Statistical Evaluation of the Effects of the 2024 Acoustic Rain Enhancement Experiments in Jimusaer County, Xinjiang (Final Printed Version)

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Abstract

Acoustic rainfall enhancement technology employs ground-based high-intensity sound sources to emit low-frequency acoustic waves into clouds, thereby accelerating cloud droplet collision-coalescence and enhancing precipitation. This approach is characterized by not occupying airspace, convenient operation start-up and shutdown, and low operating costs. It is suitable for long-term operations in arid and semi-arid regions and enables the joint utilization of atmospheric and surface water resources through regulation and storage in reservoirs. In this study, operational sites were established and observational equipment deployed in the Xidalongkou River Basin of Jimusar County, Changji Hui Autonomous Prefecture, Xinjiang, during May–August 2024, and acoustic rainfall enhancement contrast experiments were conducted, yielding a total of 13 valid operational days and 8 valid control days. Based on ground-based precipitation observations, an impact-area identification algorithm was developed on the basis of the double-ratio analysis method and the Mann–Whitney U test to conduct statistical analysis of the enhancement range and effect of the acoustic rainfall enhancement experiments. The results show that: (1) Acoustic operations modified the local spatial distribution of precipitation, with rainfall enhancement at the operation site and in the downwind area, and an effective impact area of 91 km^2. (2) The precipitation increase ratio within the impact area was 58%, with the Mann–Whitney U test indicating statistical significance (P-value = 0.008). (3) Across the 13 valid operational days, the accumulated rainfall enhancement depth reached 68.4 mm, corresponding to a volumetric rainfall increase of 6.22$\times10^{6}$ m^3, while the potential increase in precipitation during the experimental period was 8.21$\times10^{6}$ m^3. This study provides empirical support and technical references for the implementation of Xinjiang' s “water

augmentation" strategy; however, verification experiments on larger temporal and spatial scales and in-depth investigations into cloud microphysical processes are still required to further promote the operational application of acoustic rainfall enhancement technology.

Full Text

Statistical Analysis of 2024 Experimental Acoustic Rainfall Enhancement, Jimsar County, Xinjiang

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Abstract

Acoustic rainfall enhancement (ARE) technology employs ground-based high-intensity sound sources to emit low-frequency acoustic waves into atmospheric clouds, accelerating cloud droplet collision and coalescence to enhance precipitation. This technology offers several operational advantages, including no airspace occupation, flexible operational control, and low operational costs, making it particularly suitable for long-term operations in arid and semi-arid regions. Furthermore, it enables integrated utilization of atmospheric and surface water resources through reservoir storage. From May to August 2024, field experiments were conducted in the Xidalongkou River Basin, Jimsar County, Changji Hui Autonomous Prefecture, Xinjiang Uygur Autonomous Region, China. An operational site was established and observational instruments were deployed to conduct comparative ARE experiments. Using ground-based precipitation observations from 13 valid operational days and 8 valid control days, an impact area identification algorithm was developed based on the double-ratio method and Mann-Whitney U test to statistically analyze the spatial extent and effectiveness of ARE. The results are as follows: (1) Acoustic operations altered the local spatial distribution of rainfall, with enhanced precipitation observed at the sound emission site and downwind areas, yielding an effective impact area of 91 km^2. (2) The rainfall enhancement effect achieved statistical significance, with substantial augmentation observed. The Mann-Whitney U test yielded P-value = 0.008, confirming statistical significance. Within the impact area identified through double-ratio analysis, the rainfall enhancement ratio was 58%, corresponding to an enhanced rainfall depth of 68.4 mm and an enhanced rainfall volume of 6.22×10^6 m^3 during the 13 operational days. (3) The total augmentable rainfall volume during the experimental period was 8.21×10^6 m^3. This study provides empirical evidence and technical reference for implementing Xinjiang' s water augmentation strategy. However, operational application of this technology requires further validation at larger spatiotemporal scales and in-depth investigation of cloud microphysical processes.

