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Analysis of Weather Modification Operations as Mitigation for Hydrometeorological Disasters in West Sumatra: A Case Study of the December 2025 Emergency Response

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A B S T R A C T

The hydrometeorological disaster following flash floods in West Sumatra requires a rapid emergency mitigation response. The extreme topography of the Bukit Barisan mountains poses a particular challenge in efforts to control rainfall potential through weather modification technology. This study aims to analyze the implementation mechanism, tactical seeding strategy, and effectiveness of Weather Modification Operations (WMO) in redistributing rainfall in complex orographic areas during the emergency response period. The study uses a qualitative descriptive method with a field study approach conducted from December 10 to 22, 2025. Data were collected through operational observations of 69 flight sorties, analysis of the use of 68 tons of seeding materials (51 tons of NaCl and 17 tons of CaO), and spatial validation using flight path overlays and CMAX weather radar imagery. The results showed that the Sectoral Interception strategy implemented in the West and Northwest sectors was effective in triggering rainfall in coastal and marine areas before the air mass entered the mountainous area. The combination of the Competition Mechanism technique using NaCl and Cloud Disruption using CaO proved capable of breaking up massive convective cloud concentrations. The operation faced significant constraints in the form of Minimum Safe Altitude (MSA) limitations and rapid orographic cloud growth, which limited the effective operation time window to 07:00–16:00 WIB. Overall, OMC was effective in reducing the potential for extreme rainfall in disaster-prone upstream areas through the mechanism of rainfall redistribution. This study recommends the need for specific operational protocols for weather modification operations in areas with extreme topography.

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INTRODUCTION

Hydrometeorological disasters have once again escalated in Indonesia with the occurrence of flash floods that hit the West Sumatra region on November 28, 2025. This event was triggered by extreme rainfall anomalies that drenched the upstream areas along the Bukit Barisan mountain range, causing surface water runoff to exceed the capacity of the river basin (DAS) with its steep topography (Purwaningsih et al., 2020). The destructive impact of this flash flood not only damaged vital infrastructure and residential areas, but also revealed the vulnerability of hilly areas to soil saturation due to prolonged rainfall. This event served as a stark warning of the need for emergency mitigation measures capable of responding quickly to atmospheric dynamics before extreme rainfall hits critical areas (Amri & Giarno, 2024).

The characteristics of disasters in West Sumatra are different from those in lowland areas. In mountainous areas, the time it takes for water to flow from upstream to downstream is very short, so structural mitigation methods such as levees or dams are often insufficient to withstand sudden peak flows (Subekti et al., 2023). In the emergency response situation following the events of November 28, 2025, the top priority is to prevent further flooding that could exacerbate the evacuation and recovery process. Therefore, Weather Modification Operations (WMO) are being implemented as a non-structural solution to break the rainfall cycle upstream through precipitation redistribution mechanisms (Akhmad & Bayuadji, 2020).

The application of OMC in responding to flash floods in West Sumatra presents unique operational challenges that have not been widely explored in Indonesian atmospheric science literature. The majority of previous studies on the effectiveness of weather modification have focused more on operations in areas with flat topography, such as flood mitigation in Jakarta or handling forest and land fires (Karhutla) in eastern Sumatra and Kalimantan (Sidauruk et al., 2023). In some of these cases, the seeding aircraft had high maneuverability and a wide, open target area. In contrast, operations in West Sumatra had to contend with extreme orographic complexity, where the seeding targets were located between narrow valleys and hillsides (Suryanti et al., 2020).

The technical difficulty of this operation increased significantly due to flight safety factors in mountainous areas. Pilots and flight scientists were faced with strict Minimum Safe Altitude (MSA) restrictions to avoid collisions with cliffs, while at the same time having to reach cloud bases that were often covered in thick fog (Basuki Rochmat & Sukendra Martha, 2021). In addition, the dynamics of convective cloud growth in West Sumatra are greatly influenced by orographic lifting, which causes clouds to grow into the mature phase (Cumulonimbus) much faster than clouds growing over the sea. This creates a very narrow window of opportunity for the operations team to carry out seeding before the clouds become dangerous or drop rain in undesirable locations.

The urgency of implementing OMC after a disaster is not only to reduce rainfall volume, but also a precise effort to move potential rainfall from saturated upstream areas to safer areas such as the sea or protected forests far from residential areas. Failure in this cloud interception strategy risks triggering fatal flash floods. Therefore, an in-depth analysis of seeding strategies that are adaptive to extreme topography and dynamic local weather conditions is very important. A scientific study is needed to compare standard operating procedures in flat areas with the tactical adjustments made in the mountains of West Sumatra.

