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Post-tsunami land use monitoring to support sustainable coastal management

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Abstract*. Monitoring land use in tsunami-prone coastal areas has an important role in disaster risk reduction. This study was conducted to map temporal land-use patterns in the post-2004 tsunami coastal area in Aceh. The research method was carried out through a spatial approach by overlaying land use maps for the years 2005, 2009, 2014, and 2019 to find out patterns and changes in land use. Landsat 5 and Landsat 8 image analysis was carried out through supervised classification (maximum likelihood). Based on the land-use pattern analysis, the results showed that tsunami-prone coastal areas were still widely used as residential areas. This study shows that over the past 15 years, there has been an increase in the number of settlements covering an area of 7 418.99 ha, and there has been a decrease in open land covering an area of 6743.73 ha. While land use in the form of high-density vegetation experienced an increase of 672.76 ha, likewise, low-density vegetation increased by 459.11 ha after the tsunami. The growth of settlements in a tsunami-prone area might be highly risky if a similar disaster occurs again. Efforts to regulate, monitor, control, and evaluate land use appropriately in tsunami-prone areas are necessary so that the level of disaster risk can be reduced.*

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INTRODUCTION

The tsunami in Aceh in 2004 was the worst disaster in Indonesia, even the world history. The earthquake with a magnitude of 9.3 on the Richter Scale resulted in a tsunami with wave heights reaching 35 m to 51 m (Lavigne *et al*., 2009). It did not only hit Indonesian waters, but it also had a massive impact (Boen, 2014) on 14 other countries, namely Sri Lanka, Thailand, India, Bangladesh, Myanmar, Malaysia, The Maldives, The Seychelles, Madagascar, Somalia, Keynia, Tanzania, and South Africa (Alles, 2012) with the death toll reaching 280 000 people and losses up to 28.7 trillion. Several studies have stated that the tsunami in Aceh caused many fatalities due to the lack of community preparedness and the low level of public understanding of the tsunami disaster (Alles, 2012), the inappropriate utilization and use of land in coastal areas (Utami *et al.*, 2019), coastal morphological conditions with open characteristics and the inexistence of effective earthquake and tsunami disaster mitigation.

Post-tsunami 2004 became a milestone and a lesson for Indonesia and several other countries about the importance of disaster management (Jauhola, 2010; Sipe and Vella, 2014). Several studies related to post-disaster: rehabilitation-reconstruction Sengara *et al*. (2008); efforts to reduce the level of vulnerability (Stephan *et al*., 2017); community life after the tsunami (Lee *et al*., 2014); disaster mitigation, and strengthening community capacity (Kurien, 2017); assistance, and development infrastructure to reduce the impact of disasters has been studied by many researchers. This is due to the potential for megathrust earthquakes and tsunamis in the subduction source zone, namely in the southwest of the island of Sumatra, is still very likely to occur, considering that at this location, there is a meeting of the Indo-Australian plate and the Euro-Asia plate, the Sumatra fault zone (SFZ) with a subduction zone rate of about 60 to 70 mm/year, and several earthquakes with very large magnitudes that have occurred (Sengara *et al.*, 2008).

Mitigation efforts by mapping the level of disaster vulnerability based on the South Asia Pacific Applied Geosciences Commission (SOPAC) through the variables of the physical condition of the area, the socio-economic conditions of the population, the level of danger that may occur, and an assessment of the level of community capacity/resilience becomes one of the mechanisms to formulate a method of disaster risk reduction. In this context, physical aspects, among which are land use, population, and building density, become indicators in determining the level of vulnerability in an area (Muthusankar *et al*., 2018). In coastal area management in various countries, land use monitoring is one of the important things to decide on the right policy in determining the function and direction of spatial use (Farhan and Lim, 2014; Bao *et al*., 2018; Kuo and Lu, 2018; Almarshed *et al*., 2020).

