Determining the initial time of anthropogenic subsidence in urban area of Indonesia

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Abstract. Land subsidence in urban area of Indonesia like Jakarta, Bandung, Semarang, Pekalongan and others is quite well known today. Base on the geodetic measurements (e.g. Leveling, GNSS and InSAR) we can identify rates per year and also magnitude in certain periods. Nevertheless the initial time of its occurrence, especially a part influenced by anthropogenic causes, in many cases still remains unclear due to data limitation. This is an interesting research question because the initial time is crucial for determining total magnitude, while this total magnitude is important information for assessing the impact of subsidence. For example to understand the occurrence of tidal inundation, widening area of flood, calculating cost of adaptation, water table inversion, etc. we need to know quite exact the total magnitude of anthropogenic subsidence from its first initiation. Luckily we have long data measurements of subsidence in Jakarta, long data observation of groundwater in several urban areas and times series of images satellite that can be used for determining the initial time of anthropogenic subsidence in urban area of Indonesia. This paper will highlight how these data set answering quite well the research question.

1. Introduction

Land subsidence is defined as a decrease in the surface of the ground with respect to a reference system of height such as the sea surface, geoid or ellipsoid surface. Geodetic measurements (e.g. Leveling, GNSS and InSAR) can identify rates per year and also magnitude even is small value[1, 2, 3, 4, 5, 6] in certain periods of times in some part on the surface of the ground on our Earth (figure 1), including urban area of Indonesia like Jakarta, Bandung, Semarang, Demak and Pekalongan. Generally 1-20 centimeter per year and a total 1-4 meter are being observed. The Land subsidence can be caused by several factors, divided into tectonic, geo-technique, and geo-hydrology factor. Tectonic given the value to subsidence in a way of plate interaction and fault activities; Geo-technique play role to subsidence from load of buildings and constructions, natural consolidation of alluvium soil, soil setting/reclamation, etc.; The geo-hydrology given consequences to subsidence from excessive groundwater extraction. Geo-technique and geo-hydrology strongly correlate each other through effective stresses and compaction processes, and both influenced much by soil properties. Excluding the tectonic and natural consolidation factors, all others define as anthropogenic causes.

The impact of land subsidence is evident, especially in cities or urban areas in the coastal region. These impacts can be in the form of sea water inundation, infrastructure damage, expansion of flooding,
and sea water intrusion to a decrease in environmental quality [7, 8, and 9]. The significant impact of land subsidence is categorized as an ecological disaster (figure 2). Million of dollar is expected need to be spent due to that ecological disaster in one urban area. In this regard, mitigation and adaptation are very important in reducing disaster risk. In the future if actions taken are less, there will be more significant disaster.

Figure 1. Graphics of land subsidence in several coastal city in the world including Jakarta Indonesia from 1920 until recent years. Note that Jakarta has fastest rate at the moment [1,2,3,4,5,6].

Figure 2. The impact of land subsidence in a form of tidal inundation, that is in some places is already significant and chategorize as ecological disaster.

The initial time of the subsidence occurrence (especially the anthropogenic) is crucial for determining total magnitude, while this total magnitude is important information for assessing the impact of subsidence. For example to understand the occurrence of tidal inundation, widening area of flood, calculating cost of adaptation, etc. we need to know quite exact the total magnitude of anthropogenic subsidence from its first initiation. Nevertheless the initial time of its occurrence, especially part influenced from anthropogenic causes, in many cases still remains unclear due to data limitation. Luckily we have long data measurements of subsidence in Jakarta, long data observation of groundwater in Jakarta and several urban areas and times series of images satellite that can be used for determining the initial time of anthropogenic subsidence in urban area of Indonesia. This paper will highlight how these data set answering the initial time of anthropogenic subsidence.
2. Data and methods
Some research findings [10, 11 and 12] clearly conclude the relationship between land subsidence and groundwater exploitation. The beginning of loss of artesian pressure and the starting decline in groundwater level (water table or piezometric head decline) will be accompanied by the beginning of anthropogenic land subsidence. This means that the initial time of anthropogenic subsidence if the measurement records somehow are not known then it can be estimated by water table decline. The reverse situation also applies when we find land subsidence, we can estimate water table decline. Figure 3 shows the graph of land subsidence in correlation with the graph of water table decline from deep well monitoring in Tokyo Japan (a) and San Jose America (b). Once recovered from the water table exists, the subsidence is generally stopped.

