Remotes sensing capabilities on land subsidence and coastal water hazard and disaster studies

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Abstract. Lowering on land surface which is commonly known as land subsidence is quite an issue in Indonesia today especially for coastal low elevation young sediment area, including cities or urban area lies on top of it. Jakarta is one of the city with most famous for land subsidence at the moment. If we go along northern coast of Java, many cities are experiencing the same situation as Jakarta and even more. As the impact from land subsidence, those coastal areas may experience water disaster such as sea water inundation and intrusion, wider expansion of flood and aquifer damage. Investigation of such areas in large and even regional scale with limited research budget is a problem. Nevertheless we found way for at least reducing the problem by using the capabilities of remote sensing product, geological and geostatistic data. We can identify land subsidence, coastal effected by subsidence like mentioned above by only time series of satellite image archive such as Google earth or Landsat free distributed, geological map and published geostatistic data like water consumption and population growth, with sample validated by land subsidence measurement and groundwater monitoring points. This paper will highlight our finding.

1. Introduction

Land subsidence is defined as lowering of the ground with respect to times and a reference system of height such as the sea level, geoid or ellipsoid surface. Geodetic measurements (e.g. Leveling, GNSS and InSAR) as depicted in figure 1 can identify rates per year and also magnitude even is small value [1-6]. Generally 1-20 centimeter per year and a total 1-4 meter are being observed. In Indonesia today especially for coastal low elevation young sediment area, including cities and urban area lies on top of it, land subsidence is quite an issue. Jakarta is one of coastal city with most famous for land subsidence at the moment. Beside Jakarta if we go along northern coast of Java many cities and urban area are experiencing the same situation as Jakarta (see figure 2). Beside land subsidence, those coastal areas may experience water disaster such as sea water inundation, wider expansion of flood, sea water intrusion and aquifer damage.

The impact of land subsidence is evident, especially in cities or urban areas in the coastal region. These impacts can be in the form as water disaster mentioned above. Infrastructures damage to a decrease in environmental quality are also form of subsidence impacts [7-9]. The significant impact of land subsidence is categorized as an ecological disaster (figure 3). Millions 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.

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 [10, 11]; Geo-technique play role to subsidence from load of buildings and constructions, natural
consolidation of alluvium soil, soil setting/reclamation, etc.[12, 13]; The geo-hydrology given consequences to subsidence from excessive groundwater extraction [14-16]. 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.

Figure 1. Geodetic measurements (e.g. Levelling, GNSS and InSAR) can identify rates per year and also magnitude even is small value of land subsidence

Figure 2. Graphics of land subsidence in several coastal city in Indonesia including Jakarta city from 1970 until recent years. Note that subsidence started to occur in late seventy to early eighty
The impact of land subsidence in a form of tidal inundation, that is in some places is already significant and categorize as ecological disaster.

Investigation of such areas in large and even regional scale like along northern coast of Java with limited research budget is a problem. Establishing GNSS (Global Navigation Satellite System) Network and purchasing and processing InSAR (Interferometric Synthetic Aperture Radar) data is somehow quite costly for such large area. We try to found way for at least reducing the problem by using the capabilities of others remote sensing product beside the GNSS and InSAR and also some geostatistic data like information of water consumption and population growth. We try to identify land subsidence area, coastal subsidence affected area such as sea water inundation and sea water intrusion and even aquifer damage by only analyzing time series of satellite image archive such as Google earth or Landsat free distributed with sample validated by land subsidence measurement and groundwater monitoring points as well as mentioned geostatistic data. This paper will highlight our finding.

2. Data and methods

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. 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 [17]. It can be seen how the increase in people population is accompanied by an increase in the water supply. Population growth can be depicted from land cover change. The more color of resident area existed the more population expected to existed as well. While the land cover change derived from time series of remote sensing image data, the information of population growth and consumption of water generally come from published geostatistic data.

According to some research findings [14-18] clearly conclude the relationship between land subsidence and groundwater exploitation. The beginning of loss of artesian pressure and the starting decline in ground water 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 and even the potential of aquifer damage. Figure 5 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.

