

Tidal inundation mapping under enhanced land subsidence in Semarang, Central Java Indonesia

Muh Aris Marfai · Lorenz King

Received: 18 October 2006 / Accepted: 13 May 2007 / Published online: 5 September 2007
© Springer Science+Business Media B.V. 2007

Abstract Tidal inundation by high tide under enhanced land subsidence is a damaging phenomenon and a major threat to the Semarang urban area in Indonesia. It impacts on economic activities, as well as the cost of an emergency program and causes interruption of public services, danger of infectious diseases and injury to human lives. This study examines a spatial analysis tool on the GIS-raster system for the tidal inundation mapping based on the subsidence-benchmark data and modified detail digital elevation model. Neighborhood operation and iteration model as a spatial analysis tool have been applied in order to calculate the encroachment of the tidal inundation on the coastal area. The resulting map shows that the tidal flood spreads to the lowland area and causes the inundation of coastal settlement, infrastructure, as well as productive agricultural land, i.e., the fish-pond area. The monitoring of the vulnerable area due to the tidal inundation under the scenario of extended land subsidence plays an important role in long-term coastal zone management in Semarang.

Keywords Land subsidence · Tidal inundation · Neighborhood operation and iteration · Semarang · Indonesia

1 Introduction

Coasts have geomorphologically complex processes that are highly dynamic systems. Many pressures are exerted by physical processes and humans on the coastal area. The physical processes, such as waves, tidal inundation, sea level rise, erosion, sedimentation,

M. A. Marfai (✉) · L. King
Institute of Geography, Justus-Liebig-University, 35390 Giessen, Germany
e-mail: Muh.Marfai@geogr.uni-giessen.de

M. A. Marfai
Geography Faculty, Gadjah Mada University, Yogyakarta 55281, Indonesia

and various weather phenomena play an important role in coastal landscape development. Furthermore, coasts also face many environmental challenges relating to human-induced impacts. A large part of the global population inhabits urban areas near the coast to take advantage of marine and coastal resources. Human development of coastal areas for industrial, residential, and recreational uses contribute to aesthetic problems of land use, reduced natural coastal habitat, and increasing groundwater withdrawal leading to land subsidence.

Natural geomorphic processes are considered hazards when human populations are affected by them. For example, tidal inundation, land subsidence, storms, hurricanes, and tsunamis are natural driving forces of coastal processes and also may cause loss of life and property in coastal communities. The tide, as the regular rising and falling of the ocean's surface resulting from the gravitational attraction exerted on ocean water by the Moon and the Sun has a number of components which are important with regard to natural hazards. According to Hinton (2000), the tidal cycles have an effect on the other coastal processes; the tidal range affects the vertical height of the land interface, whilst the speed of the rise and fall determines the duration of inundation at any given level. This phenomenon is generally called a coastal tidal flood. In other words, a coastal tidal flood is also 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 (Smith and Ward 1998). In many regions and countries tidal floods are the damaging phenomena that affect the social and economic of the population.

Tidal hazards in coastal environment are composed of three parts (Hinton 2000):

- (1) Tidal current, which causes sedimentation along the coast. The speed and direction of currents is important for sediment movement, erosion, deposition, and pollutant dispersal.
- (2) Mixing of fresh-and saline-water when the extent of tides flows up rivers and other watercourses.
- (3) Tidal inundation includes the height of water level, extent of the tidal range and the duration of inundation.

Flood inundation by a high tide and in combination with land subsidence is a major threat for urban communities in Indonesia. Flood from the sea can cause overflow or overtopping of flood-defenses like dikes, as well as flattening of dunes. Land behind the coastal defense may be inundated or undergo damage. Flood inundation by a high tide is frequently observed in the low-lying area of several cities in Indonesia; for example in Semarang the impact of tidal inundation is already noted (Soedarsono 1996; Yusup 1999; Kombaitan 2001; Sutanta 2002; Pinem 2002; Kobayashi 2003; Marfai 2004; Marfai et al. 2005). Land subsidence caused by the withdrawal of ground water for industry and households also contributes to the tidal inundation phenomenon.

In the inundated area several buildings have been abandoned and the infrastructures have been disrupted, such as roads, offices, factories, and commercial sector. In addition, the sea water area extends to the land leading, to the loss of land, and change of the coastline. The total inundated areas of the northern part of Semarang now cover about 1.610 ha extending up to 2 km from the coast (Kobayashi 2003). The damaging effects of flooding also increase in areas where the urban-poor live, because their population density means more waste to clog drains. Furthermore, tidal inundation also gives indirect impact such as cost of emergency program, interruption of public services (communication, electricity, water and gas supply), and danger of infectious diseases such as malaria and yellow fever.

Several measures have been taken to minimize the impact of the tidal flood by the local government and citizens. Among these are: creation of the small dykes along the drainage system in residential areas, excavations to take out sedimentations from the drainage channel, reconstruct houses, rise floors, and build a small barriers in front of the houses to prevent the water from flowing in. Local government of Semarang has installed a system polder-pilot project for tidal inundation mitigation. This pilot project was expected to protect about 70 ha areas from tidal inundation (Sawarendro 2003). However, the polder pilot project has not solved the entire inundation problem in this area. The impacts of the tidal inundation still remain and are illustrated in Fig. 1. Since the inundated areas increase annually, in the future it will be worse when the inundation estimated and modeled under the scenario of sea level rise. This will be a crucial problem for the local government and also the inhabitants.

Understanding the broad-scale ramifications of the increased tidal inundation under enhanced land subsidence requires a map of the land that could be inundated. Producing such maps requires an elevation information and appropriate tools in geo-information technology. Geographic Information Systems (GIS) allow mapping and spatial modeling for natural hazard phenomenon (Table 1). GIS exhibits two main advantages for natural hazards research. First, the technology allows long-term time-series studies and storage of the information. Second, GIS improves information accessibility through digital mapping. GIS can bring together vast amounts of information from a wide variety of sources and make the information quickly visible and applicable in emergency situations. Moreover, advanced spatial analysis in GIS software such as neighborhood and connectivity



Fig. 1 Example of the impacts of the tidal inundation; (a) Tidal inundation on the main road (Kobayashi 2003); (b) Inundated in a house (reach up to 50 cm) (Sawarendro 2003); (c) Permanent inundation on the coastal area and sea water is extending to the land leading to the loss land and change the coastline (dash-dot line was the former coastline); (d) Inundation in front of house causes health problem, e.g., malaria and yellow fever (Marfai et al. 2005)

Table 1 Examples of GIS applications for natural hazards management

Function	Potential applications
Data display	Aid in the analysis of spatial distribution of socio-economic infrastructure and natural hazard phenomena Use of thematic maps to enhance reports and/or presentations Link with other databases for more specific information
Land information storage and retrieval	Filing, maintaining, and updating land-related data (land ownership, previous records of natural events, permissible uses, etc.)
Zone and district management	Maintain and update district maps, such as zoning maps or floodplain maps Determine and enforce adequate land-use regulation and building codes
Site selection	Identification of potential sites for particular uses
Hazard impact assessment	Identification of geographically determined hazard impacts
Development/land suitability modelling	Analysis of the suitability of particular parcels for development

Modified from Levine and Landis (1989) and Department of Regional Development and Environment (DRDE-US) (1991)

calculations allows GIS spatial-encroachment modeling. Neighborhood operations evaluate the characteristics of a specified location and its surrounding area. These GIS-attributes are the reason why they are increasingly being implemented by those charged with the task of managing natural hazards.

