

## Remote sensing and GIS application for monitoring drought vulnerability in Indonesia: a review

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### ABSTRACT

Agricultural drought is one of the hydrometeorological disasters that cause significant losses because it affects food stocks. In addition, agricultural droughts, impact the physical and socio-economic development of the community. Remote sensing technology is used to monitor agricultural droughts spatially and temporally for minimizing losses. This study reviewed the literature related to remote sensing and GIS for monitoring drought vulnerability in Indonesia. The study was conducted on an island-scale on Java Island, a provincial-scale in East Java and Bali, and a district-scale in Indramayu and Kebumen. The dominant method was the drought index, which involves variable land surface temperature (LST), vegetation index, land cover, wetness index, and rainfall. Each study has a strong point and a weak point. Low-resolution satellite imagery has been used to assess drought vulnerability. At the island-scale, it provides an overview of drought conditions, while at the provincial-scale, it focuses on paddy fields and has little detailed information. In-situ measurements at the district-scale detect meteorological drought accurately, but there were limitations in the mapping unit's detailed information. Drought mapping using GIS and remote sensing at the district-scale has detailed spatial information on climate and physiographic aspects, but it needs temporal data monitoring.

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## 1. INTRODUCTION

Drought is a natural disaster in the form of a lack of water for a certain period which causes a problem to activities, groups, and other environmental sectors [1]. In 2016, Hobbins *et al.* [2] explained that meteorological drought would decrease evapotranspiration and groundwater moisture in agricultural drought. The meteorological drought would also decrease river flow and surface storage in hydrological drought. Wilhite, 1985 and UN/ISDR, 2007 [3], [4] define that there are four types of droughts, i.e. (1) meteorological drought, (2) agricultural drought, (3) hydrological drought, and (4) socio-economic drought. The drought process begins with a decrease in rainfall intensity from normal conditions in a season called a meteorological drought [5]-[7]. Then there is a deficit of groundwater so that it is no longer able to meet water needs for plants, or it is known as agricultural drought [8], [9]. The final process, which is a reduction of surface water supply and groundwater in the long term and can potentially impact the social, economic, and environmental sectors, is known as hydrological drought [10].

Drought in Indonesia often occurs during the dry season but gets worse during El-Nino events such as in 1988, 1999, 2007, and 2015 [11]-[13]. Drought causes physical problems such as crop failure (puso) [14], [15] and triggering forest and land fires [16]. Java Island, as the highest population in Indonesia, has main foodstuff rice. The occurrence of puso on agricultural land will have severe consequences on the population. Various studies on agricultural drought in Indonesia have been conducted using both in-situ data and remote sensing data. In-situ data uses precipitation from meteorology stations [17]. In 2017, Adhyani [17] examine drought using standardized precipitation index (SPI) from precipitation station data in Java, Bali, and Nusa Tenggara. A combination of spatial and in-situ data to identify drought has been studied by Habibie *et al.* [18] in East Java. Drought assessment in Indonesia using remote sensing data such as Dirgahayu [19], which examines Indramayu Regency. As well as outside Java, such as in Batam by Lubis *et al.* [20] shows the importance of analyzing agricultural drought in Indonesia.

Remote sensing and GIS provide a spatial description of an area; therefore, analysis of agricultural drought is widely studied for monitoring large areas with this technology [21]. The use of the drought index has grown over time [22]-[24]. Starting with the SPI index based on rainfall [6], [25]-[28], palmer drought severity index (PSDI) [5] based on rainfall and soil moisture, standardize precipitation evapotranspiration index (SPEI) based on rainfall and evapotranspiration [29]-[31], temperature vegetation dryness index (TVDI) [32] and vegetation temperature condition index (VTCI) [33]-[35] based on vegetation and temperature. Then this index develops into drought index groups. The drought index groups based on vegetation include moisture stress index (MSI) [36], simple ratio water index (SRWI) [37], normalized difference water index (NDWI) [38], normalized difference drought index (NDDI) [39], land surface water index (LSWI) [40], vegetation condition index (VCI) [30], [41], [42], and drought severity index (DSI) [43]-[45]. Index groups based on soil physical conditions are perpendicular drought index (PDI) [46], [47]. Combination of vegetation and soil in the study of Wang *et al.* [47] and Ahmadalipour *et al.* [48]. Also, indices that combine both of them i.e. shortwave infrared water stress index (SIWSI) [49], normalized multiband drought index (NDMI) [50], and visible and shortwave drought index (VSDI) [51]. The combination between indices has been studied by Fang *et al.* [52] which combine NDVI and SPI using the copula method [53], [54] while Zuo *et al.* [55] combine rainfall and NDVI which is called combine deficit index (CDI). Until now more indices have been developed with machine learning and cloud computing technologies. In 2020, Liu *et al.* [56] build the IDI index using neural network machine learning while Han *et al.* [57] investigate the relationship between drought and precipitation, temperature, vegetation, and evapotranspiration using random forest. Meteorological drought forecast using machine learning had been performed by Rhee and Im [58]. Early use of cloud computing technologies combined Google Earth Engine (GEE) and GIS technology such as Sazib *et al.* [59] and Shen *et al.* [60] build comprehensive meteorology and agriculture drought models using deep learning. It assesses drought using global soil moisture data, land cover, and SPI. Meanwhile, GEE to compute several indices of drought indicators in Vietnam found that NDDI is good for agricultural land and vegetation health indeks (VHI) good for forestry [61]. In 2021, Venkatappa *et al.* [62] used GEE to know the impact of drought and flood on cropland and crop production in Southeast Asia.

