Sea level rise impact modelling on small islands: case study gili raja island of east java

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Abstract. Coastal regions and small islands are areas that will be adversely affected by the phenomenon of sea level rise globally. In general, Sea Level Rise (SLR) will result in coastal impacts as follows: increased frequency and intensity of floods, changes in ocean currents and widespread intrusion of sea water. This research was conducted in Gili Raja Island of Sumenep Madura. Objectives of this research were to demonstrate the ability of combining remote sensing and GIS method to determine the impact of SLR on a small island and to model its scale using different scenario. GIS based run-up model were performed to estimate and predict the impact of SLR to the island’s area. Three water level scenario (0.5 m, 1.0 m and 1.5 m) were applied. The results showed that in the first scenario 8.73% of the island was flooded by sea water, furthermore in two other scenario the flooded area was increase significantly (15.88% and 22.38%). Keywords : sea level rise, small island, geographic information system

1 Introduction

Sea Level Rise (SLR) is one of the important issues that must be faced by coastal or island countries in the world. Some studies explain that at least 3 factors are considered to be the main cause of SLR. Those factors are: melting ice in both earth’s poles, extreme climatic events and land subsidence. According to the IPCC (International Panel on Climate Change) report, the average global surface temperature increased from 0.3 to 0.6 °C since the late 19th century. Moreover, until 2100 the earth's temperature is expected to rise around 1.4 – 5.8 °C [1]. The global rise of Sea Surface Temperature (SST) lead to melting ice in the North and South Pole of the Earth. As the consequence, there was an increase in sea level. It is estimated from the year 1999 - 2100 sea level could rise around 1.4 - 5.8 meters [2]. Indonesia was predicted to suffer a significant loss of coastal land as the result of SLR’s impact. Using numerical modeling, it was estimated that in 2050 over 30,120 km² of coastal land will be inundated. Moreover, in 2100 the flooded areas were estimated to increase approximately 90,260 km² [3].

The above figures emphasized this natural event needs to be taken into account in all coastal area management activities, as it can have a direct impact on coastline retreat and may disrupt the population's assets and economic development of the region and even lead to

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displacement of populations that inhabit vulnerable areas along the coast [4]. In addition to the SLR threat, several countries in the Pacific have reported the lost of small island areas caused by sea level rise. Therefore, a global awareness should be raised among the scientists and governments to predict the occurrence and impact of SLR events in coastal areas particularly small islands.

Coastal regions are areas with great potential for economic development, but very vulnerable to sea level rise. Many large industries are established in coastal areas because of the transportation access. Developments in coastal areas are then encouraging the growth of the economy in the region. The value of economic losses will be very different for every type land use. The magnitude of the value of economic losses will depend on the level of productivity of the flooded land. The loss of land due to sea level rise, not only cause economic losses but also loss of biodiversity in the region [5].

Sea water run-up model is one way to estimate the impact of Sea Level Rise on coastal areas in the future. Using combination of remote sensing data and Geographic Information System (GIS) methods, distribution and impact of sea level rise can be determined [6]. This research is conducted in Gili Raja Island of Sumenep Region Madura. Some parts of the island have been inundated by sea water during the tide. This phenomenon was suggested to be an indicator of SLR effect on the island. Objectives of this research are to demonstrate the ability of combining remote sensing and GIS method to determine the impact of SLR on a small island and to model its scale using different scenario.

2 Material and Method

Coastal impact models can help determine the vulnerability of areas and populations to changes in sea level. Model outputs may be used to guide decisions about the location and design of future protected areas and development, and to prioritize adaptation of existing protected area investments [7]. A number of studies have been done to develop models of SLR impact on coastal areas. Most of the models were developed using numerical and empirical approach [8,9]. Furthermore, some of the studies incorporate SST and SLR to create Cyclone Prediction Model [10], whereas this research focuses on using GIS model to generate spatial information of SLR impact to a small island. GIS modeling approaches have been widely used to provide spatial information of coastal regions as well as to model the effect of natural and anthropogenic events to the environment. However, specific requirements of data-set have become issues that determine the reliability and validity of the model. This research employed common and generally available spatial data such as land use types and elevation. Land use map of the island was built based on ALOS-AVNIR-2 satellite imagery data.