This study aims to map land use and land use changes in 2005-2009-2014 and 2019. The study results are expected to be used as monitoring and evaluation material on whether the determined land use is in accordance with the regional spatial plan and whether the existing land is currently available. The pattern of utilization is in accordance with disaster mitigation efforts. Knowing land use and land use changes, it can be used to indicate whether an integrated coastal management scheme is implemented in the study area. Land use plays an important role in disaster mitigation in order to realize sustainable human life (Berke and Smith, 2010). Studies conducted by Suppasri *et al*. (2015) and Utami and Wibowo (2019) show that inappropriate land use in coastal areas, namely dense residential buildings/settlements, could result in a high number of victims and losses in the event of a tsunami disaster.

Appropriate land use is certainly able to reduce the risk, both in terms of casualties and related to economic losses, in the event of a disaster. Suppasri *et al*. (2015) in his study, showed that Sri Lanka is one of the countries that implemented settlement reconstruction after the 2004 tsunami strictly. To reduce the level of risk that may occur, the government established regulations so that the development of economic centers, government, and settlement is not carried out in coastal areas, especially with open coastal conditions. Likewise, in Japan, India, the Netherlands, South Africa, and Florida, the regulation of the use and utilization of space in coastal areas is regulated in detail so that the level of risk can be reduced (Koshimura and Shuto, 2013; Kuo and Lu, 2018; Almarshed *et al*., 2020).

The use of remote sensing imagery is the right choice as part of the effort to monitor land use in an area. The studies conducted Erasu (2017) show that remote sensing image data analysis and geographic information system applications (Harris and Shaw, 2007) are very effective for natural resource and post-disaster monitoring. Land use monitoring is carried out by utilizing the advantages of multitemporal Landsat imagery (Amiri *et al.*, 2014; Yuan *et al*., 2005; Coban *et al*., 2010) for the Landsat images are the kind of images that have a fairly complete data record and have stored spatial data for quite a long time since it was orbited in 1972 (Zharicov *et al.*, 2018).

METHODS

Research Location

This study was conducted in areas along the coast of Banda Aceh and part of the coast of Aceh Besar where at the time of the 2004 tsunami was severely damaged due to the open nature of the beach. The description of the research location is presented in Figure 1.

