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Research Article
Drought Risk Mapping in East Nusa Tenggara Indonesia Based on Return Periods

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Abstract

Background and Objectives: Drought has been one of the major causes of disaster in Indonesia. The Regional Disaster Management Agency (BPBD) of East Nusa Tenggara (hereafter denoted as NTT) Province in Indonesia has reported that there were 20 districts in NTT affected by drought in 2015. This study aimed to map drought risk in NTT by using the Standardized Precipitation Index (SPI). The drought duration as well as the magnitude based on return periods of 5, 25 and 50 years were estimated as the basis of mapping. **Methodology:** The study were carried out by examining daily rainfall data recorded by several meteorological stations in NTT with in the period of 1999-2015. Return periods were estimated by quantifying the probability of extreme events, which thus translated into Scale-Duration-Frequency (TDF) and Time Scale Magnitude-Frequency (TMF). **Results:** The SPI analysis showed that NTT has experienced about 25 months of drought events within the periods of 1999 to 2015. The mapping results showed that Gewayantana is a district with the longest drought duration (reaching 30 months in 50 years) and strongest drought magnitude (11.2 SPI level) for all specified return periods. Meanwhile, Komodo and Frans Sales Lega districts are two regions with the lowest risk indicated by shortest drought duration and lowest magnitude compared to the others. The longest drought duration were mostly started in November. **Conclusion:** The drought risk maps derived from the magnitude and duration of the future drought in NTT clearly indicated that the severity of drought events in NTT increases over the time. However, the drought duration and magnitude for 50 years return period seems to be over-estimated.

Key words: Disaster, drought, risk, scale-duration-frequency (TDF), time scale magnitude-frequency (TMF)

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Drought is a condition when the availability of water is far below the water requirement needed for the necessities of life, agriculture, economic activities and environment. When drought happens in an area during one or more seasons, it may cause a prolonged shortage of water supply. As the result, it may affect the economic and social conditions as well as the environment. Drought has been a major cause of disaster in Indonesia in particular of the NTT province.

The Head of the NTT's Regional Disaster Management Agency (BPBD) has mentioned that 20 districts (consisting of 270 villages and urban villages) in NTT have been affected by severe drought[1]. The drought has caused dry of agricultural land and water scarcity for daily life. Moreover, the Indonesia Food Security Monitoring Bulletin[2] has also listed NTT on the first priority of province in Indonesia which significantly affected by drought and hence, it is highly vulnerable to the drought risk. The first priority districts are districts that had no rain for more than 60 days and have poverty level above 20%.

One of the strategies to reduce the drought risk is by providing information about potential drought-affected area as well as developing early warning to predict future drought events. Drought risk mapping is useful to provide information that may increase public awareness and actions to reduce the drought risk in a certain area[3]. Studies on drought risk mapping have been carried out by many researchers. Skakun *et al.*[4] maps drought risk in Ukraina using satellite data information. Lin *et al.*[5] assessed the drought risk in Western-Inner Mongolia by integrating remote sensing, geo-computation and geographic information. More recent study by Dahal *et al.*[6] used temporal and spatial analysis to assess the drought risk in central Nepal. Dalezios *et al.*[7] provides a comprehensive concept to identify risk of agricultural drought.

Several measures have been introduced to assess and monitor drought severity. One of the most useful and commonly used indicators is the Standardized Precipitation Index (SPI), which was firstly introduced by Mckee *et al.*[8]. The Agency for Meteorology, Climatology and Geophysic (BMKG) Indonesia regularly develops drought map for Indonesia region based on the SPI. However, the map is a monitoring tool with a limited information about drought events in the future as the basis of assessing long term drought risk. Therefore, a tool which may provide information about future drought prediction is required in order to minimize the risk. One of the ways is by developing drought maps through the estimated magnitude and drought duration based on return periods.

