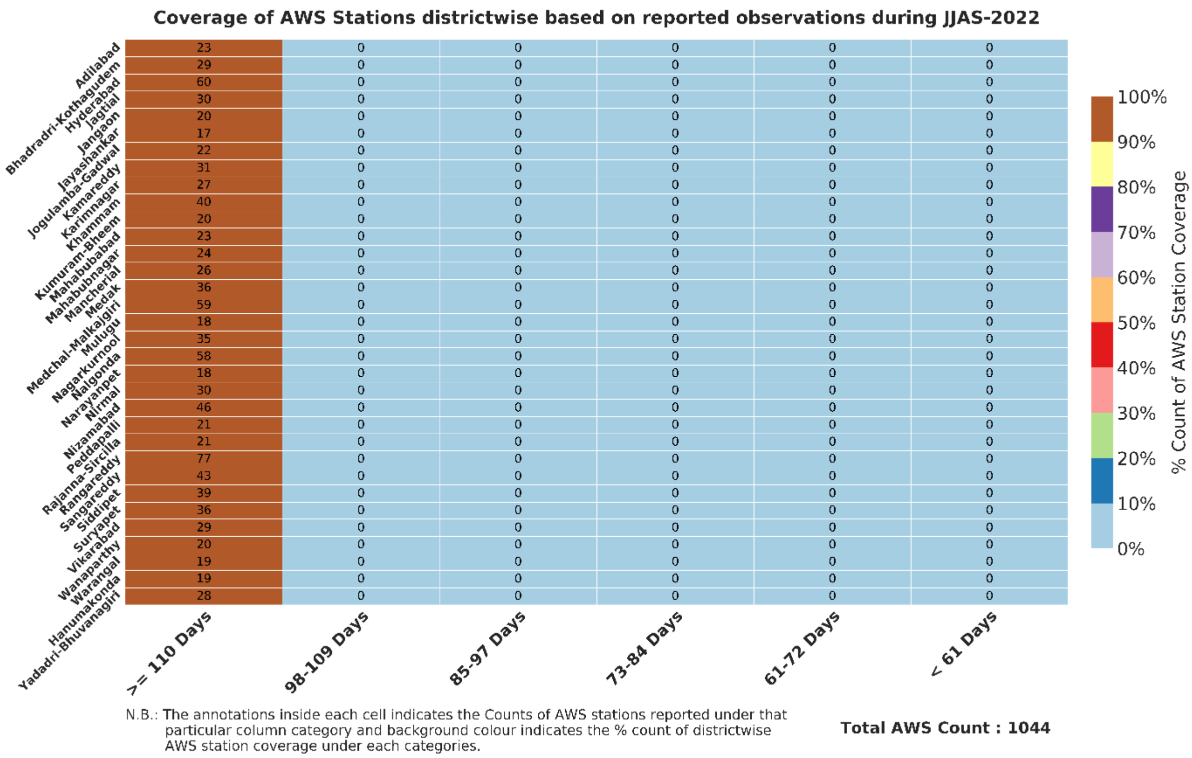

Fig. 3c. *Same as Figure 3a but for JJAS-2022.*

The other categories contain zero AWS counts, indicating that the AWS stations in the TSDPS network were highly active and consistently reported rainfall observations. Compared to Table 1, which shows the number of AWS stations in each district, the high percentage of AWS stations reporting rainfall observations for more than 90% of the JJAS-days in all districts during JJAS-2020 to JJAS-2022 indicates the robustness of the TSDPS network in capturing daily rainfall data. The information presented in Figure 3 provides valuable insights into the temporal coverage and consistency of rainfall observations by AWS stations across the districts of Telangana state. This facilitates informed decision-making in water resource management, agricultural planning, and district-level hydrological modeling. Additionally, this analysis enhances our understanding of the spatial distribution of rainfall data and the reliability of the TSDPS observational network in Telangana.

5. Assignment of Quality Flags to each TSDPS-AWS stations: Spatial Coverage

Assigning quality flags to AWS stations in Telangana is crucial due to the state's diverse topography, which affects rainfall patterns and circulation dynamics. Significant weather events during the monsoon season can disrupt data collection, making quality assessment necessary for reliable performance evaluation. As a result, it is essential to build a strong framework for quality assurance and control and continuously monitor the operation and quality of these AWS stations inside the high-density urban network. Previous studies by Saha et al. (2021, 2023) have established a framework for assigning real-time rainfall quality flags to the IMD-maintained AWS/ARG network in the PAN-India and Mumbai regions, respectively. Quality flags ranging from 0 to 9 are attached to rainfall reported by each AWS/ARG station, with 0 representing the best quality. Flags 7-9 are assigned to irregular stations, while flags 1-6 indicate different levels of quality, allowing end-users to select data based on specific applications.

After the "Outlier Data Removal" step in the Methodology section, a number of statistical measures are generated for each AWS site, including the Pearson's correlation coefficient, relative BIAS, and mean rainfall observations. These figures are compared with rainfall data from neighboring sites, GPM retrieved rainfall, IMD gridded rainfall and MSG integrated rainfall data for the JJAS periods of 2020 to 2022. Similar to Saha et al. (2021, 2023), each AWS station is given a quality flag based on the statistics that were calculated, more especially the highest correlation and minimum relative BIAS values. Flags 0-5 are categorized as "Regular and Usable Stations," flag 6 is termed as "Regular but Non-Usable Stations," and flags 7-9 are designated as "Irregular Stations." The methodology used for assigning the quality flags can be found in the Appendix. This approach ensures a systematic assessment of data quality and aids in distinguishing stations based on their reliability and usability.

Now, Figure 4 depicts the coverage of TSDPS-AWS stations assigned with Quality Flags appeared maximum times during each monsoon month of 2020 to 2022 over Telangana state. Since the Rainfall Quality Flag assignment is a qualitative approach, it cannot be averaged within a season. Therefore, the counts of maximum-assigned Quality Flags (ranging from 0-9) indicate the 'Dominating Rainfall Quality Flag' for that particular season. During JJAS-2020, out of 1043 stations, 843 stations ranges from Flag 0 to Flag 5, 200 stations lie in Flag 6 category and no station have been assigned to Flag 7 to Flag 9 (Figure 4A). This actually indicates 843 AWS stations were actually "Regular" and may be utilized by the end user for particular applications (Figure 4Aa), while 200 stations lying in Flag 6 category were "Regular but Non-Usable" (Figure 4Ab) and no stations were designated as "Irregular" station (Figure 4Ac) during JJAS-2020. It is observed that ~ 3.25% of AWS stations (34 out of 1043) were assigned "Flag-0", while ~ 73% (759 out of 1043) were allocated "Flag-1" and ~ 5% of AWS stations (50 out of 1043) were assigned to "Flag-2". "Flag-6" was assigned to 200 stations (~ 19%), designating them as regular but non-usable stations during JJAS-2020. There were no contributions from the rest of the Flag categories. These proportions are also reflected in the pie chart of Figure 5a, with over 80% of stations cumulatively falling within Quality Flags 0-5 and ~19% of stations in "Flag-6" categories.

