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Analysis of a Mountain Flood Disaster Caused by a Rainstorm in Datong, Qinghai Province on August 18, 2022 and Countermeasures

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Abstract In the early hours of August 18 in 2022, a mountain flood disaster occurred in Datong Hui and Tu Autonomous County, Xining City, Qinghai Province, resulting in 31 deaths. This typical incident of multiple casualties resulting from a mountain flood disaster caused by heavy precipitation. In this paper, the mountain flood disaster was analyzed from three aspects, the distribution of the observation station network, assessment of minute-level precipitation, and quantitative precipitation estimated by Xining radar data during August 17 – 18, 2022. It aims to identify the critical gap in comprehensive monitoring systems, and explore effective monitoring methods and estimation algorithms of minute-level quantitative precipitation. Moreover, subsequent defense countermeasures were proposed. These findings offer significant guidance for enhancing meteorological disaster prevention capabilities, strengthening the first line of defense in disaster prevention and mitigation, and supporting evidence-based decision-making for local governments and flood control departments.

Key words Datong; Qinghai; Mountain flood; Rainstorm

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Datong County (100°51′ – 101°56′ E, 36°43′ – 37°23′ N), located in the Hehuang Valley in the east of Qinghai Province, at the southern foot of the Qilian Mountains, and in the Beichuan River basin in the upper reaches of the Huangshui River, is in the transitional zone between the Qinghai – Xizang Plateau and the Loess Plateau[1]. The altitude ranges from 2 280 to 4 622 m. It is higher in the northwest and lower in the southeast, and has a plateau continental climate. The total area of the county is 3 090 km^2. It governs 9 towns (Qiaotou Town, Chengguan Town, Ta'er Town, Dongxia Town, Huangjiazhai Town, Changning Town, Jingyang Town, Duolin Town, and Xinzhuang Town) and 11 townships (Qinglin Township, Qingshan Township, Xunrang Township, Jile Township, Baoku Township, Xiegou Township, Liangjiao Township, Xianghua Tibetan Township, Hualin Township, Shuobei Tibetan Township, and Shishan Township), and has 26 ethnic groups such as Han nationality, Hui nationality, Tu nationality, Tibetan nationality and Mongol nationality. It has been twice named "the Hometown of Folk Art and Culture in China" by the Ministry of Culture[2]. According to the data from the seventh national census, the permanent resident population of Datong County was 403 368 as of 00:00 on November 1, 2020.

Datong County has a plateau continental climate. The annual average temperature is 4.9 ℃, and the extreme maximum temperature is 35.6 ℃, while the extreme minimum temperature is –26.1 ℃. The maximum depth of permafrost is 114 cm, and the maximum thickness of snow cover is 18 cm. The annual precipitation is 523.3 mm, and the number of precipitation days throughout a year is 168 d. The highest precipitation occurred in August, and the average precipitation is 115.1 mm. The extreme daily precipitation is 145.2 mm and appears on August 22, 2013; the second extreme daily precipitation was 68.9 mm, happening on August 2, 1967[3].

At 21:00 on August 17, 2022, precipitation occurred in Datong County, and was accompanied by thunderstorms, short-term heavy rainfall and other severe convective weather. A sudden rainstorm hit Qinglin Township and Qingshan Township under its jurisdiction at 22:25, and short-term heavy rainfall occurred from 22:00 to 23:00, with precipitation of 39.3 and 34.6 mm/h, respectively. The hourly rainfall intensity in Qinglin Township was the strongest in Datong County since 1984. The rainfall reached over 37.2 mm within 30 min, hitting a historical record. Sudden heavy rainfall triggered mountain floods and mudslides, causing rivers to change course and overflow. As a result, a total of 6 245 people, 1 517 households, 6 villages, and 2 towns were affected by the disaster, among which 975 households and 3 111 people were severely affected, and 31 people died[4].

In this paper, a mountain flood disaster caused by a rainstorm in Datong County during August 17 – 18, 2022 is analyzed from the aspects of observation station network distribution, minute-level precipitation assessment, and quantitative precipitation measurement using Xining radar. The study aims to identify the weaknesses in the meteorological departments' comprehensive observation station network and explore more effective monitoring methods and algorithms for estimating minute-level precipitation. Additionally, subsequent defense countermeasures were proposed.

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It has certain guiding significance for effectively enhancing the disaster prevention and mitigation capabilities of meteorological departments, giving full play to the role of the first line of defense in disaster prevention and mitigation, and providing effective decision-making information for local governments and flood control departments.

1 Data and methods

The main data used are as follows: minute-level observation data of precipitation from regional stations in Qinghai Province were provided by the Tianqing system of the Qinghai Meteorological Information Center; the 6-minute observation data of Xining radar was offered by the Xining Weather Radar Station of Qinghai Meteorological Observatory.