Land use analysis was performed using Maximum Likelihood Algorithm (MLA) continued by ROI statistical calculation to determine the Separability Index of each land use types. The main assumption of MLA is that the spectral response for each class is normally distributed [10]. Moreover, for an \((m)\) class case, the decision process calculates the probability of a pixel belonging to each of \((m)\) predetermined classes, and the class with the highest probability is assigned to that pixel [11]. The estimated probability density function or Likelihood function for a given class \((wi)\) is calculated as :

\[
p(x; wi) = \frac{1}{(2\pi)^{\frac{n}{2}}} \exp \left[-\frac{1}{2} \frac{(x-\mu_i)^2}{\sigma_i^2}\right]
\]

where, \(x\) is one of the brightness values on the x-axis, \(\mu_i\) is the estimated mean of all the values in the class and \(\sigma_i\) is the estimated variance of all the measurements in this class. In addition, for multispectral satellite imagery data which usually consists of more than one band for a class of interest, assuming the number of bands is \((n)\), then the n-dimensional multivariate normal density function can be calculated as follows:
The multivariate normal density function can be calculated as follows:

\[
p(X; w_i) = \frac{1}{(2\pi)^{n/2}} \exp\left\{-\frac{1}{2}(X - M_i)^T V_i^{-1} (X - M_i)\right\}
\]

where, \((M_i)\) is the mean vector for class \(i\), \((V_i)\) is the covariance matrix for class \(i\), \(|V_i|\) is the determinant of the covariance matrix for class \(i\), \(V_i^{-1}\) is the inverse of the covariance matrix for class \(i\), and \((X - M)^T\) is the transpose of the vector \((X - M)\).

Afterwards, land use types were used to generate Roughness Surface Map [10] as it can be seen in Table 1. Another important data for this analysis was a Digital Elevation Model of island’s surface. This data was obtained from 30x30 meter SRTM images. This image was used to generate a surface contour and slope map which very useful to delineate the boundary of sea water inundation. Furthermore, analysis was continued by modeling of water inundation height (run-up) using mathematical equation as follows [11].

\[
H_{LOSS} = (167n^2/H_o^{1/2}) + 5 \sin S
\]

Explanation: \(H_{LOSS}\) : decrease of water level from original distance
\(n\) : roughness index
\(H_o\) : water level at coastline
\(S\) : Slope

<table>
<thead>
<tr>
<th>No</th>
<th>Types of Land Use</th>
<th>Roughness Coefficients Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Settlements (buildings and houses)</td>
<td>0.080</td>
</tr>
<tr>
<td>2</td>
<td>Mixed Vegetations</td>
<td>0.070</td>
</tr>
<tr>
<td>3</td>
<td>Mangrove Vegetations</td>
<td>0.025</td>
</tr>
<tr>
<td>4</td>
<td>Wasteland</td>
<td>0.015</td>
</tr>
<tr>
<td>5</td>
<td>Fish/Salt Ponds</td>
<td>0.010</td>
</tr>
</tbody>
</table>

**Table 1. Roughness Surface Coefficients**

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**Fig. 1. Data Analysis Flow Chart**
3 Result and Discussion

Gili Raja Island is located in the Madura Strait, south of Sumenep district. Geographic coordinate of the island is 07°13’10.774”S and 113°46’40.345”E. Total area of the island approximately 1,139 Ha, it consists of 4 villages with total population around 15,000 people. Most of the people are fishermen and farmers. In addition, access to the island can be reached from Talango Island which is 11.93 miles away, whereas the nearest island is Gili Genting about 5.30 nautical miles east of the island. The island can be classified as a flat island, elevation ranges from 0-50 meters above sea level. Sandy beaches can be found on the north and east part of the island. Meanwhile, the south and west parts are dominated by rocky beaches. Moreover, traditional salt ponds were also found on the island, located in the north and operated by local communities. Residential areas are distributed on entire island, but mostly concentrated in the south.

