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# Application of the Markov Chain Method in Analyzing Rainfall during Cloud Seeding Activities in the Citarum Watershed, West Java

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Title

# Application of the Markov Chain Method in Analyzing Rainfall during Cloud Seeding Activities in the Citarum Watershed, West Java

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Abstract

Weather Modification Technology (WMT), particularly cloud seeding, has been widely implemented as an effort to enhance rainfall and support water resource management. However, the evaluation of cloud seeding operations has generally focused on changes in accumulated rainfall amounts, which may not fully represent changes in the temporal dynamics and persistence of rainfall events. This study proposes a stochastic evaluation framework based on the Markov Chain approach to analyze changes in rainfall transition behavior during weather modification operations in the Citarum Watershed, West Java, Indonesia.

Daily rainfall observation data from 59 rain gauge stations during the WMT operational period from October 22 to November 20, 2019, were analyzed. Rainfall conditions were categorized into several states representing different rainfall regimes or conditions, and transition probability matrices were constructed separately for seeded and unseeded conditions. Comparisons between the two conditions were performed to evaluate changes in rainfall triggering probability, rainfall persistence, and the characteristics of transitions among rainfall states.

The results show that cloud-seeded conditions tend to increase the transition probability toward wet states and enhance rainfall event persistence compared with unseeded conditions. The Markov Chain approach provides additional information beyond cumulative rainfall parameters by describing how cloud seeding operations may influence the temporal patterns and continuity of rainfall events.

Analysis of NaCl seeding material intensity indicates that increasing the amount of seeding material does not always produce a proportional increase in rainfall. This finding suggests the potential occurrence of a diminishing return effect under certain atmospheric conditions. These results emphasize the importance of considering rainfall temporal dynamics and probabilistic characteristics when evaluating the operational effectiveness of weather modification technology. Correlation data demonstrate that in State 0 (unseeded), the naturally occurring rainfall event in the Citarum Watershed averages 1.77 mm (natural rainfall). Seeding agent amount in State 1 (< 1 Ton) resulted in a transition of average rainfall from 1.77 mm to 4.33 mm. Seeding agent amount in State 2 (2 Tons) resulted in a transition of average rainfall from 4.33 mm to 4.49 mm compared to unseeded conditions.

Keywords: cloud seeding; Markov Chain; Rainfall.

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**Statements and Declarations**

Ethics, Consent to Participate, and Consent to Publish declarations: not applicable

## Statements and Declarations of Data Avaibility

The data used in this paper include rainfall, NaCl Powder seeding material, and cloud seeding flight sortie data. All of these data are owned by the Weather Modification Technology Research Group, Research Center for Limnology and Water Resources, National Research and Innovation Agency.

## 1. Background

Cloud seeding has been implemented in various countries as a Weather Modification Technology (WMT) method to increase rainfall and support water resource management, including reservoir operations, agricultural water supply, and drought mitigation (Nebel, 2008), (M. Yusef Tiansyah, 2024), (Morrison et al., 2009), (Alzahrani & Abdelbaki, 2025), (Hydrological, 2025). Various operational cloud seeding programs have been conducted using different evaluation approaches to measure changes in rainfall under modified atmospheric conditions (Bruintjes, 1999), (Al Hosari et al., 2021), (Wirawan et al., 2023), (Wang et al., 2024), (Sadeghi & Yaghoubi, 2025), (Xue et al., 2013), (Essien, 2021), (Lin et al., 2023), (Krauss & Ph, 2005), (Abshaev et al., 2022).

In Indonesia, Weather Modification Technology has been utilized for various purposes, including enhancing water availability, reducing drought impacts, and supporting hydrological management (Seto H T et al, 2019). Although the operational implementation of WMT has been quite extensive, evaluating the effectiveness of cloud seeding still faces challenges due to the stochastic nature of rainfall and high natural atmospheric variability (Silverman & Sukarnjanaset, 2000), (Bruintjes, 1999), (Wu et al., 2018a), (Zheng et al., 2021), (Vongsamut et al., 2022), (Institute, 2023), (Hydrological, 2025).

Previous approaches in cloud seeding evaluation generally compared rainfall amounts between seeded and non-seeded conditions. Commonly used methods include target–control regression analysis (K. R. Biswas, Dennis & Aeronautics, 1971), (Wu et al., 2018a), (Morrison et al., 2009), double ratio (K. R. Biswas, Dennis & Aeronautics, 1971), the Weather Research and Forecasting Model (Lin et al., 2023), and crossover randomization experiments (Morrison et al., 2009). Although these approaches provide critical information regarding potential rainfall increases, they focus primarily on rainfall volume and do not fully explain temporal changes in rainfall occurrence patterns.
Rainfall is a complex atmospheric process characterized by high variability and stochastic properties (Murty et al., 2026), (Siems, 2013), (Al Hosari et al., 2021). A rainfall event at a specific time is often influenced by preceding atmospheric conditions, thereby generating temporal dependencies within the rainfall time series (Murty et al., 2026). Therefore, stochastic modeling approaches such as Markov Chains can be used to describe the evolution of rainfall events through transition probabilities between rainfall states (Bernard W. Taylor III, n.d.), (Levin et al., 2008).

The Markov Chain model has been widely used in hydrology to analyze rainfall occurrences, rainfall persistence, and changes in rainfall regimes. By comparing the transition probability matrices between seeded and non-seeded conditions, this approach enables the evaluation of changes in rainfall dynamic characteristics resulting from cloud seeding activities (Sadeghi & Yaghoubi, 2025), (Ricardo M. Czekster, 2021), (Silverman & Sukarnjanaset, 2000).