2 Distribution of the observation station network

The severely affected Qinglin Township and Qingshan Township are about 30 km away from northwest of Datong County. Qinglin Township borders Qingshan Township in the east, and the straight-line distance between the two townships is 5 km. As shown in Fig. 1, the terrain gradually rises from southeast to northwest. There are mostly high mountains in the upper reaches, and most monitoring stations of rainfall are distributed in the lower reaches. However, the box area in Fig. 1 means a blind spot for rainfall monitoring. From the perspective of topographic distribution, the precipitation in the blind spot for rainfall monitoring would converge downstream along the crisscrossing gullies and river valleys, which directly affected Qinglin Township and Qingshan Township. It can be clearly seen from the distribution of monitored lightning in Fig. 2 that during the period of heavy precipitation in the blind spot for rainfall monitoring, dense negative flashes were detected, indicating that heavy precipitation occurred in this area. However, due to the lack of monitoring stations, the precipitation data of this area were not obtained.

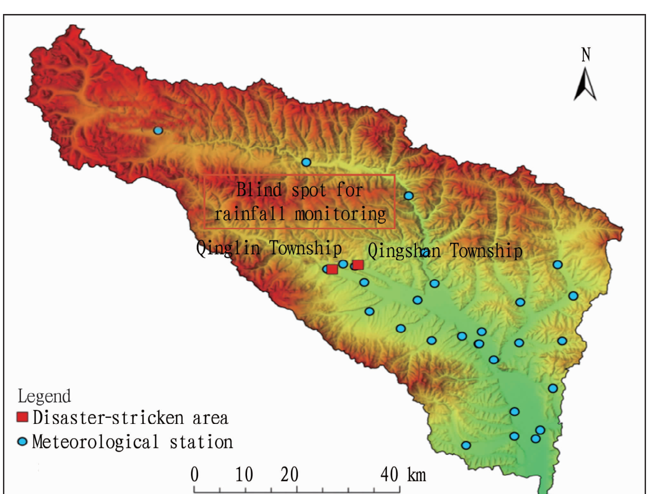


Fig. 1 Topography and distribution of meteorological stations in Qinglin Township and Qingshan Township, Datong County, Qinghai Province

It can be concluded that the monitoring stations were spare, so it was impossible to obtain the data of precipitation in the upper reaches of disaster-stricken areas. Therefore, it is extremely urgent to strengthen the construction of monitoring station networks in key areas.

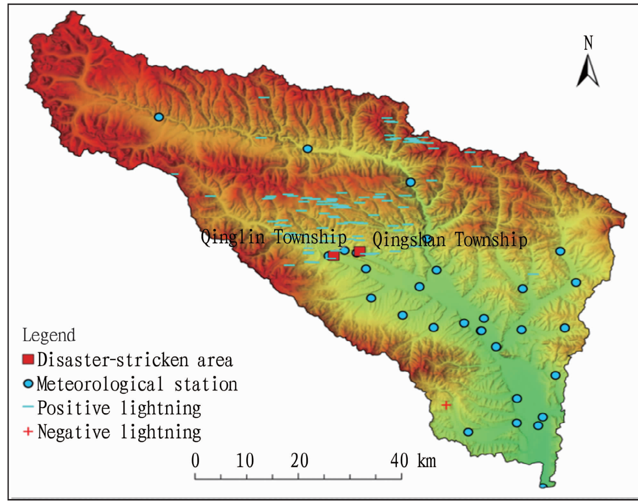
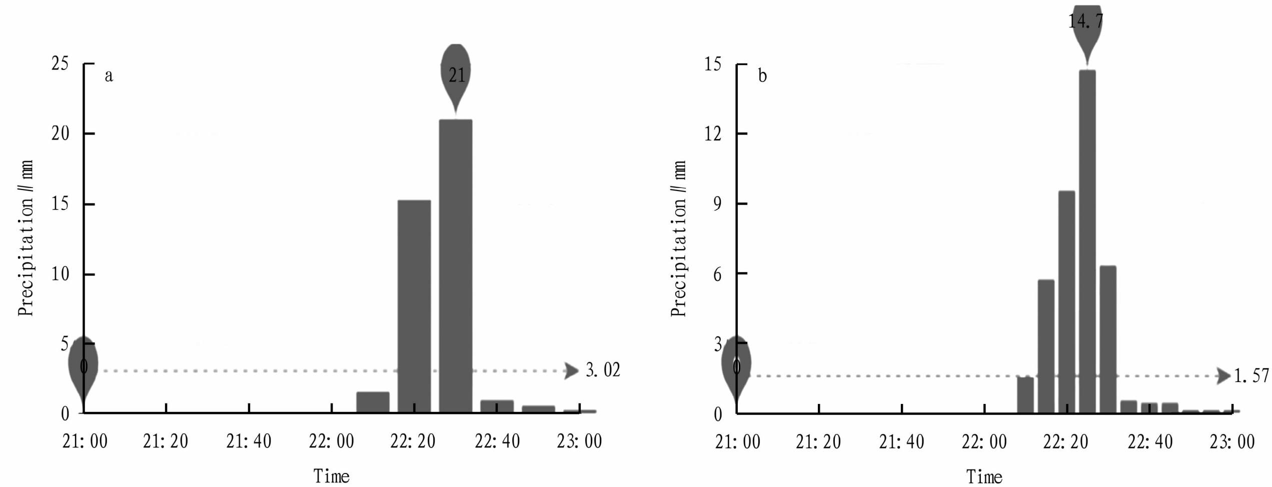