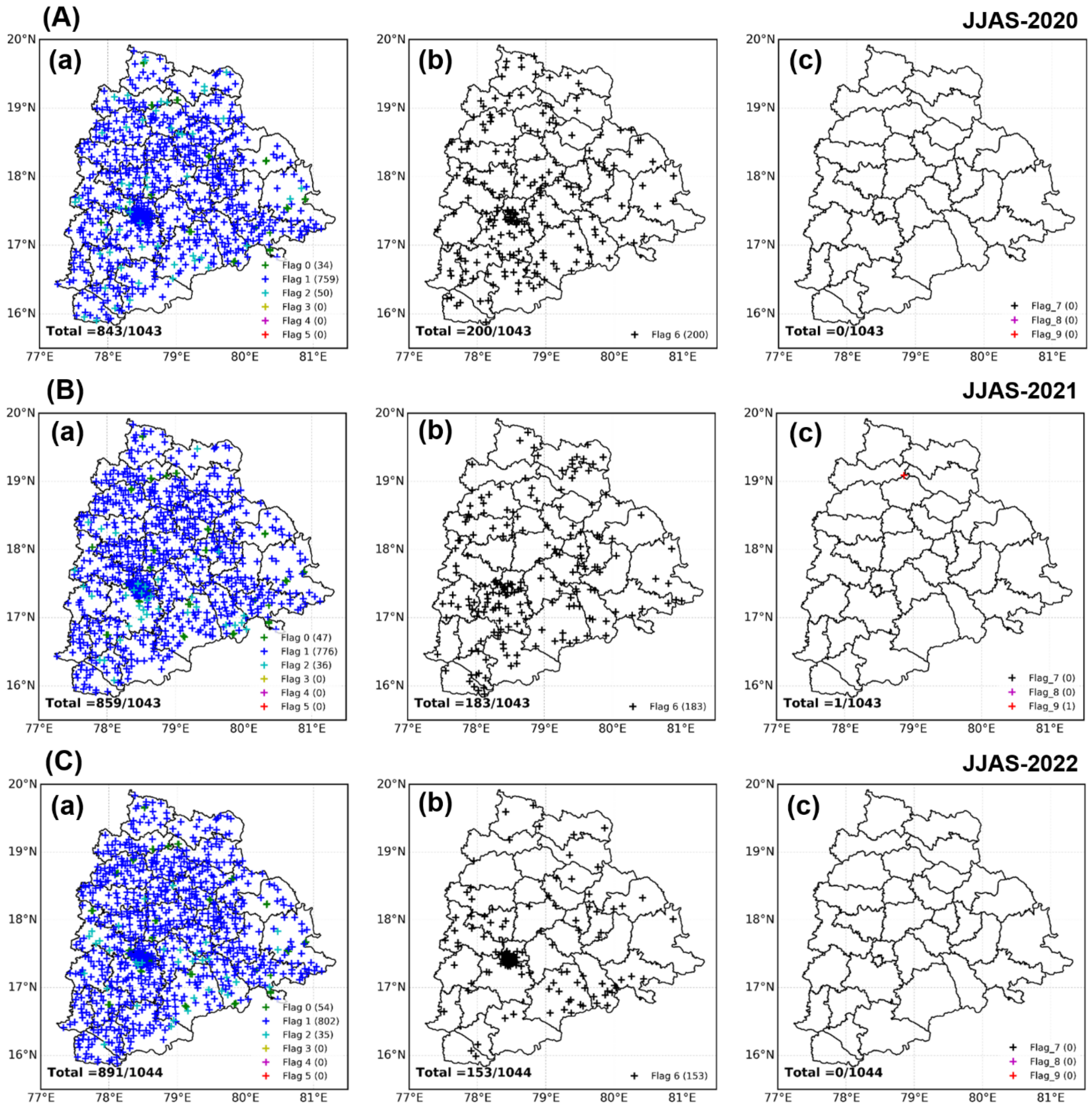

Fig. 4. *Coverage of TSDPS-AWS stations assigned with maximum times of (a) “Flag 0” to “Flag 5”, (b) “Flag 6”, and (c) “Flag 7” to “Flag 9” Quality Flags within the monsoon (June-September, JJAS) months of (A) 2020, (B) 2021 and (C) 2022.*

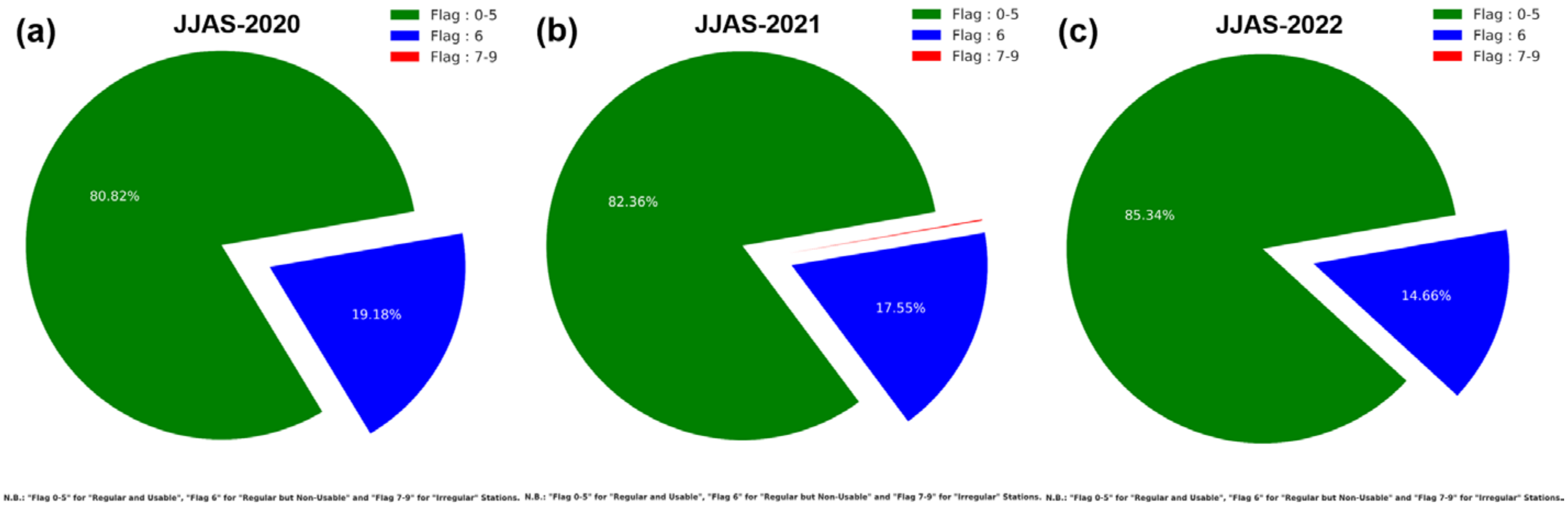

Fig. 5. *Pie-chart statistics showing the percentage count of assigned Quality Flags for TSDPS-AWS stations over Telangana during monsoon (June-September, JJAS) months of (a) 2020, (b) 2021 and (c) 2022.*

Likewise, during JJAS-2021, out of 1043 stations, 859 stations were of “Regular and Usable” category (Figure 4Ba), while 183 stations were “Regular but Non-Usable” (Figure 4Bb) and only 1 station was simply “Irregular” one (Figure 4Bc). Hence, during JJAS-2021, more than 70% of AWS stations (776 out of 1042) were assigned "Flag-1," while less than 5% of AWS stations were assigned with "Flag-0", "Flag-2" and "Flag-9" and ~ 17.5% of the AWS stations were assigned to "Flag-6" category. Similarly, during JJAS-2022, out of 1044 stations, 891 stations were of “Regular and Usable” category (Figure 4Ca), while 153 stations were “Regular but Non-Usable” (Figure 4Cb) and no stations were designated as “Irregular” ones (Figure 4Cc).