Keywords: acoustic rainfall enhancement; statistical testing; double-ratio method; Ka-band cloud radar; semi-arid region

1 Introduction

Atmospheric water substance constitutes a critical component of Earth' s hydrosphere, existing primarily as water vapor that transforms into clouds and precipitation through condensation and deposition processes, ultimately forming utilizable surface water resources. From a utilization perspective, a portion of atmospheric water substance can be defined as atmospheric water resources. Research indicates that China possesses abundant atmospheric water resources, yet exhibits low natural conversion efficiency and limited artificial utilization technology, resulting in a low proportion converted to surface water resources. This challenge is particularly pronounced in northwestern arid and semi-arid regions. Constructing a new model of integrated atmospheric-surface water resource utilization represents a feasible approach to address water scarcity challenges. This involves two key aspects: first, implementing weather modification operations to improve precipitation conversion efficiency of atmospheric water resources within specific spatiotemporal ranges; and second, matching rainfall enhancement areas with surface water engineering facilities and water demand to achieve coupled regulation of atmospheric and surface water resources.

Acoustic rainfall enhancement represents an emerging technology for atmospheric water resource utilization. Its primary mechanism involves emitting high-intensity low-frequency acoustic waves into clouds, where mechanisms such as co-phase aggregation effects and acoustic wake effects intensify relative motion among cloud droplets, increase collision probability, accelerate particle growth, and ultimately enhance precipitation. Compared to traditional artificial rainfall enhancement using silver iodide nucleating agents, acoustic rainfall enhancement offers advantages including no airspace occupation, low operational threshold, cost-effectiveness, rapid responsiveness, and clearly defined impact areas, making it an effective approach for alleviating water shortages in arid and semi-arid regions.

Despite theoretical analyses, numerical simulations, and laboratory experiments having preliminarily validated the physical mechanisms of acoustic rainfall enhancement, practical application remains constrained by a critical bottleneck: how to demonstrate through field experiments that ground-based acoustic source performance meets rainfall enhancement requirements and to verify enhancement effects through rigorous testing. Due to substantial natural variability in cloud and precipitation processes, distinguishing artificial rainfall enhancement from natural precipitation remains challenging. The U.S. National Research Council stated in 2003 that "no scientific evidence exists that proves the efficacy of weather modification." With the extensive implementation of artificial rainfall enhancement operations, particularly the emergence of new technologies such as acoustic rainfall enhancement, ensuring scientific validity and effectiveness of impact assessments has become an urgent requirement.

Artificial rainfall enhancement evaluation primarily focuses on randomized experiments, addressing both statistical testing of rainfall data and physical interpretation of cloud-precipitation development processes. The U.S. Climax and Israeli Tuftedal experiments became classic cases due to their combination of statistical significance and clear physical mechanisms. French et al. provided compelling evidence for the complete microphysical process chain of orographic cloud seeding. Most studies emphasize statistical testing; for example, Tuftedal et al. employed the double-ratio method to evaluate long-term effects of the North Dakota Cloud Modification Project (NDCMP), demonstrating significant rainfall enhancement with an average increase of 24.5%. Randomized experiments at the Gutian Reservoir in Fujian indicated that silver iodide seeding could increase rainfall by 29.49%, with a distinct downwind tendency. Statistical assessments of artificial snow enhancement in Karamay, Xinjiang, showed increases of 16.59 mm, while winter snow enhancement in Altay region yielded increases of 20.80 mm.

In acoustic rainfall enhancement effect verification, previous studies have made limited progress. Tulaikova et al. observed through radar measurements that acoustic waves enhance cloud echo intensity. Pan et al. quantified changes in raindrop spectrum characteristics under acoustic intervention, specifically showing increased average droplet size and particle number concentration. Shi et al. constructed a multi-dimensional monitoring system in the Yellow River source region, revealing significant microphysical parameter responses during stratiform cloud precipitation processes under acoustic action. Wang et al. proposed precipitation duration as an indicator of acoustic rainfall enhancement potential and identified downwind migration patterns of precipitation centers. Yao et al. employed a combined physical-statistical testing method to demonstrate that acoustic intervention in Leizhou Peninsula experiments not only significantly enhanced rainfall intensity in downstream areas but also effectively extended the mature precipitation stage of operational units.