This paper presents maps illustrating the coastal inundation area. This study is also intended for examining the digital elevation model (DEM) and GIS-raster environment for tidal inundation mapping in the Semarang coastal area under enhanced land subsidence. All the GIS work include spatial analysis using neighborhood operation and iteration was undertaken on ILWIS software version 3.3.

2 Geographic condition of Semarang

Semarang is positioned at the coordinates of about at 6°58' S and 110°25' E (Fig. 2). It is one of the biggest cities in Indonesia and situated in Central Java. The city of Semarang is planned to grow as a center of national development along with other cities such as Jakarta, Medan, Surabaya, and Denpasar. The hierarchy city planning is very important in redistributing resources including human resources across the country especially since Indonesia is an archipelago. The city consists of 16 subdistricts and covers an area of approximately 373.7 km². Regionally speaking, Semarang can be divided into two major landscapes, namely lowland and coastal area on the northern part with elevations ranging from 0 m to 10 m and a hilly area on the southern part with elevations ranging from 10 m to 453 m above mean sea level. However, a large part of the city center is only around 5 m above sea level. That is one reason why flooding is still a major problem of this city. The city center is situated on the lowland area and it is growing rapidly in line with the increasing population.

According to the Development Planning Board of Semarang (DPB) (2002), the meteorological condition of the Semarang coastal area consists of a temperature range between 25.8°C and 29.3°C with an annual humidity of 62–84% and a mean-annual wind velocity of 5.7 km/h. In the rainy season, rainfall is generally brought about by northwestern humid

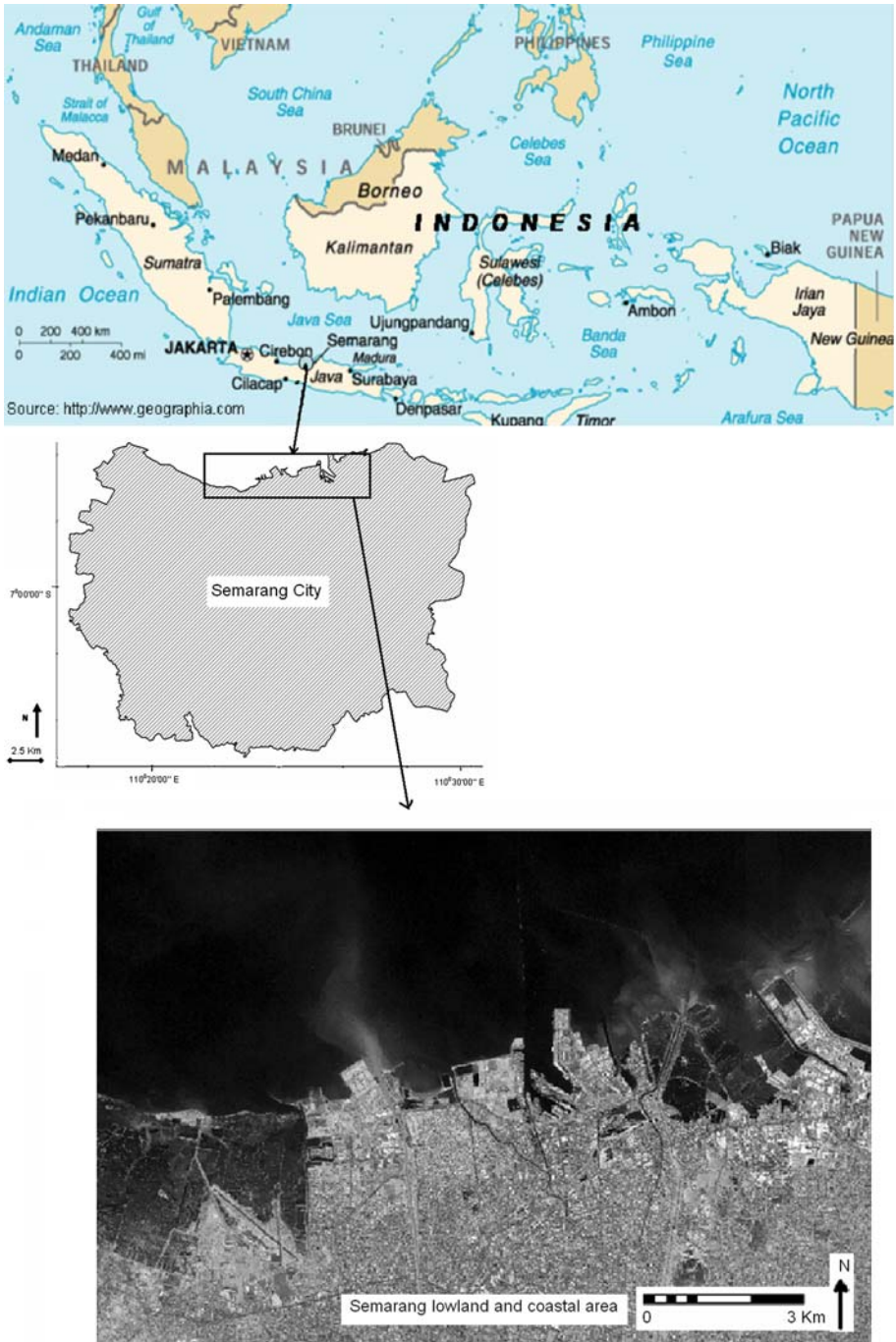


Fig. 2 Location of Semarang coastal area

winds blowing from the Java Sea. Rainfall continues in general for approximately 2–12 h, starting in the afternoon and lasting until midnight. The annual rainfall is about 2,065–2,460 mm and the maximum rainfall occurs in the months of December and January.

The dominant geological materials in Semarang coastal area are sedimentary rock from marine origin and alluvial sediment. Sedimentary rock consists of clay stone and is dominated by sandstone. Alluvial sediment consists of beach deposits formed by clay and sand with a thickness of more than 80 m with the age of the Holocene period (Verstappen 1975). From the geomorphological point of view, this area consists of the alluvial-coastal plain and delta, with intensive erosion and sedimentation (Yusup 1999; DPB 2002; Marfai 2003).

