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Insight into the Correlation between Land Subsidence and the Floods in Regions of Indonesia

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Abstract

Land subsidence by definition is the lowering of ground level from certain elevation references. The rates of subsidence can commonly vary between 1 and 20 centimeters per year and even more in certain places. Subsidence produces impacts such as infrastructure damage, problems with drainage, wider expansion of flood water, as well as tidal inundation (flooding by sea water at coastal areas experiencing land subsidence). These impacts are quite costly. All this is disastrous. In a number of regions of Indonesia, land subsidence and negative impacts in the shape of flooding and tidal inundation clearly exist. In Jakarta and Bandung we can see that the subsiding areas close to rivers frequently suffer from flooding. Tidal inundation is a regular feature at subsiding coastal areas such as Jakarta, Blanakan, Semarang, and Demak. Since these negative impacts are clearly formed a disaster while mitigation and or adaptation is still a big homework, in this case for better adaptation and mitigation in the future, understanding deeply the correlation of land subsidence and flooding is necessary as discussed in this chapter. We conclude that the correlation is quite tremendous and indeed producing a disaster.

Keywords: land subsidence, impact, flood, correlation, adaptation and mitigation

1. Introduction

Land subsidence is quite a well-known phenomenon in some regions of Indonesia, especially around urban areas such as Jakarta, Bandung, and Semarang. Rates of about 1–20 centimeters per year can be found at these regions from geodetic measurements such as Global Navigation Satellite System Global Positioning System (GNSS GPS) surveys, InSAR, and leveling. After

some decades a magnitude of 3–4 meters of subsidence has taken place in Jakarta and Bandung, and probably in other unsurveyed areas. The impacts or consequences from land subsidence can be seen in several forms such as infrastructure damage, wider expansion of flood water, as well as tidal inundation (flooding by sea water at coastal areas experiencing land subsidence).

In certain regions of Indonesia, the impact of land subsidence in the form of flooding and tidal inundation clearly exists. In Jakarta and Bandung we can see that the areas close to rivers, which suffer significant subsidence, are frequently being flooded. Tidal inundation is also a regular feature in the coastal areas of Jakarta, Blanakan, Semarang, and Demak, which are also experiencing large magnitudes of subsidence. This is inevitable when lowland coastal areas are lower than the level of the sea after experiencing subsidence; this leads to sea water flooding these areas.

This chapter will explain in detail the impact of land subsidence on flooding (in other words, the correlation of land subsidence and flooding) in regions of Indonesia. The way this is achieved is mostly descriptive using available data. Nevertheless, descriptive datasets would provide new insights into what is going on in these regions regarding the correlation, and will hopefully give a detailed understanding of these two phenomena so one can better adapt to or mitigate these disastrous situations. These impacts also give rise to the future risk of global climate change and its consequences.

2. Land subsidence and its impacts

Land subsidence by definition is a lowering of the ground level from a reference height system such as geoids or the level of the sea. The rates of subsidence can commonly vary between 1 and 20 centimeters per year and even more in some places. Over decades a magnitude of 4 to even 10 meters of subsidence can be found in some places in the world [1–9]. Capital or big cities, industrial areas, peatland areas, oil and gas fields, geothermal fields, and underground mining areas are the most common places where significant land subsidence may occur.

Geodetic measurements such as GNSS GPS surveys, InSAR, and leveling can reveal the rate and magnitude of land subsidence accurately. Other geotechnical approaches also commonly used are the extensometer and tilting measurement. **Figure 1** shows how to monitor subsidence using GNSS GPS and InSAR survey methods, while **Figure 2** illustrates the use of GPS data acquisition in the field. With GPS, several points, which are placed on the media (e.g. benchmarks) covering the area of investigation, are accurately positioned using GPS survey relative to a certain reference (stable) point. The precise coordinates of the benchmarks are periodically or continuously determined. By simply evaluating the rate of changes of the height coordinates from time to time, subsidence characteristics can be revealed. With InSAR, by using two or more synthetic aperture radar (SAR) images of an area, surface movements over time can be identified. The phase signal of InSAR records information on the distance between the satellite and the Earth's surface. By differential InSAR, where we use two SAR images of the same area acquired at different times, subsidence can be revealed if the distance between the ground and the satellite has changed.

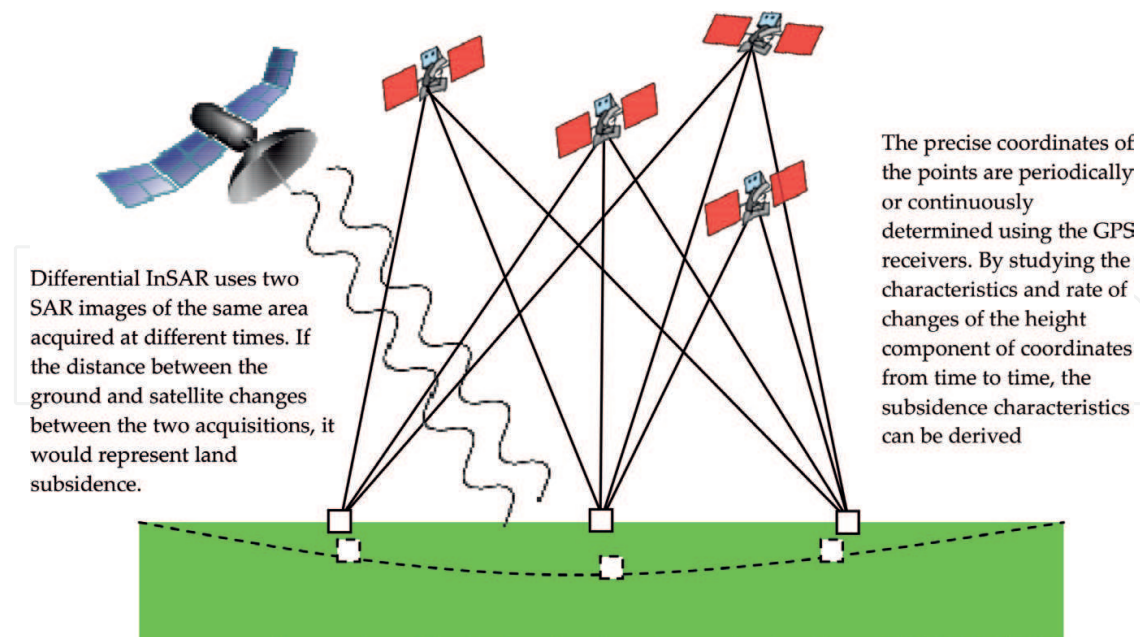


Figure 1. Principle of monitoring land subsidence by geodetic measurements (source: authors).



Figure 2. Field survey GPS observation to derive land subsidence (source: authors).

