

Potential vulnerability implications of coastal inundation due to sea level rise for the coastal zone of Semarang city, Indonesia

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Abstract Sea level rise (SLR) as a result of global warming has an impact on the increasing inundation on the coastal area. Nowadays, Semarang coastal area in Indonesia is already subject to coastal hazard due to tidal inundation and land subsidence. The impact of the inundation is predicted to be even more severe with the scenario of sea level rise. This paper concentrates on the risk assessment to the population, land use, and monetary losses as a result of coastal inundation under enhanced sea level rise. This paper uses the scenario of the depth of inundation to generate coastal inundation model using GIS-Technology. Anticipatory issues including methodology development for hazard assessment would be necessary for Semarang coastal area, and therefore, geo-information technology can be considered as a useful tool to rapidly assess the impact of the coastal hazard and evaluate the economic losses.

Keywords Sea level rise · Inundation model · Vulnerability · GIS · Semarang · Indonesia

Introduction

The Intergovernmental Panel on Climate Change (IPCC) reported that sea level rise (SLR) as a consequence of

global warming is considered one of the most serious problems faced by coastal communities (IPCC 2001). In general, mean sea levels rose 10–25 cm over the last century and are expected to rise about 0.5 m by 2100 (Nicholls and Mimura 1998). The most serious physical impacts of SLR are: (1) coastal erosion, (2) inundation and displacement of wetlands and lowlands, (3) increased coastal storm flooding and damage, and (4) increased salinity of estuaries and aquifers (Barth and Titus 1984). The low-gradient areas such as beach ridges, coastal plains, deltas, mudflats, estuaries, lagoons and bays would be the most suffering areas due to the coastal inundation under enhanced SLR. As it is summarized by Nicholls and Mimura (1998) that assuming there is no human response to SLR, a one meter rise of sea level would cause the loss of about 2,165 Km² of land in the Netherlands and 13,900 Km² of land in Germany, while, in West Africa, an example in Nigeria, 18,000 Km² of land would be subjected to coastal inundation. Meanwhile in Asia, a 1-m scenario of sea level could cause loss of about 29,846 Km² of land in Bangladesh. For Indonesia, the scenario of 60 cm of SLR would subject about 34,000 Km² of land to inundation. Data on the land losses due to SLR in various regions in the world is shown in Table 1.

According to IPCC report (1998) a 30-cm rise of the sea level would increase flood damages by 36–58%. In regions with low elevation the frequency of inundation would increase dramatically. The increased risk of flooding as a result of sea-level rise is greater for small islands, the southern Mediterranean coast, the African Atlantic coast, and the Indian coast (Hoozemans et al. 1993). The effects of SLR would be spatially non-uniform because of the difference in the regional oceanographic responses to global warming and the regional uplift or subsidence of the land surface (Klein and Nicholls 1998). Furthermore,

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Table 1 Land loss due to SLR in various regions in the world (As summarized from various reports by Nicholls and Mimura (1998))

Country	SLR scenario (cm)	Land loss	
		Km ²	%
<i>Europe</i>			
The Netherlands	100	2,165	6.7
Germany	100	13,900	3.9
Poland	100	1,700	0.5
<i>West Africa</i>			
Senegal	100	6,000	3.1
Nigeria	100	18,000	2.0
Benin	100	230	0.2
<i>Asia</i>			
Bangladesh	100	29,846	20.7
India	100	5,763	0.4
Indonesia	60	34,000	1.9
Malaysia	100	7,000	2.1
Pakistan	200	1,700	0.2
Vietnam	100	40,000	12.1

the regional setting and coastal characteristics such as lithology, geomorphology, wave climate, current and storm frequencies (Gornitz 1991) play an important role in response to the effects of SLR.

With its long coastline of about 88,000 Km and more than 17,500 islands, Indonesia is considered to be vulnerable to SLR. Extended coastal inundation would be a serious problem not only to the urban coastal areas such as Jakarta, Semarang and Surabaya, but also for small islands, wetlands and coastal farmland area. The increasing coastal inundation may lead to substantial socio-economic losses such as the loss of coastal structures, damage to buildings and settlements, dislocation of the population, and the loss of the agricultural production. Semarang coastal area in Central Java Province Indonesia is suffering from tidal inundation and land subsidence. With the prediction of regional SLR, the impact is expected to be even worse. This study addresses the risk assessment of coastal inundation under the scenario of SLR in Semarang. This paper concentrates on the effects of extended coastal inundation due to SLR on populations, land use, and the monetary losses analysis.

Study areas and their coastal features

Semarang coastal area is located on the northern part of Central Java Province in Indonesia between latitudes 6°58'S and 110°25'E (Fig. 1). Semarang has a total area of about 373.7 km². Its population of approximately 1.5 million makes it the fifth largest city in Indonesia. Being one of the most important harbors of Central Java

region, the city of Semarang plans to develop and become the center of national development. In the 1990s, the development was more centralized in the northern coastal and low-lying areas, which led to rapid urbanization and environmental problems such as coastal erosion and sedimentation, over-exploitation of ground water resources, land subsidence, and tidal inundation.