Groundwater exploitation will be closely related to people population. The more population, the more water needs and it is possible that more groundwater exploitation will be carried out if other water sources are not well available [10, 11 and 13]. Figure 4 shows the graph of population growth in Australia in correlation with the graph of total annual supply of water from 1950 to 2000 [14]. It can be seen how the increase in people population is accompanied by an increase in the water supply.

Figure 3. Graph of land subsidence in correlation with graph of water table decline (piezometric head) from deep well monitoring in Tokyo (a) and San Jose (b). Once recovered of water table existed, the subsidence is generally stop.

Figure 4. Graph of population growth in Australia in correlation with graph of total annual supply of water since 1950 to 2000 [modify from 14].
From the two paragraphs of data and method section above, we can simply predict the initial time of anthropogenic land subsidence by a simple method which is analyzing of correlating of land subsidence data with initial water table decline. Furthermore, water table decline can be related to city growth through land cover change information. If we can find two data which are land cover changes (especially first period of city or urban development) and record of initial water table decline, then we can estimate the initial time anthropogenic land subsidence quite accurately.

Luckily as mentioned in the introduction, we have long data measurements of subsidence in Jakarta, long data observation of groundwater in several urban areas and times series of images satellite that can be used for determining the initial time of anthropogenic subsidence in urban area of Indonesia. Figure 5 shows graph of land subsidence in Jakarta area base on leveling measurements, GNSS and InSAR (a) and graph of land subsidence in correlation with graph of water table decline from deep well monitoring. Meanwhile figure 6 shows three maps showing land cover of Jakarta area in 1972, 1993, and 2005 (modified from Indonesia Geology Agency) [15]. The city growth represent by red color on the map in figure 6.

![Graph of land subsidence in Jakarta area base on measurements leveling, GNSS and InSAR (a). Graph of land subsidence in correlation with graph of water table decline (piezometric head) from deep well monitoring.](image)

**Figure 5.** Graph of land subsidence in Jakarta area base on measurements leveling, GNSS and InSAR (a). Graph of land subsidence in correlation with graph of water table decline (piezometric head) from deep well monitoring.

![Three maps showing land cover of Jakarta area in 1972, 1993, and 2005 (modified from Indonesia Geology Agency). Red color represents large number development of housing and the typical while the blue one is fish pond area and the green one is open space area including agricultural and plantation area.](image)

**Figure 6.** Three maps showing land cover of Jakarta area in 1972, 1993, and 2005 (modified from Indonesia Geology Agency). Red color represents large number development of housing and the typical while the blue one is fish pond area and the green one is open space area including agricultural and plantation area.
3. Result and discussion

With the collected land subsidence information of Jakarta area that is long enough time series, namely from 1925 to 2015 (as in the figure 7), we finally know that from 1925 to 1975 it can be said that there is no anthropogenic land subsidence. Before 1975 it was dominated by natural compacting alone. After 1975 until now there has been a land subsidence with even a significant rate per year. The graph in Figure 7 clearly shows the initial anthropogenic land subsidence in Jakarta since 1975. Around the same year, a loss of artesian pressure and declining water table has begun to occur. This becomes empirical evidence of how the correlation occurs between land subsidence and groundwater exploitation. One meter land subsidence will correlate with approximately twenty meters of water table decline due to overexploitation. The time of decline is quite identical to the time of subsidence. So here if we find the initial water table decline data but we don't find the initial subsidence data, then the water table decline initiation can be concluded as the initial anthropogenic land subsidence.

Figure 7 also shows how land subsidence correlates spatially with changes in residential land. It seems that the more residential areas are spread, the more subsidence are also there and spread. Residential land or settlement will be closely related to people population. The more population, the more land will be converted into settlements. Meanwhile, the more the population, the more water supplies will be needed which can be taken from ground water. Here we can see the correlation between growing population and water table decline through land cover change. If we get initial land cover change data on residential areas and groundwater consumption information, the combination of these two data can predict initial anthropogenic land subsidence.

