Radar Quantitative Precipitation Estimation (QPE) Calibration Methods: A Systematic Literature Review

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ABSTRACT

High-quality Quantitative Precipitation Estimation (QPE) beyond a sizable area with high spatial and temporal precision is important for many hydrological and meteorological applications. The development of the weather radar over the past 60 years has made it possible for QPE to effectively identify the rainfall location and has enabled the former's use in actual hydrometeorological processes such as flood forecasting. These capabilities are made possible by the radar QPE's exceptionally high temporal and spatial resolutions. Through the enhancement of radar QPE for rainfall estimation, this research contributes to the field by offering critical analysis and assessment of the focus studies. The current study takes into account publications from reputable internet search libraries published between 2010 and 2023. The former will help academics analyze the most recent work on radar QPE, adopting the most advanced and improved techniques, and provide a baseline for future comparisons and directions.

Keywords-weather radar rainfall; quantitative precipitation estimation; radar QPE calibration; QPE; SLR

I. INTRODUCTION

The two most extensively used rainfall sensors are rain gauges and radar, which provide direct and indirect readings of rainfall intensity, respectively. Rain gauges constitute a reliable equipment for measuring rainfall at specific locations, but their spatial distribution is sparse in remote areas, particularly in mountainous terrain, resulting in insufficient spatial resolution for accurate rainfall pattern mapping [1]. On the other hand, weather radars, unlike gauges, can generate high spatial and temporal resolution precipitation estimations over a large area. In modern times, as a result of recent advancements in radar devices, data processing, and numerical modeling, hydrological models, when combined with radar- derived QPEs, have been evolved into a viable replacement for rain gauges. QPEs are essential in the development of meteorological, hydrological, and geological hazard alerts. When precipitation rates are incorporated into flood forecast models, the accuracy of flood forecasting can be greatly enhanced [2-4]. High-quality weather radar data are very important for hydrological application [5]. More efficient quality control techniques have emerged as a consequence of more advanced image processing approaches and increased computational capabilities. Radar errors, on the other hand, are difficult to be diagnosed, and therefore difficult to be totally eliminated. Hence, data from various measurement systems, specifically from rain gauge networks, are utilized in order to enhance the radar-based QPE by adjusting it or by combining several sources. Currently, most radar QPEs are based on developed Z-R relationships explored by the authors in [6]. The variable power law relationship (Z-R relationship) between radar reflectivity, Z (mm^6/m^3), and rainfall rate, R (mm/h), can be deployed to obtain QPE products. Nevertheless, there are numerous issues when attempting to convert radar observational data into efficient QPE products, which can be used in future applications. This challenge, if not addressed properly, can possibly result in significant errors and uncertainties in the surface of rainfall estimation, such as ground clutter, beam blocking, sampling error, and attenuation. Throughout the years, numerous studies have been conducted by radar researchers worldwide to increase the precision and dependability of weather radar QPEs [7, 8]. During the past ten years, the trends in estimating rainfall, utilizing radar QPE for environmental monitoring, disaster management, water resource planning, and climate research have drawn greater attention. However, due to the indirect nature of rainfall estimation by the radar, researchers are still exploring for the best radar QPE calibration technique. The aim of this paper is to exhaustively search and review the radar QPE calibration methods currently employed by researchers from various regions, using a Systematic Literature Review (SLR) approach.

II. METHODOLOGY

A high-quality SLR is one that achieves its goal by offering the condensed knowledge of the needed research topic for a particular period of time. An efficient SLR requires a thorough research process with step-by-step instructions. The Preferred Reporting Items for Systematic Reviews and Meta- Analyses (PRISMA) standards were deployed for conducting this systematic review [9, 10]. The SLR is required to provide an accurate picture of the present techniques for radar QPEs in order to identify future research and development opportunities.

A. Defining the Research Questions

As the first phase of a meta-analysis utilizing this methodology, the research questions were specified pertinent to the study purpose, and thus the following issues that the SLR needed to address were identified:

- Research Question 1 (RQ1): Which calibration technique is utilized or suggested for radar-based quantitative precipitation estimation?
- Research Question 2 (RQ2): What are the limits of optimization analyses and how may they be solved in future work?
- Research Question 3 (RQ3): How is the performance of calibration method evaluated?