Fig. 2 Distribution of lightning monitoring from 21:50 to 22:20 on August 17, 2022

3 Analysis of data of minute-level precipitation

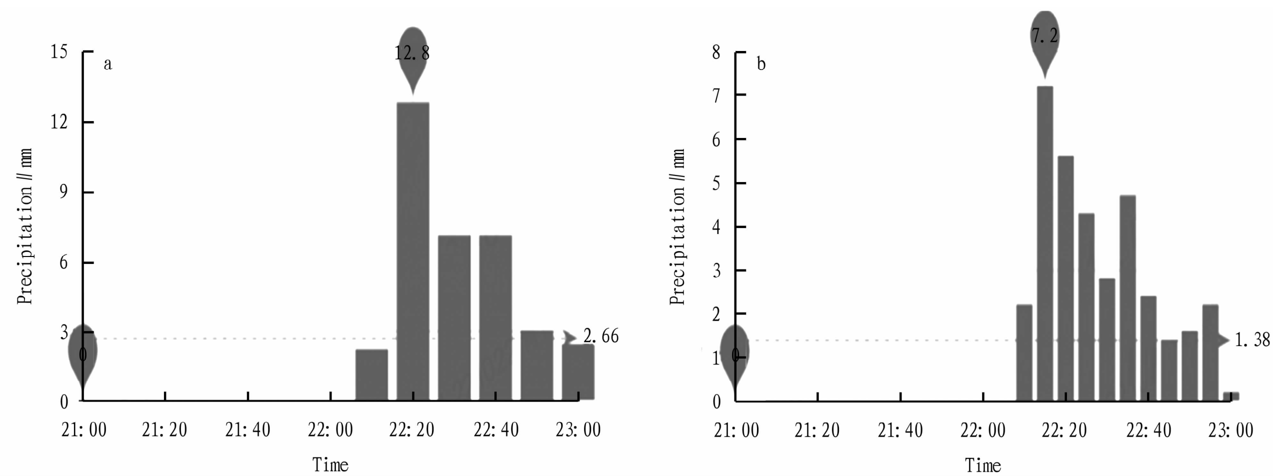
3.1 Qinglin Township The observation data of minute-level precipitation can reflect the intensity of precipitation at that time. Currently, the meteorological departments of Qinghai Province can obtain real-time precipitation data every 5 and 10 min, enabling them to promptly grasp the local precipitation situation and effectively improve near-term forecasting capabilities. Fig. 3 shows the minut-level data of precipitation observed by the precipitation station in Qinglin Township. It can be seen that the precipitation in Qinglin Township mainly occurred from 22:10 to 22:30. The maximum precipitation within 5 min was 14.7 mm (Fig. 3a), happening between 22:20 and 22:25. The maximum precipitation within 10 min was 21 mm (Fig. 3b). The time of the maximum precipitation at the minute level coincided. The hourly cumulative precipitation from 22:00 to 23:00 on August 17 was up to 39.3 mm.

3.2 Qingshan Township Fig. 4 presents the minut-level data of precipitation observed by the rainfall station in Qingshan Township. It can be seen that the precipitation in Qingshan Township was concentrated from 22:10 to 22:40. The maximum precipitation within 5 min was 7.2 mm, appearing between 22:10 and 22:15 (Fig. 4a). The maximum precipitation within 10 min was up to 12.8 mm, occurring between 22:10 and 22:20 (Fig. 4b). The hourly cumulative precipitation from 22:00 to 23:00 on August 17 reached 34.6 mm.



Note: a. 5 min; b. 10 min.

Fig. 3 Distribution of minute-level precipitation in Qinglin Township from 21:00 to 23:00 on August 17, 2022



Note: a. 5 min; b. 10 min.

Fig. 4 Distribution of minute-level precipitation in Qingshan Township from 21:00 to 23:00 on August 17, 2022

Based on the above analysis, it can be concluded that when the 5-minute and 10-minute precipitation approached or exceeded 10 mm, and the hourly precipitation reached or exceeded the standard of short-term heavy precipitation, the possibility of mountain flood disasters occurring in this area was relatively high. Relevant responsible units should be promptly and resolutely notified to pay close attention and to strengthen analysis and judgment.