![Figure 7](image_url)

Figure 7. Visualization of spatial and graph correlation among land subsidence, land cover change and water table decline. As we can see the anthropogenic subsidence started when the city grown, use groundwater that making water table to decline.
Since we already known initial of anthropogenic land subsidence in Jakarta as shown above, in this case we can create model of sea water inundation around coastal area of Jakarta through times. By utilizing Digital Elevation Model (DEM) data with referenced to MSL (Mean Sea Level), obtained from the acquisition of LIDAR data, then corrected with a map of the land subsidence and sea level rise per year (considering the initial time of subsidence), then we can see anywhere in Jakarta that is under the sea, which potential for sea water inundation in certain years. Further verification is carried out on the field whether the area is experiencing inundation or not. In 2012 field verification was carried out, and the results were quite compatible with sea water inundation in the fields and model events. With data modeling we can also see forward projections and also estimate what has happened behind. From the model made in 2000 around 10.53% of the Jakarta area was exposed to coastal inundation, while in 2007 around 15.58% and in 2012 around 18.78%.

**Figure 8.** Model of tidal inundation in coastal area of Jakarta city Indonesia due to land subsidence and sea level rise in year 2000, 2007 and 2012.

From knowing initial anthropogenic land subsidence in Jakarta we can also make model widening area of flood due to land subsidence through times. By utilizing the DEM data we can see clearly the effect of the expansion of the flood area due to land subsidence. By using the same flood scenario (for example floods in 2007) but the DEM corrected in each land subsidence event, we can calculate that in 2007 around 9,057 hectares of the Jakarta area were flooded, while in 2012 around 10,325 hectares and in 2017 around 12,366 hectares. It is very visible how the expansion of floods occurred. Figure 9 shows in red color, widening of flooding area in Jakarta as consequences from land subsidence. With this figure along with figure 8 we can understand how the important of determining initial anthropogenic land subsidence in some area is.

**Figure 9.** Model of widering are of flood Jakarta city Indonesia in year 2007, 2012 and 2017 due to the effect of land subsidence.
For the Semarang case, we can see in Figure 10 that we have information on the dynamics of the water table decline starting from zero decline, initial decline to the current position of decline in recent year. The dynamics interval of water table decline was recorded from 1950 to 2010. Meanwhile, land subsidence data was recorded only from 1996 to the present. Based on information from land subsidence measurement data, we do not know when the initial anthropogenic land subsidence occurred in the Semarang area. However, after we know the correlation between land subsidence and water table decline, therefore we can estimate the initial anthropogenic land subsidence. Initial water table decline occurred in approximately 1975-1980 that means the initial anthropogenic land subsidence also occurred at that time. By knowing this, the estimated total magnitude is obtained and becomes an important parameter in the analysis of the impact of subsidence, etc.

Figure 10 also shows how land subsidence and water table decline correlates spatially with changes in residential land. It seems that the more residential areas are spread, followed by land subsidence and water table decline. The correlation would be as follows: Residential land or settlement will be closely related to people population, the more population, the more land will be converted into settlements, the more the population, the more water supplies will be needed which can be taken from ground water that causing land subsidence.

Figure 10. Visualization of spatial and graph correlation among land subsidence, land cover change and water table decline. As we can see the water table decline is starting to happen on the beginning the city growth. Assumed this is the initial time of anthropogenic land subsidence.
For the case of Bandung (as seen in figure 11), we can see information on land subsidence and water table decline is not very long in time series. Both data are only available in the 2000s to the present. On the other hand we can see how land cover changes have occurred since 1985 to the recent year. In 1985 the distribution of resident had quite a lot of meaning the initial anthropogenic land subsidence was possible before 1985. If we look at the case in Jakarta where the initial anthropogenic land subsidence occurred around 1975, then maybe in Bandung also the same time, because the development of the city of Jakarta and Bandung after the new order of second President of Indonesia (orde baru) began around the same time. This is a simple method for determining the initial time of anthropogenic land subsidence in some places. It is not very accurate but accurate enough and important for the purpose of impact analysis of subsidence.