Infrastructure and building cracks, problems with drainage, the wider expansion of flooding areas, and tidal inundation as mentioned earlier are several impacts from subsidence (**Figure 3**). Surprisingly, many capital cities in the world (e.g. Jakarta, Tokyo, Osaka, Venice, Bangkok, and Ho Chi Mien) have suffered from land subsidence. The consumption of huge amounts of groundwater has led each city to subside significantly over many decades [1, 5–8, 10, 11]. Increased stress followed by compaction in an aquifer will result in subsidence of the surface of the ground. Some research has concluded that impact or the consequence of land subsidence is a disaster that takes place over time. However, over time impacts such as cracks on infrastructure or floods are worsening and will result in a real disaster. These infrastuctural cracks will eventually become a real danger. Road or bridge damage can be a danger for transport. The wider expansion of flooded areas is also due to continuing subsidence. Economically, huge amounts of money are needed to fix the problems of land subsidence.

In many places, short-term measures have been created to mitigate these disasters such as building temporary dykes, fixing or elevating roads, repairing houses and land, including



Figure 3. Example of documentation of the impact of subsidence such as cracks in buildings and infrastructures, and tidal inundation (sources: [12, 13]).

building up mangrove areas. Long-term measures include either building giant sea walls around some coastal areas or stopping land subsidence. Giant sea walls are recognized in places such as New Orleans, Tokyo, and Osaka.

3. Land subsidence in regions of Indonesia

Indonesia is shaped from the interaction of several major plates (e.g. Australia and Eurasia). As a consequence, Indonesia has many sediment areas. Flat sediment areas are the best places for urban and city development, especially around coastal sediment areas. Jakarta and Semarang are examples of coastal sediment cities in Indonesia. Interestingly, sediment areas are places where land subsidence generally exists. Based on our investigation of at least 17 sediment areas in Indonesia, cities, farms, fishpond areas, or peatlands, these regions are experiencing land subsidence with rates varying between 1 and 20 centimeters per year [3–5, 8, 9, 12, 14, 15] (**Figure 4** and **Table 1**).

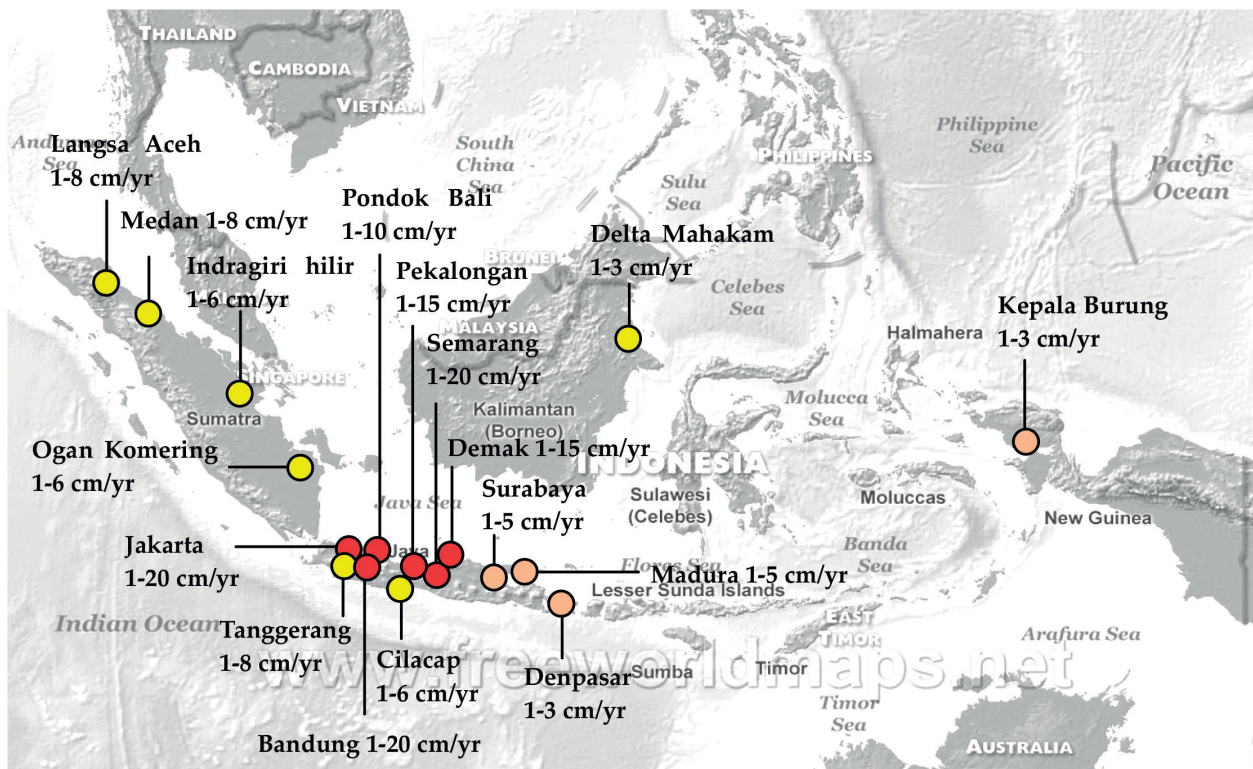


Figure 4. Places of land subsidence in Indonesian regions (sources: [3–5, 8, 9, 12, 14, 15]).

Jakarta city is a well-known place for land subsidence in Indonesia. According to some publications (e.g. [3, 5, 8]) the rates of subsidence in Jakarta generally range from 1 to 10 centimeters per year and may reach 20–26 centimeters in certain places, especially in the northern part of the city (**Figure 5**). Subsidence will continue since mitigation is beyond the priority program. The linear trend of subsidence can be seen as an indicator.

Bandung is another well-known city for land subsidence in Indonesia. According to some publications (e.g. [2, 3, 8, 14]) the yearly amount of Bandung's subsidence generally ranges from 1 to 20 centimeters per year. The highest rate existed around Cimahi district in the north-western part of the city (**Figure 5**). Generally, a linear trend can be seen, which means that subsidence may continue for quite sometime.

Semarang is also quite well known for land subsidence in Indonesia. According to some reports, subsidence in Semarang has been predicted to continue for more than 100 years. Based on some publications (e.g. [8, 9]) the yearly amount of Semarang's subsidence generally ranges from 1 to 17 centimeters per year, and in certain places, especially in the northeastern part of Semarang, it may reach 20 centimeters (**Figure 5**).

Excessive groundwater extraction in combination with natural compaction of sediments and probably tectonic deformation, land setting/reclamation, loading from the construction of new buildings, oil and gas extraction, underground mining, drainage of peatlands, etc. are considered possible causes of land subsidence in regions of Indonesia, including Jakarta, Bandung, and Semarang.