Based on this, this study aims to analyze the implementation of Weather Modification Operations in mitigating the impact of flash floods in West Sumatra, with an emphasis on operational and technical reviews. This study will evaluate how topographical and meteorological constraints affect the effectiveness and strategy of operations compared to other regions. The results of this study are expected to provide new insights into hydrometeorological disaster mitigation protocols in mountainous topographical areas, as well as serve as a reference for policy makers in handling similar disasters in the future.

LITERATUR REVIEW

Hydrometeorological Disasters and Orographic Topography

Hydrometeorological disasters in Indonesia, such as the flash floods in West Sumatra, are often triggered by extreme rainfall anomalies that drench the upstream areas along the Bukit Barisan mountain range (Judijanto, 2026). In mountainous areas, the time it takes for water to flow from upstream to downstream is very short, meaning structural mitigation methods like levees or dams are often insufficient to withstand sudden peak flows. This destructive impact reveals the vulnerability of hilly areas to soil saturation caused by prolonged rainfall. Consequently, there is an urgent need for emergency mitigation measures capable of responding quickly to atmospheric dynamics before extreme rainfall hits critical areas.

Weather Modification Operations (WMO) as Non-Structural Mitigation

In emergency response situations, Weather Modification Operations (WMO) are implemented as a non-structural solution to break the upstream rainfall cycle through precipitation redistribution mechanisms. However, the application of WMO in responding to flash floods in West Sumatra presents unique operational challenges that have not been widely explored in atmospheric science literature. The majority of previous studies on weather modification effectiveness have focused on flat topographies, such as flood mitigation in Jakarta or handling forest fires. In those cases, seeding aircraft possessed high maneuverability and wide, open target areas. In contrast, operations in West Sumatra must contend with extreme orographic complexity, targeting seeding locations positioned tightly between narrow valleys and hillsides (Heimes et al., 2022).

Flight Safety and Operational Challenges

The technical difficulty of these operations increases significantly due to flight safety factors in mountainous regions. Pilots and flight scientists are bound by strict Minimum Safe Altitude (MSA) restrictions to avoid collisions with mountain cliffs, while simultaneously needing to reach cloud bases that are frequently obscured by thick fog.

Cloud Dynamics and Seeding Strategy

Furthermore, the dynamics of convective cloud growth in West Sumatra are heavily influenced by orographic lifting, which causes clouds to develop into the mature Cumulonimbus phase much faster than clouds forming over the sea. Because of these extreme updraft rates, relying solely on hygroscopic seeding materials like Sodium Chloride (NaCl) is often insufficient. To counteract this, recent operational strategies incorporate Calcium Oxide (CaO) as a cloud disruption agent. The exothermic hydration reaction of CaO releases heat energy that breaks the thermal stability of the air column, inhibiting the vertical growth of cumulonimbus clouds. This synergistic chemical strategy allows operations to not only trigger early precipitation but also actively reduce the potential for severe storms in critical, disaster-prone areas (Allen & MacMillan, 2012).

METHODOLOGY

This study uses descriptive analysis with a field study approach. This method was chosen to provide a comprehensive overview of the mechanisms, technical strategies, and operational dynamics of Weather Modification Operations (WMO) in disaster emergency response situations. The qualitative approach allows researchers to explore phenomena in the field in depth, particularly those related to tactical decision-making in the face of topographical constraints and extreme weather conditions. (Waruwu, 2024).

The research was conducted during the operation period, from December 10, 2025 to December 22, 2025. The research location was centered at the Weather Modification Operation Command Post (Posko) at Minangkabau International Airport (BIM), Padang Pariaman, as the operational control center. Meanwhile, the target area for seeding was focused on the upstream area of the watershed in the Bukit Barisan mountain range, which covers the upstream watershed areas in Agam, Tanah Datar, and Padang Pariaman regencies. The data collected in this study consisted of primary and secondary data. Primary data was obtained through participatory observation at the Command Post and documentation of daily activities, which included:

1. Daily Operation Data, covering the number of flights (sorties) and flight duration,
2. Seeding Material Data, including the tonnage of salt (Sodium Chloride/NaCl) and Quicklime (Calcium Oxide/CaO) used,
3. Flight Track Maps recorded using GPS from the SpiderTracks application to visualize seeding maneuvers in complex topography areas.

All collected data were analyzed descriptively to describe the relationship between the operational strategies implemented and the actual conditions in the field. The data analysis process was carried out by adopting an interactive analysis model that included the stages of data reduction, data presentation, and conclusion drawing. In the reduction stage, raw data in the form of daily flight logs and seed usage reports were classified based on temporal and spatial parameters. Data on the number of sorties and seed materials (NaCl and CaO) were recapitulated to identify trends in daily operation intensity. Next, data presentation was carried out by integrating the operational data into statistical graphs and frequency tables to facilitate the reading of operational response patterns to daily weather dynamics.