If we extrapolate based on data and the relationship between land subsidence data and water table decline (e.g. one meter land subsidence is roughly correlated with 20 meters water table decline), the results of the extrapolation show an approximately the same year, around 1975, is initial year anthropogenic land subsidence in the Bandung area. Once again it can be said that the method used is quite simple, not of high accuracy but quite accurate and important for the purpose of analyzing the impacts caused by land subsidence.

![Figure 11](image-url)

**Figure 11.** Visualization of spatial and graph correlation among land subsidence, land cover change and water table decline. We can assumed (extrapolate) the anthropogenic land subsidence and water table decline are starting to happen on the beginning the city growth.
From the three examples in Jakarta, Bandung and Semarang, we already have an idea of how to determine anthropogenic land subsidence. This method can be adopted for other places in Indonesia. The fact is that in Indonesia there are at least 15 urban areas that have experienced land subsidence. Not to mention when we talk about peat lands, land around oil and gas exploitation, land around subsurface mines, it turns out that there are quite a lot and wide enough land subsidence occurs in Indonesia. Figure 12 shows Map of potential places for land subsidence in Indonesia (the blue color) and list of urban area that are confirmed to have land subsidence. Sea level rise value around ocean of Indonesia is also noted on the map. In some places the impact of land subsidence is evident especially in cities or urban areas in the coastal region, in the form of sea water inundation, infrastructure damage, expansion of flooding, and sea water intrusion to a decrease in environmental quality. Mitigation and adaptation should be made. The impact can be more even in forms of social and economic impact. Indeed the significant impact of land subsidence is categorized as an ecological disaster. It is like a silent killer. In the future if actions taken are less, slowly but sure there will be real disaster in some part of Indonesia.

![Figure 12. Map of potential places for land subsidence in Indonesia (the blue color) and list of urban area that are confirmed to have land subsidence. Sea level rise value around ocean of Indonesia is also noted on the map.](image)

Knowing the initial anthropogenic land subsidence is one of the first steps as well as an important step in mitigation and adaptation efforts. If we can understand how the expansion of flooding since initial subsidence or total magnitude since initial subsidence, then we can take a good direction and also comprehensive mitigation measures. Indeed in some cases we are running out for better mitigation and or adaptation since the disaster is already existed and potentially worsening. Initial anthropogenic land subsidence can also be used in the analysis of the effects of non-anthropogenic factors such as natural and tectonic compacting. Initial anthropogenic subsidence can help to quantify natural and technical compaction even better. This will also help the accuracy of the mitigation and adaptation efforts mentioned above.
4. Conclusions

Even the land subsidence in urban area of Indonesia like Jakarta, Bandung, Semarang, Pekalongan and others is quite well known today (e.g. rate per year and or magnitude in certain periods of years) base on the geodetic measurements (e.g. Leveling, GNSS and InSAR), but the initial time of its occurrence, especially part influenced from anthropogenic causes, in many cases remains unclear due to data limitation. As mentioned previously the initial time is crucial for determine total magnitude, while this total magnitude is an important information for assessing the impact of subsidence. For example to understand the occurrence of tidal inundation, widening area of flood, calculating cost of adaptation, etc. we need to know very exact the total magnitude of anthropogenic subsidence from its first initiation.

We already have an idea of how to determine anthropogenic land subsidence. We can simply predict the initial time of anthropogenic land subsidence by a simple method which is analyzing of correlating of land subsidence data with initial water table decline. Furthermore, water table decline can be related to city growth through land cover change information. If we can find two data which are land cover changes (especially first period of city or urban development) and record of initial water table decline, then we can estimate the initial time anthropogenic land subsidence quite accurately and sufficient.

This method can be adopted for other places in Indonesia. The fact is that in Indonesia there are many urban areas that have experienced land subsidence. Not to mention when we talk about peat lands, land around oil and gas exploitation, land around subsurface mines, it turns out that there are quite a lot and wide enough land subsidence occurs in Indonesia. In some places the impact of land subsidence is evident especially in cities or urban areas in the coastal region. Mitigation and adaptation should be made. The impact can be more even in forms of social and economic impact. Indeed the significant impact of land subsidence is categorized as an ecological disaster. In the future if actions taken are less, slowly but sure there will be real disaster in some part of Indonesia. Knowing the initial anthropogenic land subsidence is one of the first steps as well as an important step in mitigation and adaptation efforts.

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