4 Detailed analysis of radar data

Doppler weather radar is an active remote sensing device, and its observational data has high spatial and temporal resolution. It can not only detect the spatial structure of large-scale precipitation fields but also accurately track the real-time movement of heavy precipitation areas, thus becoming an important tool for monitoring and warning of heavy precipitation[5]. In 2019, with the strong support of the China Meteorological Administration, the Doppler weather radar Xining was successfully upgraded and renovated, playing an active role in weather monitoring in the eastern agricultural areas of Qinghai Province.

4.1 Analysis of the $Z-I$ relation of Precipitation The proximity estimation of rainfall intensity mainly relies on the empirical relation between the weather radar reflectivity factor and rainfall intensity, which is commonly referred to as $Z-I$ relation. The theoretical basis of the $Z-I$ relation of precipitation is that under certain assumed conditions, there exists a simple power-exponential relation between radar reflectivity factor Z and precipitation intensity I, namely $Z=AI^b$, where A and b are statistical empirical parameters. Based on this relation, precipitation can be directly inverted from the radar reflectivity factor. At present, the more commonly used $Z-I$ relational expressions of precipitation can be expressed as follows:

$$Z=200I^{1.6} \quad (1)$$

$$Z=300I^{1.4} \quad (2)$$

Among them, expression (1) is very close to the relational expression derived from theory, and is mostly used for the estimation of layered precipitation cloud clusters. Expression (2) is obtained from the statistics of summer deep convective precipitation in the southern region of the United States. It is the default relational expression of the precipitation inversion system for the operation of the WSR-88D radar service in the United States and the relational expression of the generalized application of its precipitation series algorithms. However, these typical $Z-I$ relational expressions are only applicable to the average situation.

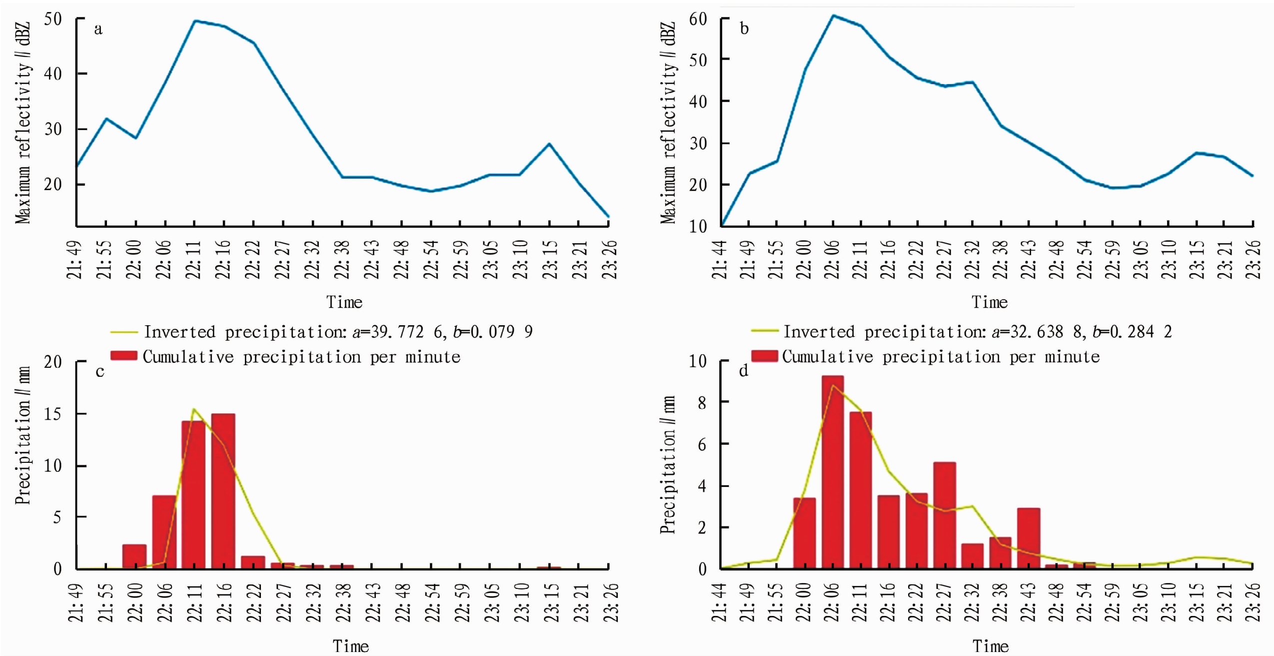


Fig. 5 Maximum reflectivity factor, actual precipitation and inverted precipitation in Qingshan Township (a, c) and Qinglin Township (b, d) from 21:00 to 23:00 on August 17, 2022