A. Literature Search Method

Initially, as evidenced in Table I, relevant keywords are defined in order for publications correlated with the research topic to be traced. Three electronic databases, which are Scopus (2010-2023), Science Direct (2010-2023), and Web of Science (2010-2023), were considered. The search terms were discovered in the titles, abstracts, and keywords of previously published articles in these databases. The keywords "radar quantitative precipitation estimation", "calibration QPE", and "bias correction QPE" were applied and searched without regard to time or document limitations. The next step is the study selection. This phase is crucial to ensure that only the most pertinent research articles are selected.

TABLE I. SEARCHES BY KEYWORD AND PUBLICATION SELECTION

Keywords	Scopus	Science Direct	Web of Science
Radarquantitative precipitation estimation	641	3635	675
Calibration QPE	56	214	71
Bias correction QPE	57	174	66
Total	754	4023	812

A. Inclusion and Exclusion Criteria for the *Selection of Studies*

The contour of the selection boundary is observed in the following step. This activity entails two parts: inclusion criteria and exclusion criteria. Articles that meet the criteria for inclusion will be considered for the next step, whereas those that meet the criteria for elimination will be taken out of the screening process.

- Inclusion Criteria:
  - Papers which are published from 2010 until 2023.
  - Papers which are written in English.
  - Papers which are available in journals or conferences.
  - Papers which have presented the radar QPE calibration methods that are related to rainfall estimation.
- Exclusion Criteria:
  - Papers which are not in English.
  - Papers published before 2010.
  - Papers which are not related to radar QPE and rainfall estimation.
  - Papers which do not evaluate the performance of the proposed method.

B. Data Screening and Extraction

The screening procedure must be carried out following the completion of the paper selection search, as previously indicated. The screening procedure was structured as follows: after reading the titles, abstracts, and whole texts, any papers that did not pertain to the stated field of study and those that did not specifically declare radar QPE calibration techniques as a primary goal were rejected. In addition, journal articles published in other languages as well as the number of nominal articles not available through the university library were removed.

C. Quality Evaluation

The systematic research procedure was ensured to adhere to the quality requirements in order to accomplish the study objectives. The following steps were taken to certify that the results were of high quality.

- Research articles were extracted from reputable, legitimate web libraries.
- Recent research was reflected in the choice of newest research publications.
- The selection procedure was impartial.
- All legitimate phases of the systematic research procedure were implemented.

III. RESULTS AND DISCUSSION

The review was performed for the time period from 2010 to 2023. Through the assessment of the three electronic databases, literature search results revealed that the "radar quantitative precipitation estimation" keyword context had been explored more than the "calibration QPE" and the "bias correction QPE", as observed in Table 1. A further literature search was carried out, this time with restrictions imposed on article types and open access, until no new papers or inclusion criteria were discovered. In addition, identical publications detected in multiple databases or duplicate ones were also eliminated. As a result, a total of 334, 524, and 395 documents were discovered on Scopus, Science Direct, and Web of Science, respectively, after the selection completion. The process continues with the assortment of only English-language journals, which gave a total of 107 documents found on Scopus, 365 documents found on Science Direct, and 136 documents found on Web of Science. A total of 608 relevant publications were considered for the next step. In the beginning, an evaluation of the titles and abstracts was carried out, which ultimately resulted in 326 different articles being compiled. The remaining 326 articles were then subjected to a manual full-text examination. As a consequence, 72 papers satisfied the requirements for inclusion in this study's data synthesis. The selection process and exclusion reasons are illustrated in Figure 1. Throughout the reading process, irrelevant works for the intended area of study, as well as those that did not specify sizing as a main aim, were discarded.