Figure 5b corroborates this information, with approximately 82% of TSDPS-AWS stations falling into the "Regular and Usable" category, and approximately 18% in “Flag-6” category. In JJAS-2022, a similar trend emerged, with "Flag-1" dominating the quality distribution (802 out of 1044 stations, i.e., more than 75%). The remaining quality flag categories had been assigned to less than 5% of AWS stations, except for "Flag-6," which was assigned to ~ 15% of the stations (153 out of 1044). Cumulative analysis in Figure 5c further confirms these patterns, with approximately 85% of TSDPS-AWS stations classified as "Regular and Usable" during JJAS-2022. The remaining stations fell into Flag-6 category, representing less than 15% of the total stations. Thus, Figure 4 and Figure 5 indicate a gradual improvement in station maintenance quality during JJAS-2022 compared to the previous seasons in 2020 and 2021, since there has been a gradual increase in “Regular and Usable” Stations (Flags 0-5) while a decrease in stations with “Regular but Non-Usable” (Flag 6) and “Irregular” (Flags 7-9) category. These findings shed light on the quality control and maintenance efforts undertaken for the TSDPS-AWS stations over the studied monsoon seasons, highlighting improvements in data reliability and usability for various applications.

5.1 Districtwise coverage of the TSDPS-AWS Station Quality Flags

Figure 6 depicts a comprehensive representation of cumulative statistics for both the percentage count and reported count of rainfall observations by AWS stations, taking into account the assigned Quality Flags, across all districts during JJAS-2020 to JJAS-2022. The figure provides a clear depiction of the reported rainfall observation counts, specifically highlighting the distribution of AWS stations within each district. Each cell within the figure represents the corresponding Quality Flag assigned based on the analysis of rainfall data obtained from ground-based in-situ measurements (AWSs), neighboring AWS sites, satellite-based GPM data, gridded

IMD data, and the merged satellite-gauge MSG dataset. Furthermore, the background color within each cell indicates the percentage count of AWS station coverage reported within each district based on the respective Quality Flags. Figure 6a provides detailed insights into the quality assessment of AWS stations in the districts during the JJAS-2020 monsoon season. Around 90-100% of the stations in Rajanna Sircilla, Warangal Rural and Urban districts, 80-90% of the stations in Hyderabad, Medchal-Malkajgiri districts, 70-80% of the stations in Khammam, Kumuram Bheem, Medak, Nizamabad, Suryapet, Vikarabad, Wanaparthy, Yadadri Bhuvanagiri districts, 60-70% of the stations in Rangareddy district were assigned with the "Flag-1" Quality Flag. This indicates that these stations consistently provided reliable rainfall data suitable for various applications. A maximum of 30-40% of the stations in 5 districts were assigned with "Flag-6" Quality Flag. Rest of the flag categories can be interpreted easily from the figure itself.

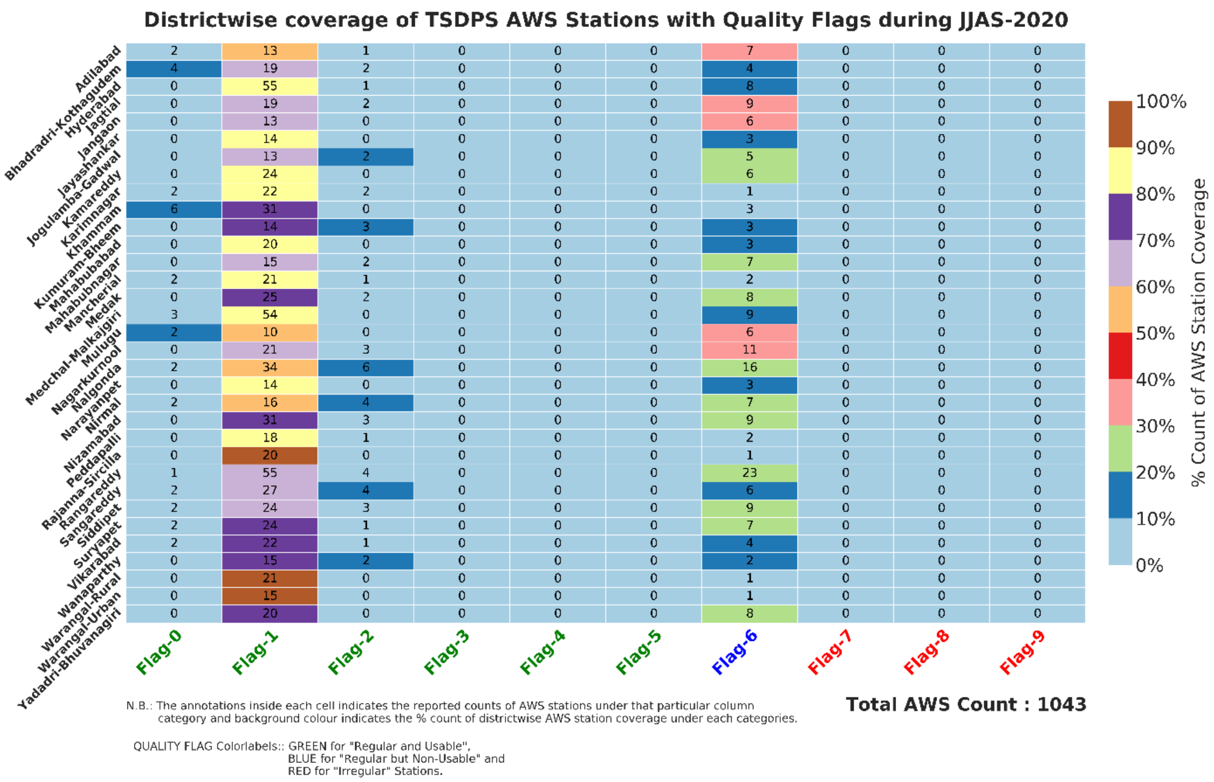

Fig. 6a. *Heatmap Statistics showing the features of reported count and percentage count of rainfall observations by TSDPS-AWS stations assigned with Quality Flags (Flag-0 to Flag-9) in each of the districts in a single frame during monsoon (June-September, JJAS) months of 2020.*