3 Land subsidence phenomenon in Semarang

Semarang has a high potential of groundwater hydrology, especially along the alluvial plain, and limited groundwater discharge on the hilly area. The groundwater resources of Semarang are used for many purposes, such as for domestic needs and industrial estates. Domestic needs are usually operated on the shallow groundwater in the low aquifer at a depth of 10–40 m, and the optimum capacity is about 0.07–1.3 l/s. Shallow extraction in the low aquifer is usually done through dug wells and operated with small-electrical pumps or even buckets by hand. Meanwhile deep extraction on the deep aquifer (more than 40 m) is mostly done by industry and it has a relatively high extraction rate per well. According to Japan International Cooperation Agency (JICA) (2003) exploration of groundwater in providing the water supply in Semarang was about $0.43 \times 10^6 \text{ m}^3$ per year in 1990 and increased to about $35.64 \times 10^6 \text{ m}^3$ per year in 1998. According to the Public Works Department of Semarang (PWD) (2000) there were 670 deep wells used for industrial purposes. Deep groundwater extraction in Semarang started in the early 1900s, and is in line with the population growth. The trend of the groundwater extraction during the past 100 years is shown in Fig. 3.

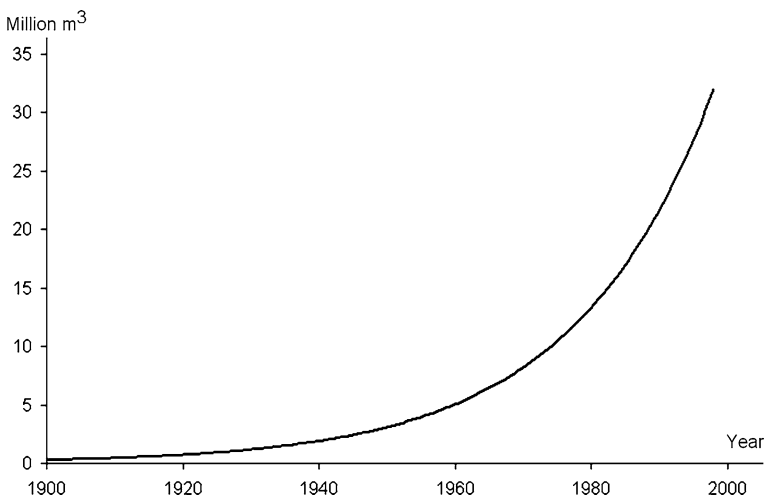


Fig. 3 Rate of groundwater extraction in Semarang during the last 100 years (Marfai and King 2007)

According to PWD (2000) the demand for water supply by Semarang City in 1995 was 57.28 million m³ per year and in 2000 it was 75.89 million m³ per year, and part of the demand, which was about 40 million m³ per year was supplied from surface water. Therefore the amount of groundwater extracted is likely to continue until additional surface water supplies are made to function and connected to the users. The permanent reduction of groundwater level due to the extensive groundwater extraction is followed by the reduction of pore water pressure and loss of water from the soil pores, which causes soil consolidation. However, increased urbanization on the lowland area of Semarang also triggers land subsidence. Due to building loads, particularly on the clayey sediments layer the ground will be lowered from previous elevation. Therefore land subsidence is more likely to be a problem in areas with underlying clay-bearing layers such as those in the coastal area of Semarang.

Since 1983 government agencies have monitored subsidence and implemented several measures to mitigate the problem. Points of reference for a measurement have been installed by city government in Semarang area, both on the hilly and coastal areas with the serial number JP, TTG and BM. However, there was a major issue surrounding benchmark datum and standard of accuracy of field survey data. According to PWD (2000), the reference benchmark needs to be stable and serial number of benchmark TTG-447 (Year 1983 with elevation + 104.987 m) is considered stable as a reference benchmark. Benchmark in Semarang City is presented in Table 2 and Fig. 4. Figure 4 reveals that the subsidence in Semarang City varies: the maximum rate of land subsidence is about 16 cm per year and the minimum is about 1 cm per year. It is also shown that land subsidence mostly occurred at a rate of 2 up to 10 cm per year. In general, the rate of subsidence from benchmark data 1997–2000 is relatively higher than year 1996 and the previous year. It is, however, due to urban growth and increased groundwater extraction.

The map of the subsidence rate has been made using point interpolation based on the benchmark data from PWD (2000) and modified high-spot data using Global Positioning System (GPS) measurement by Sutanta (2002) (Fig. 5). A high-subsidence rate occurs especially along the coastal area and it has resulted in tides moving into low-lying areas that were previously above high-tide level and leading vulnerable areas to tidal inundation (Marfai and King 2007). Therefore several villages along the coastal area are suffering not only from subsidence, but also from tidal inundation. They are, among others, Tambakharjo, Tawang Sari, Panggunlor, Bandarharjo, Tanjung Mas, and Terboyo Kulon (Fig. 6).

4 Improving digital elevation model

Effort to project coastal inundation requires data on land-surface elevations (Titus and Richman 2001). Therefore, DEM in the present research is considered as the main input for the generating of tidal inundation on GIS-raster environment. Since, land subsidence has an impact on the surface elevation of the study area, the DEM data has been updated with regard to the land subsidence phenomenon. Several parts near the coastline are under-sampled with a very-limited number of spot heights and it may affect the DEM result. Therefore, 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, additional control points by geodetic and GPS measurement have been made in the area near the coastline to solve this problem. The last update of the DEM was made using

Table 2 Benchmarks in Semarang City

No	BM no.	Year	Elevation (m)	Elevation in 1996 (m)	Elevation in May 2000 (m)
1	BM 1	Oct 1997	0.593	–	0.415
2	BM 2A	Oct 1997	2.026	–	1.614
3	BM 14	Oct 1997	0.892	–	0.874
4	BM 16	Oct 1997	5.023	–	4.955
5	BM 17A	Oct 1997	2.543	–	2.431
6	BM 19	Oct 1997	2.687	–	2.548
7	BM 20	Oct 1997	3.460	–	3.422
8	BM 21	Oct 1997	4.495	–	4.453
9	BM 22	Oct 1997	7.497	–	7.425
10	BM 23A	Oct 1997	7.017	–	6.982
11	BM 27	Oct 1997	2.387	–	2.248
12	BM 28	Oct 1997	1.549	–	1.370
13	BM 29A	Oct 1997	2.547	–	2.471
14	BM 30	Oct 1997	7.02	–	6.920
15	DTK 000	1991	5.494	5.421	–
16	DTK 008A	1991	20.777	20.743	–
17	DTK 009	1991	7.906	7.860	–
18	DTK 013	1991	5.222	5.117	–
19	DTK 135	1993	3.305	3.232	–
20	DTK 136	1993	1.409	1.288	–
21	DTK 218	1993	1.016	0.915	–
22	DTK 221	1993	1.148	1.002	–
23	DTK 222	1993	1.532	1.358	–
24	DTK 223	1993	2.010	1.834	–
25	DTK 224	1993	2.228	2.085	–
26	JP 1	Oct 1997	0.922	–	0.633
27	JP 2	Oct 1997	1.015	–	0.859
28	JP 3	Oct 1997	0.926	–	0.658
29	JP 4	Oct 1997	0.744	–	0.509
30	JP 5	Oct 1997	2.999	–	2.792
31	JP 6	Oct 1997	0.986	–	0.864
32	JP 8	Oct 1997	2.864	–	2.766
33	JP 10	Oct 1997	7.980	–	7.900
34	TTG-442	Oct 1997	6.338	–	6.283
35	TTG-443	Oct 1997	4.137	–	4.096
36	TTG-446	Oct 1997	4.362	–	4.256
37	TTG-926	1984	1.612	0.640	–
38	TTG-927	Oct 1997	3.234	–	3.039

