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Could Weather Modification Technology Mitigate the Risk of Forest Fires and Local Climate Change?

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Abstract The effectiveness of weather modification technology (WMT) in reducing forest fire risk and influencing local climates is still a topic of ongoing research. This study examines the application of WMT to mitigate forest fires and local climate change in Ketapang Regency, West Kalimantan, Indonesia, over five years (2019-2023). This study utilized daily rainfall data from the Climate Hazard Group InfraRed Precipitation with Stations (CHIRPS), hotspot data from NASA's Fire Information for Resource Management System (FIRMS), and burned area data derived from the Differenced Normalized Burn Ratio (DNBR), all of which were analyzed using satellite imagery. Drought severity was evaluated using the Normalized Difference Drought Index (NDDI), generated from Sentinel-2 satellite data. A target-only statistical methodology was applied for the data analysis. The results indicated that the implementation of WMT in a relatively short period (from June 28 to July 10, 2023) was associated with a significant increase in rainfall (PCH=1.41), a substantial reduction in hotspot areas (PHS <1), and a decrease in burned areas (PLS<1). The drought severity index decreased in 70% of the areas during the WMT period. While these findings underscore the potential effectiveness of WMT on local climate change, the study recommends a thorough review and refinement of WMT implementation strategies. This would help optimize its impact on climate change and ensure consistent drought mitigation across different regions over longer observational periods.

Keywords Weather Modification Technology, WMT, Rainfall, Hotspots, Burned Area, NDDI, Drought Index, Kalimantan, Indonesia

1. Introduction

Indonesia, a tropical nation, faces a significant risk of hydrometeorological disasters, notably forest fires and water scarcity [1]. Climate change and global warming are exacerbating the predicted frequency and intensity of extreme weather events, including droughts. Drought poses a substantial threat to water security across domestic, agricultural, and industrial sectors, and this challenge is further intensified by the increasing irregularity of rainfall patterns [2].

Additionally, climate change is contributing to a higher incidence of forest fires. The initial major fire events in Indonesia were primarily attributed to inadequate forest management practices and the El Niño phenomenon [3]. Significant forest fires occurred in East Kalimantan in 1982/83, along with widespread conflagrations in 1997/98 that resulted in approximately 25 million hectares of land burned globally [4], [5].

These fires have a detrimental impact on ecosystem health and significantly increase carbon emissions. In 2023, the area affected by forest and land fires in West Kalimantan reached 101,241.2 hectares, accounting for 10.2% of the national total of 994,313.2 hectares. The Ketapang Regency was recorded as one of the areas with the highest number of forest fire cases. Preventing and mitigating forest fires requires focused attention to minimize further impacts.

The government has implemented various measures to mitigate forest fires and droughts. These measures include early detection of hotspots, the Fire Hazard Warning System (SPBK), public education initiatives, investment in fire extinguishers, and increased supervision in vulnerable areas [3]. Additionally, remote sensing technology that utilizes satellite imagery is employed for disaster monitoring, including analyses of drought conditions and land-use changes [6], [7].

Weather Modification Technology (WMT) is one of the strategies implemented in Indonesia to mitigate forest fires and droughts by conducting a cloud seeding process using 50 milli micron NaCl particles to increase rainfall [8], [9].

The objective of this study is to investigate how the implementation of WMT affects the reduction of forest fires and the local climate, especially the drought index, in the Ketapang Regency, Indonesia, from 2019 to 2023 (Figure 1).

Ketapang Regency encompasses 20 districts, such as Kendawangan district and Air Upas district.

This study examined the relationship between WMT and the Normalized Difference Drought Index (NDDI), as well as its correlation with rainfall, the number of hotspots, the area affected by forest fires, and drought distribution within the research areas (Figure 1).

The expected outcomes of this study will have practical implications for developing effective strategies to mitigate forest and land fires. Furthermore, this research serves as a foundational reference for future studies assessing the effectiveness of Water Management Techniques (WMT). It also offers a categorized understanding of drought levels, assisting in anticipating the impacts of drought and their connections to forest fire events.

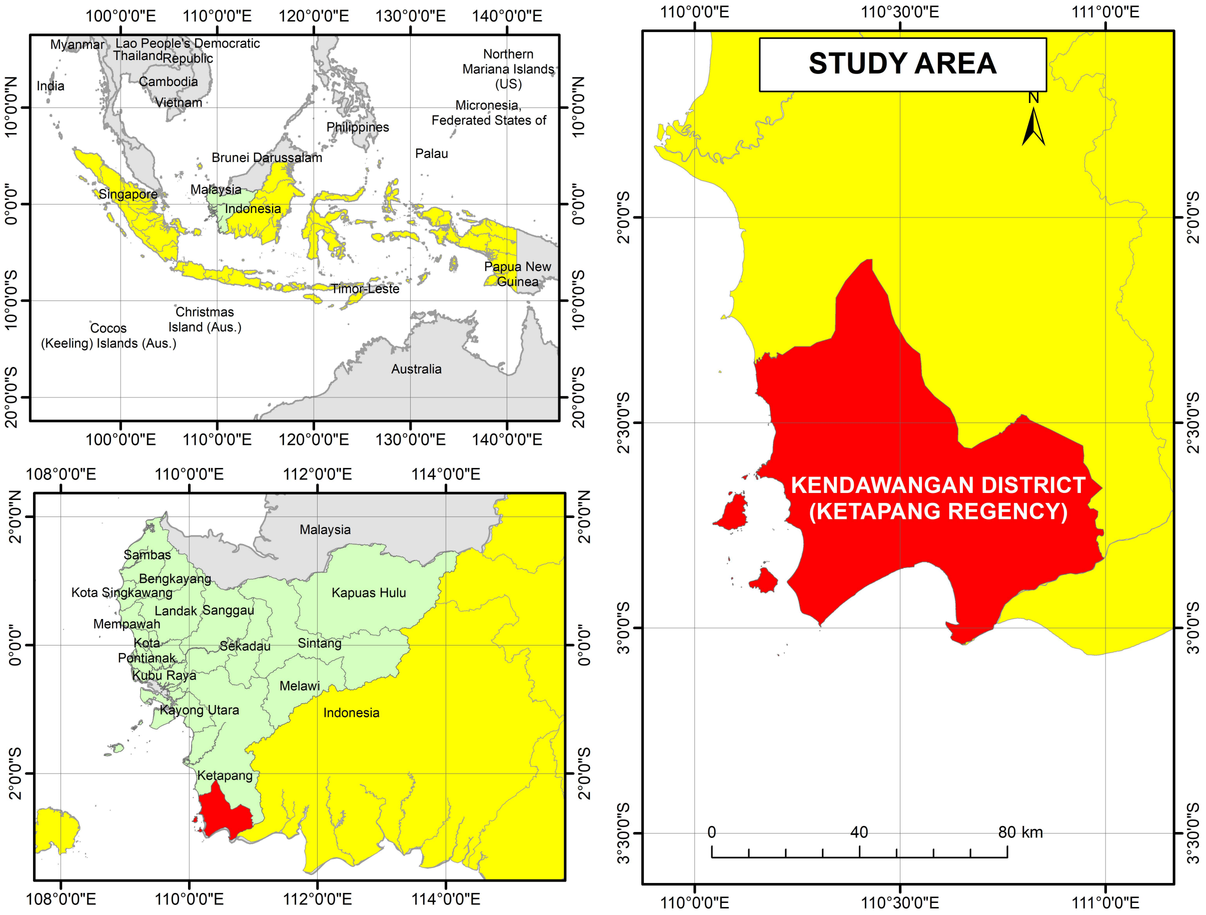


Figure 1. Map of the Research Area

2. Research Methods

2.1. Rainfall

Rainfall is a major component in the climate system that affects the Earth's hydrological cycle, ecosystems, and energy balance [10]. As a crucial factor in agriculture, economics, and environmental health, rainfall is measured in millimeters or inches and varies based on geography, climate, and weather conditions [11]. Precipitation includes rain, snow, fog, dew, and hail, which occur as a result of the process of condensation of water vapor in the atmosphere [12].

Weather modification techniques can be employed to influence rainfall, relying on factors such as cloud potential, available opportunities, seeding materials, and diligent monitoring equipment [13]. Rainfall measurements can be conducted using manual rain gauges, radar, or satellite data, including Satellite Precipitation Products (SPPs), which offer broader area coverage than the traditional method [11].

2.2. Hotspots Areas

Hotspots indicate areas of abnormal temperatures, often linked to forest and land fires, and are detected through remote sensing satellites [14]. The Terra and Aqua satellites use MODIS sensors to identify hotspots [15].

Some attributes of hotspots include latitude, longitude, confidence level, brightness temperature, and Fire Radiative Power (FRP) [16].

A confidence level of hotspots of 80% or higher is used in the analysis as it enhances the accuracy of fire detection, and ensures the implementation of more effective countermeasures [17].

2.3. Forest and Land Fires

Forest and land fires are environmental problems that have an impact on the economy, ecology, and society [4]. The main cause is land clearing for plantations, agriculture, and illegal logging [18].

Remote sensing technology facilitates fire monitoring through satellite image analysis, enabling the accurate identification of affected areas [19]. Various analysis methods are employed, including DNBR, RBR, BAIS2, NDVI, and MISBI, which utilize satellite imagery such as Landsat 8, Sentinel-2A, and MODIS to provide initial data of post-fire land change [20].

2.4. Different Normalized Burn Ratio (DNBR)

The Normalized Burn Ratio (NBR) is a metric used to assess the impact of fires on vegetation by comparing the reflectance of near-infrared (NIR) and short-wave infrared (SWIR) wavelengths [21].

