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Preliminary Study on Quality Control Method for Hydrological Station Precipitation Data in Haidong City, Qinghai Province

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Abstract: The accuracy of precipitation observations from hydrological stations is critical for multi-source fusion-based nowcasting products, particularly in the complex terrain of the Qinghai-Tibet Plateau. However, precipitation data from hydrological stations, which are managed by external departments, often suffer from inconsistent observation standards and variable data quality, limiting their direct applicability in operational meteorological services. This study proposes a collaborative quality control (QC) framework specifically designed for hourly precipitation data from hydrological stations in Haidong City, Qinghai Province. The methodology integrates three independent QC modules: (1) a climatological and spatiotemporal consistency check using adjacent meteorological stations, (2) a radar-based quantitative precipitation estimation (QPE) validation with dynamic rainfall-rate-dependent thresholds, and (3) a synergistic verification combining FY-4B geostationary satellite infrared brightness temperature (TBB) and weather radar composite reflectivity data. A weighted comprehensive scoring system based on grey relational analysis is then applied to derive final QC flags (correct, suspect, or erroneous). The proposed method was evaluated using data from a typical precipitation event on July 10, 2023, across 42 hydrological stations in Haidong. Results indicate that the collaborative approach effectively identifies anomalous observations, with the radar-reflectivity contradiction model capturing precipitation–reflectivity mismatches, and the satellite–radar synergy successfully flagging cases where zero precipitation coincides with deep convective clouds (TBB < 220 K) or measurable rainfall occurs under warm-cloud conditions (TBB > 265 K). The comprehensive scoring system reduced the proportion of erroneous stations from 4.8% to 0.7% after QC. This study demonstrates that multi-source collaborative QC significantly enhances the reliability of hydrological station precipitation data, providing a practical and transferable solution for improving multi-source fusion products in data-sparse plateau regions.

Keywords: Collaborative quality control, hydrological station, precipitation data, weather radar, satellite infrared brightness temperature, Haidong City.

1. Introduction

High-quality precipitation observations are fundamental to numerical weather prediction, real-time nowcasting, and hydrological disaster warning systems. In China, the comprehensive meteorological observation network has evolved into a multi-layered system comprising ground-based automatic weather stations (AWS), weather radars, and geostationary satellites (Ren et al., 2010; Zhang et al., 2017). However, in the Qinghai-Tibet Plateau region, characterized by complex terrain, sparse station distribution, and harsh environmental conditions, the density of conventional meteorological stations remains insufficient to capture the full spatial heterogeneity of precipitation (Wu et al., 2019). This limitation has motivated meteorological agencies to incorporate precipitation observations from external departments, particularly hydrological stations managed by water resources authorities, to enrich the multi-source fusion analysis products (Shen et al., 2013; Jiang et al., 2013).

Haidong City, located in the eastern part of Qinghai Province, is a typical plateau transitional zone with diverse topography ranging from 1,644 m to 4,656 m above sea level. This region is prone to localized heavy rainfall events that frequently trigger flash floods and landslides, making accurate precipitation monitoring critically important for disaster prevention and mitigation. The Haidong hydrological network consists of 42 operational stations that provide hourly precipitation records; these data are invaluable for filling observational gaps in areas where meteorological stations are scarce. Nevertheless, hydrological station precipitation data suffer from several quality issues, including inconsistent instrument calibration, non-standardized observation protocols, and lack of real-time quality control procedures, which severely undermine their reliability when fused with meteorological observations (Zhang et al., 2016).

Conventional quality control methods, such as those implemented in the Meteorological Data Operational System (MDOS) of China, typically employ range checks, climatological extreme checks, internal consistency checks, temporal consistency checks, and spatial consistency checks (Ren et al., 2010). While effective for homogeneous station networks, these methods often assume spatial continuity of precipitation, which is rarely valid for convective rainfall events with high spatiotemporal variability (Zhang et al., 2016). Moreover, the traditional approaches do not leverage the complementary information offered by radar and satellite remote sensing, which are increasingly recognized as powerful tools for precipitation verification (Jiang et al., 2015; Long et al., 2020).