Datum: Benchmark TTG-447 (Year 1983 with elevation + 104.987 m) is considered stable as a reference benchmark (*Source: PWD 2000*)

geodetic technique and GPS by Sutanta (2002). Furthermore, the adapted values have been put on the DEM data following the drainage network and rivers path. This is referred to as controlled DEM manipulation. The GPS recorded point and the benchmark data has been adapted on the DEM data using map calculation operation in raster GIS (Fig. 7). Further

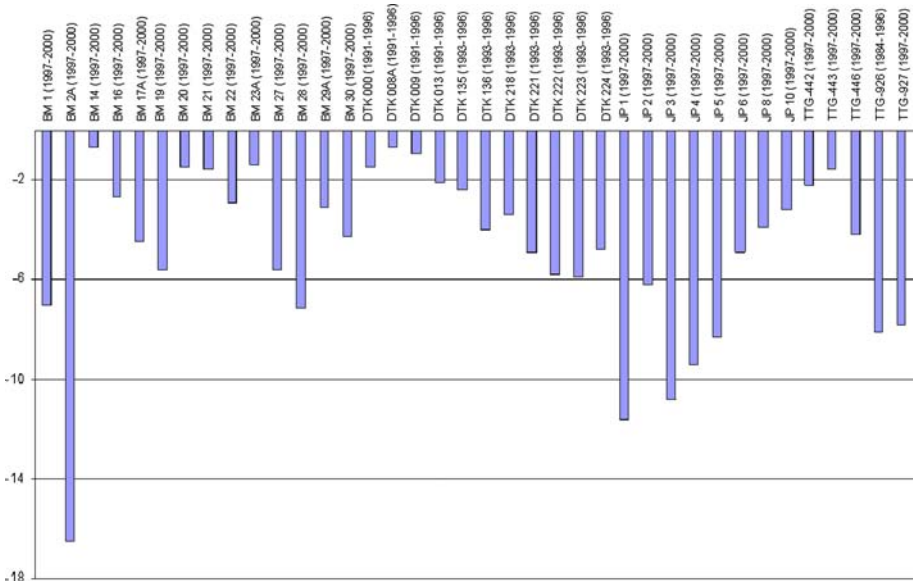


Fig. 4 Rate of subsidence based on the benchmark data

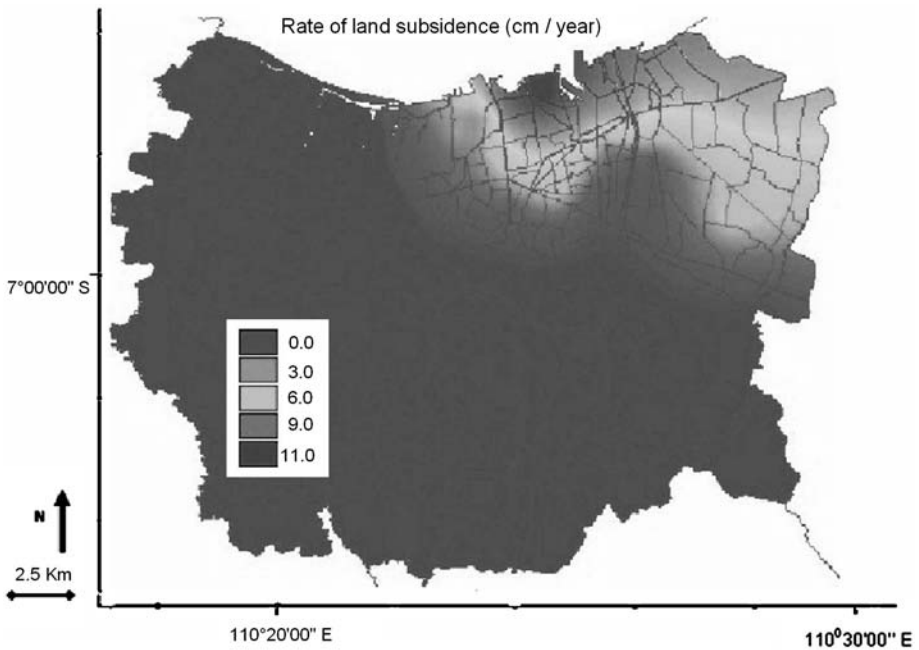


Fig. 5 Rate of subsidence map (modified from Sutanta 2002 and PWD 2000)

assessment has been made in order to evaluate the quality of the DEM by calculating root mean square (RMS) values of the elevation. RMS calculation has been done by Sutanta (2002) using Eq. 1.