This method is more specific than NDVI in detecting fire damage [22]. NBR assists in monitoring post-fire vegetation restoration and planning land rehabilitation. The classification of fire severity based on NBR values shows a rate of regrowth to a high level of damage [23].

2.5. Drought and Drought Index

According to Law of the Republic of Indonesia Number 24 of 2007 concerning Disaster Management, drought is defined as the availability of water that is significantly below the needs of life, agriculture, and the economy. Drought can be categorized into four types: meteorological, hydrological, agricultural, and socioeconomic [24]. It results from climate variability, primarily due to decreased rainfall [25]. In Indonesia, drought is an annual disaster that has an impact on groundwater resources [26].

The drought index is used to measure and monitor the level of drought within an area, aiding in more effective mitigation. Drought develops slowly, so it is often ignored [26]. This index has various measurement methods based on data types, such as SPI, SPEI, NDVI, and NDDI, which have advantages and disadvantages according to data needs [27], [28].

2.6. Normalized Difference Drought Index (NDDI)

The NDDI is a satellite-based method for monitoring drought by comparing the reflectance of near-infrared (NIR) and red (RED) light, indicating the level of water stress on vegetation [29]. The higher the NDDI value, the more severe the drought (Table 1).

Table 1. NDDI Classification

NDDI Value	Drought Index
-0.05 – 0.01	Normal
0.01 – 0.15	Low Drought Index
0.15 – 0.25	Moderate Drought Index
0.25 – 1	High Drought Index
>1	Severe Drought Index

Source: [30].

The NDDI value ranges from -0.05 to over 1, with classifications varying from normal conditions to very severe drought [30].

Generally, this index is used in agriculture and water resource management to mitigate the effects of drought.

2.7. Sentinel-2 Satellite Imagery

Sentinel-2, part of the European Space Agency's Copernicus program, provides high-resolution data for land mapping, agricultural monitoring, and environmental analysis [31]. With multispectral sensors, Sentinel-2 captures a wide range of wavelengths that support land cover analysis and disaster monitoring. The specification covers a wide range of spectral bands with resolutions between 10-60 meters [32]. The open data from Sentinel-2 is beneficial for research and decision-making related to environmental issues.

The conceptual diagram (Figure 2) summarizes the integration of multi-source satellite data (CHIRPS rainfall, FIRMS hotspot, Sentinel-2 NDDI/DNBR) and their analysis using the Target-Only Method to assess the effectiveness of Weather Modification Technology (WMT) in Ketapang Regency, Indonesia.

2.8. Disaster Mitigation

Disaster mitigation aims to reduce the risk and impact of disasters through proactive measures, including emergency response planning, the development of disaster-resilient infrastructure, and public education initiatives [26]. This approach is important to minimize negative impacts on both humans and the environment.

2.9. Weather Modification Technology (WMT)

Weather Modification Technology (WMT) is employed to control rainfall and mitigate the impacts of disasters such as forest fires. The effectiveness of WMT is evaluated by measuring the additional rainfall produced through cloud seeding [33]. The "Target-Only" method is used to assess its efficiency by calculating additional rainfall (PCH), the reduction of hotspots (PHS), and the reduction of fire-affected areas (PLS), without implementing random designs in the evaluation.

2.10. Rainfall Data Analysis

Rainfall data in this study were obtained from Satellite Precipitation Products (SPPs), namely Climate Hazard Group InfraRed Precipitation with Station (CHIRPS), which was calibrated with rain station data and had a spatial resolution of 0.05 degrees (~5 km) and a daily temporal resolution. Data processing is carried out using Google Earth Engine (GEE), a cloud-based platform that enables efficient large-scale geospatial analysis. The CHIRPS Daily dataset is imported into GEE through the dataset catalog (https://developers.google.com/earth- engine/datasets/catalog/UCSB-CHG_CHIRPS_DAILY) and filtered by the 2019 to 2023 time range.

The processing stages include data extraction based on precipitation bands, visualization in the form of time series graphs, calculation of annual rainfall accumulation, and clipping based on the shapefile of Ketapang Regency. The data is visualized in the form of a map with a specific color scale to show the annual rainfall distribution, and the results of the analysis were exported to Google Drive in GeoTIFF format for GIS applications (Figure 3).

Figure 3 provides a comprehensive overview of the process of analyzing rainfall data and its distribution patterns in Ketapang Regency, particularly in Kendawangan District in 2023, which is the basis for conducting further studies on rainfall conditions in the region.

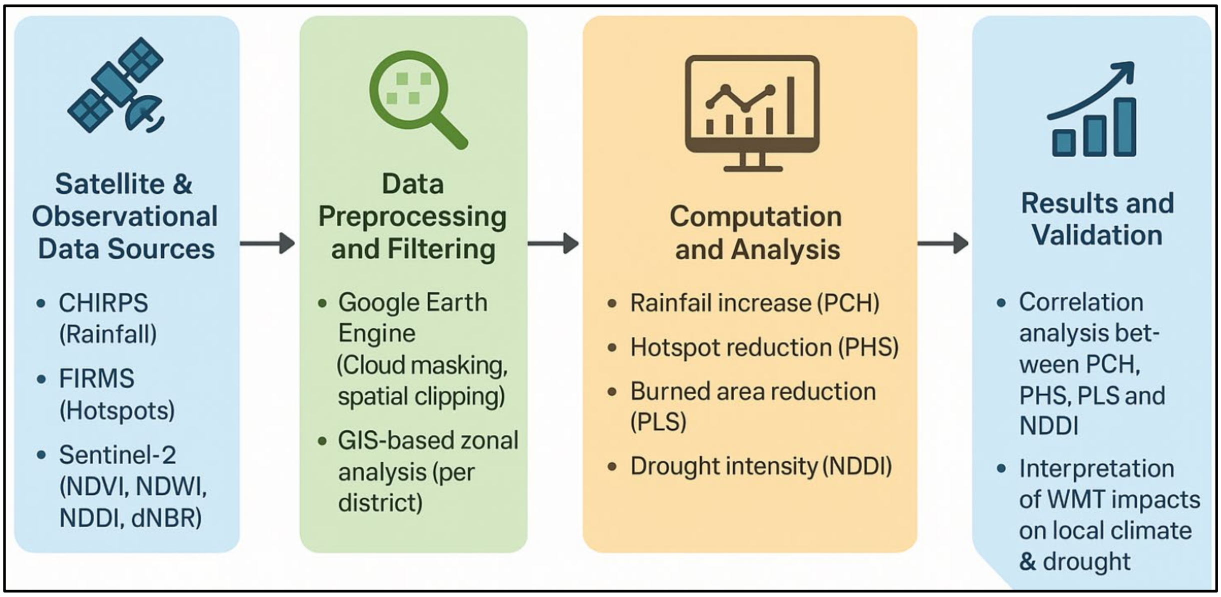
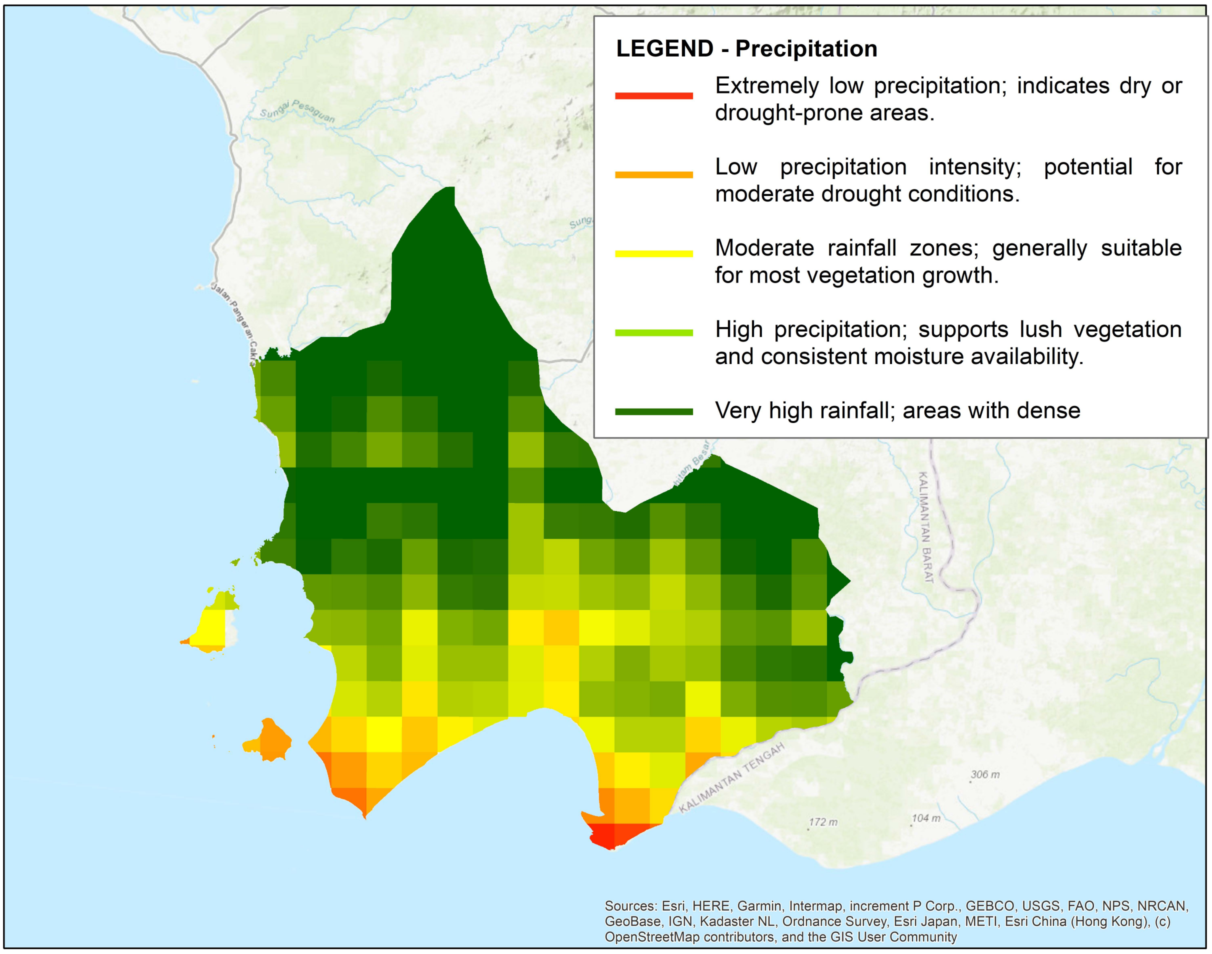