The consequences of land subsidence in Jakarta, Bandung, Semarang, and other places in Indonesia can be seen in several forms such as cracking of buildings and infrastructures,

Regions	Rate subsidence (cm/year)	Notes
1. Langsa Aceh	1–8	Possible main cause oil and gas extraction
2. Medan	1–8	Possible main cause groundwater extraction
3. Indragiri Hilir	1–6	Possible main cause peatland draining
4. Ogan Komering	1–6	Possible main cause peatland draining
5. Tangerang	1–8	Possible main cause groundwater extraction
6. Jakarta	1–20	Possible main causes groundwater extraction and load of building
7. Bandung	1–20	Possible main cause groundwater extraction
8. Pondok Bali	1–10	Possible main cause oil and gas extraction
9. Cilacap	1–6	Possible main cause oil extraction
10. Pekalongan	1–15	Possible main cause groundwater extraction
11. Semarang	1–20	Possible main causes groundwater extraction and land reclaimed
12. Demak	1–15	Possible main cause groundwater extraction
13. Surabaya	1–5	Possible main cause groundwater extraction
14. Madura	1–6	Possible main cause oil and gas extraction
15. Denpasar	1–3	Possible main cause groundwater extraction
16. Delta Mahakam	1–3	Possible main cause oil and gas extraction
17. Kepala Burung	1–3	Possible main cause gas extraction

(Sources: [3–5, 8, 9, 12, 14, 15]).

Table 1. Land subsidence information in Indonesian regions.

problems with drainage, the wider expansion of flooding areas, tidal inundation, and increased inland sea water intrusion (**Figures 6 and 7**). The coastal area of Semarang city regularly suffers from tidal inundation at high tide. The same situation was happening in Jakarta before the sea dyke was established. Within this chapter we will look at the impact of land subsidence in the shape of flooding, including its wider expansion. More specifically, we will see how they are significantly correlated with each other in deriving disaster.

The consequences of land subsidence in the affected areas also badly influence the quality and amenity of the living environment, e.g., sanitation and public health. Indeed, some villagers in coastal areas have been evacuated from their homes due to permanent land sinking into the sea. The dispute as to who is responsible for these impacts is ongoing. People are spending their own money to stem these impacts, while the government is spending money on elevating roads and bridges, road repairs, and other consequences of subsidence. It is possible that there are some who contribute to subsidence along with its consequences and they should be responsible for compensating for any damage. Nevertheless, the government should have overall responsibility regarding any disaster.

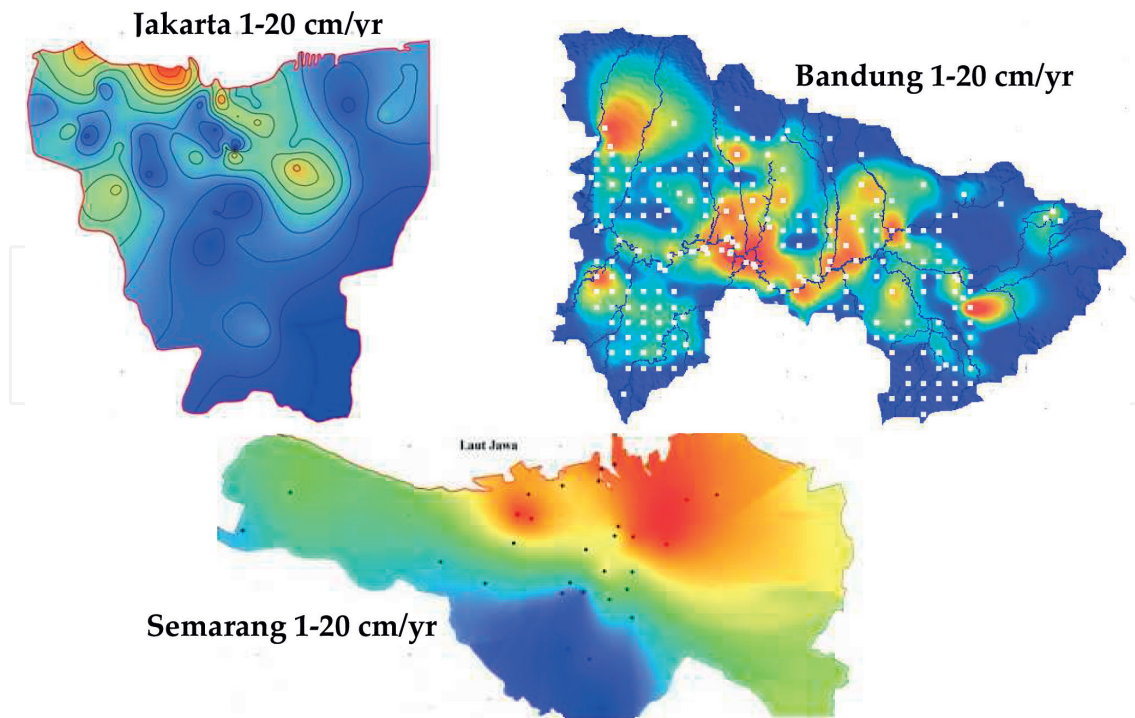


Figure 5. Map of land subsidence in Jakarta, Bandung, and Semarang. Highest rate of 20 centimeters per year is represented by the red color. North Jakarta and northeastern Semarang areas are experiencing the highest rate. Meanwhile the highest rate in the Bandung area is in the industrial areas (modified from [5, 9, 14]).



Figure 6. Pictures of the impact of subsidence (e.g. cracks in buildings and infrastructures and tidal inundation) in Jakarta, Bandung, and Semarang (source: authors).



Figure 7. Pictures of the impact of subsidence (e.g. cracks in buildings and infrastructures and tidal inundation) in other regions of Indonesia (source: authors).



Figure 8. Short- and long-term mitigation and adaptation against the consequences of land subsidence (e.g. elevating roads and housing, and building dykes, mangrove areas, and giant sea walls) (sources: authors, [12, 16]).

Comprehensively collecting information on the characteristics of land subsidence (e.g. rate, magnitude, places, causes, and impacts) in regions of Indonesia or elsewhere is appropriate for short- and long-term adaptation and mitigation (**Figure 8**). Respectively for Indonesia, short-term mitigation has been created against disasters that result in building temporary dykes, elevating the land, roads, housing, etc., including building up mangrove areas in many places along the subsiding coastal area. Long-term mitigation includes building giant sea walls around some coastal areas in an effort to stop subsidence by artificial recharge and/or stopping groundwater extraction.

4. Land subsidence and flooding insight correlation

As mentioned earlier we will look at the impact of land subsidence in the shape of flooding in some regions of Indonesia. More specifically, we will see how these are significantly correlated with each other and what the consequences of disaster would be. Fortunately, we can see quite clearly the qualitative and quantitative expected correlation between land subsidence and flooding using databases. Below is a detailed explanation of what is happening in Jakarta, Bandung, Semarang, Demak, and Pondok Bali Blanakan, which can best highlight the correlation examples. We will see clearly that the correlation is producing many problems.