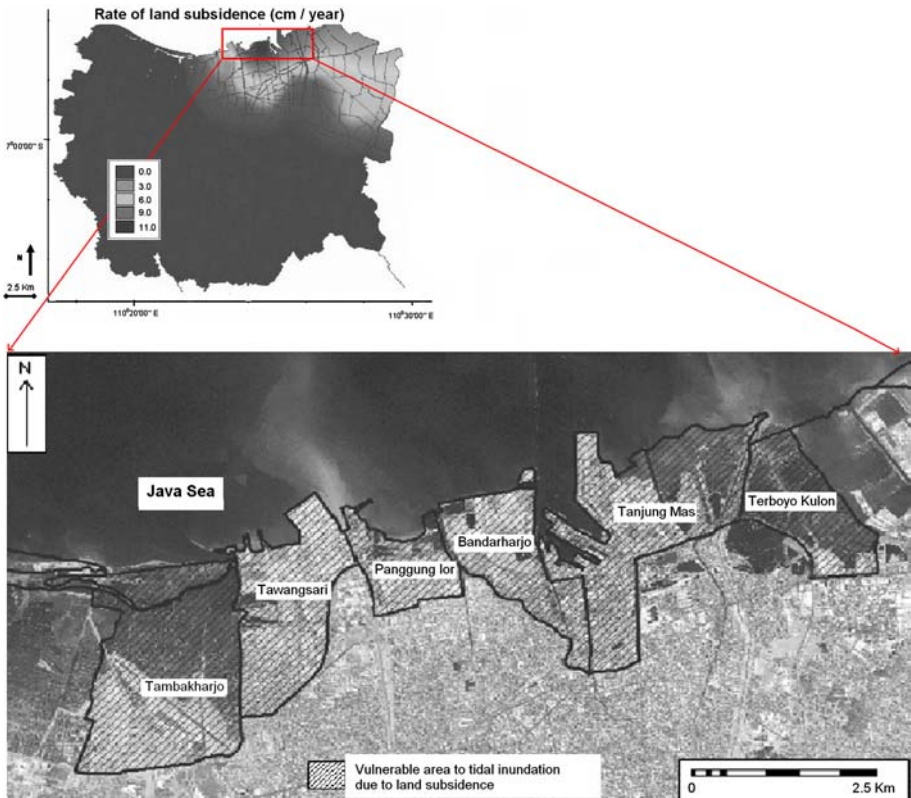


Fig. 6 Vulnerable areas to tidal inundation under enhanced land subsidence

$$RMS = \sqrt{\frac{\sum_{i=1}^n d_i^2}{n}} \tag{1}$$

$$d_i = Z_{ground.i} - Z_{dem.i}$$

where $Z_{ground.i}$ is ground elevation recorded at point i , and $Z_{dem.i}$ is DEM elevation at point i . Based on the RMS calculation, the average differences between DEM and GPS survey measurement for the 52 points is 0.35 m (Fig. 8). This is sufficiently accurate for this study, considering the availability of data.

5 Tidal inundation and their mapping

The tide is the cyclic rising and falling of Earth’s ocean surface caused by the tidal forces of the Moon and the Sun acting on the Earth. Tides cause changes in the depth of the sea, and also produce oscillating currents known as tidal streams. Globally, the height of the high and low tides (relative to mean sea level) varies around the world (Fig. 9). On the coastal area, tides may cause the inundation on the low-lying area.

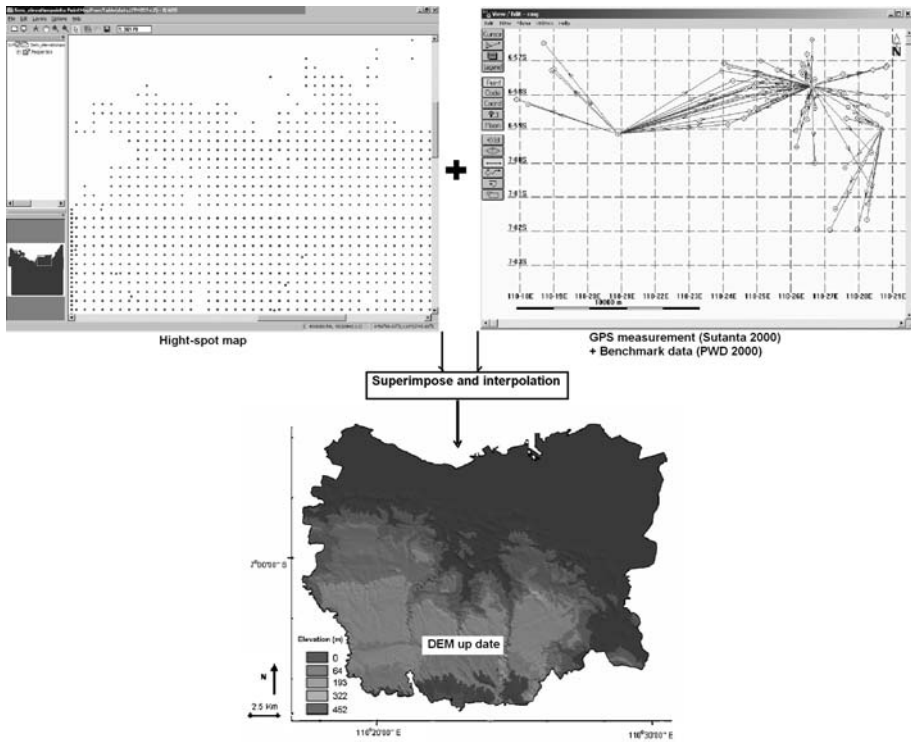


Fig. 7 Schema of the map calculation operation

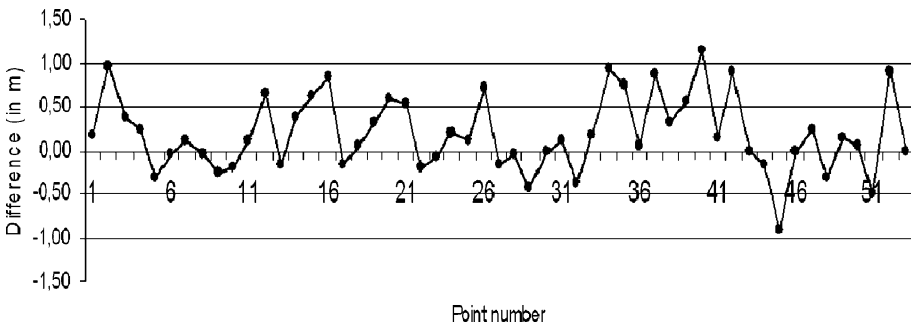


Fig. 8 Difference of value between DEM and GPS measurement (Sutanta 2002)

Tidal inundation, which occurs due to high tides combined with land subsidence, gives rise to a hazard problem at the villages on the coastal area. However, nowadays the impact of the tidal inundation increases in line with the subsidence phenomenon and extending urban size. Unlike the river floods, which occur only during the rainy season, tidal inundation occurs daily with variation depending on the tidal heights.

The waves from the Pacific and Indian Oceans play an important role for the tidal dynamic on the Indonesian waters include the Java Sea (North of Semarang). According to Bird and Ongkosongo (1980), from the north–west moves the wave into the Straits of Malacca (between Malaysia and Sumatra Island), expanding its range and creating strong

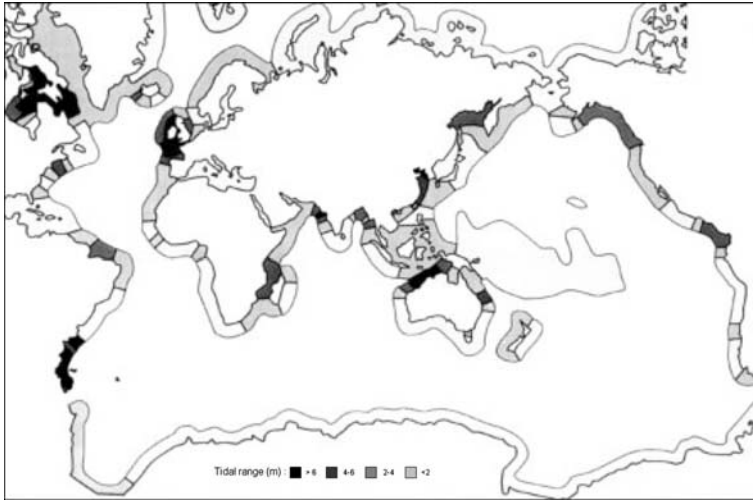


Fig. 9 Spring tidal range around the world (Hinton 2000 after Davies 1972)

currents. Another wave arrives from the South China Sea and produces an interacting system with the Malaccan tides south of Singapore. This tidal dynamic implies spring tide ranges in Indonesian waters. The highest spring tide range occurs on the narrows of the Straits of Macassar (between Kalimantan and Sulawesi Island) for about 3 m, but only a meter or less on the south–west coast of Sumatra. On the north coast of Java they are less than 1 m, but reach up to 1.5 m on the south coast of Java, except in the Straits of Madura (East of Java), which is 1.7 m. On the north coast of Java, pointed on the north of Semarang coastal area, the spring tide range reaches up to 40 cm (Fig. 10).