Nevertheless, the application of the Markov Chain approach to evaluate the effects of cloud seeding, particularly in tropical regions such as Indonesian watersheds, remains relatively limited. Therefore, this evaluation aims to analyze the influence of cloud seeding operations on rainfall transition dynamics in the Citarum Watershed using a first-order discrete-time Markov Chain approach (Sadeghi & Yaghoubi, 2025). While evaluation methods previously conducted by experts estimate increases in rainfall amount, the Markov Chain framework captures the temporal memory of the rainfall system.

This evaluation not only assesses changes in rainfall volume but also analyzes whether cloud seeding activities are associated with changes in rainfall persistence and probabilistic transition patterns of rainfall states (Sadeghi & Yaghoubi, 2025), (Siems, 2013), (Malik, 2018), (Pal & Mesikepp, 2025), (Assessment, 2024), (Abshaev et al., 2022).

## 2. Methodology

### 3.1 Study Area and Data

This evaluation was conducted in the Citarum Watershed area, West Java, Indonesia, during Weather Modification Technology (WMT) operations from October 22 to November 20, 2019. The data used consists of daily rainfall from 59 rain gauge stations scattered across the Citarum Watershed (Fig. 1). The spatial average of rainfall was calculated to represent the regional rainfall response of the watershed during the observation period.

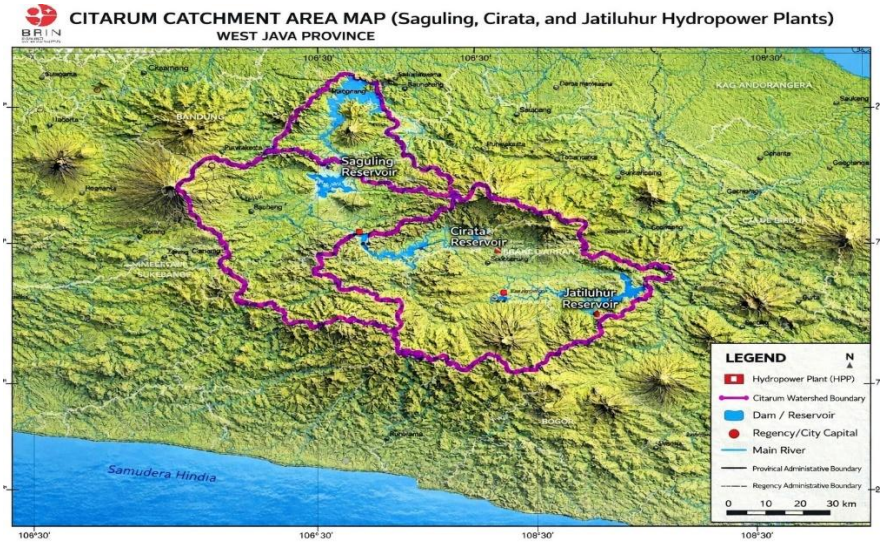



Figure 1. Operational Map of Weather Modification Technology (WMT) Activities in the Citarum Watershed (Source: National Research and Innovation Agency).

Cloud seeding activities are represented as a binary intervention variable: *Seeded* (1), indicating days when cloud seeding operations were conducted, and *Unseeded* (0) for days without cloud seeding operations (Fig.2)

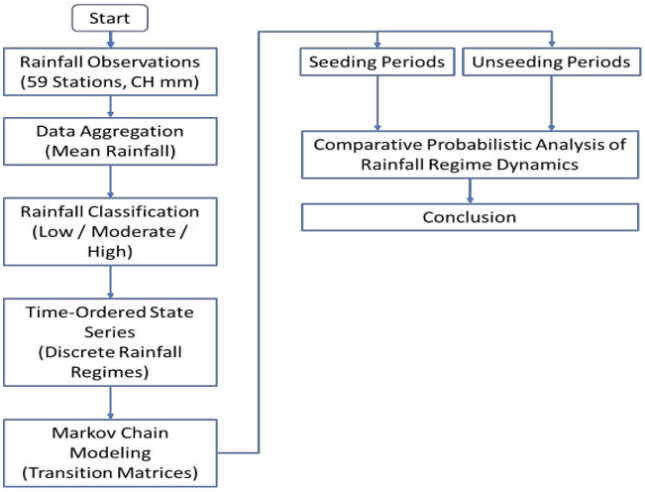



Figure 2. Methodology Flowchart

The data utilized for the evaluation of Cloud Seeding Impacts on Rainfall Persistence and Transition Dynamics Based on a Markov Chain Framework are tabulated in (Table 1) below.

Table 1. Rainfall Data of Cloud Seeding Operations, 22 October – 20 November 2019.

| Date | Rainfall (mm) | Seeding Category (1 = Seeded, 0 = Unseeded) | Seeding Agent Amount (NaCl - Tons) |
|---|---|---|---|
| 22 Oct | 0 | 0 | 0 |
| 23 Oct | 0 | 0 | 0 |
| 24 Oct | 0 | 0 | 0 |
| 25 Oct | 0.71 | 1 | 0.8 |
| 26 Oct | 8.12 | 1 | 1 |
| 27 Oct | 6.47 | 1 | 2 |
| 28 Oct | 2.22 | 1 | 1 |
| 29 Oct | 9.48 | 1 | 1 |
| 30 Oct | 0.58 | 0 | 0 |
| 31 Oct | 10.26 | 1 | 1 |
| 1 Nov | 6.81 | 1 | 1 |
| 2 Nov | 3.34 | 0 | 0 |
| 3 Nov | 10.0 | 0 | 0 |
| 4 Nov | 3.35 | 0 | 0 |
| 5 Nov | 6.85 | 1 | 1 |
| 6 Nov | 1.48 | 1 | 1 |
| 7 Nov | 2.61 | 1 | 1 |
| 8 Nov | 11.03 | 1 | 2 |
| 9 Nov | 4.01 | 1 | 2 |
| 10 Nov | 3.38 | 1 | 1 |
| 11 Nov | 0.76 | 1 | 2 |
| 12 Nov | 0.64 | 1 | 1 |
| 13 Nov | 1.21 | 1 | 1 |
| 14 Nov | 0 | 1 | 2 |
| 15 Nov | 4.12 | 1 | 2 |
| 16 Nov | 0.30 | 0 | 0 |
| 17 Nov | 0.01 | 0 | 0 |
| 18 Nov | 0.13 | 0 | 0 |
| 19 Nov | 5.04 | 1 | 2 |
| 20 Nov | 2.55 | 1 | 1 |

Source: National Research and Innovation Agency 2019

The daily average rainfall from 59 rain gauge stations was utilized as the primary variable. Information regarding cloud seeding operations was represented as a binary variable: *seeded* (1) and *unseeded* (0).

