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Assessment of post-tsunami disaster land use/land cover change and potential impact of future sea-level rise to low-lying coastal areas: A case study of Banda Aceh coast of Indonesia

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Abstract

The objective of this study is to investigate the impact of the projected sea-level rise to the coastal land use/land cover (LULC) at a disaster-prone coastal area, encompassing an engineering time-scale, based on a couple of sea-level rise scenarios. We investigate the Banda Aceh coast, a low-lying coastal area vulnerable to multiple hazards such as tsunamis and co-seismic land subsidence, which is typical along the Indonesian coastlines. Three sets of multi-temporal Google Earth Engine images acquired in 2004 (pre-tsunami December 2004), 2011 and 2017 were utilized to obtain the areal coverage of various types of LULC. The scenarios of coastal inundation were pre-determined at elevation +1.0 m and +1.5 m forecasting the projection of the sea-level rise in the next couple centuries. Aquaculture ponds, buildings and bare land are the top three most pre-dominant land covers in Banda Aceh coast. The finding of this study reveals that the aquaculture ponds are at the highest risk to the future sea-level rise, and potentially contribute to the unproductive swamp area. The bare land which has a huge potential to be converted into settlement area (buildings, housing, etc.), experienced remarkable loss due to both future inundation scenarios. The coastal area of Banda Aceh in the next couple of centuries, thus, will be highly vulnerable to the projected sea-level rise, providing the fast-growing and ever-expanding built environment very close to the coastline. A sustainable coastal management taking into account the disaster risk should, therefore, be incorporated within the decision making for the protection of the coastal area.

Keywords: sea-level rise, tsunami, land use/land cover (LULC), Remote Sensing, GIS

1. Introduction

Most of the population in~~of~~ the developing countries living in low-lying coastal areas are marginalised in the economy. Poorest people are often the hardest hit by climate change impacts, either because they already live on small lands, such as riverbanks, deforested areas, or floodplains, or because they have the lowest adaptive capacity due to a lack of education, financial resources, physical resources, and/or government support. As a result, a very large number of people are especially vulnerable to climate change and hydro-meteorological disasters. Indonesia is the fourth largest populated country~~ion~~ and one among the top ten nations whose population are living in low-lying coastal areas (WOR 1, 2010). Recent trends in Indonesia show that hydro-meteorological-borne natural disasters are overtaking geophysical disasters in terms of frequency of occurrences, mortality, and damages. Indonesia's National Disaster Management Agency (BNPB) reported that 87% of all disasters that occurred between 1982-2012 were hydro-meteorological disasters in the forms of floods (38%), landslides (18%), typhoons (18%), droughts (13%), and surges (<1%), which together caused close to 14,000 human casualties (Sofian, 2010).

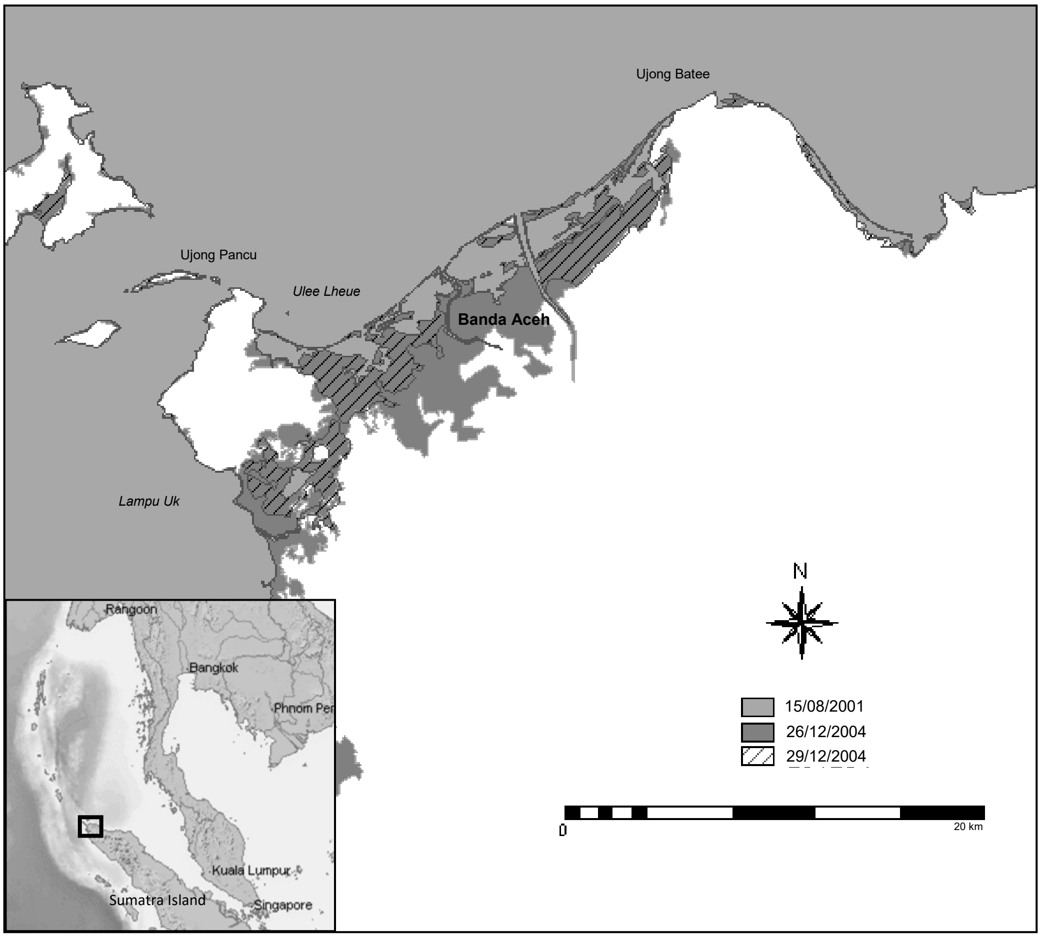
Given the rate of sea-level rise in the Indonesian waters could reach as high as 0.2 - 0.6 cm/year according to Intergovernmental Panel on Climate Change (IPCC, 2007), the projected future inundation of the coastal areas can be in the order of a few meters high by the next couple of centuries. Analysis and projection of sea-level rise by the Indonesian Climate Change Sectoral Roadmap (ICCSR) concluded that globally, sea level rise (SLR) is about 3.1 mm/year at present, while the average sea level rise in the 20th century is only 1.7 mm/year (Sofian, 2010). More than a third of sea level rise is caused by the melting of ice caps in the Greenland and Antarctica, and by the retreat of glacial ice. Some recent research shows that the melting of glacial and polar ice will increase as global warming intensifies (Shepherd, *et al.*, 2018; Spada and Galassi, 2016; Shepherd, *et al.*, 2010). If the warming and the melting of ice continue at a rate similar to that of the past 5 years, then the predicted sea level rise in 2100 could be as much as 80 cm to 180 cm (Sofian, 2010). The dynamic of natural processes influenced by ~~the~~ global climate change and seismicity operating over a few tenth kilometres coastline should, therefore, be incorporated in order to make ~~a~~ sound management of the coastal areas.

