Mapping of Tornado Wind Vulnerability using Satellite Data (Study case of Humbang Hasudutan Regency, North Sumatera)

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Abstract. Tornado wind often occurs in Humbang Hasudutan (Humbahas), North Sumatra. Even though the map of tornado vulnerability has constructed by The National Agency for Disaster Countermeasure (BNPB), but several regions did not yet have this map due to limited observation data. This study's objective is to map the vulnerability of tornado in Humbahas using satellite data where the satellite data has more significant quality in area coverage and time-series data. The Composite Mapping Analysis (CMA) has been used to model the vulnerability map. There were three factors has used in this model, such as rainfall, land cover, and slope. Based on the tornado vulnerability map, there was an 802,406.24 ha area (74.63%) in Humbahas, classified as "high" risk to Tornado disaster. There was 271,945.46 ha (25.29%), which assigned as "moderate" risk. About 786.51 ha (0.07%) of the Humbahas area has a "low" risk of tornado disaster. As a result, the study area has a "moderate" to "high" risk of tornado wind disaster, then the adaption and mitigation plans need to be done in handling tornado hazard in this region.

1. Introduction

In recent years, several regions worldwide have experienced a variety of natural disasters such as tsunamis, earthquakes, forest fires, cyclones, drought, and tornado. Besides, a disaster will have an impact on the economy because of the damage to infrastructure. Also, there is a tendency for natural disasters to spread more and more intensely according to predictions of climate change. These are the two things that encourage the emergence of initiatives from governments from various countries to reduce the risk of disasters as set out in the HFA (Hyogo Framework for Action). One of the priority programs is identifying, assessing, and monitoring disaster risks and improving early warning.
capabilities. Indonesia is one of 160 countries that have ratified the HFA and put it in the form of Law number 24 of 2007 concerning disaster management (BNPB Head Regulation no. 3 of 2012) [1].

The mandate of the Act was followed up with the preparation of the 2010-2014 National Disaster Management Plan, which included 4 (four) issues, namely: threat, vulnerabilities, and capacity as well as disaster risk. Furthermore, BNPB issued PERKA (Head Regulation) BNPB number 02 of 2012, which is more specific about dealing with 13 disasters such as earthquakes and extreme weather (tornado) to social conflicts. The disaster risk index and classification (low, moderate, and high) for each disaster have been calculated based on specific indicators. For example, a tornado risk index is determined through a combination of 3 indicators and their weighting using the AHP (Analytical Hierarchy Procedure) technique [2]. The three indicators which be used by BNPB are slope, land cover, and annual rainfall for a land. The risk index is then mapped using the GIS technique. In a disaster management scenario, the vulnerability map and capacity have a vital role because a mitigation and adaption plan will be determined based on those maps [1].

In response to the release of the risk index map produced by the BNPB, Paharuddin, et al. (2015) has verified the tornado disaster map from the BNPB [2]. Based on their verification results, they concluded that the accuracy of the tornado disaster index by BNPB was still low. The low accuracy of the BNPB tornado risk map because this map cannot identify un-observed areas due to limited of observation data. Based on the tornado disaster index map produced by BNPB in 2010, there are still many areas that do not have a tornado disaster index because of limited observation data in the region, including Humbang Hasudutan (Humbahas) Regency (Figure 1). Compared to the observation data, satellite data has a more robust profile in spatial coverage and time series.

In this study, the rainfall data of observation data will be replaced by the rainfall from satellite data of Climate Vulnerabilities Group InfraRed Precipitation with Station data (CHIRPS). CHIRPS is a new 30+ year quasi-global groundwater level dataset. It has area scanning from 50°S to 50°N in all longitudes, which is the daily data that has duration from 1981 to present. For spatial resolution, CHIRPS incorporates 0.05° resolution satellite imagery, which validates by station data to create gridded groundwater level time series for many applications. Since February 12th, 2015, version 2.0 of CHIRPS is finished and opened to the public. Compared to other satellite data (GSMaP, IMERG, and CHIRPS,) CHIRPS has a better correlation to the observation data in Indonesia, especially for monthly periods [3]. Moreover, the slope data also provided based on the Shuttle Radar Topography Mission (SRTM). This study aims to map the tornado wind vulnerability by using satellite data in Humbang Hasudutan (Humbahas) Regency. This study will fill the tornado map gap due to limited data in some regions in Indonesia (Figure 1).
Figure 1. Tornado Disaster Risk Map from BNPB (2010). No data (brown circle)
2. Materials and Methods