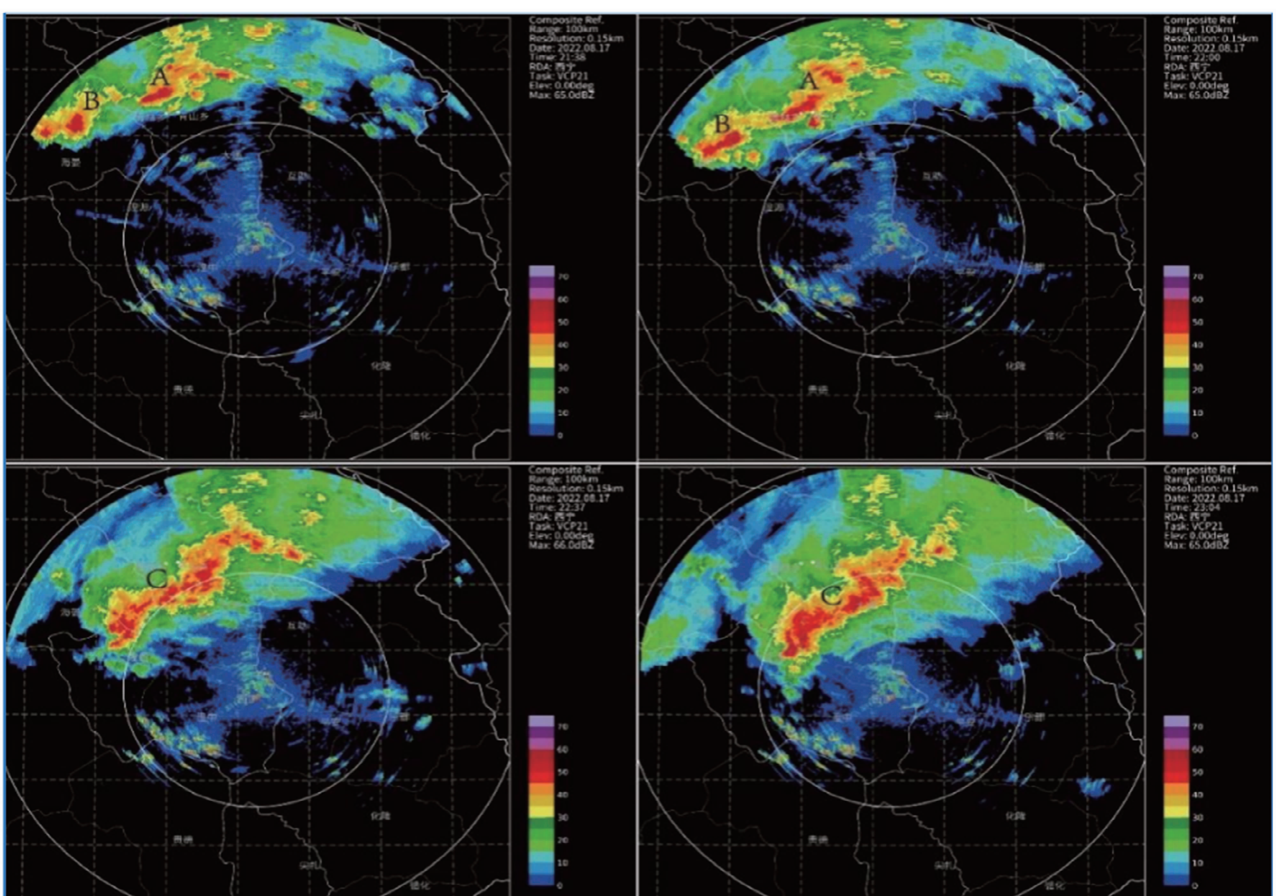


Fig. 6 Evolution of composite reflectivity detected by Xining radar from 21:38 to 23:04 on August 17, 2022

To effectively estimate the rainfall intensity of this precipitation, $Z-I$ relation was adopted to analyze the minute-level precipitation and reflectivity factor, and then appropriate coefficients A and b were calculated. The maximum reflectivity factor, actual minute-level precipitation and inverted precipitation in Qingshan Township and Qinglin Township are shown in Fig. 5. It can be seen that when coefficient A was between 32.7 and 39.8 and coefficient b was between 0.08 and 0.28, the inverted precipitation was most consistent with the actual precipitation, which has certain indicative significance for the judgment of nearby rainfall intensity.

Based on the above analysis, as well as the evaluated coefficients A (32.7 − 39.8) and b (0.08 − 0.28) by minute-level quantitative precipitation estimation, the expression of Z is as follows:

$$Z = (32.7 - 39.8)\ I^{0.08-0.28} \quad (3)$$

The above conclusion is merely drawn from one individual case. If it is to be applied in business, a large number of individual cases are still needed to support it.