Understanding the consequence of tidal spreading on the coastal area requires a model of inundated area due to tide water level. In term of GIS environment, the simple model of the real world, such as an inundation area can be represented as a tidal inundation map. Tidal inundation mapping under enhanced land subsidence in Semarang coastal area is considered as an important effort to provide information and valuable data for coastal

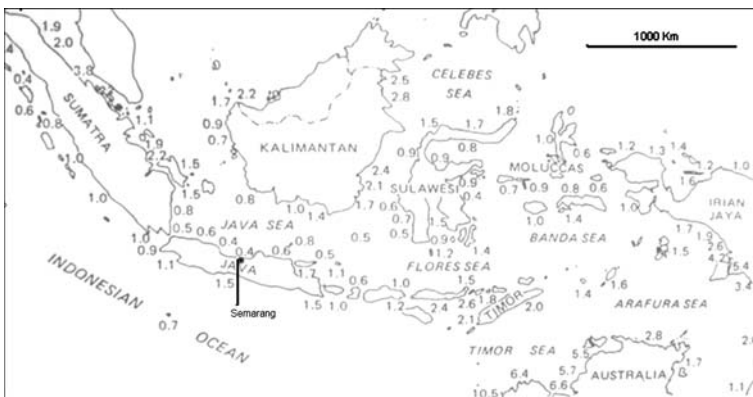


Fig. 10 Spring tidal range (in m) in Indonesian waters (Bird and Ongkosongo 1980)

management. For this purpose, geo-information technology has the advantage of rapidly assessing the combined impact of land subsidence and inundation by water tide on an urban environment. GIS is increasingly being applied on tidal inundation mapping and studies, for instance by Thumerer et al. (2000); Bryan et al. (2001); Mastin and Olsen (2002); Kresch et al. (2002); Marfai (2003). A raster tidal inundation map has been constructed based on the tide height and DEM value. Based on the research conducted by Soedarsono (1996) and Kobayashi (2003), the height of inundation reaches 40–60 cm from the ground. In the present research, simulation of the encroachment area has been done using a scenario of 60 cm, which is a highest tide based on research by Soedarsono and Kobayashi.

Neighborhood operation, as a spatial analysis tool on the GIS-raster system, has been applied on DEM data in order to calculate the spreading of the tidal inundation on the coastal and low-land areas. This operation could be performed on user-selected pixels and on whole maps. The outcome of an operation depends directly on the value of the neighboring pixels. This computation makes use of a small calculation window (e.g., 3×3 cells) that repeats a specified calculation on every pixel on the map, considering the values of its neighbors (ILWIS 2000). The neighborhood function for tidal encroachment computation is an iterative procedure. Iteration is a consecutive repetition of a mathematical operation, using the result of one calculation as input for the next. The calculation stops when the difference of the output compared to the input is insignificant, or if the number of iterations, as defined before is reached. Iterative calculations are performed line-by-line, pixel-by-pixel and take place in all directions on the digital map.

The input map for iteration is called a start map and contains pixels, which act as the starting point of the calculation. The iteration expression defines a certain condition or defines a calculation to be performed. Once the start map has been created, the iteration operation can be done. In ILWIS format, the iteration formula is written down as follows:

$$\text{Iteration result} = \text{MapIterProp}(\text{startmap}, \text{iterexpr}, \text{nr of iterations}) \quad (2)$$

where: Iteration result is the name of the output raster map that will contain the result of the iteration. MapIterProp is the iteration-expression which defines the calculation to be performed. Startmap is the name of the input map which contains one or more pixels acting as the starting point for the calculation. Iterexpr is the iteration-expression which defines the calculation to be performed and nr of iterations is the number of iterations to be performed.

To obtain the tidal inundation area of Semarang, the operation of Eq. 3 has been applied, and to show the example of the gradual step of the spreading of the tidal inundation, the simulations model in Fig. 11 is presented.

$$\text{Inundation map} = \text{MapIterprop}(\text{start.mpr}, \text{iff}(\text{dem} > 0.60, \text{start}, \text{nbmax}(\text{start}\#\#\#)) \quad (3)$$

where: Inundation map is result map, mapIterProp is iteration operation with propagation, start.mpr is the start map for start the iteration, dem is DEM data, number 0.60 is a high tide, and nbmax is return the largest value of the values found by a neighborhood matrix. This means that if the altitude in the DEM (Fig. 11a) is more than 0.60 m, then return the pixel values of raster map start which are undefined (Fig. 11b). Otherwise, assign the maximum value of the neighboring pixels found in raster map start, which is a value of 1 on the result map (Fig. 11c). Since the tidal inundation happens due to the tide wave, the source of the water for the inundation comes only from the sea and therefore the encroachment of the tidal inundation began from the coastline with 0 m elevation, representing 0 value on the first row of Fig. 11a. Those values will be changed into 1 value as