The entire systematic process—encompassing data treatment stages, the formulation of the frequency contingency matrix, and row normalization of probabilities—is visually summarized in Methodological Flowchart, while the characteristics of the raw dataset are detailed in Table 1.

### 3.2 Rainfall State Classification

Daily rainfall was converted into discrete states to describe various rainfall characteristics. The state classification is defined as follows: State 0: Dry condition; State 1: Light rain; State 2: Moderate rain; and State 3: Heavy rain (Geofisika, 2020). This classification was used to differentiate rainfall characteristics that have relevance to hydrological responses (Hydrological, 2025).

### 3.3 Markov Chain Model

A first-order discrete-time Markov Chain model was employed to describe the transitions between rainfall states (Levin et al., 2008), (Sadeghi & Yaghoubi, 2025). The Markov assumption states that the probability of a rainfall state at the next time step depends solely on the current state:

$$P\left(X_{t+1=j} \mid X_{t=i}\right) \quad (1.1)$$

where:
X represents the rainfall state,
i and j denote the current state and the subsequent state, respectively.
The transition probability matrix is expressed as:

$$P = [p_{ij}] \quad (1.2)$$

where:
pij is the transition probability from state i to state j.
The sum of the probabilities for each row satisfies $\Sigma p_{ij} = 1$:

### 3.4 Comparison of Seeded and Unseeded Conditions

Transition matrices were calculated separately for seeded and unseeded conditions. The evaluation was conducted based on the following criteria:

1. Rainfall triggering probability, which provides an indication of the likelihood of transition from a dry condition to a rainfall state.
2. Rainfall persistence probability, which offers insight into the capacity of a specific rainfall state to persist into the following day.
3. Transition probability toward higher rainfall intensity, which serves as an indicator of the system's likelihood to shift from a lower rainfall state to a higher one.

### 3.5 Uncertainty Analysis

Since the transition probabilities were calculated based on a relatively short observation period, an uncertainty analysis was performed using the bootstrap resampling method on the available data to estimate statistical uncertainty with 5,000 iterations. Confidence intervals (95% CI) were calculated to evaluate the reliability of the differences in transition probabilities between the seeded and unseeded conditions (B. Efron, 1979), (Wood, 2005).

$$\mathbf{x} = (\boldsymbol{x_1}, \boldsymbol{x_2}, \dots, \boldsymbol{x_n}) \quad (2.1)$$

$$\hat{\boldsymbol{\theta}}_{\mathbf{1}}^{*}, \hat{\boldsymbol{\theta}}_{\mathbf{2}}^{*}, \dots, \hat{\boldsymbol{\theta}}_{\boldsymbol{B}}^{*} \quad (2.2)$$

$$\overline{\boldsymbol{\theta}}^{*} = \frac{\mathbf{1}}{\boldsymbol{B}} \sum_{\boldsymbol{b}=\mathbf{1}}^{\boldsymbol{B}} \hat{\boldsymbol{\theta}}_{\boldsymbol{b}}^{*} \quad (2.3)$$

$$\widehat{\boldsymbol{SE}}_{\boldsymbol{B}} = \sqrt{\frac{\mathbf{1}}{\boldsymbol{B}-\mathbf{1}} \sum_{\boldsymbol{b}=\mathbf{1}}^{\boldsymbol{B}} \left(\hat{\boldsymbol{\theta}}_{\boldsymbol{b}}^{*} - \overline{\boldsymbol{\theta}}^{*}\right)^{\mathbf{2}}} \quad (2.4)$$

### 3.6 Analysis of the Influence of NaCl Seeding Agent Amount

The relationship between the amount of NaCl seeding agent and rainfall response was analyzed by comparing rainfall characteristics across various levels of seeding agent utilization. The results were interpreted as an associative relationship between the amount of seeding agent and the rainfall response, rather than as a direct causal link (K. R. Biswas & Dennis, 1970), (Lin et al., 2023).

## 4. Results

### 4.1 Rainfall Characteristics During the WMT Operational Period

During the observation period from October 22 to November 20, 2019, daily rainfall characteristics exhibited high temporal variability across the Citarum Watershed. This condition reflects the natural behavior of tropical rainfall, which is influenced by atmospheric dynamics ranging from local to regional scales (Silverman & Sukarnjanaset, 2000). The observation period encompassed conditions...with cloud seeding operations (*seeded*) and without seeding (*unseeded*) (Istrate et al., 2025). The differences in rainfall characteristics between the two conditions were analyzed using a probabilistic approach to evaluate changes in the transition patterns between rainfall states.

The results of the analysis indicate that the rainfall distribution differs not only in terms of accumulated volume but also in the transition patterns between rainfall states. This suggests that evaluating based solely on rainfall volume is insufficient to capture the shifting dynamics of rainfall events.

### 4.2 Rainfall Transition Probability Based on the Markov Chain

The initial stage of data processing involved organizing the daily rainfall data into a chronologically ordered time series and grouping them based on seeded and unseeded conditions. Subsequently, the average rainfall amounts were discretized as previously described.