2.1. Study area
The study area is located in the central part of North Sumatra Province. Humbang Hasundutan Regency is located on the lines 20° 1’ – 20° 28’ LU and 98° 10’ – 98° 58’ BT. The area of Humbang Hasundutan Regency is 251,765.93 Ha and consists of 10 sub-districts (Pakkat sub-district, Onanganjang sub-district, Sijamapolang sub-district, Lintongnihuta sub-district, Paranginan sub-district, Doloksanggul sub-district, Pollung sub-district, Parlilitan sub-district, Tarabintang sub-district, and Baktiraja sub-district).

2.2. Data used
We used several data, including land cover data, precipitation, Humbahas Regency administration map data, and elevation. Land cover data was obtained from the Director-General of Forestry Planning in 2011. The precipitation data relied on satellite processing, which was available Climate Vulnerabilities Group InfraRed Precipitation with Station data (CHIRPS) in 2006-2019 with a spatial resolution of 5 km. Elevation data is based on the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 30 meters.

2.3. Methods
The method used in this research is the multi-criteria analysis by looking at the main factors which causing tornado disasters in an area. Tornado analysis will also be conducted to see tornado vulnerability areas. Digital Elevation Model-Shuttle Radar Topographic Mapping (DEM-SRTM) extracted the resulting slope information. At the same time, the CHIRPS was extracted by rainfall information. In comparison, information on land openness was obtained from the Director-General of Forestry Planning in 2011. From the analysis of the causes of tornado coupled with the three tornado variables mentioned above, then a multi-criteria analysis was carried out with a spatial analysis of tornado events so that tornado vulnerability models will be generated.

Determination of tornado vulnerability models in the Humbahas Regency uses several variables, including rainfall, land cover, and slopes. The tornado vulnerability modeling process requires each tornado variable’s weight, and each tornado variable has a criterion class. Ranking and score of each criterion & each factor refer to BNPB (2010) scoring. For more details, the stages or steps in the Composite Mapping Analysis (CMA) process. Weight calculation for tornado vulnerability modeling using Composite Mapping Analysis (CMA) which follows these steps [4]:

1. Determination of tornado event maps based on location and tornado frequency that ever occurred in the study area.
2. Assigning several factors which support the potential zone of Tornado based on BNPB (2010).
3. Ranking and scoring of each criterion and each factor refer to previous research.
4. Furthermore, the tornado distribution map is overlaid with each tornado variable, where tornado variables include: rainfall, land openness, and slopes. The overlapping process carried out with each of these tornado variables results in a tabulation of the overlay results for each tornado variable.
5. A composite of all variables will be performed, so that the total weight of each variable causing tornado can be obtained.
6. Based on the class division, each total polygon value is categorized into five tornado disaster risk level classes, namely: "Low," "Moderate," and "High."
3. Results

3.1. Weight Calculation in the Tornado Vulnerability Model

Composite Mapping Analysis (CMA) has been used to calculate the tornado vulnerability weight. It has been done based on the frequency of tornado events occurring in the field, average rainfall, land coverage, and slope. Tornado histories over Humbahas can be seen in Table 1. The historical data obtained from the news on the internet that was successfully collected. The limitations of historical tornado data in the disaster database of BPNB is one of the challenges for collecting the tornado events in the past. From the 11 of tornado events, ten tornado events occurred in the Doloksanggul sub-district. This data will be a guideline that becomes the standard and verification of tornado models. For the land cover, it was used in the land openness based on land cover from the Director-General of Forestry Planning in 2011.

Table 1. History of the Tornado Event

| No | Date       | Village    | Sub-district       | Impact                        |
|----|------------|------------|--------------------|-------------------------------|
| 1  | 09-May-16  | Saitnihuta | Doloksanggul       | 1 elementary school and 11 houses damaged |
| 2  | 26-Apr-16  | Janji      | Doloksanggul       |                               |
| 3  | 26-Apr-16  | Matiti 1   | Doloksanggul       |                               |
| 4  | 15-Mar-15  | Purba Dolok| Doloksanggul       |                               |
| 5  | 03-Sep-14  | Pasaribu   | Doloksanggul       | 14 houses damaged             |
| 6  | 03-Sep-14  | Matiti 2   | Doloksanggul       |                               |
| 7  | 07-Dec-12  | Doloksanggul | Doloksanggul     | 12 houses damaged             |
| 8  | 02-Nov-12  | Matiti II  | Doloksanggul       |                               |
| 9  | 2012       | Sitio      | Lintongnihuta      | 11 houses damaged             |
| 10 | 15-Oct-11  | Saitnihuta | Doloksanggul       | 1 elementary school badly damaged |