4.2 Analysis of Xining radar Composite reflectivity factor can directly display the structure and shape of convective cloud clusters and the distribution of convective fields in severe convective weather. Based on the observation data of composite reflectivity by Doppler Weather Radar in Xining, at 21:00, a convective cloud cluster emerged in the northwest of Qinglin Township and Qingshan Township. It was mainly divided into two main echoes (A and B), and showed zonal distribution from northeast to southwest. The zonal strong echoes continuously moved southeastwards, developed and strengthened during this movement. At 21:38 (Fig. 6), the intensity in the echo center developed to 65 dBZ, and Qingshan Township and Qinglin Township were located to the southeast of echo A. At 21:49, echo A moved southeastwards into Qinglin Township to affect it. After 22:00, echo A was always located in Qingshan Township and Qinglin Township, lasting for 7 − 8 scans. Until 22:37, echo A merged with echo B to its southwest, and strengthened to form echo C. The intensity in the center increased to 66 dBZ. Qingshan Township was affected by echo C. At 23:04, echo C moved out of Qingshan Township, ending its impact on them. It can be seen that Qingshan Township and Qinglin Township were mainly affected by strong echo A, and the strong echo had undergone a process of intensification − merging − intensification in Qingshan Township and Qinglin Township, thus causing the continuous impact of heavy precipitation on the two places.

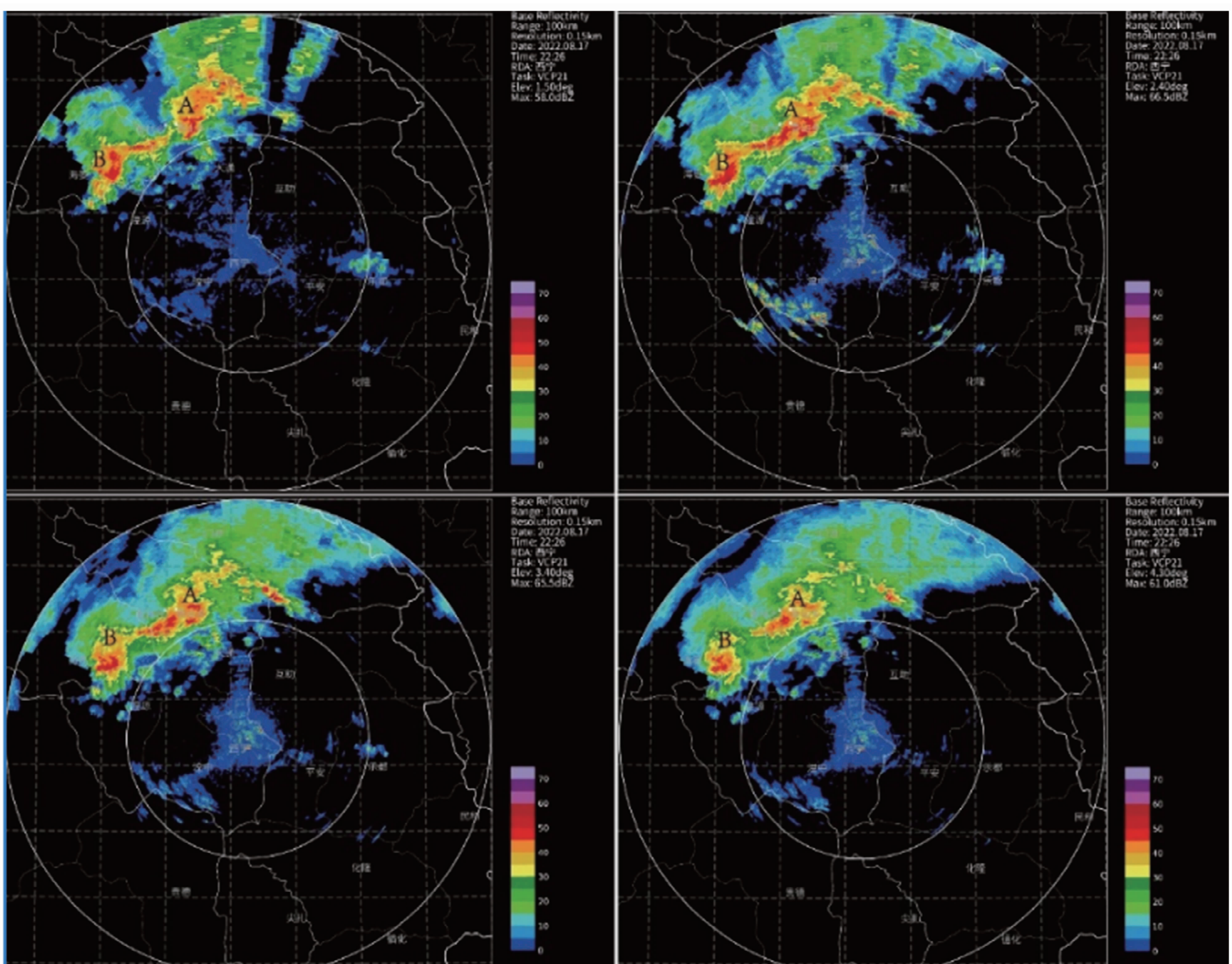


Fig. 7 Evolution of the basic reflectivity of Xining radar at different elevation angles at 22:48 on August 17, 2022

Based on the above analysis of composite reflectivity, it can be concluded that the intensity of echoes responsible for short-term heavy precipitation was at least 60 dBZ or higher, and the strong echoes persisted in the affected area for more than 30 min.