Drought monitoring using remote sensing and GIS technology has been widely used in Indonesia but never reviewed technology used in different study scales. The review can be used to analyze the strength and weaknesses of the method that could be improved in the next study. The monitoring of drought in Indonesia from remote sensing data has been carried out based on the VHI index with MODIS and TRMM images on an island-scale by Roswintarti *et al.* [63] and on provincial-scale by Amalo *et al.* [64]. Dirgahayu [19] also use MODIS and TRMM images at the regency-scale based on a combination of drought types. Prasetyo *et al.* [65] conducted drought monitoring using Landsat-8 images at province-scale in Central Java using vegetation index and machine learning. At the district-scale, they used Landsat-8 imagery with VHI index [66] and NDDI index [67]. The use of in-situ data on a district-scale has been performed by Pramudya *et al.* Geographic Information System (GIS) techniques are also used for combining drought type [19] and analyzing the spatial distribution [66]. All the studies mentioned in Indonesia focus on agricultural land especially the paddy field. Therefore, it is important to review drought vulnerability assessment, especially in paddy fields. This study aims to review several scientific studies about agricultural drought in Indonesia using remote sensing and GIS.

## 2. RESEARCH METHOD

The locations of reviewed studies consisted of three regional coverage scales in Indonesia, i.e. (1) island-scale with the case study of Java Island [63], (2) provincial-scale with the case study of East Java [68], and (3) district-scale with case studies of Indramayu [19], Tegal [68], and Subang and Karawang [66]. Figure 1 shows that Java Island located in 106°00'E-116°00'E and 6°00'S-8°30'S, East Java province located in 111°00'E-114°30'E and 6°30'S-9°15'S. At a district-scale, Indramayu located in 108°00'-108°30' and 6°15'-

6°40", Tegal located in 108°55'E-109°20'E and 6°50'-7°10'S, Subang and Karawang located in 107°00'-108°00' and 6°00'-6°50". The location selection represents each mapping scale and the study location that can be significantly affected by drought and uses different methods to be compared with one another.

Monitoring of drought vulnerability was conducted in Java Island from June to August 2009 when ENSO occurred. On the provincial-scale in East Java, monitoring is conducted during drought periods in the El Nino event 2015. In the Indramayu district, a drought monitor was conducted in the year 2008. In Tegal, the district study is analyzed based on the precipitation index which focuses on the El Nino event from 1985-2015. In Subang and Karawang districts, the study is conducted in the dry season of 2000, 2005, 2010, and 2015.



Figure 1. Study area in Indonesia; (a) island scale: Java Island, (b) province scale: East Java, (c) district scale: Indramayu, Tegal, Subang and Karawang

The data used was divided into three categories i.e., remote sensing data in raster format, shape files in vector format, and in-situ data. Remote sensing imagery that has been used is 1 x 1 km MODIS low-resolution is extracted into land surface temperature (LST), enhanced vegetation index (EVI), and NDVI

variables [19], [63], [64]. The TRMM precipitation image has a spatial resolution of 1 x 1 km [19], [63]. Medium resolution images of Landsat-8, i.e., OLI with a pixel size of 30 x 30 m and TIRS with a pixel size of 100 x 100 m to extract NDVI and LST [66]. Vector data represent paddy field areas and administrative boundaries. Also, there is in-situ data in the form of rainfall data from Tegal city station located in 6° 87' S and 109°12' E, 54.0 m above sea level.