For the Humbahas, the area is classified into five classes of land coverage, which consists of dryland agriculture, including open land, rice fields, settlements, dryland forests, and industrial forests. From the results of the classification of land coverage that the Humbahas regency is dominated by rice fields, settlements, mixed gardens, and ponds, as shown in Figure 2.

The slope condition in Humbahas Regency is produced from the extraction of Digital Elevation Model - Shuttle Radar Topographic Mapping (DEM-SRTM) spatial resolution of 30 meters, where the Humbahas Regency area consists of 5 slope classes, consisting of 0-8% class, 8-15%, 15-25%, and 25-45%, and > 45% where the Humbahas Regency is dominated by slopes with grades 0-8% and classes 8-15%, while slopes with classes 25-45% and > 45% are rarely found in the Humbahas district. The slope map in Humbahas can be seen in Figure 3.

For the average annual rainfall in the Humbahas Regency, it is produced by the Climate Vulnerabilities Group InfraRed Precipitation with Station data (CHIRPS) extraction with a data period of 13 years (1 January 2006 - 31 December 2019), where the Humbahas Regency area is divided into 5 bulk classes of rainfall data, consisting of classes <1000 mm / year (very dry), 1000 - 1500 mm / year (dry), 1501 - 2000 mm / year (quite wet), 2001 - 2500 (wet),> 2500 (very wet). For Humbahas, this is dominated by rainfall in the "wet" class (2001 - 2500) and "very wet". The slope map in Humbahas can be seen in Figure 4.
Figure 2. Land cover in the Humbang Hasudutan Regency

Figure 3. Slope in the Humbang Hasudutan Regency
In this study, the weighting of the three variables using the weighting given by BNPB (2010) is as follows:

**Table 2. Weighting for Tornado vulnerability map**

| No. | Variable          | Weight |
|-----|-------------------|--------|
| 1   | Land cover        | 33.3   |
| 2   | Slope             | 33.3   |
| 3   | Rainfall          | 33.3   |

Based on the recommendations of BNPB (2010), it is known that the weights used for the three variables are the same that is equal to 33.3. Mathematically the tornado vulnerability model in Humbahas can be formulated as follows:

\[
S_{CMA} = (33.3 \times SKL) + (33.3 \times SL) + (33.3 \times SCH)
\]

Where \( S_{CMA} \) is tornado CMA model vulnerability scoring, SCH is rainfall score value, SKL is a score of Land Cover and SL is slope score. For the weighting and scoring of tornado vulnerability maps in Humbahas Regency based on each variable from BNPB (2010) where the results of weighting and scoring calculations on each variable and tornado criteria can be seen as in Table 3.

According to the total scoring and weighting, tornado vulnerability can be explained into three (3) of tornado vulnerability classes, namely: "low", "moderate" and "High" tornado risks. The tornado class interval was calculated by the maximum score (355) which subtracted by the minimum score (211), then the output is divided by the number of classes the minimum score for each tornado variable divided by the number of classes (3 classes). The tornado vulnerability classes are obtained as in Table 4.
Table 3. Weighting and Scoring on all three research variables

| No. | Variable   | Criteria                              | Score | Weight |
|-----|------------|---------------------------------------|-------|--------|
| 1   | Land Cover (LC) | Dry land / open land / water           | 5     | 33.3   |
|     |            | Paddy fields (cropland)                | 4     |        |
|     |            | Urban area                             | 3     |        |
|     |            | Settlement                             | 2     |        |
|     |            | Dryland Forest                         | 1     |        |
|     |            | Industrial Forests                    |       |        |
| 2   | Slope (S)  | Flat - Ramps 0 - 8%                    | 5     | 33.3   |
|     |            | Choppy 8 - 15%                         | 4     |        |
|     |            | A bit steep, hilly 15 - 25%           | 3     |        |
|     |            | Steep 25 - 45%                        | 2     |        |
|     |            | Very Steep > 45%                      | 1     |        |
| 3   | Precipitation (P) | > 2500 (very wet)       | 5     | 33.3   |
|     |            | 2001 - 2500 (wet)                     | 4     |        |
|     |            | 1501 - 2000 mm / year (quite wet)     | 3     |        |
|     |            | 1000 - 1500 mm / year (dry)           | 2     |        |
|     |            | <1000 mm / year (very dry)            | 1     |        |

