Historical, Recent, and Future Threat of Drought on Agriculture in East Java, Indonesia: A Review

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Abstract. Climate change intensifies hydroclimate variability, leading to more frequent and severe drought, which pose significant challenges to water, food, and energy security. Droughts are complex natural hazards that area difficult to predict spatially and temporally. East Java, with its historically extreme droughts and reliance on agriculture, exemplifies these challenges. This study investigates the definition, measurement, driving mechanisms, and historical and future projections of drought occurrences in the region. Notably, a strong correlation is observed between El Niño and drought events, predominantly impacting the northern areas that heavily depend on rice irrigation. East Java's prolonged dry season and limited rainfall exacerbate the recurring threat of extreme drought. With global warming amplifying these patterns, urgent action is imperative. This paper highlights the need for a comprehensive understanding of drought dynamics to develop effective mitigation and adaptation strategies of agricultural activity. By examining the interplay between climate phenomena, rainfall patterns, and droughts impacts on agriculture, valuable insights are gained to foster sustainable water resource management and build resilience to drought in East Java.

1 Introduction

Water, food, and energy are fundamental for achieving sustainable development goals. Climate change poses a significant challenge in realizing sustainable development. Changing climate is characterized by shifts in rainfall patterns, increased temperatures leading to higher evapotranspiration, and intensified frequency and intensity of extreme hydroclimate conditions [1]. Drought and floods are prominent expressions of extreme hydroclimate variability [2,3]. Drought is expected to become more severe in conjunction with global climate change [4].

Drought is defined as a water balance deficit resulting from elevated temperatures and below-average rainfall within specific spatial and temporal conditions [5]. Despite being a slow-onset phenomenon with less observable direct impacts, drought can be highly destructive, particularly affecting agriculture, ecosystems, livelihoods, and environmental

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conditions [6]. Prolonged drought has been proven to pose a threat to food security, leading to food shortages and exacerbating the climate cycle [7]. Drought impacts terrestrial ecosystems by limiting vegetation growth, increasing the risk of wildfires, and reducing net primary production [8].

Drought is one of the types of disasters that is difficult to predict in terms of location and timing. Often, such events are only recognized when they turn into natural disasters [9], causing economic and social impacts. Based on the Indonesian Law on Environmental Protection and Management Number 32/ 2009, drought is included in the criteria for climate-related damage (Article 21, paragraph 4 of the Law on Environmental Protection and Management).

Severe drought in Java which coinciding with the El Niño event in 1997/1998, resulted in dry season rainfall decrease [10]. Rainfed agriculture was immediately affected by the drought. East Java Province is among the priority areas for drought management in Indonesia. As a monsoonal climate region, drought can occur during the dry season and the transition from dry to rainy season (October-November). Data from the National Disaster Management Agency (BNPB) in July 2019 showed that 45 percent of drought-prone districts were located in East Java Province [11].

The agriculture sector in East Java supports national rice production, with a harvested area of 1.75 million hectares and paddy production of approximately 10 million tons. Furthermore, 37 percent of the economy is supported by the agriculture sector [12], with 30 percent of it being non-irrigated land. Drought occurring during the generative stage can lead to crop failure or empty grain husks.

Mitigating and preparing for disasters have a crucial role in minimizing the destructive consequences of disasters and reducing the susceptibility of households to poverty [13]. Due to the creepy behaviour of drought to environment, it is crucial to provide a comprehensive overview of drought characteristics in East Java Province as theoretical and actual occurrence, both historical and future projection. The provided overview can indeed serve as a basis for future research directions on drought.

2 Definitions, Measurements, and Driving Mechanisms

2.1 Definitions of Drought

Drought can be defined as condition in which the supply of water fails to meet the environmental demand. The World Meteorological Organization (WMO) highlights that drought arises from a prolonged deficiency of precipitation resulting in a water shortage [14]. Furthermore, The Intergovernmental Panel on Climate Change (IPCC) identifies drought as: a) a rain deficit resulting in decreased water storage for various activities, and b) a prolonged dry period leading to hydrological imbalance [15]. In summary, drought is characterized by insufficient precipitation compared to the average over a specified period. It results in decreased soil moisture, poses threats to crops, and can deplete surface water and groundwater reserves.