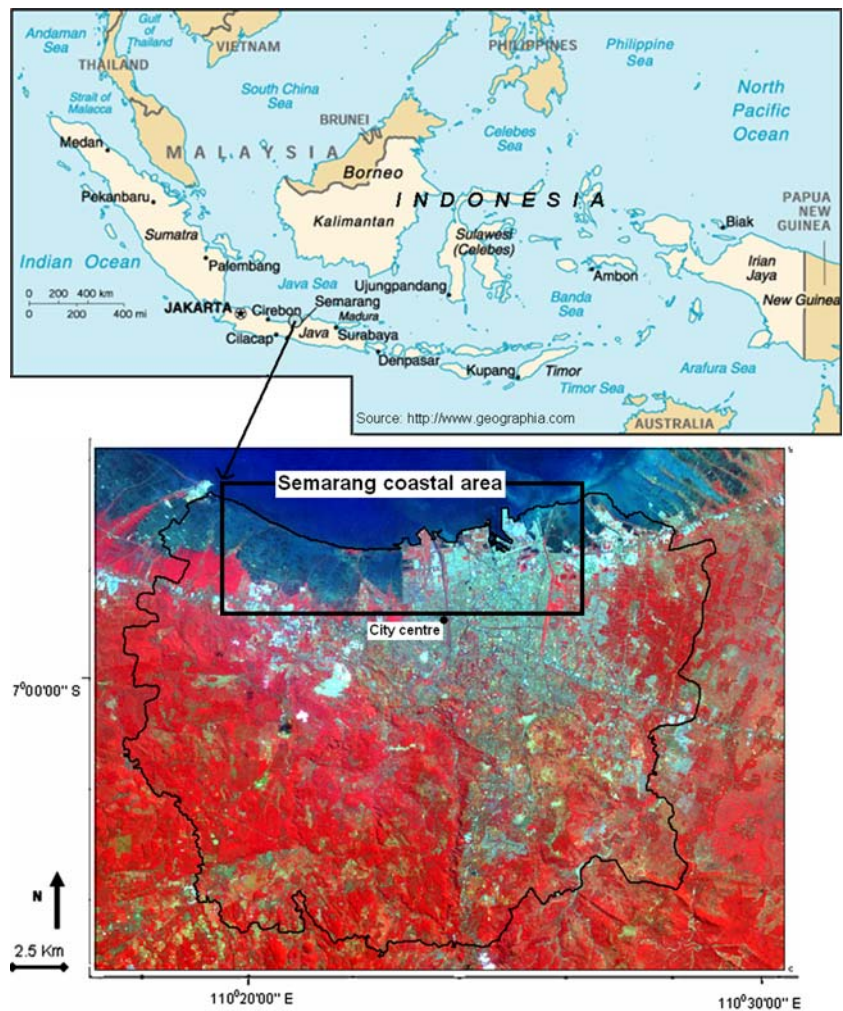
Long time sedimentation process occurs along the Semarang coastline due to sediment supply from rivers, long-shore sediment movement, and dynamic water levels at the coastal area. Moreover, manmade infrastructure such as landfills and reclamation for harbor development, leads to coastal accretion and new beach deposit. The rate of sedimentation along Semarang coast varies from 8 up to 15 m per year (Suhandini 1988). It is on this deposit (coastal sedimentation), where the land subsidence and tidal inundation occurs.

As an important natural resource in Semarang, groundwater provides water supply for the communities and industries. According to the Public Works Department (PWD) (2000) the demand for water supply was 57.28 million m³ per year in 1995 and 75.89 million m³ per year in 2000. Surface water provides the supply of up to 40 million m³ per year. Therefore groundwater extraction is likely to continue until additional surface water supplies are made more available. Groundwater over-extraction leads to the permanent reduction of groundwater level that will be followed by the reduction of pore water pressure. In turn, the loss of water from the soil pore causes the soil consolidation to subside (Purnama 2005).

Land subsidence in Semarang has affected the coastal population and land use. Sinking area is predicted to gradually increase from 362 ha in the year 2010 to 1,377.5 ha in the year 2015 and up to 2,227 ha in the year 2020 (Marfai and King 2007) (Table 2). There are six villages located on the most suffering area of land subsidence in Semarang, and more than 72,000 people living in areas situated below mean sea level (Fig. 2; Table 3). These people are very vulnerable to land subsidence and other types of coastal hazards such as coastal inundation.