Specifically, this study emphasizes spatial analysis by overlaying flight path data recorded by SpiderTracks GPS with digital topographic maps of West Sumatra. This step was taken to visualize aircraft maneuvers in complex orographic areas and verify the application of sectoral interception strategies. This analysis aims to empirically prove how topographical constraints, such as the height of the Bukit Barisan ridge and the narrowness of the valley, influence pilots' decisions in determining flight paths and safe yet effective seed release points.

To ensure the validity of the findings, this study applied data source triangulation techniques. Operational data reported by the Posko operators was compared with meteorological data from BMKG (rainfall and radar imagery). The correlation between seeding time and the decrease in rainfall intensity in the target area was evaluated to measure the effectiveness of the operation. The final conclusion was based on a synthesis of all data components to answer the research question regarding the effectiveness of the OMC's implementation mechanisms and technical strategies in mitigating the risk of cold lava floods in the study area.

RESULT AND DISCUSSION

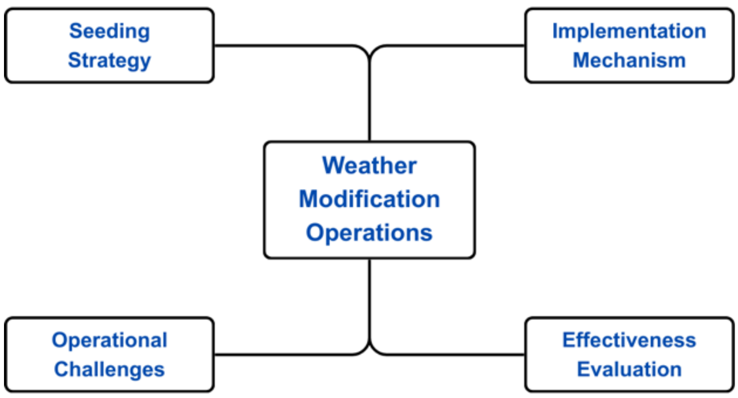

Fig. 1 Discussion Framework

To provide a comprehensive and structured overview of the implementation of Weather Modification Operations (OMC) in hydrometeorological disaster mitigation in West Sumatra, the analysis in this study is mapped into three main dimensions as visualized in Figure 1. The discussion framework focuses on three interrelated aspects,

1. Implementation Mechanism, describing the daily operational workflow and supporting infrastructure at the main command post
2. Seeding Strategy, analyzing tactical approaches in determining target areas and the use of seeding materials (NaCl and CaO) based on weather data
3. Operational Challenges, evaluating specific constraints in the field, particularly related to mountainous topography and local cloud growth dynamics

4. Effectiveness Evaluation, serving as the final parameter for measuring the success of operations through comparative analysis of rainfall reduction trends in disaster areas after OMC.

This analytical framework aims to identify the overall effectiveness of operations, from technical planning to execution in extreme terrain.

A. Implementation Mechanism

The implementation of Weather Modification Operations (OMC) in the context of mitigating hydrometeorological disasters in West Sumatra is centered at the Command Post (Posko) located at Minangkabau International Airport (BIM), Padang Pariaman. This location was chosen based on the availability of navigation facilities, logistical support for seeding materials, and proximity to the target area in the mountainous region. This operation is supported by a fleet of CESSNA CARAVAN aircraft with low-speed maneuverability specifications, which are crucial for operations in areas with extreme contours. These aircraft are capable of carrying 1,000 kg of seeding materials, hygroscopic materials (NaCl) or (CaO) per sortie.

Table 1. Aircraft Specifications

Aircraft Type	Registration Number	Capasity	Location
	PK-AKR	Maximum 6 people & 1,000 kg of planting material for 1 flight	Minangkabau International Airport. Padang Pariaman, West Sumatra

Operationally, the daily activity cycle follows a systematic workflow to ensure flight effectiveness and safety. The cycle begins with a Morning Briefing involving the Flight Scientist (FS) team from the implementing operator, BMKG, and disaster authorities. At this stage, weather radar data and potential cloud growth are analyzed to determine the target coordinates for seeding. Once the target is set, the Material Loading stage is carried out by loading the seeding material into the aircraft console. The execution or Sortie stage is carried out by flying the aircraft towards the potential target cloud. The cycle is closed with an Activity Evaluation to calculate the total seeding material used and analyze the initial impact on rainfall in the target area.

