Postprint: Effectiveness Analysis of Warm-Season Artificial Precipitation Enhancement Operations in the Bayinbuluke Mountains Based on the Budyko Model

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Abstract

As a commonly used indicator for artificial water augmentation effect analysis, precipitation is influenced by geographical, economic, and technical factors, often resulting in a limited number of representative data stations available for research and analysis, which to some extent affects the accuracy of regional effect verification. To address this issue, based on daily meteorological data from the Bayanbulak Meteorological Station and monthly runoff data from the Dashankou Hydrological Station in the upper reaches of the Kaidu River from May to September during 1973-2018, a runoff simulation equation was constructed using the Budyko model. Statistical methods including sequential test, unpaired rank-sum test, and t-test were employed to explore the differences in effect verification of artificial water augmentation operations using different statistical indicators during the warm season in this region. The results show that: (1) The runoff derived from the Budyko model and precipitation exhibit not only an extremely high correlation (R^2=0.9971, $P<0.001$) but also consistent rate and trend changes, indicating that simulated runoff can not only accurately reflect precipitation variation trends but also represent the influence of precipitation on runoff. (2) Using measured runoff, simulated runoff, and precipitation as statistical variables, unpaired rank-sum test and t-test analysis revealed significant increases in precipitation and runoff after artificial water augmentation operations ($P<0.02$). (3) Precipitation serves as the statistical indicator with the best test power; after artificial water augmentation operations, only an 11.59% increase is needed to significantly detect the effect. The test power value of simulated runoff is 3.72% lower than that of measured runoff, indicating an improvement in test power. (4) Selecting a 90% confidence interval at the statistical significance level, it was found that during the operation period (1994-2018) compared to the historical period (1973-1993), the absolute

increase in warm-season monthly average precipitation was 5.38 mm, with a relative increase rate of 12.05%; the absolute increase in simulated runoff was 4.53 $m^3 \cdot s^{-1}$, with a relative increase rate of 14.7%; and the absolute increase in measured runoff was 28.48 $m^3 \cdot s^{-1}$, with a relative increase rate of 18.48%, demonstrating that the artificial water augmentation operations in the Bayanbulak mountainous area during the warm season have achieved significant effects.

Full Text

Effect Analysis of Warm-Season Artificial Precipitation Enhancement in the Bayanbulak Mountain Area Based on the Budyko Model

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Abstract

Precipitation serves as a common indicator for evaluating artificial precipitation enhancement effects, yet its utility is constrained by geographical, economic, and technical factors that often limit the number of representative data stations available for analysis, thereby compromising regional assessment accuracy. To address this limitation, this study utilized daily meteorological data from the Bayanbulak weather station and monthly runoff data from the Dashankou hydrological station (located at the headwaters of the Kaidu River) during the warm season (May–September) from 1973 to 2018. A runoff simulation equation was constructed using the Budyko model, and statistical methods including sequence testing, unpaired rank sum testing, and t-testing were employed to examine differences in effectiveness verification using various statistical indicators for warm-season artificial precipitation enhancement operations in this region. The results demonstrate: (1) Runoff derived from the Budyko model exhibits an extremely high correlation with precipitation ($R^2 = 0.9971$, $P < 0.001$), with consistent rates and trends of change, indicating that simulated runoff not only accurately reflects precipitation variation patterns but also quantifies precipitation' s influence on runoff. (2) When measured runoff, simulated runoff, and precipitation were used as statistical variables in unpaired rank sum and t-tests, both precipitation and runoff showed significant increases ($P < 0.02$) following artificial precipitation enhancement operations. (3) Precipitation proved to be the most effective statistical indicator, requiring only an 11.59% increase to detect significant effects, while the test efficiency of simulated runoff was 3.72% lower than that of measured runoff, demonstrating improved verification efficacy. (4) Using a 90% confidence interval at the 0.05 significance level, the absolute increase in warm-season monthly average precipitation during the operation period (1994–2018) was 5.38 mm, representing a relative increase of 12.05%; the absolute increase in measured runoff was 28.48 $m^3 \cdot s^{-1}$ (18.48%

relative increase), while simulated runoff increased by 4.53 $m^3 \cdot s^{-1}$ (14.7% relative increase). These findings indicate that warm-season artificial precipitation enhancement operations in the Bayanbulak mountain area have produced significant effects.