Nowadays the height of inundation in the coastal and low-lying area reaches about 40–60 cm from the ground (Soedarsono 1996; Kobayashi 2003). Several steps have been taken to minimize the impact of the inundation and some among these are; dike construction along the drainage system in residential areas, houses and raised-floor reconstruction, construction of pumping station system to pump out the water into drainage channel, and the installation of a pilot project, the polder system for tidal inundation mitigation (Fig. 3). This polder pilot project is expected to protect about 70 ha of area from tidal inundation (Sawarendro 2003). The polder pilot project, unfortunately, has not solved the entire inundation problem

Fig. 1 Semarang coastal area showing the study area location



in the area. The local government is still improving the polder with the installation of supporting infrastructure such as additional drainage systems and pumping stations. This improvement would require an additional financial support of more than €10 million (Statistic of Semarang 2001).

The increase of the inundated areas as per year, and coupled by the estimated and modeled inundation under the scenario of SLR will deteriorate the condition in the near future. It is therefore considered important to assess the vulnerability and potential hazard to Semarang coastal area

Table 2 The prediction of future land subsidence in Semarang (in ha) (Source: Marfai and King 2007)

Year	Elevation below sea level (cm)				Total
	0–50	50–100	100–150	150–200	
2010	328.5	31.5	2.0	–	362.0
2015	1162.0	187.0	25.0	3.5	1377.5
2020	1464.5	607.0	128.0	27.5	2227.0

as a result of land subsidence and tidal inundation under enhanced scenario of SLR.

Methodology

Several methods have been implemented in order to achieve the objectives of the research. As an important data input for this research, Digital Elevation Model (DEM) has been generated using GIS raster technology in ILWIS (Integrated Land and Water Information System) package. Recent ground elevation is affected by land subsidence and therefore requires the DEM to be constantly modified and improved. The coastal land use map has been built based on Ikonos image. The model of the coastal inundation has been generated using neighborhood operation and iteration calculation in GIS-raster environment (Marfai 2003).

Researches pertaining to flood risk assessment using GIS technology have been done by various researchers, for instance by King and Xu (1997), Wang et al. (1999), King and Gemmer (2001), King et al. (2001), and Gemmer (2004). In

Fig. 2 The most suffering area due to land subsidence in Semarang

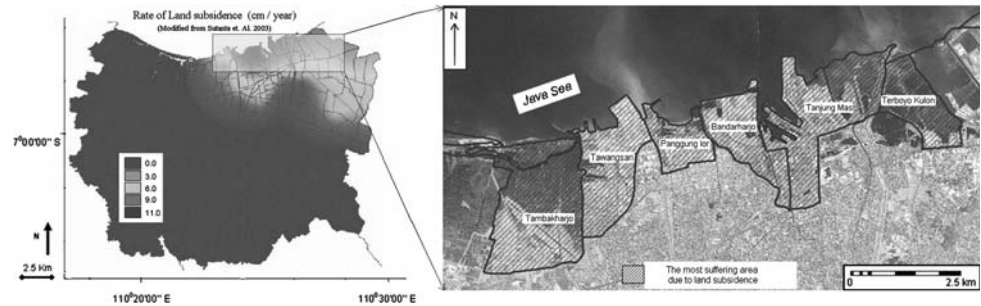


Table 3 People presently living in the most suffering area due to land subsidence (Source: DPB (2000) and Statistic of Semarang (2001))

	Villages						Total
	Tambak-harjo	Tawang-sari	Panggung-lor	Bandar-harjo	Tanjung-mas	Terboyo Kulon	
Population	1,553	5,875	14,295	18,946	28,414	3,820	72,903
Area (ha)	375.8	209.2	123.5	343.0	324.0	285.4	1660.9

Fig. 3 Several actions to minimize the impact of inundation, **a** dikes construction along the drainage system in residential areas, **b** houses and rise floors reconstruction, **c** construction of pumping station system, **d** the installation of a polder system



terms of coastal inundation assessment, several papers by authors such as El-Rey et al. (1999), Mastin and Olsen (2002), Yanli (2002), Kresch et al. (2002), Demerkisen et al. (2006), and Kumar (2006), give an idea for the development of the methodology. In this study, risk assessment of the economic value has been done using the superimpose method between the inundation model, the land use map, and has been calculated using today's value market. The details of the methodology are shown in Fig. 4.

DTM generation

The effort to analyze the impact of the coastal inundation requires data on the land surface elevations (Titus

and Richman 2001). Therefore DEM data on the present research are considered to be the main input for generating coastal inundation. DEM data of Semarang area were generated from a point map containing an elevation data in the ILWIS software using a moving average interpolation method. The DEM data have been updated with regard to the land subsidence phenomenon on the study area. The benchmark data, which were installed in coastal areas for subsidence monitoring have been used as one of the input data for updating DEM. Furthermore, the last update of the DEM was made using additional control points by geodetic and Global Positioning System (GPS) measurement by Sutanta (2002). The benchmark data and GPS recorded point have been adapted on the

DEM data using a map calculation operation in raster GIS.

