Environmental Impacts of Land Subsidence in Urban Areas of Indonesia

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Key words: land subsidence, Jakarta, Bandung, Semarang, GPS, InSAR, flooding

SUMMARY

Land subsidence is natural-anthropogenic hazard affecting several large urban areas in Indonesia, i.e. Jakarta, Bandung and Semarang. Geodetic based results from various techniques (e.g. Leveling, GPS and InSAR) show that land subsidence rates in all three cities generally have spatial and temporal variations, and their magnitude is in average about 5-10 cm/year and can reach up to about 20 cm/year at certain locations and times. This type of silent hazard is mainly caused by the combination of excessive groundwater extraction, natural consolidation of alluvium soil, load of constructions and tectonic activities. In general, information related to characteristics of land subsidence is important for urban spatial planning and development activities, environmental management, and risk assessment efforts. Therefore, systematic and continuous monitoring of land subsidence in urban areas is obviously needed and critical to the welfare of the peoples. Land subsidence impacts in urban areas are quite numerous and can be categorized into infrastructural, environmental, economic and social impacts. In urban areas of Indonesia the subsidence impacts can be seen already in the field in forms of cracking and damage of housing, buildings and infrastructure; wider expansion of (riverine and coastal) flooding areas, malfunction of drainage system, changes in river canal and drain flow systems and increased inland sea water intrusion. In general, land subsidence phenomena will increase the maintenance and rehabilitation costs for the affected environment, buildings and infrastructures. It also badly influences the quality of living environment (e.g. health and sanitation condition) and (social and economic) life in the affected areas. This paper concentrates on the environmental impacts of land subsidence in those three large cities in Indonesia, namely Jakarta, Bandung and Semarang.

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1. INTRODUCTION

Geometrically, land subsidence can be defined as the downward displacement of land surface relative to certain reference surface, such as mean sea level (MSL), geoid, or reference ellipsoid, or relative to a certain assumed stable point outside the prone subsidence area, as illustrated in Figure 1. In this case, if the heights of certain point in land subsidence prone area with respect to MSL (geoid) or the reference ellipsoid at epochs i and j are: H(i) and H(j), or h(i) and h(j), then land subsidence between the two epochs i and j, LS(i,j), can be estimated using the following relation:

$$LS(i,j) = H(j) - H(i), \text{ or } LS(i,j) = h(j) - h(i) \,. \qquad (1)$$

If the heights of that point are known relative to certain stable point outside the subsidence prone area, namely dH(i) and dH(j), or dh(i) and dh(j), then land subsidence between the two epochs i and j, LS(i,j), can be estimated using the following relation:

$$LS(i,j) = dH(j) - dH(i), \text{ or } LS(i,j) = dh(j) - dh(i) \,. \qquad (2)$$

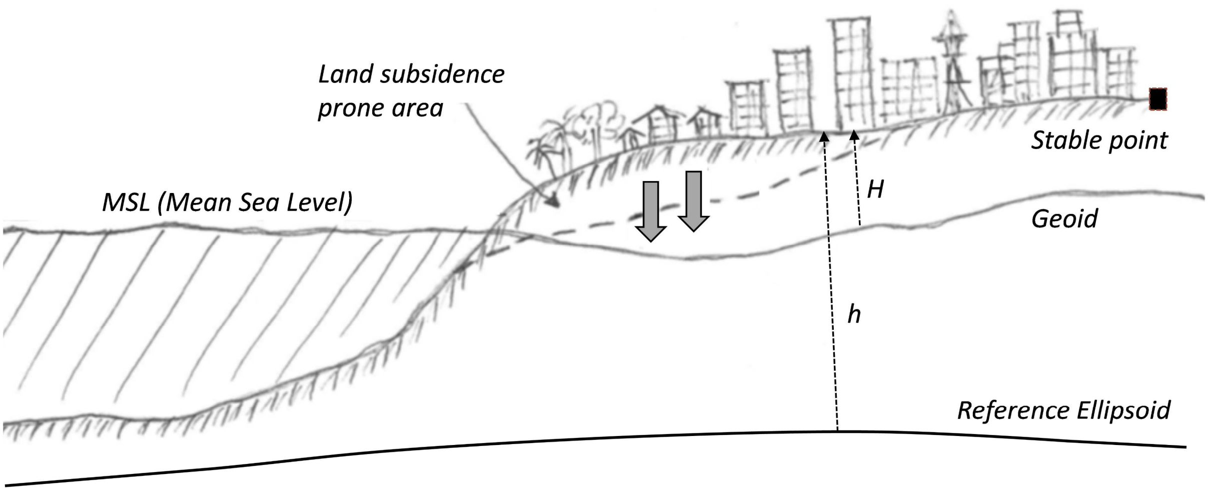


Figure 1. Geometrical illustration of land subsidence

This natural-anthropogenic hazard phenomena can be caused by natural and/or human activities, such as tectonic activities (e.g. earthquake and faulting), volcanic activities, landslide, underground mining activities, excessive groundwater or oil/gas extraction, natural consolidation of alluvium soil, and load of constructions. At present times, there are quite many large urban areas (cities) in the world are affected by this silent-type hazards, such as Venice (*Carbognin et al.,* 2004), New Orleans (*Burkett et al.,* 2002), Houston (*Buckley et al.*, 2003), Mexico City (*Cabral-Cano et al*., 2008), Osaka (*Murayama*, 1970), Tokyo (*Ishii et al.*, 1970), Shanghai (*Chai et al.*, 2004), Tianjin (Qingzhi and Xioujun, 1986), Taipei (*Chen et al.*, 2007), Manila (*Rodolfo*, 2014), and Bangkok (*Phien-wej et al.*, 2006). In urban areas of Indonesia, on-going land subsidence has been observed in Jakarta (*Abidin et al.*, 2001, 2008a, 2010a, 2011), Bandung (*Abidin et al.*, 2008b, 2009, 2012a, 2013), and Semarang (*Abidin et al.*, 2010b, 2012b). Based on preliminary studies, land subsidence is also expected to occur in Surabaya (*Kurniawan,* 2011) and Medan (*Simanjuntak,* 2014). Land subsidences in the urban areas usually caused by the combination of excessive groundwater extraction, natural consolidation of alluvium soil, load of constructions (i.e. settlement of high compressibility soil), and sometimes tectonic activities.

In general, the impacts of land subsidence in urban areas can be seen in various representation in the field, and can be categorized into infrastructure, environmental, economic, and social impacts (see Table 1). Subsidence representation impacts can be seen in various forms, such as cracking of permanent constructions and roads, tilting of houses and buildings, 'sinking' of houses and buildings, changes in river canal and drain flow systems, wider expansion of coastal and/or inland flooding areas, and increased inland sea water intrusion. If the coastal areas of the cities have significant subsidence rates, then coastal flooding can occur during the high tides. In the coastal areas of Jakarta and Semarang, frequent and severe coastal flooding not just deteriorates the function of building and infrastructures, but also badly influences the quality of living environment and life (*Abidin*, 2010a, 2012b). This paper presents and discusses the environmental impacts of land subisdence in three large cities of Indonesia, namely Jakarta, Bandung and Semarang.

Table 1. Characteristics of land subsidence impacts.

No.	Category	Representation of impact	Level of impact
1.	Infrastructural	cracking of permanent constructions and roads	direct
		tilting of houses and buildings	direct
		'sinking' of houses and buildings	direct
		breaking of underground pipelines and utilities	direct
		malfunction of sewerage and drainage system	indirect
		deterioration in function of building and infrastructures	indirect
2.	Environmental	changes in river canal and drain flow systems	indirect
		frequent coastal flooding	indirect
		wider expansion of flooding areas	indirect
		inundated areas and infrastructures	indirect
		increased inland sea water intrusion	indirect
		deterioration in quality of environmental condition	indirect
3.	Economic	increase in maintenance cost of infrastructure	indirect
		decrease in land and property values	indirect
		abandoned buildings and facilities	indirect
		disruption to economic activities	indirect
4.	Social	deterioration in quality of living environment and life (e.g. health and sanitation condition)	indirect
		disruprion to daily activities of people	indirect

2. OBSERVED LAND SUBSIDENCE

In large urban areas, such as Jakarta, Bandung, and Semarang, good and reliable information on land subsidence characteristics is important for several aspects of urban development and risk assessment efforts, such as spatial-based groundwater extraction regulation, effective control of (inland and coastal) flood and seawater intrusion, conservation of environment, design and construction of infrastructures, sub-surface utility planning, sewerage and drainage system design, and spatial development planning in general. Therefore, for supporting urban development activities, good and systematic monitoring of land subsidence is necessary.