The return period can be predicted by several methods. Bonaccorso *et al.*[9] derived analytically the parameters of the probability distribution of drought severity based on the stochastic process as the basis of estimating the return period. Cancelliere and Salas[10] predicted return period through the probability distribution of drought events considering drought duration and accumulated intensity. Several studies used copula approach to estimate return period (Chen *et al.*[11], Francis and Aremu[12], Liu *et al.*[13] among others). This paper analyzed drought differently to the afero mentioned studies, in which the return periods are pre-determined. This paper aimed to predict the drought duration and magnitude in NTT Indonesia based on the specified return periods i.e. 5, 25 and 50 years, derived from the intensity-duration analysis as in Saravi *et al.*[14]. The selection of the return periods refers to the criteria of drought intensity used in hydrological fields in order to characterize the level of dryness.

MATERIALS AND METHODS

Research duration, location and periods of study: This research was carried out in 2017. The data used in this research is daily rainfall or precipitation rate (mm) observed in East Nusa Tenggara (NTT) Indonesia, which spans from the period of 1999-2015. The data can be downloaded from the official website of Meteorological Office, Indonesia. The NTT province is a province consisting several islands. The data were collected from nine meteorological stations in NTT located in different island. The location of those nine meteorological stations in NTT Indonesia was shown in Fig. 1.

Figure 1 clearly showed that the nine stations were spreaded throughout the islands. In fact, the stations uses in this study are the only stations available in NTT. Therefore, the results of analyzing data from a specific station represents the condition of district in that region and its surrounding area.

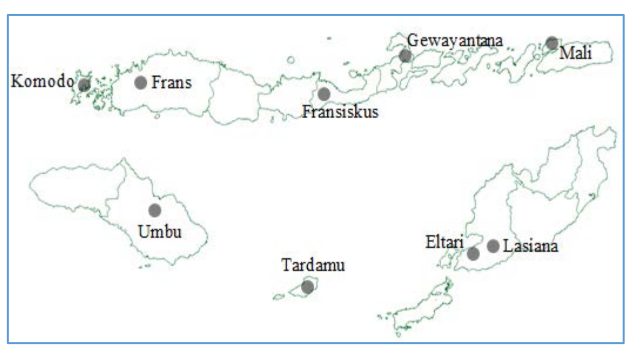

Fig. 1: Location of the meteorological stations in NTT

Standardized precipitation index (SPI): Drought can be defined as a temporary reduction in water supply that is significantly below the normal. Drought can also be defined as a period of below-average precipitation leading to prolonged shortage in the water supply. Standardized Precipitation Index (SPI) is one of the measures which can be used to characterize drought. The calculation of drought index by using the SPI method was firstly developed by McKee *et al*.[8]. The drought categories based on SPI according to McKee *et al*.[8] were as follows: $-0.99 \leq SPI \leq 0$ (Near Normal), $-1.49 \leq SPI \leq -1$ (Moderate Drought), $-1.99 \leq SP \leq -1.5$ (Severe Drought) and $SPI \leq -2$ (Extreme Drought). Besides these categories, drought can be characterized by its duration, severity/magnitude, intensity and relative frequency. Thompson[15] defined the magnitude of a considered drought event as the cumulative water deficit over the drought period, while the mean intensity is defined as the average of this cumulative water deficit over the drought period.

Statistical analysis: This paper fitted and tested the (joint) distribution to estimate the duration and magnitude of the drought events as written in Eq. 2 and then develop the Time Scale-Duration-Frequency (TDF) and Time Scale Magnitude-Frequency (TMF) graphs. More detail about the analysis was described as follow:

Estimation of magnitude and duration: According to Haan[16], return period is the average of the occurrence of an event with a certain magnitude or greater. The return periods of 5, 25 and 50 years were determined by defining the type of distribution that matches the data. The distribution (in this case Gamma distribution) is tested by using Chi-square test at the 5% significant level. The formula to determine return period (T) was given in Eq. 1:

$$E(\tau) = T = \frac{1}{p} \quad (1)$$

where, p is the probability of extreme occurrence. The drought duration and magnitude can be estimated from the Gamma distribution as in Eq. 2:

$$X_T = \alpha\beta + k_T\sqrt{\alpha^2\beta} \quad (2)$$

With:

$$k_T = \frac{2}{CS}\left[\left(\frac{CS}{6}\left(u - \frac{CS}{6}\right) + 1\right)^3 - 1\right]$$

and:

$$CS = \frac{\alpha}{|\alpha|}\frac{2}{\sqrt{\beta}}$$

$$u = W - \frac{c_0 + c_1W + c_2W^2}{1 + d_1W + d_2W^2 + d_3W^3}$$

$$W = \begin{cases} \sqrt{-2\log\left(\frac{1}{T}\right)} & , \text{ if } \frac{1}{T} < 0.5 \\ \sqrt{-2\log\left(1 - \frac{1}{T}\right)} & , \text{ if } \frac{1}{T} \geq 0.5 \end{cases}$$

$$c_0 = 2.515517,\ c_1 = 0.802853,\ c_2 = 0.010328$$

$$d_1 = 1.432788,\ d_2 = 0.189269,\ d_3 = 0.001308$$

Where:
X_T = Duration/magnitude on T year return period
α = Shape parameters
β = Scale parameter
k_T = Frequency factor of Gamma distribution

A graph called Time Scale-Duration-Frequency (TDF) and Time Scale Magnitude-Frequency (TMF) are made based on the value of the return period. Moreover, Joint probability density function (PDF) is used to determine probabilistic characteristics of drought parameters[17]. The Joint PDF between the duration and severity/magnitude of the drought represents the correlation between the two variables (drought factors).

Steps of the analysis: The analysis was carried out by the following steps.

Step 1: Pre-processing and aggregate the daily rainfall data into monthly rainfall data and convert the monthly data into SPI.

Step 2: Calculate the drought factors i.e. duration, magnitude, intensity and the relative frequency of drought based on the SPI data. The definition of each factor are:

- Duration (D) is defined as the time between the beginning of drought event (indicated by negative SPI) and the end of drought (indicated by positive SPI)
- Magnitude is the cumulative SPI of all months during the period of drought events

- Intensity is the ratio of magnitude to duration
- Relative frequency is the proportion of the number of drought that occurs (the total duration values divided by the total number of months) during the period analyzed

Step 3: Estimate the drought duration and magnitude in NTT by carrying out the following steps:

- Formulate the joint PDF between the duration value and magnitude for each observation stations
- Define the distribution type that is appropriate with the duration and magnitude, by using Chi-square test at the 5% test level. Furthermore, determine the return periods for 5, 25 and 50 years and obtain the duration and magnitude for each return periods
- Develop Time Scale Duration-Frequency (TDF) graph and Time Scale Magnitude-Frequency (TMF) graph of drought to find out the characteristics of drought in NTT

Step 4: Develop drought risk mapping in NTT based on the return periods.

RESULTS AND DISCUSSION

Preprocessing of the rainfall data: Data preprocessing was necessary to be conducted as the data contains missing values in all stations. The missing data were mostly found in the Fransiskus Meteorological Station, which is almost 30% of the total period, while Komodo Meteorological Station is the station with the least amount of missing data which is about 3%. A simple missing data imputation has been conducted by estimating the missing values with the average of observations on the corresponding date from the other periods of time. Moreover, in some cases the imputation has been done by performing regression analysis between data at the corresponding station with the nearest station.

The summary statistic of daily rainfall in NTT during 1999-2015 is given as follows. The highest daily rainfall occurred in Kupang district (where Eltari Meteorological Station is located) which reached 280 mm per day. The average daily rainfall in all stations was very low i.e. between 2.00-10.00 mm day^{-1}. These values were calculated by simply averaging all observations and hence, it should not be interpreted as simple as usual because the seasonality effect has not been taken into account. However, the values informed that almost all districts in NTT were dry area with low rainfall intensity. As NTT has experienced some periods of drought, there were conditions that the rainfall was zero as can be seen from the range in the last column. The largest rainfall variability with score 17.38 observed in Frans Sales Lega Meteorological Station, while rainfall in Sikka district and its surrounding (represented by Francis Xaverius Seda Meteorological Station) had the smallest rainfall variability.