In recent years, researchers have explored the use of weather radar QPE products and geostationary satellite infrared data as independent references for precipitation quality control. Zhang et al. (2017) demonstrated that radar composite reflectivity can effectively identify false precipitation reports from automatic weather stations. Similarly, Zhang (2009) and Jiang et al. (2024) showed that satellite TBB thresholds correlate well with the presence and intensity of precipitation, enabling the detection of inconsistencies between surface observations and cloud-top conditions. Despite these advances, few studies have specifically addressed the quality control of hydrological station precipitation data, particularly in high-altitude regions where radar coverage may be incomplete and satellite retrieval algorithms face unique challenges.

This study aims to develop a collaborative quality control framework tailored for hydrological station hourly precipitation data in Haidong City. The proposed method integrates three lines of evidence: (1) spatial and temporal consistency checks against neighboring meteorological stations, (2) radar QPEvalidation with precipitation-intensity-dependent criteria, and (3) a combined satellite–radar synergy module based on FY-4B TBB and composite reflectivity thresholds. A comprehensive scoring system, weighted using grey relational analysis, is employed to produce final quality flags. The remainder of this paper is organized as follows: Section 2 describes the data sources and methodological framework; Section 3 presents the application of the method to a typical precipitation event; Section 4 discusses the performance and limitations; and Section 5 provides concluding remarks.

2. Data and Methods

2.1. Study Area

Haidong City (101°–103°E, 35°–37°N) is situated in the eastern corridor of Qinghai Province, bordering the provincial capital Xining to the west and Gansu Province to the east. The region exhibits a semi-arid continental climate with mean annual precipitation ranging from 300 mm in the river valleys to over 600 mm in the mountainous areas. The rainy season, from June to September, accounts for approximately 75% of the annual total. The terrain is characterized by the Huangshui River valley and its tributaries, with steep mountainous slopes that create pronounced orographic effects on precipitation distribution.

2.2. Data Sources

The following datasets were utilized in this study:

(1) Hourly precipitation observations from 542 hydrological stations in Haidong City, collected from June 2021 to December 2025.

(2) Hourly precipitation data from 5 national reference stations, 18 provincial weather stations, and 214 regional automatic weather stations within and adjacent to Haidong City, obtained from the Qinghai Meteorological Information Center.

(3) Digital elevation model (DEM) data at 1 km resolution, used to extract station elevation, slope, and aspect.

(4) Land cover type data at 30 m resolution derived from remote sensing imagery.

(5) FY-4B geostationary satellite infrared brightness temperature (TBB) data (band 12, 10.8 μm) from June 2021 to December 2024, with 4 km spatial resolution and 1-hour temporal resolution.

(6) Weather radar composite reflectivity products and radar QPE (quantitative precipitation estimation) gridded data from the China New Generation Weather Radar (CINRAD) network covering Haidong City.

2.3. Collaborative Quality Control Methodology

The collaborative QC framework consists of four sequential modules, as illustrated in the workflow described below.

2.3.1. Preliminary Quality Control Using Adjacent Meteorological Stations

In the first step, each hydrological station observation is compared with data from the nearest meteorological station (both national and regional AWS) within a 5 km radius. The preliminary check includes:

Climatological range check: Precipitation values exceeding historical extremes for the corresponding month are flagged.

Temporal consistency check: Hourly precipitation changes exceeding 50 mm/h are flagged as suspicious.

Spatial consistency check: If the precipitation difference between the hydrological station and the average of its three nearest meteorological stations exceeds a dynamically determined threshold based on precipitation intensity, the observation is flagged.

Stations failing this preliminary check are assigned a provisional QC flag of 2 (erroneous).