In the last decades, research topic on change detection of surficial features of the earth, including changes of the coastal areas are increasing (Halls *et al.*, 2018; Meilianda *et al.*, 2010; Muttitanon and Tripathi, 2010; Foody, 2002; Chen, 1998; Weismiller *et al.* 1977). This is in particular advantaged by the ~~advanced~~ state-of-the-art ~~technology of~~ remote sensing technology which offers multi-temporal satellite images as one of the primary data sources to characterize environmental change (Foody, 2002). Several studies related to change detection of terrestrial water bodies, such as lake monitoring, watershed or flood events ~~were~~ have been conducted using multi-temporal moderate resolution Landsat images (Zhu *et al.*, 2015; Taravat *et al.*, 2016; Rokni *et al.*, 2014; Zheng *et al.*, 2015). Other studies have focused on hydrological impacts of LULC (Petchprayoon *et al.*, 2010), impacts of LULC cover change and urbanization on flooding (Zope *et al.*, 2016), or assessment of LULC changes and sea level rise (Balukkarasu *et al.*, 2016).

The present study assesses the impact of potential sea-level rise induced by climate change to LULC at a low-lying coastal area that once severely affected by another extreme event, such as a tsunami. A low-lying coastal area is often vulnerable to multiple hazards. A tsunami event has its capacity to change the morphological state of a coastal area instantaneously (Meilianda *et al.*, 2010; Monecke *et al.*, 2015), while a climate-induced sea-level rise may slowly alter the coastal morphology due to lack of sediment transport capacity so that the coast may constantly be in non-equilibrium state (Monecke *et al.*, 2017; Cooper and Pilkey 2004; Morton *et al.*, 2004). Future scenarios of how such tsunami-prone coastal area changes, therefore, should address the two parameters to understand the risks the coastal area would face, and then to formulate comprehensive mitigation measures to reduce those risks.

2. Study area

The coastal area of Banda Aceh, located at the northern tip of Sumatra Island of Indonesia is selected as the study area. Banda Aceh is the capital city of Aceh Province, situated between 05°16'15"N and 05°36'16"N, and between 95°16'15"E and 95°22'35"E. The coastal city of approximately 61,36 km^2 is representing a typical low-lying coastal area vulnerable to multiple hazards such as tsunamis and tectonic land subsidence (Meilianda, *et al*, 2010), and at the same time is threatened by the increasing intensity of wave surges and coastal flooding, particularly during the rough monsoon months. The largest outflow crossing the city ~~are~~ is the Krueng Aceh River and the Alue Naga Floodway Canal which dissect the coastline into three coastal cells. Most parts of the coastal areas which are encroached up to 1 km inland are low-lying which elevation merely between -0.5 to +1.0 m from the mean sea level. The tidal range is averaged~~ly~~ less than 1.0 m, which is categorised as micro-tidal. The entire coast is at the highest risk of potential tsunami hazards (Fig. 1).



(a)

(b)

Figure 1. Banda Aceh coast, the study area at the northern tip of Sumatra Island of Indonesia. (a) The map of Banda Aceh showing the inundation of the 2004 tsunami at the coastal area on 26 December 2004 (denoted by the dark gray color), and the receding inundated area after four days on 29 December 2004 (denoted by the stripped gray color); (b) The aerial photo at the lower panel was taken in 1998 facing south-eastern coastal area, revealing the low-lying characteristics of the coastal system.

3. Data and Methods

3.1. Rate of sea-level rise

The rate of sea-level rise from the last 10 years data (Fig. 2) were recorded from the Permanent Service for Mean Sea Level (PSMSL) database maintained by BMKG (Indonesian Meteorological and Climatological Agency) at the Sabang Station (5°52'36"N, 95°20'24"E), located ca. 27 km North of Banda Aceh coastline. Assuming that the influence of vertical movements due to seismic activities was negligible to the records of sea-level fluctuation, the records reveal an average trend of sea-level rise of 6.2 ± 0.4 mm/year. Taking this rate into account, we project the arising sea-level up to +1.0 m from the present sea-level would be reached by 151 to 172 years later, and +1.5 m higher would be reached by 227 to 258 years later. Providing the probability of mega-tsunami recurrence of 200 years (Natawidjaja, *et al.* 2007), and the period considered fit into the engineering time-scale for coastal management, the scenario of sea-level rise to map the coastal inundation in the present study are set up as 0 m, +1.0 m and +1.5 m.