In order to have better understanding about the monthly rainfall pattern, an illustration about the rainfall observed from Komodo Meteorological Station was given in Fig. 2.

Figure 2a showed the average monthly rainfall pattern at Komodo Meteorological Station (Manggarai District and its surrounding), which forms a monsoon pattern. The peak of the rainy season at Komodo Meteorological Station occurred in January with the average rainfall of 7.56 mm day^{-1}. Indeed, this rainfall intensity is far below the average monthly rainfall in Indonesia. The average monthly rainfall in NTT decreased over the months and reaches the lowest rate on July and August with almost no rain. Indeed, the periods of June to October were supposed to be dry season, while November was a transition period from dry to rainy season. The monthly rainfall pattern observed at the other eight stations also showed a monsoon pattern. This finding was consistent with the BMKG finding that NTT is grouped into climate category A which is monsoonal pattern (Aldrian and Susanto[18]).

Standardized precipitation index (SPI), drought duration, magnitude and intensity: The characteristics of monthly SPI during 1999-2015 in Manggarai district and its surrounding area (represented by Komodo Meteorological Station) can be seen from Fig. 2b. From the figure, there were 18 Drought Duration (DD) events with the longest period of 5 months (December 2009-April 2010). After careful investigation, the detail of drought events with its duration, magnitude and intensity were listed in Table 1.

Table 1: Drought observed at komodo meteorological station in 1999-2015

Year	Month	Duration (month)	Magnitude	Intensity
1999	May	1	1.16	1.16
2000	Dec.	1	2.36	2.36
2001	April	1	1.60	1.60
2001	Dec.	1	1.33	1.33
2002	May to July	2	2.36	1.18
2002	Oct.	1	1.32	1.32
2003	March	1	2.20	2.20
2004	Jan. to Feb.	2	2.69	1.34
2004	Oct. to Nov.	2	1.83	0.92
2005	Jan. to Feb.	2	2.75	1.38
2005	May	1	1.57	1.57
2006	Nov.	1	2.61	2.61
2007	Jan. to Feb.	2	3.30	1.65
2008	Nov.	1	1.09	1.09
2009-2010	Dec. to April	5	4.34	0.87
2012	April	1	1.16	1.16
2014	Sept. to Nov.	3	3.36	1.12
2015	Sept. to Dec.	4	2.07	0.52