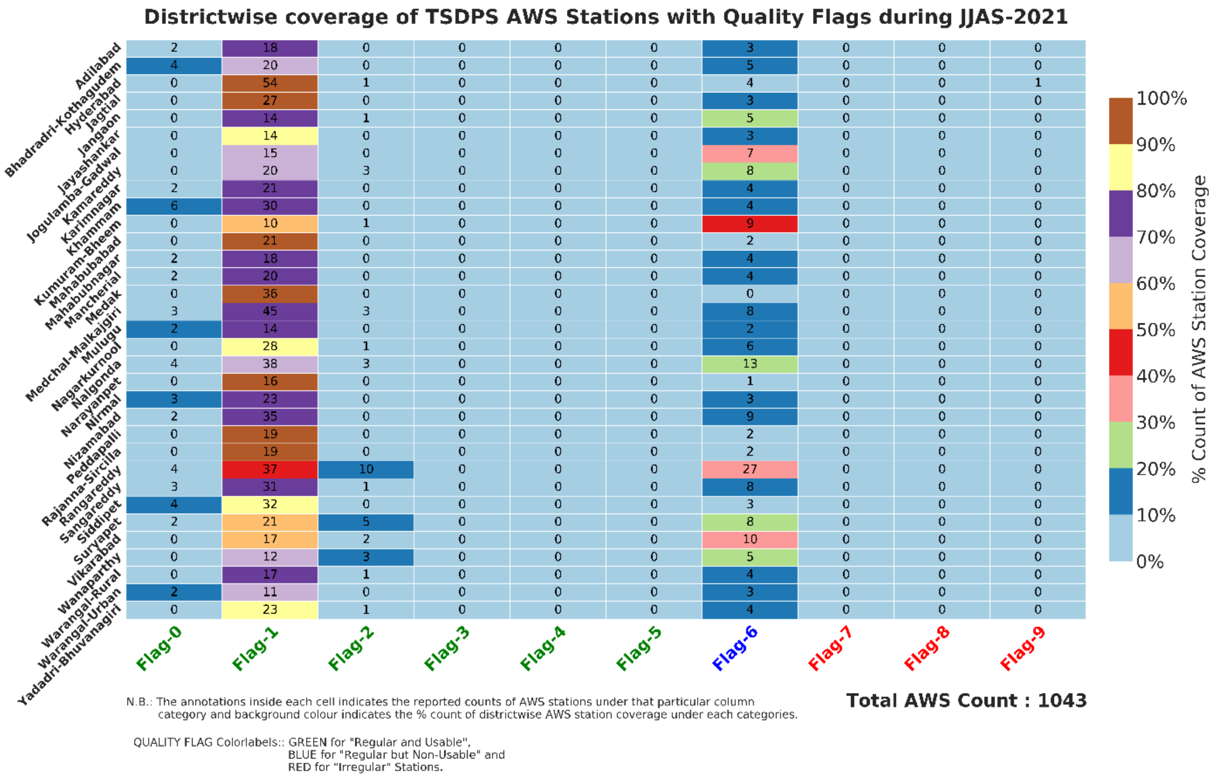

Fig. 6b. *Same as Figure 6a but for JJAS-2021.*

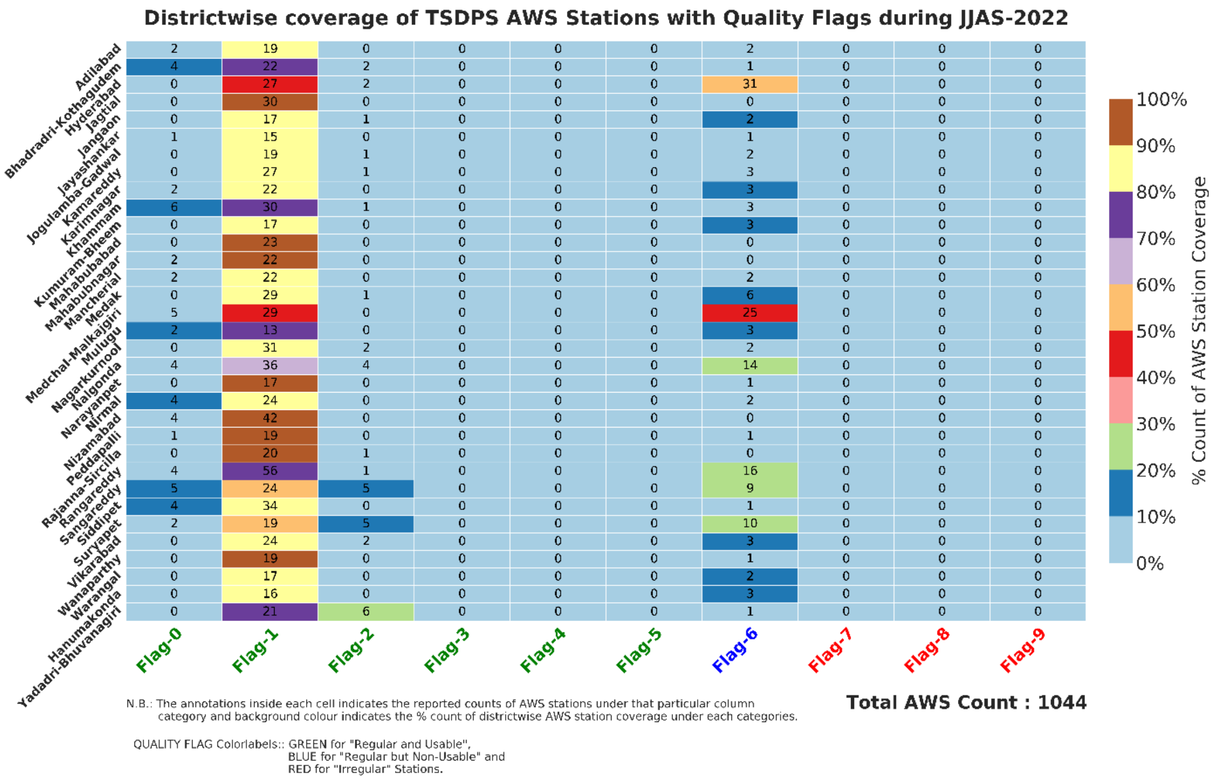

Fig. 6c. *Same as Figure 6a but for JJAS-2022.*

Similarly, as illustrated in Figure 6b and 6c, during JJAS-2021 and JJAS-2022, the majority of AWS stations were assigned the "Flag-1" category. Districts like Jagtial, Mahabubabad, Rajanna Sircilla, Narayanpet, Pedapalli, Siddipet, Nagarkurnool and Nizamabad exhibited a high number of stations assigned to this quality flag, indicating high-quality and reliable data. These findings were consistent in both JJAS-2021 and JJAS-2022. It is noteworthy that despite Hyderabad being the smallest district, it exhibited a considerable number of stations in “Flag-1” category. The majority of stations across all districts were classified under "Flag-1" and "Flag-6" categories. It is to mention that the newly emerged district, Hanumakonda, in JJAS-2022 had approximately 80-90% of its AWS stations falling under the "Flag-1" category. It is also to be noted that there were negligible number of stations in “Flag-7” to “Flag-9” category during JJAS-2020 to JJAS-2022.