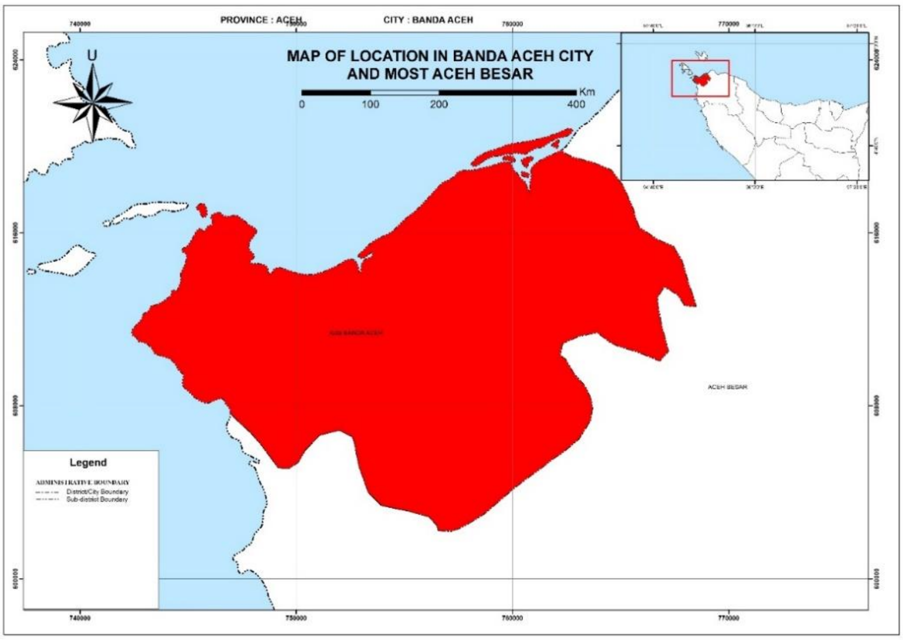


Figure 1 Research location

Data Collection

Land use/land cover data were obtained from multitemporal Landsat imagery, namely Landsat 5, for 2005 and 2009 images and Landsat 8, for 2014 and 2019 images. Landsat 8 is a new generation of imagery that brings two sensors, namely OLI and Infrared Thermal (TIR) sensors. This tool collects images through nine infrared bands, short infrared waves, and two thermal waves. Landsat 8 has high signal noise radiometer performance, allowing quantification of data up to 12 bits. This condition certainly can provide a greater number of bits for a better interpretation of land cover characteristics (Pour and Hashim, 2015). Landsat 8 is the latest development of Landsat, which was launched in 2013 (Erasu, 2017). Meanwhile, Landsat TM5 imagery, which was first launched in 1984, is satellite imagery that has been widely used for land use/land cover analysis (LULC) because it has seven spectral bands, namely bands 1, 2, and 3 for visible light, bands 4, 5, and 7 for close and medium infrared, and band 6 for thermal infrared (Osgouei and Kaya, 2017).

Data Analysis

This research was carried out through spatial analysis by overlaying multitemporal land use maps in 2005, 2009, 2014, and 2019. To obtain quality and accurate image data in this study, atmospheric, radiometric, and geometric correction processes were carried out. Landsat 5 and Landsat 8 image analysis was carried out using a maximum likelihood approach to obtain land use classification. The periodic land use map is then overlaid to map land use changes after the tsunami disaster. The flow chart of this research is presented in Figure 2.

In this study, land use classification is divided into built-up land, high-density vegetation, low-density vegetation, open land, and bodies of water. The classification system emphasizes settlements to identify the distribution pattern of community settlements and the settlement growth in the study area. Meanwhile, the classification of vegetation cover is divided into high-density and low-density vegetation. This vegetation mapping was made to find out the density level and distribution pattern. In this study, an integrated coastal management (ICM) approach is used to analyze whether the development represented by land use and utilization is in line with the ICM concept. The implementation of ICM is an important part, especially in Aceh as a disaster-prone area, so that development-oriented economic interests can coexist with environmental interests so that sustainable development can be realized. Spatial planning is certainly one of the important regulations in regulating and controlling the existing space for the protection of the area/local community.