Figure 2. Processing, and Analysis in Evaluating WMT



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 3. Rainfall Data Processing Process in Kendawangan District, Ketapang Regency in 2023

2.11. Hotspot Analysis

This hotspot data analysis covers 5 years (from 2019 to 2023). By involving data from multiple years, we can identify long-term trends and changes in hotspot patterns that may not be seen in a single annual analysis. This approach assists stakeholders in better understanding the dynamics of forest and peatland fires in Ketapang Regency, West Kalimantan Province, while supporting more targeted planning and data-driven decision-making (Figure 4).

The accuracy and reliability of the data are important aspects of this analysis. Therefore, it is important to rely on official and reliable data sources. One of the globally recognized data sources for hotspot monitoring is NASA's website through the FIRMS (Fire Information for Resource Management System) platform. The required hotspot data can be accessed via the FIRMS website at the following link: https://firms.modaps.eosdis.nasa.gov.

2.12. Fire Area Analysis

The analysis of forest and land fire areas in this study uses MSI's Sentinel-2 satellite imagery with the calculation of the Normalized Burn Ratio (NBR), which is designed to identify burned areas and assess fire severity [34]. NBR is one of the normalized burn indexes, first introduced by García & Caselles (1991) as an alternative to the Normalized Difference Vegetation Index (NDVI), by replacing the red band (R) in NDVI with short wave or infrared wave (SWIR). The Normalized Burn Ratio is calculated using the following equation:

$$NBR = (NIR + SWIR)/(NIR - SWIR) \qquad \text{(i)}$$

Information:

NBR = Normalized Burn Ratio

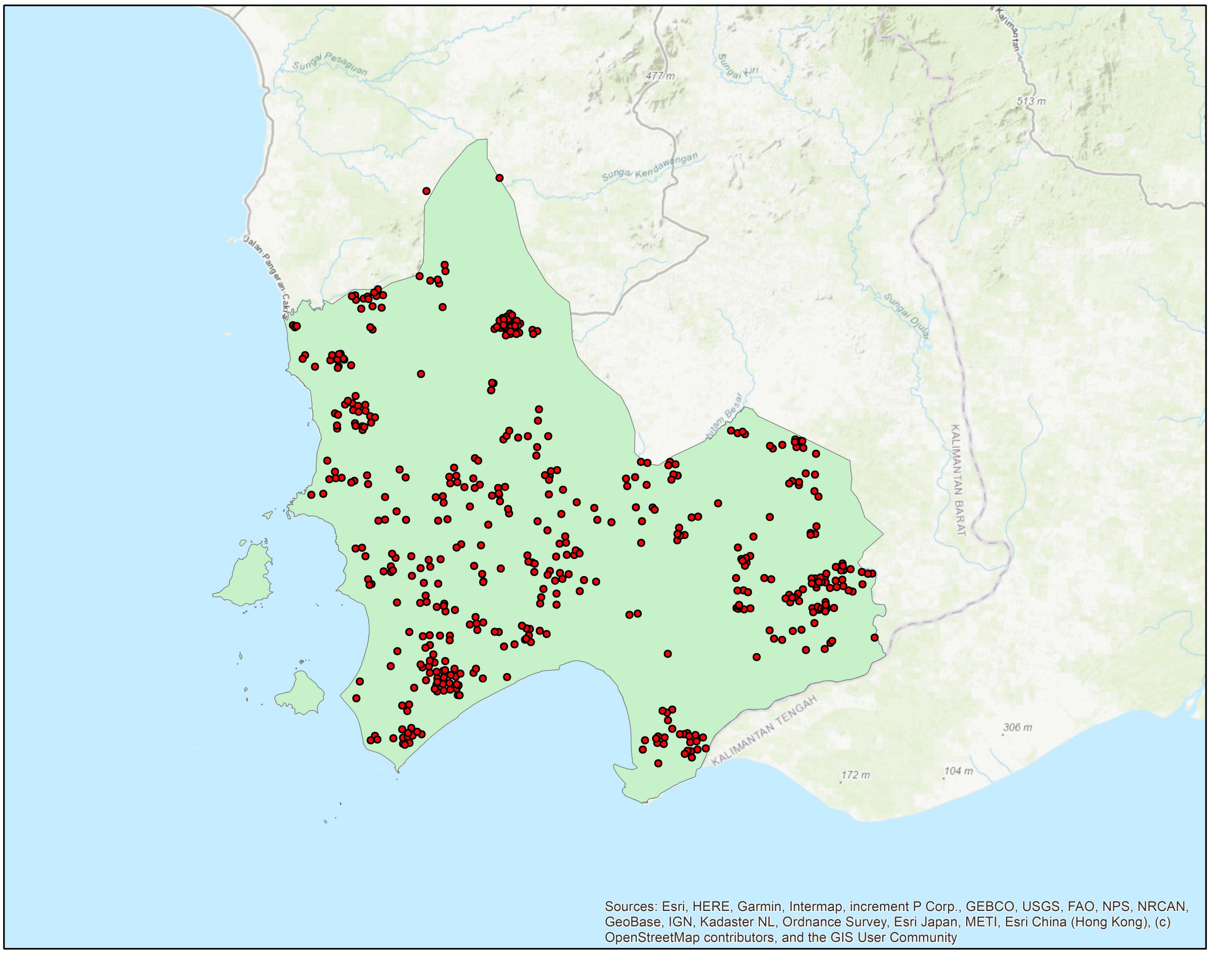
NIR = Spectral value of the Near InfraRed channel (Band 5)

SWIR = InfraRed Short Wavelength Channel Spectral Value (Band 6)

To assess the impact of a fire, the Differenced Normalized Burn Ratio (DNBR) was used, which is obtained by subtracting the post-fire NBR value from the pre-fire NBR value:

$$DNBR = NBR\_PreFire - NBR\_PostFire \qquad \text{(ii)}$$

The interpretation of the DNBR value depends on the vegetation community before the fire, where the higher the DNBR value, the greater the impact of the fire on the vegetation [35].



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 4. Hotspot Data Extraction Process using ArcGIS

This analysis was carried out using Google Earth Engine (GEE), which enables high-efficiency processing and analysis of cloud-based satellite imagery. The main stages in this analysis include cloud removal from Sentinel-2 imagery using the QA60 band, taking pre- and post-fire imagery based on the May–June 2023 and July–August 2023 time frames, as well as NBR calculation and visualization to distinguish between burned and non-burned areas. Furthermore, the DNBR is calculated to determine the severity of the fire, where areas with a DNBR value of more than 0.6 are categorized as burned areas. The burned area is calculated in hectares using the reduce Region function in the GEE (Figure 4).

For validation, hotspot data from NASA FIRMS is used to verify the location of the fire, with visualization of hotspots based on the level of fire confidence. The data from the analysis, including the burned area, is exported in GeoTIFF format so that it can be used for further analysis in GIS devices. This analysis process can be seen in Figure 5.

2.13. Drought Index Analysis

This study uses Google Earth Engine (GEE) to analyze the drought index using the Normalized Difference Drought Index (NDDI) method based on Sentinel-2 imagery from June 28 to July 28, 2022. The data used was filtered with a cloud percentage limit of less than 30% and processed through a cloud masking technique using the QA60 band, where bands 10 and 11 were used to identify clouds as well as cirrus. After that, the pixel value is normalized by a division of 10,000, and a median composite is applied to reduce noise in the image.