6. Extreme Rainfall Cases: Time Series plots

Based on the amount of accumulated rainfall in a day for extreme event studies, India Meteorological Department (IMD) has classified rainfall intensities into different categories, viz. i) Heavy Rainfall (HR, 64.5 mm $< R \leq$ 115.4 mm), ii) Very Heavy Rainfall (VHR, 115.5 mm $< R \leq$ 204.4 mm) and iii) Extremely Heavy Rainfall (EHR, $R \geq$ 204.5 mm), where R indicates Rainfall. An attempt has been made to verify the cases where TSDPS-AWS stations over Telangana could capture this extreme rainfall events during JJAS 2020 to 2022.

6.1 AWS stations capturing Extreme Rainfall observations

Figure 7A (a-d) illustrates the time-series plots depicting the rainfall observations recorded by the TSDPS-AWS network. These stations effectively captured the extreme rainfall events and exhibited good agreement with the rainfall mean from neighboring AWS stations within a 3 km radius, gridded rainfall observations from IMD/NMSG, and satellite-retrieved rainfall data from GPM during the JJAS-2020 to JJAS-2022 period. The close proximity of the TSDPS-AWS stations, with inter-gauge distances ranging from 1-5 km, enables the utilization of neighboring station data to assess the performance of individual base stations. While rainfall estimates from IMD/MSG and GPM may underestimate or overestimate extreme events, neighboring stations are expected to accurately capture such events if they are functioning properly. If a station is found to be non-functional, the collocated station within a 3 km radius can be used to validate the rainfall data. Thus, the statistical verification metrics incorporate the mean rainfall from neighboring stations. Figure 7Aa presents the validation of reported rainfall observations by the "Dharmasagar" station in Warangal-Urban District (Mandal: Dharmasagar) during JJAS-2020. This station effectively captured various extreme rainfall events, including a heavy rainfall (HR) event on June 10, 2020, and an extremely heavy rainfall (EHR) event on August 12, 2020. The statistical metrics are provided in the figure. Similarly, Figure 7Ab showcases the validation of rainfall observations by the "Sangem" station in Warangal-Rural District (Mandal: Sangem) during JJAS-2020. This station accurately captured the HR event on July 8, 2020, and EHR events on August 12, 2020. During JJAS-2021, the rainfall observations from the "Asifabad" station in Kumuram Bheem District (Mandal: Asifabad) demonstrated regularity, and the station effectively captured an extremely heavy rainfall event (> 300 mm) on July 21, 2021. The statistical metrics, along with comparisons to other rainfall sources, affirm the station's efficiency in capturing extreme rainfall occurrences over Telangana (Figure 7Ac). Likewise, the "Pembi" station in Nirmal District (Mandal: Pembi) recorded numerous HR and very heavy rainfall (VHR) events during JJAS-2022 (Figure 7Ad). In conclusion, the TSDPS-AWS stations exhibit the capability to accurately capture extreme rainfall events in Telangana.

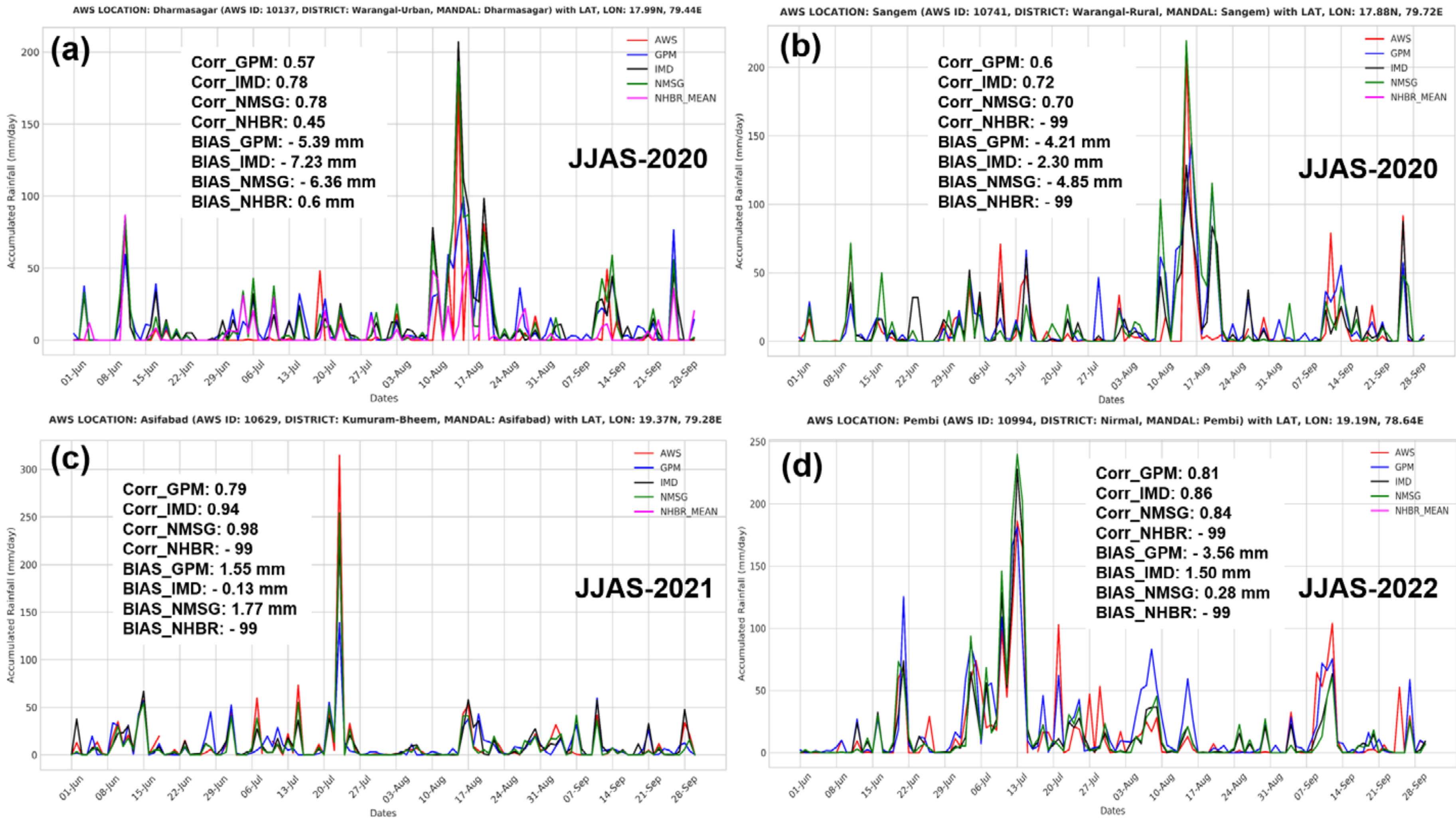

Fig. 7A. AWS stations that captured extreme rainfall events during (a)-(b) JJAS-2020, (c) JJAS-2021 and (d) JJAS-2022.

Based on the above findings, the TSDPS-AWS network has demonstrated its efficacy in capturing extreme rainfall occurrences over Telangana. This is a significant contribution to the understanding of rainfall patterns and trends in the region, particularly during the monsoon season. The successful capture of extreme rainfall events by the TSDPS-AWS stations offers valuable insights into the frequency, intensity, and duration of such events in Telangana. The reliability and efficiency of the TSDPS-AWS stations in capturing extreme rainfall events pave the way for further research on the drivers and mechanisms of extreme rainfall, aiding in the development of localized forecasting models and early warning systems for mitigating the impacts of extreme weather events. The network's ability to provide reliable and high-resolution rainfall data has implications for various sectors, including agriculture, hydrology, urban planning, and climate research. Thus, this information is very crucial for understanding the vulnerability and resilience of the region to heavy rainfall and also contribute to the scientific understanding of extreme rainfall patterns and trends, thereby facilitating effective climate change mitigation and adaptation strategies in the state.

