Mapping Cloud Seeding Potential Areas from MODIS Cloud Top Pressure

Shamsul Anuar S.N.[1], Haron Narashid R.[1*], Razak T.R.[2] and Abdul Rahman A.N.[1]

[1]Faculty of Built Environment, Universiti Teknologi MARA, Perlis Branch, Arau Campus, 02600 Arau, Perlis, Malaysia

[2]Faculty of Computing Science, College of Computing, Informatics, and Mathematics, Universiti Teknologi MARA, 40450 Shah Alam, Malaysia

*rohayuharon@uitm.edu.my

***Abstract*:** *Cloud seeding is a weather modification technique that involves materials such as silver iodide or hygroscopic salts being introduced into clouds to stimulate rainfall. However, the variability of weather patterns and the unsuitability of clouds often limit its effectiveness. Low clouds at elevations of 0 to 2 km are favourable for cloud seeding operations (CSOs). Nowadays, the location of low clouds can be detected using satellite remote sensing. Therefore, this study aims to identify potential areas for CSOs by analysing remotely sensed low cloud distribution during the inter-monsoon season. The potential areas were retrieved from the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Cloud Top Pressure (CTP) data using an International Satellite Cloud Climatology Project (ISCCP) threshold method and mapped with Geographic Information System (GIS) overlay analysis. The results show a strong spatial relationship between the identified areas and actual CSO locations conducted by the Malaysian Meteorological Department (MET) in 2019 and 2023, with low cloud thresholds between 680 and 1000 hectopascals (hPa). Thus, potential location areas based on low clouds can be detected and mapped using remote sensing satellite images. While some dams consistently met the criteria for seeding, others exhibited interannual variability due to complex atmospheric factors. This emphasizes the importance of real-time weather monitoring and adaptive strategies to improve the effectiveness of cloud seeding operations.*

Keywords: cloud seeding, cloud classification, cloud top pressure, low cloud, remote sensing

Introduction

Cloud seeding is a weather modification technique that alters weather conditions using various technologies and methods to increase precipitation, reduce hail, and disperse fog in arid and semi-arid regions (Dong et al., 2021; Abshaev et al., 2022; Agrawal et al., 2024; Wang et al., 2024). Fang et al. (2022) and Lou et al. (2023) explained that CSOs disperse substances such as silver iodide or hygroscopic salts into clouds, which act as condensation or ice nuclei to initiate droplet and ice crystal formation. CSOs have been implemented worldwide, including in the United States, China, Australia, Saudi Arabia, and Malaysia, to address water scarcity and support agriculture (Pokharel et al., 2021; Hua et al., 2024; Alzahrani et al., 2025; Anuar et al., 2024). For example, Huang et al. (2021) discussed that cloud seeding supports Sustainable Development Goal (SDG) 6 by enhancing water availability for human needs, agriculture, and industry. By inducing rainfall, cloud seeding helps stabilize food production and reduce the risks of crop failure that may lead to shortages. It can also lessen extreme events such as hailstorms, contributing to climate change mitigation under SDG 13 (Branch et al., 2019). In Malaysia, prolonged drought during the Southwest Monsoon reduced reservoir levels to below 40 percent in several states (Saadi et al., 2025; Audrey Dermawan, 2025), emphasizing the role of CSOs in maintaining sufficient raw water supply (Hazali et al., 2022; Muhammad et al., 2020).

The success of CSOs depends on factors such as cloud type, humidity, wind, and cloud cover. McFarquhar (2022) found that precipitation patterns vary significantly across different temporal and spatial scales, mainly due to differences in cloud microphysical properties (the small-scale physical characteristics of cloud particles), topography, and atmospheric circulation. Since only certain clouds are favourable for seeding, low clouds below 2000 m altitude (Brown, 2022) are often targeted for their precipitation potential. Cumulus clouds are particularly ideal due to their vertical extent and the presence of supercooled liquid water (water droplets that remain liquid below freezing point), which can enhance rainfall (Mazzetti et al., 2021; Essein, 2023).