Building up the coastal land use-GIS data

For the loss estimation model, a spatial distribution of the assets, such as a detail land use map is needed. High-resolution satellite images such as Ikonos in GIS system is used to identify land use classes in order to assess the vulnerable areas and socio-economic impacts. Its applications include both urban and rural mapping of natural resources and of natural disasters. Their high resolution from 1 to 4 m makes the images very valuable for detail coastal land use mapping. Ikonos image for the present study is available in panchromatic with one meter pixel resolution. The image was acquired in the year 2003. To generate the administrative boundary, a 1992 scanned and geo-referenced digital topographic map of the Semarang coastal area in pixel resolution of 5 m and scale of 50,000 has been used.

To build the GIS layers, this study employed the ILWIS, which serves as a remote sensing and GIS software, together with integrated images and thematic data in one unique and powerful package on the desktop. ILWIS delivers a wide range of features including digitizing,

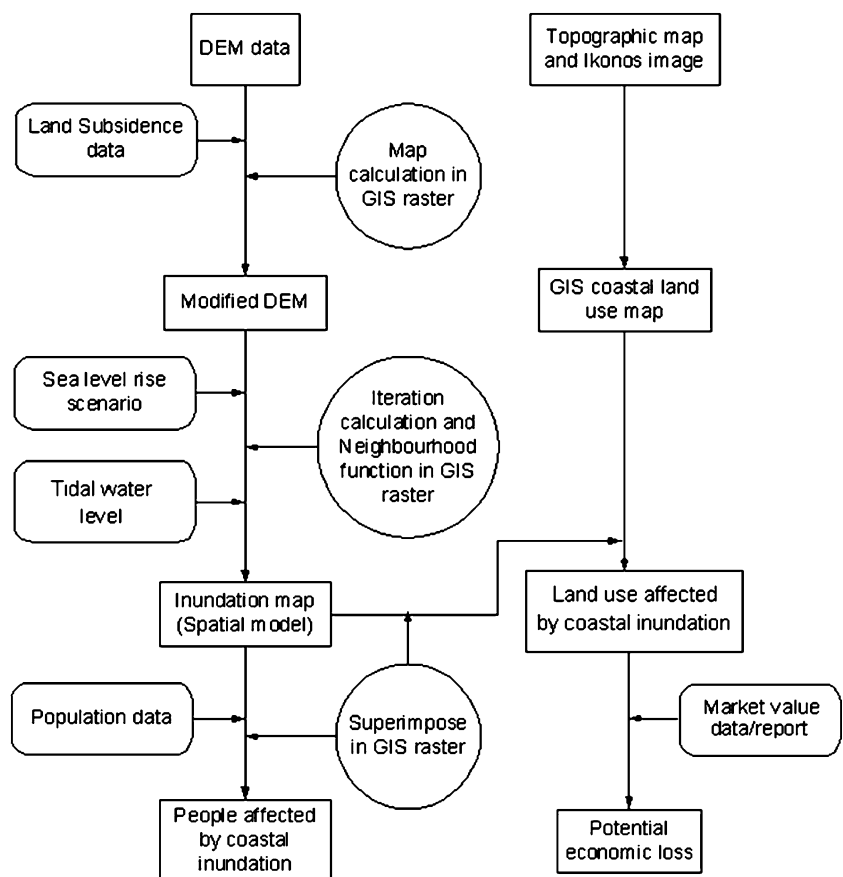
editing, analysis and display of data as well as production of quality maps (ILWIS 2001).

Coastal inundation model

According to Smith and Ward (1998), coastal tidal inundation is defined as flood in low-lying coastal areas caused by high tide, including estuaries and deltas, involving inundation of land by brackish or saline water. In the Semarang case, land subsidence also plays an important role for the extended inundation in the coastal area. Furthermore, under the scenario of sea level rise, coastal inundation would be even worse. The danger of the coastal inundation is associated with a number of different parameters, such as the depth of water, duration, and velocity. In this research, the depth of water parameter has been used to determine the impact of the coastal inundation under enhanced SLR.

Understanding of the consequence of inundation and its spreading on the coastal area requires a model of the inundated area as a result of high water level. For this purpose, geo-information technology has the advantage to model the spatial spreading of the inundation. Using various methods, some researchers such as Thumerer et al. (2000), Bryan et al. (2001), Marfai (2004), and Marfai et al. (2005) have developed the inundation mapping and modeling

Fig. 4 Flowchart methodology



taking advantage of the state-of-the-art GIS technology. In this study, coastal inundation mapping has been constructed based on the scenario of water depth and DEM data using spatial analysis tool in GIS-raster environment.

The inundation model has been generated using different possible scenarios of water depth to represent a range of possible outcomes. The model prediction is projected for the year 2100 based on the sea level rise prediction by Nicholls and Mimura, and the sufficient mitigation actions of land subsidence. Various subsidence rates in the study area cause various depth of inundation. Furthermore, other environmental conditions such as coastal sedimentation and erosion also affect land subsidence and inundation processes. However, to incorporate different subsidence rates and sedimentation process would be exceedingly complex for modeling. Therefore this model has been simplified by using a single value of inundation due to land subsidence based on the Kobayashi result. Other environmental factors are not taken into consideration in this model generation.