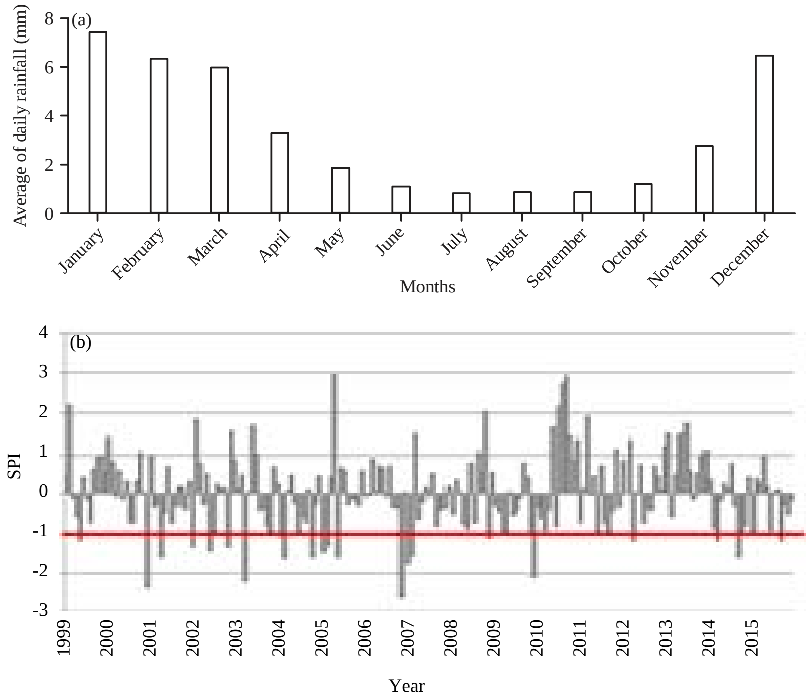

Fig. 2(a-b): (a) Monthly rainfall pattern observed at Komodo Meteorological Station and (b) Monthly SPI observed at Komodo Meteorological Station in 1999-2015

The highest drought magnitude recorded at Komodo Meteorological Station was 4.34 (December 2009-April 2010) as shown in Table 1, while the highest drought intensity was 2.61 happened in November 2011 and the relative frequency of drought events during past 17 years Komodo region was 15.69%.

The result of SPI analysis showed that Mali and Franciscus Xaverius Seda had never been experienced drought as the SPI had never reached below-1.00. Severe drought was observed at Sales Lega Meteorological Station which was happened in October 2006 with SPI of -2.92. Moreover, extreme drought had occurred at Tardamu district. in January 2005 with SPI about -2.22. As data in a station represents the condition in the corresponding district, therefore the term "station" is replaced by "district" hereafter for simplicity. Six of the seven drought-affected districts had SPI less than -2.00 i.e. Komodo, Frans Sales Lega, Umbu Mehang Kunda, Lasiana, Eltari and Tardamu. Meanwhile, the Gewayantana district has SPI score between -1.00 and -2.00. The longest drought duration in NTT was 9 months which occurred in Frans Sales Lega and Gewayantana districts, with magnitude of 8.58 and 7.61, respectively. While the longest drought in Komodo districts which lasted for 5 months was the shortest with magnitude of 4.34. As for other districts, such as Umbu Mehang Kunda and Eltari, the longest drought occurred in 8 months, while the longest drought occurred in Lasiana and Tardamu was 6 months. Furthermore, the intensity indicated that from seven drought-affected districts, only Umbu Mehang Kunda district that had an intensity of more than 1. It means that the district had stronger drought intensity compared to others.

In general, the proportion of drought event was about 12-15%, indicating that most of the NTT regions have been experienced drought for at least 25 months over the period of 204 months (17 years). The largest proportion of drought occurred in Frans Sales Lega district which was about 24.51%, while the smallest proportion occurred in Umbu Mehang Kunda with about 11.76%. The summary of the longest drought duration with its corresponding magnitude and intensity for all regions was given in Table 2. Note that the intensity performed in the table is not necessarily to be the highest one. The table also showed that the longest droughts was mostly begun on November.

Joint probability density function (PDF) and return period: After obtaining the drought duration and magnitude for each station, the next step is to estimate the joint PDF. The joint PDF between duration and magnitude of drought events Komodo district was illustrated in Fig. 3.

Figure 3 gives information about the correlation between duration and magnitude of drought in Komodo district. It can be seen that drought with duration of about 1-4 months has a relatively small magnitude, which was about less than 3.5. As

Table 2: Summary of longest drought duration, magnitude and intensity

Station	Month	Year	Duration	Magnitude	Intensity
Komodo	2009-2010	Dec. to April	5	4.34	0.87
Frans	2009-2010	Nov. to Feb.	4	2.54	0.64
Gewayantana	2003-2004	Nov. to July	9	7.61	0.85
Umbu	2004-2005	Nov. to June	8	8.26	1.03
Lasiana	2012	Jan. to June	6	4.60	0.77
Eltari	2004-2005	Nov. to July	8	5.35	0.67
Tardamu	2002	Feb. to July	6	5.07	0.85