Different perspective viewed drought is considered a normal occurrence due to decreased rainfall [16] and [17]. However, if the decline persists continuously over an extended period, the situation can transform into a disaster [9]. In fact, drought is recognized as one of the most economically damaging natural events globally [18].

Drought can be classified into meteorological drought, agricultural drought, hydrological drought, and socio-economic drought [19]. Drought begins with a decrease in rainfall (meteorological) over a period of time, which results in a reduction of both groundwater and surface water reserves [20]. Prolonged meteorological drought directly impacts agriculture, leading to agricultural drought [19]. Decreased soil moisture causes reduced infiltration and groundwater storage [21]. Low rainfall results in minimal water entering the soil, leading to insufficient replenishment of the aquifer (hydrological drought). As rainfall decreases further, the loss of rainwater due to evaporation and surface runoff becomes significant, resulting in a decline in available water storage. Moreover, under high air temperatures, the limited amount of rainfall is lost through evaporation and evapotranspiration, failing to replenish groundwater reserves [22]. If dry conditions persist, it can have socio-economic implications. This phase of drought is commonly known as socio-economic drought.

Based on the given definition, the diversity of rainfall patterns and decreasing precipitation pose a greater risk to drought compared to temperature increase [23]. In the context of global warming, the threat of drought is directly proportional to precipitation intensity. Temperature acts as a catalyst for drought, accelerating its occurrence with strong intensity [22,24], particularly in tropical regions [25].

2.2 Drought Measurements

Identification of drought is the initial step in preventing future risks. The steps are challenging due to the slow and creeping nature of drought. Quantification efforts are considered an efficient approach to identify drought, leading to the development of various drought indices. One type of drought that is believed to be used as an initial risk reduction measure is meteorological drought. Meteorological drought serves as the first indicator of decreasing rainfall and the presence of water deficits [16,26]. The precipitation decreasing for consecutive periods reducing soil water moisture thus affected surface water availability. In the long term, hydrological drought impacted water reservoirs leading to water shortages and water scarcity in the socio-economic perspective [27]. Practically, drought indicators providing valuable information for monitoring drought conditions [28,16].

The first drought index introduced was the Palmer Drought Severity Index (PDSI) developed by Wayne Palmer [29]. Identifying drought based on the PDSI has advantages as it incorporates location, humidity, and wind. The PDSI is calculated based on water balance and its input and output. However, the use of the index in regions with large variations in maximum and minimum rainfall can result in high errors [30]. Additionally, the PDSI is most suitable for regions with similar soil types and soil moisture levels. Subsequently, a simple drought analysis technique based solely on monthly rainfall data, known as the Standardized Precipitation Index (SPI) introduced [31]. Similar to SPI, the Effective Drought Index (EDI) [32] uses effective rainfall as the primary indicator of meteorological drought.

Another developed index is the Standardized Precipitation Evapotranspiration Index (SPEI) [33]. SPEI incorporates temperature data together with rainfall data. Temperature data is necessary in drought analysis as rainfall data alone cannot reveal water losses due to evaporation and evapotranspiration. This index is similar to PDSI in that it uses water balance to determine dry or wet conditions. However, the SPEI has lower sensitivity compared to PDSI. PDSI considers additional factors that accelerate evaporation, such as wind coefficients, air humidity, and latitude. The use of SPEI is more recommended for regions with data scarcity. Nevertheless, in tropical regions with low annual temperature fluctuations, the analysis using SPEI does not differ significantly from SPI [34]. Rainfall serves as the primary control for drought on Java Island. Therefore, government institutions such as the BMKG solely use rainfall as an indicator of drought.