Where a lowland area is experiencing land subsidence as a result of a cone of subsidence or there is a subsidence bowl, water will directly flow into it and create a flood zone. If the subsidence continues over time, in this case the cone of subsidence would become larger. As a consequence, wider expansion of flooding will likely occur as well. From all parameters that may create a flood (rain intensity, retention capacity, run-off, infiltration, land subsidence, land use, etc.), the subsidence parameter will likely influence a deeper and wider flood over time.

When we speak of a disaster from subsidence and flooding, we are likely to face economic and other losses. Millions of dollars have to be spent fixing problems from both land subsidence and flooding, and millions more will be spent in the future [17] (**Table 2**). With these kinds of losses, therefore, mitigation and/or adaptation are necessary. One key point regarding better mitigation and/or adaptation is to understand insight correlation between land subsidence and flooding. If flooding is proven to be influenced significantly by land subsidence, in this case reducing or even stopping the subsidence might be the best mitigation.

Geologically speaking, Jakarta is a lowland flood basin area. Thirteen rivers run across the area. Therefore, Jakarta is prone to frequent flooding. When a river is beyond its capacity to retain water from heavy rainfall, then flooding will occur. On the other hand, many places in Jakarta and the surrounding area experience land subsidence. With this situation, Jakarta is even more prone to frequent flooding. Spatially, the correlation between subsidence area and flood-prone area is very clear in Jakarta. Places that are experiencing high rates of subsidence are coincidentally those places most prone to flooding, such as Pluit, Sunter, Kamal Muara, and Joglo (**Figure 9**). In Pluit and Sunter, based on people's experience, floods seem to be

Problems to fix	Cost	Notes
1. Elevated roads	\$1 million for 1 kilometer	Spent
2. Elevated bridges	\$1 million for one long bridge	Spent
3. Fixing drainage	\$200,000 for 1 kilometer	Spent
4. Social cost	\$100 million/year	Estimated
5. Temporary dyke	\$5 million for 1 kilometer	Spent
6. Giant sea wall	\$600 million for 40 kilometers	Estimated

(Source [17]).

Table 2. Cost of fixing problems from land subsidence and floods.

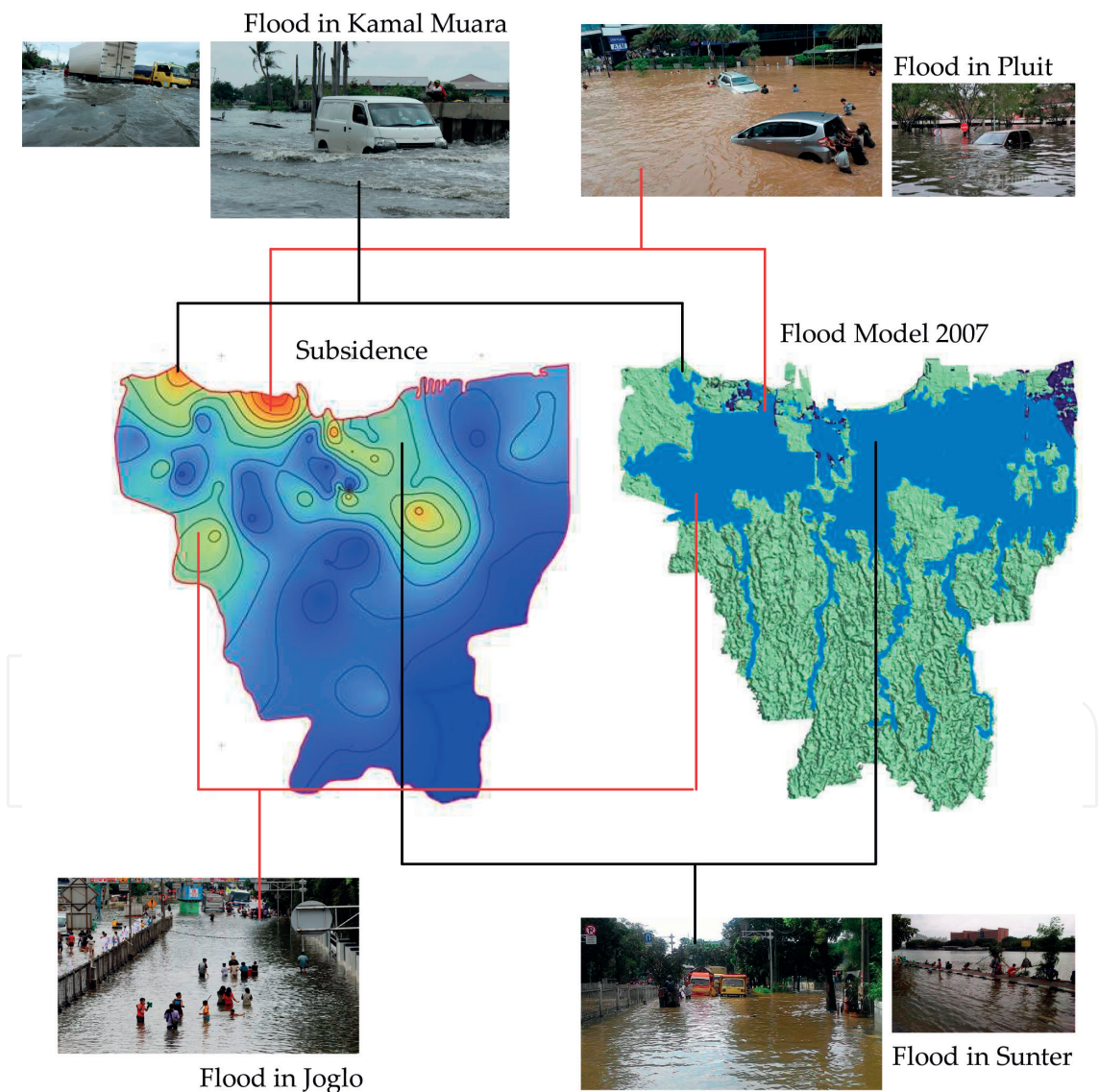


Figure 9. Map of land subsidence in Jakarta (modified from [5]) correlated with a model of existing flooding in the area. Some pictures show flooding in the field (sources: authors, [18]). We can see that a significant area suffering from subsidence is also constantly suffering from flooding.

wider and deeper over time. Generally, this is one of the indicators of true spatial correlation between land subsidence and flooding.