6.2 AWS stations not capturing the Extreme Rainfall observations

Figure 7B (a-d) presents the time-series plots depicting the AWS rainfall observations obtained from stations within the network that exhibited deficiencies in capturing the extreme rainfall events reported by neighbouring collocated AWS stations (within a 3 km radius), gridded rainfall observations (IMD/MSG), or satellite-retrieved rainfall data (GPM) during the period from JJAS-2020 to JJAS-2022. Notably, the AWS stations, namely, "Chandampet of Nalgonda District (Mandal: Chandampet)," "Indurthy of Karimnagar District (Mandal: Chigurumamidi)," "Issaipet of Kamareddy District (Mandal: Machareddy)," and "Shaikpet of Hyderabad District (Mandal: Shaikpet)," exhibited a complete failure in capturing the extreme rainfall events and displayed no recorded rainfall occurrences, as evidenced by NHBR_MEAN/GPM/IMD/MSG observations.

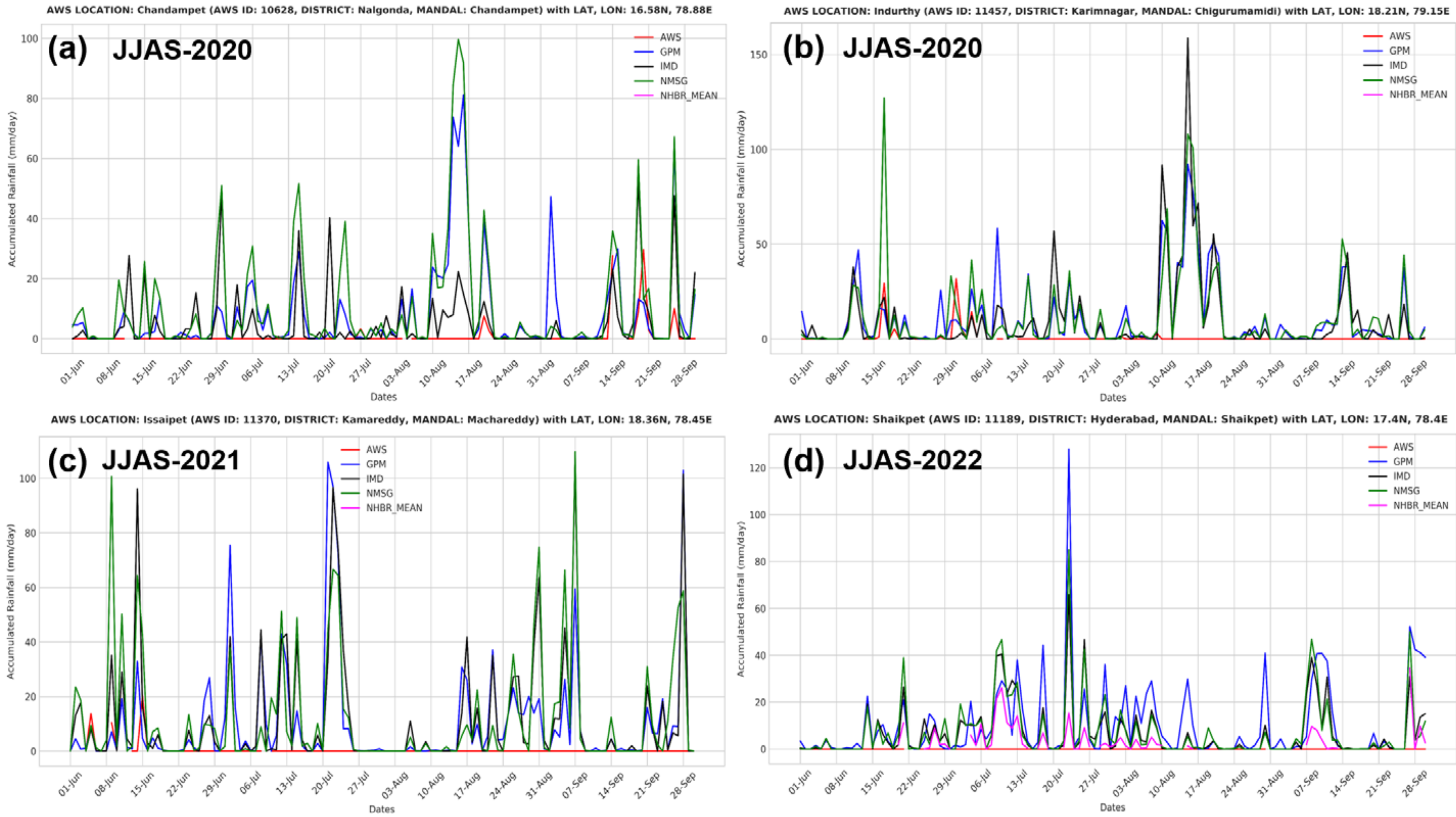

Fig. 7B. AWS stations that failed to capture extreme rainfall events during (a)-(b) JJAS-2020, (c) JJAS-2021 and (d) JJAS-2022.

Throughout the period from JJAS-2020 to JJAS-2022, such AWS stations reported zero rainfall data, indicating the occurrence of mechanical errors during extreme events or non-functional sensors due to inadequate calibration or maintenance of the AWS site (Figure 7B a-d). It emphasizes the critical need for implementing periodic maintenance protocols for all such stations, including thorough sensor checks, calibrations, and rigorous validation of the collected rainfall data, to ensure the optimal functioning and performance of these stations. To overcome the challenges associated with AWS data reliability, future research should focus on developing robust strategies for improving the functionality and performance of AWS stations, including advanced sensor technologies, remote diagnostics, and real-time data quality assessment mechanisms. With the help of these developments, it will be possible to characterise rainfall types, intensities, and hydrometeor characteristics in greater detail, which will increase our understanding of extreme rainfall events and their effects on the hydrological system. Additionally, the deployment of remote sensing techniques, such as satellite-based rainfall estimation and ground validation campaigns, can further enhance the accuracy and spatial representation of AWS observations, contributing to a more comprehensive understanding of regional rainfall patterns and trends.

7. Real-time Quality Monitoring of TSDPS-AWS Rainfall over Telangana

Monitoring the quality and performance of AWS rainfall data from the high-density network over Telangana state in real-time is very crucial. The state's diverse terrain, including plateaus, hills, and valleys, significantly influences rainfall distribution and circulation patterns, affected by the Western Ghats, Eastern Ghats, and Deccan Plateau. Proximity to the Bay of Bengal enhances interactions between moisture-laden winds and terrain, leading to mesoscale convective systems. However, significant weather events often disrupt rainfall data collection, necessitating the assignment of quality flags to ensure usability and applicability of the data in specific applications. As discussed in Section 5, rainfall reported by each AWS stations are assigned to Quality Flags ranging from Flag-0 to Flag-9, with Flag-0 as the best. Quality Flags 7-9 are assigned to irregular stations. The detailed methodology adopted for assigning Quality Flags to individual stations in Real-time is described in the Appendix section.