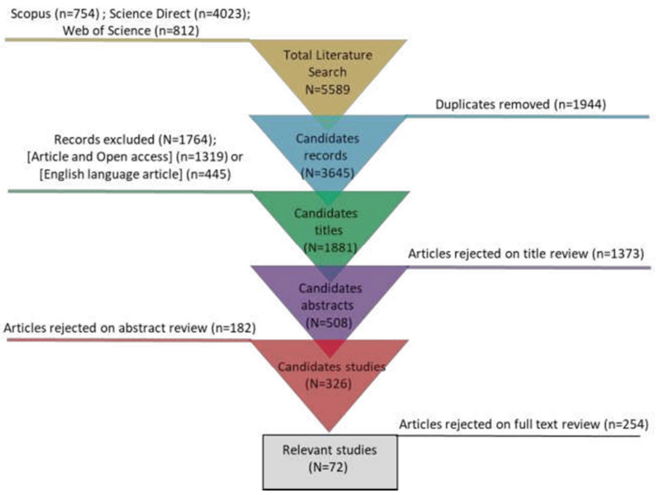

Fig. 1. Flowchart of SLR using PRISMA.

According to the SLR findings, 72 research articles were ultimately chosen for shortlisting by using the literature extraction criteria described above. The responses to the research questions gleaned through a thorough examination of the articles that made the short list can be found bellow.

A. RQ1

Table II summarizes the general approach followed to improve radar QPE according to the findings of the analysis of relevant articles. Below, several calibration methods were optimized and associated with the relevant works.

1) Z-R relationship

Twenty-nine articles in the final data set utilized Z-R relationship for the enhancement of radar QPE, as depicted in Table II. The improvements on the algorithm in the Z-R relationship are:

- R (A) = Specific Attenuation (A) used in Rainfall Rate (R) estimation.
- R (KDP) = Specific Differential Phase (KDP) utilized in R estimation.
- R (Z) = Reflectivity (Z) utilized in R estimation.
- R (ZDR) = Differential Reflectivity employed in R estimation.
- VPR = Vertical Profile of Reflectivity.
- Others = non-parametric rainfall estimation, optimization technique, CAPPI, Kraemer approach.

TABLE II. CALIBRATION METHODS EMPLOYED IN RELEVANT ARTICLES

Relevant articles	**72**
Z-R relationship [11-40]	29
Machine Learning [42-53]	12
Merging Radar [54-67]	14
Rainfall Classification [19, 68-72]	6
Kalman Filtering [73, 74]	2
Geostatistical Technique [75-77]	3
RT and SCIT Algorithm [78]	1
SMA Method [79]	1
Levenberg-Marquardt Algorithm [80]	1
Fisher Estimation [81]	1
Quantile-Matching Approach [82]	1
Bayesian Approach [83]	1

In order to improve QPE precision, the Z-R parameter that is most frequently used in the optimization process is the KDP. It is fascinating to discover that the R (KDP) is always considered in all Z-R relationship optimization analyses because it is less sensitive to Drop Size Distribution (DSD) fluctuations and more resistant to attenuation and radar miscalibration [11, 12]. The A in R estimation is the second most frequently deployed Z-R parameter. A power-law R (A) relationship is utilized to estimate R and the degree of attenuation, A, measured from Z. The Path Integrated Attenuation (PIA), appears to be widely used for attenuation correction. The R (KDP) relationship may be less sensitive to DSD for very high Rs in the C and X bands, but R (A) is less impacted by DSD variability at lower Rs [13]. In addition, retrieving rain data based on the integration of Z, Differential Reflectivity (D), and KDP has been proven to be effective in numerous former studies [14-18], while it also has advantages over traditional Z-R methods due to the availability of more DSD and hydrometeor type data [19, 20].

2) Machine Learning

Accordingly, owing to their simplicity, Machine Learning (ML) algorithms can be considered an alternative for the enhancement of quantitative precipitation estimation. Numerous ML applications, including those frequently employed in hydrology, are tool-based and are created for classification or regression with a solid foundation in probability theory and statistics. Artificial Neural Networks (ANNs), Decision Trees (DT), and Random Forests (RF) are ML tools for analyzing sample data to infer the correlation among dependent and independent variables without making any assumptions about linearity. The extensive use of ML algorithms for the modeling of natural phenomena opens up new possibilities for radar based QPEs [41]. As displayed in Table II, the authors of 12 articles in the final data set utilized an ML algorithm as a medium for radar QPE enhancement:

- Regression tree and RF [42-47].
- Deep/ANN [46, 48-50].
- Satellite [51-53].

