Spatial modelling of land conversion vulnerability in Padang watersheds North Sumatera province

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Abstract. The land use in the watersheds is the leading cause of the flood besides rainfall intensity. The objective of this study is to analyse land-use changes period 2000, 2010 and 2018, analyse the factors that influence land-use changes and analyse the level of the spatial distribution of land conversion vulnerability based on a GIS and remote sensing. Spatial modelling methods were used in this study by weighting and scoring on the factors triggering land conversion, namely biophysical land and socioeconomic. The results show that the enormous percentage change in land use between the years 2000-2010 was 49.09% in mixed dryland farming convert to dryland agriculture. While in the period 2010-2018 was an increase of 43.37 % in the fish pond. Factors that influence the chances of land conversion are biophysical and social factors such as population density and per capita income. The higher the population density tend to have, the greater the chance of a land conversion. The higher per capita income tends to have a smaller chance of a land conversion. Land conversion vulnerability in Padang Watersheds is at a vulnerable class of 50.38 % or 55,584.54 Hectares. Then in the class is very vulnerable at 27.38% or 30,213.97 Hectares.

1. Introduction

The current condition of the Padang watersheds is very critical. The problem that regularly occurs in the Padang watersheds is annual flooding. There were several large flood incidents, namely in 2003, which inundated 100 urban villages in Tebing Tinggi city and in 2010, which inundated hundreds of houses. The high rainfall intensity and the silting/sedimentation of the Padang river in the middle and downstream is the main factor of the flooding. The high erosion that occurs in the upstream area due to changes in forest land use to non-forest land [1]. [2] indicates that the watersheds quality can be observed from the water discharge ratio. The rainy season increases flooding, while during the dry season, the water flow decreases drastically. Besides, 53.29% of the peak discharge that occurs is influenced by the percentage of forest cover.

The critical forest area in the upstream area, which is a buffer zone for Tebing Tinggi city, has caused flooding in the middle and downstream areas of the Padang watersheds. The allocation of forest area reaches 28.44% of the watersheds area, but conditions have changed that only 7.17% remain of the watersheds area is still forested or 7,932 hectares. The forest area only covers the upstream area, namely the Mount Simbolon area [3].
Changes in land use will also affect water quality and aquatic habitats. Numerous research reports that river water use has altered the hydrological requirements for people in the downstream area, resulting in morphological changes [4]. Currently, the fish and water biota diversity in the Padang watersheds has decreased drastically, many of which have even become extinct. Several types of fish that were formerly superior in the Padang watersheds are challenging to obtain. Climate change due to forest conversion has reduced forest cover, increasing water temperature, which affects the water quality of aquatic habitats, especially temperature-sensitive fish [5].

The damage of the Padang watersheds is so severe because generally, the watersheds are used as a residential location, especially in Tebing Tinggi City and Tebing Syahbandar District, Serdang Bedagai Regency. The land-use change patterns into settlements had an impact mainly on reducing infiltration capacity, resulting in increased surface runoff [6]. Besides, the population increase due to high mortality and migration from another area also leads the land conversion [7]. Lack of public knowledge about the importance of watersheds ecosystems has resulted in the neglect of forest conversion and massive logging in the upstream of the Padang watersheds. The collaborative water management between all interested stakeholders needed in this watershed [8]. The use of technology-based on geographical information systems (GIS) and remote sensing to monitor the vulnerability to land conversion is quite good, with validation of 78.66% [9]. The most optimal method for estimating temporal and spatial probability is dynamic modelling by mapping the vulnerability using spatial data [10].

The objective of this study is to analyse land-use changes period 2000, 2010, and 2018 in Padang Watersheds, analyse the factors that influence land-use changes in Padang Watersheds, and analyse the level of the spatial distribution of land conversion vulnerability based on a geographical information system and remote sensing.

2. Materials and methods
This research was conducted in August to September 2020, taking place in Padang Watersheds which includes Simalungun Regency, Serdang Bedagai Regency, and Tebing Tinggi City, North Sumatra Province. The primary data in the form of land cover data from the Ministry of Environmental and Forestry, digital elevation model data (DEM) from Shuttle Radar Topographic Mission (SRTM), and supporting data is obtained from statistical Bureaus, and stakeholders (researchers, universities, and others).