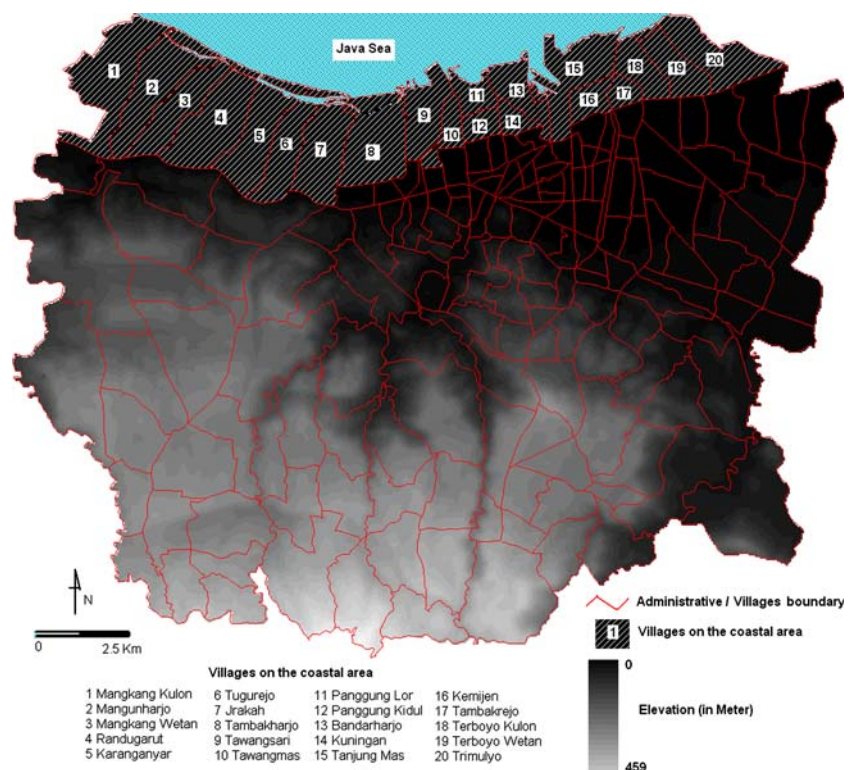
Two different scenarios of water depth have been selected: 120 and 180 cm depth of water for the low and high scenarios, respectively. The low scenario assumes that the continuous measurement for protection of land subsidence is sufficient for the future years. It also assumes that the adaptation actions have been taken to minimize the rise of sea level. Therefore, the depth of inundation for the future years is assumed to remain the same as the recent inundation.

The scenario of 120 cm of inundation, as the sum of the depth of the tidal inundation in recent condition and the regional scenario of SLR, has been used for the low scenario. Meanwhile the high scenario, the worst scenario, assumes that the measurement for protection of land subsidence is not sufficient compared to the rate of the subsidence and that sea level rises to some extent on the low lying area. The inundation as a result of land subsidence would be much higher. It is expected to be twice over the current situation. Simplification has been made to determine the high scenario of 180 cm, as the sum of the regional scenario of SLR and twice over the existing depth of inundation.

Risk assessment

Potential risk assessment has been done for population, land use and its economic value. People affected by coastal inundation were analyzed based on the inundation map and statistical data of the population of certain sub districts. Spatial analysis and table calculation of inundation model and land use map were applied in order to obtain the land use affected by coastal inundation. A single socio-economic scenario based on today's situation has been used for assessing direct monetary losses. However, this risk assessment has not taken into consideration the possible indirect losses as well as intangible damage, such as the increased insurance costs, the loss of personal income and business, reduction in property values, psychological