2.2.1 Suitability of Drought Indices for Java Island, Indonesia

Java Island is composed of a main island and several small islands that surround the Java Sea (**Fig. 1**). The topography of East Java exhibits both meridional and latitudinal characteristics. The northern part is predominantly an alluvial plain, which is suitable for rice cultivation. In contrast, the central region is marked by volcanic mountains, while the southern region consists of steep hills. East Java is located in the southern hemisphere and experiences a tropical monsoon climate. In tropical regions, there is no significant inter-season temperature difference, making rainfall the main influencing factor for drought conditions.

Total rainfall is a key factor in drought occurrence in tropical regions with low annual temperature variations [35]. Factors influencing rainfall amount and spatial-temporal distribution form the basis of drought mapping studies. This is based on the understanding that every type of drought originates from a deficit in rainfall over a specific period of time, often referred as meteorological drought.

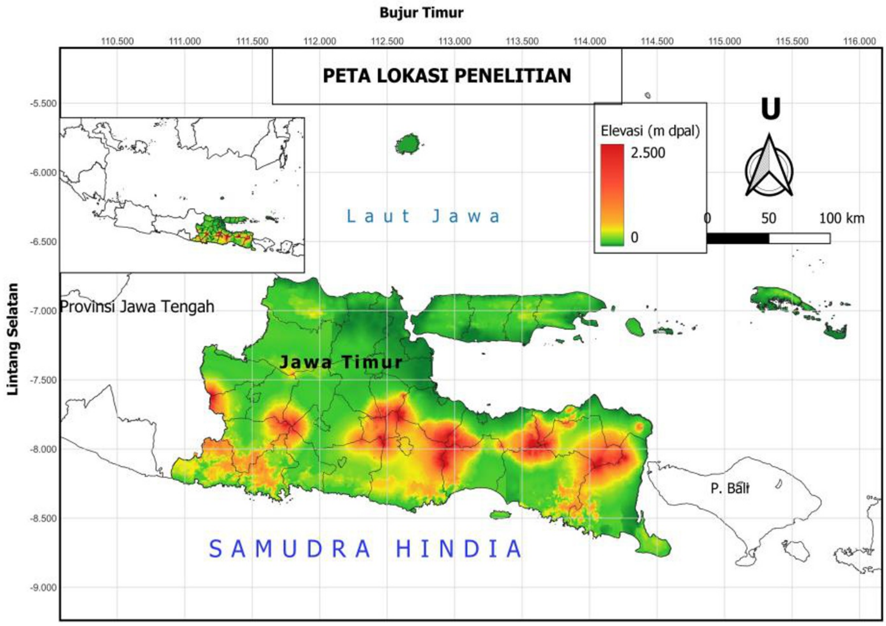

Fig. 1. Topographical View of East Java Province

The Standardized Precipitation Index (SPI) was first introduced by [36] to assess the degree of drought in a specific area based on monthly precipitation data. The advantage of SPI is its spatiotemporal nature, allowing for the analysis of drought risk as well as the risk of excessive rainfall occurrences [37]. SPI is widely recognized as a drought index, although it can also represent wetter or drier conditions. The values derived from SPI calculations represent the probability of events within a given observation period, both in the long and short term. SPI is obtained by transforming the probability density function (PDF) into a cumulative density function (CDF) using a zero mean and unit variance. Positive values in SPI indicate wetter than usual conditions, while negative values indicate drier than usual conditions. A value of zero represents the normal condition, which is the median of the entire cumulative probability. A recommended time frame for SPI analysis is 30 years [36], while [37] suggests that for extreme event analysis, data spanning more than 100 years is required.

The calculation of SPI can be performed for various time scales with maximum 24 months for accurate SPI values [37]. SPI 1 is commonly used for analysing drought conditions for a specific month and represents the percentage of normal precipitation for that particular month. For example, SPI 1 for the month of October is calculated based on the probability of October rainfall in a given year compared to all the historical October data. SPI 1 is suitable for climate analysis because if a particular month is dry, the SPI value will become highly negative, indicating extreme dryness. SPI 3 is often used for assessing agricultural drought risk. It also provides information on short-term and medium-term moisture conditions. SPI 3 for the month of October, for instance, represents the probability of rainfall in July and the two preceding months (August-September-October) relative to the total three-month rainfall in the observation record.

The Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG) categorizes drought based on SPI values as normal, slightly dry, dry, and severely dry. If the SPI value is ≤ -2.00, it is classified as severely dry. Dry conditions occur when the SPI is between -1.50 and -1.99. SPI values in the range of -0.99 to 0.99 are considered normal. In accordance with BMKG Regulation No. 9 of 2019, the Meteorology, Climatology, and Geophysics Agency (BMKG) incorporates the number of rainless days, forecasted probability of ten-day rainfall, and the standardized precipitation index (SPI) in the early warning system for meteorological drought.

2.3 Driving Mechanisms of Drought

Rainfall is the primary input in the water balance of tropical regions. The water balance during the dry season in monsoonal climate regions in Indonesia is characterized by a water deficit due to higher evaporation rates compared to precipitation. As for subtropical region, the largescale circulation patterns, daytime heatwaves, minimum daily extreme precipitation, and geographic position may contribute to the drought pattern. The basis of drought relevant to the wind which bringing the convective cloud to forming precipitation. Monsoon failure has recognized the cause of megadrought during the last millennium [38]. The late onset of wet monsoon Indonesia affected by ocean-atmosphere circulation in Pacific and Indian Ocean.

The El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) phenomena influence seasonal rainfall in Java Island through the mechanisms of monsoon strengthening or weakening [39–42]. However, the regions affected can vary. The IOD strongly affects rainfall in western Java, while its impact is weaker in eastern Java [43,44]. Conversely, ENSO has a stronger correlation with rainfall in eastern Java, with a weaker influence from IOD. However, ENSO and IOD are phenomena that can mutually influence each other through the Indonesian Throughflow mechanism [43]. Therefore, the effects of ENSO and IOD can either reinforce or weaken each other.

Based on these studies, the rainfall variations in Java Island are influenced by geographical-topographical differences [45], and coastal factors related to distance from the coast and sea surface temperatures of surrounding waters [46–48]. Regionally, rainfall is influenced by changes in the strength and movement of the Asia-Australia monsoon [49–51] al., 2016). The monsoon is affected by the ocean-atmosphere circulation occurring in the Pacific Ocean and the Indian Ocean. These variations result in localized rainfall in the Java region, influenced by both internal circulation and external factors.

The occurrence of drought in Java Island is a climatological phenomenon. The key factors contributing to severe/extreme global droughts is anomalies in sea surface temperature/pressure. Similar patterns can be observed in Java Island, where droughts are strongly associated with ENSO and IOD. The relationship between ENSO, IOD, and drought in Java Island is actually a local event. Each region has different sensitivities, even within a very narrow location [44]. This relationship becomes more straightforward when extreme ENSO anomalies occur. Extreme ENSO events result in severe droughts across almost the entire Java Island, particularly in eastern Java [52,53].

3 Historical Drought in East Java

Historical climatology and paleoclimatology have been studying by climatologist [54–56]. Coral analysis suggest that Java droughts were more severe during the mid-Holocene [57]. Numerical drier conditions over century occurred during 960-1090 C.E., 1260-1300 C.E., 1380-1450 C.E., 1600-1690 C.E., 1790-1800 C.E., and 1840-1900 C.E. Before the 10th century, it is proven that climate in Java dominated by wetter conditions [58]. Mainly part of Java recording strong correlation between positive IOD with drought event in Java [59]. During 19th century, drought relate strongly with strong positive IOD and Pacific sea surface temperature anomaly. There are consistent statements that drought in Java found during El Ninos coincide with negative equatorial wind.