This discretization process was conducted to categorize rainfall variability, thereby enabling the application of the Markov Chain Model. Once the rainfall states were defined, the Markov transition matrices were constructed by counting the transition frequencies between consecutive rainfall states and then normalizing them into transition probabilities. Separate transition matrices were developed for the seeded and unseeded conditions. A comparison

between these matrices was used to assess the differences in rainfall transition patterns and the level of rainfall persistence during the cloud seeding operations (Bernard W. Taylor III, n.d.).

The data processing from Table 1, including the calculation and estimation of the Markov Chain transition matrices for both seeded and unseeded conditions, was executed using Python programming (Ricardo M. Czekster, 2021). The resulting computational outputs served as the basis for the analysis.

Prior to the scientific interpretation, the frequency and transition probability matrices generated by the algorithm were reviewed. The Markov Chain calculations for the cloud seeding operations in the Citarum Watershed under unseeded (0) and seeded (1) conditions are detailed below.

a. Unseeded Condition (0)

The total number of transition samples was 10 days, and the formulated Transition Frequency and Probability Matrix Model is as follows:

$$(P\ Unseeding) = \begin{pmatrix} F00 & F01 \\ F10 & F11 \end{pmatrix} = \begin{pmatrix} 4 & 2 \\ 0 & 4 \end{pmatrix}$$

- F00 (Frequency from 0 to 0): The number of occurrences where a dry day is followed by another dry day (Persistence of Dry Condition).
- F01 (Frequency from 0 to 1): The number of occurrences where a dry day is followed by a rainy day (Conversion from Dry to Wet Condition).
- F10 (Frequency from 1 to 0): The number of occurrences where a rainy day is followed by a dry day (Rainfall Cessation).
- F11 (Frequency from 1 to 1): The number of occurrences where a rainy day is followed by another rainy day (Persistence of Wet Condition).

The transition matrix above provides indicators of and records the influence of unseeded conditions on rainfall events occurring over the Citarum Watershed, with the detailed explanation and tabulation provided below (table.2).

Table 2. Transition Matrix Model for Unseeded Conditions

| PROBABILITY ($P_{Unseeding}$) | | Dry | Wet |
|---|---|---|---|
| | Dry | 66,67 % | 33,33 % |
| | Wet | 00,00 % | 100,00 % |

b. The total number of transition samples was 19 days, and the formulated Transition Frequency and Probability Matrix Model is tabulated as follows:

$$(P\ seeding) = \begin{pmatrix} F00 & F01 \\ F10 & F11 \end{pmatrix} = \begin{pmatrix} 0\ 1 \\ 2\ 15 \end{pmatrix}$$

Table 3. Transition Matrix Model for Seeded Conditions

| PROBABILITY ($P_{Seeding}$) | | Dry | Wet |
|---|---|---|---|
| | Dry | 00,00 % | 100,00 % |
| | Wet | 11,11 % | 88,89 % |

The Markov Chain transition probability matrices indicate changes in the likelihood of rainfall state transitions from one day to the next. Under unseeded conditions, the highest probabilities occur in transitions that maintain the same state, particularly during dry conditions (Sadeghi & Yaghoubi, 2025). This indicates the persistence of dry atmospheric conditions over certain periods. Conversely, under seeded conditions, there is an increase in the transition probability from dry conditions to rainfall states (table.3). Furthermore, rainy conditions exhibit a tendency to maintain their rainy status into the following day.

The differences between these transition matrices demonstrate that the seeded condition possesses distinct rainfall dynamic characteristics compared to the unseeded condition. However, these shifts in transition probabilities must be understood as an associative relationship between WMT operational conditions and rainfall dynamics, given that atmospheric conditions favoring rain cloud formation can also influence the decision to execute cloud seeding. The comparison between the unseeded and seeded conditions can be represented visually in the chart in Figure 3 below.