Table 3: Estimated duration (in month) and magnitude based on the return periods

Observation stations	Duration (month)			Magnitude (SPI)		
	5 years	25 years	50 years	5 years	25 years	50 years
Komodo	3	4	5	2.8	4.0	4.50
Frans	3	8	12	4.0	6.9	8.30
Gewayantana	5	17	30	4.9	9.3	11.20
Umbu	3	7	8	4.1	7.1	8.40
Lasiana	3	5	6	3.0	4.3	4.80
Eltari	4	7	8	3.5	5.2	5.80
Tardamu	3	6	7	2.8	7.2	10.70

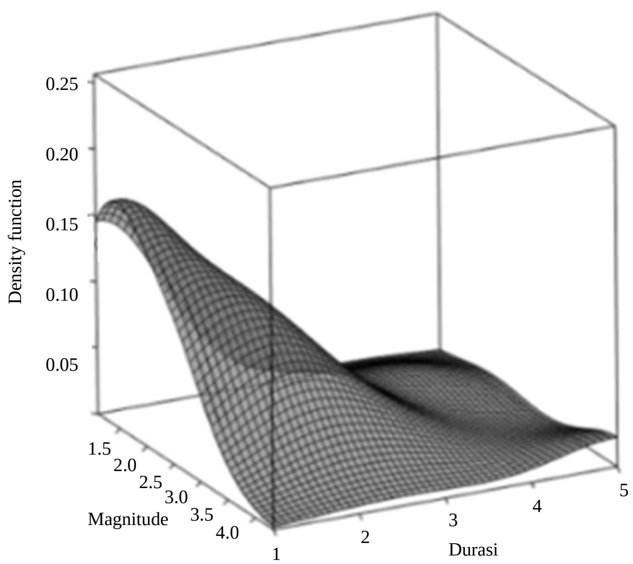

Fig. 3: Joint PDF of duration and magnitude at Komodo district

for the duration of 5 months, drought rarely happened but it had a relatively high magnitude. The joint PDFs for other districts as almost the same as the Komodo district. The only difference is about the shape of the tail of the joint PDF indicating the pattern of extreme drought events. The duration and magnitude estimated from its distribution have been tested by Chi-square test for the goodness of fit. For the duration, some districts such as Komodo, Umbu Mehang, Lasiana, Eltari and Tardamu have Gamma distribution for the drought duration, while Frans Sales Lega and Gewayantana fits Log Person Type III well. In line with the duration, the magnitudes were mostly dominated by Log Normal 3 parameters, although some districts have gamma distribution.

Furthermore, using the parameters from each distribution and the return period of 5, 25 and 50 years, the duration and magnitude of drought in each region can be estimated. The complete results of the estimated duration and magnitude are presented in Table 3.

The drought duration and magnitude for each corresponding return period was shown in Table 3. Both duration and magnitude at Komodo area fit Gamma distribution well. Using the PDF of Gamma distribution, the drought duration were 3, 4 and 5 months for the return periods of 5, 25 and 50 years, respectively. Moreover, the predicted magnitude as listed in Table 3 were 2.8, 4 and 4.5. This simply means that the average drought duration every 5 years at Komodo district are 3 months with average magnitude of 2.8. The drought period and magnitude in 5 years return period is close to the historical drought in Komodo in which only two events happened more than 3 months with average magnitude of 2.17. Among those 7 districts, Geyawantana is more likely to be the highly risk district toward drought events with refers to the predicted duration and magnitude. In fact, the historical drought events in NTT showed that Gewayantana had experienced longer drought and stronger magnitude compared to the others. The results above can be presented in a Time Scale-Duration-Frequency (TDF) graph and a Time Scale Magnitude-Frequency (TMF) graph as presented in Fig. 4.

The TDF graph shows that the Komodo Meteorological Station has the lowest risk in term of the duration of drought for the examined return periods, while Gewayantana has the highest risk. Drought magnitude for return period of 5, 25 and 50 years are shown by Time Scale Magnitude-Frequency (TMF) graph in Fig. 4. The figure shows that at the same return period, the drought durations occurred in those seven districts have different magnitude levels. In general, the longer the return period the strongest the magnitude.