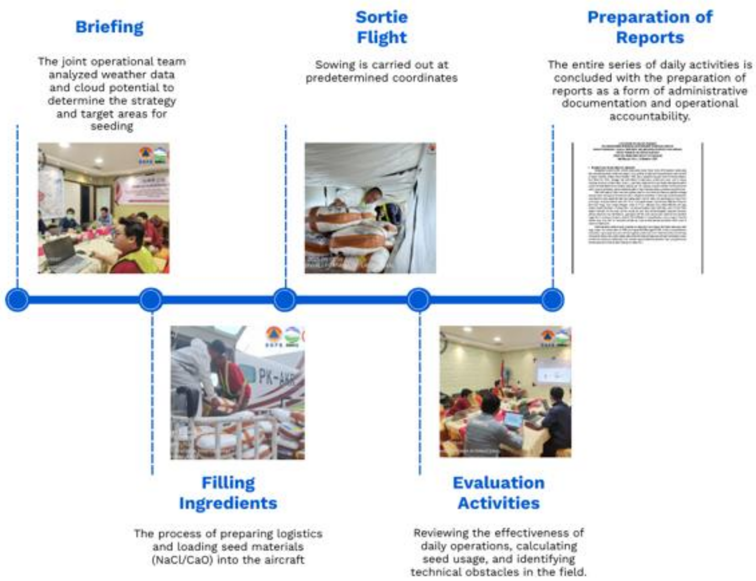

Fig. 2 Weather Modification Activity Flow

Operationally, Weather Modification Operations (OMC) follow a systematic and structured daily work cycle (Figure 2). The series of activities begins with a Morning Briefing, where the joint operational team analyzes weather data and cloud potential to determine the strategy and target seeding areas. Following the meteorological data analysis during the briefing session, the operational team develops a flight plan that serves as a tactical guide for pilots and flight scientists. Details of a typical daily flight plan are shown in Table 2 below.

Table 2. Flight Schedule

NO	SUMATERA LOCAL TIME	AIRCRAFT	MISSION	REGION	HEIGHT (FEET)
1	04.00 - 06.00	PK - AKR	*Cloud Seeding*	West Sumatera	8.000 - 10.000
2	08.00 - 10.00	PK - AKR	*Cloud Seeding*	West Sumatera	8.000 - 10.000
3	11.00 - 13.00	PK - AKR	*Cloud Seeding*	West Sumatera	8.000 - 10.000
4	14.00 - 16.00	PK - AKR	*Cloud Seeding*	West Sumatera	8.000 - 10.000
5	17.00 - 19.00	PK - AKR	*Cloud Seeding*	West Sumatera	8.000 - 10.000
6	20.00 - 22.00	PK - AKR	*Cloud Seeding*	West Sumatera	8.000 - 10.000

Based on Table 2, the operation plan is specifically designed to include estimated departure times, aircraft types, missions, target seeding areas, and flight altitudes. The target coordinates in the table are not determined randomly, but refer to sectors that are predicted to have the potential for active convective cloud growth. This plan document is dynamic, but it is a vital instrument to ensure that each sortie has a measurable objective before the aircraft takes off.

Once the flight plan has been finalized, the next stage is seed loading, which is the process of preparing logistics and loading seed material (NaCl/CaO) into the aircraft according to its carrying capacity. The main execution stage is carried out through flight sorties, where seeding is carried out at predetermined coordinates. After the flight, the cycle continues with an Activity Evaluation to review the effectiveness of daily operations, calculate the use of seeding materials, and identify technical obstacles in the field. The entire series of daily activities is concluded with the preparation of a Report as a form of administrative documentation and operational accountability.

Table 3 Daily Recap

DATE	Total Sorties	Flight Hours	Seed Material NaCl (kg)	Seed Material CaO (kg)
10-Dec-25	5	10 hours 1 minute	5.000	0
11-Dec-25	7	12 hours 39 minute	7.000	0
12-Dec-25	7	11 hours 56 minute	7.000	0
13-Dec-25	5	9 hours 6 minute	5.000	0
14-Dec-25	5	9 hours	4.000	1.000
15-Dec-25	5	10 hours 28 minute	1.000	4.000
16-Dec-25	5	8 hours 26 minute	4.000	1.000
17-Dec-25	3	7 hours 8 minute	3.000	0
18-Dec-25	6	11 hours 17 minute	4.000	2.000
19-Dec-25	6	11 hours 13 minute	2.000	4.000
20-Dec-25	6	10 hours 33 minute	6.000	0
21-Dec-25	5	8 hours 49 minute	2.000	3.000
22-Dec-25	4	7 hours 24 minute	1.000	2.000
Total	**69**	**128 hours 0 minute**	**51.000**	**17.000**

B. Seeding Strategy

The strategy for implementing Weather Modification Operations (OMC) in West Sumatra applies a dynamic and adaptive approach, relying entirely on weather forecast data analysis released by the Meteorology, Climatology, and Geophysics Agency (BMKG). The determination of seeding techniques and locations is not done statically, but is adjusted to wind patterns and potential cloud growth detected in real time.