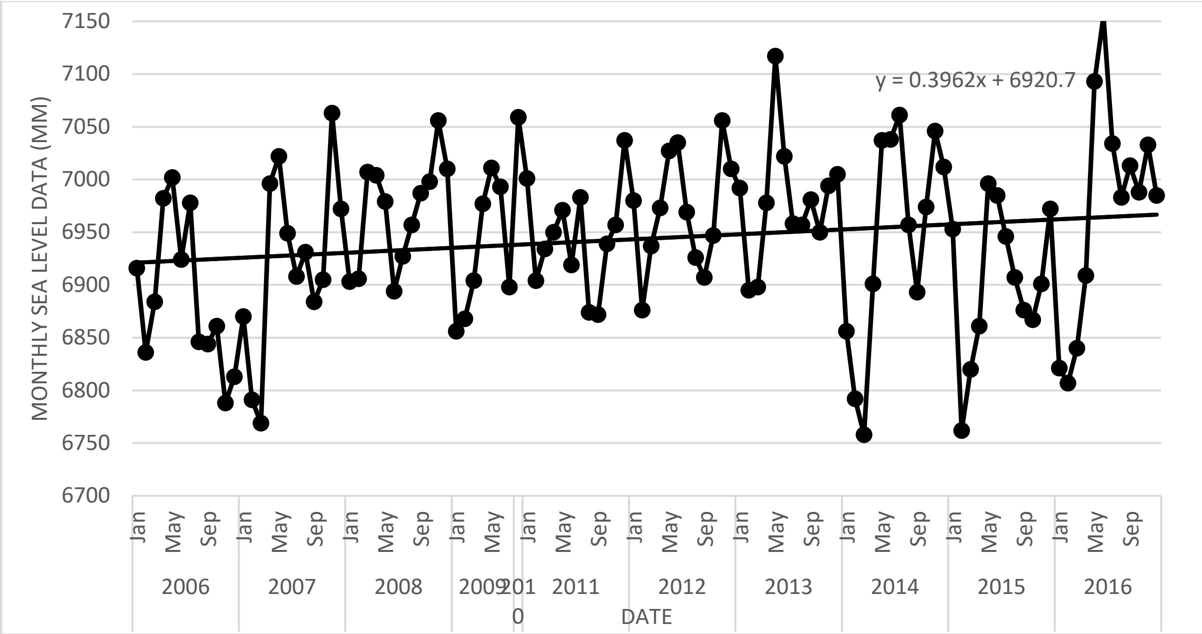


Figure 2. Trend of sea-level rise at Sabang Station north to Banda Aceh City of Sumatra Island of Indonesia (Modified from PSMSL database by BMKG)

3.2 Data analysis methods

Literature study conducted by Ye, *et al.* (2018) shows that the polygon-based classification design is a more favourable method for mapping specific land types, impervious surfaces and vegetation patches compared to pixel-based (raster) method. In this study, the LULC classification combines visual ~~the office~~ interpretation and field data. We identify and compare objects and patches from each satellite image based on our familiarity with the study area after conducting several fieldworks for the previous post-tsunami 2004 studies (Meilianda, *et al.*, 2010; Meilianda, 2009 ; Meilianda, *et al.*, 2007), from most recent studies on the post-tsunami coastal development at Banda Aceh coast (Syamsidik, *et al.*, 2017; Achmad, *et al.*, 2015; Rusdi, *et al.*, 2015), and from the visually comparable identified objects using the high-resolution satellite images. Three sets of high-resolution satellite images acquired on 23rd June 2004 (pre-tsunami December 2004), 1st March 2011 and 14th May 2017 retrieved from the Google Earth Pro - Digital Globe, were utilized for LULC delineation using ArcGIS software. Each of acquired satellite image was already geo-referenced and spatially rectified. The LULC from each image~~s~~ were obtained by digitization of discernible~~discernable~~ objects into polygons. The digitization was performed ~~for~~ by using the unsupervised LULC classification scheme, extracted from each high-resolution satellite image of 30 x 30 cm pixels, with areal coverage of 15 km^2.

In addition to the spatial works, the land cover types were further verified by ground-truth survey and interview with the local inhabitants and the planning agency of Banda Aceh Municipality. These procedures were resulting in a classification of the type of LULC which are commonly identified in all of the three datasets.

a. Scenarios of shoreline positions of the projected sea-level rise

As for the analysis of the inundation extent at the coastal area by different scenarios of projected sea-levels, a set of Digital Elevation Model (DEM) of 30 m vertical resolution data acquired from the Shuttle Radar Topography Mission (RSTM). The inundation marked as the boundary between land and water (±0.0 m, +1.0 m and +1.5 m) in polygon vector maps. Herein, we used only the LULC polygon map of 2017 as the most recent situation upon which the projected sea-level scenarios are applied. Then, this boundary line was clipped onto the LULC polygon map to cut off the inundated areas. From there, the final non-inundated areas (in hectare) were re-calculated. The results of the entire mapping operation are the polygon maps of LULC of ± 0 m, +1.0 m and +1.5 m. The overall methodological workflow is depicted in Fig. 3.