Table 2. Land Use Classes of Gili Raja Island

<table>
<thead>
<tr>
<th>No</th>
<th>Types of Land Use</th>
<th>RCI</th>
<th>Total Area (Ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Settlements (buildings and houses)</td>
<td>0.080</td>
<td>178.25</td>
</tr>
<tr>
<td>2</td>
<td>Mixed Vegetations</td>
<td>0.070</td>
<td>232.58</td>
</tr>
<tr>
<td>3</td>
<td>Mangrove Vegetations</td>
<td>0.025</td>
<td>6.49</td>
</tr>
<tr>
<td>4</td>
<td>Empty Lands</td>
<td>0.015</td>
<td>439.88</td>
</tr>
<tr>
<td>5</td>
<td>Fish/Salt Ponds</td>
<td>0.010</td>
<td>281.79</td>
</tr>
</tbody>
</table>

ALOS satellite imagery data in this study was used to identify land use types on island’s surface. Supervised classification method with MLA was employed to group pixels based on their spectral value compared to selected sample areas. As the results, land use types in this island were divided into 5 classes ie settlements (houses and buildings), mixed vegetation cover, mangroves, fish ponds and bare land. Satellite image analysis and land use types calculation showed that most of the Gili Raja island area was dominated by wasteland (38.62%), fish ponds (24.74%), mixed vegetation cover (20.42%), settlements (15.65%) and mangroves (0.57%). The results of overall accuracy was 78.54%, it considered to be acceptable for this study (OA value > 75%). Moreover, Kappa value=0.702 represents probability of 70.2% better accuracy than if the classification resulted from random unsupervised classification instead of using MLA. Table 2 showed the complete results of land use classification of Gili Raja Island. Afterwards, land use classes were converted into roughness surface map based on roughness coefficient index.

Table 3. MLA Results of Gili Raja Land Use Classification

<table>
<thead>
<tr>
<th>Class Name</th>
<th>RT</th>
<th>CT</th>
<th>NC</th>
<th>PA (%)</th>
<th>UA (%)</th>
<th>Kappa Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settlements</td>
<td>102</td>
<td>60</td>
<td>59</td>
<td>58.84</td>
<td>94.17</td>
<td>0.812</td>
</tr>
<tr>
<td>Mixed Vegetations</td>
<td>135</td>
<td>75</td>
<td>65</td>
<td>57.85</td>
<td>77.17</td>
<td>0.739</td>
</tr>
<tr>
<td>Mangrove Vegetations</td>
<td>25</td>
<td>20</td>
<td>18</td>
<td>78.15</td>
<td>85.29</td>
<td>0.837</td>
</tr>
<tr>
<td>Wasteland</td>
<td>55</td>
<td>48</td>
<td>46</td>
<td>87.27</td>
<td>82.58</td>
<td>0.624</td>
</tr>
<tr>
<td>Fish/Salt Ponds</td>
<td>10</td>
<td>8</td>
<td>9</td>
<td>77.12</td>
<td>75.47</td>
<td>0.792</td>
</tr>
</tbody>
</table>

Overall Classification Accuracy : 78.54%
Overall Kappa Value : 0.702

RT : Reference Total; CT : Classified Total; NC : Number Correct
PA : Producer’s Accuracy; UA : User’s Accuracy

Beside land use types of the island, elevation and surface’s slope data are important input to build SLR inundation model. Those data was derived from Digital Elevation Model (DEM) with 30x30 pixel resolution. Analysis results showed that 63.22% of the islands was dominated by low land and flat areas (elevation ranges from 0-17 meters above sea level and slope < 15%). These areas were mostly located in the north side of the island. Whereas higher
and steeper area of the island were located in the south side where elevation ranges from 18-50 meters and slope > 25%. According to this condition, therefore settlements, cultivated areas and fish/salt ponds were concentrated in the north.

Fig. 2. Digital Elevation Model (DEM) of Gili Raja Island

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Furthermore, tide analysis results explain that in the past 10 years there have been gradual increases in water level. In 2006 highest water level during high tide was approximately 1.08 meter, however in 2016 the level was increased and reached around 1.20 meter. It means that in the last 10 years, water level nearby Gili Raja Island has increased around 0.016 meter/year. This result can be used to predict the height of water level in the next 50 years or so. Afterwards, using GIS-based water run-up model combined with cost distance function, flooded area of the island can be estimated at the same period. The prediction results are explained in this following table.