Integrating passive satellite remote sensing can retrieve cloud-top properties. This approach is useful for monitoring and predicting clouds and atmospheric conditions. Wei et al. (2024) and Wojciechowska (2025) stated that Cloud Top Pressure (CTP) characterizes cloud properties and supports the retrieval of additional information. Satellites, such as Moderate Resolution Imaging Spectroradiometer (MODIS), Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), and Microwave Integrated Retrieval System (MiRS), provide CTP data. These data can be compared to enhance retrieval accuracy (Cho et al., 2021; Bao et al., 2024). Liu et al. (2023) and Nguyen et al. (2025) revealed that MODIS derives CTP using the CO_2 slicing method. This method applies infrared bands between 12 and 15 μm within the CO_2 absorption range. Various methods have been proposed for cloud detection. Threshold methods (Ackerman et al., 1998; Ahmad et al., 2014), machine learning, and artificial intelligence methods have all been described (Zaitoun et al., 2019; Mahajan et al., 2020; Shang et al., 2024). Mahajan et al. (2021) mentioned that combining classification methods, such as threshold-based and machine learning approaches, can improve accuracy. It can also add complexity to the classification process.

Despite the importance of cloud classification in meteorology and CSOs, there is limited spatial analysis specifically focused on cloud classification in Malaysia. This gap hinders the accurate classification of potential locations due to differences in cloud layers and types. To address this challenge, threshold-based methods and GIS analysis techniques serve as tools for improving analysis. Anuar et al. (2023) revealed that MODIS cloud threshold methods detect clouds by applying specific thresholds. This separates clouds from non-cloud pixels and is commonly used to classify low, middle, and high clouds. Choi et al. (2022) further emphasized that advanced threshold techniques using CTP images can distinguish clouds from haze and snow. These methods help reduce misclassification and improve data accuracy. Therefore, this study aims to determine clouds in Peninsular Malaysia using the Terra MODIS satellite and the International Satellite Cloud Climatology Project (ISCCP) CTP threshold. The objectives were to classify clouds with the ISCCP CTP threshold and evaluate clouds for potential cloud seeding locations.

Study Area

The research area is situated in Peninsular Malaysia, covering approximately 131,732 km² and located between latitude 3.9743°N and longitude 102.4381°E, as shown in Figure 1 (Ng et al., 2024). The region experiences two main monsoons, namely the Northeast Monsoon (November to March), which brings heavy rainfall to the east coast states, and the Southwest Monsoon (May to September), which tends to be drier, especially along the east coast. In between, two inter-monsoon periods cause convective activity and localized thunderstorms. Studies indicate that inter-monsoon periods create favourable conditions for CSOs due to atmospheric instability, cumulus cloud development, and high moisture levels (Ahmad, 2023; Korneev et al., 2022; Essien, 2023). Peninsular Malaysia has 83 dams that serve as the main sources of water for domestic, agricultural, and industrial needs, highlighting the role of CSOs as a strategy to boost precipitation and ensure water security.