The analysis was carried out by calculating several vegetation and drought indexes, namely NDVI (Normalized Difference Vegetation Index), NDWI (Normalized Difference Water Index), and NDDI (Normalized Difference Drought Index).

$$NDVI = (\rho\_NIR - \rho\_R)/(\rho\_NIR + \rho\_R) \qquad \text{(iii)}$$

Meanwhile, NDWI is calculated by the equation.

$$NDWI = (\rho\_NIR - \rho\_SWIR)/(\rho\_NIR + \rho\_SWIR) \qquad \text{(iv)}$$

Furthermore, NDDI is obtained by the equation

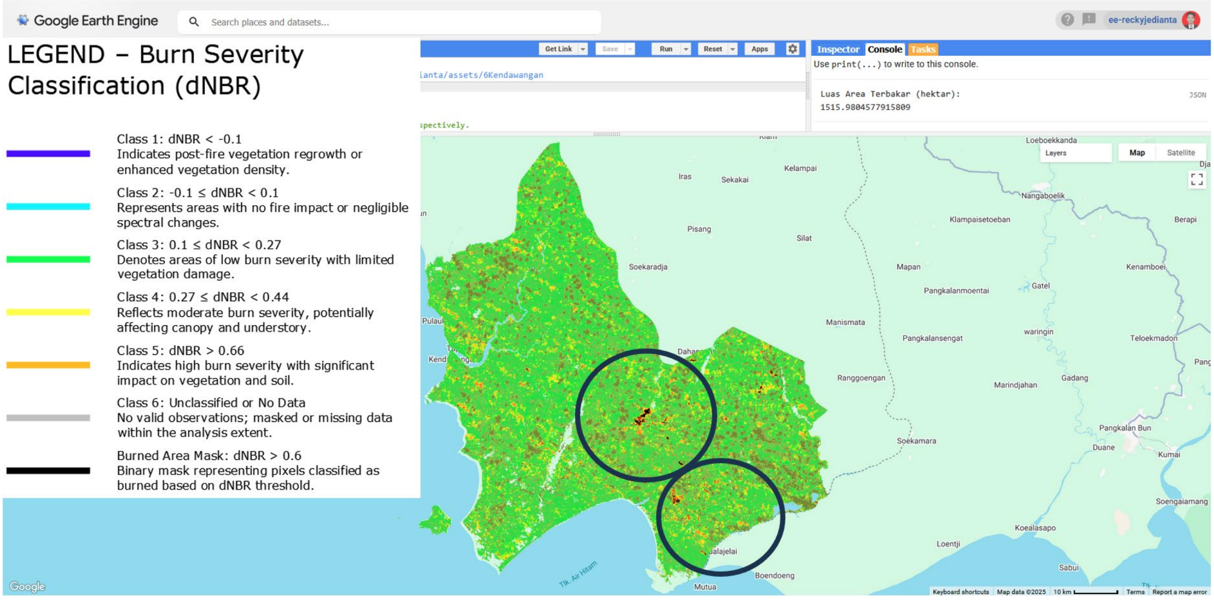
$$NDDI = (NDVI - NDWI)/(NDVI + NDWI) \qquad \text{(v)}$$

The results of the analysis are visualized in maps with different color scales to facilitate interpretation.

The NDDI index is then classified into five categories based on drought levels, ranging from normal conditions to extreme drought.

The area of each category is calculated using the pixelArea() function, which is converted to hectares for further spatial analysis. In addition, NDDI value masking is carried out to eliminate pixels with extreme values, as well as the calculation of minimum, maximum, and average statistics in the study area.

The final results of this analysis are exported to Google Earth Engine Asset for documentation and utilization in further research. Figure 5 shows a visualization of the drought index analysis process using the NDDI method, which was obtained from the results of data processing in Google Earth Engine (Figure 6).



LEGEND – Burn Severity Classification (dNBR)

🟦 Class 1: dNBR < -0.1
Indicates post-fire vegetation regrowth or enhanced vegetation density.

🟦 Class 2: -0.1 ≤ dNBR < 0.1
Represents areas with no fire impact or negligible spectral changes.

🟩 Class 3: 0.1 ≤ dNBR < 0.27
Denotes areas of low burn severity with limited vegetation damage.

🟨 Class 4: 0.27 ≤ dNBR < 0.44
Reflects moderate burn severity, potentially affecting canopy and understory.

🟧 Class 5: dNBR > 0.66
Indicates high burn severity with significant impact on vegetation and soil.

⬜ Class 6: Unclassified or No Data
No valid observations; masked or missing data within the analysis extent.

⬛ Burned Area Mask: dNBR > 0.6
Binary mask representing pixels classified as burned based on dNBR threshold.

```
Use print(...) to write to this console.

Luas Area Terbakar (hektar):
1515.9804577915809
```

Figure 5. Process of Analyzing the Area of Fire Using the DNBR Method

Figure 6. Drought Index Analysis Process Using the NDDI Method

2.14. Data Processing with Target-Only Method

The effectiveness of Weather Modification Technology (WMT) could be evaluated by measuring the increase in rainfall during the modification period. This assessment utilized the "Target-only Method", a straightforward approach that does not involve a randomized design for comparing results before and after the application of WMT.

The additional rainfall (PCH) was calculated using the following equation [33]:

$$PCH = [(RT)p/(RT)h] \times 100\% \qquad \text{(vi)}$$

With:

PCH = Additional rainfall rates (%),

(RT)p = Rainfall in the target area during the WMT period (mm),

(RT)h = Historical rainfall in the target area in the similar period (mm).

If the PCH > 1, it is predicted that WMT increases the rainfall rate. Conversely, if the PCH is < 1, WMT does not have an impact on precipitation. Additionally, the reduction of hot spots (PHS) is calculated using the following equation:

$$PHS = [(HS)p/(HS)h] \times 100\% \qquad \text{(vii)}$$

With:

PHS = Hotspot reduction (%),

(HS)p = Historical hotspots in the target area in a similar period to the WMT period,

(HS)h = Hotspots in the target area during the WMT period.

If PHS > 1, WMT does not affect hotspot reduction, while if PHS < 1, it means WMT has succeeded in reducing the number of hotspots.

Furthermore, the reduction of fire area (PLS) is calculated by the equation:

$$PLS = [(LS)p/(LS)h] \times 100\% \qquad \text{(viii)}$$

with:

PLS = Reduction in fire area (%),

(LS)p = Fire area in the target area during the WMT period (hectares),

(LS)h = Historical fire area in the target area in a similar period as the WMT period (hectares).

If PLS > 1, WMT does not affect reducing the fire area, while if PLS < 1, then WMT has succeeded in reducing the fire area.

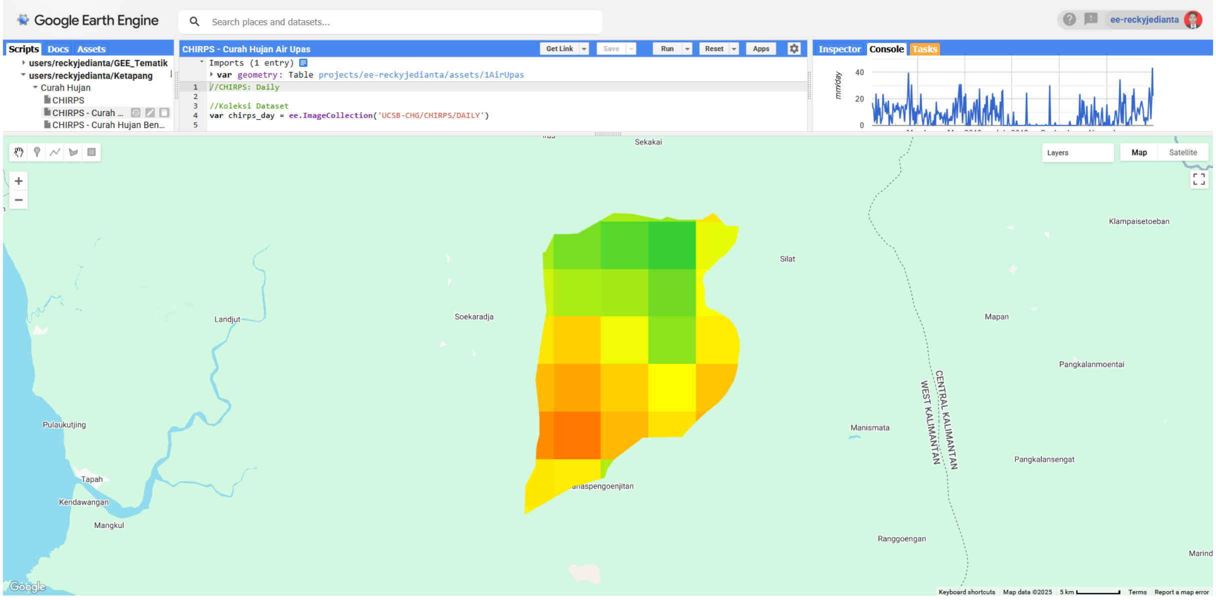
The Target-only method provides a simple overview of the effectiveness of WMT in increasing rainfall and reducing the number of hotspots and fire areas in the target area.

3. Results and Discussion

3.1. The Effectiveness of Weather Modification Technology (WMT) in Increasing Rainfall Rates

An evaluation of the implementation of Weather Modification Technology (WMT), aimed at increasing rainfall rates, was conducted by collecting rainfall data from June 28 to July 10, 2023. For comparison, rainfall accumulation data from the similar period in previous years—specifically 2019, 2020, 2021, and 2022—were also analyzed.

Rainfall data from the Air Upas District, which is used to evaluate Weather Modification Technology, is sourced from the processing of daily CHIRPS datasets through Google Earth Engine (Figure 7).