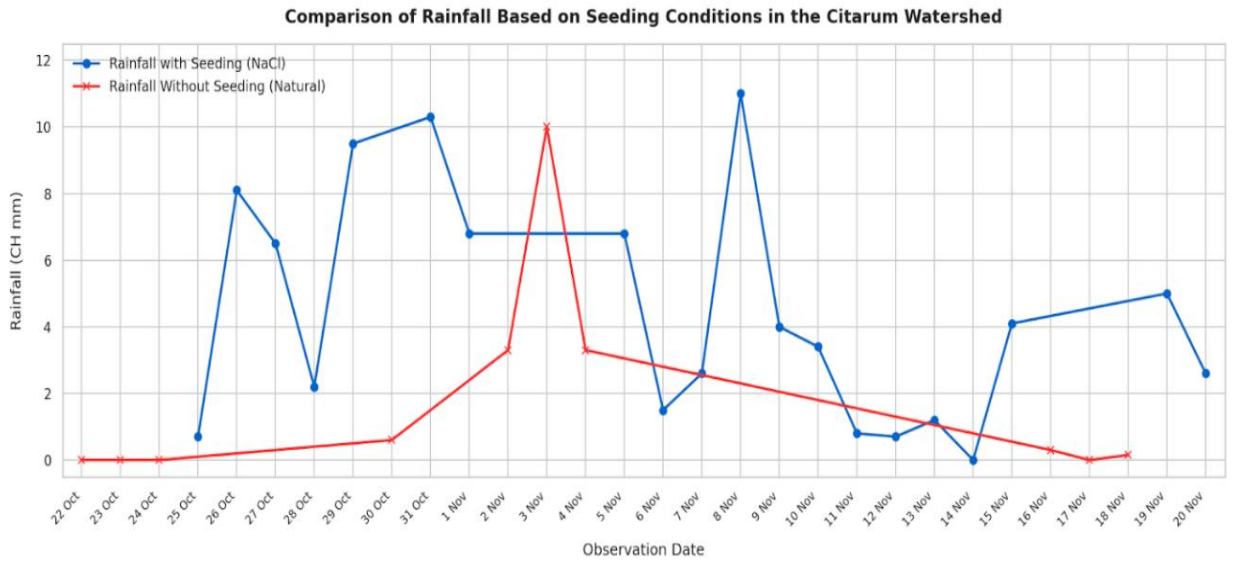



Figure 3. Comparison chart of rainfall under seeded and unseeded conditions

4.3 Rainfall Persistence Analysis

Rainfall persistence was calculated based on the probability of a rainy condition continuing into the following day. The results indicate that the probability of maintaining rainy conditions was higher during the seeded period compared to the unseeded period. This pattern suggests a tendency toward increased sustainability of rainy conditions during cloud seeding operations (Sadeghi & Yaghoubi, 2025).

In the context of Markov Chains, an increase in the diagonal values of the transition matrix reflects enhanced stability of a particular rainy condition. However, due to the limited number of observation days, the estimation of transition probabilities carries inherent uncertainty. Therefore, the interpretation incorporates the confidence intervals from bootstrap results to account for selection bias and endogeneity. Bootstrapping is defined as a resampling method from available data to estimate statistical uncertainty (Efron, 1979). The calculation is as follows:

Table 4. Bootstrap Statistics (5000 iterations, 95% CI)

| Variable | Mean (CH mm) | CI 95% Lower | CI 95% Upper |
|---|---|---|---|
| Seeding | 4.39 | 3 | 5.9 |
| Unseeding | 2.14 | 0.6 | 3.9 |
| Difference in Seeding Effect | 2.25 | 0.2 | 4.5 |

The average rainfall during seeded days (4.39 mm) was higher than that during unseeded days (2.14 mm). The bootstrap analysis with 5,000 iterations demonstrates a positive association between seeded conditions and increased rainfall (with the confidence interval not predominantly including zero), resulting in a mean difference of approximately +2.25 mm. The bootstrap diagram can be more clearly understood in Figure 4.

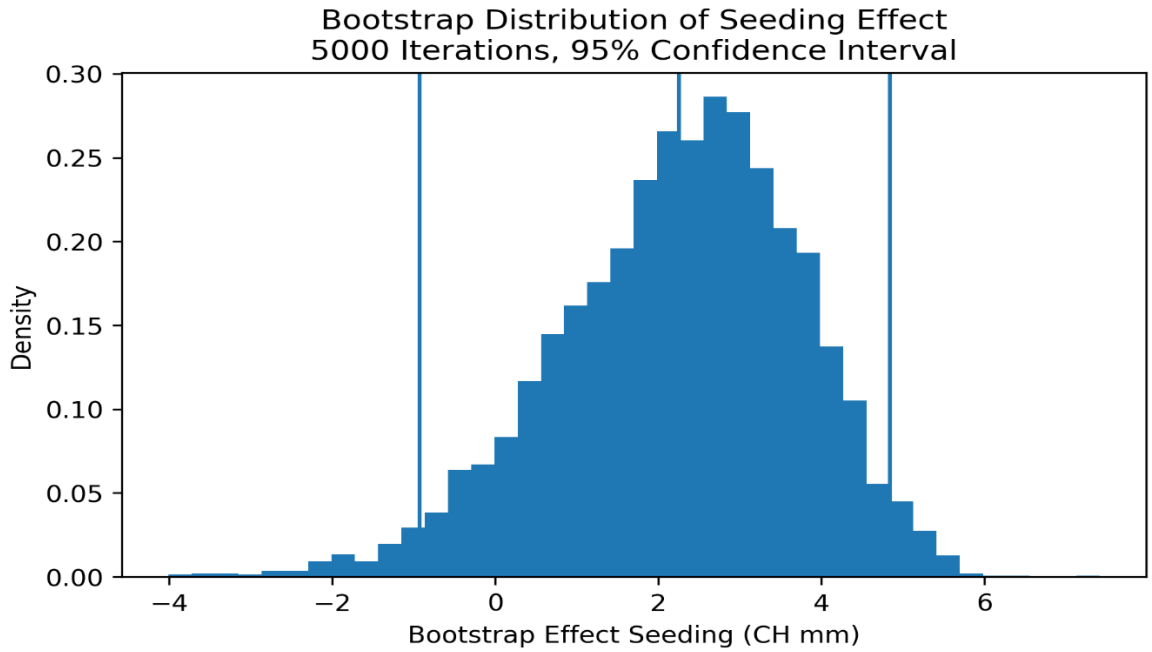



Figure 4. Bootstrap Distribution of Seeding Effect

4.4 Analysis of the Influence of NaCl Seeding Agent Amount

Analysis based on the amount of seeding agent indicates that an increase in the quantity of NaCl does not always yield a linear increase in rainfall. Conditions with higher amounts of seeding agent do not consistently exhibit a greater transition probability toward rainfall states compared to those with lower seeding agent amounts (Wu et al., 2018a), (Essien, 2021).