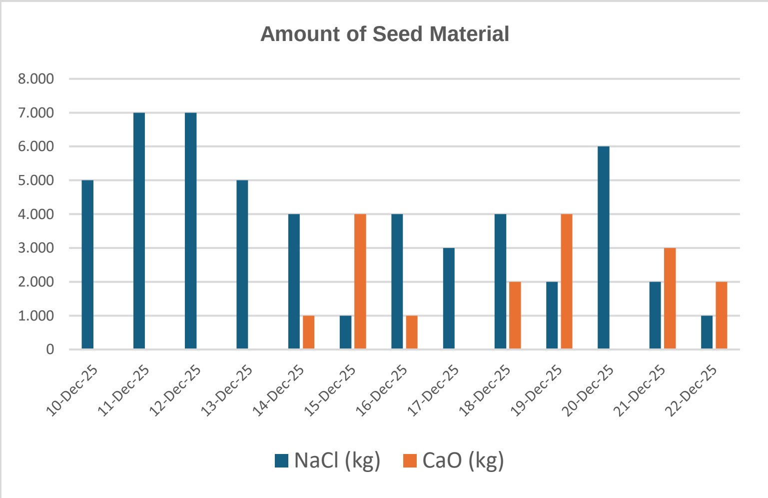

Fig. 3 Seed Composition Chart

The effectiveness of operations in West Sumatra is highly dependent on the application of a hybrid seeding strategy that combines the hygroscopic properties of sodium chloride (NaCl) and the exothermic properties of calcium oxide (CaO). The use of NaCl alone is often insufficient to counteract orographic clouds with extreme updraft rates. Therefore, CaO is used as a cloud disruption agent. The hydration reaction of CaO ($CaO + H_2O \rightarrow Ca(OH)_2$ + Heat) releases 15.9 kcal/mol of heat energy, which is capable of breaking the thermal stability of air columns and practically inhibiting the vertical growth of cumulonimbus clouds. This synergy allows the operations team to not only trigger rain, but also reduce the potential for storms in critical areas (Branch & Wulfmeyer, 2019).

In addition to chemical and physical aspects, the accuracy of determining the target for seeding is highly dependent on the integration of meteorological data from the BMKG. This dependence is not a weakness, but rather a form of data-based Decision Support System. Given the topography of the Barisan Mountains, which creates a complex microclimate, the use of global weather prediction model data often has a high degree of bias. (Yulihastin, 2024). Therefore, Nowcasting data from BMKG weather radar becomes the main validation instrument to minimize errors in determining seeding coordinates, ensuring that seeding materials are released precisely on cloud cells that have optimal liquid water content.

The surge in the use of CaO seeding material on December 15 and 19, 2025 in Figure 3 was carried out in response to the appearance of massive storm clouds detected by radar in the morning, requiring a more aggressive cloud breaking strategy than on other days.

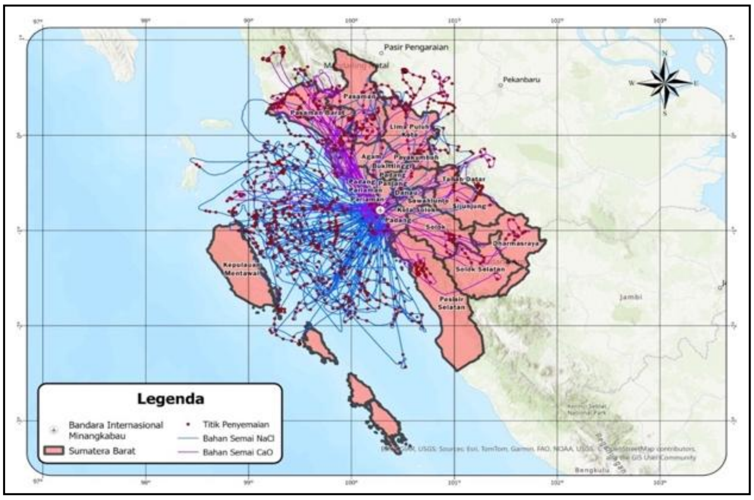

Fig. 4 Sorting Lane Accumulation

Figure 4 presents a spatial visualization of all flight paths and seeding points during the operation period from December 10 to 22, 2025. Based on the map, it is clear that Minangkabau International Airport functions as an operational control center, with flight paths spreading in various directions but with a certain concentration pattern. The main focus of operations is clearly dominant in the western and northwestern sectors of West Sumatra. Salt (NaCl), marked with blue lines, and quicklime (CaO), marked with purple lines, are mostly spread over sea areas and along the coastline. This pattern confirms that the strategy employed is an Interception Strategy. This means that aircraft actively block rain clouds moving from the Indian Ocean before they can penetrate far inland and reach mountainous areas.