In principle, land subsidence in urban areas can be observed using several geodetic methods, such as leveling, GPS survey, InSAR, microgravity, and geometric-historic. Each geodetic method has its own strengths and limitations in revealing characteristics of subsidence phenomena in urban areas, and therefore in order to have good and reliable information on land subsidence phenomena, results from various geodetic observations results should be integrated (Abidin et al, 2015). Moreover, the integration will also allow the comparison and validation of results from various methods, which can then lead to more reliable subsidence information.

Land subidence phenomena in Jakarta, Bandung and Semarang have been studied using several geodetic methods since 1982, 1999, and 2000, respectively. The observed subsidence phenomena in these cities have both spatial and temporal variations, with typical subsidence rates of about 5 to 10 cm/year in average. However, land subsidence can have higher rates at certain locations and times. Summary of the results is given in Table 2. More detail results from these studies can be seen in *Abidin et al.* (2001, 2008a, 2008b, 2009, 2010a, 2010b, 2011, 2012a, 2012b, 2013a, 2013b, 2014, 2015a, 2015b), *Sutanta et al.* (2005), *Fukuda et al.* (2008), *Supriyadi* (2008), *Kuehn et al.* (2009), *Lubis et al.* (2011), *Ng et al.* (2012), *Sumantyo et al.* (2012), *Chaussard et al.* (2013), and *Yuwono* (2013).

Table 2. Summary of observed land subsidence rates in Jakarta, Bandung, and Semarang, after *Abidin et al.* (2015a).

No.	Method	Subsidence Rates (cm/year)		Observation Period	References
		Min - Max	Typical		
JAKARTA					
1	Leveling Surveys	1 - 9	3 - 7	1982 - 1991	*Abidin et al.* (2001, 2008a, 2010a, 2011, 2012a, 2012b, 2013a), *Ng et al.* (2012)
		1 - 25	3 - 10	1991 - 1997	
2	GPS Surveys	1 - 28	4 - 10	1997 - 2011	
3	InSAR	1 - 12	3 - 10	2006 - 2010	
BANDUNG					
1	GPS Surveys	1 - 23	4 - 11	2000 - 2010	*Abidin et al.* (2008b, 2009, 2012a, 2013b), *Chaussard et al.* (2013), *Chatterjee et al.* (2013)
2	InSAR	1 - 19	5 - 12	1999 - 2010	
SEMARANG					
1	Leveling Surveys	1 - 17	2 - 10	1999 - 2003	*Abidin et al.* (2010b, 2012b), *Kuehn et al.* (2009), *Murdohardono et al.* (2007, 2009), *Supriyadi* (2008)
2	GPS Surveys	1 - 19	3 - 10	2008 - 2011	
3	PS InSAR	1 - 10	3 - 8	2002 - 2006	
4	Microgravity	1 - 15	2 - 10	2002 - 2005	

3. ENVIRONMENTAL IMPACTS OF LAND SUBSIDENCE

The impacts of land subsidence in urban areas are quite numerous and can be categorized into infrastructural, environmental, economic and social impacts. The resulting losses from its direct and indirect effects also quite huge, and cannot be under estimated (see Figure 2). Cracking of buildings and infrastructures, and wider expansion of coastal and inland flooding areas, are common impacts of land subsidence which can be seen in Jakarta, Bandung, and Semarang. Besides affecting land surface and (surface and underground) infrastructures, land subsidence usually deteriorates the quality of living environment and life (e.g. health and sanitation condition) in the subsidence affected areas. Development and maintenance costs of infrastructures in subsidence affected areas will usually be higher than in the normal situation. Social and environmental costs due to direct and indirect impacts of land subsidence are usually also quite significant.