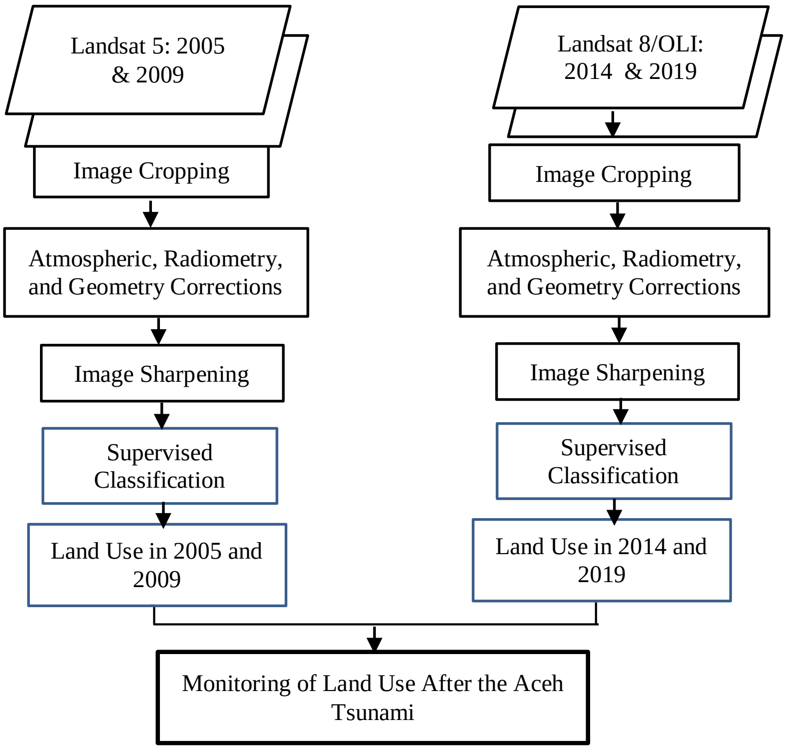


Figure 2 Research flow chart

RESULTS AND DISCUSSION

Landsat, as an imagery presented in the United States Geological Survey (USGS), has the advantage of monitoring natural resources, so it is ideal for mapping various mappings related to natural resources and LULC mapping (Almazroui *et al*., 2017). In addition, Landsat also has the advantage of a fairly high temporal resolution, which is once every 16 days, and a fairly wide recording coverage, making it useful for various spatial data analyses. To analyze land use pattern in this study, image selection was carried out at the location where a quite malignant tsunami occurred in Aceh in 2004, precisely in the coastal areas with open coastal conditions and morphology in the form of lowland.

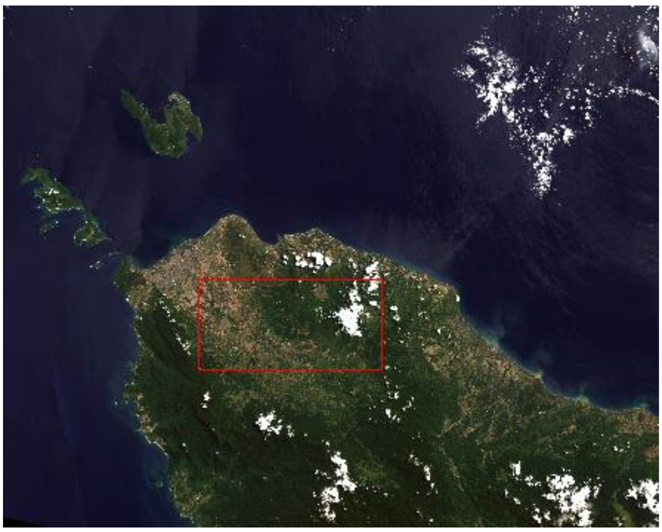
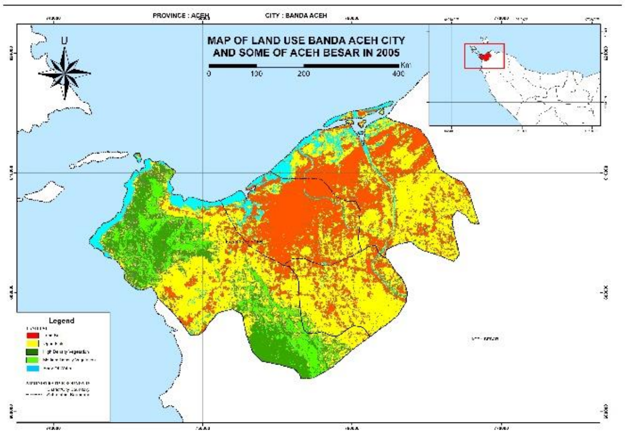


Figure 3 Geometric and atmospheric correction process

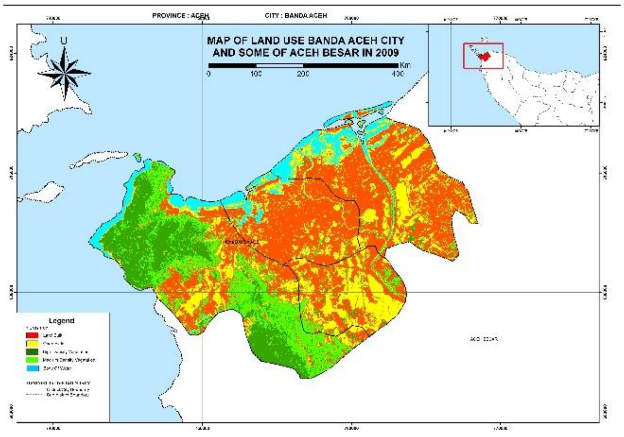
To get images with high accuracy, image correction process was carried out in this study in the form of atmospheric, radiometric, and geometric corrections. Geometric correction was carried out so that the images analyzed has high accuracy, close to the earth's surface actual condition. The radiometric correction was carried out so that the processed satellite images do not interfere with their wavelength. Meanwhile, image sharpening was carried out to obtain satellite images that have spectral sharpness and facilitate digital data analysis. The pre-analysis of digital image data in the form of atmospheric correction is shown in Figure 3.