Table 1. Method comparison of drought monitoring research in Indonesia

Type of Drought and Researcher	Data dan Method	Coverage scale and Location	Strength	Weakness
Meteorology and Agriculture Drought Roswintiarti <i>et al.</i> [63]	TRMM image with rainfall index (SPI) MODIS image with vegetation index and temperature (VHI)	Island: Java	It provides a spatial and temporal overview of drought events quickly and widely. It provides an overview of the drought from the rainfall parameters that cause vegetation to wilt and crop failure.	The detailed information has not focused on rice fields. It did not combine meteorological and agricultural drought.
Agriculture Drought Amalo <i>et al.</i> [64]	MODIS image with vegetation index and temperature (VHI)	Province: East Java	It provides a spatial and temporal overview of drought events quickly and widely. The study compares drought of El Nino year with La Nina and Normal condition	The spatial information has not focused on rice fields and has a low resolution on a district scale. It only considers vegetation aspects not yet hydrology drought.
Meteorology, Agriculture, and Hydrology Drought Dirgahayu [19]	TRMM and MODIS imagery with vegetation index, LST, evapotranspiration, rainfall. It combines meteorological, agricultural, and hydrological drought indices into a drought-prone index.	District: Indramayu	It combined drought meteorology, agriculture, and hydrology into one drought map so that beginners easily understand it. They are focusing on paddy fields to monitor crop failure.	They are using low-resolution imagery on a provincial scale. However, detailed information is still lacking, i.e., 1 km pixel size while the rice fields are less than 1 km in size.
Meteorology Drought Pramudya and Onishi [68]	Drought is calculated from in-situ rainfall data using a SPI.	District: Tegal district	The temporal drought calculation is accurate because it uses field measurement data at station locations for 32 years.	The result only represents the station location, not spatially throughout the Tegal city area. It only uses rainfall data, not yet considering vegetation and hydrology aspects.
Agriculture Drought Sholihah <i>et al.</i> [66]	Landsat 8 imagery was used to produce a drought map using VHI, TCI, and VCI indices.	District: Subang and Karawang	It uses a medium resolution image for a district scale. Thus it provides detailed spatial information of the sub-district and villages. The study compares the dry season of various years.	It only focuses on vegetation drought not yet considering meteorology and hydrology aspects. Also, the study does not provide monthly temporal data.

SPI is a method to calculate the meteorological drought of an area. In this study, it is used to identify meteorology drought of island scale by Roswintiarti *et al.* [63] and district scale by Dirgahayu [19] and Pramudya *et al.* [68]. The SPI index is extracted from long-term normalized and average monthly rainfall values. The following is SPI formula [6]:

$$SPI = \frac{X_{ij} - X_{im}}{\sigma} \quad (1)$$

where  $X_{ij}$  is actual rainfall,  $X_{im}$  is the long-term mean rainfall, and  $\sigma$  is its standard deviation.

VHI is a remote sensing index based on the vegetation and the land surface temperature. This index reflects vegetation stress due to adverse climatic factors. VHI is calculated to identify the agricultural drought of an area. In this study, this index is used by Roswintiarti *et al.* [63] to identify drought on an island scale, Amalo *et al.* [64] on the provincial scale and Sholihah *et al.* [66] on the district scale. The VHI formula is explained as [41]:

$$VHI = 0.5(VCI + TCI) \quad (2)$$

where VCI is vegetation condition index, and TCI is temperature condition index. VCI and TCI formula is described as:

$$VCI = 100 \times \frac{VI - VI_{min}}{VI_{max} - VI_{min}} \quad (3)$$

$$TCI = 100 \times \frac{LST_{max} - LST}{LST_{max} - LST_{min}} \quad (4)$$

Where VI is vegetation index (EVI or NDVI) and LST is land surface temperature.

In 2012, Dirgahayu [19] developed a method for monitoring district-scale drought vulnerability. They were combining meteorological, agricultural, and hydrological drought indices. The meteorological drought index is based on rainfall and evapotranspiration data. The agricultural drought index is based on the value of the enhanced vegetation index (EVI). The hydrological drought index is based on soil moisture index extracted from MODIS band 6,2,1.