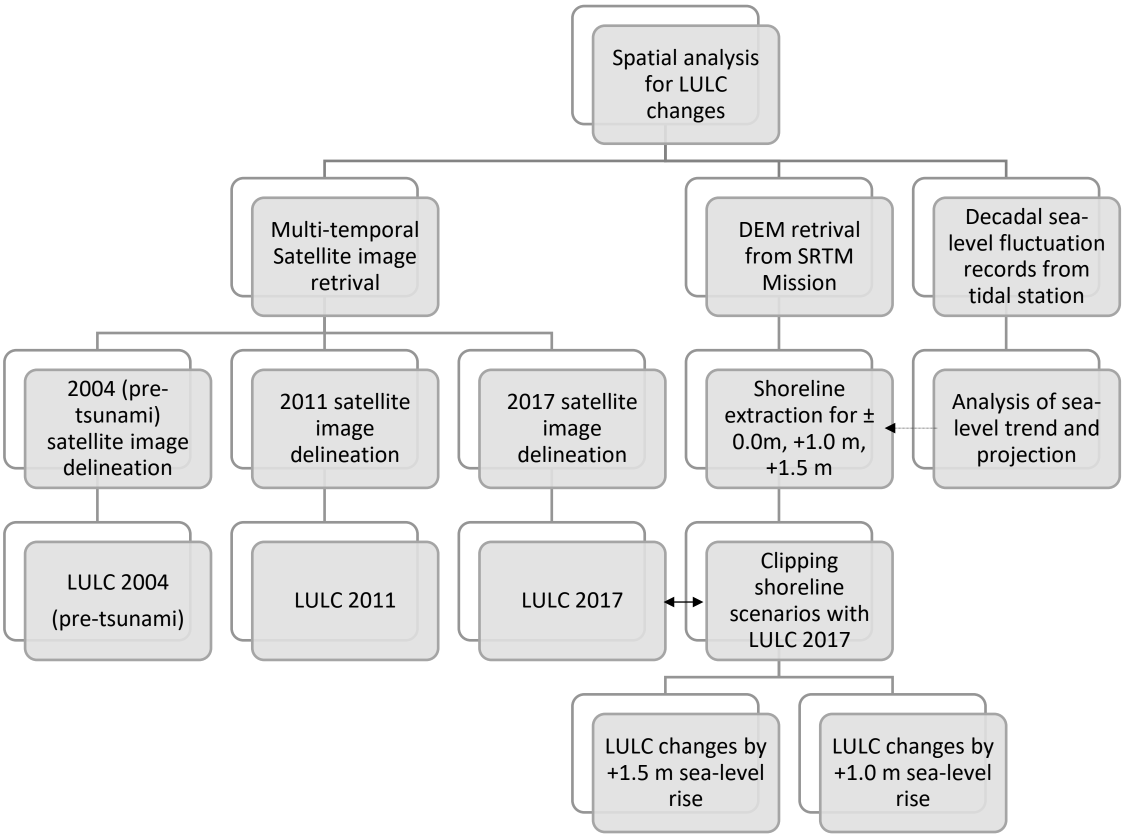


Figure 3. Overall methodological work flow adopted in this study.

b. Uncertainty analysis on LULC delineation

The uncertainty of LULC is measured by the change detection of the size of comparable fixed objects (e.g. buildings, land boundaries, road networks, etc.) in different satellite images. Here, the uncertainty of the resulting polygon maps was assessed by the degree of similarity in the size of an extracted object and the size of the corresponding object presented in the measured reference data (Zhan, *et al.* 2005).

$$Sim\_Size_i = \frac{\min(A_{obj}, A_{ref})}{\max(A_{obj}, A_{ref})} \quad (1)$$

$$Mean_{Sim\_Size} = \frac{1}{n}\sum_{i=1}^{n} Sim\_Size_i \quad (2)$$

$$Std_{Sim\_Size} = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(Sim\_Size_i - Mean_{Sim\_Size}\right)^2} \qquad (3)$$

wWhere A_{obj} denotes the size of the extracted object, and A_{ref} denotes the size of the corresponding object presented in the reference data. Herein, the most recent polygon data were used as the corresponding objects, while the older ones used as the reference data. $Mean_{Sim\_Size}$ is a measure that indicates the average similarity in terms of the size of all extracted objects. Std_{Sim_Size} is the standard deviation of similarity in terms of the size of all extracted objects.

Six types of LULC were delineated for the individual satellite images in 2004, 2011 and 2017 consisting of the areas of buildings, bare land, aquaculture ponds, mangroves, rice fields and swamp. Herein, we selected buildings, aquaculture ponds patches and mangroves areas as the representative LULCs, since they are well-distributed across the studied coastal area. By pairing the 2011 and 2017 datasets, we selected the polygon sample pairs of each LULC type which have similarity in shape and size. Herein, the 2011 datasets serve as the reference object, while the 2017 datasets serve as the extracted object. The 2004 or pre-tsunami datasets were not included in the uncertainty analysis because of remarkable changes occurred to almost all of the LULC types due to the tsunami event on 26 December 2004. Table 1 displays the overall results of the uncertainty analysis in this study.

Table 1Uncertainties of polygon delineation of LULC types

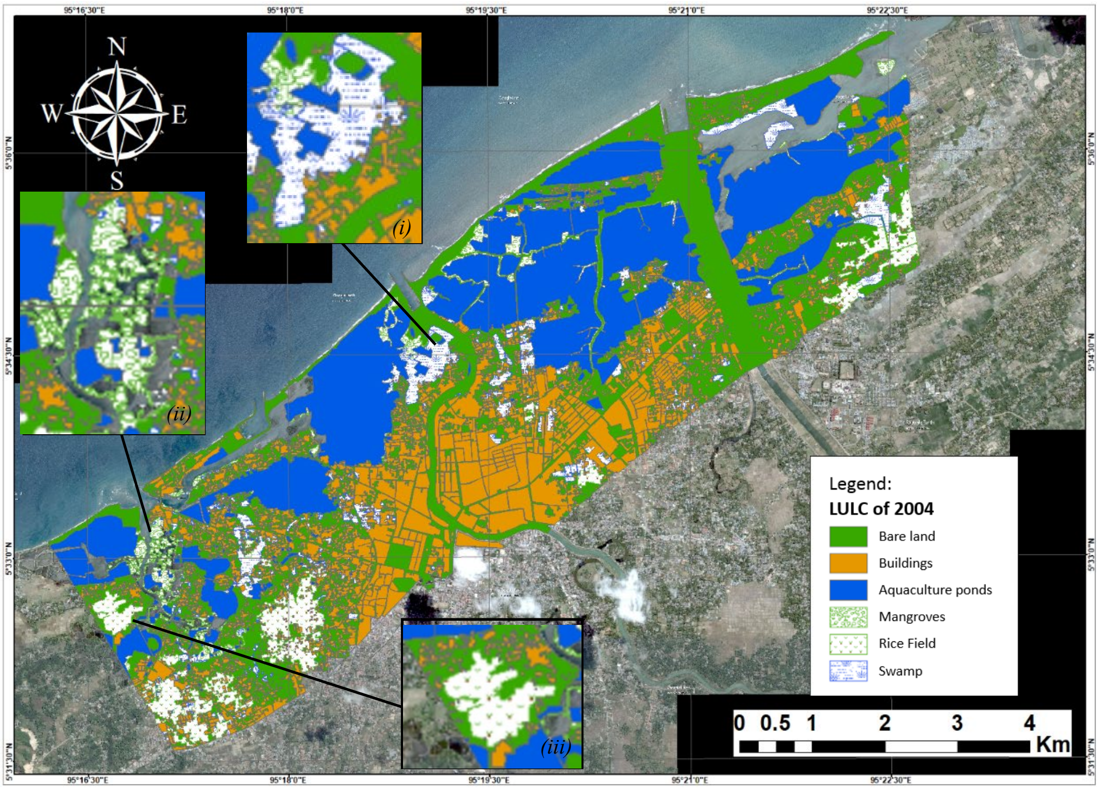
No.	LULC Type	Sample	Mean	Standard Deviation
1	Buildings	2900	0.96	0.05
2	Aquaculture ponds	140	0.98	0.04
3	Mangroves	138	0.98	0.08