Drought risk mapping in NTT based on return periods: The drought duration and drought magnitude estimated for 5 , 25 and 50 years of return periods in NTT can be used for mapping. The maps are developed for duration and magnitude of each return period. In the map, the larger dot size indicates longer drought duration will occur in that district. There are 2 stations in NTT (i.e. Mali and Fransiskus) that have zero drought duration and drought magnitude. This is because there has been no drought happened in these two districts based on SPI values over past 17 years. The drought duration maps for return periods of 5, 25 and 50 years are displayed on left panel of Fig. 5, while the

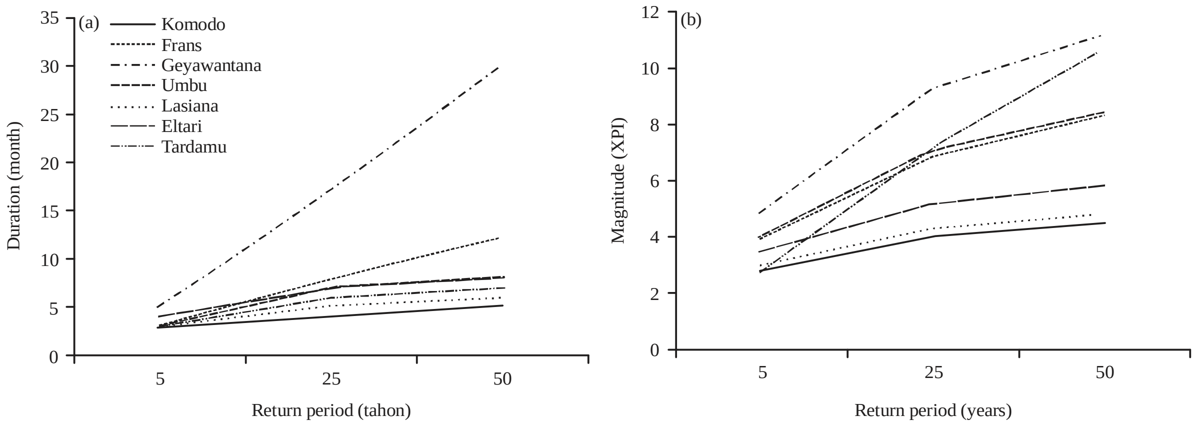

Fig. 4(a-b): (a) TDF (upper panel) and (b) TMF (lower panel) Graphs based on return period