Post-tsunami Land Use

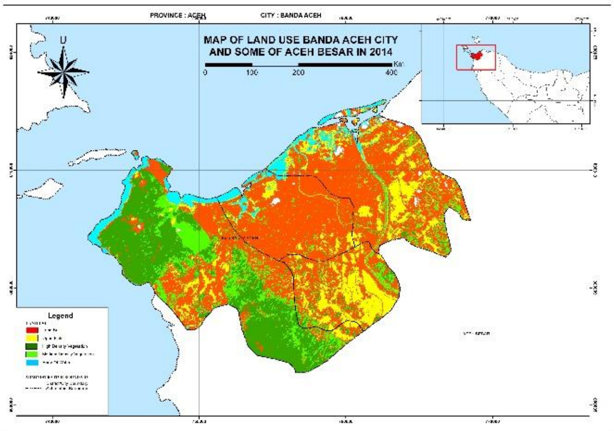
In the presentation of spatial data, remote sensing images provided information in the form of land cover that was used to indicate land use. Image processing was completed to extract digital data into land cover data by using Landsat TM5 and Landsat 8. The color composite used in this study was in the form of visible wavelength, namely the band 3-2-1 or red, green, and blue. Meanwhile, land cover analysis was conducted through supervised classification. This analysis was carried out by providing a training area/giving a sample to the targeted object.



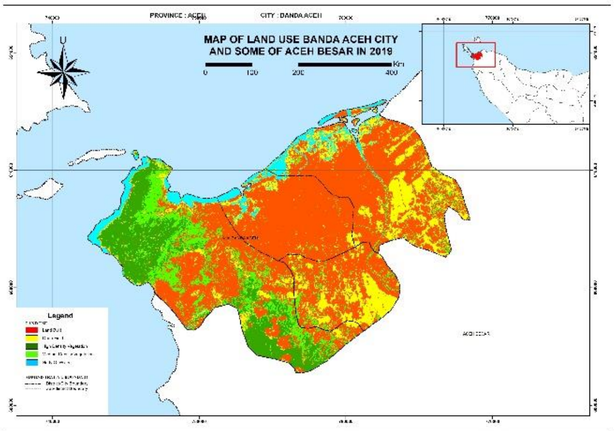
Map of land use in 2005



Map of land use in 2009



Map of land use in 2014



Map of land use in 2019

Figure 4 Analysis results of landsat image classification in 2005, 2009, 2014, and 2019

In carrying out the supervised analysis, the researcher provided the training area correctly, that is, a sample of pure pixels, meaning that when viewed manually, the satellite images have the same color. Providing examples of the training area for the supervised analysis was done on at least ten objects located differently so that the sample given was close to the correct value. The supervised analysis was chosen in order to make the resulting land use classification accurate/in accordance with the existing condition of the earth's surface. The results of the spatial data classification of Landsat TM5 and Landsat 8 images are presented in Figure 4.

Land Use Monitoring

Land use has a major influence on disaster mitigation efforts. Suppasri *et al*. (2015) stated that land use in coastal areas, especially those with disaster vulnerability, should be used as conservation areas, protected areas, or a barrier to disaster threats. In some countries such as India, Sri Lanka, South Africa, or Japan, coastal areas affected by tsunamis are established as conservation areas; even natural or artificial barriers are built to prevent adverse effects in case a tsunami reoccurs (Willemse and Goble, 2018; Okura and Hiraishi, 2018). However, it all depends on the stakeholders in preparing and implementing spatial planning in the regions, especially in disaster-prone areas.