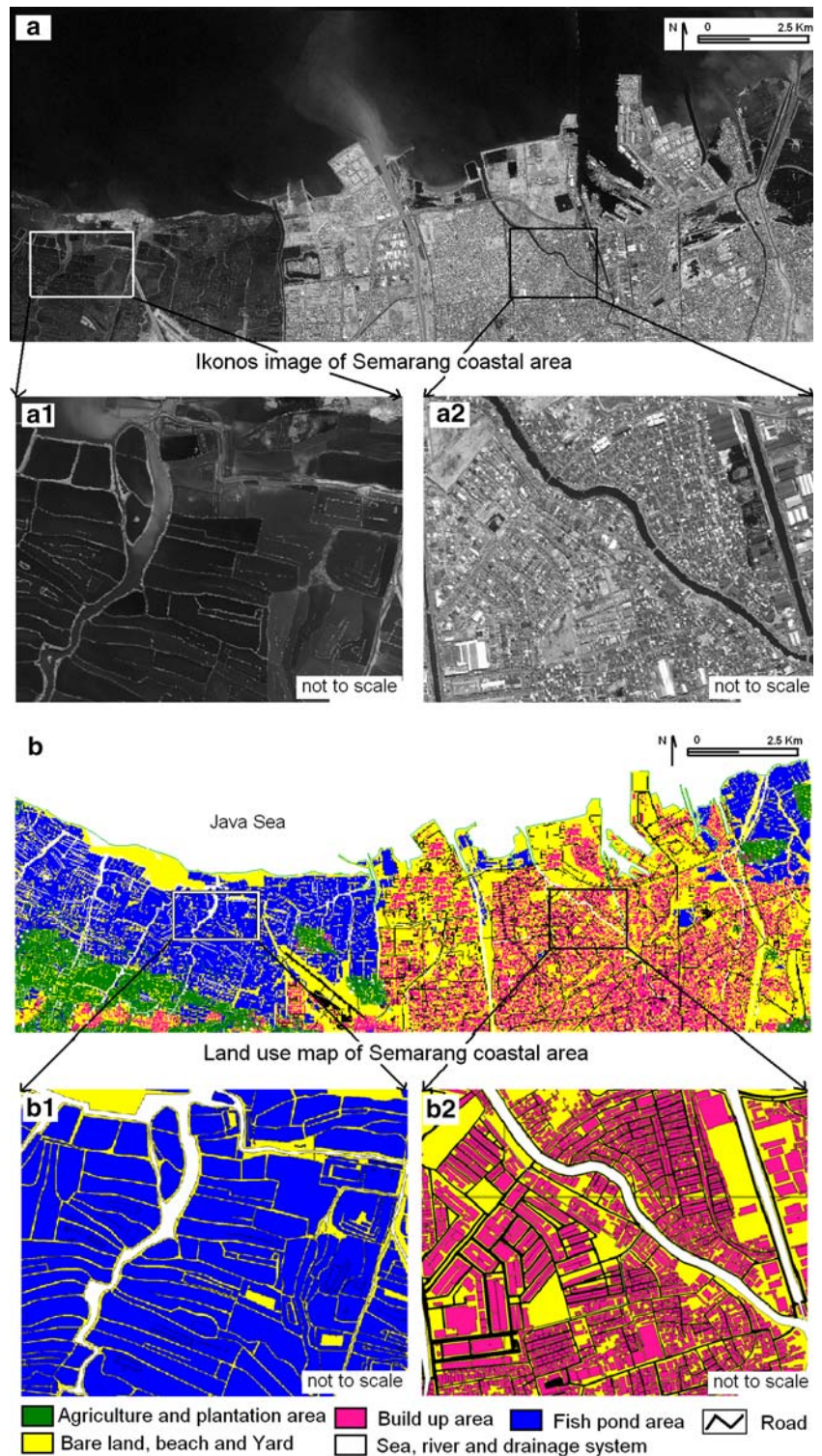
Fig. 5 Administrative boundary and DEM data of the study area



trauma, and disturbance of ecosystem. The land use assets were estimated in a unit value per hectare referring to the government report (DPB 2002) and national report of mitigation of geo-hazards project, a cooperation between Indonesian and Germany Governments (Directorate of Geological and Mining Area Environment/DGME 2004).

The National Coordination Board for Natural Disasters Management and Matters of Refugees-Indonesia (Bakornas PB); Ministry of Home Affairs-Indonesia; Department of Energy and Mineral Resources-Indonesia; Federal Ministry for Economic Co-operation and Development-Germany (BMZ); Federal Institution for Geosciences and Raw

Fig. 6 Ikonos image (A) and land use map (B) of the coastal area of Semarang, (A1) shows the fishpond pattern from Ikonos image, (B1) shows fishpond block in land use map, (A2) shows the build up area pattern from Ikonos image, and (B2) shows the build up block in land use map



materials-Germany (BGR); and German Society for Technical Co-operation (GTZ), are participants in this project.