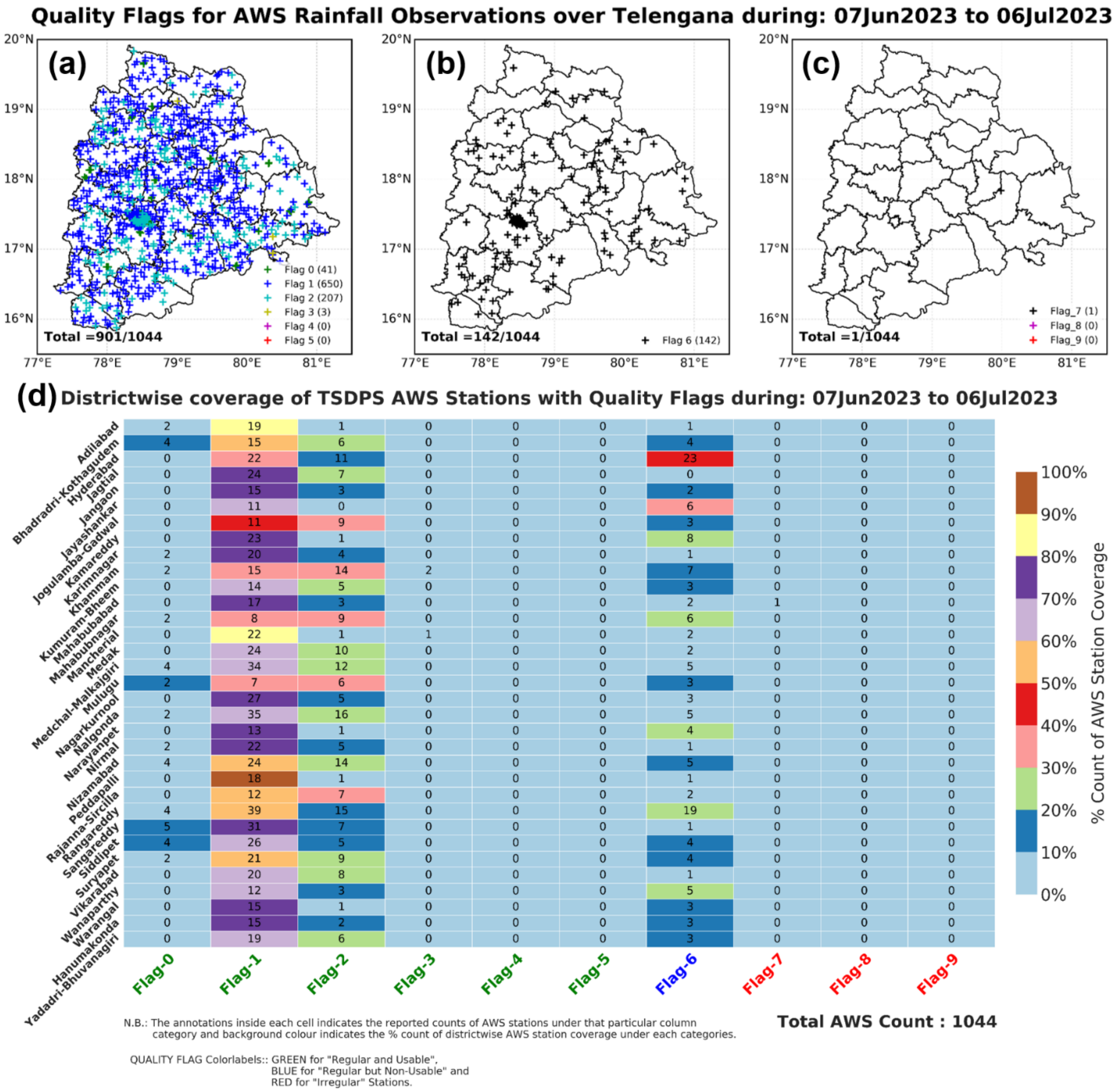

Fig. 8. *Spatial Coverage of AWS stations assigned with Quality Flags with (a) "Flag 0" to "Flag 5", (b) "Flag 6", and (c) "Flag 7" to "Flag 9". (d) Heatmap distribution for Districtwise coverage of the rainfall stations on 7 July 2023 over Telangana.*

For real-time monitoring purpose, figures with assignment of flags from Flag-0 to Flag-9 are plotted daily based on the locus of each AWS stations over Telangana as shown in Figure 8. The figure represents the spatial distribution of AWS stations assigned with Quality Flags on 7 July 2023 (i.e. previous 30 days span of 7 June 2023 to 6 July 2023) over the state. It can be depicted from Figure 8, on 7 July 2023, out of 1044 stations, a totality of 901 stations were flagged as "Flag 0" to "Flag 5", while 142 stations were flagged as "Flag 6" following the corollaries of STEP-1 and STEP-2 of Quality Flagging Determination method and these latter stations were designated as "Regular but Not-Usable" stations (Figure 8 a-b). Only 1 station out of total 1044 AWS stations have reported irregular rainfall observations and was flagged within "Flag 7" to "Flag 9" category following the STEP-3 criteria of Quality Flagging (Figure 8c). Figure 8d depicts a comprehensive representation of cumulative statistics for both the percentage count and reported count of rainfall observations by AWS stations, taking into account the assigned Quality Flags, across all districts on 7 July 2023. As discussed in Section 5.1 above, in a similar way, the figure will provide a detailed insight into the quality assessment of AWS stations in the districts in real-time. Approximately 10-20% of the stations in Bhadradri Kothagudem, Mulugu, Sangareddy and Siddipet districts have been assigned with "Flag-0" while 90-100% of the stations in Pedapalli district and 80-90% of the stations in Adilabad and Mancherial districts were assigned with the "Flag-1" Quality Flag (Figure 8d). One can easily visualize and interpret the rest of the quality flags assigned to different AWS stations over each districts in Telangana on 7 July 2023.

8. Summary and Conclusions

This study presents the preliminary results for the validation and quality checking of high-density AWS network of Telangana State Development Planning Society (TSDPS) during monsoon months (June-September, JJAS) of 2020 to 2022. The network consists of ~1043 AWS stations that were deployed over 33 districts of Telangana state (15.5^{0}N-20.0^{0}N, 77.0^{0}E-81.5^{0}E). The main conclusions are listed below as:

1. The high-density AWS network in Telangana consistently reported daily rainfall data during the monsoon seasons of 2020-2022, with an average of 1043 actively reporting stations, demonstrating exceptional coverage and density.

2. The TSDPS-AWS network in Telangana exhibited exceptional coverage and dependability, with a consistently high number of stations reporting 90% or more of the 122 JJAS days, indicating a robust and reliable network capturing rainfall data across the region (1042 stations in 2020, 1043 stations in 2021, and 1044 stations in 2022).