The density of red dots in coastal areas such as Padang Pariaman, Agam, and West Pasaman indicates high seeding intensity in these zones. The aim is to trigger rain to fall earlier over the sea. In this way, the volume of water carried by the wind towards the mainland can be significantly reduced, thereby minimizing the risk of high-intensity rainfall.

C. Operational Challenges

The implementation of weather modification operations in West Sumatra faces a significant level of technical complexity due to the topography of the region, which is dominated by the Bukit Barisan mountain range. Unlike operations in flat areas, the steep mountain contours with extreme elevation variations create strict limitations on the Minimum Safe Altitude (MSA) for flight safety. Pilots and flight scientists are required to perform precision maneuvers between valley gaps in order to reach the cloud base, while still maintaining a safe distance from the mountain cliffs. These conditions limit the aircraft's maneuverability, especially when seeding in the upstream sector, which is in close proximity to the peaks of Mount Marapi and Mount Singgalang. (Utomo et al., 2023).

These topographical challenges are exacerbated by local weather dynamics characterized by rapid cloud growth due to orographic lifting mechanisms. Moist air masses driven by westerly winds are forced to rise abruptly when they collide with mountain walls, triggering strong atmospheric instability. As a result, Cumulus clouds can transform into massive Cumulonimbus (CB) clouds accompanied by high turbulence in a matter of hours. This phenomenon requires a much faster operational response than operations in other regions, as even a slight delay in the interception process can cause the clouds to develop into storms that endanger seeding aircraft. (Nugraha et al., 2021).

The interaction between difficult terrain and dynamic weather conditions has a direct impact on the narrow window of opportunity for operations. Based on an evaluation of daily implementation data, the effective time for seeding is generally limited to the morning to afternoon hours, namely between 07:00 and 16:00 WIB. Outside this time frame, pilot visibility is often reduced due to mountain fog or convective clouds blocking access to the target area. This limited duration forces the operation strategy to prioritize sorting intensity with frequent intervals in the morning to maximize rain redistribution before weather conditions deteriorate in the afternoon. (Amal & Wiranata, 2023).

D. Effectiveness Evaluation

The success of OMC implementation is measured through comparative analysis between seeding activities and actual rainfall trends measured on the surface. The evaluation focuses on the ability of operations to reduce rainfall intensity in the target area and move it to the waters off West Sumatra. Rainfall Trends in the Target Area Based on weather radar monitoring, rain clouds were successfully intercepted before entering the target area. At times of high seeding intensity, as seen in the sortie number graph, rainfall at observation posts around Bukit Barisan tended to be recorded in the light to moderate category, even though the potential for regional cloud growth was relatively high. This indicates that the intervention of NaCl seeding material successfully accelerated the rainfall process before the clouds reached the peak orography.