The data collected is spatial data in the form of digital maps of road, digital maps of rivers, digital maps of administration, as well as non-spatial data in the form of population density data and per capita income data. Spatial data processing in this study using ArcGIS 10.5 software. Analysis of land cover change based on the data from MEF. The altitude and slope maps are obtained from DEM (Digital Elevation Model). Furthermore, the creation of a buffer zone from rivers, buffer zone from roads, buffer zones from settlements is obtained by making buffering with a specific distance interval. The spatial map of population density and per capita income is obtained by integrating the data population density data and per capita income data from the Statistical Bureau to administrative map.

Furthermore, the altitude map, the slope map, the distance from the road map, the distance from the river map, the buffer zones from the settlement map, the population density map, the per capita income map were analysed to get the land conversion vulnerability map of Padang Watersheds. The method used in the tabular analysis stage is the scoring method, which is each parameter determining forest land conversion in the form of biophysical and socioeconomic factors [9,11,12]. Table 1 is given a specific score, and then in each unit, the score analysis is summed up. The result of summing the score (final score) is further classified to determine the level of the vulnerability of land land conversion. Furthermore, a thoroughness test is carried out with validation of the actual conditions in the field. Validation is done by ground checking at several purposively selected observation points while paying attention to the representation and dissemination of data using GPS (Global Positioning System). The spatial modelling in this research use following equation:
Final score = \((5 \times \text{altitude score}) + (15 \times \text{slope score}) + (15 \times \text{buffer zones from road score}) + (15 \times \text{buffer zones from river score}) + (25 \times \text{buffer zones from settlement score}) + (15 \times \text{population density score}) + (10 \times \text{income per capita score})\) 

(1)

### Table 1. Land conversion vulnerability determination parameters.

| No | Parameters                           | Unit     | Weights | Criteria and scores                                                                 |
|----|--------------------------------------|----------|---------|------------------------------------------------------------------------------------|
| 1. | Input                                |          |         |                                                                                    |
|    | a. Biophysical land                  |          |         |                                                                                    |
|    | • Altitude                           | Masl     | 5       | 0 masl – 500 masl (9), 500 masl – 1000 masl (7), 1000 masl – 1500 masl (5), 1500 masl – 2000 masl (3), > 2000 masl (1) |
|    | • Slope                              | %        | 15      | 0 – 8 % (9), 8 – 15 % (7), 15 – 25 % (5), 25 – 40 % (3), > 40 % (1)               |
|    | • Buffer zones from road             | M        | 15      | 0 m – 200 m (9), 200 m – 400 m (7), 400 m – 600 m (5), 600 m – 800 m (3), > 800 (1) |
|    | • Buffer zones from river            | M        | 15      | 0 m – 200 m (9), 200 m – 400 m (7), 400 m – 600 m (5), 600 m – 800 m (3), > 800 (1) |
|    | • Buffer zones from settlement       | M        | 25      | 0 m – 1000 m (9), 1000 m – 2000 m (7), 2000 m – 3000 m (5), 3000 m – 4000 m (3), > 4000 m (1) |
|    | b. Socioeconomic                     |          |         |                                                                                    |
|    | • Population Density                 | People/Km² | 15     | >700/Km² (9), 600/Km² - 700/Km² (7), 400/Km² - 600/Km² (5), 300/Km² - 400/Km² (3), <300/Km² (1) |
|    | • Income per capita                  | IDR/year | 10      | < 15 (9), 15 – 30 (5), > 30 (1)                                                    |
| 2. | Output                               |          |         |                                                                                    |
|    | Vulnerability                        | -        | -       | Very unvulnerable (100-260)                                                         |
|    |                                      |          |         | Unvulnerable (261-420)                                                              |
|    |                                      |          |         | Moderate vulnerable (421-580)                                                       |
|    |                                      |          |         | Vulnerable (581-740)                                                                |
|    |                                      |          |         | Very vulnerable (741-900)                                                           |