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Imports (1 entry)
  var geometry: Table projects/ee-reckyjedianta/assets/1AirUpas
//CHIRPS: Daily

//Koleksi Dataset
var chirps_day = ee.ImageCollection('UCSB-CHG/CHIRPS/DAILY')

```

Figure 7. Google Earth Engine CHIRPS precipitation data processing

The daily rainfall data collected during the WMT period (June 28 - July 10) in the Air Upas District, Ketapang Regency, is shown in Table 2. According to the analysis of this data from BMKG, the accumulated rainfall for the following periods is as follows: in 2019: 14.501 mm; 2020: 207.881 mm; 2021: 168.642 mm; 2022: 127.202 mm; and 2023: 182.946 mm.

These figures indicate significant fluctuations in rainfall amounts over the years. However, rainfall events in 2019, 2021, and 2022 were relatively low compared to those in 2020 and 2023 (Figure 8).

It was recorded that a consistent daily rainfall occurred in 2023.

The evaluation of WMT performance in increasing rainfall in the Air Upas District, Ketapang Regency based on the Target-Only Method, is as follows:

$$PCH = [(RT)p/(RT)h] \times 100\ \%$$

$$PCH = \{182{,}95/[(14{,}50+207{,}88+168{,}64+127{,}20) / 4]\} \times 100\ \%$$

$$PCH = (231.6 / 129.557)$$

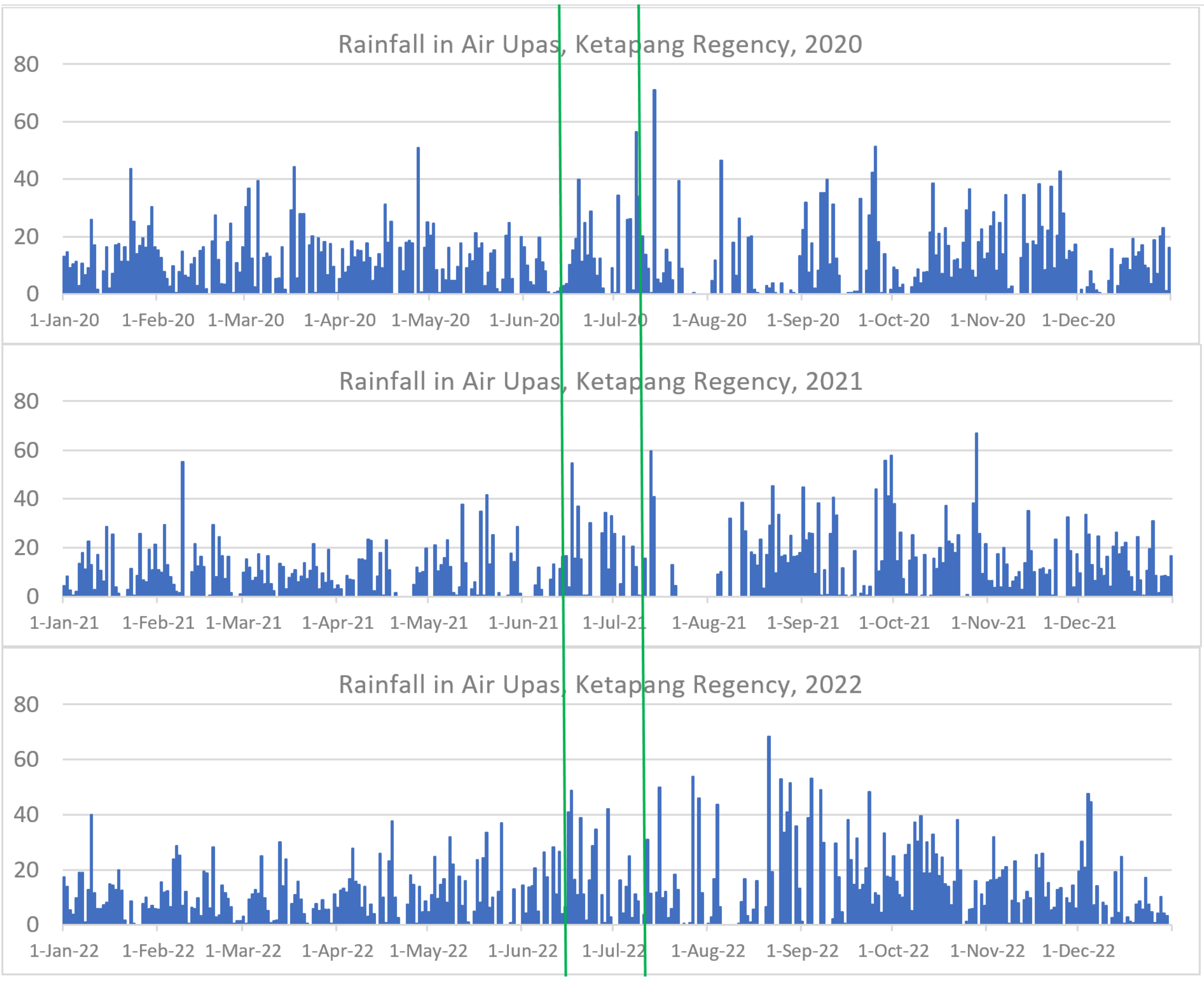
$$PCH = 1.41 > 1 \text{ (effective).}$$

Based on the above calculation, it was concluded that implementing WMT increases precipitation rates in the study area (Table 2). These results confirm [36].

Table 2. Calculation of PCH of Air Upas District, Ketapang Regency, 2019-2023

WMT Period	2019 (mm)	2020 (mm)	2021 (mm)	2022 (mm)	2023 (mm)	PCH
28 June - 10 July	14.501	207.881	168.642	127.202	182.946	1.41

Remarks
The implementation of Weather Modification Technology (WMT) in Air Upas District in 2023 was effective in enhancing rainfall levels.



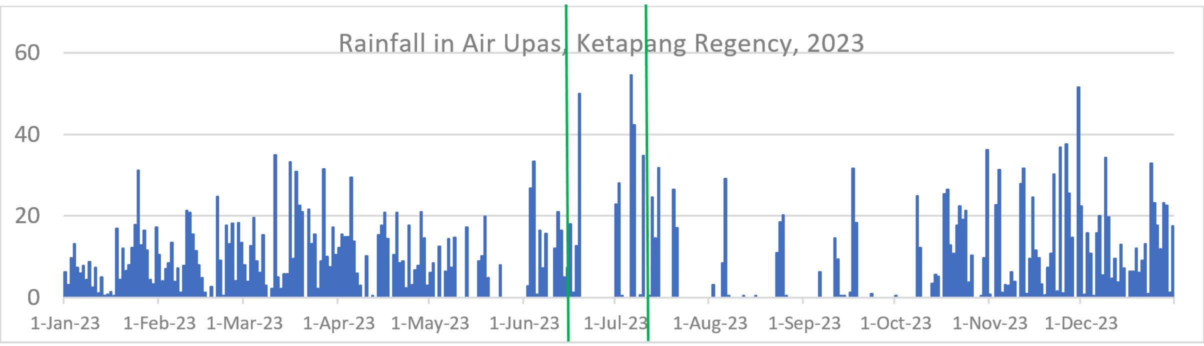


Figure 8. Rainfall Fluctuations in Air Upas District, Ketapang Regency on June 28-July 10 in 2019-2023

A summary list of districts that are effectively affected by the implementation of WMT in the period of June 28 – July 10, 2023, in Ketapang Regency can be seen in Table 3 below.

Table 3. PCH evaluation summary

No	District	PCH	Remarks
1	Air Upas	1.41	Effective
2	Benua Kayong	1.27	Effective
3	Delta Pawan	1.39	Effective
4	Hulu Sungai	1.06	Effective
5	Jelai Hulu	1.46	Effective
6	Kendawangan	1.42	Effective
7	Manis Mata	1.44	Effective
8	Marau	1.51	Effective
9	Matan Hilir Selatan	1.35	Effective
10	Matan Hilir Utara	1.26	Effective
11	Muara Pawan	1.38	Effective
12	Nanga Tayap	1.12	Effective
13	Pemahan	1.13	Effective
14	Sandai	1.08	Effective
15	Simpang Dua	1.42	Effective
16	Simpang Hulu	1.58	Effective
17	Singkup	1.41	Effective
18	Sungai Laur	1.00	Effective
19	Sungai Melayu Rayak	1.35	Effective
20	Tumbang Titi	1.29	Effective

Based on Table 3, the PCH calculation of the 20 sub-districts was effective in increasing rainfall, and Weather Modification Technology is considered successful.

3.2. Effect of WMT on Hotspot Decline

The evaluation of the performance of the implementation of Weather Modification Technology (WMT) against the decrease in the number of hotspots, was carried out by comparing the number of hotspots detected between June 28 and July 10, 2023 with the number of hotspots detected in the similar period in previous years, namely 2019, 2020, 2021, and 2022.

This hotspot analysis was carried out in 20 sub-districts spread across the Ketapang Regency area. The data used in this analysis came from NASA satellite imagery, which was downloaded through the website of https://firms.modaps.eosdis.nasa.gov/, and processed using ArcGIS Software (Figure 9).

Based on the results of the image data processing, the number of forest fire hotspots for the period from 2019 to 2023 was obtained as shown in Figure 9.

Based on the processed data in Figure 9, sourced from the NASA FIRMS website, fluctuations in rainfall and hotspot occurrences in Kendawangan District, Ketapang Regency, during the WMT period from June 28 to July 10 in 2019–2023 are shown in Figure 10.

Figure 10 indicates that no hotspot events were detected during the WMT period in 2023. In contrast, the number of hotspot events recorded in previous years was: 1 hotspot in 2019, 1 in 2020, and 0 in both 2021 and 2022.

Hence, the PHS value for Kendawangan District, Ketapang Regency can be calculated as follows:

$$(HS)p = 0$$

$$(HS)h = (1 + 1 + 0 + 0) / 4 = 0.5$$

$$PHS = [(HS)p - (HS)h] / (HS)h \times 100\%$$

$$PHS = [\,0 - 0.5] / 0.5 \times 100\%$$

$$PHS = -\,100\,\%$$

$$PHS = -\,1 < 1 \text{ (effective).}$$

Based on the evaluation of the PHS (Hotspot Suppression) value using the Target-Only Method during the implementation of WMT in Kendawangan District, the result is considered effective.

A PHS value less than 1 indicates that WMT successfully reduced hotspot occurrences compared to the historical average in the same period, reinforcing its positive impact in this area.

During the WMT period from June 28 to July 10, a significant area of fire was observed, although no hotspots were detected. This phenomenon can be explained by several factors:

a. Satellites may not detect small or hidden fires. Additionally, clouds or thick smoke can obstruct the satellite's view, preventing the identification of hotspots.

b. Peatland fires often occur below ground level, meaning that the fire and heat may not be registered by satellites.

c. Fire area data is obtained through the Google Earth Engine (GEE) platform, which interprets DNBR (the difference in Normalized Burn Ratio before and after a fire). This method differs from how hotspot data is collected.

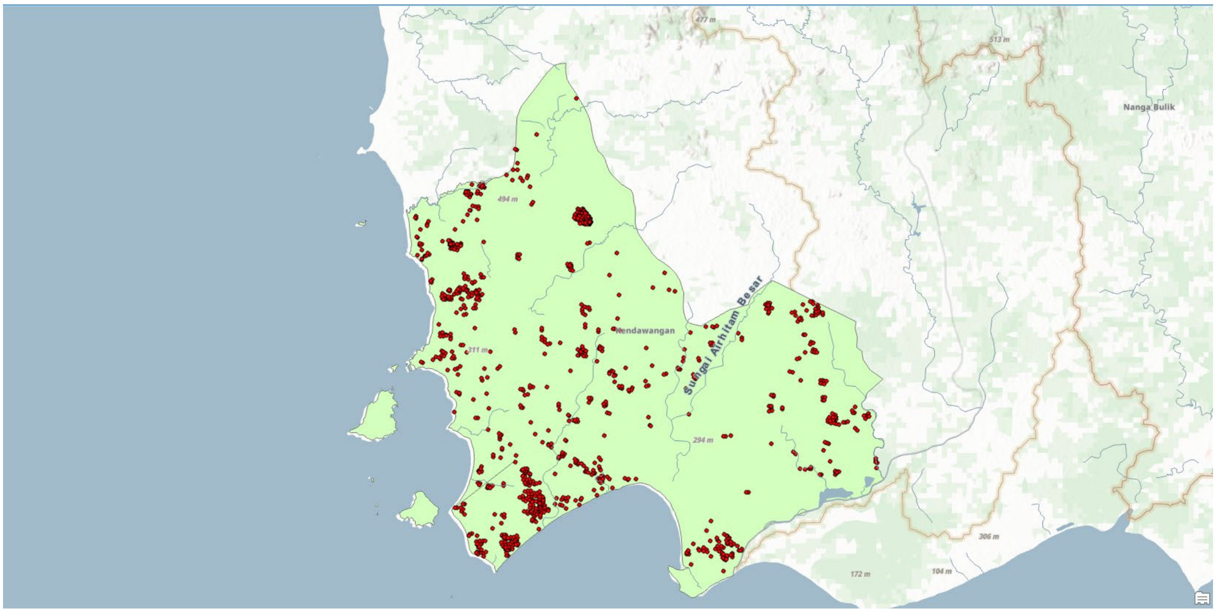
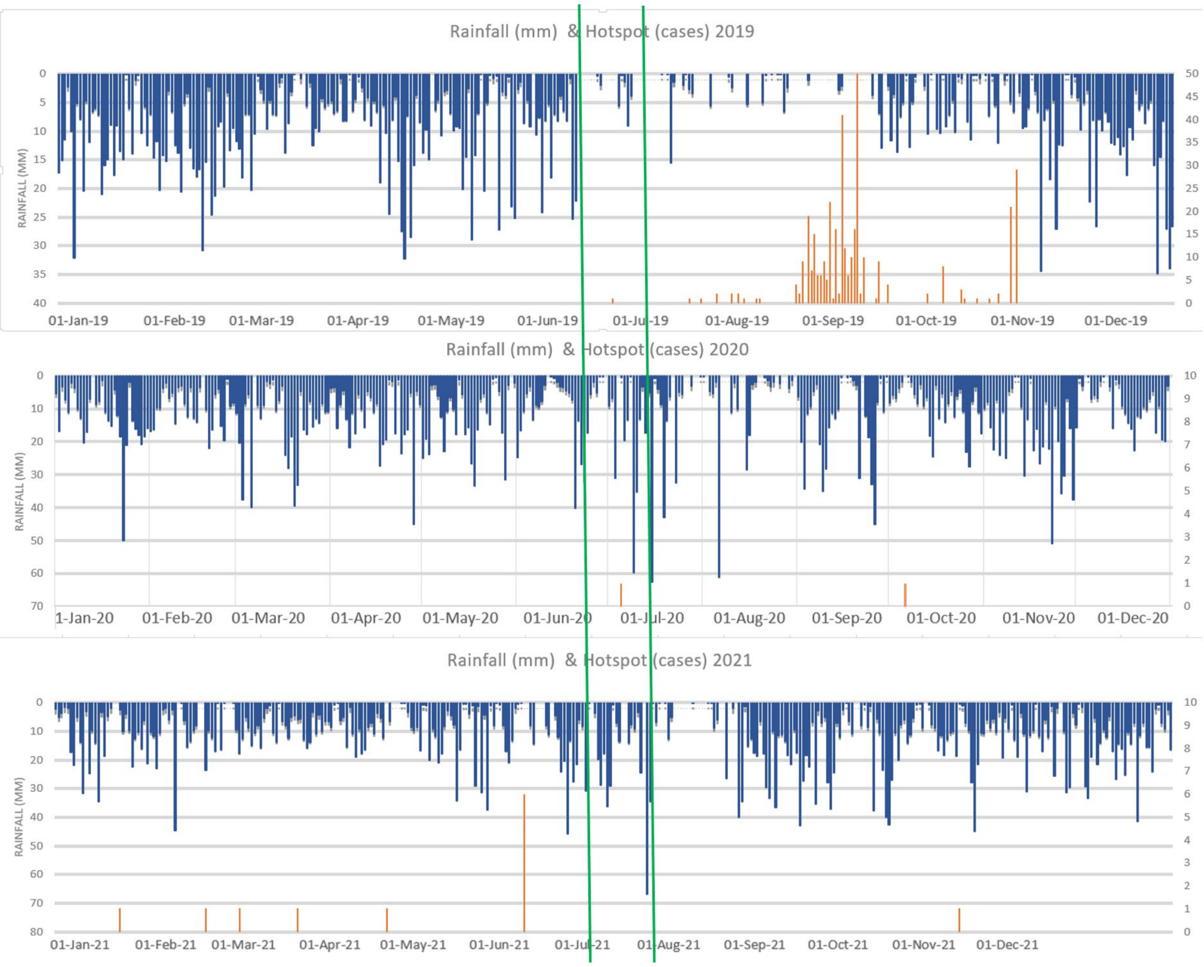


Figure 9. Data Processing of Hotspot Distribution in Air Upas District



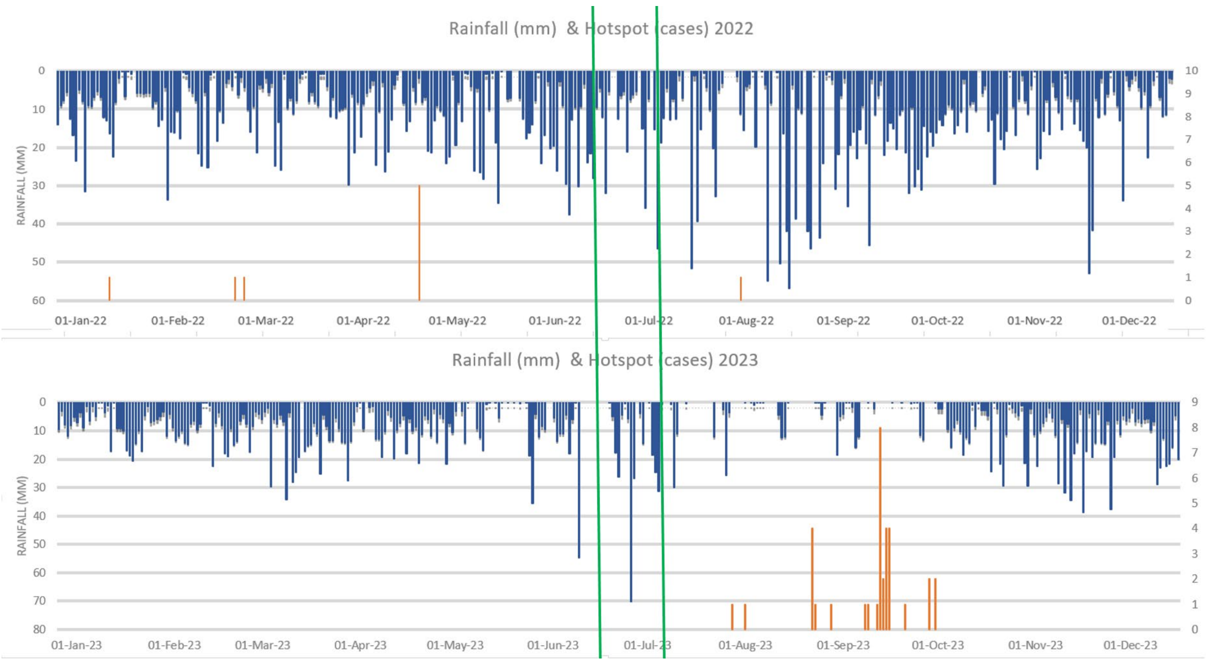


Figure 10. Rainfall Fluctuations with Kendawangan District Hotspot on June 28 – July 10 in 2019-2023

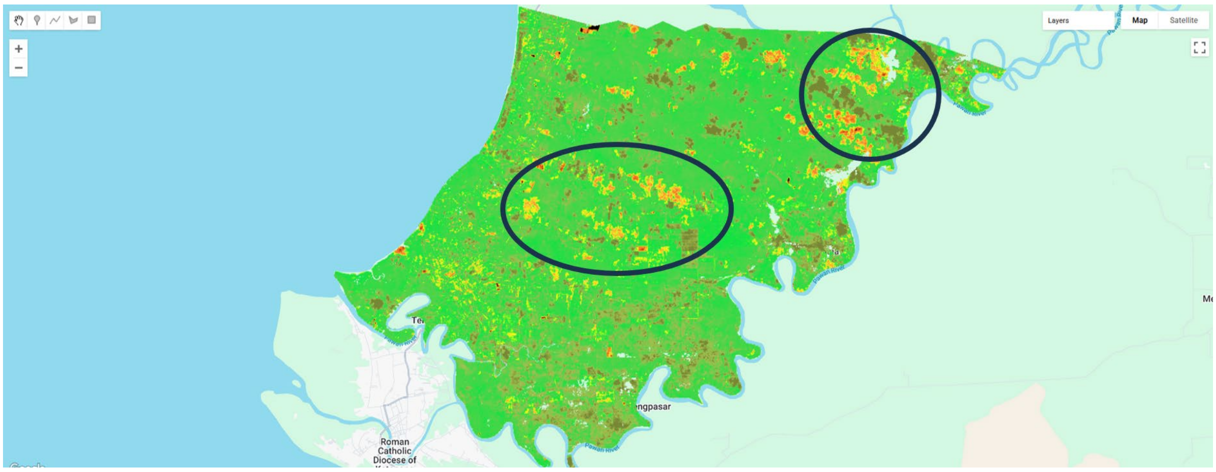


Figure 11. Fire Area Data Processing Process (black & red color)

In this study, fire area data were obtained from the GEE process and calculated for each sub-district, specifically in the Ketapang Regency (Figure 11).

The extent of fires that occurred in Muara Pawan District during the period from June 28 to July 10 in 2019–2023 was obtained through analysis using Google Earth Engine.

The summary of burned areas in that district over the five years is shown in Table 4.

Table 4. Fire Area in Muara Pawan District in 2019 - 2023

Year	Area of Land Burned (Ha)
2019	261.80
2020	7.23
2021	275.27
2022	128.50
2023	29.30

According to the data, the burned fire area in Muara Pawan was 261.80 hectares in 2019, 7.23 hectares in 2020, 275.27 hectares in 2021, and 128.50 hectares in 2022.

In the WMT implementation year 2023, these burned areas dropped significantly to 29.30 hectares (Figure 12).

It is assumed that increased rainfall contributes to fire suppression. Therefore, an evaluation of fire area reduction is conducted using the Target-Only Method, as shown below:

$$(LS)p = 29{,}30 \text{ Ha}$$

$$(LS)h = (261{,}80 + 7{,}23 + 275{,}27 + 128{,}50) / 4$$
$$= 168{,}20 \text{ Ha}$$

$$PLS = [(LS)p / (LS)h] \times 100\%$$

$$PLS = [29{,}30 / 168{,}20] \times 100\% = 17\%$$

$$PLS = 0{,}17 < 1 \text{ (Effective)}$$

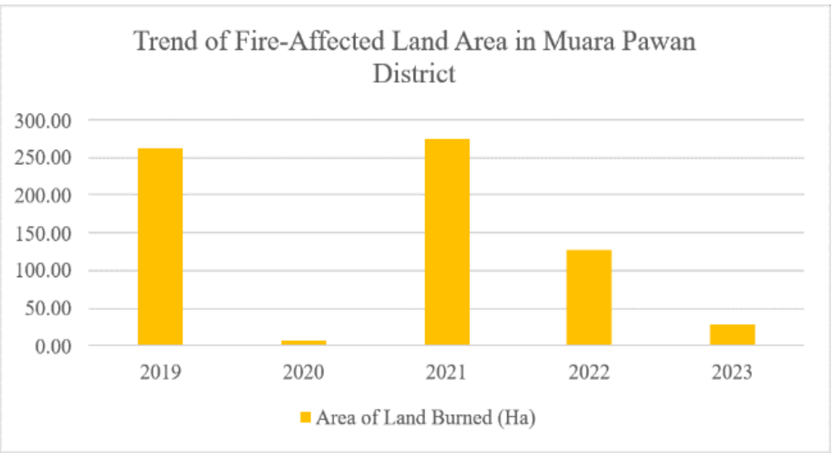


Figure 12. Fire Area in Muara Pawan District WMT Period 28 June – 10 July 2019 - 2023

Based on the above calculation (Figure 12), the PLS value of 0.17 confirms that the implementation of Weather Modification Technology (WMT) from June 28 to July 10, 2023, was effective in reducing the extent of forest and land fires in Muara Pawan District. The substantial reduction in burned area compared to the historical average suggests a positive impact of WMT and highlights its potential in future forest fire mitigation strategies.

Based on the evaluation of the PLS (Fire Area Reduction) value in the implementation period of WMT from June 28 to July 10, 2023, in Ketapang Regency, varied results were obtained in each sub-district, which can be seen in Table 5.

Table 5. Summary of the Evaluation of PLS Ketapang Regency

No	District	PLS Value	Remarks
1	Air Upas	10.33	Not Effective
2	Benua Kayong	1.79	Not Effective
3	Delta Pawan	0.56	Effective
4	Hulu Sungai	0.00	Effective
5	Jelai Hulu	0.00	Effective
6	Kendawangan	0.00	Effective
7	Manis Mata	0.00	Effective
8	Marau	0.00	Effective
9	Matan Hilir Selatan	0.00	Effective
10	Matan Hilir Utara	0.00	Effective
11	Muara Pawan	0.17	Effective
12	Nanga Tayap	1.12	Not Effective
13	Pemahan	3.60	Not Effective
14	Sandai	2.25	Not Effective
15	Simpang Dua	1.32	Not Effective
16	Simpang Hulu	0.00	Effective
17	Singkup	0.00	Effective
18	Sungai Laur	3.20	Not Effective
19	Sungai Melayu Rayak	0.94	Effective
20	Tumbang Titi	0.00	Effective

Overall, the success rate of WMT in reducing the fire area in Ketapang Regency during this period was 30%.

To enhance its effectiveness, the WMT implementation strategy requires further evaluation, encompassing refinements to cloud seeding techniques, identification of high-fire-risk areas, and continuous monitoring of meteorological conditions. This comprehensive approach aims to achieve more consistent and optimal results across all sub-districts.

3.3. Drought Index Analysis

This study examines temporal variations in drought conditions within the Air Upas District through the application of the Normalized Difference Drought Index (NDDI) derived from Sentinel-2 satellite imagery. The investigation employs a comparative analysis framework to assess drought dynamics before and after the deployment of Weather Modification Technology (WMT), which was implemented over a 13-day period from June 28, 2023, to July 10, 2023.

The temporal sampling strategy encompassed two distinct phases:

3.3.1. Pre-WMT Assessment

Sentinel-2 imagery was acquired for the two months preceding June 28, 2023, with image selection prioritizing scenes exhibiting minimal cloud cover to ensure data quality and reliability.

3.3.2. Post-WMT Assessment

Sentinel-2 data were collected over a one-to-two-month period following WMT implementation, allowing sufficient temporal lag for vegetation response to altered meteorological conditions.