Jakarta is one of the biggest coastal cities in Indonesia and even in the southeast of Asia. It is quite remarkable how the city has rapidly grown through the decades. Nevertheless, the coastal area of this city is a place where the highest rate of subsidence exists. The lowering of coastal land due to subsidence will result in tidal inundation. Continuing land subsidence in combination with the rise in sea level has made the city prone to significant tidal inundation. We use the LiDAR Digital Elevation Model to look at the subsidence over time and create a projection of tidal inundation in Jakarta. Surprisingly, based on the model we found that around 26.86% of Jakarta would be below sea level in 2025 and potentially suffer from

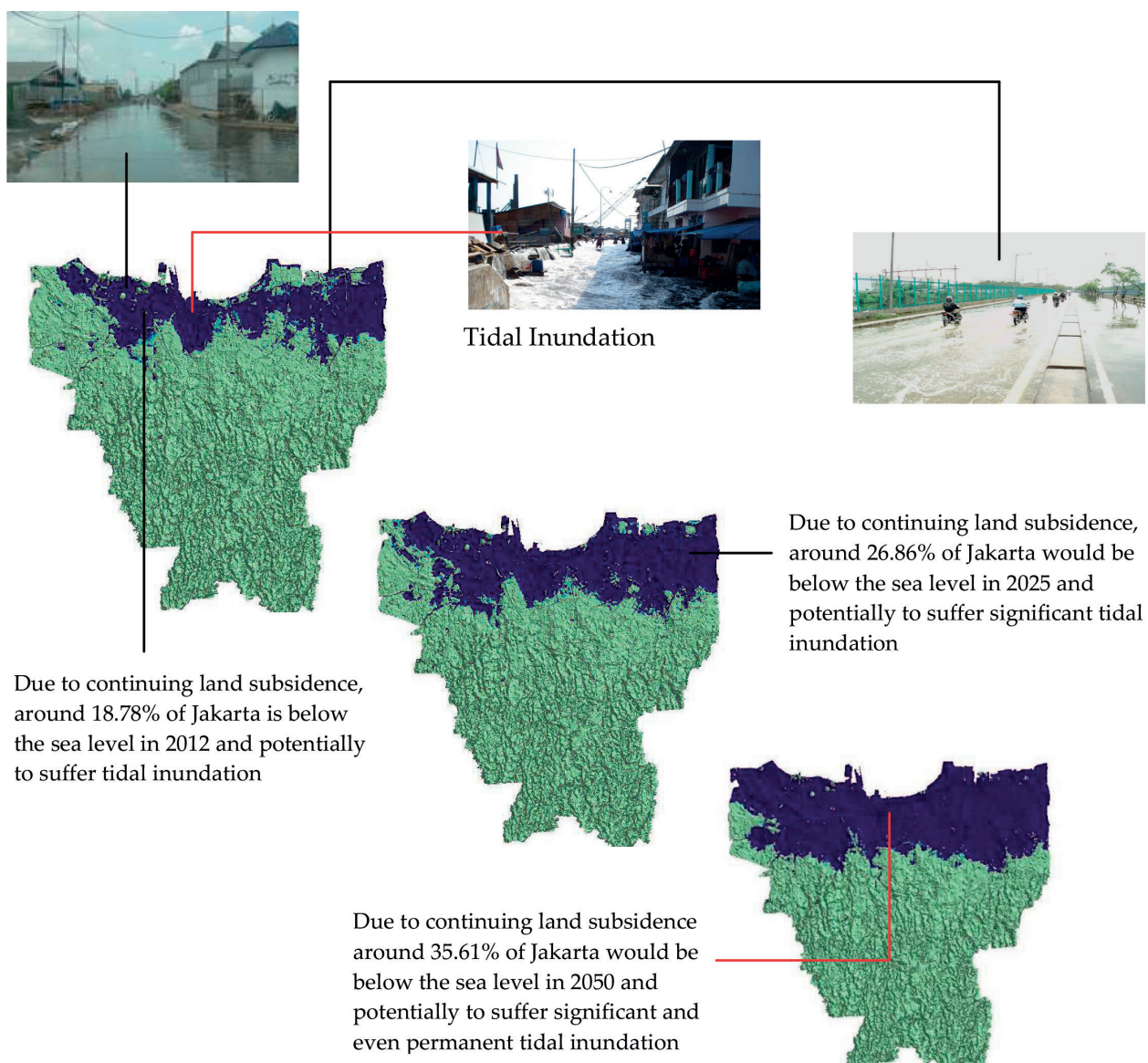


Figure 10. Map of tidal inundation in the area of Jakarta and the future tidal inundation projection as a consequence of continuing land subsidence in the area. Some pictures are given here to describe the existing tidal inundation in the field (source: authors).

significant tidal inundation, and around 35.61% of Jakarta would be below sea level in 2050 and potentially suffer from significant and even permanent tidal inundation (Figure 10).

The city of Bandung and its suburbs is located on a high land basin formed from the ancient crater of Gunung Sunda (super volcano). Thick sediment is overlaid below this area. Lying across the basin is the Citarum River. Land subsidence exists in Bandung Basin at a very significant rate per year. In certain places it may reach 20 centimeters per year. If we take a close look, subsidence mostly takes place around the industrial area, which is mainly located near the Citarum River and its tributaries (e.g. Dayeuh Kolot, Gedebage, Majalaya). When industry takes large amounts of groundwater, subsidence occurs in the area and creates a subsidence bowl. When heavy rain comes and the river cannot hold the water, then the surrounding area, including the subsidence bowl, is flooded (Figure 11). This clearly shows that the area suffering from land subsidence is constantly suffering from flooding.

Semarang is the biggest coastal city in Indonesia after Jakarta. Half of the city unfortunately is experiencing land subsidence, especially around the northeastern part. As a consequence of