### 3. RESULTS AND DISCUSSION

Monitoring of drought vulnerability in Java while ENSO 2009 happened based on research Roswintiarti *et al.* [63]. It shows mild drought conditions throughout Java due to a lack of rainfall since June leading to meteorological drought. The method is an SPI index with an index value of  $1.0 \leq SPI < 0$  in Figure 2. As a result, the meteorological drought continued into an agricultural drought. It is shown by the VCI and TCI index values, which is less than 36. Both showed vegetation stress where VCI from the humidity aspect developed in East Java in Figure 3 while TCI from the temperature developed in West Java in Figure 4.

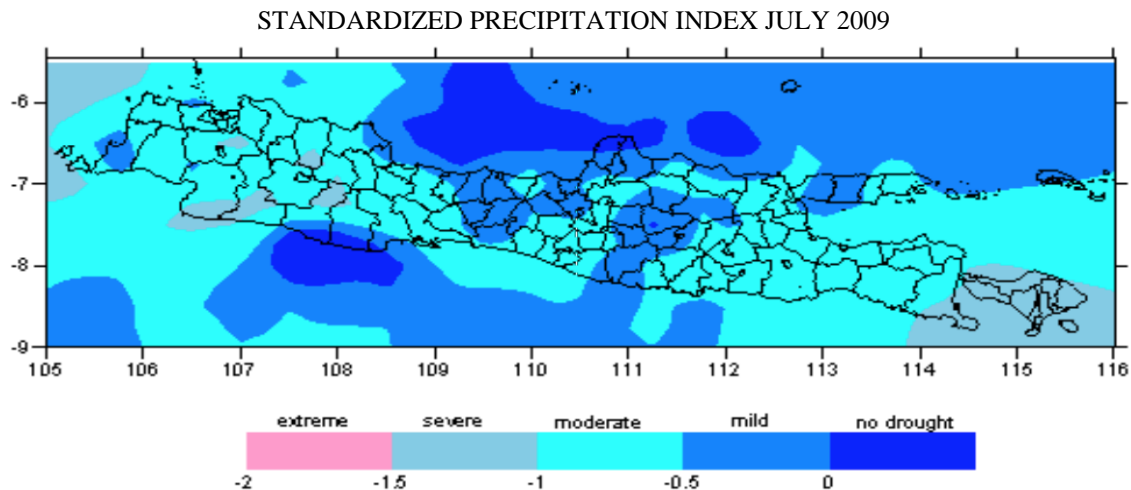


Figure 2. SPI Map of Java Island for July 2009 [63]

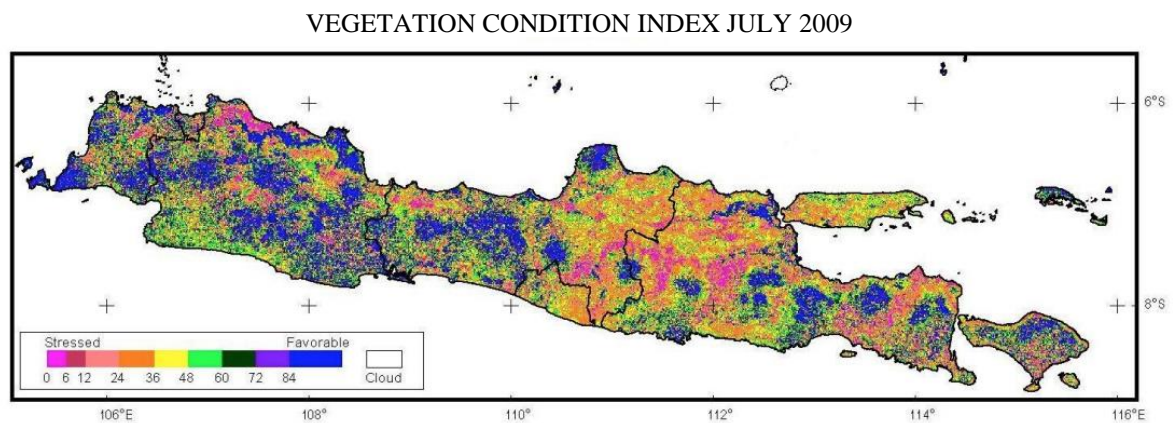


Figure 3. VCI Map of Java Island for July 2009 [63]



The study of drought on Java Island provides an overview of the potential hazard of drought based on rainfall and vegetation conditions. Meteorological drought due to rainfall deficit in Java has occurred since June and extended to August 2009. From June to August 2009, there was also an agricultural drought in the form of vegetation stress. A map of agricultural drought or vegetation stress can be seen in Figure 5. Drought and crop failure will result from the lowest vegetation stress in the paddy fields. Therefore, a severe drought appears to have occurred in several areas across the provinces of Java Island. This study provides an overview of the agricultural drought process that occurs due to a continuous deficit of rainfall, which is shown for three months. It has resulted in a severe agricultural drought.