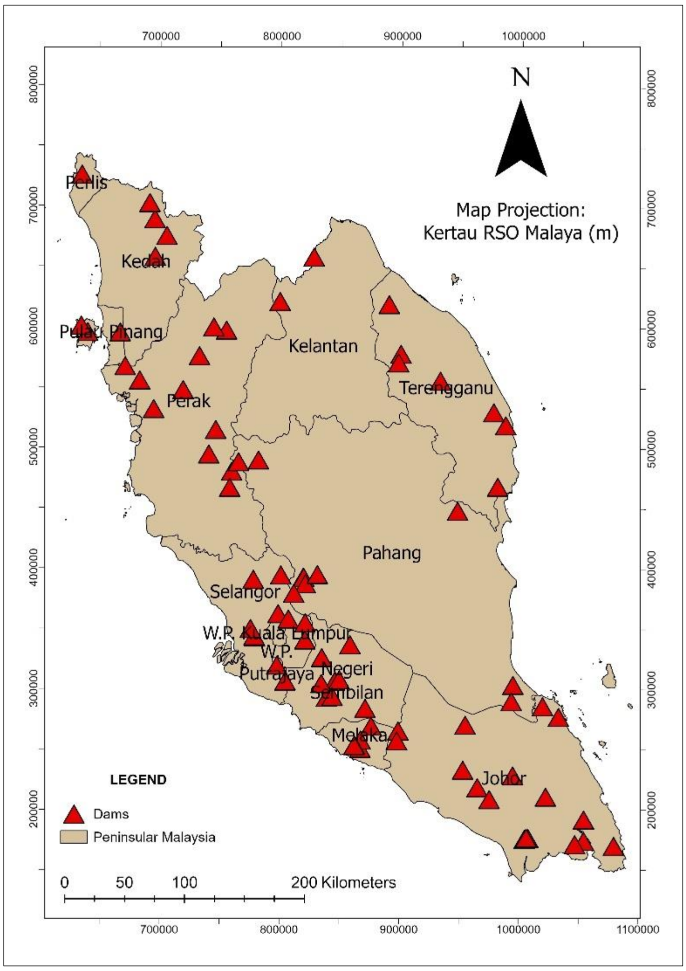

Figure 1: Study Area

Methodology

Figure 2 illustrates the four primary phases implemented to achieve the study's objectives: data acquisition, pre-processing, data processing, and integration of low cloud data using the Geographic Information System (GIS) analysis tool. The analysis utilized two cloud datasets derived from MET operations conducted on April 29, 2019, and May 4, 2023.

a. Pre-Processing

The Terra MODIS cloud top pressure (CTP) underwent atmospheric correction and MODIS georeferencing in phase two (2). Atmospheric correction was applied to improve the quality of remote sensing satellite images by removing atmospheric scattering and absorption effects from the reflectance values (Merzah et al., 2020). MODIS georeferencing is a crucial step in pre-processing to ensure that spatial information is accurate and in the same coordinate system, facilitating consistent spatial analysis. Van et al. (2018) explained that this process allows for precise overlay and comparison with other geospatial datasets. Thus, the MODIS georeferenced tool in ENVI was used to reproject the satellite images into the Kertau RSO Malaya (meters) coordinate system, thereby accurately representing Peninsular Malaysia.

b. Rescaling

According to Jiang et al. (2010), all MODIS 06 products were stored as 16-bit integers to reduce the Hierarchical Data Format (HDF) file size. The conversion of these integers back to floating-point values for CTP required the application of a scale factor and an additional offset value from each Scientific Data Set (SDS) attribute to retrieve accurate data (Lawson et al., 2017). Therefore, a rescaling computation, as shown in Equation 1, was applied in phase three (3). The scale factor was used to convert the integer values into their corresponding floating-point values, while the additional offset was added to the scaled values to obtain the final floating-point values in hectopascals (hPa).

$$\textit{Scaling} = \textit{scale factor} * (\textit{digital number (DN)} - \textit{additional offset}) \qquad (1)$$

c. ISCCP CTP Threshold for Cloud Classification

Liu et al. (2023) highlighted that MODIS uses the 11-µm infrared window channel to determine CTP by comparing the brightness temperature with temperature profiles from meteorological analyses. CTP is one parameter used to identify cloud levels or etages, including high, middle, and low, based on the ISCCP CTP threshold values. Studies have shown that CTP values greater than 680 hPa indicate low clouds (refer to Table 1). This threshold helps distinguish low clouds from middle and high clouds. Meanwhile, CTP values 440 hPa and 680 hPa, classified as middle clouds and high clouds, lie below 440 hPa (Satoh et al., 2018; Săftoiu et al., 2022; Nguyen et al., 2025). Liang et al. (2017) stated that this classification of clouds based on CTP is consistent with the ISCCP standards. The method relies on established ISCCP CTP thresholds, which are widely applied in long-term cloud climatology studies (Nguyen et al., 2025).