3) Merging Radar

Although some methods seem inaccurate, they are actually complementary. As a consequence of this, the concept of combining data on precipitation obtained from a variety of sources in order to improve the accuracy of rainfall estimation came about naturally. As evidenced in Table II, the authors of 14 articles in the final data set utilized merging radar for radar QPE enhancement.

- Authors in [54] used a combination of radar, rain gauges, and orographic rainfall climatology to produce accurate rainfall measurements that resolve radar QPE biases.
- Authors in [55-57] came up with a blending method that combines the beneficial aspects of the two radar systems. The combination of the two distinct radar types resulted in the production of a long-range radar that has high temporal resolution.
- Authors in [58] utilized the Spirec algorithm to combine satellite data, radar mosaic data, and rain gauge, deploying Poisson's equation.
- Authors in [59] employed a radar merging methodology comparable to Météo France's ANTILOPE technology, but with a better resolution network. The tool used is the Estimages toolbox merger, which is based on the Krigine with External Drift (KED) algorithm and has been observed to provide positive outcomes in QPE enhancement.
- Authors in [60] enhanced precipitation spatial representations by smoothly mixing numerous precipitation sources inside the Multi-Radar Multi-Sensor (MRMS) system.
- Authors in [61, 62] applied adaptive data fusion to merge radar-gauge data and integrate S- and C-Band dual polarization radars.
- Authors in [63] added a Mean Field Bias (MFB) correction, kriging of rain gauge data, a basin-uniform estimate from a single gauge in the watershed, and uncorrected radar data to their works.
- Authors in [64, 65] implemented the MFB method to calculate the correction factor by comparing radar estimations to rain-gauge observation values.
- Authors in [66] made some improvements to correction methods, including those for MFB and static adjustment.
- Authors in [67] developed an algorithm that makes use of the Combined Radar Quality Index (CRQI) to improve the QPE performance.

4) Rainfall Classification

As shown in Table II, the authors of six articles in the final data set utilized rainfall classification for radar quantitative precipitation estimation enhancement.

- Authors in [68-70] analyzed the microphysical characteristics of rainfall and the estimation accuracy by implementing disdrometer measruements. The disdrometer of DSD is then used to simulate radar parameters to increase the accuracy of QPE.
- Authors in [71] achieved improved radar QPE by classifying rainfall as tropical-stratiform or tropical-convective, using an Fuzzy Logic (FL) algorithm.
- Authors in [19] created a novel rainfall algorithm that is guided by Hydrometeor Identification (HID).
- Authors in [72] developed new Z-R relationships for the three distinct types of rain events: lower and more particular rainfall characteristics during monsoon seasons.

5) Kalman Filtering

The authors of two papers in the final data set utilized the Kalman filtering algorithm as a medium for radar quantitative precipitation estimation enhancement.

- Authors in [73] used a technique to reduce bias between weather radar rainfall that combines the Kalman filter and a multivariate analysis technique.
- Authors in [74] employed a Kalman filter and a multiple regression technique to minimize radar rainfall errors caused by system and quantification noises.

6) Geostatistical Technique

The authors of three papers in the final data set followed geostatistical techniques for radar quantitative precipitation estimation enhancement.

- Authors in [75, 76] proposed a process that requires two stages for calculating the accuracy of rain forecasting. First, normalized variograms were used to compute kriging normalized ESDs (sill equal to 1). Second, the kriging ESDs were denormalized deploying a cross-validation method based on the idea that the relationship between the standard deviation and the mean of the variable of interest is linear.
- Authors in [77] discarded the bias in the radar rainfall data that is caused by an ambiguous Z–R relationship by using kriging techniques to apply a local bias coefficient to a region that exhibits the same regional climate rainfall feature as that of the rest of the area.