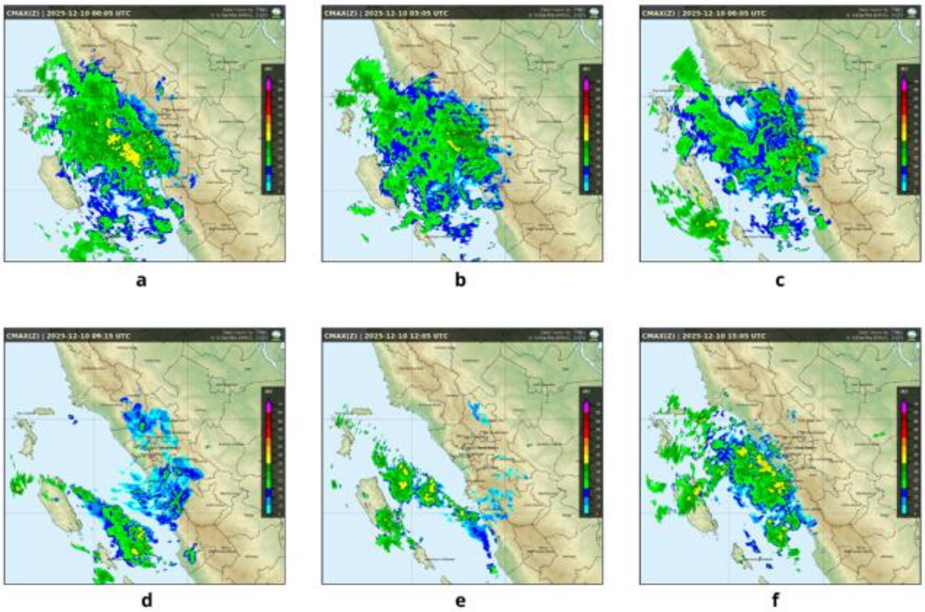

Fig. 5 Weather Radar Image Accumulation

In addition to surface rainfall data, effectiveness was also evaluated through spatial evolution analysis of rain clouds using weather radar imagery (CMAX Reflectivity). Figure 5 presents a time series of cloud growth and decay on the sample operation date of December 10, 2025, from 00:05 UTC to 15:35 UTC. The radar visualization shows the dynamics of the seeding intervention results as follows:

1. Growth Phase:
   In images (a) and (b) at 00:05 – 03:05 UTC, convective cloud cells can be seen forming over the Indian Ocean and moving towards the coast of West Sumatra. It is during this phase that the interception strategy is carried out intensively through early morning sorties to seed the clouds with NaCl.
2. Mature & Interception Phase:
   On panel (c) at 06:35 UTC, the cloud cell reached its mature phase with maximum reflectivity ranging from yellow to green. However, based on its spatial pattern, it appears that significant precipitation occurred in coastal areas and over the sea. This indicates the success of the rain breaking mechanism, whereby water masses were dropped before the clouds entered the mountainous terrain of the Bukit Barisan range.
3. Decay Phase:
   In panels (d), (e), and (f) at 09:15 – 15:35 UTC, the clouds appear to undergo rapid mass decay as they enter the afternoon and evening hours. The mountainous area on the eastern side appears relatively clear from radar reflections. This condition confirms that OMC intervention is effective in reducing cloud energy and preventing the accumulation of extreme rainfall that could potentially trigger flooding upstream during critical hours.

Spatial Verification of Rainfall The effectiveness of the redistribution strategy was also confirmed by visual weather radar data and field observation reports. Heavy rainfall was concentrated in the western coastal areas and marine waters, in line with the planned scenario. Conversely, the upstream areas, which were designated as disaster red zones, experienced a significant reduction in hydrological load during the active operation period, thereby optimally mitigating the risk of flooding.

CONCLUSIONS AND RECOMMENDATIONS

The implementation of Weather Modification Operations (OMC) in the context of mitigating hydrometeorological disasters in West Sumatra has been carried out using an adaptive strategy approach to topographical conditions and extreme weather. During the operation period, a total of 69 sorties were recorded, with a cumulative flight time of 128 hours. A total of 68 tons of seeding materials, consisting of 51 tons of Sodium Chloride (NaCl) and 17 tons of Calcium Oxide (CaO), were distributed to modify cloud growth.

Technically, this operation successfully implemented the Sectoral Interception strategy by focusing seeding in the upwind West and Northwest regions. Analysis of flight path maps shows that the rainfall redistribution strategy was effectively carried out by triggering rainfall in coastal and marine areas before the air mass entered the orographic area. The use of a combination of NaCl seeding material for rain initiation and CaO for the decomposition of high instability clouds has been proven to reduce the potential for extreme rainfall upstream.

However, operations in West Sumatra face significant challenges in the form of the topography of the Bukit Barisan mountains, which limits aircraft maneuverability, and the rapid dynamics of cloud growth. This results in a very limited window of operation, which is only effective between 00:00 and 09:00 UTC. Based on these findings, this study recommends the need to develop a Fixed Weather Modification Operation Protocol for mountainous areas that differs from standard procedures in lowland areas. This protocol should include: (1) Flight Envelope Adjustments that set more conservative maneuvering and minimum safe altitude limits, (2) Mandatory use of portable weather radar or real-time radar data access on aircraft for cloud gap navigation, (3) Intensive Morning Sortie Strategy to precede the afternoon convection cycle.

ADVANCED RESEARCH

While this study demonstrates the effectiveness of the Sectoral Interception strategy in West Sumatra, several limitations remain that offer opportunities for further investigation. The current analysis primarily relies on qualitative descriptive methods and spatial visualization. Future research should incorporate quantitative statistical modeling to calculate the precise percentage of rainfall reduction attributable solely to Weather Modification Operations (WMO) versus natural meteorological decay.