In this evaluation, the role of NaCl in the cloud seeding process also warrants analysis (K. R. Biswas & Dennis, 1970). Therefore, a Markov Chain transition analysis is required to determine the percentage contribution of the NaCl seeding material to rainfall events during cloud seeding operations in the Citarum Watershed. The transition matrix for the seeding agent was computed using Python. Based on the summary of the algorithm's output from the time-series data processed by Python, the calculated transition probability values for the NaCl seeding agent used during cloud seeding operations in the Citarum Watershed yielded the following transition matrix:

Table 4. Model Markov Chain Transition Matrix for NaCl Seeding Material.

| Current Day \ Subsequent Day | State 0 (0 Ton) | State 1 (≤ 1 Ton) | State 2 (2 Ton) | Precipitation Amount (mm) |
|---|---|---|---|---|
| State 0 (0 Ton) | 60,00% | 30,00% | 10,00% | 1,77 |
| State 1 ( ≤ 1 Ton) | 16,67% | 50,00% | 33,33% | 4,33 |
| State 2 (2 Ton) | 14,29% | 57,14% | 28,57% | 4,49 |

Based on the Markov Chain mathematical calculations and the average rainfall correlations generated by the Python program (Ricardo M. Czekster, 2021), the following scientific analysis highlights the indicated relationship between seeding intensity and rainfall response. This Transition Probability Matrix (P) reflects the operational dynamics of Weather Modification Technology (WMT) execution, providing transition data from day or time $t$ to the subsequent day t+1 (Sadeghi & Yaghoubi, 2025).

These results indicate the potential existence of an optimal atmospheric condition, wherein an additional amount of seeding agent does not consistently yield a proportional increase in rainfall response (Murty et al., 2026). This phenomenon may be linked to the limitations of cloud microphysical conditions, the volume of precipitable water available within the clouds, and the atmospheric dynamics occurring during the seeding process (Fig.5).

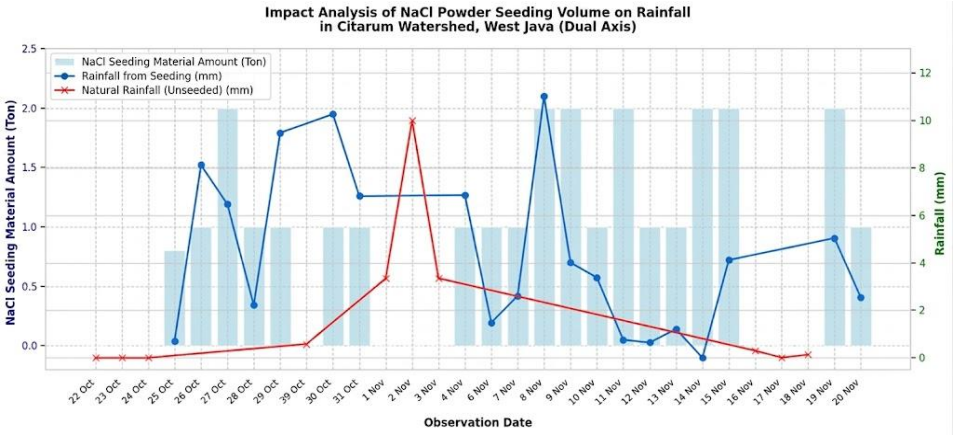



Figure 5 Chart Impact Analysis of NaCl Powder Seeding Material

Based on Table 4 above, the physical effectiveness of NaCl powder as a hygroscopic condensation nucleus is demonstrated (Colin Ward, 2026). The evaluation results reveal that seeded conditions are associated with higher persistence of wet states and an increased transition probability toward rainy conditions (Wu et al., 2018b; Lin et al., 2023; Xue et al., 2013).

Correlation data demonstrate that in State 0 (unseeded), the naturally occurring rainfall event in the Citarum Watershed averages 1.77 mm (natural rainfall).

Seeding agent amount in State 1 (< 1 Ton) resulted in a transition of average rainfall from 1.77 mm to 4.33 mm.

Seeding agent amount in State 2 (2 Tons) resulted in a transition of average rainfall from 4.33 mm to 4.49 mm compared to unseeded conditions.

## 5. Discussion

### 5.1 Interpretation of Shifting Rainfall Dynamics

The Markov Chain approach offers a distinct perspective on evaluating cloud seeding operations. In contrast to previous evaluations conducted by cloud seeding researchers who focused solely on changes in total accumulated rainfall, transition analysis enables the identification of temporal behavioral shifts in rainfall events.

An increase in the transition probability toward rainy conditions during the seeded period indicates that cloud seeding operations are associated with changes in the temporal characteristics of rainfall within the study area. Nevertheless, these results cannot be directly interpreted as a causal link, given that the rain-formation process is influenced by various atmospheric factors, including humidity, atmospheric stability, the presence of potential clouds, and synoptic conditions. Synoptic factors refer to large-scale atmospheric conditions that influence the probability of cloud and rain formation, such as the Asian monsoon, wind convergence zones, or air pressure patterns (Geofisika, 2020; Overy, 2026).

### 5.2 The Role of Atmospheric Factors and Potential Selection Bias

One of the primary challenges in evaluating cloud seeding is the potential presence of selection bias. Cloud seeding operations are generally executed when potential clouds are detected based on atmospheric monitoring. Consequently, seeded conditions may naturally possess a higher baseline probability of rainfall compared to unseeded conditions.

Thus, the observed shifts in transition probabilities represent a combination of initial atmospheric conditions and the potential influence of seeding operations (Wehbe & Peninsula, 2026; Mountains, 2026). The Markov Chain approach in this evaluation serves as a method to analyze rainfall dynamics rather than as a tool for direct causal inference (Pal & Mesikepp, 2025).

### 5.3 Implications for Weather Modification Technology Evaluation

The evaluation results indicate that the assessment of Weather Modification Technology (WMT) can be expanded from volume-based approaches toward approaches based on

stochastic characteristic shifts. Information regarding rainfall persistence and transition probabilities can provide additional insights in:

a. determining operational periods,
b. evaluating target area responses, and
c. understanding changes in rainfall occurrence patterns.

This approach has the potential to serve as a complementary framework to previously established WMT evaluation methods.

### 5.4 Limitations of the Evaluation

This evaluation has several limitations. First, the observation period is relatively short, which limits the number of transitions available for estimating Markov probabilities. Second, this evaluation has not incorporated additional atmospheric variables such as:

a. air humidity,
b. convection indices,
c. wind conditions, and
d. cloud characteristics.