So by using the explanation above, we can relate land subsidence with land cover change information (from Landsat data processing), geostatistic population growth data and water supply and geological map as boundary. If we don’t have land subsidence measurement data, especially land subsidence maps, then...
we can expect whether land subsidence occurs or not from land cover changes accompanied by geostatistic and geological data as mentioned. In the results and discussion section, some examples are given of how the allegations are relevant or not. We have the records of land subsidence measurements in Jakarta and Semarang, including data on groundwater consumption indicated from the water table decline data as validator. The hypothesized results do not yet reflect high accuracy, however they can be used as reliable general evaluation in spite the research we do with the constraints of limited research funding.

![Figure 4](image)

**Figure 4.** Graph of population growth in Australia in correlation with graph of total annual supply of water since 1950 to 2000 [modify from Collin and John]

![Figure 5](image)

(a) ![Figure 5](image) (b)

**Figure 5.** 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 (modify from Kaneko Toyota and Gavin Galloway)

By collecting time series data such as satellite images from Google data, in the coastal area, we can see the hue of sea water inundation. We can simply say that the area experienced land subsidence. Sea water inundation can occur because coastal areas which are generally low in elevation to sea level, due to subsidence, the coastal area eventually becomes lower in elevation to sea level and finally there is sea water inundation. Estimation of sea water intrusion and potential of coastal aquifer damage is also can be though from those remote sensing data. In the results and discussion section, some examples are given of how the allegations are relevant or not. We have the results of the measurement of land subsidence in Pekalongan and Demak, in the eyes of the time series data, etc.
3. Result and discussion

Land cover change information can be relatively easy to process from time series satellite images like Landsat images. Figure 6 shows land cover in the Jakarta area starting from 1972, then 1993 and in 2005 (modified from Indonesia Geological Agency [19]). It is seen that the resident area shown by red is still relatively small with concentration in the central part of Jakarta to the north in 1972. In 1993 the resident area extends to almost all regions and leaves only open space in some parts south of Jakarta. Meanwhile in 2005 the Jakarta area was dominated mostly by residents. Figure 7 shows the land cover in the Semarang area in 1972, 1992 and 2005 [19]. In 1972 the resident area indicated by red was concentrated in the northeast part of Semarang. Over time the spread of the resident was seen to the west and south. The expansion of the resident area both in Jakarta and or Semarang shows the increasing number of people polling who lives in those areas. This time series of land cover change is one of main data to study land subsidence as explain in introduction as well as on section data and methods. We assumed resident area will be correspond with land subsidence area. Any support data for the assumption would be number of population growth, information on water consumption and information of geological data on investigated areas. For data validation we collected land subsidence from geodetic measurements and water table decline from well monitoring.

![Figure 6](image_url)  
**Figure 6.** Three maps showing land cover of Jakarta area in 1972, 1993, and 2005 (modified from Indonesia Geology Agency). Red color represent 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.

![Figure 7](image_url)  
**Figure 7.** Three maps showing land cover of Semarang area in 1972, 1992, and 2005 (modified from Indonesia Geology Agency). Red color represent large number development of housing and the typical while the purple one is fish pond area and the green one is open space area including agricultural and plantation area.
With the collected land subsidence information of Jakarta area from 1970 to 2015 (as in the figure 8) using several geodetic technique including remote sensing, we would know that the initial anthropogenic land subsidence in Jakarta is started since 1975. Around the same year, a loss of artesian pressure and declining water table has begun to occur as well base on well monitoring. 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 or vice versa. Meanwhile figure 8 also shows how land subsidence and water table decline correlates spatially with changes in residential land derived from remote sensing data. It seems that the more residential areas are spread, followed by land subsidence and water table decline.

So, if somehow due to limited research budget as mentioned several times before, we cannot afford to measure land subsidence, we can try to use time series of land use change by processed remote sensing data (e.g. Lansat). From resulted processing, the grown of residential area might indicate land subsidence area if the people consume a lot of groundwater. How we might know is by collecting geostatistic data. As for the boundary of subsidence area, beside boundary of resident area we can include boundary of sedimentation area from geological map as constrain.