Beyond these limited studies, current statistical testing research on acoustic rainfall enhancement effects remains scarce. There is an urgent need to establish a statistical testing methodology framework aligned with acoustic rainfall enhancement technology characteristics and to conduct application validation using larger sample sizes and higher-density precipitation observations. This study utilizes acoustic rainfall enhancement experiments conducted in Jimsar County, Xinjiang from May to August 2024 and associated ground-based rainfall observation data. Based on the double-ratio method and Mann-Whitney U test, an impact area identification algorithm was designed to quantitatively analyze rainfall enhancement extent and effects, aiming to enhance assessment accuracy and provide methodological support for establishing standardized acoustic rainfall enhancement effect evaluation protocols.

1.1 Study Area Overview

The acoustic rainfall enhancement experimental base is located in the southwestern part of Jimsar County, Changji Hui Autonomous Prefecture, Xinjiang, upstream of the Xidalongkou Reservoir, with base coordinates of 43.91°N, 88.74°E and an elevation of 1500 m (Figure 1). The Xidalongkou River, situated on the northern foothills of the Tianshan Mountains, is a typical piedmont river with a watershed area of approximately 420 km^2 and multi-year average runoff of $6.99 \times 10^8\ \text{m}^3$. The region features a mid-temperate continental arid climate with annual precipitation of 505.2 mm, concentrated from May to August (accounting for 70% of annual precipitation). Precipitation exhibits strong spatiotemporal heterogeneity, with evaporation capacity far exceeding precipitation, creating prominent water resource supply-demand contradictions. The Xidalongkou Reservoir, serving as the primary water source for downstream agricultural irrigation, faces severe water supply pressure during spring sowing and summer crop growth critical periods, necessitating artificial rainfall enhancement to increase water resource replenishment.

Based on acoustic wave propagation characteristics in the atmosphere and atmospheric water resource utilization requirements, the Xidalongkou River Basin offers unique advantages for acoustic rainfall enhancement experiments: (1) The base is backed by the Tianshan Mountains in a typical piedmont windward slope position, conducive to water vapor uplift and cloud system development; (2) Higher ground elevation combined with lower cloud base height provides favorable conditions for reducing geometric diffusion attenuation of acoustic propagation, resulting in higher sound pressure levels reaching cloud layers; (3) The experimental area is remote and sparsely populated, avoiding noise impacts and facilitating long-term experiments; (4) The 试验区 is located upstream of the reservoir, with primary rainfall enhancement areas within the reservoir catchment, allowing enhanced rainfall to convert into inflow. Notably, several traditional artificial rainfall enhancement sites are deployed along the northern Tianshan foothills. This experimental base is located over 30 km east of the Jimsar County Ergong River weather modification site, ensuring independence of acoustic rainfall enhancement effect assessment by excluding operational days from the Ergong River site during subsequent data preprocessing.

1.2 Operational and Observational Equipment

A complete operational and integrated observation system was deployed at the acoustic rainfall enhancement experimental base, comprising three components: acoustic emission devices, cloud microphysical detection equipment, and a ground precipitation monitoring network. The acoustic emission system employs a rotary siren resonant horn sound generation system (Figure 1), consisting of an integrated controller, rotary siren generator, resonant horn, and air compressor. The core technology utilizes acoustic resonance theory to convert jet shock waves into single-frequency high-intensity sound waves at specific frequencies, forming a conical acoustic beam with clear directivity through the horn' s radiation effect. Measured data indicate that under stable operating conditions, the sound pressure level at the horn outlet reaches 149.6 dB@125 Hz, ensuring effective concentration and propagation of acoustic energy.