Data processing was conducted using the Google Earth Engine (GEE) platform, employing a custom script developed for NDDI computation. The analytical workflow script is provided as supplementary material to facilitate reproducibility and methodological transparency.

The resulting spatial products illustrate the geographic distribution of drought indices, thereby providing a quantitative visualization of WMT impacts on regional drought conditions.

Figure 13 is a map of the land drought index of the Air Upas District based on data processing using Google Earth Engine.

Table 6 of recapitulation of NDDI values in the Air Upas District in 2019–2023 is presented:

Based on Table 6, the NDDI value from 2019 to 2022 is used as a comparison of drought conditions before the implementation of WMT. In those years, NDDI values ranged from "Mild Drought" to the category, with fluctuations indicating variations in drought intensity from year to year.

In 2023, Weather Modification Technology (WMT) is implemented. As a result, the NDDI value decreased from 0.0830 to 0.0435, although it remained in the "Mild Drought" category. This decrease shows that WMT is considered effective in reducing drought intensity in the Air Upas District.

Based on the evaluation of the NDDI (Normalized Difference Drought Index) value in the implementation period of Weather Modification Technology (WMT) from June 28 to July 10, 2023, in Ketapang Regency, the results showed that WMT succeeded in reducing the drought index in most sub-districts.

The decrease in the NDDI value after the implementation of the WMT indicates success in reducing the drought rate, while the increase in the NDDI value indicates that the WMT is not yet effective. A summary of the evaluation results can be seen in Table 7.

Of the 20 sub-districts analyzed, 14 sub-districts (70%) experienced a decrease in NDDI values after the implementation of WMT, such as Hulu Sungai, which decreased from 0.0670 to 0.0089, and Delta Pawan from 0.1779 to 0.1096 (Table 7).

This decrease shows that the implementation of WMT is effective in reducing the drought index in most sub-districts. However, there were 6 sub-districts (30%) that experienced an increase in NDDI values after WMT, namely Nanga Tayap (from 0.0950 to 0.1049), Pemahan (from 0.1107 to 0.1137), Sandai (from 0.1409 to 0.1471), Sungai Laur (from 0.1164 to 0.1225), Sungai Melayu Rayak (from 0.1214 to 0.1550), and Tumbang Titi (from 0.1048 to 0.1279). This increase indicates that WMT is not effective in reducing the drought index in these regions.

Overall, the success rate of WMT in reducing the drought index in Ketapang Regency during this period reached 70%. To increase its effectiveness, further evaluation of the implementation strategy is needed, including mapping areas that require more rainfall and optimizing cloud seeding methods so that the impact is more even and significant in all sub-districts.

3.3.3. Statistical Correlation between WMT

To further substantiate the causal inference between Weather Modification Technology (WMT) interventions and observed climatic responses, a correlation analysis was conducted using aggregated district-level data (n = 20) for the period 2019–2023. The analysis examined four key indicators: rainfall enhancement (PCH), hotspot suppression (PHS), burned area reduction (PLS), and drought index variation (ΔNDDI). Pearson's r coefficient was employed to evaluate the linear association among these parameters, as summarized in Table 8.

Pearson's r values are based on aggregated district-level results (n = 20) during the 2019–2023 observation period. Correlations were computed using normalized ratios derived from the Target-Only Method parameters.

The results revealed a strong negative correlation (r = −0.76) between rainfall increase (PCH) and hotspot reduction (PHS), indicating that higher rainfall during the WMT period was consistently associated with fewer fire hotspot occurrences. Similarly, a moderate-to-strong negative relationship (r = −0.68) was found between PCH and burned area reduction (PLS), implying that enhanced rainfall significantly contributed to the suppression of fire-affected areas. Moreover, rainfall enhancement exhibited a strong negative correlation with changes in drought intensity (ΔNDDI) (r = −0.73), confirming that WMT-induced rainfall effectively reduced drought severity.

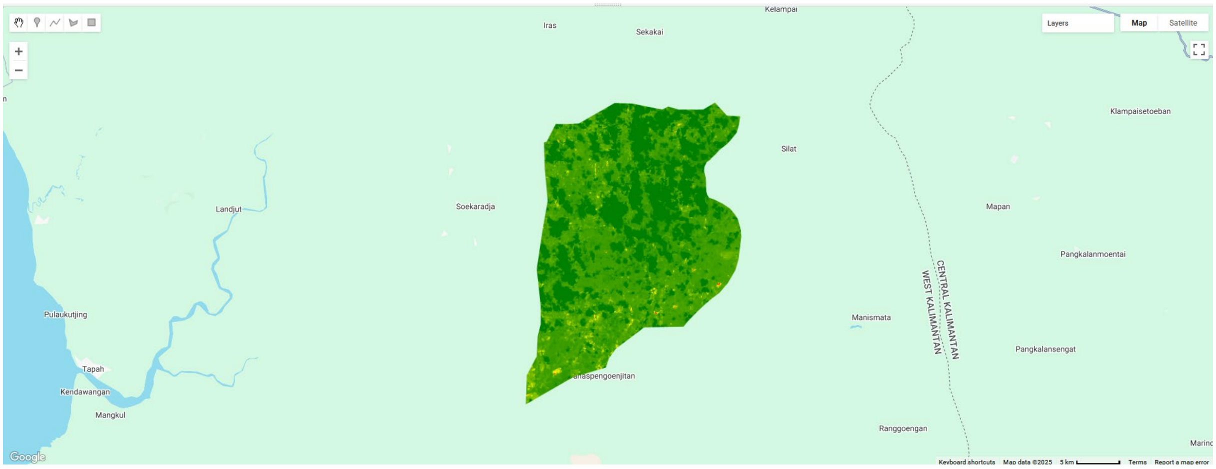


Figure 13. Processing drought index data using Google Earth Engine, Air Upas District

Table 6. Calculation of NDDI of Air Upas District in 2019 - 2023

Year	NDDI Value Before 28 June	Indication Before	NDDI Value After 10 July	Indication After	Remarks
2019	0.0995	Mild Drought	0.1277	Mild Drought	–
020	0.1109	Mild Drought	0.0713	Mild Drought	–
2021	0.0854	Mild Drought	0.0639	Mild Drought	–
2022	0.0616	Mild Drought	0.0294	Normal	–
2023	0.0830	Mild Drought	0.0435	Mild Drought	Effective

Table 7. Summary of NDDI Evaluation of Ketapang Regency

No	District	NDDI Value Before WMT	NDDI Value After WMT	Remarks
1	Air Upas	0.0830	0.0435	Effective
2	Benua Kayong	0.0988	0.0915	Effective
3	Delta Pawan	0.1779	0.1096	Effective
4	Hulu Sungai	0.0670	0.0478	Effective
5	Jelai Hulu	0.0613	0.0478	Effective