Table 4. Modelling Results

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Year</th>
<th>Highest Tide (m)</th>
<th>Increasing Water Level (m)</th>
<th>Flooded Area (Ha)</th>
<th>% Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2066</td>
<td>2.04</td>
<td>0.8</td>
<td>99.45</td>
<td>8.73</td>
</tr>
<tr>
<td>2</td>
<td>2116</td>
<td>2.84</td>
<td>1.6</td>
<td>180.89</td>
<td>15.88</td>
</tr>
<tr>
<td>3</td>
<td>2166</td>
<td>3.64</td>
<td>2.4</td>
<td>254.89</td>
<td>22.48</td>
</tr>
</tbody>
</table>

As can be seen from the results, predicted inundation on Gili Raja Island is started from the north and west side of the island (Figure 3). The higher sea level rise, the more area will be flooded. This happens because those parts of the island are in the lowlands area. The flood can easily reach a long distance from beach line when it comes to flat area. In addition, as the location has become center of the population settlement, it is estimated that sea level rise will have a serious impact on island’s population. Further analysis by overlaying inundated areas and land use map allows an assessment of the impact of inundation. The results are shown in Table 5.
different than the temporary flooding from storm surge or precipitation. Intermittent flooding of small islands make them vulnerable to SLR and other natural disasters due to climate change in fisheries resources and the loss of island’s biodiversity.

result in flooding of low-lying areas, increased sea water intrusion, coastal erosion, decline but also for settlements. GIS-based run up modeling explain that SLR on small island will obviously damage the coastal environment. Furthermore, scenario 2 predicts more flooded area on the same land use type as the previous one. Inundated areas are increase significantly around 99.45 Ha (8.73%) of the entire island’s area. It is estimated that inundation will cover 180.89% (15.88%). Finally, the same trend continues to happen in the last scenario, where up to 254.89 Ha (22.7%) areas are flooded. It brings damage not only to environment but also for settlements. GIS-based run up modeling explain that SLR on small island will result in flooding of low-lying areas, increased sea water intrusion, coastal erosion, decline in fisheries resources and the loss of island’s biodiversity.

Based on scenario 1, the most vulnerable area are fish/salt ponds and mixed vegetation along the coastline followed by wasteland and mangroves. In total, inundation will cover around 99.45 Ha (8.73%) of the entire island’s area. It is estimated that inundation will obviously damage the coastal environment. Furthermore, scenario 2 predicts more flooded area on the same land use type as the previous one. Inundated areas are increase significantly into 180.89% (15.88%). Finally, the same trend continues to happen in the last scenario, where up to 254.89 Ha (22.7%) areas are flooded. It brings damage not only to environment but also for settlements. GIS-based run up modeling explain that SLR on small island will result in flooding of low-lying areas, increased sea water intrusion, coastal erosion, decline in fisheries resources and the loss of island’s biodiversity.

Climate change is projected to affect small islands, partly by exacerbating natural disasters and partly through more gradual effects such as rising sea level. The characteristics of small islands make them vulnerable to SLR and other natural disasters due to climate change and global warming. In contrast to larger islands or main lands, natural disaster on a small island can lead to a fatal disruption of economic processes, serious impact on environmental and extensive damage to settlements [13]. Permanent flooding from SLR is different than the temporary flooding from storm surge or precipitation. Intermittent flooding

<table>
<thead>
<tr>
<th>Land Use Types</th>
<th>Scenario/ Area (Ha)</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settlements</td>
<td></td>
<td>44.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed Vegetation</td>
<td></td>
<td>33.75</td>
<td>67.97</td>
<td>78.58</td>
</tr>
<tr>
<td>Mangrove</td>
<td></td>
<td>1.98</td>
<td>4.37</td>
<td>5.78</td>
</tr>
<tr>
<td>Wasteland</td>
<td></td>
<td>17.83</td>
<td>42.14</td>
<td>45.28</td>
</tr>
<tr>
<td>Fish/Salt Ponds</td>
<td></td>
<td>45.89</td>
<td>66.41</td>
<td>80.4</td>
</tr>
<tr>
<td>Total Area (Ha)</td>
<td></td>
<td>99.45</td>
<td>180.89</td>
<td>254.89</td>
</tr>
</tbody>
</table>

Based on scenario 1, the most vulnerable area are fish/salt ponds and mixed vegetation along the coastline followed by wasteland and mangroves. In total, inundation will cover around 99.45 Ha (8.73%) of the entire island’s area. It is estimated that inundation will obviously damage the coastal environment. Furthermore, scenario 2 predicts more flooded area on the same land use type as the previous one. Inundated areas are increase significantly into 180.89% (15.88%). Finally, the same trend continues to happen in the last scenario, where up to 254.89 Ha (22.7%) areas are flooded. It brings damage not only to environment but also for settlements. GIS-based run up modeling explain that SLR on small island will result in flooding of low-lying areas, increased sea water intrusion, coastal erosion, decline in fisheries resources and the loss of island’s biodiversity.