3. Rangareddy, Medchal-Malkajgiri, Hyderabad, Nalgonda and Nizamabad districts consistently had the highest number of actively reporting AWS stations during the monsoon seasons of 2020-2022, followed by Sangareddy, Khammam, Siddipet and Suryapet districts.

4. The majority of AWS stations in each district reported rainfall observations for over 90% of the monsoon days, highlighting the effectiveness of the TSDPS-AWS network in capturing rainfall data throughout the season and ensuring consistency in extreme rainfall observations.

5. The assignment of quality flags to TSDPS-AWS stations in Telangana during the monsoon seasons of 2020-2022 showed an improvement in data quality and reliability. The majority of stations fell within the "Regular and Usable" category (Flags 0-5), with a significant decrease in "Irregular" stations (Flags 7-9) across the seasons.

6. In JJAS-2020, out of 1043 stations, 843 were classified as "Regular and Usable," indicating high reliability and usability. Similar trends were observed in JJAS-2021 and JJAS-2022, with an increase in "Regular and Usable" stations and a decrease in "Irregular" stations.

7. Most AWS stations were assigned "Flag-1," indicating relatively good quality and usability of rainfall data, while the distribution of quality flags varied among districts.

8. Real-time daily monitoring and quality checking of AWS stations indicate the regularity and usability of stations for validation purposes in real-time applications.

9. The TSDPS-AWS network effectively captured extreme rainfall occurrences, providing valuable insights into their frequency, intensity, and duration. This information contributes to a better understanding of monsoon rainfall patterns and has implications for sectors like agriculture, hydrology, urban planning, and climate research.

Acknowledgments

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Appendix

1. Quality-Flag Determination Method: Maximum Correlation with Minimum BIAS

For Quality Flag determination, the statistics has been computed over a period of 122 days of every monsoon 2020 to 2022. Based on 122 days of rainfall data, maximum correlation with minimum BIAS are considered to assign Quality Flags to individual stations.

Neighbouring Station Rainfall: NHBR,
Satellite-derived rainfall: GPM,
Gridded gauge rainfall: IMD,
Merged satellite-gauge rainfall: NMSG
Corr: Correlation, Flag: F
Let us consider,
Corr_NHBR = C1, Corr_GPM = C2, Corr_IMD = C3, Corr_NMSG = C4,
BIAS_NHBR = B1, BIAS_GPM = B2, BIAS_IMD = B3, BIAS_NMSG = B4,
Mean_AWS/ARG = M0, Mean_NHBR = M1, Mean_GPM = M2,
Mean_IMD = M3, Mean_NMSG = M4
R1 = 30% of the mean AWS rainfall
R2 = 150% of the mean AWS rainfall

STEP 1: When NHBR is PRESENT,

Corollary 1: If C1 ≥ 0.6:
- (a) If min(B1, B2, B3, B4) ≤ R1, then F = 0
- (b) If R1 < min(B1, B2, B3, B4) ≤ R2, then F = 3
- (c) If min(B1, B2, B3, B4) > R2, then F = 5

Corollary 2: If 0.5 ≤ C1 < 0.6:

(A) If max (C2, C3, C4) ≥ 0.6:
- (a) If min(B1, B2, B3, B4) ≤ R1, then F = 1
- (b) If R1 < min(B1, B2, B3) ≤ R2, then F = 4
- (c) If min(B1, B2, B3, B4) > R2, then F = 5

(B) If 0.5 ≤ max (C2, C3, C4) < 0.6:
- (a) If min(B1, B2, B3, B4) ≤ R1, then F = 2
- (b) If R1 < min(B1, B2, B3, B4) ≤ R2, then F = 5
- (c) If min(B1, B2, B3, B4) > R2, then F = 6

(C) If 0.4 ≤ max (C2, C3, C4) < 0.5:
- (a) If min(B1, B2, B3, B4) ≤ R1, then F = 3
- (b) If R1 < min(B1, B2, B3, B4), then F = 6

(D) If max (C2, C3, C4) < 0.4: then, F = 6 [NO OTHER CHECKS ARE DONE]

Corollary 3: If C1 < 0.5:

(A) If max (C2, C3, C4) ≥ 0.6:
- (a) If min(B1, B2, B3, B4) ≤ R1, then F = 1
- (b) If R1 < min(B1, B2, B3, B4) ≤ R2, then F = 4
- (c) If min(B1, B2, B3, B4) > R2, then F = 5

(B) If 0.5 ≤ max (C2, C3, C4) < 0.6:
- (a) If min(B1, B2, B3) ≤ R1, then F = 2
- (b) If R1 < min(B1, B2, B3, B4) ≤ R2, then F = 5
- (c) If min(B1, B2, B3, B4) > R2, then F = 6

(C) If 0.4 ≤ max (C2, C3, C4) < 0.5:
- (a) If min(B1, B2, B3, B4) ≤ R1, then F = 3
- (b) If R1 < min(B1, B2, B3, B4) ≤ R2, then F = 6

(D) If max (C2, C3, C4) < 0.4: then, F = 6 [NO OTHER CHECKS ARE DONE]

STEP 2: When NHBR is NOT PRESENT,

Corollary 1: If C2 ≥ 0.6, C3 ≥ 0.6 and C4 ≥ 0.6:
(a) If min(B2, B3, B4) ≤ R1, then F = 0
(b) If R1 < min(B2, B3, B4) ≤ R2, then F = 3
(c) If min(B2, B3, B4) > R2, then F = 5

Corollary 2: If max (C2, C3, C4) ≥ 0.6:
(a) If min(B2, B3, B4) ≤ R1, then F = 1
(b) If R1 < min(B2, B3, B4) ≤ R2, then F = 4
(c) If min(B2, B3, B4) > R2, then F = 5

Corollary 3: If 0.4 ≤ max (C2, C3, C4) < 0.6:
(a) If min(B2, B3, B4) ≤ R1, then F = 2
(b) If R1 < min(B2, B3, B4) ≤ R2, then F = 5
(c) If min(B2, B3, B4) > R2, then F = 6

Corollary 4: If max (C2, C3, C4) < 0.4: then, F =6 [NO OTHER CHECKS ARE DONE]

STEP 3: For IRREGULAR STATIONS,

Corollary 1: If 53 ≤ Day_Count < 61: then F = 7, i.e. in between 43-50% out of 122 days

Corollary 2: If 34 ≤ Day_Count < 53: then F = 8, i.e. in between 27-43% out of 122 days

Corollary 3: If Day_Count < 34: then F = 9, i.e. less than 27% out of 122 days

2. Real-time Quality-Flag Determination Method:

For Real-time processing of Quality Flag determination, the statistics has been computed over a period of previous 30 days span. Now, based on last 30 days rainfall data, maximum correlation with minimum BIAS are considered to compute and assign Quality Flags to each individual stations. It is to be noted that, the method is exactly similar to Point No. 1 discussed above up to STEP-2, but for STEP-3, i.e. to determine irregular stations, the following Corollaries should be considered in case of real-time processing:

STEP 3: For IRREGULAR STATIONS (in case of real-time processing for previous 30 days),

Corollary 1: If 12 ≤ Day_Count ≤ 14: then F = 7

Corollary 2: If 8 ≤ Day_Count ≤ 11: then F = 8

Corollary 3: If Day_Count < 8: then F = 9