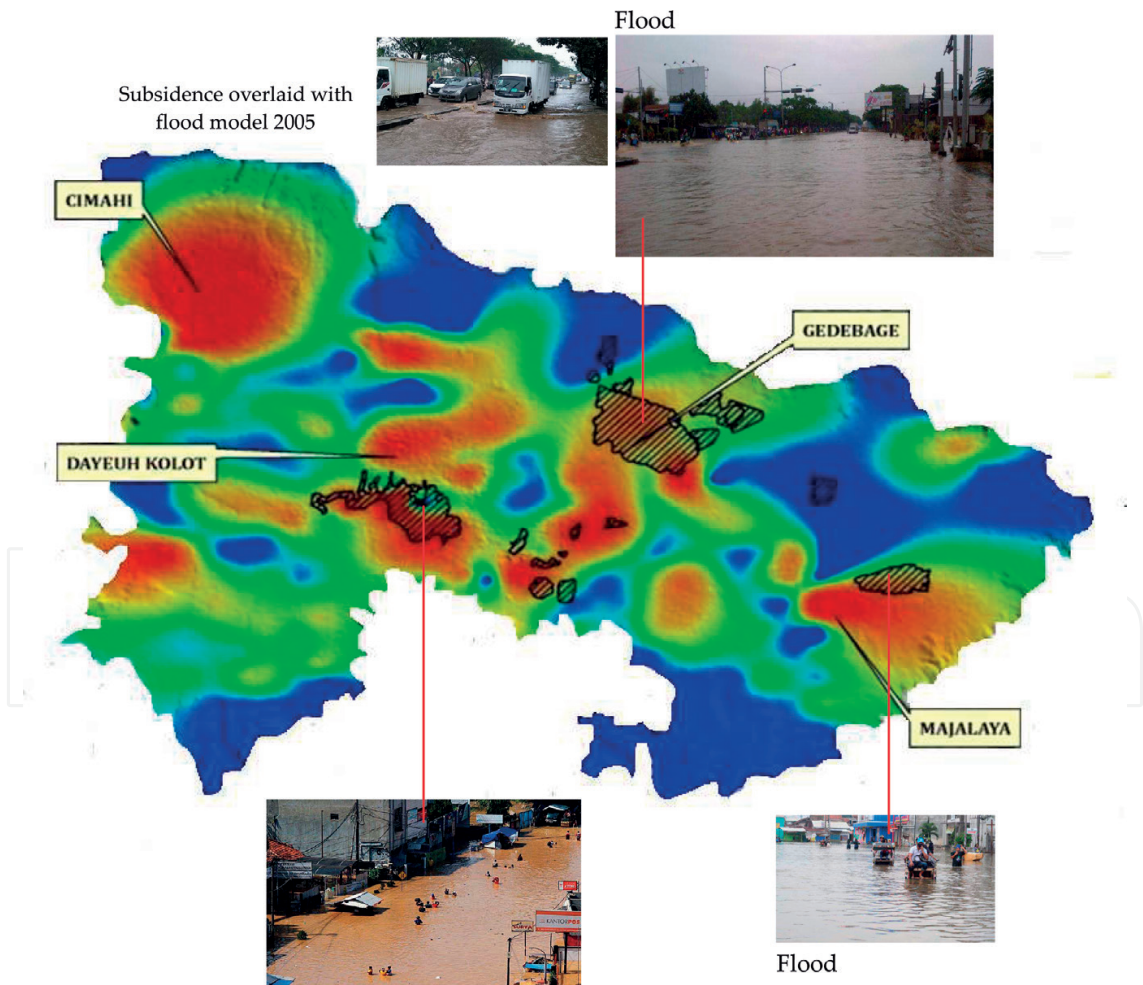


Figure 11. Map of land subsidence in Bandung (modified from [14]) correlated with the model of existing flooding in the area. Some pictures are given to describe flooding in the field (sources: authors, [18]). The area suffering from subsidence is constantly suffering from flooding.

lowering land due to subsidence, this place is prone to either flooding from rainfall or flooding from the sea or tidal inundation (**Figure 12**). When the high tide comes at the same time as heavy rainfall, what happens in northeastern Semarang is a real disaster. The place is drowning in the sea. Indeed, some parts of the area are permanently drowning as endorsed by analysis using the time series of high-resolution satellite image data as depicted in **Figure 12**. It is an undoubted fact of correlation between subsidence and flooding creating a real disaster. Sometime in the future this problem may worsen if we see a significant linear rate of subsidence in this area; on the other hand, attempts to mitigate or adapt to this situation are still not a priority.

Moving a little further east from Semarang we find a district called Demak. It is a coastal area used mostly for farming and fishing. At the southern part of the district are many industrial areas. It is not surprising that these industrial areas have taken huge amounts of groundwater; what is also surprising is that farming and fishing have also taken huge amounts of groundwater from deep aquifers. As a consequence, the Demak area is suffering from a significant rate of land subsidence. While the low land of the coastal area is sinking, over time more frequent tidal inundation will make things worse and in certain places it has already become permanently inundated. Based on high-resolution satellite image analysis, it is surprising that 3000 hectares of the Demak area are suffering from

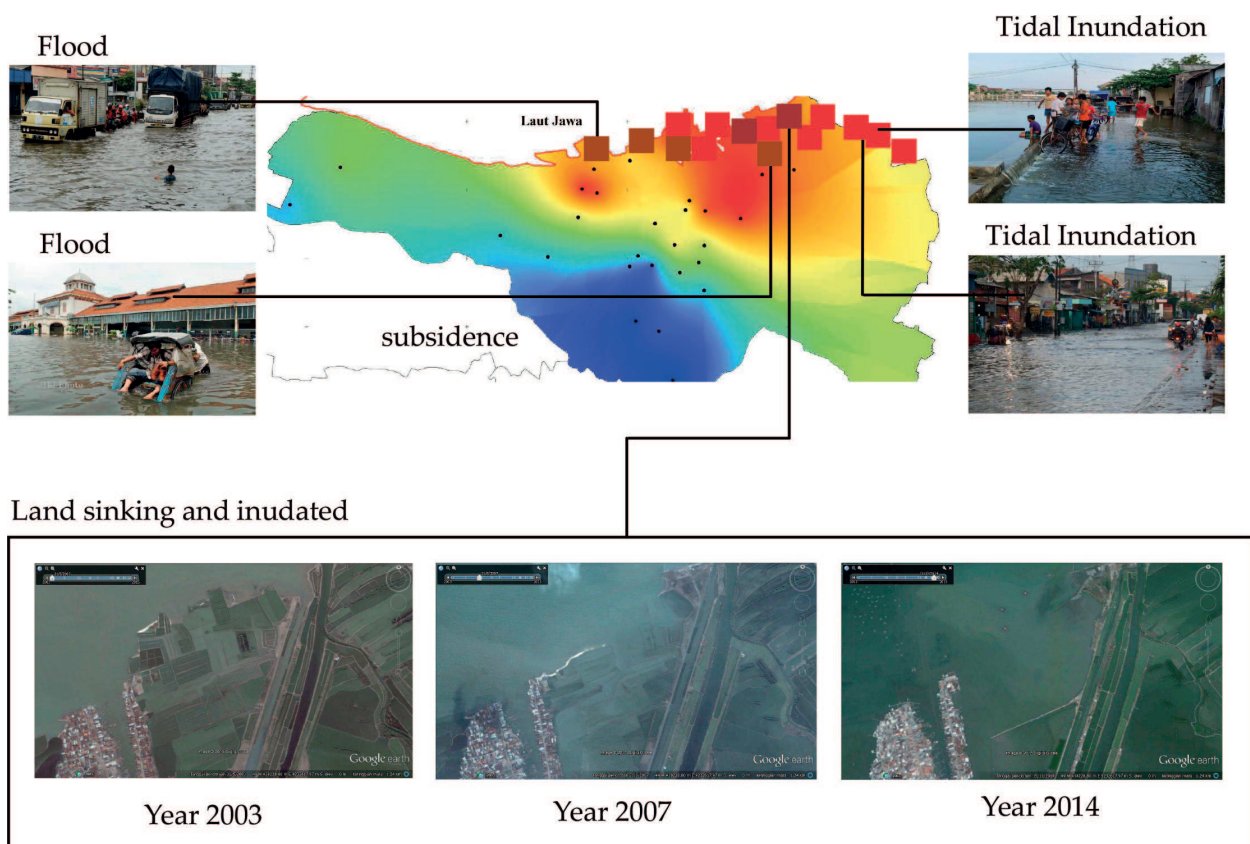


Figure 12. Map of land subsidence in Semarang (modified from [9]) correlated with existing flooding and tidal inundation in the area and also with satellite images of the land sinking (sources: authors; [18, 19]). We can see that the significant area suffering from subsidence is also constantly suffering from both flooding and tidal inundation.