Climate change is projected to affect small islands, partly by exacerbating natural disasters and partly through more gradual effects such as rising sea level. The characteristics of small islands make them vulnerable to SLR and other natural disasters due to climate change and global warming. In contrast to larger islands or main lands, natural disaster on a small island can lead to a fatal disruption of economic processes, serious impact on environmental and extensive damage to settlements [13]. Permanent flooding from SLR is different than the temporary flooding from storm surge or precipitation. Intermittent flooding
recedes once a storm passes while SLR flooding is permanent and can be expected to
encroach further inland over time. Sea level rise not only permanently alters the coast line; it
also widens the area vulnerable to storm surge [14]. In addition, as the consequence of SLR,
water shortages and the shrinking of land suitable for agriculture and fish ponds would cause
other social and political disruptions, including forced migration and conflict. Small island
will thus face much larger economic costs from climate change than larger peers. The impact
on important economic sectors (agriculture, tourism and fishing) and pressures on
ecosystems could exacerbate poverty and emigration [15].

Undoubtedly, SLR might cause severe impact on environment and human lives on coastal
and small island areas. Nonetheless, by having prediction and estimation on potential impact
that could occur in the future, preventive and adaptation actions may possibly be taken into
account. Local governments have responsibility to design and provide domestic policies that
can reduce the direct human and economic costs of natural disasters particularly SLR. There
are several recommendations that could be done to protect small island from SLR. Firstly, is
engineering solutions by continually pumping more sand onto beaches or building higher
berms and sea walls around communities and infrastructure. Since building solid construction
surrounding the island will need a large amount of money and its effectiveness is still
questionable, thus this solution seems unlikely to be implemented in Gili Raja Island. The
second solution is to protect the island by restoring mangrove ecosystems. Only a small
portion of Gili Raja Island is covered by mangrove vegetations. Mangrove forest ecosystem
acts as a natural barrier against potential natural disaster such as storm, SLR and tsunami.
Moreover, recent studies revealed the ability of mangrove ecosystems to cope with SLR. It
is interesting to note that the height of the soil surface in mangrove areas is often dynamic,
and in some cases appears to be building up at rates of between one and 10 millimetres every
year. Meanwhile the global mean SLR is currently 3mm per year, meaning that many
mangrove areas build up soil at a rate which keeps pace with the sea. The main reason behind
it is the ability of mangroves to trap sediment as it is carried by rivers, and the work of their
roots beneath the surface [16]. Compare to the previous solution, restoring mangrove and
wetlands needs less money, however it takes more time in order to gain the results.

4 Conclusions

This study explains the usefulness of GIS modeling for coastal disasters prediction and
management. By combining the result of satellite imagery data, DEM and tide analysis, the
inundation map can be produced and the future impact of SLR on island’s surface can be
predicted and calculated. Small island resources and its economic value are important and
beneficial to the regions development. Spatial model using GIS for small island inundation
mapping is considered as an important task to support the management plan of SLR risk
reduction initiatives. It is recommended that to provide protection for the island against SLR,
mangrove rehabilitation should be taken into account.

In order to develop more comprehensive studies in the future, several subjects remain to
be discussed for instance is the issue related to validity or accuracy assessment of the GIS
model. In this study, accuracy assessment was conducted only to the results of image
classification. It is recommended for future study to add accuracy assessments on inundation
map particularly to compare between existing and the predicted condition. Another issue is
the calculation of economic loss due to SLR. This study has demonstrated the ability of GIS
to calculate inundated area based on different land use types. It is therefore suggested that
economic value and productivity per class of land use should also be taken into account for
future studies to gain more comprehensive data analysis in particular economic overview of
the SLR impact on small islands.
References