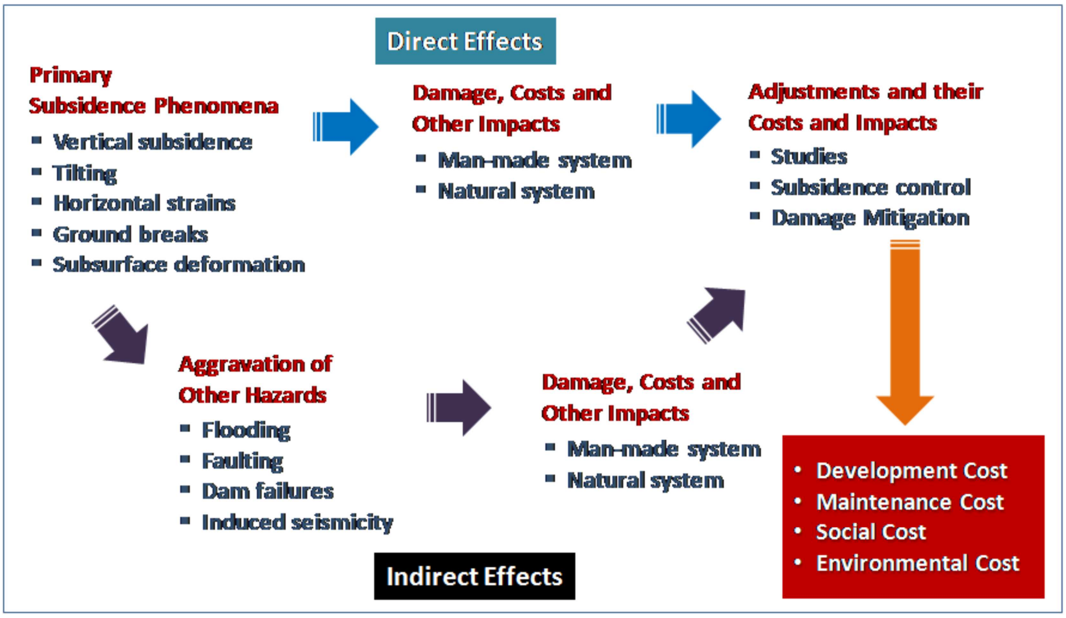


Figure 2. Losses due to land subsidence, after *Viets* (2010) and *Abidin et al.* (2014)

The infrastructural impacts of land subsidence in urban areas are usually more recognizeable in the field, compared to its environmental, economic and social impacts, as shown by example in Figure 3. Examples of infrastructural forms of subsidence in Jakarta, Bandung and Semarang in various forms is given in Figure 4. Some of this infrastructural impacts will generate other impacts, namely environmental, economic and/or social impacts.

The environmental impacts of land subsidence itself maybe seen in the field in the forms of frequent coastal flooding (for coastal cities such as Jakarta and Semarang), wider expansion of flooding areas, inundated areas and infrastructures, changes in river canal and drain flow systems, increased inland sea water intrusion, and in general deterioration in quality of environmental condition in land subsidene affected areas. Examples of environmental forms of subsidence in Jakarta, Bandung and Semarang in various forms is given in Figure 5.

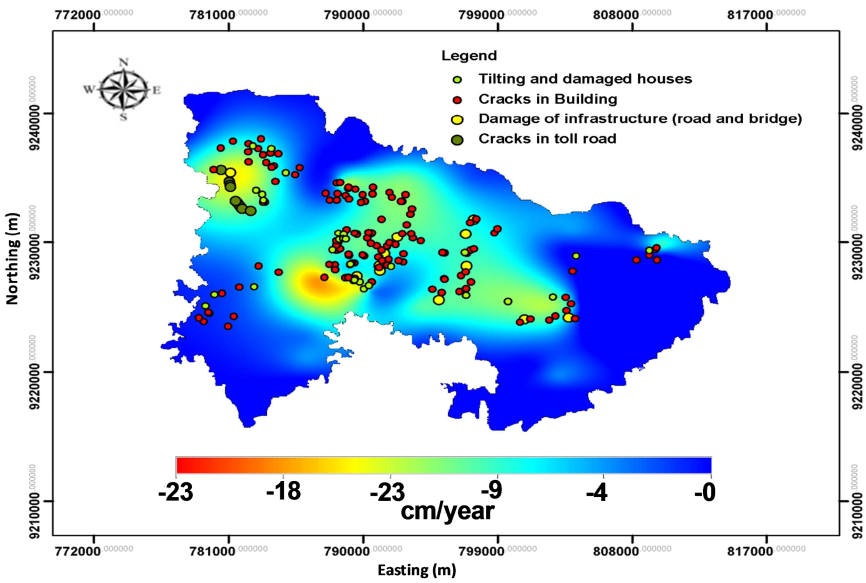


Figure 4. Distribution of (infrastructural) subsidence impacts in Bandung, overlapped with the average GPS-derived subsidence rates from 2000 to 2010; after *Abidin et al.* (2013b).


tilting structure (Jakarta)


cracking of road (Semarang)


"sinking" house (Bandung)


"sinking" house (Semarang)


cracking of higway (Bandung)


bridge structure lowering (Jakarta)


"sinking" house (Jakarta)


'sinking' of sea dyke (Jakarta)


malfunction of drainage (Jakarta)

Figure 4. Examples of infrastructural forms of subsidence impacts.