Table 4. Tornado Vulnerability Class Intervals in Humbahas Regency

| No. | Class Interval | Level of Tornado Risk |
|-----|----------------|-----------------------|
| 1.  | < 211          | Low                   |
| 2.  | ≥ 211 - < 355  | Moderate              |
| 3.  | ≥ 355          | High                  |

3.2 Tornado Disaster Risk Map in Humbahas Regency

In principle, tornado vulnerability maps are determined based on the static and dynamic variables. The static variables used include slope, which refers to the physiographic conditions. Furthermore, the dynamic variables in this modeling are land cover which refers to the land openness and rainfall as a common preliminary phenomenon a tornado wind. The final map of the tornado vulnerability map is shown in Figure 5. Based on the tornado vulnerability map, the areas which have the “high” and “low” of tornado vulnerability can be found mostly in the eastern part of Humbahas Regency, especially in the Districts of Doloksanggul, Pollung, Bakti Raja, Paranginan and some part of Parlilitan. For the west part of Humbahas regency, it mostly has a moderate vulnerability of tornado disaster.
Figure 5. Tornado Disaster Risk Map in Humbang Hasudutan Regency

The details of tornado vulnerability maps in Humbahas Regency are as in Table 5.

Table 5. Percentage by Area of Tornado Vulnerability in Humbang Hasudutan Regency

| Level of Risk | Area (ha) | Percentage (%) |
|---------------|-----------|----------------|
| Low           | 786.51    | 0.07           |
| Moderate      | 271.945.46| 25.29          |
| High          | 802.406.24| 74.63          |
| Total         | 1.075.138.21| 100            |

Based on the tornado vulnerability map in Humbahas, the "High" tornado risk class area is 802,406.24 hectares or 74.63%, the "Moderate" tornado risk class is 271,945.46 hectares or 25.29%, and the tornado risk class "Low" by 786.51 hectares or by 0.07%. From the results of the tornado vulnerability areas mentioned above, it can be said that in Humbahas Regency is included in the category of regions with high tornado wind hazard levels, so there is a need for anticipation in handling tornado vulnerability in the region. The area and percentage of tornado disaster risk areas based on sub-districts in Humbahas can be seen in Table 6.
he tornado disasters in the Humbahas district. Besides the land openness factor, which contributes to the formation of tornado winds, other factors such as rainfall, slope, and land cover also play a significant role. The rainfall in the eastern area of Humbahas is lower than the rainfall in the western area, which contributes to the occurrence of tornadoes. The slope of the land also affects the wind speed, with steeper slopes reducing wind speed and making it more difficult for tornadoes to form. The type of land cover, with most of the land cover in Humbahas Regency being dryland agriculture, open land, and bush/shrub, positively influences the formation of wind into tornado winds. By the presence of vegetation on open and flat land surfaces, it will reduce the local microclimate and the possibility of tornado winds forming in the area.

Based on the results of the overlay of land cover, most of the land cover in the Humbahas Regency is dryland agriculture, open land, and bush/shrub. This type of land cover is one of the best factors which contribute to the tornado disasters in the Humbahas district. Besides the land openness factor (land cover), the next factor is the slope. When an area has a high slope, it means that there are variations in the topography and relief of the earth’s surface in the region. When the wind blows through an area which has various surface and different tilt, it will directly reduce the wind speed and reduce some of the available energy of the wind. This mechanism influences the chance of tornado wind formation [4]. In the Humbahas district, the eastern area of the Humbahas district has a slope (0 - 8%), while the southern area of the Humbahas district has a higher slope than the eastern part. These factors also triggered many tornado disasters in the eastern region of Humbahas.