Figure 8. Visualization of spatial and graph correlation among land subsidence, land cover change and water table decline in Jakarta. As we can see the anthropogenic subsidence started when the resident area grown, use groundwater increased that making water table to decline.
Figure 9 will try to explain how the correlation between land cover, geological data and land subsidence would be. As previously assumed that the resident area can be predicted as a land subsidence area. In figure (a) of figure 9, it shows land cover in 2005 in the Jakarta area. The red color indicates the resident area. Figure (b) shows the geological setting of the Jakarta area, where light red and pink are the young alluvium sediment areas. Based on the theory and empirical evidence that the area of young alluvium sediment is an area vulnerable to land subsidence if the groundwater is taken and also if given a burden [12-16]. If we combine the resident area that is suspected to consume quite a lot of groundwater and also put a strain on the young alluvium sediment, then that is where the land subsidence is predicted (figure 9 part c). After being validated by the map of subsidence results from geodetic measurement and model interpolation, it can be seen that the suitability is quite good as shown in figure (e).

Of course we will not get a very accurate match between the data we compare because there are still many parameter data that play a role there. For example, whether everyone uses groundwater or only a part, is important data and influences the suitability of the area subsidence prediction model based on remote sensing land cover data. For this reason, as has been mentioned several times above, geostatistic data is part of the main data that information must be obtained. For example groundwater users in Jakarta are around 40% of total users, and according to information that in northern Jakarta is the place where most people use groundwater because the water supply network has not yet reached the area. From here the prediction model will be increasingly convincing. The idea of prediction of land subsidence area without any measurements in the area would be quite relevant with only use remote sensing land cover data, geostatistic and geological data, under problem of limited budget on the research activities.

![Figure 9. Maps that illustrate how to predict land subsidence from remote sensing land cover data, geological data, and land subsidence map data as a result of measurement and interpolation models as validators in the Jakarta area. It can be seen that the prediction is quite good.](image)

We can see in figure 10 that we have information on the dynamics of the water table decline starting from zero declines in early 70 to the current position of decline in recent year in Semarang area. 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 by extrapolation. Since the initial water table decline occurred in approximately 1975-1980, that means the initial anthropogenic land subsidence also occurred at that time. 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.

Once again this is an example on how we can try to use time series of land use change by processed remote sensing data (e.g. Lansat) to predict land subsidence area. From resulted processing, the grown of residential area in Semarang, it might indicate land subsidence area if the people consume a lot of groundwater. To help the conclusion we add geostatistic data and geological data and processed as previously explained.

Figure 10. Visualization of spatial and graph correlation among land subsidence, land cover change and water table decline in Semarang. 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. The city growth reflected clearly from expanding of residential area (red color on the map)

Figure 11 will try to explain one other example of how the correlation between lands cover, geological data and land subsidence looks a like. As previously assumed that the resident area with many consumption of ground water can be predicted as a land subsidence area. In figure (a) in Figure 11 shows land cover in 2005 in the Semarang area. The red color indicates the resident area. Figure (b) shows the geological setting of the Semarang area, where yellow is the young alluvium sediment area and others
color represent hard type of soil such as lime stone and mountain alluvium fan. Based on the theory and empirical evidence that the area of young alluvium sediment is an area vulnerable to land subsidence if the ground water is taken and also if given a burden. If we combine the resident area that is suspected to consume quite a lot of ground water and also put a strain on the young alluvium sediment, then that is where the land subsidence is predicted (figure 11 part c). After being validated by the map of subsidence results from measurements and model interpolation, it can be seen that the suitability is quite good as shown in figure (e).

Of course, like the results of the previous example in Jakarta, we will not get a very accurate match between the data we compare because there are still many parameter data that play a role there. We must add information whether everyone uses groundwater or only a part, because it is important data and influences the suitability of the prediction model of the area of subsidence based on remote sensing land cover data. There are also cases where open space areas such as agriculture that use a lot of ground water, the region will be vulnerable to land subsidence, but not predictable in the subsidence prediction model that we make.

Figure 11. Maps that illustrate how to predict land subsidence from remote sensing land cover data, geological data, and land subsidence map data as a result of measurement and interpolation models as validators in the Semarang area. It can be seen that the prediction is quite good.

Besides we can predict the area of land subsidence by using remote sensing land cover change data, this data can be used as an area indicator data for potential sea water inundation and intrusion and / or aquifer damage problems. Nevertheless this indicator needs to be strengthened with geostatistic population growth data, groundwater consumption and geological conditions around the coastal area. The level of accuracy is still far from what is desired but at least with all the limitations of the data, it will be quite valuable. The information would be valuable for mitigation and adaptation against land subsidence around coastal area.