7) Other Methods

The authors of six articles in the final data set deployed the following methods for radar quantitative precipitation estimation enhancement.

- Authors in [78] used the Reflectivity Threshold (RT) and Storm Cell Identification and Tracking (SCIT) techniques to assess the characteristics of individual storm cells' precipitation in relation to various rainfall events and differences in storm scale.
- Authors in [79] employed the Simple Moving Average (SMA) sorting and correction method to adjust the

measured reflectivity. A polynomial least-squares integration was used to enhance the method for stratiform and convective cloud types.

- Authors in [80] implemented the nonlinear Parameter Estimation (PEST) software as the optimization tool. The model optimization technique used by PEST is the Levenberg-Marquardt Algorithm (LMA) with Jacobian matrix updating, a gradient-based local parameter search algorithm.
- Authors in [81] improved radar quantitative estimation through the fusion of various precipitation-based radar products depending on Fisher estimation, and thus its bias-penalized contingent variant.
- Authors in [82] enhanced the accuracy of the radar QPE by applying a method called quantile matching (Q-matching).
- Authors in [83] adopted a Bayesian method to fix the bias in radar QPE.

B. *RQ2*

Estimating monsoon rainfall by using weather radar may be improved with the application of a non-parametric model, for example, an ANN. Utilizing the bias and weight vectors from the generalization model, the radar reflectivity is inverted to the rain rate. Therefore, no spatial bias correction is needed. However, this method needs a lot of training samples in order to match radar reflectivity to rain gauge data [49]. Future research may include adapting ML models to numerous radars and rainfall incidences under various weather conditions. In addition, the positive aspect of a radar and gauge pairing strategy is noticeable in minimally gauging station's locations even when storm durations have wide spatial homogeneity. As a result, deploying the pairing method would allow one to identify both the weak points and the strong points of a specific gauge and radar network in addition to lessening errors in spatial rain gauges [55, 61, 62]. Nevertheless, the absence of stations with some other weather variable data for rain gauges reduces the accuracy of the model. In order to achieve the best fit line, numerous weather data parameters and noise effect removal must be considered in the analysis conducted for research development [74].

C. *RQ3*

The performance was assessed by comparing the expected outcomes to the observed (actual) metrics. The proposed methods' performance was compared to other existing approaches using information retrieval measures and statistical methodologies, such as root mean square error, correlation coefficient, and mean absolute error.

IV. CONCLUSION

This paper provides a systematic literature review of recent research from 2010 to 2023, with a focus on enhancing the radar Quantitative Precipitation Estimation (QPE) calibration method. Based on the search criteria, 72 works were found to be relevant after the screening process. The majority of the relevant publications optimized Z-R parameter to improve the QPE reliability. The performance of radar QPE calibration is evaluated by comparing the root mean square error value seen between the relevant rainfall data from the associated rain gauge and the bias- corrected radar rainfall estimates generated from each approach. Besides, the quality of radar QPE has been examined by implementing a hydrological model and comparing it to rain-gauge based rainfall estimation. The improvement of QPE began with the use of a different approach to reduce an uncertain Z–R relationship, which is the root cause of the bias that can be found in radar rainfall estimations

Additionally, space-based rainfall products are a valuable tool for huge hydrogeological and climate studies. Satellite measurements of precipitation are thought to be a suitable option for ground-based measurements. However, the limitations of the parametric retrieval algorithms, as well as the temporal and spatial sampling are the gaps in the research noticeable during light rainfall or extreme events. Moreover, because of their simplicity, Machine Learning (ML) methods when used for QPE constitute a viable substitute for improving the radar QPE. Nonetheless, depending on the ML algorithms applied, the amount of time required to perform computations in order to build QPE models can vary and may need to be modified before the latter being employed. Its accuracy assessment in polarimetric radar is highly encouraged for ML algorithms to be more effectively evaluated in applications employed to retrieve rainfall in the future. Future work could consiuder weather radar-based rainfall climatology, including simulations over different spatial and temporal scales in order for the probabilities and return periods of extreme rainfall to be determined.

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