Table 1: ISCCP CTP Threshold for Cloud Classification

Cloud Levels	Threshold (hPa)	Description
High	50 - 440	Values below 440 hPa indicate high clouds
Middle	440 - 680	Values between 440 hPa to 680 hPa indicate middle clouds
Low	680 - 1000	Values greater than 680 hPa indicate low clouds

Source: Nguyen et al., 2025

d. Integrated Remote Sensing Cloud Classification with GIS Analysis

Phase four (4) integrated cloud classification with dam locations to identify potential areas for cloud seeding, thereby addressing the second objective of this study. The cloud classification output was intersected using ArcGIS Pro analysis tools, and the resulting layers were overlaid with 83 dam locations across Peninsular Malaysia to generate suitability maps. The final outputs were validated against daily rainfall data from ground stations and dam observations to assess the reliability of the identified areas.

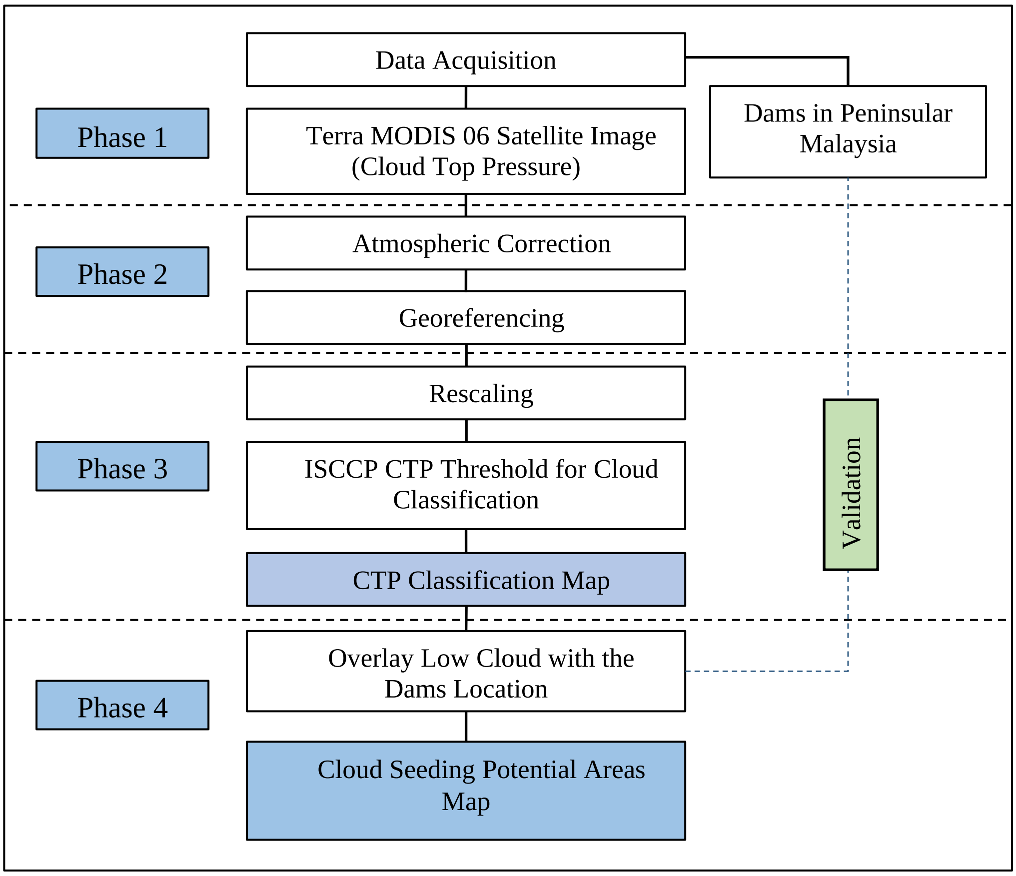

Figure 2: Research Methodology Workflow

Results and Discussion

a. Cloud Classification from Terra MODIS Cloud Top Pressure

Figure 3 shows the cloud classification over Peninsular Malaysia on April 29, 2019, and May 04, 2023. High clouds are shown in light blue (106–440 hPa), middle clouds in blue (441–680 hPa), and low clouds in dark blue (681–1000 hPa).