TEMPERATURE CONDITION INDEX JULY 2009

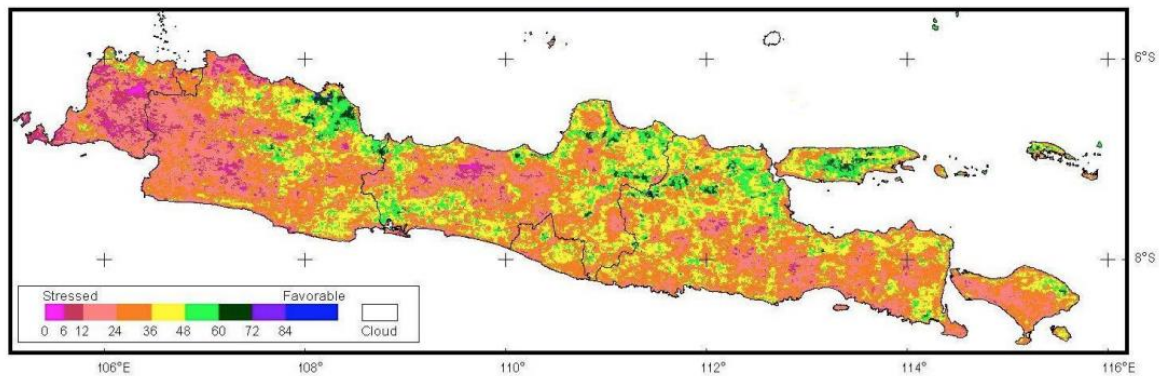


Figure 4. TCI Map of Java Island for July 2009 [63]

VEGETATION HEALTH INDEX JULY 2009

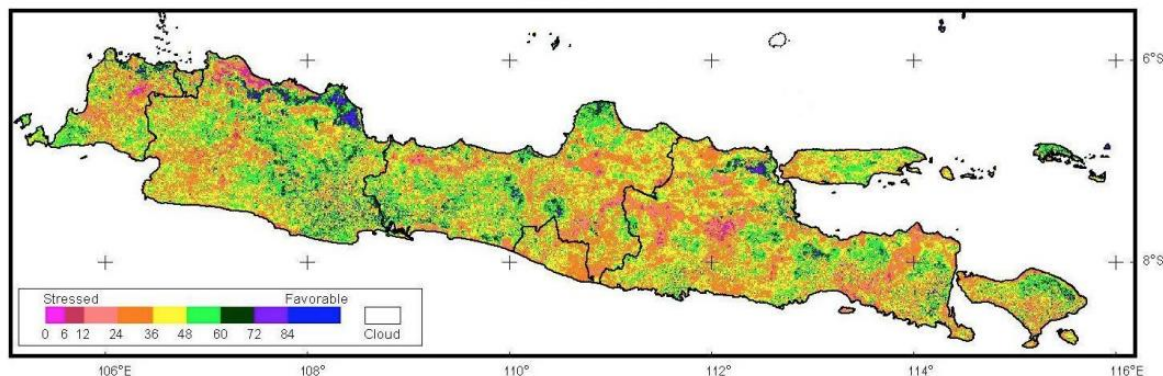


Figure 5. VHI Map of Java Island for July 2009 [63]

Drought vulnerability at the provincial scale has been studied by Amalo *et al.* [64] in East Java as the national agricultural production center. This study showed agricultural drought during EL-Nino in 2015 usually started in June, maximum in October, and ended in November. In Normal condition 2013, drought happens 3 months long, with area extent 115,443 km<sup>2</sup> and severity of mild-extreme drought (VHI 0-40). EL-Nino 2015 condition gives impact to the long drought duration and the wider area extent than normal condition. Drought duration during EL-Nino happens 5 months with an areal extent of 197,343 km<sup>2</sup>. This study, also found that the most affected area by drought is in September-December, followed by May-August, and January-April. This agriculture drought correlated with rice production.