The quality assessment results in a mean value of 0.96, 0.98 and 0.98 for similarity in size and a standard deviation of 0.05, 0.04, and 0.08 for buildings, aquaculture ponds and mangroves, respectively. These figures show a high degree of similarity in terms of polygon size; thus, the major parts of the digitized type of LULC match the corresponding buildings, aquaculture ponds and mangroves presented in the reference data. The low standard deviation shows that consistent results are obtained for those extracted LULC types.

4. Results and Discussions

4.1 Comparing the pre- and post-tsunami land cover changes

The delineation of LULC from the high-resolution satellite images of 2004, 2011 and 2017 resulted in the areal coverage (in hectare) of each individual LULC types, which are displayed in Fig. 4a, 4b and 4c. Herein, the swamp identified as the brackish water body situated inland, which are not directly connected to the sea for it has sort of natural boundaries, such as natural barrier island or spit, or man-made levee. It is not modified as aquaculture ponds patches and no existence of mangroves colonies. Whereasile, the mangroves areas are those where patches of mangroves colonies exist. The aquaculture ponds areis identified as the inundated area bounded by square embankments. The rice fields are those squared patches of land with a typically homogeneous vegetated surface.



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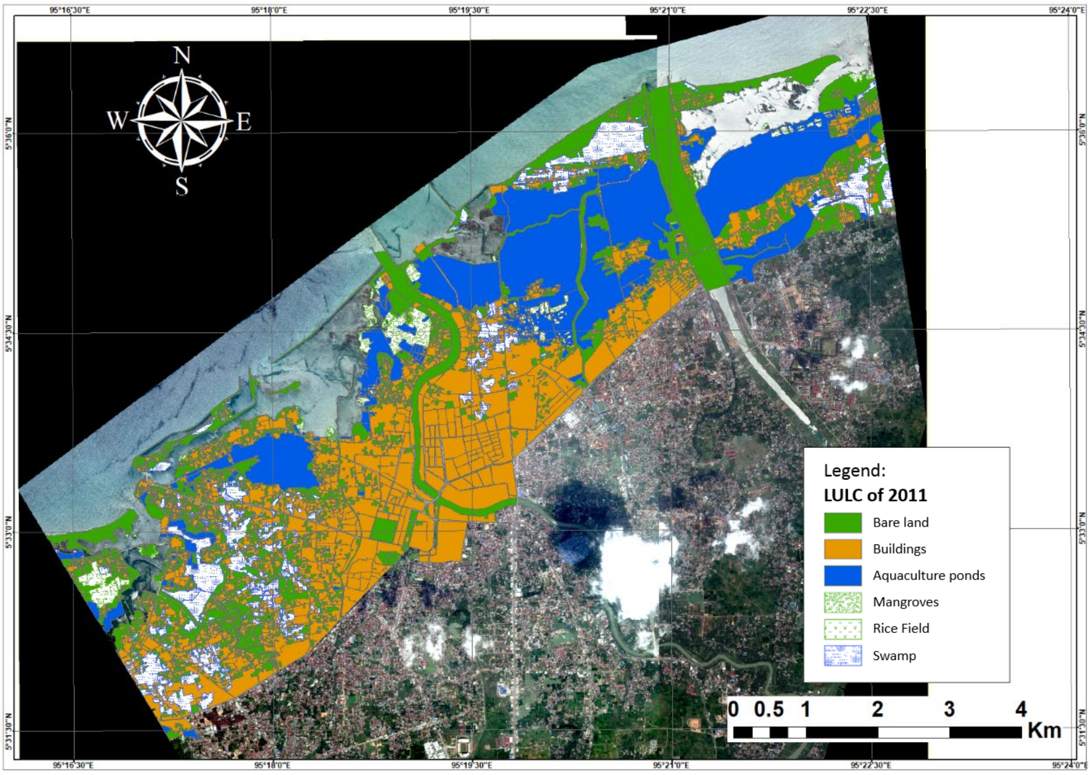