In this context, spatial planning policies in disaster-prone areas should pay attention to mitigation efforts in a comprehensive spatial utilization regulation. Spatial planning embodied in the regulations in the form of Territory Spatial Planning (RTRW) and detailed Spatial Planning/Zoning (RDTR) becomes the basis for regional infrastructure development as well as the economic and settlement sectors. Therefore, arrangements for spatial planning or infrastructure development that are not in accordance with the disaster mitigation system should be reviewed and even evaluated early on so that space utilization can be synergized with disaster risk reduction. In addition to planning, regular monitoring of land use is highly necessary to be a basis for evaluating the use and utilization of space.

Based on the results of the overlay and analysis of land use interpretation, Aceh coastal areas have a tendency to experience land use expansion in the form of built-up land or residential areas. The pattern of land use has undergone quite significant changes in line with the infrastructure development by the Aceh Provincial Government after the earthquake and tsunami disaster. During the last 15 years, it might be acceptable to say that Aceh has recovered from the disaster. This is marked by massive infrastructure development in many areas. This condition is evidenced by the provision of the government's infrastructure budget through the Ministry of Public Works and Public Housing (PUPR) for physical development in Aceh Province from 2015 to 2018, with an average of IDR 1.65 trillion per year. Based on the analysis of four multitemporal images, a map of the land-use change pattern after the tsunami disaster and a table of land use change in the period of 2004-2019 in the coastal areas of Banda Aceh and parts of Aceh Besar are shown in Figure 5 and Figure 6.

Based on Figure 5 and figure 6, changes in land use that occur indicate that settlement development in Banda Aceh and Aceh Besar has increased and there are some expansions to develop settlements towards the coast. The number of settlements increased rapidly during the 2005-2019 with period of 4 365.10 ha. It increased in the first five-year period of 2009-2014 covering 1 394.13 ha and kept increasing during the 2014-2019 period covering 1 659.65 ha. The first five-year period after the tsunami was a phase of massive rehabilitation and reconstruction, where assistance came from various sources, both from the Indonesian government and foreign aid. If observed from 2005 to 2009, the land use map shows that the development of new settlements mainly was carried out in areas far from the coastline by utilizing vacant land, while in the 2014-2019 period, settlement development near the coast started to increase.

The expansion of residential development in areas close to the coast can certainly increase the level of vulnerability and risk in the event of a disaster. Areas close to coastal areas studied (Almarshed *et al*., 2020) should be prioritized for planting breakwater plants that are able to protect the community from the threat of disaster. Integrated Coastal Zone Management *(*ICZM) (Phillips *et al*., 2018; Willemse and Goble, 2018; Sorensen *et al*., 2018) suggested that coastal management should combine environmental and economical, and social interests as well as life sustainability into a unified system. Furthermore, in several other countries, implementation of monitoring and evaluation functions, especially on land use and utilization, is an important and inseparable part of ensuring that coastal area management can support the sustainability of community life and the environment (Garten, 2016; Rivis *et al*., 2016; Song *et al*., 2018; Ramírez-Vargas *et al*., 2019).