Amalo *et al.* [64] focus on monitoring agriculture drought monthly and compare between El-Nino, Normal, and La-Nina condition. From the monthly information could be identified month of drought and could be compared one month condition to another month. The method in this study is similar to Roswintarti *et al* which use MODIS to extract the VHI index. VHI index as the result of agricultural drought is shown in Figure 6. This study gives information on vegetation drought in 1 km resolution at the provincial-scale. This information represents the condition of the province in a wide area. However, it still needs improvement in considering another aspect such as rainfall that refers to meteorology drought or soil moisture that refers to hydrology drought.

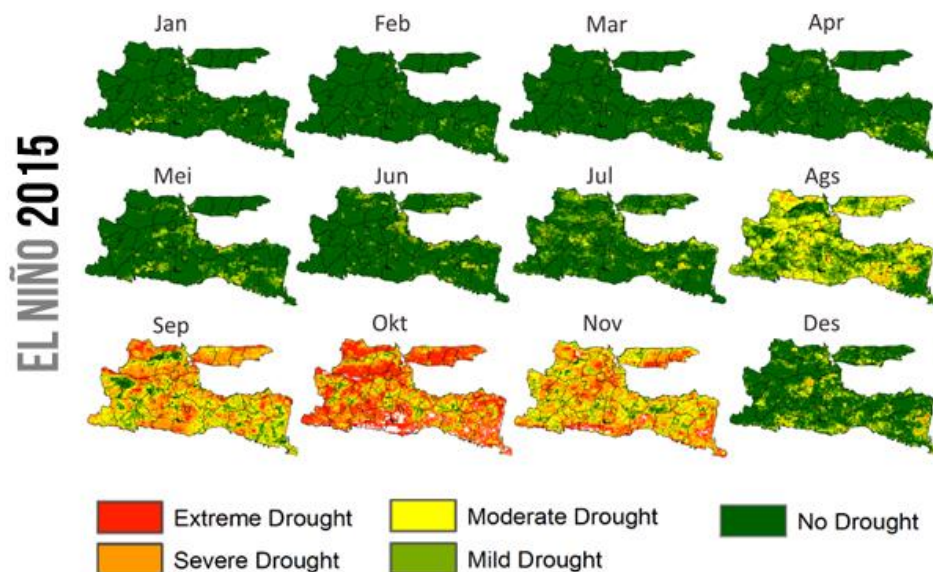


Figure 6. Monthly monitoring of agricultural drought 2015 in East Java Province [64]

In 2012, Dirgahyu [19] study about identifying drought vulnerability on a regional scale i.e. Indramayu district. This study builds the *Indeks Rawan Kekeringan* (IRK) algorithm which combines meteorology, vegetation, and hydrology droughts using MODIS and TRRM images and focuses on paddy fields. Model of IRK has been used in drought monitoring of LAPAN (<https://sipandora.lapan.go.id/app/sipanda/sumber-daya-wilayah-darat/map/4321>). Figure 7 shows the information on the drought map in the paddy field in August 2021.

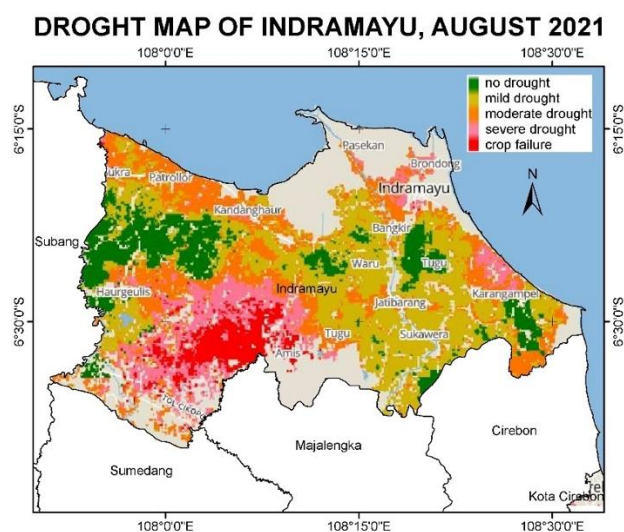


Figure 7. Drought map of paddy field in August 2021 in Indramayu District [19]

The study of Dirgahayu provides a complex alternative method of drought identification by paying attention to all types of drought by using the green level of vegetation (TKV), especially in paddy fields. TKV represents the condition of vegetation health, which is influenced by the amount of water. Low water in a long period will affect soil moisture which is called hydrology drought in this study. TKV and low rainfall cause a shortage of water supply, causing severe drought in Indramayu in Mei-August 2008. This study is more focused and detailed to maintain food availability and rice productivity. It gives a good temporal analysis of drought every 8 days using MODIS. However, it is a lack of spatial resolution which is a lack of information at the sub-district level. Also, this research still needs development in the accuracy check of the identification results.

