UNIVERSITI TEKNOLOGI MARA

CLOUD CLASSIFICATION AND ATMOSPHERIC CONDITIONS ASSESSMENT FOR RAIN ENHANCEMENT USING FUZZY LOGIC AND KRIGING IN SATELLITE REMOTE SENSING

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Thesis submitted in fulfilment
of the requirements for the degree of
Master of Science
(Built Enviroment)

Faculty of Built Environment

February 2026

ABSTRACT

Rain enhancement, also known as cloud seeding, is a weather modification technique that utilises materials such as silver iodide or hygroscopic salts to stimulate artificial precipitation in hazy or drought-affected regions. Low-level cloud and atmospheric conditions, such as cloud cover and wind speed, are essential factors in cloud seeding operations (CSOs). However, CSOs have often yielded only limited success, primarily due to the variability of weather patterns, unsuitable cloud types, and unfavourable atmospheric conditions. To address this challenge, integrating satellite remote sensing data with machine learning and GIS techniques offers a promising approach to optimise CSOs. This study aims to determine clouds and the atmospheric conditions in Peninsular Malaysia using the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) with Fuzzy Logic classification and GIS-based interpolation methods for rainfall enhancement. To achieve the aim of the study, the objectives of this study are: i) to classify the MODIS cloud threshold and Fuzzy Logic techniques, ii) to determine the atmospheric conditions based on cloud cover and wind speed related to rainfall formation, and iii) to evaluate clouds and atmospheric conditions for potential rain enhancement. There were five (5) datasets of Terra MODIS remote sensing satellite imagery and ground wind speed from previous CSOs, covering the years 2019, 2020, 2022, and 2023. A Fuzzy Logic System (FLS) approach was used to classify the cloud threshold of Terra MODIS data based on cloud top height (CTH), cloud top pressure (CTP), and cloud top temperature (CTT) as input variables. Cloud cover was computed by rescaling images into percentage units and mapping the estimated cloud cover. Kriging interpolation was then applied to estimate wind speed patterns at the seeding height of 2 km. The potential CSO areas were mapped by integrating cloud classification results with cloud cover estimation and wind speed patterns. The findings showed that MODIS cloud threshold data combined with the Fuzzy Logic technique classified the potential of low-level clouds across the study area. Cloud cover estimates of 50 to 100 percent indicate a high potential for successful seeding and could increase precipitation. All wind speeds observed over the dam areas were suitable for seeding, which remained below 11.1 m/s at the target seeding height. By integrating cloud classification with atmospheric conditions, five (5) potential areas were identified, including KADA (Kelantan), Ahning and Muda Dams (Kedah), and Air Itam and Teluk Bahang Dams (Pulau Pinang). These areas fall within previously seeded regions operated by MET Malaysia. In addition, several other suitable dams across Peninsular Malaysia were identified. While some dams consistently met the CSO criteria, others displayed year-to-year variability, highlighting the importance of real-time weather monitoring and adaptive strategies to enhance the effectiveness of CSOs. Overall, this study demonstrates the potential of combining satellite remote sensing with machine learning and GIS analysis to assess cloud characteristics and atmospheric conditions for rainfall enhancement.

ACKNOWLEDGEMENT

First and foremost, I would like to thank Allah S.W.T., the Almighty, for His countless blessings, strength, and guidance throughout the completion of this thesis. Truly, hardships often prepare ordinary people for an extraordinary destiny.

I want to express my deepest appreciation to my supervisor, Dr. Rohayu Haron Narashid, and co-supervisor, Dr. Tajul Rosli Razak, for their continuous support, guidance, insightful feedback, and endless patience from the beginning of this research until its completion. Thank you for always being available whenever I had questions or concerns, whether in person or through online meetings.

To my dearest parents, Shamsul Anuar Mohamed Ismail and , my sister, Siti Zulfa, and all my beloved family members, thank you for your unwavering love, prayers, and sacrifices. Thank you for allowing me to chase my dreams and always believing in me, even when I struggled to believe in myself. This achievement is as much yours as it is mine.

To my B110 lab mates, thank you for your companionship, motivation, and constant support throughout this Master's journey. Your presence made the long hours in the lab, challenging tasks, and tight deadlines much more bearable. Whether it was sharing knowledge, offering encouragement, or simply making me laugh during stressful times, I am genuinely grateful for every moment we shared.

To all my dear friends, thank you for being a constant source of encouragement, laughter, and support. Your kind words, thoughtful gestures, and understanding meant more than I can express. From late-night messages to shared struggles and simply being there, your presence made this experience lighter and far more meaningful.

Last but not least, I wanna thank me, I wanna thank me for believing in me, I wanna thank me for doing all this hard work, I wanna thank me for having no days off, I wanna thank me for never quitting.

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INTRODUCTION

1.1 Research Background

Climate change has a significant impact on temperature and precipitation. According to Lu (2024), some areas may experience prolonged drought, while others may face continuous rainfall and flooding disasters. A drought is a prolonged dry period that results in a water shortage exceeding the average volume of water available on the land surface (Hasan et al., 2021). Estrela et al. (2024) discuss long-term changes in rainfall patterns and drought affecting a recharge area of the hydrological system. Yang et al. (2023b) reported that drought conditions are likely to persist and intensify over time, with the affected area projected to expand from about 1 percent to 30 percent during the 21st century.

In Southeast Asia, droughts have frequently led to crop damage, forest fires, and the depletion of water supplies (Suhana et al., 2023). Throughout the dry period of the Southwest Monsoon, from May to September in Peninsular Malaysia, increased water demand and rising drought occurrences have raised concerns about a water shortage. Dąbrowska et al. (2023) stated that prolonged water supply disruptions during severe drought events will impact many settlements in urban areas, resulting in scheduled water rationing. Therefore, rain enhancement, also known as cloud seeding operations (CSOs), must supply the dams with sufficient raw water. This is essential to meeting human water demands and preserving the river system and dams (Angelakis et al., 2024; Deng et al., 2025).

Rain enhancement involves dispersing ice nuclei materials such as silver iodide (AgI) and potassium iodide (KI) into supercooled clouds. These compounds serve as cloud condensation nuclei (CCN), thereby altering the microphysical processes within the targeted cloud (Essien, 2023; Azeez et al., 2024). In the past, rain enhancement was even used as a weapon. Sudhinaraset (2024) and Angalapu et al. (2025) report that the United States military used weather modification by seeding clouds over Laos and areas along the Ho Chi Minh trail to extend the monsoon season to damage and disrupt those regions. Today, weather modification is a sophisticated meteorological technique used to increase rainfall, reduce hail, and disperse fog (Jung et al., 2022).