Map 3(a) displays the widespread presence of high clouds, including Cirrus, Cirrocumulus, and Cirrostratus (Skorokhodov et al., 2022), scattered across the northern region, especially over Perlis, Kedah, northern Perak, and parts of Kelantan on April 29, 2019. Middle clouds, which include Altocumulus, Altostratus, and Nimbostratus (Ambilduke et al., 2023), were prevalent in the central and eastern areas, such as Pahang, Terengganu, and Kelantan. Low clouds, like Stratus, Cumulus, Stratocumulus, and Cumulonimbus (Filipiak, 2021), cover the southern and central regions, including Kuala Lumpur, Putrajaya, Selangor, Negeri Sembilan, and parts of the west coast. On May 4, 2023, most of Peninsular Malaysia was covered by low clouds, as shown in Figure 3(b). Little middle clouds were in the central and eastern areas, like southern Pahang and Terengganu. Conversely, high clouds appeared in the central and eastern regions.

According to Jamaluddin et al. (2019), low, middle, and high clouds typically form under convective systems influenced by varying wind patterns during the inter-monsoon season. Previous studies by Ayoub et al. (2024) and Jayakrishnan et al. (2021) found that the interaction between sea breezes from the Straits of Malacca and easterly winds from the South China Sea significantly enhances local convection. Generally, local convective systems play a key role during the inter-monsoon season, contributing to the formation of low clouds by increasing atmospheric instability (Lin et al., 2022) and humidity (Wang et al., 2020). Dong et al. (2023) stated that these clouds mainly form through shallow rather than deep convection. In comparison, middle clouds develop through shallow to moderate convection. This cloud formation is affected by atmospheric stability, moisture, and wind patterns (Chen et al., 2021). However, weaker deep convection limited high clouds during these seasons (Johnston et al., 2018).

Based on the cloud distribution in both datasets, Yang et al. (2021) reported that regions of cloud formation were linked to atmospheric instability, which provided favourable conditions for cloud development. Studies by Na et al. (2023) stated that high surface temperatures and humidity contribute to this instability. Ayoub et al. (2024) highlighted that land and sea breezes often trigger convection, where rising warm air cools and condenses, leading to frequent afternoon thunderstorms and extensive cloud formation during the inter-monsoon season. In contrast, Sahu et al. (2020) and Wang et al. (2024b) mentioned that the reduction of atmospheric moisture may limit cloud formation, thus leading to a decline in cloud cover.