Cloud microphysical detection relies on a Ka-band vertical profiling cloud radar with 1-minute temporal resolution, operating frequency of 35 GHz, spatial resolution of 20 m, and maximum detection height of 20 km. By obtaining multi-dimensional parameters including reflectivity factor (Z), radial Doppler velocity (V), velocity spectrum width (W), and linear depolarization ratio (LDR), the system precisely monitors cloud structure and retrieves microphysical characteristics of cloud and precipitation particles, providing critical basis for target cloud screening, operational parameter optimization, and effect evaluation.

The ground rainfall monitoring network consists of 23 tipping-bucket self-recording rain gauges (referred to as RG) deployed within a 10 km radius centered on the acoustic emission point (Figure 1). The rain gauges feature a resolution of 0.1 mm, orifice diameter of 200 mm, and data recording interval of 1 minute. This high-density observation network accurately captures spatiotemporal precipitation distribution characteristics, providing reliable ground data for quantitative assessment of rainfall enhancement effects.

1.3 Comparative Experimental Design

Currently, the spatial impact range of acoustic rainfall enhancement operations and the duration of catalytic effects represent key scientific questions constraining effect evaluation. Traditional artificial rainfall enhancement statistical testing typically designates a downwind range from the operational area as the target zone, but accurately defining this range remains challenging in practice. Existing studies indicate that fixed acoustic emission devices affect approximately 10 km, with precipitation enhancement effects forming a significant core area near the emission point and decaying exponentially with radial distance. However, existing meteorological observation networks exhibit significant spatial coverage deficiencies in remote mountainous areas, making it difficult to meet synchronous observation requirements for target and control areas. Therefore, dense rainfall monitoring through self-established networks is necessary.

This study employs a fixed operational date comparative experimental protocol, scheduling experiments based on odd/even calendar dates to construct datasets for operational days and control days. Specifically, under precipitation-suitable conditions, acoustic interventions are implemented on odd-numbered dates (operational days) while natural-state observations are maintained on even-numbered dates (control days). Acoustic equipment activation criteria include: (1) Cloud systems over the operational area being stratiform, cumuliform, or stratocumulus; (2) Cloud base height < 2 km; (3) Cloud thickness ≥ 1 km; (4) Sky cloud coverage $> 80\%$; (5) Sustained cloud core radar reflectivity $>$ 5 dBZ. Deactivation criteria include: (1) Cloud core radar reflectivity < 5 dBZ; (2) Sustained rainfall intensity < 0.1 $\mathrm{mm} \cdot \mathrm{min}^{-1}$ for 10 minutes.

2 Data and Methods

2.1 Data Preprocessing

This study is based on high-density rainfall monitoring network data (May–August 2024) from the Jimsar County acoustic rainfall enhancement experimental base. To ensure data quality, the following quality control procedures were implemented: (1) All stations underwent weekly maintenance by trained personnel, including data collection, rain gauge cleaning, and calibration; (2) Abnormal values caused by instrument failure or human interference were removed based on maintenance records, with missing data filled using synchronous data from the nearest station; (3) Invalid rainfall days with daily precipitation < 0.2 mm were excluded, with remaining qualifying days classified as valid rainfall days; (4) Among valid rainfall days, dates when the Ergong River weather modification site conducted operations were further excluded to ensure data truly reflected natural conditions and acoustic-only influences.