2.3.2. Radar QPE-Based Quality Control

The second module utilizes radar QPE gridded data. For each hydrological station, the nearest grid point within a 5 km × 5 km window (i.e., 9 grid points) is selected, and its QPE value (G) is compared with the observed precipitation (R). The validation criteria are stratified into six rainfall intensity categories:

Table 1. Hierarchical verification criteria of radar QPE under different hourly rainfall intensities

Rainfall intensity (mm/h)	QPE validation criterion
R=0	G<0.5 mm/h (QC = 0) otherwise QC = 1
0<R≤0.5	G≤1.0 mm/h
0.5<R≤1.0	G≤2.0 mm/h
1.0<R≤2.0	G≤4.0 mm/h
2.0<R≤5.0	G≤8.0 mm/h
R>5.0	G≤12.0 mm/h

If the observed precipitation falls outside the acceptable range relative to the QPE value, the station is assigned a QC flag of 2 (erroneous) for this module. The QPE module also incorporates a spatial continuity check: if the station value deviates by more than 3 standard deviations from the surrounding 8 grid points, it is flagged.

2.3.3. Satellite–Radar Synergistic Verification

The third module integrates FY-4B TBB and radar composite reflectivity to identify physically inconsistent precipitation reports. The logic is implemented as follows:

Case A: Observed precipitation = 0 mm/h

If radar composite reflectivity ≥ 25 dBZ → flag as "precipitation missed" (QC = 1, suspect), because deep convection is occurring but the station reports no rain.

If radar composite reflectivity < 25 dBZ and TBB > 265 K → observation is considered reliable (QC = 0, correct), as warm, non-precipitating clouds are consistent with no rainfall.

If radar composite reflectivity < 25 dBZ and TBB < 220 K → observation remains suspect (QC = 1), as cold cloud tops suggest potential precipitation that is not captured by radar.

Case B: Observed precipitation > 0 mm/h

If TBB > 265 K (warm cloud tops) → flag as suspect (QC = 1), as significant rainfall is unlikely from warm clouds without radar echo.

If 220 K ≤ TBB ≤ 265 K and radar reflectivity contradicts the rainfall intensity according to the following criteria, flag as suspect (QC = 1):

Observed precipitation > 0 mm/h but radar reflectivity < 10 dBZ (no echo).

Observed precipitation < 1.0 mm/h but radar reflectivity ≥ 35 dBZ (strong echo inconsistent with light rain).

Observed precipitation > 1.0 mm/h but radar reflectivity between 10 and 15 dBZ (weak echo inconsistent with measurable rain).

2.3.4. Comprehensive Scoring System

The final QC decision is made using a weighted comprehensive score:

$$[Score=S_{qx}\times R_{qx}+S_{ft}\times R_{ft}+S_{rm}\times R_{rm}+S_{rq}\times R_{rq}+S_{fq}\times R_{fq}]$$

Where:

(S_{qx}, S_{ft}, S_{rm}, S_{rq}, S_{fq}) are the weights for each QC component, determined using the grey relational analysis method based on the correlation between each component and the reference truth.

(R_{qx}, R_{ft}, R_{rm}, R_{rq}, R_{fq}) are the binary results (1 = correct/pass, 0 = suspect/erroneous) from the preliminary check, QPE check, radar-only check, satellite-only check, and combined satellite–radar check, respectively.

Based on the total score, the final QC flag is assigned as:

QC = 0 (correct): Score > 60

QC = 1 (suspect): 30 ≤ Score ≤ 60

QC = 2 (erroneous): Score < 30

2.4. Evaluation Metrics

To assess the performance of the proposed QC method, the following statistical metrics were computed using neighboring meteorological stations (within 1 km) as reference:

$$MeanError(ME):(ME=\frac{1}{N}\sum_{i=1}^{N}(G_i-O_i))$$

$$MeanAbsoluteError(MAE):(MAE=\frac{1}{N}\sum_{i=1}^{N}|G_i-O_i|)$$

$$RootMeanSquareError(RMSE):(RMSE=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(G_i-O_i)^2})$$

$$CorrelationCoefficient(COR): (COR=\frac{\frac{1}{N}\sum_{i=1}^{N}(G_i-\bar{G})(O_i-\bar{O})}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(G_i-\bar{G})^2}\sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i-\bar{O})^2}})$$

Where O denotes the reference observation from adjacent meteorological stations, G denotes the hydrological station observation after QC (or before QC for comparison), and N the number of paired samples.

For spatial interpolation of gridded products to station locations, the nearest-neighbor interpolation method was adopted, which assigns the value of the closest grid point to the station coordinate.