Keywords: artificial precipitation enhancement; statistical analysis; effect evaluation; Bayanbulak mountain area

Water resources constitute a critical material foundation for sustainable human development. However, population growth and socioeconomic expansion have intensified water demand. Following the pioneering work of Schaefer and Vonnegut, who proposed seeding cold clouds with catalysts (dry ice and silver iodide) to induce precipitation, numerous countries initiated experimental research on artificial precipitation enhancement, providing important guidance for weather modification development and water scarcity solutions. As one of the world’ s water-poor nations, China’ s per capita water availability is less than one-third of the global average, with pronounced spatiotemporal heterogeneity in water resource endowment. In northwestern China particularly, water resources have become a primary constraint on high-quality socioeconomic development. Consequently, developing atmospheric water resources through artificial precipitation enhancement has emerged as a crucial measure for ecological protection, restoration, and water security in this region.

With strong support from government and society, artificial precipitation enhancement operations have expanded significantly, drawing increasing attention to their effectiveness. However, natural cloud and precipitation processes are complex, making scientific and rational evaluation of operational effects challenging. To date, only Israel’ s winter cloud seeding experiments have gained widespread recognition, demonstrating 13–15% precipitation increases. Notable experiments also include the Wyoming Weather Modification Pilot Project (WWMPP), which achieved 10-15% snowpack enhancement, and China’ s Fujian Gutian Reservoir experiment, which attained 20–24% precipitation increases through scientific operations. Recent studies have further investigated mechanisms and effects using various methods. Liu et al. analyzed microphysical characteristics using raindrop spectrum data, finding significant increases in large droplets and broadened drop size distributions after seeding. Li et al. employed regional regression analysis to examine relationships between rocket seeding methods and enhancement effects. Chen et al. used numerical simulation to demonstrate effective rainfall increases from seeding convective clouds. These studies confirm that scientifically conducted artificial precipitation enhancement is effective, and that appropriate analytical methods can successfully verify enhancement effects.

1.1 Study Area Overview

The Bayanbulak mountain area is located on the southern slopes of the central Tianshan Mountains in Xinjiang, comprising large and small Yulduz basins and hilly grasslands. The region features numerous Kaidu River tributaries, permanent snow cover, and glaciers [Figure 2400: see original paper]. With elevations generally exceeding 2400 m, the area exhibits a high-cold climate characterized by low annual temperatures and minimal evaporation. Winters are long, summers short, and snow cover persists for 139.3 days annually. The warm season (May-September) represents the most suitable period for human activities, with relatively higher monthly temperatures that show an increasing trend. Precipitation, precipitation days, and annual runoff are concentrated in this period. Consequently, intensive artificial precipitation enhancement operations have been conducted annually from May to September to alleviate increasingly severe water shortages, making this region the largest operational area in the Bayingol Mongolian Autonomous Prefecture.

However, due to geographical, economic, and technical constraints, limited meteorological observation capabilities prevent effective monitoring of cloud-precipitation changes before and after operations, complicating effect verification. Previous research indicates that selecting runoff in the target area as a statistical variable can scientifically verify enhancement effects. Given the complex factors influencing surface runoff formation, direct use of measured runoff may introduce significant errors. Therefore, this study employs the Budyko hydrothermal coupling balance hypothesis to simulate long-term runoff data influenced by precipitation, aiming to improve verification accuracy.

1.2 Data Sources

Required data include daily precipitation, temperature (average, maximum, minimum), relative humidity, sunshine duration, wind speed, and measured monthly runoff data, obtained from the Bayanbulak National Reference Weather Station and the Dashankou hydrological control station at the Kaidu River outlet for May-September 1973-2018. According to the Bayingol Mongolian Autonomous Prefecture Weather Modification Office, operations began in 1994, with May-September as the primary operational period, averaging 20 missions annually using 200 rockets. For analysis, 1973-1993 is designated as the historical period (pre-operation) and 1994-2018 as the operational period. All meteorological and hydrological data underwent rigorous quality control.

1.3.1 Runoff Simulation Based on Budyko Hypothesis

To avoid substantial verification errors, given that surface runoff in the Bayanbulak mountains is primarily recharged by precipitation and snow/ice melt, this study employs the Budyko hydrothermal coupling balance hypothesis, which quantifies the influence of precipitation and potential evapotranspiration on runoff. Under the assumption of an independent watershed with unchanged long-term underlying surface conditions, runoff can be considered the sum of precipitation and actual evapotranspiration. The following runoff simulation equation was constructed:

$$R = P - ET_0 \cdot \left[1 + \left(\frac{w \cdot P}{ET_0}\right)^{-n}\right]^{-1/n}$$

where R represents precipitation-influenced runoff (mm), ET_0 is potential evapotranspiration (mm), w is a parameter reflecting underlying surface characteristics, P is precipitation (mm), and n is an integration constant. Potential evapotranspiration ET_0 is calculated using the FAO56-PM formula recommended by the Food and Agriculture Organization.