During the May–August 2024 acoustic rainfall enhancement experiment in Jimsar County, 21 valid precipitation days were obtained, including 13 operational days and 8 control days. Notably, one planned operation on August 2 was not conducted due to equipment failure and was therefore included in control day statistics. A total of 19 acoustic operations were performed during the 13 operational days, with cumulative duration of 61.6 hours. Specific operational parameters, weather conditions, and rainfall at the acoustic emission point for each operation are detailed in Table 1. Figure 2 shows rainfall amount and intensity distributions for valid rainfall days during the experimental period. Daily rainfall amounts varied significantly, ranging from 0.24 mm to 112.9 mm, with regional average daily rainfall of 22 mm and maximum hourly intensity of 37 $\mathrm{mm} \cdot \mathrm{h}^{-1}$, highlighting strong precipitation variability in semi-arid regions. Average daily rainfall (23.7 mm) and intensity (4.4 $\mathrm{mm} \cdot \mathrm{h}^{-1}$) on operational days were 3.9 and 4.0 times those on control days (6.1 mm and 1.1 $\mathrm{mm} \cdot \mathrm{h}^{-1}$), respectively, indicating substantially greater precipitation during acoustic operations. However, sample grouping bias cannot be excluded and requires subsequent methods to assess actual acoustic rainfall enhancement effects.

2.1.1 Double-Ratio Method The double-ratio method is a widely adopted statistical approach in weather modification effect evaluation. The method' s core principle involves establishing a baseline precipitation ratio (natural single ratio) between impact and control areas using non-operational period data, then assessing enhancement effects by comparing observed ratios during operational periods against this baseline. This design effectively eliminates natural climate variability common to both areas. The method is based on an important climatic assumption: precipitation spatial correlation between impact and control areas remains stable across study periods, i.e., regional climate characteristics undergo no systematic changes. The technical methodology is as follows:

Using daily precipitation as a time period, calculate the regional average rainfall collected by all rain gauges in the target area (R_{target}) and control area ($R_{control}$) for each period, where n represents the number of effective rain gauge stations in the region.

For statistical testing, the precipitation ratio serves as the statistical variable. First, calculate spatial single ratios for each period (e.g., daily). The single ratio SR_i for operational period time i is calculated as:

$$SR_i = \frac{R_{target,i}}{R_{control,i}}$$

where $R_{target,i}$ is the average rainfall in the impact area during operational period i, and $R_{control,i}$ is the average rainfall in the control area during operational period i.

The single ratio $SR_{n,j}$ for control period time j is calculated as:

$$SR_{n,j} = \frac{R_{n,target,j}}{R_{n,control,j}}$$

where $R_{n,target,j}$ is the average rainfall in the target area during non-operational period j, and $R_{n,control,j}$ is the average rainfall in the control area during non-operational period j.

The double ratio DR across the entire statistical period is calculated as:

$$DR = \frac{\frac{1}{m}\sum_{i=1}^{m} SR_i}{\frac{1}{n}\sum_{j=1}^{n} SR_{n,j}}$$

where m is the number of periods in the operational period and n is the number of periods in the non-operational period. When $DR = 1$, no rainfall enhancement effect exists; when $DR > 1$, rainfall enhancement effects are present, with the enhancement ratio calculated as:

$$\text{Enhancement Ratio} = (DR - 1) \times 100\%$$

2.1.2 Mann-Whitney U Test The Mann-Whitney U test is a non-parametric method used as an alternative to independent samples t-tests for non-normally distributed data, capable of determining whether two independent samples originate from populations with identical distributions. This study constructs two comparison datasets: single ratios between experimental and control areas during operational days (SR_{test}), and single ratios between experimental and control areas during control days ($SR_{contrast}$). Test result interpretation follows these principles: when the test P-value is less than the preset significance level α (typically 0.05), the null hypothesis is rejected, indicating statistically significant differences between the two datasets; conversely, the null hypothesis is accepted, suggesting statistical homogeneity between datasets.

For statistical testing, this study employs one-tailed statistical tests for specific target-control area combinations. The method determines statistical inference by assessing whether the distribution’ s critical region exceeds (or falls below) specific values. For instance, when the double ratio exceeds 1, it suggests potential precipitation increase effects from acoustic rainfall enhancement. To verify significance of double-ratio results, the following hypothesis testing framework is established: the null hypothesis (H_0) states “experimental and control group samples originate from the same population (i.e., no significant acoustic rainfall enhancement effect),” while the alternative hypothesis (H_1) states “the two groups originate from different populations (significant differences exist).”