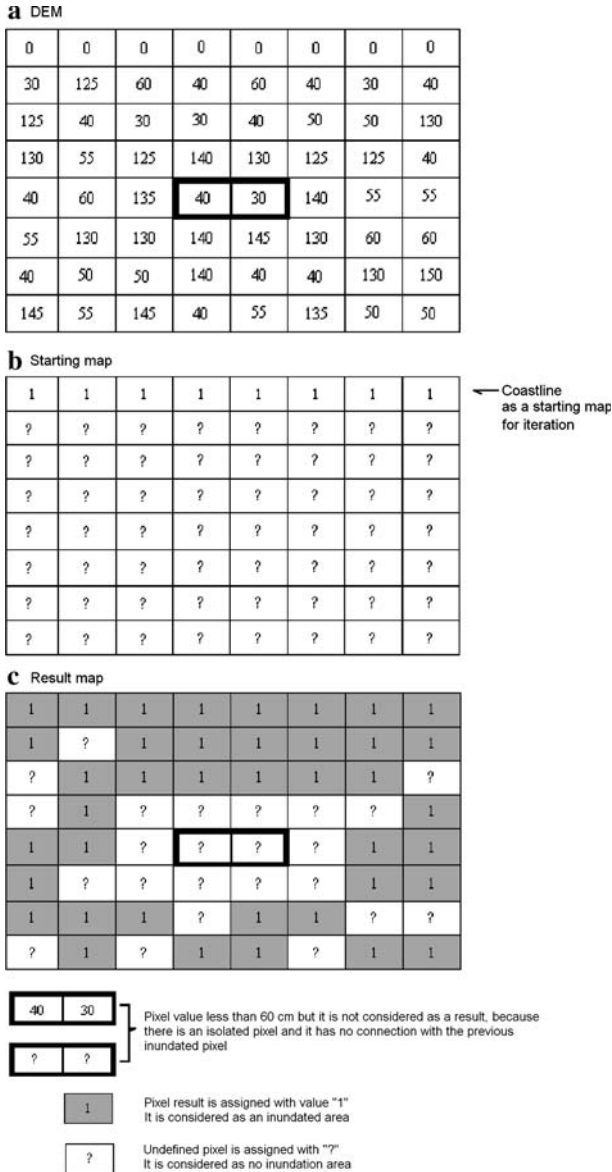


Fig. 11 Illustration of the procedure of the neighborhood operation and iteration

starting pixels (first row of the Fig. 11b). In every iteration, the neighboring pixels that satisfy the condition (altitude < 0.60 m) will get the same value as the starting pixel. This will continue until the next neighboring pixels have an altitude of more than 0.60 m. The program will calculate in a downward, upward, left, and right directions. When no changes occur after a full iteration, the final map is generated.

The result shows that every inundated area (assigned as value 1) has a path and the pixels are connected to each other. This is pointed as a realistic model, where the tidal water spreads to the low area lower than the high-tide range (60 cm) and with a certain

path to reach it. When there are no paths or connection to the previous inundated area, then the area will be isolated and not replaced as an inundated area, even if they have a value of less than 60 cm (see small square box in Fig. 11). Using this model the tidal inundation has been generated and is shown in Fig. 12. The figure also shows the land cover affected by tidal inundation, (see the selected areas A, B, and C). Understanding of the connected water path for the tidal spreading process is illustrated in Fig. 13 and it is clearly shown that all the inundated areas are connected.

6 Conclusions and remarks

Semarang-coastal area has environmental complex processes, such as land use change, land subsidence phenomenon, and tidal inundation. Groundwater withdrawal in the coastal area and the growth of the industrial estate, as well as building-block density are pointed to be the most significant factors that cause subsidence. Therefore, escalated tidal inundation under enhanced land subsidence is a major threat for the Semarang urban communities, and their mapping, as well as vulnerability assessment is considered as an important task to provide information and valuable data for coastal management.

Geographic Information System modeling that is flexible as to scale and time and has become relatively not so costly, is considered as a useful tool for coastal zone management and planning in Semarang. GIS-raster environment provide spatial analysis tool, e.g., neighborhood operation, to develop the spreading model such as a case of inundation. The present model is recognized as a realistic model considering the characteristic of the tidal spreading process. The result map shows that every inundated area has a path and pixels are connected to each other. In

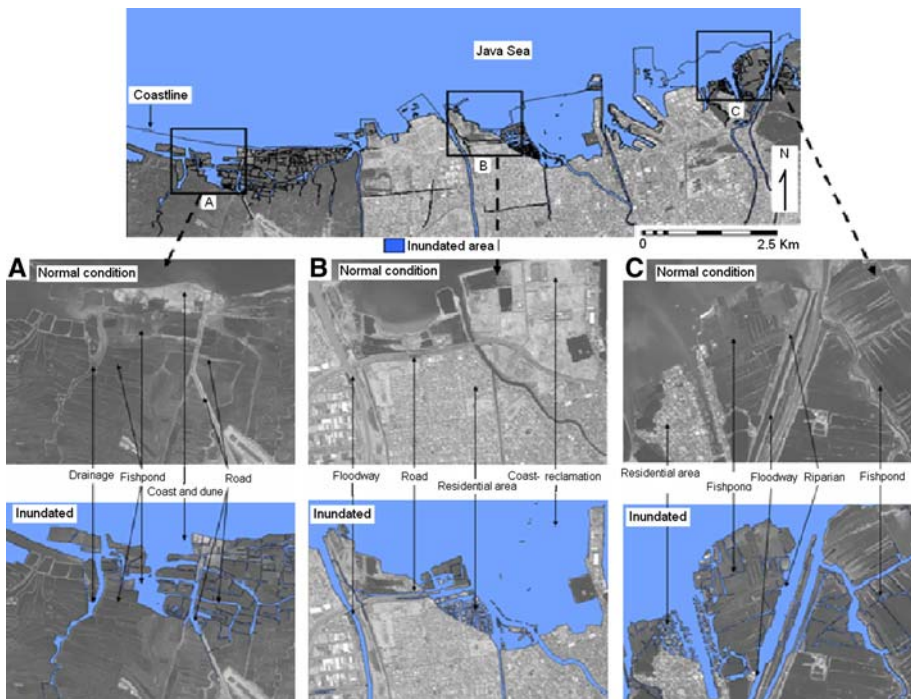


Fig. 12 Tidal inundation on Semarang coastal area

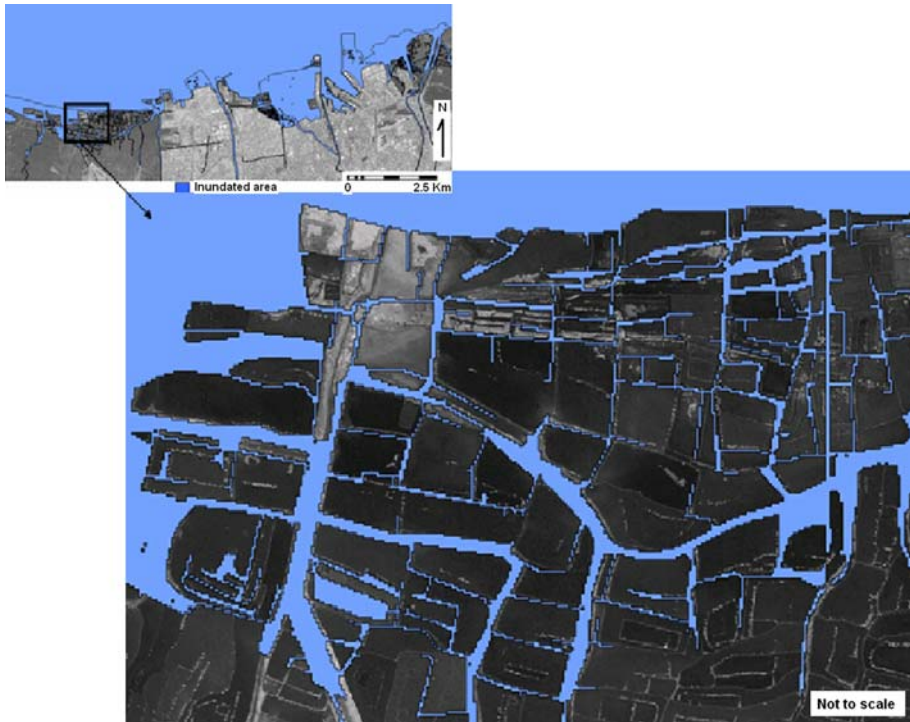


Fig. 13 Path system on tidal encroachment (every pixels on the inundated area are connected)

this case, the GIS-raster tool and mathematic calculation such as iteration is considered as an advantage technique on the geo-information technology to determine the spreading area of tidal inundation. However, field measurement and observation to establishing a more refined understanding of local high-water levels and tidal datum is also needed and suggested in the future work to give a greater attention to the validation of the model.