1.3.2 Sequence Test Method

The sequence test is commonly used in artificial precipitation enhancement experiments, employing historical period averages as natural expectation values for the operational period to determine enhancement effects. This study analyzed artificial precipitation enhancement effects by comparing differences in statistical variable averages between periods.

1.3.3 Unpaired Rank Sum Test

The unpaired rank sum test is a non-parametric method for assessing changes in statistical variables before and after operations. The procedure involves ranking all observations, calculating rank sums (T), and comparing the smaller sample' s T value. For sample size $n \geq 10$, T approximates a normal distribution $N\left(\frac{n(N+1)}{2}, \frac{n(N+1)(N-n)}{12}\right)$, where N is the total sample size. The test statistic u is calculated as:

$$u = \frac{T - \frac{n(N+1)}{2}}{\sqrt{\frac{n(N+1)(N-n)}{12}}}$$

For two-tailed tests, significance is indicated when u falls outside $(-1.96, +1.96)$ at $\alpha = 0.05$; for one-tailed tests, $u \geq 1.64$ indicates significance.

1.3.4 t-Test Method

When statistical variables follow a normal distribution, parametric testing is appropriate. For small samples, the t-test is most suitable, though it requires constant variance. Therefore, Shapiro-Wilk and F-tests were used to verify normality and homogeneity of variance. The t-test formula is:

$$t = \frac{\bar{y}_k - \bar{y}_n}{\sqrt{\frac{S_k^2}{k} + \frac{S_n^2}{n}}}$$

where $\bar{y}_k$ and $\bar{y}_n$ are operational and historical period means, k and n are sample sizes, and S_k and S_n are standard deviations. Significance is determined at $\alpha = 0.05$.

Confidence interval estimation for enhancement effects uses:

$$\bar{E} = \bar{y}_k - \bar{y}_n \pm t_\alpha \sqrt{\frac{S_k^2}{k} + \frac{S_n^2}{n}}$$

where $\bar{E}$ is the mean absolute increase and t_α is the critical value. Relative increase rate R and test efficacy d are calculated as:

$$R = \frac{\bar{E}}{\bar{y}_n} \times 100\%$$

$$d = \frac{t_\alpha \sqrt{\frac{S_k^2}{k} + \frac{S_n^2}{n}}}{\bar{y}_n}$$

When F-tests reveal significant variance differences, Welch' s t-test is used with adjusted degrees of freedom:

$$\nu = \frac{\left(\frac{S_k^2}{k} + \frac{S_n^2}{n}\right)^2}{\frac{S_k^4}{k^2(k-1)} + \frac{S_n^4}{n^2(n-1)}}$$

2.1 Selection of Statistical Variable Samples

For scientifically analyzing warm-season artificial precipitation enhancement effects in the Bayanbulak mountains, the historical sample size should exceed 10 years. While precipitation is the primary verification indicator, alternative variables must correlate significantly with precipitation.

2.1.1 Correlation Analysis Between Precipitation and Runoff

Figure 2 shows that maximum, minimum, and average warm-season monthly precipitation during 1994-2018 increased by 31.58%, 6.71%, and 18.97% respectively compared to 1973-1993, with significant linear correlation to surface runoff ($R^2 = 0.4743$, $P < 0.001$). This indicates that 1994-2018 was a period of rapid precipitation increase, with runoff changes clearly precipitation-driven, making runoff a viable verification indicator.

Figure 3 reveals that simulated and measured warm-season monthly runoff both show significant increasing trends (R^2*{sim} = 0.2013, P = 0.0018; R*^{2}{meas} = 0.1396, P = 0.0097), though measured values increased faster with earlier abrupt changes. This discrepancy is attributed to increased snow/ice melt in the arid northwest region. Simulated runoff shows consistent volatility and growth rates with precipitation, exhibiting an extremely significant correlation ($R^2 = 0.9971$, $P < 0.001$) and nearly identical trends.

In summary, using measured runoff for verification introduces errors, while Budyko-model-simulated runoff accurately reflects precipitation trends and their impact on runoff, making it more suitable as a verification variable.