2.1.3 Delineation of Impact and Control Areas Figure 3 illustrates the dynamic selection process for acoustic rainfall enhancement impact areas, determined according to the following principles: First, the initial impact area must include the rain gauge site at the acoustic emission point. Second, using the emission point as the center, the Thiessen polygon expansion method is employed to gradually incorporate surrounding rain gauge stations. During expansion, if adding a new gauge station increases double-ratio test result significance (P-value decreases), the station is included in the impact area; conversely, if it decreases significance (P-value increases), the station is assigned to the control area. Through this iterative process, when the P-value reaches a global minimum, the delineated area is defined as the most definitive impact area. To ensure area continuity, newly added stations are limited to those adjacent to the current impact area (as numbered sequentially in Figure 3), and connection lines of impact area rain gauge stations cannot enclose control area stations. Additionally, stations not selected after each double-ratio test can re-enter subsequent screening, ensuring algorithm optimality.

2.1.4 Quantitative Metrics for Rainfall Enhancement Effects To quantitatively assess actual acoustic rainfall enhancement effects, a rainfall enhancement effect quantification system was established based on double-ratio analysis results, comprising three core metrics: enhanced rainfall depth, enhanced rainfall volume, and augmentable rainfall volume.

Enhanced rainfall depth represents rainfall increase expressed in depth units (mm). Since the observed average cumulative rainfall in the impact area during operational days ($R_{target,test}$) includes both natural precipitation and acoustic enhancement, and the denominator of the enhancement ratio (Δ) represents natural rainfall, the acoustic-induced rainfall increase can be separated from total rainfall. Therefore, enhanced rainfall depth ΔR_{target} is calculated as:

$$\Delta R_{target} = \Delta \times R_{target,test}$$

Enhanced rainfall volume represents the rainfall increase expressed in volumetric units (m^3) resulting from acoustic effects. Based on the determined enhanced rainfall depth Δ and impact area size S, the enhanced rainfall volume V is calculated as:

$$V = \Delta \times S$$

Augmentable rainfall volume refers to the total rainfall increase achievable in the impact area under known weather conditions if acoustic operations were applied to all rainfall events, comprising both actual enhancement achieved during operational days and potential enhancement achievable during control days. Augmentable rainfall volume is calculated separately from enhanced rainfall depth and impact area using:

$$V_{augmentable} = \Delta \times (R_{target,test} + R_{target,contrast})$$

where $R_{target,contrast}$ is the measured average cumulative rainfall in the impact area during control days.

3 Results

3.1 Spatial Distribution of Rainfall Comparison

Figure 4 shows the spatial distribution of cumulative ground rainfall for valid operational days and control days. Control day cumulative rainfall exhibits an overall south-high, north-low distribution pattern (Figure 4a), consistent with the topographic characteristics of higher southern terrain. The three southernmost stations (Nos. 21, 22, and 23) recorded 64.9 mm, 72.7 mm, and 67.6 mm, respectively. Although macro-scale distribution gradients persist, a significant high-value zone emerges around Station No. 1 (the acoustic emission point) during operational days (Figure 4b), with cumulative rainfall reaching 307.8 mm, 293.1 mm, and 286.4 mm at Stations 1, 2, and 3, respectively. This characteristic results from two factors: (1) vertically emitted acoustic waves produce the strongest local effects, and (2) acoustically-affected clouds continue moving downwind. Consequently, rainfall increases both locally at the acoustic emission point and in downwind areas, consistent with findings from Shi et al. and Yao et al.