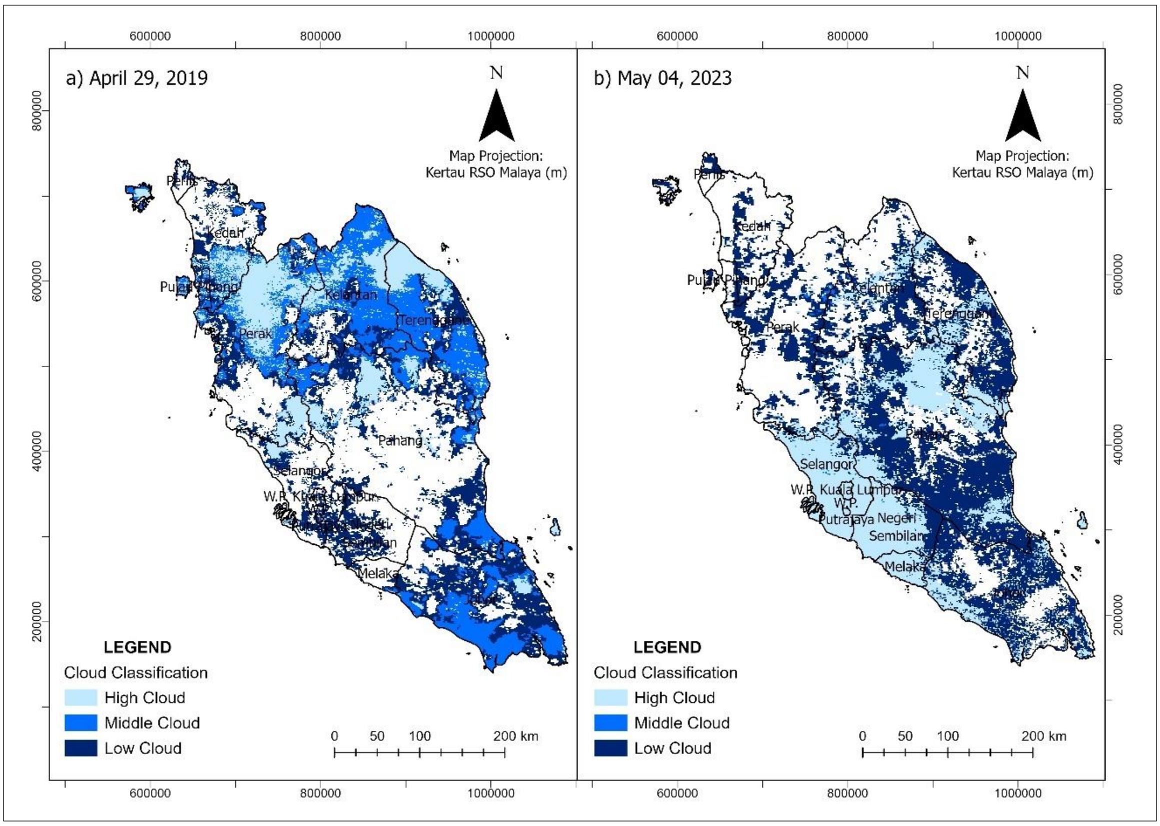

Figure 3: Cloud Classification from Terra MODIS Cloud Top Pressure on (a) April 29, 2019, and (b) May 04, 2023

b. Cloud Seeding Potential Areas in Peninsular Malaysia

The low cloud results from the cloud classification maps were overlaid with the locations of 83 dams across the study area to create potential cloud seeding maps, as shown in Figure 4. The identified potential areas are summarized in Table 2.

Table 2 shows 18 dam locations out of 83 dams identified as potential areas based on CTP values ranging from 705 hPa to 985 hPa, indicating favorable cloud conditions on April 29, 2019 (refer to Figure 4 (a)). Among the states, Negeri Sembilan recorded the highest number of potential areas with four dams: Teriang, Kelinchi, Sungai Terip, and Gemencheh. Although Johor exhibited dominant low cloud formation, only three of its nine dams were identified as favourable for seeding. In the northern region, Kedah had the highest number of potential dams in Beris, Pedu, and Ahning, while Pulau Pinang and Perak each had only one potential dam.

On May 4, 2023, the number of potential dam locations increased to 30, compared to 2019. This increase was influenced by widespread low cloud coverage, with CTP values ranging from 780 to 985 hPa. Johor recorded eight potential dam areas, mainly due to extensive coverage by low clouds. In Pulau Pinang, the number of potential dams rose to three, including Air Itam, Teluk Bahang, and Bukit Panchor, with CTP values ranging from 855 hPa to 930 hPa, compared to only one potential dam, Mengkuang, identified in 2019. This indicates increased low cloud coverage across the state, improving its suitability for CSOs. However, in Kedah, only one dam, Padang Saga, met the criteria for seeding in 2023, compared to three potential dams identified in 2019. In Perak, the number of potential dams increased to three in 2023, including Bukit Merah, Jor, and Air Kuning, whereas only Jor was selected in 2019.