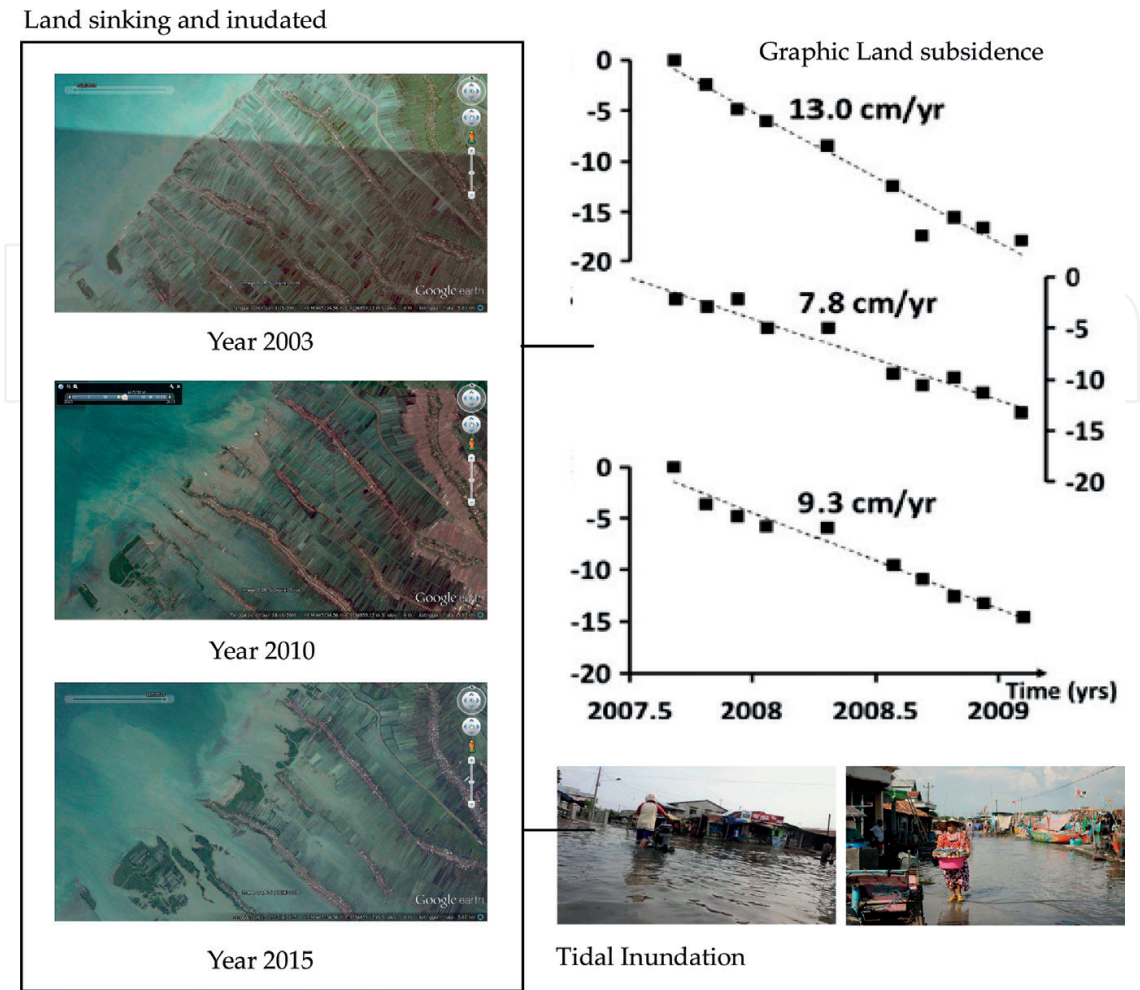


Figure 13. Graph of land subsidence in Demak (modified from [8]) correlated with pictures of existing tidal inundation and also with satellite images of land sinking (sources: authors, [18, 19]). We can see the general linear trend of subsidence indicating the sinking of the land.

inundation. **Figure 13** shows a graph of the subsidence in the Demak area along with a picture of tidal inundation in the field, as well as a depiction from a time series of high-resolution satellite image.

Pondok Bali Blanakan is a coastal area a few hundred kilometers east of Jakarta, and is mostly a farming and fishing area. First, it is quite surprising that this natural farming and fishing area is suffering from significant land subsidence. Nevertheless, after a detailed investigation we found that the area is an oil and gas exploitation area. The huge amount of oil and gas exploitation is causing subsidence. While the low land of the coastal area is sinking over time, more frequent tidal inundation is attacking the area and in certain places it has already become permanently inundated. Based on high-resolution satellite image analysis, it was found that a few hundred hectares of the Pondok Bali Blanakan area are suffering from inundation. **Figure 14** shows a graph of the subsidence in the area along with a picture of tidal inundation in the field, as well as a depiction from time series of high-resolution satellite image analysis. Again, we can see clear evidence of disaster.