Results and discussion

GIS layers

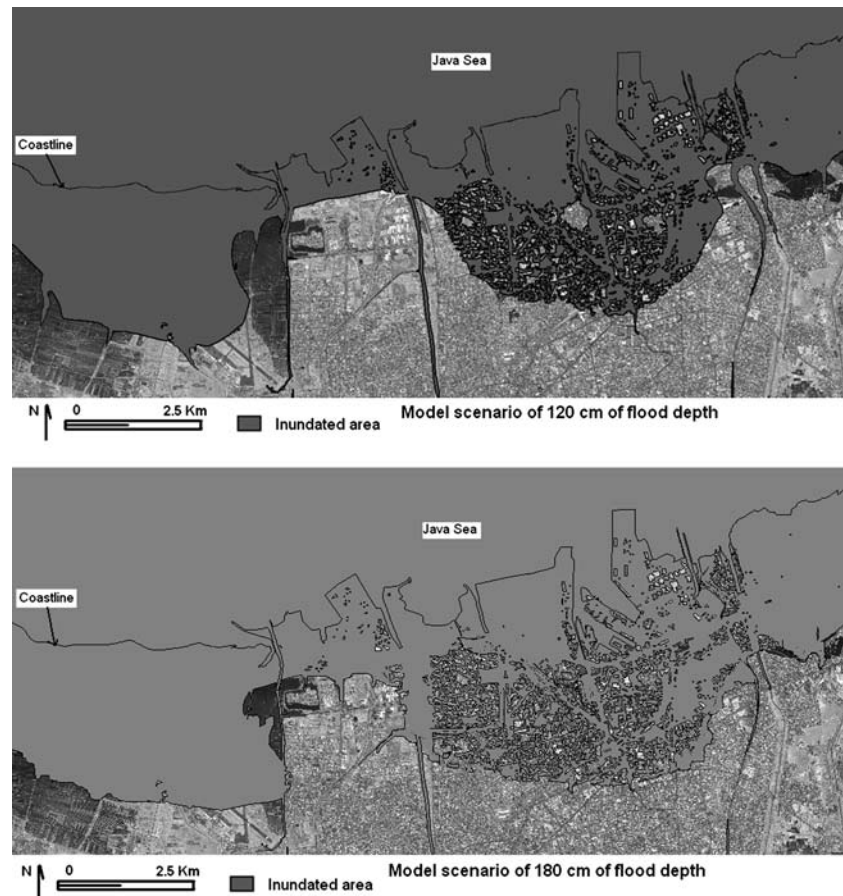
Administrative boundaries including villages' boundary in coastal area have been built based on the topographic map from the year 1992. Meanwhile, the DEM data have been modified based on the subsidence report from PWD (2000) and Sutanta et al. (2003). The administrative boundaries and DEM data are shown in Fig. 5.

Land use data plays an important role in risk assessment. It defines the spatial variable vulnerability or exposure since different land use can be assigned to different economic values. Semarang coastal and low-lying area comprises four types of land use, namely the agricultural and plantation areas; bare land, beach and yard; built up area; and fishpond area. Additional layers such as water bodies and road network have been adjusted on the land use map (Fig. 6).

Inundation encroachment

Coastal inundation encroachment model has been generated based on the DEM data using the neighborhood operation and iterative calculation in GIS raster format. Neighborhood operation, as a spatial analysis tool on the GIS-ILWIS system, has been applied on DEM data in order to calculate the spreading of coastal inundation. This operation makes use of a small computation window (e.g., 3×3 cells) that repeats a specified calculation on every pixel in the map, taking into consideration the values of its neighbors (ILWIS 2001). The neighborhood operation for inundation encroachment model is an iterative procedure. It is a consecutive repetition of a mathematical operation, using the result of one calculation as input for the next. Iterative calculations are performed line-by-line, pixel-by-pixel and take place in all directions on the digital map. Two different scenarios of the depth of water have been applied on the calculation. After completing the iteration, the inundation model is generated and it can be superimposed on the top of the Ikonos image to get an understanding of the affected area (Fig. 7).

Fig. 7 Coastal inundation maps



Potential risk due to coastal inundation

Most of the inhabitants of Semarang live in the city center, which is situated on the elevation between 5 and 10 m above sea level. However, the number of people living in the lower areas such as on the villages near the shore is also significant. There are 20 villages in the coastal area and neighboring the coastline, which are most vulnerable to coastal inundation. The population of the villages varies depending on the distance toward city activities. Villages closer to the city activities such as harbors or center of the city are more densely populated. Table 4 shows the population of the villages on the coastal area. With the assumption of zero-growth population in the future years, more than 148,000 people would be suffering from inundation. The most vulnerable areas are Tanjung Mas, Bandarharjo, Pangung Lor, Kuningan and Kemijen with populations of 28,414; 18,946; 14,295; 13,189; and 13,053 people, respectively.

Overlaying the inundated areas and land-use map allows an assessment of the impact of the inundation. The total land use affected by coastal inundation is shown in Fig. 8. Figure 8 reveals that fishpond area is the most affected area due to coastal inundation. The inundation would have an impact on the fish production and cause disturbance to the ecosystem of water environment. With

Table 4 Population of the villages on the coastal area (Source: DPB (2000) and Statistic of Semarang (2001))

No.	Villages	Population	Area (ha)
1.	Mangkang Kulon	2,886	399.8
2.	Mangunharjo	4,988	347.1
3.	Mangkang Wetan	4,544	347.8
4.	Randugarut	1,442	475.5
5.	Karanganyar	2,557	223.7
6.	Tugurejo	5,202	796.8
7.	Jerakah	2,526	153.4
8.	Tambakharjo	1,553	375.8
9.	Tawang Sari	5,875	209.2
10.	Tawangmas	5,821	249.4
11.	Pangung Lor	14,295	123.5
12.	Pangung Kidul	5,586	68.9
13.	Bandarharjo	18,946	343.0
14.	Kuningan	13,189	41.5
15.	Tanjung Mas	28,414	324.0
16.	Kemijen	13,053	140.9
17.	Tambakrejo	9,327	69.7
18.	Terboyo Kulon	3,820	285.4
19.	Terboyo Wetan	1,168	127.5
20.	Trimulyo	2,956	295.9
Total		148,148	5398.8