2.2 Sequence Test Results

Table 1 shows absolute increases during the operational period ranked as: measured runoff > simulated runoff > precipitation. Relative increase rates ranked as: measured runoff (18.48%) > simulated runoff (14.70%) > precipitation (12.05%). Simulated runoff' s absolute increase was 23.19% smaller than measured runoff but only 0.09% smaller in relative increase rate, demonstrating that watershed runoff analysis better reflects operational effects than single-station precipitation, and that simulated runoff is a feasible verification indicator.

2.3 Unpaired Rank Sum Significance Analysis

The parameter w in the Budyko model, which reflects underlying surface characteristics, is complex to calculate. Therefore, values from Yao et al. were adopted: $w = 1.21$ and $n = 2.6$.

Table 2 presents unpaired rank sum test results for precipitation, simulated runoff, and measured runoff. All variables showed significant increases during the operational period (one-tailed u values < -1.64, $P < 0.05$), confirming significant enhancement effects.

2.4 t-Test Evaluation and Verification

2.4.1 Normal Distribution Test Shapiro-Wilk tests on precipitation, simulated runoff, and measured runoff from both periods (Figure 4) showed that, except for operational-period measured runoff and historical-period simulated runoff (which were somewhat discrete), most samples closely followed theoretical normal distributions. SPSS 27.0 calculations yielded probabilities $P > 0.05$ for all variables (precipitation: $P_{hist} = 0.29$, $P_{op} = 0.71$; simulated runoff: $P_{hist} = 0.23$, $P_{op} = 0.87$; measured runoff: $P_{hist} = 0.18$, $P_{op} = 0.13$), confirming normal distribution.

2.4.2 Variance Test F-tests for homogeneity of variance (Table 3) showed that precipitation and simulated runoff had smaller F-values than measured runoff, indicating non-significant variance differences for these variables but significant variance change for measured runoff. Therefore, precipitation and simulated runoff are suitable for standard t-tests, while measured runoff requires Welch' s t-test.

2.4.3 Test Calculation Table 4 shows precipitation had the best test efficacy, requiring only an 11.59% increase to detect significant effects. Simulated runoff ranked second, with test efficacy 3.72% lower than measured runoff. At the 0.05 significance level with 90% confidence intervals, simulated runoff' s relative increase rate was 3.78% higher than precipitation but 2.65% lower than measured runoff. Considering that measured runoff is influenced by snow/ice melt and represents watershed-scale rather than point precipitation, simulated runoff results are more credible. In summary, Budyko-modeled runoff provides high verification accuracy and improved test efficacy, confirming significant precipitation and runoff increases after operations.

3 Discussion

Given that long-term precipitation data in the Bayanbulak mountains are primarily from single stations while operational impact areas are extensive, relying solely on single-station data may limit regional effect assessment. Based on theory that surface runoff forms from entire watershed precipitation and the extremely significant correlation between watershed runoff and representative station precipitation ($P < 0.001$), using runoff as a verification indicator is justified. However, complex mountain runoff formation can bias results. The Budyko model effectively addresses this, as evidenced by simulated runoff' s relative increase rate differing from precipitation by only 2.65% and showing 3.72% better test efficacy than measured runoff. This demonstrates that Budyko-modeled runoff, representing precipitation' s impact on runoff, is more suitable than measured runoff for verification.

Statistical test results are method-dependent and generally provide reference values, whereas physical verification based on mechanism changes is more convincing. Future research will incorporate weather radar echo analysis to validate statistical findings.

4 Conclusions

(1) Due to the extensive operational area and limited long-term representative precipitation stations in the Bayanbulak mountains, using Kaidu River runoff as a statistical indicator ($R^2 = 0.4743$, $P < 0.001$) provides a feasible approach for comprehensive effect verification.

(2) Direct use of measured runoff for verification introduces bias because of complex runoff composition. Budyko-modeled runoff not only synchronizes with measured runoff trends but also shows near-perfect correlation with precipitation ($R^2 = 0.9971$). Therefore, simulated runoff better represents precipitation's impact and is more suitable as a verification indicator.

(3) In both sequence and t-tests, simulated and measured runoff showed greater relative increases than precipitation. Simulated runoff' s test efficacy was 3.72% lower than measured runoff' s, indicating that watershed-scale precipitation differs from single-station precipitation.

Using Budyko-modeled runoff improves verification precision and yields more reasonable conclusions.

(4) At 90% confidence level, warm-season monthly average precipitation increased by 5.38 mm (12.05%), simulated runoff by 4.53 $m^3 \cdot s^{-1}$ (14.70%), and measured runoff by 28.48 $m^3 \cdot s^{-1}$ (18.48%). These results demonstrate significant enhancement effects from warm-season artificial precipitation enhancement operations in the Bayanbulak mountain area.

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