Land sinking and inudated

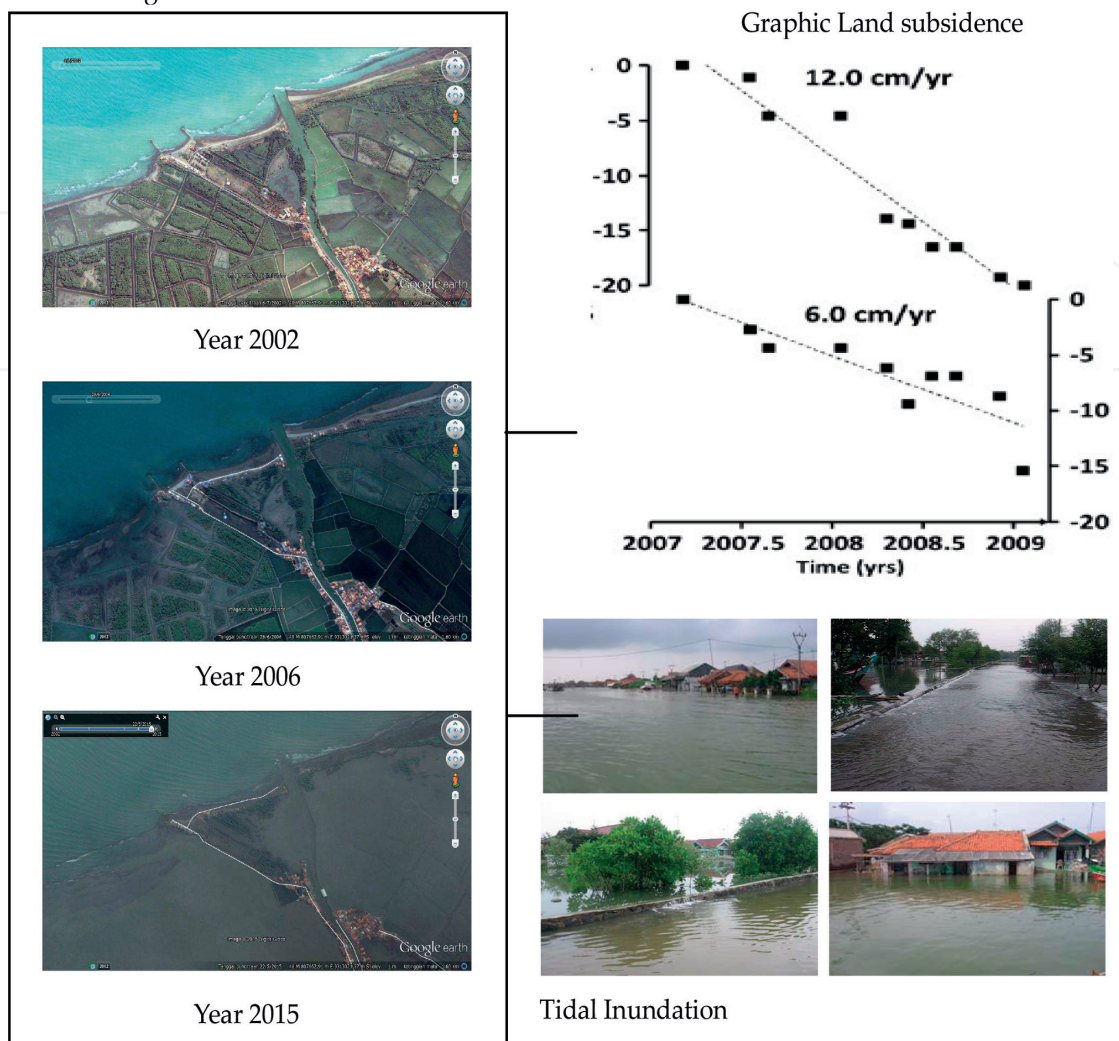


Figure 14. Graph of land subsidence in Pondok Bali Blanakan (modified from [8]) correlated with existing tidal inundation and also with the satellite images of land sinking (sources: authors, [18, 19]). We can see the linear trend of subsidence indicating the sinking of land and making it regularly inundated.

5. Discussion

Based on the correlation between land subsidence and flooding in some areas in Indonesia we can see clearly that the correlation between them is very strong and may result in disastrous situations. We can see that the significant area suffering from subsidence is also constantly suffering from flooding and tidal inundation. When we speak of disaster, we tend to think of economic loss. Indeed, millions of dollars have to be spent fixing problems from both land subsidence and flooding, and it seems more will be spent in the future. So, based on this fact we need better mitigation and/or adaptation. For example, if indeed flooding proves to be influenced significantly by land subsidence, in this case reducing or even stopping the subsidence might be the best mitigation. This fact shows that it is possible to stop land subsidence by stopping groundwater extraction and/or recharging artificially [8–10, 14, 20].

As far as we have seen, mitigation and/or adaptation are still beyond the best agenda in Indonesia. Only sporadic or short-term measures have been created against these problems such as building temporary dykes, elevating the land, roads, housing, etc., including building up mangrove areas in many places along coastal subsiding areas. Long-term measures such as building giant sea walls or stopping subsidence are still ongoing or are being planned and discussed. In fact, talking about stopping land subsidence is still an issue. Note that sometime in the future these problems may worsen if we see significant linear rate of subsidence in those areas; on the other hand, attempts to mitigate or adapt to this situation are still beyond the best agenda.

Indonesia is one of the fastest-growing countries in the world. In spite of this remarkable achievement, the ecological potential disaster from subsidence and flooding as explained in this chapter is quite serious. It is perhaps one of the mistake actions on growing the country. This descriptive chapter can be a lesson to learn for other growing countries. Do not make the same mistake. Do not let subsidence happen significantly. If possible do not let it happen at all. Singapore is a prime example for less subsidence. This country forbids the extraction of any groundwater.

We have been warned of global climate change consequences. Melting of ice caused by rising global temperatures is making the sea level rise. This sea level rise is projected to cause risk of flooding in coastal areas of the world. By this descriptive chapter we can see the risk is even multiple higher. The rates of sea level rise are generally a few millimeters per year [21, 22], while coastal subsidence can be up to a decimeter per year. This means that global climate change consequences may arrive earlier for coastal-subsiding areas such as Jakarta, Semarang, and probably others in the world.

6. Conclusions

Subsidence produces a number of impacts such as infrastructure damage, problems with drainage, wider expansion of flooding, as well as tidal inundation. The impacts can be quite costly. In some regions of Indonesia, land subsidence and the negative impacts in the shape of flooding and tidal inundation clearly exist. In Jakarta and Bandung we can see that subsiding areas close to rivers are frequently suffering from flooding. Tidal inundation comes regularly to subsiding coastal areas such as Jakarta, Blanakan, Semarang, and Demak. This typical situation can probably also be seen in other regions of Indonesia. Based on insight and looking at the correlation between land subsidence and flooding, we can conclude that the correlation between them is very strong and can be disastrous.

We need to perform mitigation and/or adaptation respectively. Nevertheless, as mentioned in the discussion, as far as we have seen, mitigation and/or adaptation are still beyond the best agenda in Indonesia. Only sporadic or short-term measures have been created against these disasters such as building temporary dykes, elevating the land, roads, housing, etc., including building up mangrove areas in many places along coastal-subsiding areas.

The descriptive explanation throughout this chapter can hopefully provide better mitigation and/or adaptation in Indonesia such as building giant sea walls or stopping subsidence. Note

once again that in the future these disastrous situations may even worsen if we see a significant linear rate of subsidence. This chapter will hopefully become a lesson learnt for other places around the world, especially those growing countries prone to subsidence and flooding.

Acknowledgements

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