As shown in Fig. 7, at 22:26 on August 17, the reflectivity of echoes A and B was 40 – 50 dBZ when the elevation was 1.5°. At this height, the center of echo A was stronger, and its area was larger, with the central intensity of 58 dBZ. As the elevation was 2.4°, the influence of terrain at this height was not obvious, and a linear echo A running from northeast to southwest could be seen. The intensity of the echo near Qingshan Township and Qinglin Township was 66.5 dBZ. At an elevation of 3.4°, the shapes of echoes A and B were clear, and the maximum intensity was maintained at 65 dBZ. As the elevation increased to 4.3°, the area of echoes A and B was relatively small. However, it can be observed that the center of the strong echo A was located near Qingshan Township and Qinglin Township, and its intensity was 61 dBZ. Therefore, the optimal elevations for the analysis of basic reflectivity of Xining radar were 2.4° and 3.4°. At these elevations, the intensity and profile of the echoes could be clearly analyzed, and they were also reliable and genuine.

Fig. 8 shows the evolution of vertically integrated liquid water content (VIL) during the period of heavy precipitation from 22:00 to 23:00 on August 17, 2022. In actual radar observation, VIL has very good indicative significance in identifying strong water flow weather, and can play a very good role especially in identifying short-term heavy precipitation and other disastrous weather. According to the observation results of Xining Doppler Radar (Fig. 8), VIL was low before 22:00, only 0.5 kg/m^2. By 22:00, the maximum of VIL reached 16.7 kg/m^2 (Fig. 8a), within just one scan. At 22:10, the maximum was up to 26.4 kg/m^2 (Fig. 8b). Hereafter, VIL remained at around 20 kg/m^2 (Fig. 6b and Fig. 6c), and dropped sharply to below 5 kg/m^2 by 22:40. It can be seen that before the start of the short-term heavy precipitation, VIL increased sharply. Accordingly, the cloud body developed rapidly, and the intensity and height of the echoes within the cloud body rose rapidly. When heavy precipitation began, the intensity and height of the echoes reach their maximums, and VIL changed slightly. Later, as the release of precipitation potential, VIL had a significant decrease. During the short-term heavy precipitation, VIL suddenly increased, then maintained, and suddenly decreased, and the duration of its large value coincided with the occurrence period of the heavy precipitation.