Multi-year astronomical variation plays also an important role in tidal-cycle analysis. Therefore, it is also suggested for the future work that the lunar nodal cycle and the seasonal variations in the tides El Nino/La Nina cycle should be considered as important input factors for analysis. Coastal vulnerability assessment which takes into account the short-term assessment and the long-term assessment, is important for future coastal zone management in Semarang. The short-term assessment includes identification of the vulnerable area, i.e., due to the coastal erosion, tidal inundation, and storm. The long-term assessment should take into account the monitoring of the vulnerable area due to the tidal inundation under the enhanced scenario of sea level rise and the prediction of extended land subsidence.

Acknowledgements This article derives from research in progress by M.A. Marfai on risk assessment of tidal inundation under the scenarios of sea level rise and land subsidence. This project is being done at the Justus-Liebig-University Giessen, Germany, supported by The German Academic Exchange Service (DAAD). The authors express their gratitude to the reviewers for their helpful advice.

References

Bird ECF, Ongkosongo OSR (1980) Environmental changes on the coasts of Indonesia. United Nations University Press, The United Nations University

- Bryan B, Harvey N, Belerio T, Bourman B (2001) Distributed process modeling for regional assessment of coastal vulnerability to sea level rise. *Environ Model Assess* 6:57–65
- Davies JL (1972) Geographical variation in coastal development. Oliver & Boyd, Edinburgh
- Department of Regional Development and Environment (DRDE-US) (1991) Primer on natural hazard management in integrated regional development planning. <http://www.oas.org/usde/publications/Unit/oea66e/Contents>. Cited 21 Jan 2006
- Development Planning Board of Semarang (DPB) (2002) Semarang City planning 2000–2010. Government of Semarang, Indonesia (In Indonesian)
- Hinton AC (2000) Tidal changes and coastal hazards: past, present and future. *Nat Hazards* 21:173–184
- ILWIS (2000) Integrated land and water information system. Geographic information system. Version 3.1. International Institute for Geo-Information and Earth Observation, ITC, Enschede, The Netherlands
- Japan International Cooperation Agency (JICA) (2003) Master plan on water resources development and feasibility study for urgent flood control and urban drainage in Semarang City and suburbs. Public Works Department, Semarang, Indonesia
- Kobayashi H (2003) Vulnerability assessment and adaptation strategy to sea-level rise in Indonesian coastal urban areas. National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure and Transport, Asahi-1, Tsukuba-city, Japan
- Kombaitan (2001) Sustainable urban coastal planning: searching of frame analysis for the mitigation of the impact of sea level rise (In Indonesia). In: Seminar Proceeding of the impact of sea level rise in Indonesian urban environment, Public Works Department—Indonesia and Building Research Institute—Japan, Bandung, 19–20 March 2001
- Kresch DL, Mastin MC, Olsen TD (2002) Fifty-year flood-inundation maps for Olanchito, Honduras. US Geological Survey, Tacoma, Washington, USA
- Levine J, Landis J (1989) Geographic information systems for local planning. *J Am Plann Assoc* 55(2): 209–220
- Marfai MA (2003) GIS modelling of river and tidal flood hazards in a waterfront city: case study, Semarang City, Central Java, Indonesia. M.Sc. thesis, International Institute for Geo-Information and Earth Observation, ITC, Enschede, The Netherlands
- Marfai MA (2004) Tidal flood hazard assessment: modelling in raster GIS, case in western part of Semarang coastal area. *Indones J Geogr* 36(1):25–38
- Marfai MA, King L (2007) Monitoring land subsidence in Semarang, Indonesia. *Environmental Geology*. DOI 10.1007/s00254-007-0680-3
- Marfai MA, Sudrajat S, Budiani SR, Sartohadi J (2005) Tidal flood risk assessment using iteration model and geographic information system (In Indonesian). The competitive research grants scheme no ID: UGM/PHB/2004. Research Centre, Gadjah Mada University, Yogyakarta, Indonesia
- Mastin MC, Olsen TD (2002) Fifty-year storm-tide flood-inundation maps for Santa de Aqua, Honduras. US Geological Survey, Tacoma, Washington, USA
- Pinem F (2002) The use of aerial photographs for susceptibility mapping of flood hazard in Kali Garang Semarang Central Java (In Indonesian). Undergraduate thesis, Geography Faculty, Gadjah Mada University, Yogyakarta, Indonesia
- PWD (Public Works Department of Semarang) (2000) Semarang urban drainage master plan project. Public Works Department, Semarang, Indonesia
- Sawarendro (2003) System polder management based on community participation. Technical agreement Ministry of Public Works—Indonesia and Ministry of transport public work and water management—Netherlands. Municipality of Semarang
- Smith K, Ward R (1998) Floods: physical processes and human impacts. John Wiley and Sons, Chichester, USA
- Soedarsono (1996) Impact of flood inundation due to sea level rise on settlement area in Semarang City (In Indonesian). Master Thesis, Geography Faculty, Gadjah Mada University, Indonesia
- Sutanta H (2002) Spatial modeling of the impact of land subsidence and sea level rise in a coastal urban setting, case study: Semarang, Central Java, Indonesia. M.Sc. thesis, International Institute for Geo-Information and Earth Observation, ITC, Enschede, The Netherlands
- Thumerer T, Jones AP, Brown D (2000) A GIS based coastal management system for climate change associated flood risk assessment on the east coast of England. *Int J Geogr Inf Sci* 14(3):265–281
- Titus JG, Richman C (2001) Maps of lands vulnerable to sea level rise: modeled elevations along the US Atlantic and Gulf coasts. *Clim Res* 18(3):205–228
- Verstappen H (1975) Landforms and inundations of the lowlands of South-Central Java. *ITC J* 75/4:511–520
- Yusup Y (1999) Study of flood vulnerability and hazard in Semarang area (In Indonesian). Undergraduate Thesis, Geography Faculty, Gadjah Mada University, Yogyakarta, Indonesia