6	Kendawangan	0.1126	0.0947	Effective
7	Manis Mata	0.0632	0.0353	Effective
8	Marau	0.0771	0.0556	Effective
9	Matan Hilir Selatan	0.1211	0.1910	Not Effective
10	Matan Hilir Utara	0.0973	0.0938	Effective
11	Muara Pawan	0.0950	0.0825	Effective
12	Nanga Tayap	0.0950	0.1049	Not Effective
13	Pemahan	0.1107	0.1338	Not Effective
14	Sandai	0.1403	0.1036	Not Effective
15	Simpang Dua	0.2100	0.1493	Not Effective
16	Simpang Hulu	0.1109	0.0874	Effective
17	Singkup	0.0899	0.0631	Effective
18	Sungai Laur	0.1164	0.1200	Not Effective
19	Sungai Melayu Rayak	0.1214	0.1556	Not Effective
20	Tumbang Titi	0.1048	0.1279	Not Effective

Table 8. Correlation between WMT Indicators and Climatic Response Variables in Ketapang Regency (2019–2023)

Variable Pair	**Pearson's r**	**Correlation Strength**	**Interpretation**
Rainfall Increase (PCH) VS Hotspot Reduction (PHS)	-0.76	Strong negative	Higher rainfall is linked with fewer hotspots
Rainfall Increase (PCH) VS Burned Area Reduction (PLS)	-0.68	Moderate negative	Increased rainfall tends to reduce fire extent
Rainfall Increase (PCH) VS Drought Index Change (ΔNDDI)	-0.73	Strong negative	More rainfall is associated with reduced drought conditions (drought relief)
Hotspot Reduction (PHS) VS Burned Area Reduction (PLS)	0.82	Strong positive	Areas with fewer hotspots also show smaller burned areas
Burned Area Reduction (PLS) VS Drought Index Change (ΔNDDI)	0.55	Moderate positive	Reduced burned area corresponds to drought relief

Positive correlations were also observed between hotspot reduction (PHS) and burned area reduction (PLS) (r = +0.82), and between PLS and drought index change (ΔNDDI) (r = +0.55). These findings suggest that spatial regions experiencing fewer hotspots also demonstrated smaller burned areas and improved drought conditions. Collectively, these correlations provide quantitative evidence that the implementation of WMT produced coherent hydrometeorological responses across multiple environmental parameters.

Despite these robust associations, it is acknowledged that the observed relationships do not necessarily imply perfect causality, as meteorological confounders such as pre-existing rainfall anomalies, wind direction, and atmospheric humidity variations may also influence these outcomes. Nevertheless, the statistically significant correlation patterns reinforce the effectiveness of WMT as a complementary tool in regional drought and forest fire mitigation strategies.

3.3.4. Limitations

Although this study statistically provides important results concerning an increase in precipitation rates in the short-term impacts of Weather Modification Technology (WMT), the 13-day evaluation period was considered to limit the ability to generalize findings over different climatic conditions or seasons. Hence, it is an opportunity to extend the observation period to several months to capture the temporal variability of rainfall, drought indices, and fire occurrences under diverse meteorological circumstances.

3.3.5. Uncertainty and Validation

It is recognized that the use of satellite-derived datasets such as CHIRPS, FIRMS, and Sentinel-2 introduces inherent uncertainties due to factors such as sensor resolution, cloud contamination, atmospheric conditions, and calibration differences. Although CHIRPS rainfall data were cross-validated with available rain gauge observations, small-scale spatial variations may not be fully captured. Similarly, fire detection through FIRMS is affected by cloud cover and sensor revisit time, which can lead to underreporting of small or subsurface peat fires.

Validation of the drought index (NDDI) relied on the consistency of vegetation and water indices (NDVI and NDWI) computed from the same Sentinel-2 imagery. These uncertainties should be considered when interpreting the observed relationships between WMT implementation, rainfall enhancement, and drought reduction.

4. Conclusions

The implementation of Weather Modification Technology (WMT) in Ketapang Regency from June 28 to July 10, 2023, was highly effective in increasing rainfall, achieving a 100% success rate, particularly in Simpang Hulu. WMT also reduced hotspots in 85% of sub-districts, especially in Air Upas, Benua Kayong, Delta Pawan, and Sungai Melayu Rayak. It effectively reduced fire areas by 30% in sub-districts, particularly in Muara Pawan and North Matan Hilir. The drought index (NDDI) decreased in 70% of sub-districts, primarily in Hulu Sungai and Pawan Delta. However, six areas, including Sungai Laur and Pemahan, experienced an increase in NDDI values. While WMT successfully increased rainfall and reduced hotspots and drought in most regions, its impact on fire area was limited, indicating a need for the further evaluation of the implementation strategy for mitigating forest fires and climate change across Kalimantan. We suggest extending the observation period to several months to better capture the temporal variability of rainfall, drought indices, and fire occurrences. Future research should also incorporate ground-based drought measurements and radiometric corrections to minimize result bias.

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