Another study at the district level was conducted by Pramudya and Onishi in 2018 using in-situ rainfall data [68]. The study calculates SPI for 30 years from 1982-2015. It shows that meteorology drought occurred in year 1982-2015 with index value respectively, for SPI 1 are (-3.11) in 1985 and (-2.51) in 2015, for SPI 3 are (-2.29) in 1997 and (-1.82) in 2015, for SPI 6 are (-2.40) in 1997 and (-1.84) in 2015, for SPI 9 are (-1.12) in 2015, and for SPI 12 are (-1.19) in 2015. Figure 8 reflects 32 years of SPI values in Tegal city. This study is accurate in the station location since it uses a direct measurement meteorological data station. However, this study only provides one station data location which does not represent another area of Tegal. Also, this study calculates drought from rainfall without considering vegetation and soil condition.

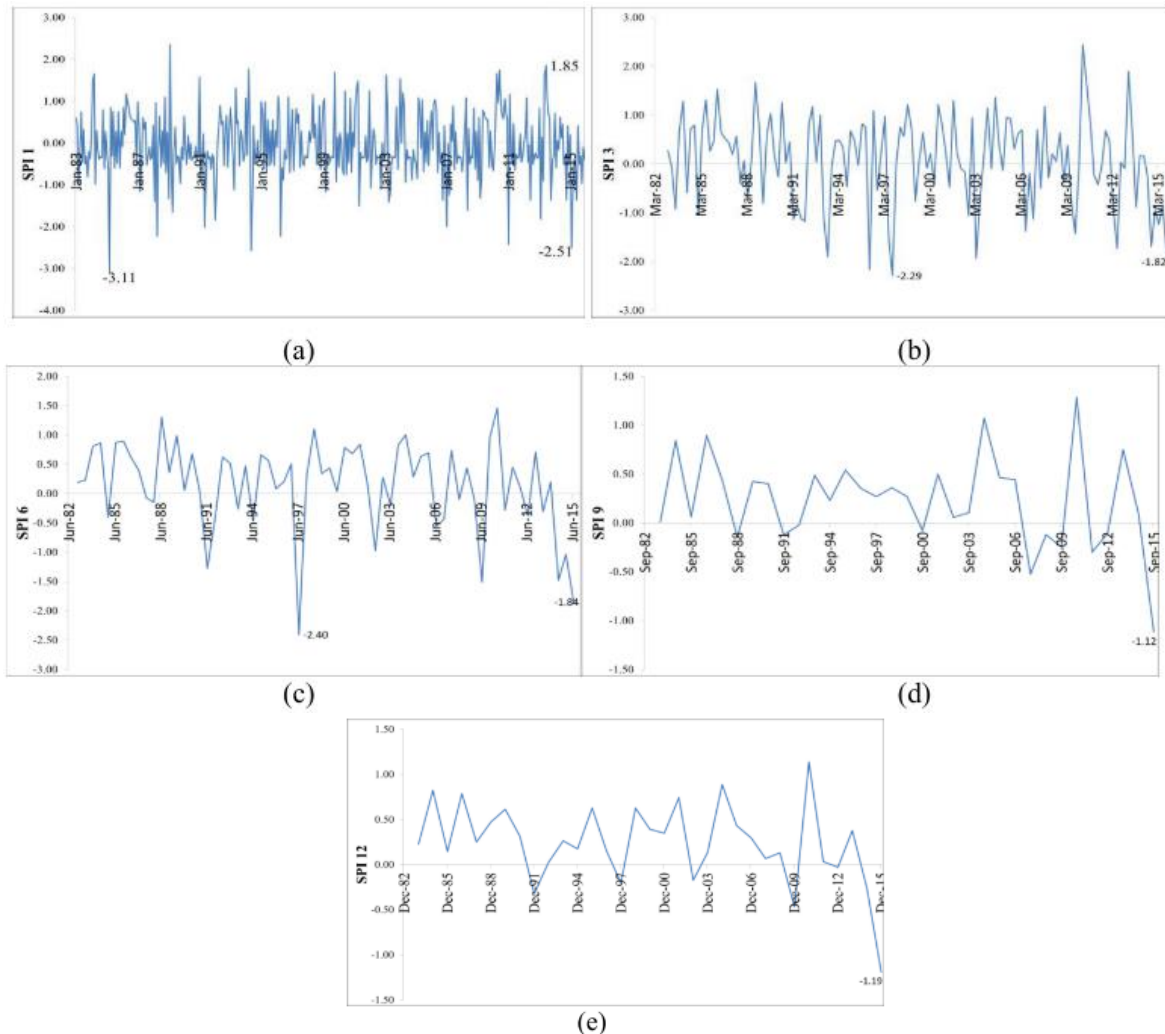


Figure 8. SPI values for Tegal city meteorological station with (a) 1-month time scale; (b) 3 month time scale; (c) 6-month time scale; (d) 9-month time scale; (e) 12-month time scale [68]

In 2016, Sholihah *et al* [66] conducted a study on drought in Subang and Karawang Districts in El Nino year 2015. The identified drought is vegetation drought from the VHI index which represents vegetation stress. Different from Roswintiarti *et al.* and Amalo *et al.*, this study uses a Landsat-8 image that has a 30 m x 30 m pixel size. The result of this study has more detailed information than the study using MODIS at the district level. This study is suitable to interpret paddy fields with a small area. The result shows