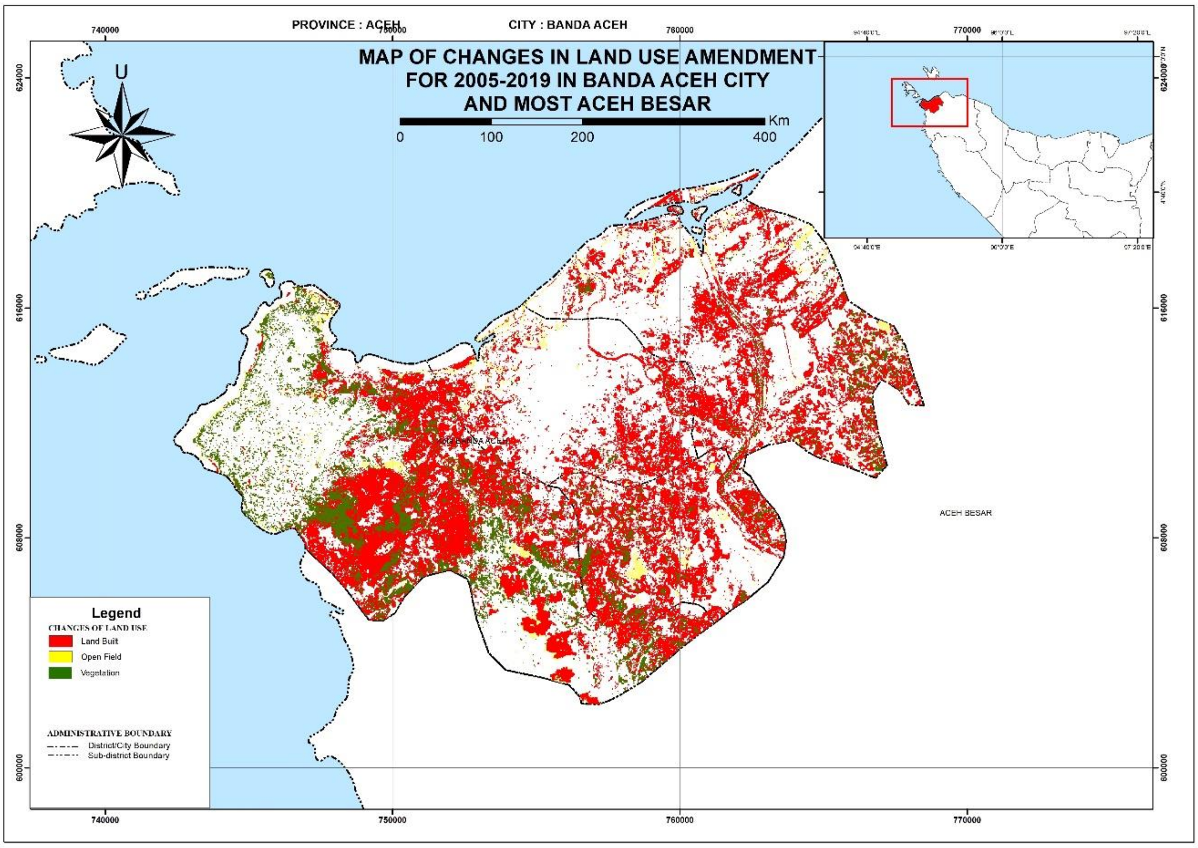


Figure 5 Map of land use change in 2005 – 2019 period

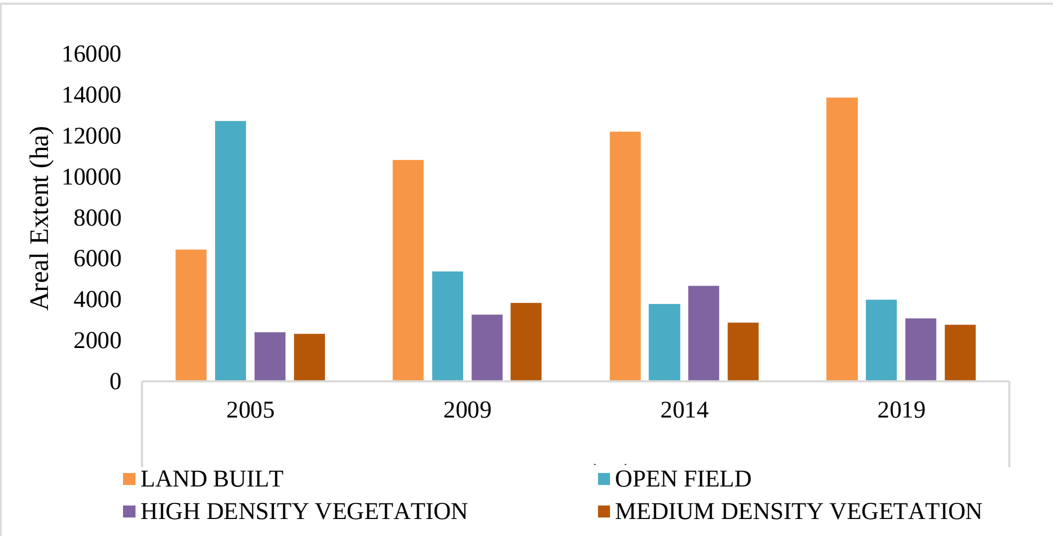


Figure 6 Chart of land-use change in 2005, 2009, 2014, and 2019

This study also shows that the reduction in the area of open land was very significant in the first five years after the tsunami, namely 2005-2009, covering an area of 7 361.19 ha. This was influenced by the simultaneous rehabilitation and reconstruction programs. The reduction in open land also occurred from 2009 to 2014, with an area of 1 588.61 ha. Meanwhile, land use of high-density vegetation increased in the 2009-2014 period. However, during this period, a reduction in medium-density vegetation and open land occurred again due to population growth. This period experienced a significant increase reaching up to 2.29% (BPS of Aceh Province, 2015), and the growth of industry, fisheries, and tourism developed rapidly during this period

(Bappenas, 2015). This could have a negative impact on the existence of vegetation as natural breakwaters. The reforestation program promoted by the government and initiated by local communities, especially around the coast of Aceh, is very important to support the efforts to reduce disaster risk that may occur in the future. Efforts to increase preparedness that are initiated from the early stage and carried out simultaneously, especially on the aspect of spatial use, are in some cases quite effective in reducing the impact of disaster risk.

Population growth in coastal areas that occurred in Aceh and in several other countries in the last few decades is indeed inevitable. Anthropogenic factors, infrastructure, settlement, aquaculture, agriculture development, mineral/mining resource exploitation, as well as economic center development in coastal areas are developing rapidly (Ramírez-Vargas *et al*., 2019). In the context of the tsunami-prone coastal areas in Aceh, integrated coastal area management is something that must be implemented. Consideration of environmental and community life sustainability by improving the level of security should be a top priority. Furthermore, policies and directions in the use/utilization of space by prioritizing economic aspects should not be the only consideration if this is done, of course, increasing the level of vulnerability (Muthusankar *et al*., 2018). Security and disaster risk reduction aspects should be the main priority and important consideration so that the impacts that may occur due to disasters can be suppressed.