Whether the high rainfall zone observed near the acoustic emission point originates from acoustic effects constitutes the core research question. Figure 5 displays rainfall spatial distributions for the 13 valid operational days. Notably, 5 operational days (June 15, 18, 22, July 19, and August 1) exhibited significant high-value zones at the acoustic emission point and adjacent areas, with spatial distribution patterns clearly associated with acoustic operations. These dates corresponded to operation durations exceeding 200 minutes and cloud systems encompassing both stratiform and convective clouds, suggesting that operation duration and cloud type may be key factors for acoustic effectiveness. Four operational days (June 16, 23, July 11, and 26) observed high-value rainfall zones along the Xidalongkou River valley upstream of the acoustic emission point, likely resulting from combined topographic effects and downwind acoustic influence. Rainfall high-value zones on remaining operational days were more scattered. Comprehensive analysis indicates that under suitable weather conditions and sufficient operation duration, acoustic operations can produce identifiable impacts on rainfall distribution patterns, though specific effects require further statistical verification.

3.2 Double-Ratio Analysis of Rainfall Enhancement Effects

The observed rainfall spatial distribution patterns indicate that acoustic intervention produces substantive macro-scale impacts on local cloud-rainfall processes, causing increased rainfall at the acoustic emission point and downwind areas. To quantitatively assess the impact range and enhancement ratio of acoustic rainfall enhancement, different impact area extents were delineated by gradually expanding outward from Station No. 1 (acoustic emission point) while establishing corresponding control areas. Based on Equation (3), double-ratio calculations and Mann-Whitney U tests were performed on daily average rainfall single-ratio sequences for operational and control days across these two areas.

Figure 6 shows the process of gradually incorporating rain gauge observation points. When the double ratio (DR) increases and statistical test P-values continuously decrease, it indicates that newly added gauge stations improve confidence in rainfall enhancement effects of the impact area relative to the control area, suggesting these points lie within the effective acoustic rainfall enhancement impact range. When the impact area includes 10 stations (Nos. 1-10), the double ratio between impact and control areas reaches its peak ($DR = 1.58$) and the P-value shows its minimum ($P = 0.008$). The area represented by these 10 stations is defined as the most definitive acoustic rainfall enhancement impact area, with remaining stations defined as the control area.

Statistical analysis of rainfall characteristics in the most definitive impact and control areas reveals that average daily rainfall in the most definitive impact area during operational days was 14.28 mm, while control area average daily rainfall was 5.56 mm. According to Equation (4), the operational day SR_{test} is 2.57. During control days, average daily rainfall in the most definitive impact area was 4.65 mm and control area average daily rainfall was 4.65 mm. According to Equation (5), control day $SR_{contrast}$ is 1.00. Using Equation (6), $DR = 2.57$ and the enhancement ratio is 58%.

3.3 Analysis of Rainfall Enhancement Range and Amount

The Thiessen polygon spatial segmentation method was used to quantify the acoustic rainfall enhancement impact area range. First, the control unit area for each observation point was calculated. When observation points near the rainfall observation area boundary were incorporated into the impact area, Thiessen polygons became difficult to close, requiring mirror completion to estimate control areas for such stations to avoid overestimation.

Figure 7 shows the area delineated by red polygons as the most definitive impact area for the Jimsar County acoustic rainfall enhancement experiment, covering 91 km^2. The most definitive impact area centers on the acoustic emission point, primarily located on the piedmont windward slope, with maximum influence distance reaching 10 km from the acoustic emission point. This spatial distribution characteristic is closely related to typical summer water vapor transport pathways in Xinjiang: under the influence of westerly circulation, precipitation cloud systems in the experimental area primarily move from west to east.

Based on the most definitive impact area range, acoustic rainfall enhancement amounts were calculated. During the experimental period, the most definitive impact area' s average cumulative rainfall was 186.3 mm. Using the enhancement ratio of 58% ($\Delta = 0.58$) determined through double-ratio analysis, the enhanced rainfall depth was calculated as 68.4 mm. Combining this with the most definitive impact area size $S = 91$ km^2, the experimental period enhanced rainfall volume was calculated as 6.22×10^6 m^3 using Equation (8). Further considering control day rainfall amounts, the augmentable rainfall volume for the entire experimental period was calculated as 8.21×10^6 m^3 using Equation (9).