Figure 5. Examples of environmental forms of subsidence impacts.

Environmental impacts of subsidence in urban areas are actually closely connected to other subsidence impacts (i.e. infrastructural, economic and social), as illustrated in Figure 6. Environmental impacts are actually indirect effects of subsidence, and mostly generated by lowering down of land surface and malfunction of river, canal and drain flow systems due to subsidence phenomena. The infrastructural impacts of subsidence can also contribute to increase the environmental impacts. Due to its relatively longer time response, the environmental impacts of subsidence are usually realized after quite sometimes when the impacts are already disrupting our daily activities.

The main environmental impacts of subsidence in urban areas are related to inundation and flooding phenomena, which in turn will generate economic and social impacts, and in general deteriorate the quality of environmental condition and disrupting the people activities. In case of Jakarta, Bandung and Semarang, the on-going subsidence is believed to have spatial relation with repeated flooding during the rainy seasons in certain areas, and with frequent coastal flooding during high tides. Subsidence in flooding prone areas will theoretically lead to expanded coverage and deeper water depth of flooded (inundated) areas. Vertical changes in water flow pattern in drainage, canal and river systems passing the subsidence area, may also affect flooding system in the respected area. More information on relation between subsidence and flooding phenomena in case of Bandung and Jakarta can be seen in *Abidin* et al. (2009, 2015b), and in case of Semarang in *Yuwono* (2013).

In the case of Jakarta, if land subsidence affected areas as derived by GPS from 2000 to 2011 is compared with the flooded areas in Jakarta on 22 January 2014 (see Figure 7), it can be realized that there is spatial correlation in certain locations. Several flooded areas are spatially coincided with the subsidence affected areas; while several flooded areas along the rivers do not show spatial correlation with subsidence phenomena. In order to have more quantitative relation relation between subsidence and flooding phenomena in Jakarta, further research is still required.