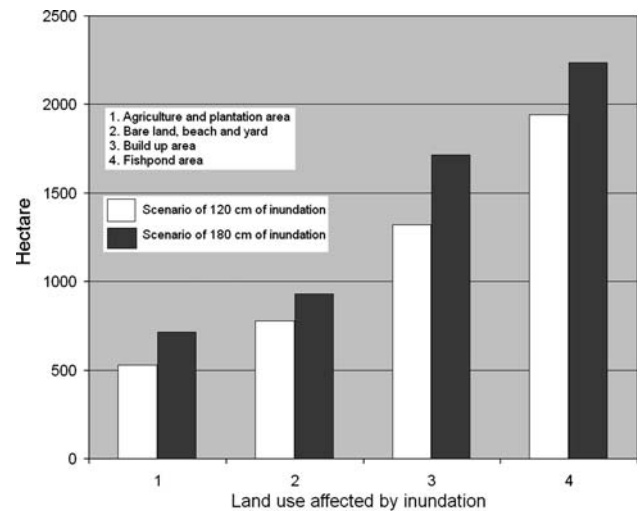


Fig. 8 Land use affected by coastal inundation

the assumption that in the future years the land use pattern would remain the same as the current situation, the total affected area for 120 cm of inundation model is about 527.8, 775.7, 1320.5, and 1943.5 ha for agricultural and plantation areas; bare land, beach and yard; build up area; and fishpond area, respectively. Meanwhile the total affected area for 180 cm of inundation model is about 712.5, 930.8, 1716.6, and 2235.0 Ha for agricultural and plantation areas; bare land, beach and yard; build up area; and fishpond area, respectively.

The GIS inundation model, land use map and the economic value per hectare of the land use have been superimposed to assign economic losses to certain land use types. An estimation of the economic value of the land use that is vulnerable to coastal inundation is shown in Table 5. For each of the land use category, the average price (in Euro/Ha) is indicated. However, the calculation of the economic value in a given year requires an assumption that the price remains the same as the statistical survey data and previous research report from DPB (2002) and DGME (2004).

Agricultural and plantation production including paddy, sweet potato, groundnut, banana, papaya, and other vegetables is one of the economic outputs of Semarang coastal area. Based on the statistical data in survey reports from DPB (2002) and DGME (2004) the value of the product of land use class agriculture and plantation area is about €80,000 per hectare. Recreational activities in the coastal bare land and beaches as well as traditional markets in open spaces and yards would be affected by coastal inundation. The economic activities in these areas would be disturbed causing economic losses due to the inundation in the bare land, beach and yard to the estimated value of €1,700 per hectare. The urban coastal area in Semarang has developed greatly since 1900s. Built up area including

Table 5 Estimation of economic value of land use vulnerable to coastal inundation

Land use	Affected area (ha)		Value in (1,000 EUR/ha)	Total value (Million EUR)	
	120 cm of inundation	180 cm of inundation		120 cm of inundation	180 cm of inundation
Agriculture and plantation area	527.8	712.5	80.0	42.2	57.0
Bare land, beach and yard	775.7	930.8	1.7	1.3	1.6
Build up area	1320.5	1716.6	1200.0	1584.6	2059.9
Fishpond area	1943.5	2335.0	95.0	184.6	212.3
Total	4567.5	5594.9		1812.8	2330.8

settlements and industrial buildings are located on the coastal and low-lying areas. Due to the coastal inundation scenario, this area would be susceptible to the damage values of an estimated €1.2 million per hectare. Meanwhile, aquatic industries such as fishpond cultivation, play important roles for the Semarang coastal area economy. This industry delivers shrimp and fresh fish not only to the local markets but also regional market in Central Java. Fishponds are located on the beach and therefore they would be heavily affected by the coastal inundation. The total value of the fishing activities is about €95,000 per hectare.

Table 5 reveals that total potential economic loss due to the coastal inundation under enhanced SLR is expected to be about €1,812.8 million for 120 cm of inundation and €2,330.8 million for 180 cm of inundation. Coastal residential areas and their communities as well as the potential aquatic cultivation such as fishpond in the Semarang coastal area would become the most vulnerable objects to inundation.

Conclusion

Expected SLR would impact on the vulnerability of the coastal area and become a potential hazard to those areas both physically and socio-economically. A presumed 120 and 180 cm of coastal inundations could diminish the coastal region on Semarang. Broad range of population and land use will suffer from extended coastal inundation due to SLR. Disaster preparedness and mitigation measures at all government levels, such as potential hazard and loss assessment program on the coastal area must also concern the possible impacts of SLR. Land use planning and policy in Semarang urban coastal area including the construction of protective structures such as a polder, drainage system, and dikes as well as the monitoring of the groundwater withdrawal are very significant to minimize the impact of land subsidence and inundation. With regard to the methodology for mitigation plan, this paper gives the preliminary support for the development of the hazard and

vulnerability assessment of Semarang urban coastal area. Geo-information technology is also useful to rapidly assess the impact of the coastal inundation.

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