that drought intensified since 2000 and increased until 2015 significantly. Figure 9 represents VHI in 2000, 2005, 2010, and 2015 in Subang and Karawang Districts. Drought area and severity are increasing from 2000 to 2015. The VHI decreased 50% and the increase of severity due to the rising of LST from 27° to 40°C. Using Landsat-8 at the district level is the best choice. However, this study still needs improvement by enriching drought type with meteorology and hydrology drought, checking the accuracy of the model, and monitoring drought monthly.



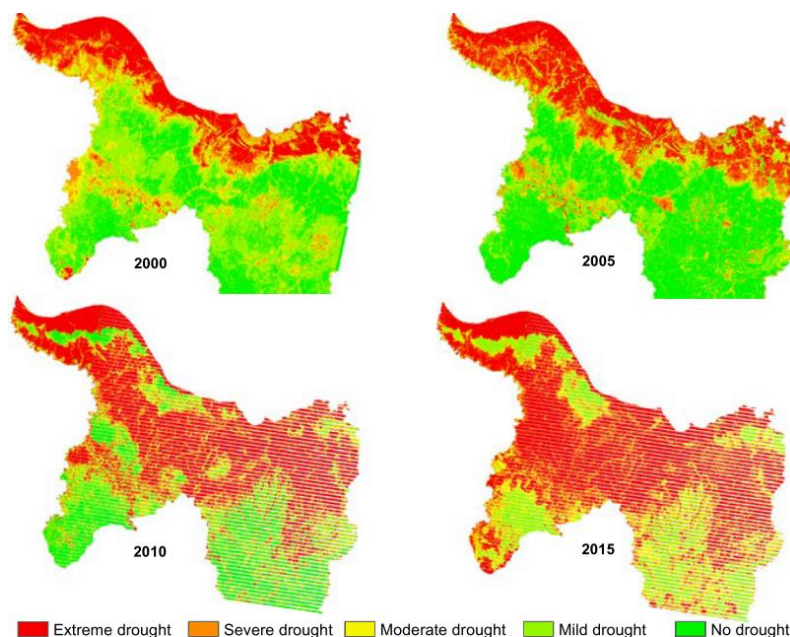


Figure 9. Drought map of Subang and Karawang [66]

#### 4. CONCLUSION

Low-resolution remote sensing imagery is used in studies of drought vulnerability at the island and provincial-scales. It provides an overview of drought conditions at the island-scale, while it focuses on paddy fields at the provincial-scale. The drought occurs in June-September, but further research is needed for accuracy testing.

In-situ measurements at the district-scale are capable of detecting a meteorological drought accurately. However, it has limitations in terms of both spatial data distribution and detailed information. Medium-resolution remote sensing imagery and GIS data processing for drought vulnerability mapping at the district-scale shows detailed information. The combination method of meteorology, agriculture, and hydrology drought in terms of monthly drought monitoring are necessary to represent the rainfall, vegetation, and soil condition during drought episodes.

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