The implementation of integrated coastal management is a strategic solution that can be carried out on the coast of Aceh as, a tsunami-prone area and prone to climate change. Spatial planning efforts that prioritize the availability of conservation areas as local protection must, of course, be allocated. On the other hand, the sustainability of the lives of people who depend on coastal/marine areas should not be neglected. Spatial planning arrangements, community/stakeholder participation, and community capacity building are the main parts of realizing integrated coastal management in several countries, including Japan (Furukawa *et al*., 2019), Virginia/USA (Nunez *et al.*, 2022), Taiwan (Lin *et al*., 2021). A study conducted by Eger *et al*. (2021) shows that planning involving stakeholder interests and leadership is one of the keys to the success of integrated coastal management. Ullah *et al*. (2021) said that monitoring and evaluation efforts related to the implementation of ICM with the sustainability of socio-economic and ecological aspects need to be carried out so that there are no conflicts between interests.

CONCLUSION

Landsat TM5 and Landsat 8 are satellite imagery of natural resources capable of recording the earth's surface with fairly complete data. Utilization of Landsat imagery through supervised analysis was able to present data on changes in land use so that it can be used for the benefit of spatial analysis of space utilization. Major changes in land use during the 15 years after the tsunami in Banda Aceh and major parts of Aceh Besar are in the form of settlement/built-up land expansion covering an area of 7 418.98 ha. This increasing pattern of settlement development does not only occur in the central mainland area but also in areas around the coast that are quite vulnerable to the threat of a tsunami. Restrictions and arrangements for proper land-use direction as well as land use monitoring are very necessary for areas that have experienced disasters or disaster-prone areas. In addition, efforts to build natural/artificial barriers as breakwaters in coastal areas should be optimized in the event of a tsunami. Comprehensive efforts to implement integrated coastal management need to be carried out so that disaster risk reduction can be implemented in the coastal areas of Aceh.

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