In spite of their limitation as briefly shows from two examples, we can use those two examples above as roles model to create prediction models of land subsidence base on remote sensing land cover change together with geostatistic and geological data for wider areas like the whole northern coast of Java. At least we can identify where is the indication of potential places of significant subsidence with high risk to become a disaster in the future. In this case problems on the budget to do research on large and even
regional scale can be reduced. In other perspective we can use the simple model of prediction of land subsidence to highlight priority areas for more intensive research.

Moved to next research focus, by collecting time series data such as satellite images from Google data, in the coastal area, fortunately we can see the hue of sea water inundation. Sea water inundation can occur because coastal areas which are generally low in elevation to sea level, due to subsidence, the coastal area eventually becomes lower in elevation to sea level and finally there is sea water inundation. So, we can simply say that the area experienced sea water inundation is the area experienced land subsidence. Figure 12 shows time series of Google images data around Demak area in 2003, 2010 and 2015 while figure 13 shows time series around Pekalongan area in 2006, 2013 and 2018. It clearly seen that both of the area is experiencing sea water inundation and it is predicted by this research because the area is also experiencing land subsidence.

![Figure 12](image1.png)

**Figure 12.** Time series of Google images data around Demak area in 2003, 2010 and 2015. It clearly seen the area is experiencing sea water inundation.

![Figure 13](image2.png)

**Figure 13.** Time series of Google images data around Pekalongan area in 2006, 2013 and 2018. It clearly seen the area is experiencing sea water inundation.

Demak coastal area which was once dominated by agricultural land and ponds, as shown in figure 12 for 2003, it turns out that in 2015 most of it has turned into a sea inundation areas. If calculated the inundation area can reach 3000 hectares. Similar to the coastal area of Pekalongan which was once dominated by agricultural land, ponds and also the resident area as shown in figure 13 for 2006, it turns out that in 2018 it was recorded that around 5,000 hectares have been turned into inundation areas due to sea flooding. If we look again, there are still many coastal areas in the northern coast of Java and even in other Indonesian coastal areas that have the same problems as Demak and Pekalongan.

To validate whether the coastal areas of Demak and Pekalongan are experiencing land subsidence, fortunately we have GPS and InSAR measurements around those areas. It turns out that it is true in both areas experiencing land subsidence. Figure 14 shows a graph of land subsidence that occurs in Demak. The graph shows that the average land subsidence can reach 9 to 13 centimeters per year. In Pekalongan area it is recorded that the rate can be up to 15 centimeter per year and even more in certain areas. The graphic patterns also tend to be linear which means that land subsidence will still occur for several years.
to come if the effort to stop it or at least reduce it is not done. In several locations in the world it has been proven that the effort to stop land subsidence is to stop taking ground water.

![Land sinking and inundated]

**Figure 14.** Satellite images shows sea water inundation, the graphs shows land subsidence and pictures shows documentation of inundation in Demak area

4. **Conclusions**

Remote sensing data beside InSAR and GNSS has the capabilities in helping studies of land subsidence and coastal water disaster, especially when we face limited research budget. We can try to use time series of land use change by processed remote sensing data to predict the land subsidence area. The grown of residential area around coastal young alluvium sediment might indicate land subsidence area if the people consume a lot of groundwater. Further consequences the coastal water disaster (e.g. sea water inundation and intrusion, damaging aquifer, etc.) can also predicted. Furthermore by collecting time series data such as satellite images from Google data, in the coastal area, indeed we can also see directly a disaster of sea water inundation. Sea water inundation can occur because coastal areas which are generally low in elevation to sea level, due to subsidence, the coastal area eventually becomes lower in elevation to sea level and finally there is sea water inundation.

Of course we will not get a very accurate prediction when we match between the data because there are still many parameter data that play a role there. For example, whether everyone uses groundwater or only a part, is important data and influences the suitability of the area subsidence prediction model based on remote sensing land cover data. Nevertheless at least we can identify where is the indication of potential places of significant subsidence with high risk to become a disaster in the future. In this case problems on the budget to do research on large and even regional scale can be reduce. In other perspective we can use the simple model of prediction of land subsidence to highlight priority areas for more intensive research. If we do more spatial analysis using GIS (Geographic Information System) tools it might improved the model prediction. We will do in the next research.
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. So, roles of remote sensing is very much expected. If we go back to the introduction we can see that the impact of land subsidence is evident especially around coastal area and in certain places they are already formed ecological disaster. We should do more mitigation and adaptation with one part come from this remote sensing research.

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