Third, the observational design did not utilize a completely independent control group; hence, the interpretation of the results warrants caution. Further evaluation featuring longer data periods and causal inference approaches is required to strengthen conclusions regarding the impact of WMT operations (Siems, 2013; Krauss & Ph, 2005; Colin Ward, 2026).

## 6. Conclusion

This study evaluated the dynamic characteristics of rainfall during the execution of Weather Modification Technology (WMT) operations in the Citarum Watershed, Indonesia, utilizing a stochastic approach based on a first-order Markov Chain model.

The evaluation results indicate that rainfall behavior during the seeded period and the unseeded period exhibits distinct transition characteristics. The seeded period shows a tendency toward increased transition probabilities from dry to rainy conditions, as well as enhanced rainfall persistence compared to unseeded conditions.

The Markov Chain framework provides additional insights that extend beyond conventional analysis based on accumulated rainfall, as it is capable of describing the temporal behavior of rainfall, including persistence and shifts between rainfall regimes. This approach can complement existing evaluation methods in assessing cloud seeding operations.

Analysis of the NaCl seeding intensity demonstrates that an increase in the quantity of seeding agent does not consistently produce a proportional shift in rainfall response. This indicates that atmospheric conditions and cloud characteristics remain critical controlling factors in determining precipitation response.

Nevertheless, the results of this evaluation must be interpreted by considering the limitations of the observation period and the potential selection bias inherent in operational cloud seeding execution. Future evaluations should consider longer observation periods, atmospheric

variables, independent control areas, and causal inference approaches to further evaluate the efficacy of cloud seeding operations.

Overall, this evaluation demonstrates the potential application of stochastic rainfall analysis as an alternative framework for understanding rainfall variability during weather modification activities.

References;


Abshaev, A. M., Flossmann, A., Siems, S. T., Prabhakaran, T., Yao, Z., & Tessendorf, S. (2022). Rain Enhancement Through Cloud Seeding. *Unconventional Water Resources*, 21–49. https://doi.org/10.1007/978-3-030-90146-2_2

Al Hosari, T., Al Mandous, A., Wehbe, Y., Shalaby, A., Al Shamsi, N., Al Naqbi, H., Al Yazeedi, O., Al Mazroui, A., & Farrah, S. (2021). The UAE cloud seeding program: A statistical and physical evaluation. *Atmosphere*, *12*(8), 1–17. https://doi.org/10.3390/atmos12081013

Alzahrani, A. S., & Abdelbaki, A. M. (2025). Evaluating cloud seeding initiatives for sustainable water supply in arid environments: insights from Al Baha, Saudi Arabia. *Ain Shams Engineering Journal*, *16*(10), 103591. https://doi.org/10.1016/j.asej.2025.103591

Assessment, T. (2024). *Cloud Seeding Technology*. *December*.

B. Efron, S. U. (1979). *Institute of Mathematical Statistics is collaborating with JSTOR to digitize, preserve, and extend access to The Annals of Statistics. ® www.jstor.org*.

Bernard W. Taylor III. (n.d.). *Introduction to Management Science*.

Bruintjes, R. T. (1999). A Review of Cloud Seeding Experiments to Enhance Precipitation and Some New Prospects. *Bulletin of the American Meteorological Society*, *80*(5), 805–820. https://doi.org/10.1175/1520-0477(1999)080<0805:AROCSE>2.0.CO;2

Colin Ward. (2026). *Cloud seeding* (Issue February 1947, pp. 1–6). https://csiropedia.csiro.au/cloud-seeding/?utm

Essien, M. (2021). *Evaluation of Cloud Seeding Techniques for Precipitation Enhancement*. *32*(3), 167–186. https://forthworthjournals.org/journals/index.php/GJCS/article/view/85/82

Geofisika, B. M. dan. (2020). *Bulletin of Meteorology*. https://www.bmkg.go.id/

Hydrological, I. (2025). *Guide to Hydrological Practice: Vol. I* (Issue 168).

Institute, D. R. (2023). Making it Snow: A Brief History and Review of the Science Behind Cloud-Seeding. *Dri.Edu*, 1–16. https://www.dri.edu/making-it-snow/

Istrate, V., Eremeico, S., Lazăr, L. I., Sîrbu, D. A., Popescu, E., Sîrbu, E., & Popescu, D. D. (2025). Radar characteristics of seeded and unseeded hail clouds in Romania. *Atmospheric Research*, *320*(March). https://doi.org/10.1016/j.atmosres.2025.108028

K. R. Biswas, Dennis, A. S. (1970). Formation of a Rain Shower by Salt Seeding. *Journal of Applied Meteorology*.

K. R. Biswas, Dennis, A. S., & Aeronautics, N. (1971). *Meteorological Observations Required for Future Weather Modification Programs*. *April*. https://ntrs.nasa.gov/api/citations/19710025081/downloads/19710025081.pdf?utm_source=chatgpt.com

Krauss, T. W., & Ph, D. (2005). *Recent Advances in Cold and Warm Cloud Rain Enhancement Methods*.