Furthermore, this study highlights significant operational constraints caused by extreme orographic complexity and rapid cloud growth. Subsequent research could explore the following areas:

- Microphysical Cloud Analysis: Investigating the specific microphysical changes within orographic clouds following the combined injection of NaCl and CaO to better understand the chemical interaction in high-updraft environments.
- Technological Integration: Evaluating the use of unmanned aerial vehicles (UAVs) or automated seeding systems to overcome Minimum Safe Altitude (MSA) limitations and increase seeding precision in narrow valleys.
- Long-term Hydrological Impact: Conducting multi-seasonal longitudinal studies to assess how continuous rainfall redistribution affects the long-term hydrological balance of the Bukit Barisan river basins.
- Radar-Based Automation: Developing AI-driven decision support systems that integrate real-time CMAX weather radar data directly into flight navigation systems to optimize the narrow operational window identified in this study.

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REFERENCES

Akhmad, A. H., & Bayuadji, G. (2020). The Effectiveness Of The Application Of Weather Modification Technology (TMC) In Order To Increase The Availability Of Water In Reservoirs To Overcome The Water Crisis. Https://Doi.Org/10.31219/Osf.Io/G87jr

Amal, N., & Wiranata, H. A. (2023). The Effect Of Rain Distribution On The Calculation Of Flood Discharge In The Martapura Watershed Swamp Area. Jurnal Kacapuri : Jurnal Keilmuan Teknik Sipil, 6(2), 217. Https://Doi.Org/10.31602/Jk.V6i2.12965

Amri, S., & Giarno, G. (2024). Analysis Of Atmospheric Dynamics In Floods, Landslides, And Strong Winds In Semarang And Demak On March 13,

2024. Jurnal Ilmiah Biosaintropis (Bioscience-Tropic), 10(1), 77–89. Https://Doi.Org/10.33474/Ejbst.V10i1.594

Basuki Rochmat, & Sukendra Martha. (2021). The Influence Of Geographical Factors On Aviation Safety In Indonesia. Journal Of The National Institutes Of The Republic Of Indonesia, 9(2), 13–23. Https://Doi.Org/10.55960/Jlri.V9i2.388

Cabang, O., & Wulfmeyer, V. (2019). Pincrease In Deliberate Rainfall Using Desert Plantations. Proceedings Of The National Academy Of Sciences, 116(38), 18841–18847. Https://Doi.Org/10.1073/Pnas.1904754116

Nugraha, R. A., Tedemaking, K. E. L., & Sacharissa, V. (2021). Penguatan Kedaulatan Negara Di Udara Dan Urgensi Sinkronisasi Hukum. Kertha Patrika, 43(1), 65. Https://Doi.Org/10.24843/KP.2021.V43.I01.P05

Purwaningsih, A., Harjana, T., Hermawan, E., & Andarini, D. F. (2020). Rainfall And Extreme Rainfall Conditions During Strong And Weak Mjo: Spatial And Seasonal Distribution In Indonesia. Journal Of Weather Modification Science & Technology, 21(2), 85–94. Https://Doi.Org/10.29122/Jstmc.V21i2.4153

Sidauruk, M., Risma Saragih, H. J., Tri Utomo, S., Widodo, P., & Kusuma. (2023). The Utilization Of Weather Modification Technology As An Effort To Overcome Hydrometeorological Disasters In Indonesia. PENDIPA Journal Of Science Education, 7(2), 195–200. Https://Doi.Org/10.33369/Pendipa.7.2.195-200

Subekti, A., Chalid, A., & Siregar, C. A. (2023). Study On Flood Mitigation Of The Rongkong River In North Luwu Regency. Techno-Socio Ekonomika, 16(2), 223. Https://Doi.Org/10.32897/Techno.2023.16.2.1776

Suryanti, K., Fitriyani, D., Muharsyah, R., & Marzuki, M. (2020). Analysis Of Diurnal Rainfall Variations In West Sumatra Using Rain Gauge Data And IMERG. POSITRON, 10(2), 1. Https://Doi.Org/10.26418/Positron.V10i2.38469

Utomo, B. W., Suliartha, E. R., & Santoso, P. N. (2023). Optimistic User Bias Flight Simulator. Teknoin, 28(2), 53–57. Https://Doi.Org/10.20885/Teknoin.Vol28.Iss2.Art6

Waruwu, M. (2024). Qualitative Research Approach: Concepts, Procedures, Advantages And Roles In The Field Of Education. Source: Journal Of Educational Research And Evaluation, 5(2), 198–211. Https://Doi.Org/10.59698/Afeksi.V5i2.236

Yulihastin, E. (2024). The Interaction Between The Atmosphere And The Ocean Triggers Extreme Weather To Improve The Accuracy Of Predictions Of

Onset Rainfall On The Coast. Penerbit BRIN. Https://Doi.Org/10.55981/Brin.1096