Meteorological drought in East Java has been identified by [52] using historical data from 1787 to 1988, which shows that drought during the early rainy season (October to November) is associated with sea surface temperature anomalies in the Pacific Ocean. Similar findings are depicted by [56] using sediment data in East Java, indicating that extreme droughts are influenced by extreme El Niño events. Therefore, drought events can be associated with extreme sea surface temperature anomalies. During El Niño, the waters around Indonesia become cooler, resulting in fewer cloud formations. As a result, rainfall in coastal areas decreases due to reduced convective clouds [48]. Potential for drought becomes significant in the case El Niño occurs at the end of the dry season

El Niño-Southern Oscillation (ENSO) is strongly associated with drought, and almost all ENSO events coincide with drought. However, research [25] shows that not all strong ENSO events result in extreme drought. The occurrence of extreme drought is highly dependent on the timing and peak of ENSO events. Research by [60] indicate that drought may occur during the rainy season, characterized by an increase in rainless days.

These studies reveal the diverse patterns of meteorological drought due to El Niño, which exhibit local characteristics and have two polarizing influences. The southern region of East Java tends to be stable against external influences, while the northern coastal region of Java is more susceptible to changes in sea surface temperatures in the Pacific Ocean. However, the distribution of drought varies significantly due to differences in topography and varying geographic positions. Historical drought studies have shown a strong connection between drought in East Java and positive ENSO events [34,52,53,56].

4 Recent Drought in East Java

Drought viewed as natural hazard somehow turned into disaster. Recent droughts have been observed over a climatic period of approximately 30-40 years. Notably, the extreme El Nino events of 1982/1983, 1997/1998 are widely recognized in the 20th century, while the 2015/2016 is the first extreme El Nino in 21th century [34,61]. The occurrence of extreme El Nino simultaneous with extreme drought in Java. These drought events have a greater influence on meteorological drought compared to global warming, as they are associated with variations in sea surface temperatures [58]. The 2015/16 El Nino phenomenon resulted in exceptionally high temperatures and severe water deficits over western Pacific [61].

Drought in Java generally associated with positive phase of ENSO and positive Indian Ocean Dipole (IOD) [34,62,63]. It has been reported that the intensity and frequency of combined Pacific and Indian Ocean circulation have increased since 1960 [64]. Statistics show that there have been 331 drought events in East Java over a 20-year period, affecting 1.5 million people [65].

5 Future Threat of Drought

5.1 Drought in Changing Climate

The rapid global climate change has had an impact on the availability of water during the growing season, resulting in a decline in terrestrial biodiversity. Climate change alters the natural variability of recurrent weather systems, exacerbating drought incidents. The characteristics of global drought are highly dependent on location, precipitation anomalies, and annual temperature anomalies. Drought in regions with low rainfall and high temperature variability can be caused not only by the amount of rainfall but also by high evapotranspiration rates [1], [27], [28]. Based on climate change scenarios, increasing temperatures will elevate the potential severity of global drought [29]-[32]. However, droughts that have occurred over the past half-century have not shown significant changes [33]. Nevertheless, projections of future drought are not solely related to global warming but are also influenced by changes in global cycles such as circulation patterns in the Pacific and Indian Oceans. Some studies indicate that global warming has led to increased frequency of sea surface temperature anomalies in the Pacific and Indian Oceans [34] [35].

Impacts of climate change on water resources relating to timing change of rainfall onset which generated extreme climatic events [1]. Drought threatening agriculture because the strong dependence on water resources for cultivation. FAO (2018) reported that drought causes 83% of total damage and loss of agriculture. The warming climate increasing the probability of co-occurrence of higher temperature and precipitation deficits [66].

Changing trend of precipitation extremes becoming primary future of climate projections [67]. In the 21st century, the climate model projected the severity and persistence of megadrought will change significant [2]. Higher temperature has been proven to change water availability, generate more intense drought, and amplify the consequences [68]. According to climate change scenarios, increasing temperatures will raise the potential severity of global drought [29]-[32]. Several studies have shown that global warming has led to an increase in the frequency of sea surface temperature anomalies in the Pacific and Indian Oceans [34], [35] which acts as driving mechanism of drought.