Levin, D., Peres, Y., & Wilmer, E. (2008). *Markov Chains and Mixing Times , second edition David A . Levin Yuval Peres With contributions by Elizabeth L . Wilmer*. 371. https://pages.uoregon.edu/dlevin/MARKOV/mcmt2e.pdf

Lin, K. I., Chung, K. S., Wang, S. H., Chen, L. H., Liou, Y. C., Lin, P. L., Chang, W. Y., Chiu, H. J., & Chang, Y. H. (2023). Evaluation of hygroscopic cloud seeding in warm-

rain processes by a hybrid microphysics scheme using a Weather Research and Forecasting (WRF) model: a real case study. *Atmospheric Chemistry and Physics*, *23*(18), 10423–10438. https://doi.org/10.5194/acp-23-10423-2023

M. Yusef Tiansyah. (2024). Analysis Of The Contribution Of Weather Modification Technology To The Regional Gross Domestic Product Of The Electricity And Drinking Water Sectors In Purwakarta Regency, West Java. *Sepuluh Nopember Institute of Technology (ITS)*, *5*(1), 70–80. https://repository.its.ac.id/105295/1/0411106032212070-Master_Thesis.pdf

Malik, S. (2018). Cloud Seeding; Its Prospects and Concerns in the Modern World -A Review. *International Journal of Pure & Applied Bioscience*, *6*(5), 791–796. https://doi.org/10.18782/2320-7051.6824

Morrison, A. E., Siems, S. T., Manton, M. J., & Nazarov, A. (2009). On the analysis of a cloud seeding dataset over Tasmania. *Journal of Applied Meteorology and Climatology*, *48*(6), 1267–1280. https://doi.org/10.1175/2008JAMC2068.1

Mountains, Q. (2026). *Cloud seeding makes rain in Gansu*. 7–9.

Murty, A. S. R., Selvam, A. M., Devara, P. C. S., Krishna, K., Chatterjee, R. N., Mukherjee, B. K., & Khemani, L. T. (2026). *11-Year Warm Cloud Modification Experiment in Maharashtra State , India*. 1–25. https://arxiv.org/html/physics/9812046/

Nebel, C. (2008). *Cloud Seeding in Tasmania 1964 to today*. *July*.

Overy, N. (2026). *State of Play ? Geoengineering in South Africa*. 1–11. https://za.boell.org/en/2018/06/05/state-play-geoengineering-south-africa

Pal, S., & Mesikepp, T. (2025). *Finite Markov chains and Monte-Carlo Methods: An Undergraduate Introduction*. http://arxiv.org/abs/2510.14165

Ricardo M. Czekster. (2021). *Markov Chains for Programmers* (Vol. 32, Issue 3). https://czekster.github.io/markov/MC-for-programmers2022.pdf?utm

Sadeghi, M., & Yaghoubi, S. (2025). Cloud seeding optimization under uncertainty: A Markov chain approach in a two-stage fuzzy-stochastic framework. *Operations Research Perspectives*, *15*(May), 100356. https://doi.org/10.1016/j.orp.2025.100356

Seto H T et al, 2019. (2019). *Final Technical Report: Weather Modification Technology Operations in the Citarum Cascade Reservoir Watershed, West Java (25 October – 20 November 2019). November*.

Siems, S. T. (2013). Cloud seeding. *Encyclopedia of Earth Sciences Series*, *December*, 92. https://doi.org/10.1007/978-1-4020-4399-4_63

Silverman, B. A., & Sukarnjanaset, W. (2000). Results of the Thailand warm-cloud hydroscopic particle seeding experiment. *Journal of Applied Meteorology*, *39*(7), 1160–1175. https://doi.org/10.1175/1520-0450(2000)039<1160:ROTTWC>2.0.CO;2

Vongsamut, V., Chaiyo, K., & Taesombat, W. (2022). Assessment of Royal Rainmaking Performance with Ground-based Rainfall in Phetchaburi River Basin. *Engineering Access*, *8*(1), 61–66. https://doi.org/10.14456/mijet.2022.8

Wang, F., Chen, B., Yue, Z., Wang, J., Li, D., Lin, D., Tang, Y., & Luan, T. (2024). A Composite Approach for Evaluating Operational Cloud Seeding Effect in Stratus Clouds. *Hydrology*, *11*(10), 1–17. https://doi.org/10.3390/hydrology11100167

Wehbe, Y., & Peninsula, A. (2026). *Looking to the Skies: The Growing Interest in Cloud Seeding Technology in the Gulf* (pp. 1–6).

Wirawan, D., Rusandi, A. B., & Fadlilah, C. (2023). Statistical Evaluation of the Implementation of Weather Modification Using CoSAT 1000 Flares in the Lake Toba Catchment Area and Its Impact on Aluminum Production. *Jurnal Sains & Teknologi Modifikasi Cuaca*, *24*(1), 25–33.

Wood, M. (2005). *Bootstrapped Confidence Intervals as an*. *8*(4), 454–470. https://doi.org/10.1177/1094428105280059

Wu, X., Yan, N., Yu, H., Niu, S., Meng, F., Liu, W., & Sun, H. (2018a). Advances in the Evaluation of Cloud Seeding: Statistical Evidence for the Enhancement of Precipitation. *Earth and Space Science*, *5*(9), 425–439. https://doi.org/10.1029/2018EA000424

Wu, X., Yan, N., Yu, H., Niu, S., Meng, F., Liu, W., & Sun, H. (2018b). Advances in the Evaluation of Cloud Seeding: Statistical Evidence for the Enhancement of Precipitation. In *Earth and Space Science* (Vol. 5, Issue 9, pp. 425–439). https://doi.org/10.1029/2018EA000424

Xue, L., Hashimoto, A., Murakami, M., Rasmussen, R., Tessendorf, S. A., Breed, D., Parkinson, S., Holbrook, P., & Blestrud, D. (2013). Implementation of a silver iodide cloud-seeding parameterization in WRF. Part I: Model description and idealized 2D sensitivity tests. *Journal of Applied Meteorology and Climatology*, *52*(6), 1433–1457. https://doi.org/10.1175/JAMC-D-12-0148.1

Zheng, W., Ma, H., Zhang, M., Xue, F., Yu, K., Yang, Y., Ma, S., Wang, C., Pan, Y., Shu, Z., Mu, J., Yang, W., & Yin, X. (2021). Evaluation of the first negative ion-based cloud seeding and rain enhancement trial in China. *Water (Switzerland)*, *13*(18). https://doi.org/10.3390/w13182473