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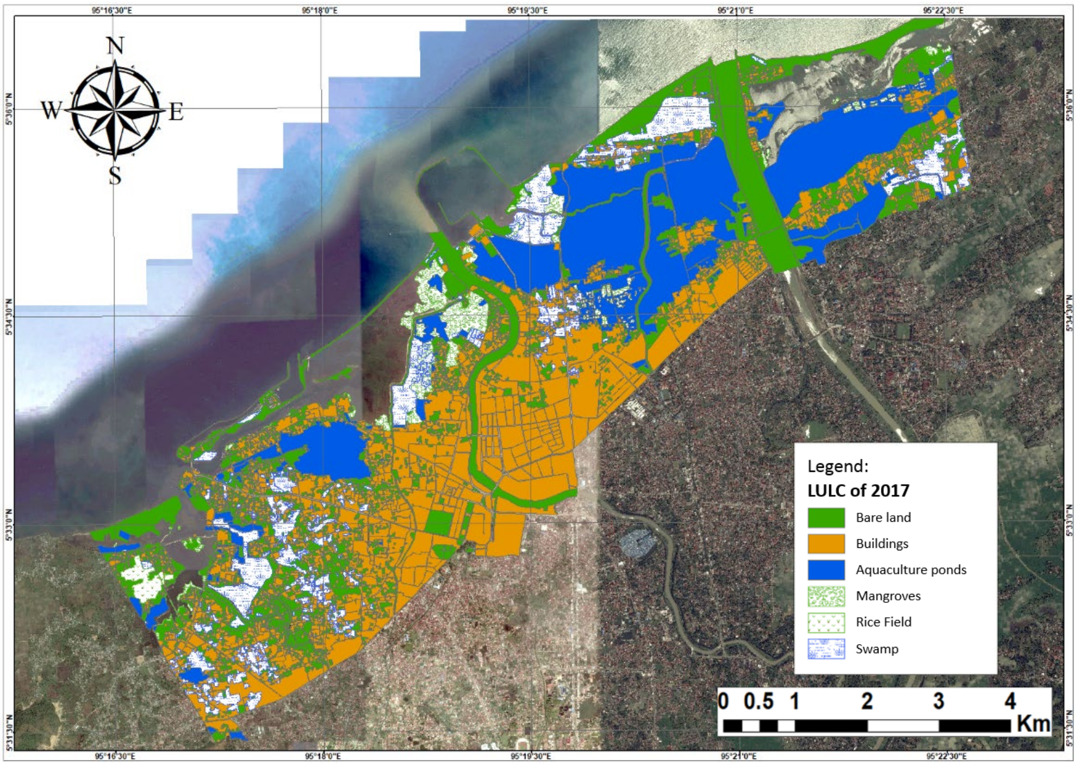
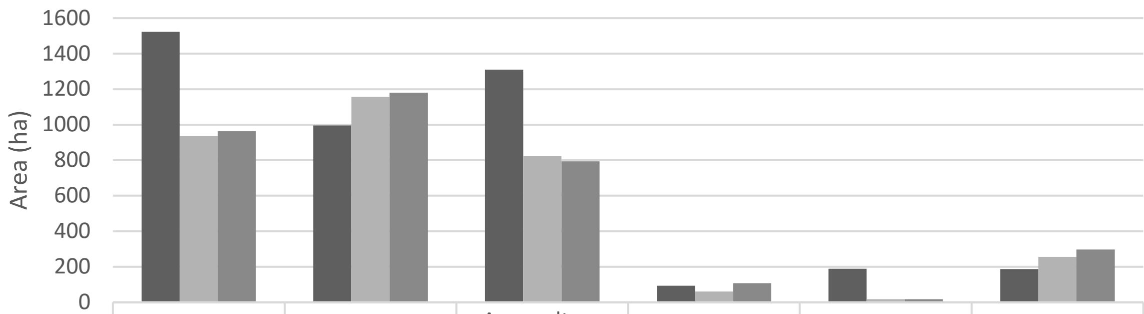


(c)

Figure 4. Maps of LULC at the Banda Aceh coast. Six types of LULC identified typically covering the coastal area of Banda Aceh for the 2004, 2011 and 2017, respectively. Three pre-dominant types are aquaculture ponds, buildings and bare land. (a) LULC map of 2004, with the mangroves, rice fields and swamp areas are zoomed-in for clarity in the insets *i, ii* and *iii*, respectively. The coverage areas of all types of ~~the~~ consecutive years are quantified in Fig. 5.



	Bare land	Buildings	Aquaculture ponds	Mangroves	Rice fields	Swamp
2004	1523	995	1310	94	189	187
2011	937	1157	823	60	17	256
2017	963	1179	793	107	17	298

Figure 5. Areal changes (in hectare) in coastal land cover at Banda Aceh coast in 2004, 2011 and 2017. The areal coverage of bare land, buildings, and aquaculture ponds are persistently the top three largest areal coverage occupying the coastal area, even after the impact of tsunami event on 26 December 2004.

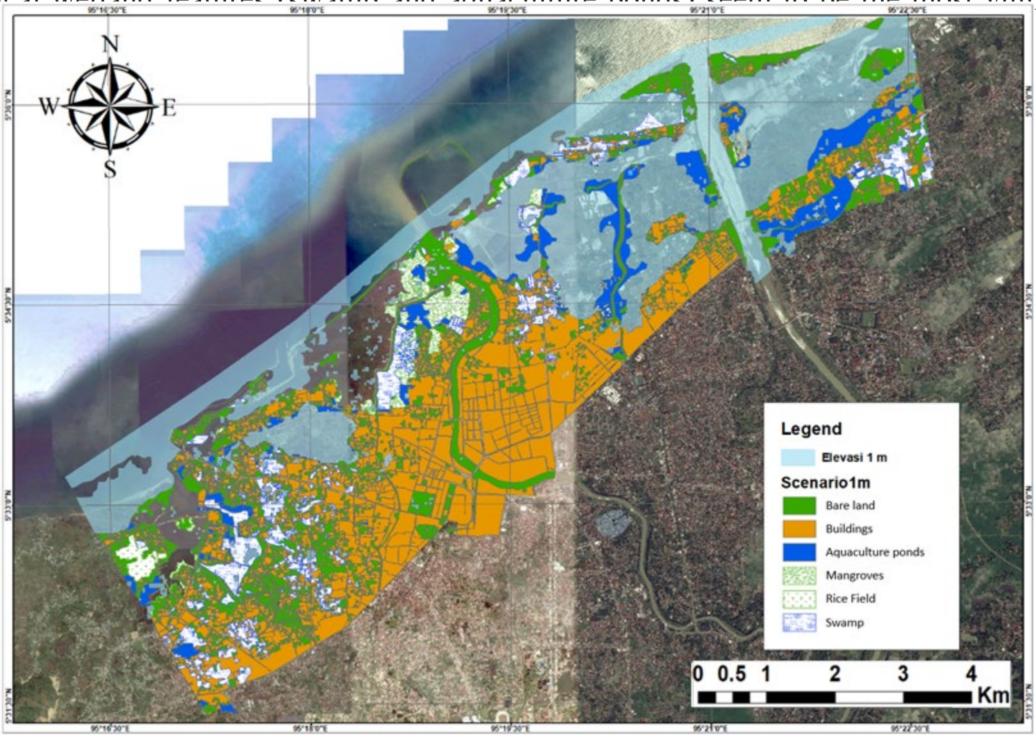
The LULC map of the pre-tsunami 2004 (Fig. 4a and Fig. 5) displays the areal coverage of bare land (1523 ha), buildings (995 ha), and aquaculture ponds (1310 ha) are the top three consecutively largest areal coverage occupying the coastal area. This is followed by the rice field, swamp and mangroves, which occupy 189 ha, 187 ha and 94 ha of the coastal area, respectively. In the following years after the tsunami destroyed the coastal area, the areal coverage of the aquaculture ponds, bare land, ~~rice~~and rice field has~~ve~~ been persistently declining. Interestingly, most of the losses of areal coverage are compensated by the increased areal coverage for buildings; which numbers are consecutively increasing from 1157 ha in 2011 to 1179 ha in 2017. Additionally, some areas where they used to be aquaculture ponds were left to become abandoned swamp areas after being destroyed by the tsunami of 2004.