5.2 Drought Threating Agriculture Systems in East Java

Drought directly impacts the availability of water resources, agriculture, and ecosystems. Additionally, drought can act as a catalyst for wildfires, leading to widespread socio-economic implications. Decreased rainfall marks the beginning of declining surface water reserves, soil moisture, and even groundwater supplies. As a result, the physical ecosystem undergoes changes, and biodiversity that is not resistant to water scarcity cannot survive, leading to alterations in food webs (Pala, 2017). Therefore, drought is closely related to the agricultural sector. Approximately 23% of land in 1922 historical Java are managed for rice cultivation. The first cultivation was taken place at the beginning of the rainy season [35]. The northern coast of Java dominated by alluvial plain which classified as the most fertile rice and sugar soils in the island. On the other hand, the southern coast is bordered by mountainous ridge descending steeply into deep ocean.

Agriculture heavily relies on water availability in the root zone. There is typically an immediate reduction in photosynthesis as a result of the decreased moisture levels during drought event. In the long term, drought leads to tree mortality and forest pattern change [69]. When there is no rainfall, the soil moisture remains low, which is not favourable for rice cultivation. If surface water reserves are depleted, agricultural activities may extract both shallow and deep groundwater to irrigate the land. The long-term consequences of such activities include a drop in groundwater levels and even land subsidence. Socio-economically, drought poses a threat to food security in a region [70].

During prehistoric, East Java experienced severe droughts, as evidenced by tree ring and sedimentation under lake. The more pronounced seasonality and lower rainfall in East Java have resulted in reduced soil fertility, decreased nutrient retention, and a decline the water holding capacity of volcanic soils [71]. Rainfed rice yields were found to be lower compared to well-watered fields. The dry seasons posed a greater threat to crop production as drought intensified. While yield losses due to drought during a typical dry season were not classified as significant, the plain region was affected [72]. It can be estimated that regions with deeper groundwater tables experienced higher reductions.

6 Dealing with Drought

Especially in agricultural regions, the amount of rainfall during dry seasons holds immense significance, particularly in the plain regions of tropical areas. Despite the relatively steady phase of the South-Eastern Monsoon in August, the mountainous regions could accumulate convective cloud which generate rainfall even thunderstorm [35,41,73]. The prolonged dry season affect mostly on the plain region, especially East Java which naturally receives lower rainfall and longest consecutive dry months. Cultivation without irrigation becomes inconceivable during these drought conditions [35]. Irrigation expansion in rain-fed croplands can be seen as a means to increase crop yields, particularly in densely populated countries like Indonesia. The rationale behind optimizing rain-fed systems is that the rainfall amount is not too affected by global circulation [74]. Nevertheless, sustainable development requires striking a balance between expanding rain-fed irrigation and conserving the recharge area to ensure long-term viability.

One of the approach to address future droughts is to localize big-climate science information and develop community-led adaptation strategies [75]. Building resilience to mitigate and adapt for future drought events is likely transform the citizen's behaviour, helping them to accept the ever-changing conditions, even during more severe extremes [2]. Drought-tolerant plant may survive the changing climate, while species unable to adapt may face extinction [76].

7 Conclusions

East Java exhibits characteristics of naturally lower rainfall and an extended dry season. Historical records of drought during the mid-Holocene period indicate the potential for recurring extreme droughts in the future. The most recent drought events occurred in 1982/1983, 1997/1998, and 2015/2016 have had devastating impacts on water resources, ecosystems, and agriculture. The recurrence of such patterns can pose a serious threat, particularly when combined with accelerated warming trend. The information on severe drought events, their association with climate phenomena such as ENSO, and the increasing intensity and frequency of combined Pacific and Indian Ocean circulation provide important insights for further investigation. Researchers could delve deeper into understanding the mechanisms and patterns of drought events to develop strategies for drought mitigation and adaptation. Additionally, exploring the interactions between drought and climate change, as well as assessing the effectiveness of current drought management approaches, can be valuable areas for future research.

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