Figure 8 displays daily rainfall in the acoustic impact area for operational and control days, with operational days distinguishing between natural rainfall and enhanced rainfall depth, and control days showing both measured natural rainfall and augmentable rainfall. All operational days recorded varying degrees of enhancement effects, with June 18 showing the most pronounced effect. This date coincided with a sustained heavy rainfall process, with an enhancement depth of 28.9 mm, 2.6 times the natural rainfall amount. Analysis reveals that when natural rainfall exceeds 5 $\mathrm{mm \cdot d^{-1}}$, enhancement depths are generally substantial, indicating that sufficient water vapor supply and sustained rainfall processes are key factors ensuring acoustic rainfall enhancement effectiveness and benefits.

3.4 Single-Point Rainfall Enhancement Effect Verification

The above analysis demonstrates that acoustic rainfall enhancement technology has a clearly defined impact range, is suitable for fixed-point long-term operations, can be synergistically deployed with surface water facilities, and enables coupled atmospheric-surface water resource utilization, providing a new technical approach for water resource regulation in arid and semi-arid regions. The impact area identification algorithm established in this study based on double-ratio analysis and Mann-Whitney U testing provides a methodological framework for quantitative assessment of acoustic rainfall enhancement effects. However, limitations remain, including small sample sizes and lack of physical testing of cloud-precipitation processes. Before operational application, further validation of acoustic rainfall enhancement effects at larger spatiotemporal scales and cost-benefit analysis are still needed to support practical water resource management applications.

To further validate single-point acoustic rainfall enhancement effects on the basis of previously identified acoustic-unaffected control areas, the acoustic emission point was used as an example for additional testing and comparison with the most definitive impact area results (Table 2). Results show that the acoustic emission point' s enhancement ratio is 153.7%, with Mann-Whitney U test P-value = 0.013, demonstrating extremely strong local rainfall enhancement effects and indicating that vertically emitted acoustic waves produce the strongest enhancement at the action origin. Simultaneously, the acoustic source exhibits a "point-source intensification, regional stabilization" spatial distribution characteristic. Comparative analysis shows that under natural conditions, the experimental area experiences relatively low precipitation, which is significantly increased during acoustic operations, achieving a transformation from a relatively low-rainfall area to an enhanced-rainfall area.

4 Conclusions

As an emerging weather modification approach, acoustic rainfall enhancement technology has demonstrated application potential in atmospheric water resource utilization. This study established an operational site and observational instruments in the Xidalongkou River Basin, Jimsar County from May to August 2024 to conduct comparative acoustic rainfall enhancement experiments. Statistical analysis was performed using rainfall data from 13 valid operational days and 8 valid control days, yielding the following conclusions:

(1) Acoustic operations altered local precipitation spatial distribution patterns. Observations revealed rainfall enhancement around the acoustic emission point and downwind areas, with a statistically determined impact area of 91 km^2.

(2) Acoustic rainfall enhancement effects achieved statistical significance with substantial augmentation. The Mann-Whitney U test yielded P-value = 0.008, confirming statistical significance. Within the impact area identified through double-ratio analysis, the rainfall enhancement ratio was 58%, corresponding to an enhanced rainfall depth of 68.4 mm, enhanced rainfall volume of 6.22×10^6 m^3, and total augmentable rainfall volume of 8.21×10^6 m^3.

(3) Acoustic rainfall enhancement exhibits a "point-source intensification, regional stabilization" spatial distribution characteristic. The operational point shows an enhancement ratio of 153.7%, demonstrating extremely strong local rainfall enhancement effects. Comparative analysis reveals that under natural conditions, the experimental area experiences relatively low precipitation, which is significantly increased during acoustic operations, achieving a transformation from a relatively low-rainfall area to an enhanced-rainfall area.

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Note: Figure translations are in progress. See original paper for figures.