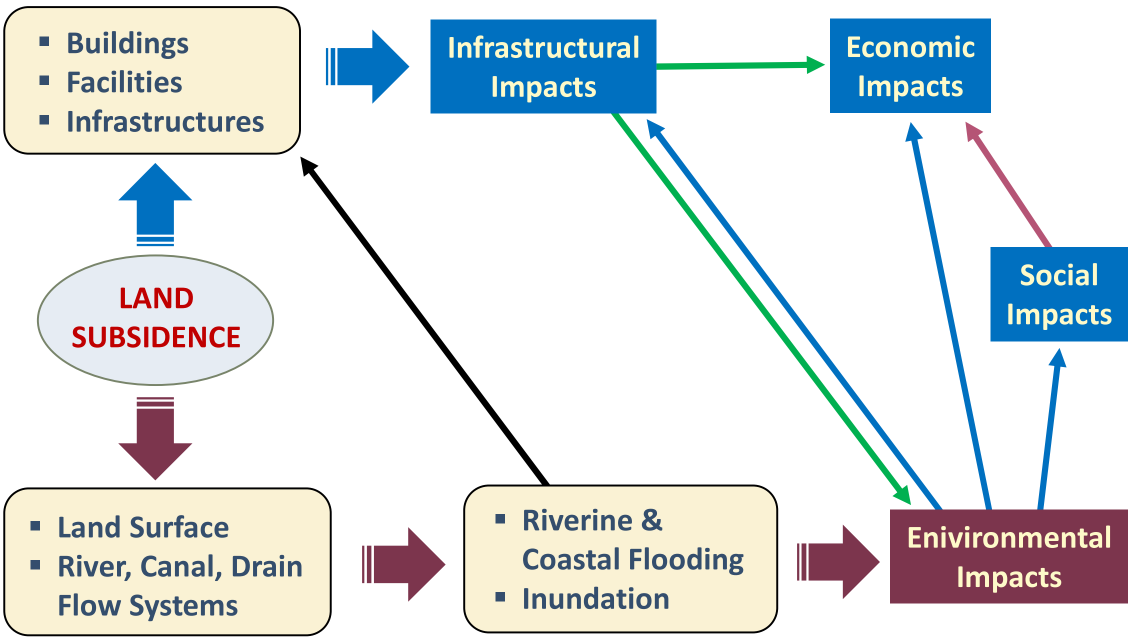
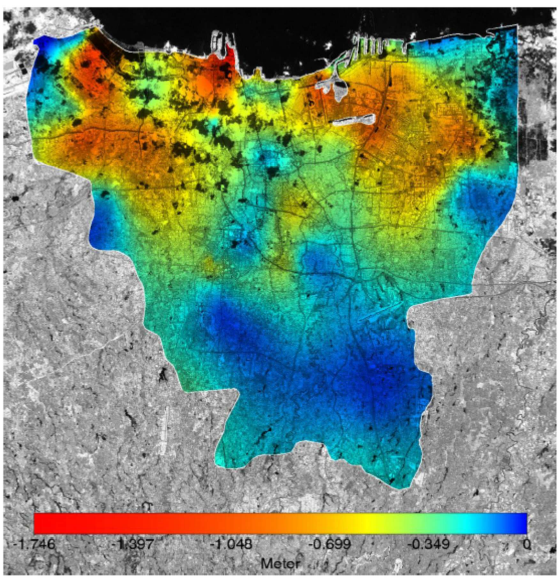
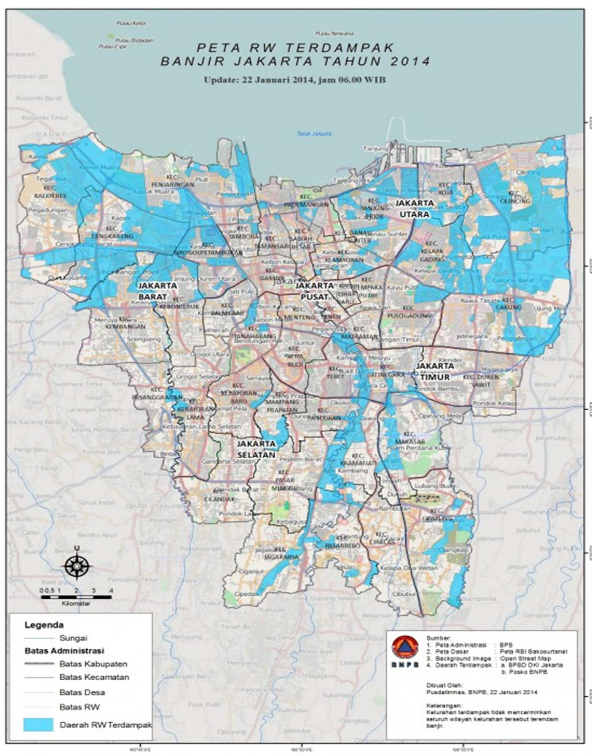


Figure 6. Land subsidence impacts and its connection system.



GPS-derived subsidence (2000-2011)



source: geospasial.bnpb.go.id

Figure 7. Spatial correlation between GPS-derived land subsidence (2000-2011) and flooding area in Jakarta (2014).

4. CLOSING REMARKS

At present times, several large urban areas of Indonesia are experiencing land subsidence phenomena, such as Jakarta, Bandung, Semarang, Medan and Surabaya. In Jakarta, Bandung and Semarang, this silent natural-anthropogenic hazard is mainly caused by the combination of excessive groundwater extraction, natural consolidation of alluvium soil, and load of buildings and infrastructures. The contribution of tectonic activities in land subsidence of the aforementioned cities is not yet certain, but if it is exist, theoretically will no be a dominant contributor.

Land subsidence impacts in urban areas are quite numerous and can be categorized into infrastructural, environmental, economic and social impacts. Environmental impacts of subsidence is usually underestimated, since it is indirect effect and its appearance usually is unseen and has a relatively longer time response than infrastructural impacts. For example, although land subsidence in urban areas contribute to inundation and flooding phenomena, however, land subsidence is usually forgotten in assessment and modeling of flooding and inundation in urban areas.

Since environmental impacts of land subsidence in urban areas are actually closely connected to other subsidence impacts (i.e. infrastructural, economic and social) and can aggravate other hazards (e.g. flooding and inundation), then study and assessment of its characteristics should be carefully performed in order to have good and reliable information.

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BIOGRAPHICAL NOTES

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