If we compare ~~between~~ the area of LULC types of ~~the~~ 2004 (pre-tsunami) and ~~the~~ 2011, and 2017 (post-tsunami) in their respective current state, the bare land, buildings and aquaculture ponds remain as the top three largest LULC types occupying the coastal area, even after the impact of tsunami event on 26 December 2004. Despite, sharp declining areas experienced by bare land and aquaculture ponds. The areal coverage of the bare land is declining by 38.48% in 2011~~,~~ and slightly increased by 36.77% in 2017. Similarly, the aquaculture ponds are sharply declining by 37.18% in 2011, and further by 39.47% in 2017 from the initial proportion in 2004 (Fig. 5). Additionally, the sharp declining areal coverage was also experienced by the rice field area, which consistently reached 91% decrease for both years. On the contrary, the areal coverage of the buildings was increasing by 16.28 % in 2011~~,~~ and even further by 18.49 % in 2017 from the initial proportion in 2004. The swamp areas were also consistently increasing by 36.9% and 59.36% in 2011 and 2017, respectively. Interestingly, despite minor occupation at the coastal area, the areal coverage of mangroves shows a remarkable decline of areal coverage in 2011, but subsequently compensated by an increase by 13.83% in 2017, even slightly larger percentage than the areal coverage in the pre-tsunami. Such dynamic implies that there are a certain amount of predominant land covers such as aquaculture ponds, bare land and rice field that experienced significant loss due to the tsunami in 2004 that are not fully recovered after several years, in the expense of buildings area expansion. In addition, some of those aquaculture ponds which were destroyed by the tsunami were abandoned and eventually have become a merely swampy area. The expansion of mangroves in the area after several years post-tsunami may suggest that the effort of mangroves planting projects during the rehabilitation and reconstruction may have been successful to some extent.

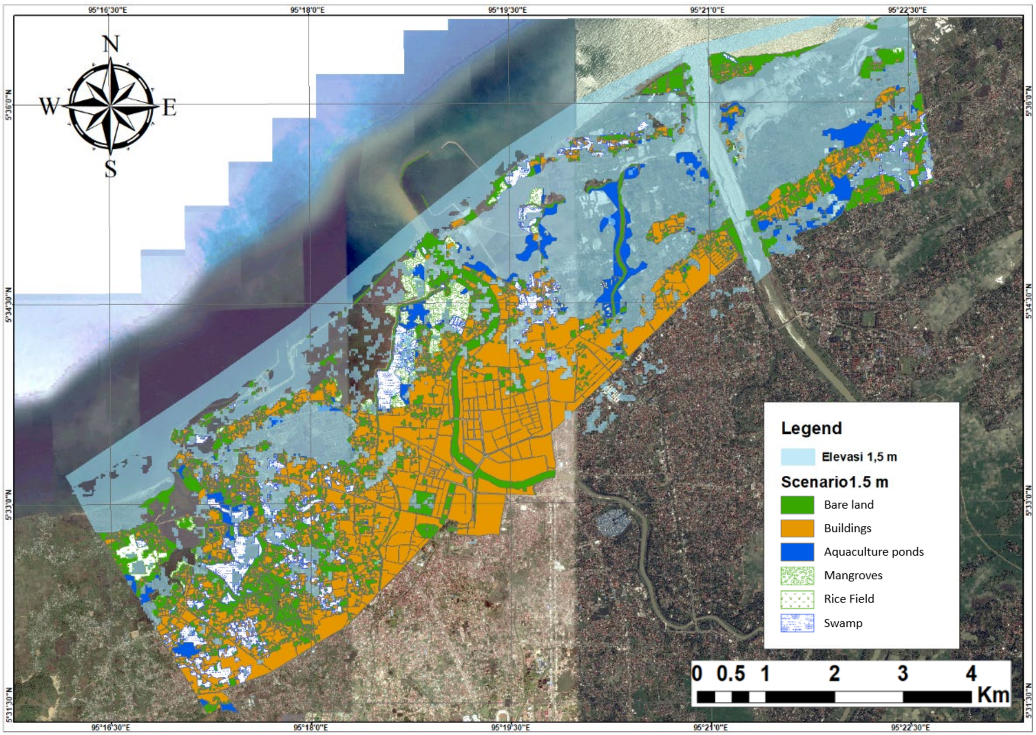
4.2 Scenario of the sea-level rise

As was depicted in Fig. 2, the monthly sea-level fluctuation was plotted by the daily average mean sea-level clearly exhibiting a non-stationary change of sea-level, which actually represents the magnitude and direction of tidal fluctuation occurring in the region. Presumably, the land-level has not changed since the 2004 tsunami (e.g. no local land subsidence or liquefaction), and the tidal range is average less than 1 m (micro tidal area); it is safely assumed that the rate of sea-level rise pre-dominantly eustatic.