For dynamic factors such as rainfall, the Humbahas have rainfall in the wet category, which is very wet (> 2001 mm / year). With such rainfall conditions, the cumulonimbus cloud formation process likely has the opportunity to form during the rain. In general, the rainfall in the eastern area of Humbahas is lower than the rainfall in the western area of the Humbahas district. From this discussion, it can be concluded that the influence of rainfall factors has a smaller effect than two other factors, namely the neck slope and land openness. This means that further research needs to be evaluated on the weighting of BNPB (2010) of 33.3% for all three variables. For the Humbahas, the

### Table 6. Tornado Vulnerability Map in Humbahas Regency per sub-district

| No | Sub-district   | Low Area (ha) | Low (%) | Moderate Area (ha) | Moderate (%) | High Area (ha) | High (%) | Total Area (ha) | Total (%) |
|----|----------------|---------------|---------|-------------------|--------------|----------------|---------|----------------|-----------|
| 1  | Bakti Raja     | 19,73         | 0,21    | 5372,15           | 56,63        | 4095,15        | 43,17   | 9487,03        | 100       |
| 2  | Doloksanngul   | 16,474        | 0,01    | 5805,88           | 3,56         | 157438,5       | 96,43   | 163260,87      | 100       |
| 3  | Lintongnihuta  | 58,674        | 0,03    | 4675,64           | 2,66         | 170807,2       | 97,30   | 175541,51      | 100       |
| 4  | Onan Ganjang   | 41,70         | 0,05    | 42998,27          | 56,53        | 33021,04       | 43,41   | 76061,01       | 100       |
| 5  | Pakkat         | 83,444        | 0,07    | 97466,67          | 76,30        | 30193,79       | 23,64   | 127743,91      | 100       |
| 6  | Paranginan     | 30,307        | 0,04    | 2085,98           | 2,43         | 83795,97       | 97,54   | 85912,25       | 100       |
| 7  | Parlipiti      | 165,81        | 0,08    | 63370,15          | 30,14        | 146709,1       | 69,78   | 210245,08      | 100       |
| 8  | Pollung        | 309,627       | 0,24    | 4574,71           | 3,57         | 123260,2       | 96,19   | 128144,56      | 100       |
| 9  | Sijamapolang   | 35,881        | 0,07    | 16735,28          | 33,80        | 32736,01       | 66,12   | 49507,17       | 100       |
| 10 | Tarabintang    | 24,87         | 0,05    | 28860,72          | 58,62        | 20349,24       | 41,33   | 49234,82       | 100       |

4. Discussions

From the research results, the tornado wind hazard map for the Humbahas district has shown that the Humbahas Regency has a high risk of tornado disasters. Based on tables 6, as much as 74.63% of the Humbahas Regency has a high risk of tornado winds. The tornado wind risk spatial pattern in Humbahas District has a dominant pattern towards the east of the Humbahas Regency. Based on table 1, which shows the historical record of tornado events in the Humbahas Regency. Doloksanngul sub-district is one of the sub-districts that used to verify this tornado vulnerability map. This model's result is acceptable since the Doloksanngul sub-district has several history disasters, for example, in three villages that have recorded historical tornado causes The villages of Matiti I, Matiti II, and Saitnihuta.

The high risk of tornado wind disasters in Humbahas is mainly due to the slope, land openness, and high rainfall. Ilham & Kadir (2009) stated that when the wind blows, it can turn into a tornado when the landscape in its path is open and climatic conditions such as air pressure and extreme temperatures [5]. Usually, this incident is accompanied by lightning and thunderstorm. The indicative trigger of a tornado is due to the layered forms of cumulonimbus clouds. In this case, the land openness factor (land cover) positively influences the formation of wind into tornado winds. By the presence of vegetation on open and flat-land surfaces, it will reduce the local microclimate and the possibility of tornado winds forming in the area.
area is classified into five classes of land coverage, which consists of dryland agriculture, including open land, rice fields, settlements, dryland forests, and industrial forests. From the results of the classification of land coverage that the Humbahas regency is dominated by rice fields, settlements, mixed gardens, and ponds (Figure 2).

5. Conclusions
Three variables can be used for making a vulnerability map for a tornado disaster in Humbahas, such as land cover, slope, and rainfall. Due to limited observation data, an unmapped area of the Tornado vulnerability map can be filled by using the satellite data. Most of the Humbahas Regency has a high-risk level for the tornado. Based on the tornado vulnerability map, the "High" tornado risk class area is 802,406.24 hectares or 74.63%, the "Moderate" tornado risk class is 271,945.46 hectares or 25.29%, and the tornado risk class "Low" by 786.51 hectares or by 0.07%.

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