### 3. Results and discussion

The enormous of land cover change in Padang watersheds in 2000-2010 was 49.09% on mixed dryland farming (Table 2). Mixed dryland farming decreased and switched to dryland farming by 46.06%. While in the period 2010-2018, the enormous percentage of land cover change was an increase of 43.37 % in the fish pond. Reduced areas of secondary dryland forests that switch to dryland agriculture and plantations can also cause flooding in the surrounding environment or downstream of Padang Watersheds. It can be seen that dryland farming and plantations are the dominating land use in the watersheds. Land needs for plantations, agricultural land was the driving force of deforestation in the Padang Watersheds [13,14]. There are several types of plantation plants owned by PTPN in the Padang watersheds area, namely rubber plants, and palm oil crops. The most dominating plant is palm oil in the central part of Padang Watersheds which is in the Serdang Bedagai Regency up to Tebing Tinggi City. Palm oil plants provide a 3.07% stem flow volume so that the distribution of rainfall reaching ground level increases [15]. The mixed dryland farming dominated in 2000 and decreasing significantly in year 2010 and 2018. For the period 2000-2018 the most extensive land use was in the use of dry land and plantations. Meanwhile, land use declined in 2010 and reappeared in 2018 (Figure 1).
Table 2. Percentage of land use in Padang watersheds in 2000, 2010 and 2018.

| No. | Land Cover                      | 2000 (Ha) | 2010 (Ha) | 2018 (Ha) |
|-----|---------------------------------|-----------|-----------|-----------|
| 1   | Water                           | 452.29    | 452.29    | 458.47    |
| 2   | Shrub                           | 7161.02   | 7139.97   | 7162.42   |
| 3   | Swamp Bush                      | 59.14     | 31.54     | 31.54     |
| 4   | Secondary Dry land forest       | 7505.60   | 7505.60   | 7433.77   |
| 5   | Secondary Mangrove Forest       | 661.40    | 319.08    | 370.81    |
| 6   | Settlement                      | 2187.22   | 2206.71   | 2206.71   |
| 7   | Plantation                      | 38662.70  | 40056.60  | 39841.70  |
| 8   | Dry Land Farming                | 6641.01   | 44781.10  | 44563.70  |
| 9   | Mixed Dry Land Farm             | 40184.00  | 0.00      | 0.00      |
| 10  | Rice fields                     | 5265.12   | 6637.20   | 6632.69   |
| 11  | Pond                            | 206.00    | 0.00      | 526.12    |
| 12  | Open Ground                     | 1354.11   | 1209.67   | 1111.78   |

| No. | Land Cover                      | Difference 2010-2000 (Ha) | Percentage Change (%) | Difference 2018-2010 (Ha) | Percentage Change (%) |
|-----|---------------------------------|---------------------------|-----------------------|---------------------------|-----------------------|
| 1   | Water                           | 0.00                      | 0.00                  | 6.17                      | 0.51                  |
| 2   | Shrub                           | -21.05                    | 0.03                  | 22.45                     | 1.85                  |
| 3   | Swamp Bush                      | -27.60                    | 0.03                  | 0.00                      | 0.00                  |
| 4   | Secondary Dry land forest       | 0.00                      | 0.00                  | -71.83                    | 5.92                  |
| 5   | Secondary Mangrove Forest       | -342.32                   | 0.42                  | 51.72                     | 4.26                  |
| 6   | Settlement                      | 19.49                     | 0.02                  | 0.00                      | 0.00                  |
| 7   | Plantation                      | 1393.90                   | 1.70                  | -214.90                   | 17.72                 |
| 8   | Dry Land Farming                | 38140.09                  | 46.60                 | -217.40                   | 17.92                 |
| 9   | Mixed Dry Land Farm             | -40184.00                 | 49.09                 | 0.00                      | 0.00                  |
| 10  | Rice fields                     | 1372.08                   | 1.68                  | -4.51                     | 0.37                  |
| 11  | Pond                            | -206.00                   | 0.25                  | 526.12                    | 43.37                 |
| 12  | Open Ground                     | -144.44                   | 0.18                  | -97.89                    | 8.07                  |

| Total | 110,339.61 | 110,339.77 | 110,339.70 |
|-------|------------|------------|------------|