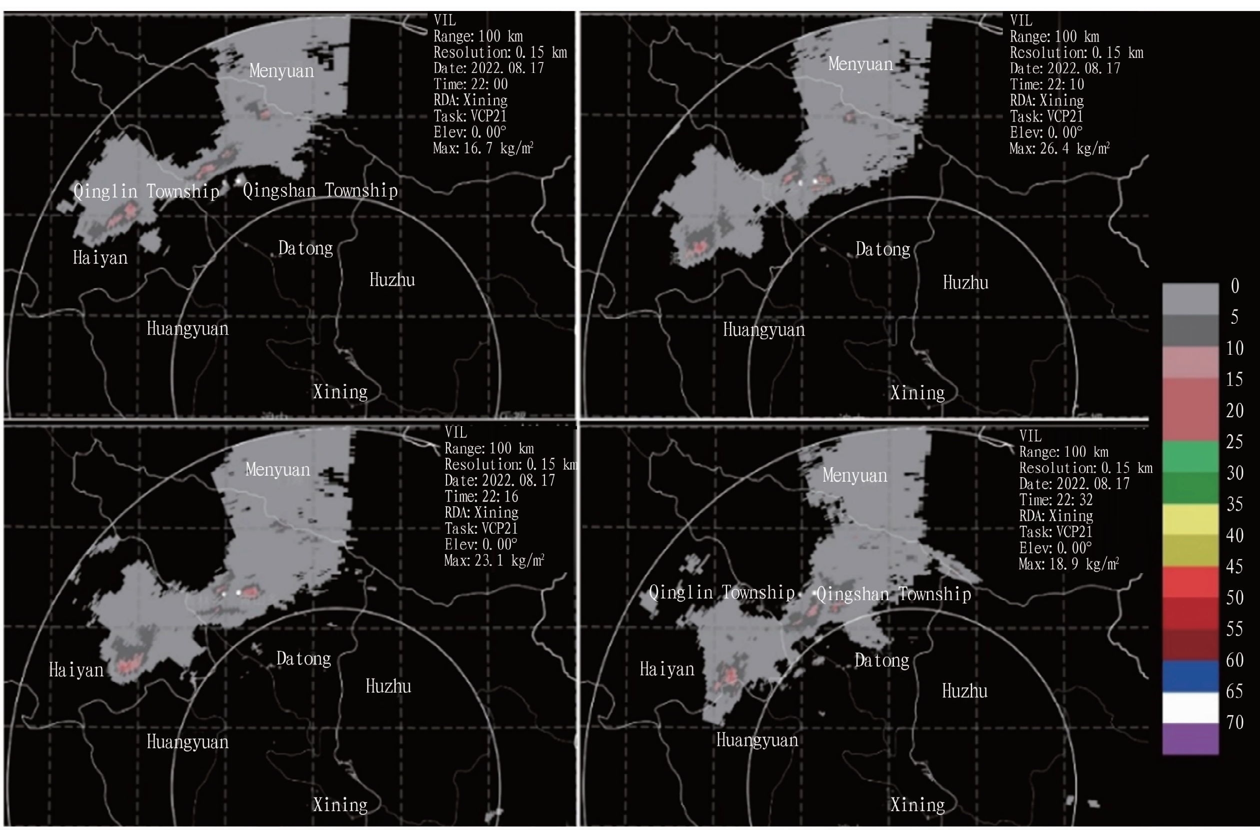


Fig. 8 Evolution of VIL during the heavy precipitation from 22:00 to 23:00 on August 17, 2022

5 Countermeasures and suggestions

Mountain flood disasters are highly sudden and difficult to prevent. Meteorological departments at all levels should adhere to the principles of putting people first and prioritizing prevention. They should carefully study the characteristics and patterns of mountain flood disasters, develop scientific and rational prevention and control strategies, schemes, and emergency response plans for defense, and implement measures to effectively guard against sudden natural disasters.

5.1 Strengthening the construction of the automatic meteorological observation station network Areas prone to major mountain floods should be classified as high-risk zones, and meteorological and hydrological observation stations should be estabished. Ground observation grids should be denser in the upper reaches of rivers where mountain floods are frequently triggered, enabling forecasters to obtain real-time rainfall data promptly.

5.2 Enhancing the capacity for precise monitoring, forecasting and early warning of sudden and local meteorological disasters Through new construction, relocation of stations, and upgrading of radars, it is necessary to address the issue of insufficient radar detection capabilities in eastern cities. Additionally, efforts should be made to further improve the accuracy of quantitative precipitation nowcasting by radar, to fully utilize all information dissemination channels for promoting the release of meteorological disaster warning information, and to maximize the effectiveness of the warning information message system.

5.3 Further improving the emergency response and coordination mechanism for meteorological disasters It is necessary to establish an emergency response system with meteorological disaster warnings as the foundation, fully implement the working mechanism of "internal response and external coordination", and promptly carry out coordinated call-and-response services when major meteorological risks occur. Meanwhile, the information sharing and joint consultation mechanism among departments should be strengthened to comprehensively assess the situation of disaster prevention and control.

6 Conclusions and discussion

(1) There was a significant blind spot in rainfall monitoring in the upper reaches of the disaster-stricken area. The terrain is higher in the northwest and lower in the southeast, and the river valley is narrow with a steep drop. As a result, local heavy precipitation and upstream mountain rainfall converged, leading to increased surface runoff and accumulation in the convergence area. This caused a sudden rise in river flow, triggering a mountain flood in a short period of time, and subsequently resulting in a mountain flood disaster.

(2) When 5-minute and 10-minute precipitation approaches or exceeds 10 mm, and hourly precipitation reaches or exceeds the standard for short-term heavy precipitation, the likelihood of a mountain flood disaster occurring in this area is relatively high. Relevant responsible units should be promptly and decisively notified to pay close attention and enhance analysis and judgment.

(3) The evaluated coefficients A and b for minute-level quantitative precipitation range from 32.7 to 39.8 and from 0.08 to 0.28. If these coefficients are to be used in operational applications, extensive validation using a large number of individual cases is still necessary.

(4) The intensity of echoes causing short-term heavy precipitation should be at least 60 dBZ or higher, and the strong echoes should remain in the disaster-stricken area for more than 30 min. The optimal elevation angles for analyzing the basic reflectivity of the radar are 2.4° and 3.4°. At these elevations, the intensity and profile of the echoes can be clearly observed, and the measurements are also reliable and genuine. During the short-term heavy precipitation, VIL suddenly increased, then remained stable, and finally declined. The heavy precipitation occurred during the maintenance stage of VIL.

(5) Against the backdrop of global warming, the precipitation in low-risk areas for mountain floods such as the arid regions of Northwest China and the Qinghai – Xizang Plateau has significantly increased, and the possibility of mountain floods or even extremely severe mountain floods in river channels has risen. The risk of repeated occurrence of mountain flood disasters in disaster-stricken areas remains high, and the defense situation remains complex and severe, so it is urgent to adopt multiple measures to enhance the awareness and ability of cadres and the public to prevent and respond to disaster risks.

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