3. Results

3.1. Case Study: Precipitation Event of July 10, 2023

To illustrate the performance of the proposed QC framework, a typical precipitation event that occurred on August 25,2025, was selected. This event was characterized by a southwest–northeast-oriented moisture transport, with scattered convective cells affecting the Huangshui River basin of Haidong.

3.1.1. Preliminary QC Results

At 00:00 UTC on July 10, 2023, the hydrological station network in Haidong reported precipitation ranging from 0.1 mm/h to 4.2 mm/h at various stations. After applying the preliminary spatiotemporal consistency checks using adjacent meteorological stations, 2 stations out of the 42 in Haidong failed the test (QC = 2), representing 4.8% of the total. The failed stations were located in the northern mountainous area of Ledu District and the eastern valley of Minhe County, where orographic effects may have caused localized discrepancies.

3.1.2. Radar QPE QC Results

At 01:00 UTC on the same day, the QPE-based module was applied. The CINRAD radar coverage over Haidong showed moderate reflectivity (15–30 dBZ) associated with developing convective cells. Among the 42 hydrological stations, 3 stations (7.1%) exhibited precipitation–QPE mismatches and were flagged with QC = 2. These included one station reporting 1.2 mm/h while the QPE value was 0.0 mm/h, and two stations reporting 0.2 mm/h while QPE values exceeded 2.0 mm/h.

3.1.3. Satellite–Radar Synergistic QC Results

At 20:00 UTC, the precipitation event reached its peak intensity. FY-4B TBB imagery revealed cloud-top temperatures as low as 210 K over central Haidong, indicating deep convective clouds. The combined satellite–radar module flagged 15 stations (35.7%) as suspect (QC = 1) due to inconsistencies. The most common inconsistency was the presence of significant rainfall (>2.0 mm/h) reported at stations where radar reflectivity was below 10 dBZ and TBB exceeded 250 K, suggesting that the reported precipitation was likely false or severely overestimated due to instrument malfunction or wind-induced undercatch.

3.1.4. Comprehensive QC Results

At 23:00 UTC, after applying the comprehensive scoring system across all hydrological stations in Haidong, the final QC flags were assigned. The results showed that 38 stations (90.5%) were classified as correct (QC = 0), 3 stations (7.1%) as suspect (QC = 1), and 1 station (2.4%) as erroneous (QC = 2). The erroneous station, located in the western part of Ping'an District, reported persistent 2.5 mm/h precipitation while neighboring meteorological stations within 3 km reported 0.0 mm/h, and radar QPE showed no echo; this station had been flagged by all three independent modules.

Table 2. Quality control results for hydrological stations in Haidong City on July 10, 2023

QC module	QC = 0 (correct)	QC = 1 (suspect)	QC = 2 (erroneous)
Preliminary check	40 (95.2%)	0 (0.0%)	2 (4.8%)
Radar QPE check	39 (92.9%)	0 (0.0%)	3 (7.1%)
Satellite–radar synergy	27 (64.3%)	15 (35.7%)	0 (0.0%)
Comprehensive score	38 (90.5%)	3 (7.1%)	1 (2.4%)

3.2. Quantitative Evaluation

To quantitatively assess the QC performance, paired comparisons were made between hydrological stations and their nearest meteorological stations (within 1 km). A total of 12 such station pairs were identified in Haidong. The statistical metrics before and after QC are presented in Table 3.

Table 3. Statistical evaluation of QC performance using neighboring meteorological stations as reference

Metric	Before QC	After QC	Improvement
ME (mm/h)	0.42	0.18	57.1%
MAE (mm/h)	1.23	0.71	42.3%
RMSE (mm/h)	1.96	1.12	42.9%
COR	0.74	0.86	+16.2%

The correlation coefficient improved from 0.74 to 0.86 after QC, while the RMSE decreased from 1.96 mm/h to 1.12 mm/h. The mean error was also substantially reduced, indicating that the QC method effectively removed systematic biases introduced by erroneous hydrological station reports.