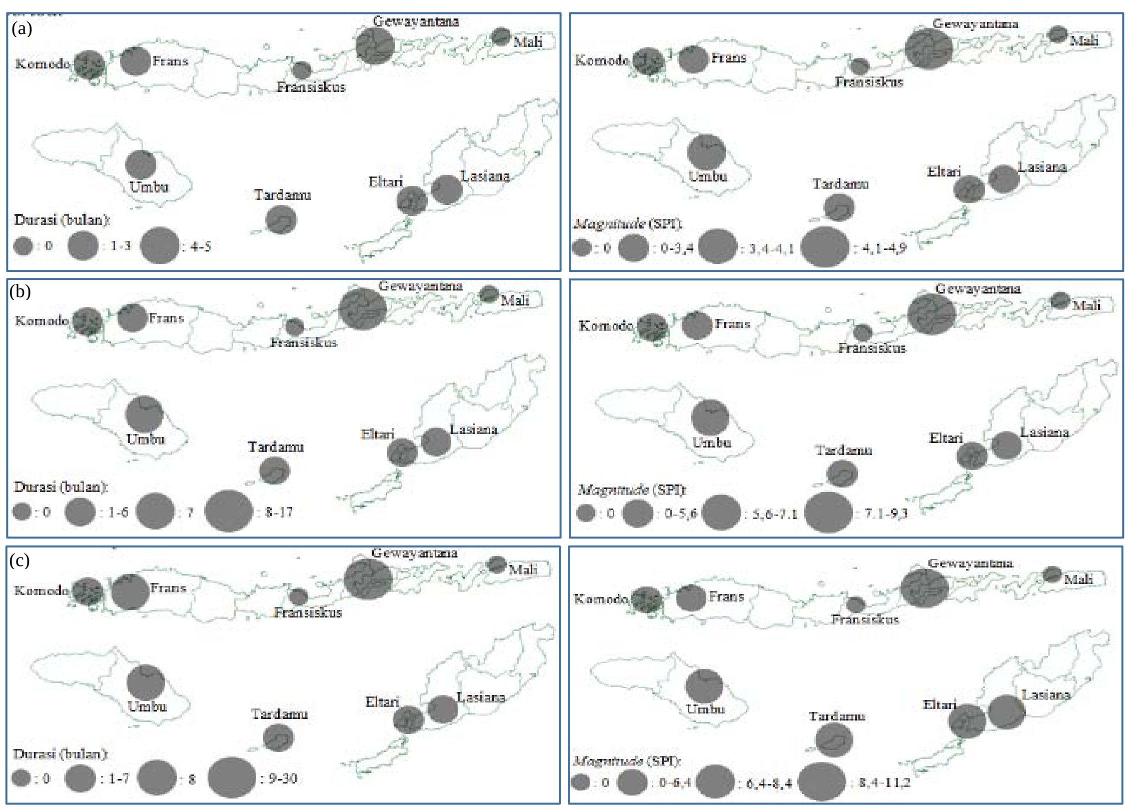

Fig. 5(a-c): Drought duration (left panel) and magnitude (right panel) maps in NTT for return periods, n(a) 5 years, (b) 25 years and (c) 50 years drought magnitude mapping for return period of 5, 25 and 50 years were shown on the right panel of Fig. 5.

The results found in this study were consistent with the short term prediction of drought events in NTT in 2017 as performed by several previous studies[19,20]. Moreover, the estimated intensity and duration predicted in this study is able to explain the drought condition in NTT well. It was also supported by the work of Adhyani *et al.*[21], who performed the drought characteristics in some regions in Indonesia including NTT. Hariadi[22] argued that the drought in Indonesia (in particular in NTT) is highly influenced by El-Nino, which made the drought severity even higher over the time. Moreover, Ge *et al.*[23] found in their study in US that spatial distributions of duration, severity and intensity of more frequent and less severe drought events could be different from those of less frequent and more severe droughts in the same time period. Considering the fact that the estimated magnitude and duration with 50 years return periods are very high, it could be an indication of over-estimation. 30 months duration simply means that there will be no rain for about 2 years. To deal with this, future research can be addressed by taking into account the spatial dependence among regions such as applied by Setiawan *et al.*[24] and Liu et al *et al.*[13]. In some cases, the spatial dependence were more likely lead to better estimators.

CONCLUSION

This study has estimated drought risk in NTT province based on drought duration and magnitude as two major factors of drought event. Simple maps have been developed for three different return periods i.e., 5, 25 and 50 years showed that Gewayantana is the districts with the longest duration and strongest magnitude and hence, the drought risk in this area is the highest one. Meanwhile, Komodo and Frans Sales Lega districts have the shortest duration and lowest magnitude compared to the others. The analysis showed that drought duration and magnitude in NTT increases by increasing the return period, which also means that the risk is increasing by the time. As drought is a natural phenomena, the risk maps can be a useful alert tool for all stakeholders, policy makers and societies in NTT to design actions in order to reduce the risk. The estimated magnitude and duration for the 50 years return periods seems to be over-estimated which means that 50 years prediction might be too long period to be explained by the analyzed data.

SIGNIFICANCE STATEMENT

This study examined drought events in NTT Indonesia which is one of the most vulnerable regions to drought events. The study applied a statistical approach based on return period in order to estimate the drought risk in the future i.e. the magnitude and duration. Detail investigation has been carried out to characterize the drought in several major cities. The information is useful for the policy maker to design the mitigation actions to reduce the disaster risk.

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