| No. | Land Cover                      | Difference 2010-2000 (Ha) | Percentage Change (%) | Difference 2018-2010 (Ha) | Percentage Change (%) |
|-----|---------------------------------|---------------------------|-----------------------|---------------------------|-----------------------|
| 1   | Water                           | 0.00                      | 0.00                  | 6.17                      | 0.51                  |
| 2   | Shrub                           | -21.05                    | 0.03                  | 22.45                     | 1.85                  |
| 3   | Swamp Bush                      | -27.60                    | 0.03                  | 0.00                      | 0.00                  |
| 4   | Secondary Dry land forest       | 0.00                      | 0.00                  | -71.83                    | 5.92                  |
| 5   | Secondary Mangrove Forest       | -342.32                   | 0.42                  | 51.72                     | 4.26                  |
| 6   | Settlement                      | 19.49                     | 0.02                  | 0.00                      | 0.00                  |
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| 12  | Open Ground                     | -144.44                   | 0.18                  | -97.89                    | 8.07                  |

| Total | 100.00 | 100.00 |

Figure 1. Land use dynamics in Padang watersheds 2000-2018.
In the year 2018, the highest population density of regency/city in the Padang Watersheds is Tebing Tinggi City with a population density 215,767 people/Km², then Serdang Bedagai Regency about 23,337 people/Km² and the lowest population is Simalungun Regency with a density 7,272 people/Km² (Figure 2). The higher the population density, the greater the chance of a land conversion. Population density is one of the factors that influence the occurrence of land-use change [16–20].

Per capita income is an indicator of a region's economic well-being. The notation that per capita income is affecting the increasing change in land use (Figure 3). Simalungun regency has a high per capita income class (> of 30 million per year) amounting to 30,098,896 IDR/year, while Serdang Bedagai regency and Tebing Tinggi city are in the medium class per capita income 29,972,080 IDR/year and 23,130,036 IDR/year respectively. The higher the per capita income of a region, the smaller the chance of land conversion in Padang Watersheds. It is known that people's income in the upstream area of Padang watersheds comes from the agriculture, forestry and fisheries sectors. The opportunity to convert land to other uses is minimal due to factors such as community culture, where farmland and forests are the ancestral heritage that must be maintained.

Figure 2. Population density in Padang watersheds area 2018.

Figure 3. Income per capita of regency/city in Padang watersheds region in 2018.
Figure 4. Spatial contribution for each parameter to land cover change vulnerability.
The spatial model of land conversion vulnerability in Padang watersheds is classified into five classes that are very unvulnerable, unvulnerable, moderate vulnerable, vulnerable and very vulnerable. Table 3 shows that the highest land conversion vulnerability in Padang Watersheds is in the vulnerable class of 50.38 % or 55,584.54 Ha. Then in the class is very vulnerable at 27.38 % or 30,213.97 Ha. The research shows that land cover with high levels of conversion vulnerability is located in almost all sub-districts in Tebing Tinggi City and Serdang Bedagai Regency (Figure 5). This area has proximity to community activity centers or settlements/villages [11,12,16,17], besides the tremendous land-use change occurred in areas close to rivers and roads [18,19].

Table 3. Distribution of land conversion vulnerability in Padang watersheds.

| No | Score | Classes of Vulnerability | Area (Ha) | Area (%) |
|----|-------|--------------------------|-----------|----------|
| 1  | 100-260| Very Unvulnerable         | 698.92    | 0.63     |
| 2  | 261-420| Unvulnerable             | 10,368.86 | 9.40     |
| 3  | 421-580| Moderate vulnerable      | 13,473.41 | 12.21    |
| 4  | 581-740| Vulnerable               | 55,584.54 | 50.38    |
| 5  | 741-900| Very vulnerable          | 30,213.97 | 27.38    |
|    |        | Total                    | 110,339.70| 100.00   |

Figure 5. Map of vulnerability land conversion in Padang watersheds.
Seeing the size of land conversion vulnerable areas in Padang watersheds, it is necessary to manage Padang Watersheds with increased of landcover with high infiltration capacity, low runoff generalization in upstream and central watersheds through planting trees, making reservoirs, making sedimentation ditches and wells and tackling narrowing river (due to garbage, debris and building) [21].

4. Conclusions
The higher the population density has a greater chance of a land conversion. The higher the per capita income of a region tends to have a smaller chance of land conversion in Padang Watersheds. The dominance of land cover conversion vulnerability in Padang Watersheds is in a vulnerable class of 50.38% or 55,584.54 Ha, then in the class is a very vulnerable class of 27.38% or 30,213.97 Ha.

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