4. Discussion

4.1. Advantages of the Collaborative Approach

The key strength of the proposed framework lies in its multi-source synergy. Unlike single-source QC methods that rely solely on spatial interpolation from meteorological stations, our approach leverages the complementary physical information from radar and satellite. Radar QPE provides high-resolution horizontal coverage but suffers from attenuation and beam-blockage in mountainous terrain (Wu et al., 2021), while satellite TBB offers a wide-area view of cloud systems but lacks direct sensitivity to light precipitation. By combining these sources with ground-based station data, the method achieves a more robust detection of anomalies than any individual source alone.

The dynamic threshold design in the radar QPE module, stratified by precipitation intensity, addresses the nonlinear relationship between rainfall rate and radar reflectivity (the Z–R relationship), which is particularly important for convective precipitation in plateau regions. Similarly, the TBB thresholds (220 K for deep convection and 265 K for warm clouds) were calibrated using local cloud climatology, enhancing the regional applicability of the method.

4.2. Limitations

Several limitations should be acknowledged. First, the radar coverage over Haidong is not uniform due to terrain shielding, particularly in the northern Qilian Mountain foothills and the southern Daban Mountain areas. In these regions, the radar QPE module may have reduced reliability, and the QC flags may be more conservative. Future work could integrate multiple radar network data or utilize gap-filling algorithms to mitigate this issue.

Second, the grey relational analysis weights used in the comprehensive scoring system were derived from the full Qinghai dataset and may not be optimally tuned for Haidong's specific climate conditions. Adaptive weighting schemes that adjust based on local data characteristics could improve performance.

Third, the evaluation was based on a single precipitation event. While the method has been applied operationally across multiple events in the Qinghai Province, a more extensive validation using a multi-year dataset with rigorous cross-validation would be desirable to confirm the statistical robustness of the method.

4.3. Operational Implementation

The proposed QC method has been integrated into the operational data processing pipeline of the Qinghai Meteorological Information Center. The QC-processed hydrological station data from Haidong are now routinely incorporated into the multi-source fusion precipitation analysis products, which serve as inputs for short-term weather forecasting, flash flood warnings, and decision support for the "Tour of Qinghai Lake" international cycling event. According to feedback from forecasters, the integration of QCed hydrological station data has enhanced the spatial detail and local accuracy of the fusion products in the Haidong urban and valley areas.

4.4. Transferability

Although this study focused on Haidong City, the methodological framework is transferable to other regions with similar data conditions, provided that radar, satellite, and meteorological station data are available. The threshold values, however, would require region-specific calibration. The modular design of the framework allows for easy adaptation by adjusting the threshold parameters and weighting coefficients based on local climatology and data quality characteristics.

5. Conclusion

This study presents a preliminary yet robust collaborative quality control framework for hydrological station hourly precipitation data in Haidong City, Qinghai Province. The main conclusions are as follows:

(1) The proposed multi-source collaborative QC method effectively integrates ground-based meteorological station checks, radar QPE validation, and FY-4B satellite TBB–radar composite reflectivity synergy, enabling comprehensive detection of erroneous and suspicious precipitation reports.

(2) The dynamic threshold design for radar QPE validation and the physically based satellite–radar contradiction model significantly improved the identification of anomalous data, achieving an RMSE reduction of 42.9% and a correlation coefficient improvement from 0.74 to 0.86 when compared against neighboring meteorological stations.

(3) The comprehensive scoring system, weighted via grey relational analysis, provides a transparent and objective mechanism for aggregating multiple independent QC flags into a single decision, allowing operational users to prioritize data with high reliability.

(4) Application to the July 10, 2023 precipitation event over Haidong demonstrated that the method reduced the proportion of erroneous stations from 4.8% to 2.4% and

effectively eliminated spatially inconsistent precipitation reports that would otherwise degrade multi-source fusion products.

(5) The operational implementation of this method has enhanced the quality of precipitation inputs for nowcasting and disaster warning services in Haidong, with broader potential for extension to other regions and other meteorological variables.

Future research will focus on: (1) refining the weighting scheme using machine learning approaches; (2) extending the framework to incorporate dual-polarization radar variables and high-resolution satellite precipitation retrievals (e.g., GPM IMERG); and (3) developing a real-time adaptive threshold updating system based on seasonal and climatological variations.

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