If we compare between the consecutive scenarios of sea-level +1.0 m and +1.5 m, the aquaculture ponds area were remarkably declining, not only between the year 2011 to 2017 without any scenario, but more importantly the declining area of aquaculture ponds area due to sea-level arising up to +1.0 m and even further on scenario +1.5 m. Such remarkable changes of typical wetland features (swamp and aquaculture ponds) seem to be the most vulnerable coastal



(a)



(b)

Figure 6. Land cover changes of Banda Aceh coast in 2017 based on two scenarios of sea-level changes. (a) The existing land cover; (b) the land cover with +1.0 m sea-level rise; (c) the land cover with +1.5 m sea-level rise.

Table 2 *Comparable areal coverage of various land cover types at Banda Aceh coast (baseline 2017)*

Land cover type	No scenario		Scenario +1.0 m		Scenario +1.5 m	
	Area	**Percentage**	**Area**	**Percentage**	**Area**	**Percentage**
Buildings	1179	35.12%	1145	34.11%	1067	31.78%
Bare land	963	28.69%	723	21.54%	619	18.44%
Aquaculture ponds	793	23.62%	246	7.33%	171	5.09%
Swamp	298	8.88%	228	6.79%	166	4.94%
Mangroves	107	3.19%	83	2.47%	72	2.14%
Rice Field	17	0.51%	17	0.51%	13	0.39%
Inundation	0	0.00%	915	27.26%	1249	37.21%
Total area	3357	100.00%	3357	100.00%	3357	100.00%

Table 2 displays the comparison of area coverage of various LULC types among scenarios of sea-level rise at the coastal area of Banda Aceh, taking into account the most recent situation; i.e., LULC of 2017, as the baseline of the sea-level rise projection. The results show that in total, the scenario of sea-level rise of +1.0 m and +1.5 m will cause a loss of land as much as 27% and 37%, respectively, in 250 years from 2017. A consistent loss of the wetlands occurred as the excessive impact by the tsunami waves attacks in 2004 as well as by the half-destroyed aquaculture ponds left to be abandoned. This results in a percentage of aquaculture ponds areal coverage plunging from 1310 ha before the tsunami, to merely 823 ha and 793 ha, in respective 2011 and 2017. Based on the scenarios of +1.0 m and +1.5 m, the aquaculture ponds would be severely affected by the sea-water inundation, leaving respectively only 7.33% and 5.09% of the total areal coverage. Adaptations to this impact most likely to consider movement inland of some operations that culture species with acceptable saline tolerance.

On the other hand, learning from the first decade of the post-tsunami recovery in Banda Aceh (e.g. Syamsidik, *et al.*, 2017; Achmad, *et al.*, 2015; Affan, *et al.*, 2015), the trend shows that there is an increase of built environment expansion towards the coastline, despite past tsunami experience. The results of this study confirm~~s~~ these views, that there was an increasing number of buildings after the tsunami, from 2011 to 2017. The results of the spatial analysis for the sea-level rise scenarios of +1.0 m and +1.5 m (see Table 2) reveals that~~,~~ being one of the largest types of LULC, the buildings slightly decrease in numbers. However, if we take into account ~~of~~ the total loss of land by the respective inundation scenarios, then they suggest that the number of buildings was~~ere~~ actually increasing considerably, closer to the coastline. The bare land which apparently has potential to be developed for the settlement area (buildings, housings, etc.) for the current situation, would also potentially suffer from inundation in future, based on both +1.0 m and +1.5 m scenarios (see Table 1, Fig. 6a and 6b).

Overall, the coastal area of Banda Aceh in the next couple of centuries will be highly vulnerable if the current fast-growing and ever-expanding built environment very close to the coastline would still be applied in the future. S~~A s~~ound coastal management to protect the coastal areas which areis still recovering from the massive destruction caused by the past tsunami event, therefore, should be planed properly by taking into account the risk of future slow on-set disaster, particularly the sea-level rise.

5. Conclusions

Banda Aceh coast at the northern tip of Sumatra Island of Indonesia is uniquely representing the coast threatened by both eustatic sea-level rise and seismic-driven tsunamis and land-level changes. Scenarios of how the projected sea-level rise in centennial time scale would inundate the low-lying coastal area are investigated in this study, to understand the potential impact to the dynamic change of LULC at the coastal city, particularly, after being devastated by the tsunami disaster in 2004. The objective of the present study is to investigate the impact of the projected sea-level rise to the coastal land covers encompassing an engineering time-scale, based on a couple of sea-level rise scenarios.

Out of six types of pre-dominant land covers at the studied area, the bare land, aquaculture ponds and buildings are among the top three largest types of LULC occupy the coastal area in Banda Aceh coast. The spatial change detection analysis reveals that in total, the scenario of sea-level rise of +1.0 m and +1.5 m will cause a loss of land as much as 27% and 37%, respectively, in the next couple of centuries from the present. The area of low-lying or wetland has been increasing, by the fact that the destroyed aquaculture ponds due to the tsunami were not all fully recovered, leaving a larger area of the abandoned swamp. Whereas, the bare land at the areas nearest to the coastline has been increasingly converted into settlement areas, which clearly reveals the potential negative impact of the accelerating sea-level rise in future.

Overall, the results of this study imply that the coastal area of Banda Aceh is expected to be more vulnerable in the future centuries. Thus, the impact of the sea-level rise to the LULC at the coastal area should be carefully considered in setting up a new master plan of the coastal city of Banda Aceh, which encompassing a long-term adaptation and mitigation strategies.

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