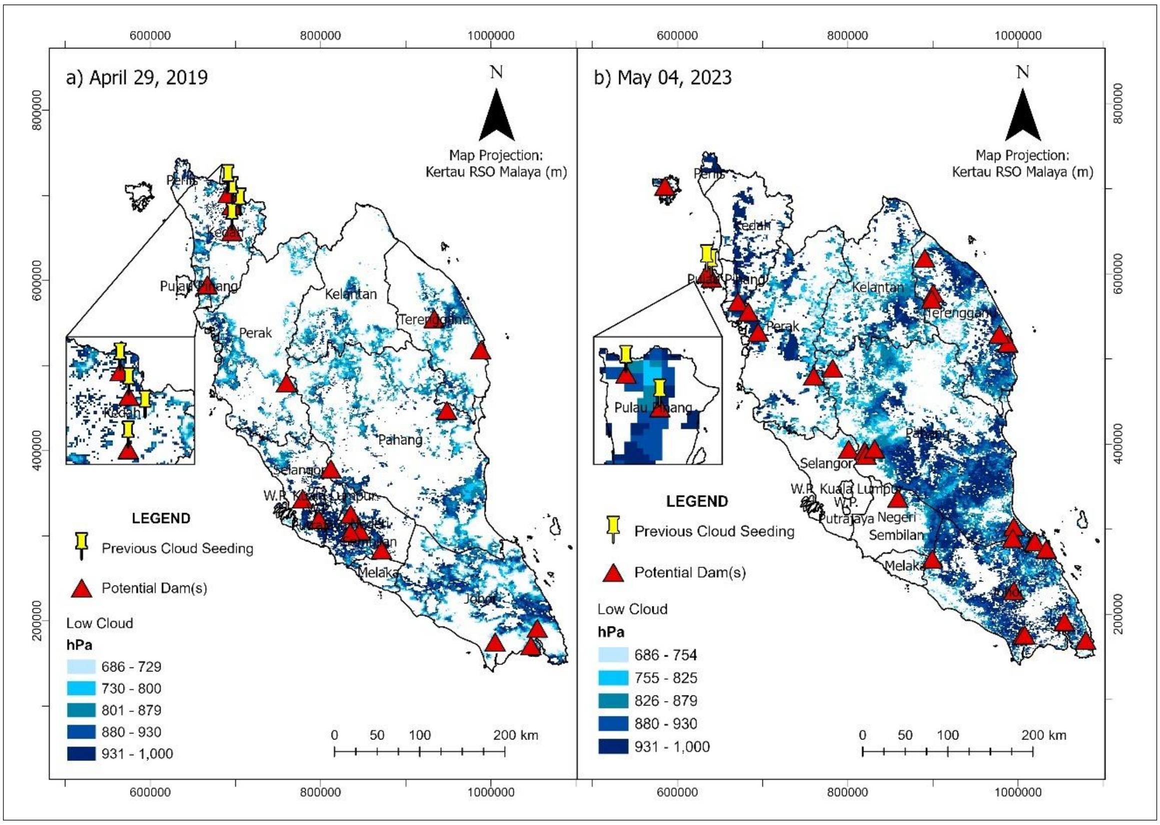

Figure 4: Cloud Seeding Potential Areas on (a) April 29, 2019, and (b) May 04, 2023

Table 2: List of potential areas for cloud seeding across Peninsular Malaysia

No.	Year	Coordinate (N, E)	State	Potential Dam	CTP (hPa)
1.	2019	5.959, 100.769	Kedah	Beris	930
2.		6.234, 100.773		Pedu	960
3.		6.362, 100.729		Ahning	930
4.		5.393, 100.506	Pulau Pinang	Mengkuang	905
5.		4.350, 101.341	Perak	Jor	705
6.		3.117, 101.509	Selangor	Sungai Baru	985

7.		2.897, 101.679	Putrajaya	Putrajaya	985
8.		2.954, 102.015	Negeri Sembilan	Teriang	985
9.		2.775, 102.112		Kelinchi	930
10.		2.759, 102.011		Sungai Terip	930
11.		2.574, 102.340		Gemencheh	930
12.		1.593, 103.534	Johor	Gunung Pulai 1	705
13.		1.553, 103.910		Layang (Upper)	960
14.		1.738, 103.977		Seluyut	705
15.		5.024, 102.906	Terengganu	Kenyir	730
16.		4.689, 103.395		Paka	880
17.		4.050, 103.034	Pahang	Chereh	880
18.		3.436, 101.806		Ceruk	855
1.	2023	6.372, 99.770	Kedah	Padang Saga	960
2.		5.396, 100.262	Pulau Pinang	Air Itam	905
3.		5.444, 100.214		Teluk Bahang	855
4.		5.140, 100.543		Bukit Panchor	930
5.		5.033, 100.652	Perak	Bukit Merah	880
6.		4.350, 101.341		Jor	905
7.		4.819, 100.756		Air Kuning	985
8.		3.573, 101.709	Selangor	Sungai Selangor	800
9.		3.050, 102.228	Negeri Sembilan	Mardi Jelebu	880
10.		2.405,102.587	Melaka	Asahan	905
11.		2.586,103.670	Johor	Labong	880
12.		2.506,103.790		Congok	780
13.		1.541,104.202		Lebam	825
14.		1.593,103.534		Gunung Pulai 1	780
15.		1.599,103.560		Gunung Pulai 2	855
16.		2.746,103.448		Pontian Kecil	880
17.		2.068,103.446		Kahang	930

18.		1.738,103.977		Seluyut	825
19.		5.597,102.522	Terengganu	Paya Peda	880
20.		5.225,102.610		Tembat	930
21.		5.160,102.593		Puah	985
22.		4.689,103.395		Paka Storage	930
23.		4.788,103.306		Dungun Storage	880
24.		3.556,101.877	Pahang	Old Repas	825
25.		3.554,101.881		New Repas	825
26.		3.506,101.893		Perting	780
27.		2.746,103.448		Pontian	880
28.		2.624,103.436		Anak Endau	930
29.		4.434,101.542		Ulu Jelai	800
30.		3.575,101.983		Kelau	855

c. Validation of Potential Seeding Areas with Previous CSOs by MET

Table 3 presents the potential dams that align with previous CSOs conducted by the Malaysian Meteorological Department (MET). Validation of these areas was performed using rainfall data and dam locations across the study area to evaluate operational effectiveness. Maki et al. (2018) reported that precipitation generally occurs 20 to 30 minutes following the operation, with intensity and duration influenced by atmospheric conditions and the type of seeding materials used.

On April 29, 2019, the operation was deemed successful, as a nearby ground station recorded approximately 1.5 mm of rainfall. Similarly, CSOs conducted on May 4, 2023, resulted in 7.2 mm of rainfall observed shortly after the operations. Of the 18 potential dams identified on April 29, 2019, three dams, including Beris, Pedu, and Ahning in Kedah, corresponded with previous MET operation areas. On May 4, 2023, two dams in Pulau Pinang, Air Itam and Teluk Bahang, were also identified as potential areas and had been targeted in prior operations. In contrast, the Muda dam in Kedah, which had previously been included in operations, was not identified as a potential area in 2019. This omission resulted from the absence of low clouds over the region, as indicated by CTP data from MODIS for that date.

Table 3: Validation of Potential Seeding Areas with Previous CSOs by MET

No.	Date	Potential Dam(s)	Potential Areas Coincide with Previous CSOs	State
1.	April 29, 2019	18	Beris Pedu Ahning	Kedah
2.	May 04, 2023	30	Air Itam Teluk Bahang	Pulau Pinang

Conclusion and Recommendation

The results show that MODIS CTP cloud classification using the threshold method effectively identifies suitable cloud types for cloud seeding across Peninsular Malaysia. Low clouds, usually below 2 km, consistently meet the conditions for CSOs and have the potential to increase precipitation over target areas due to strong vertical growth and adequate supercooled liquid water. Additionally, the ISCCP CTP threshold successfully classifies clouds into low, middle, and high categories. Combining MODIS satellite imagery with GIS analysis tools allows for the effective identification of appropriate clouds for cloud seeding operations, supporting more efficient weather modification planning in Malaysia.

Including additional atmospheric parameters like wind speed, relative humidity, temperature, and atmospheric stability indices can improve the accuracy of evaluating potential areas for cloud seeding. Finally, expanding the analysis beyond dam locations to other regions, such as agricultural zones, could reveal more favourable atmospheric conditions for these operations.

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