ESTIMATING LAND SUBSIDENCE IN RELATION TO URBAN EXPANSION IN SEMARANG CITY, INDONESIA, USING INSAR AND OPTICAL CHANGE DETECTION METHODS

Magaly Koch(1), Ahmed Gaber(2), Noura Darwish(2), Juliette Bateman(1), Sucharita Gopal(1) and Muhammad Helmi(3)

(1) Boston University, Center for Remote Sensing and Dept. Earth & Environment, Boston, USA
(2) Port Said University, Geology Dept., Port Said, Egypt
(3) Diponegoro University, CoREM, Semarang, Indonesia

ABSTRACT

Land subsidence and flooding events in coastal Semarang City, Central Java, has had severe impacts on the region's population and economy. This work presents a methodology based on a combination of InSAR subsidence mapping and optical classification and change detection techniques to estimate the spatial distribution of subsidence rate and assess its impact on urbanization growth, land conversion and coastal flooding. Significant spatial relationships were found between urban zones (building density), flood extent (shoreline retreat) and subsidence rates. The overexploitation of aquifers and city zoning development contribute to accelerate subsidence rates.

Index Terms— coastal urban hazards, land subsidence, InSAR, optical satellites, change detection

1. INTRODUCTION

Indonesia's geologic and geographic setting as part of the Pacific Ring of Fire, means that this region is particularly vulnerable to multiple geological hazards (earthquakes, landslides, land subsidence, volcanic eruptions etc.). The archipelago is characterized by a chain of volcanos and rugged topography, thus the majority of people in Indonesia live in coastal areas where flat areas are used for agriculture, aquaculture and urbanization. Coastal urban areas in northern Java, which includes three major cities (Jakarta, Semarang and Surabaya), are prone to sever flooding, beach erosion, and seawater intrusion making these areas particularly vulnerable to climate change [1].

On the other hand, land conversion is accelerating in recent years as urban areas expand, population density increases, and demands for food and water security rises. Located in a tectonically active area between the Asian and Australian plates, the whole island is subjected to tectonic movements with the southern part of Java being uplifting while the northern part is sinking. Semarang is one of the urban agglomerations in northern Java suffering from land subsidence, beach erosion and flooding. Large scale removal of mangroves for aquaculture, expansion of built-up and impervious areas along the coast have reduced the capacity of the land to buffer the effects of tidal floods and river bank overflow [2]. In this context, coastal subsidence monitoring, especially in urban settings, is critical for assessing and mitigating the effects of coastal hazards and enabling sustainable adaptation to changing conditions.

2. MATERIALS AND METHODS

This work presents a methodology based on a combination of InSAR subsidence mapping and optical classification and change detection techniques to estimate the spatial distribution of subsidence rate and assess its impact on urbanization growth, land conversion and coastal hazards. The following data processing workflow was adopted.

(1) Optical images (Sentinel-2) were used to classify urban areas into zoning areas based on compactness, patch size and density of buildings. The object is to identify zones (e.g. industrial areas, informal settlements etc.) that are particularly vulnerable to flooding and subsidence because of the proximity to the shoreline, topographic and geologic conditions (low lands and unconsolidated alluvial soil), building load and population density. Several classification methods (e.g. Maximum Likelihood, Support Vector Machine, Random Forest etc.) were tested and validated using a GIS database from Semarang city's urban planning department and high resolution Google Earth images. The resulting classification map was then compared to the subsidence map to assess which city sectors and towns are most affected by land subsidence and thus vulnerable to coastal flooding.

Time series of Landsat images from 2002 to 2018 were used to analyze changes in the city of Semarang and surrounding coastal areas. Various indices (vegetation index, built-up index, water index) [3] were used to identify land loss and land gain along the coastal area. Changes between current and historical conditions were determined by averaging monthly values for each of the three indices (vegetation/built-up/water) over a number of year and calculating the difference between current and historic monthly trends (per index) on a per-pixel basis. The objective is to correlate changing patterns in subsidence rate with changing patterns of urbanization, land conversion and flood extent along Semarang's coastal areas.

(2) The phase differences between four Sentinel-1 IW SLC products over a 1-year time period from February 2018 to January 2019 were used to estimate the land subsidence along the coastal area of Semarang City, using the following InSAR methodology. The Interferometric Wide (IW) swath mode is the main acquisition mode over land for Sentinel-1. It acquires data with a 250 km swath at 5 m by 20 m spatial resolution (single look complex). The two pairs (four SAR scenes) were co-registered into a stack after selecting the image of January 2019 as a master image and the others were selected as slaves. The orbital correction was performed using the orbit auxiliary file to correct the phase differences that are related to changes in the flying height of the satellite. In addition, the interferograms were generated by cross multiplying the master image with the complex conjugate of the slave. Moreover, the flat-Earth phase, which is the phase present in the interferometric signal due to the curvature of the reference DEM was estimated and subtracted from the complex interferograms. The coherence between master and slave images was also estimated and the 0.3 threshold value was used to select good candidate pixels for producing good interferometric results and subsequently estimating accurate deformation.

For this step, the interferograms were flattened by removing the topographic phase using a reference high resolution DEM with 5 m spatial resolution that was derived through interpolation of spot heights from a topographic map at scale 1:50,000. In order to properly unwrap the generated interferograms, the Goldstein phase filtering with 3 X 3 window size was performed to increase the signal-to-noise ratio. The filtered interferograms were exported to the Snaphu software to apply the unwrapping. The unwrapped interferograms were later ingested back to the Snap toolbox [4] to estimate the deformation and the land subsidence in Semarang City.

3. RESULTS AND DISCUSSION

The analysis of Landsat images within a 15 year time period highlights significant land use changes in response to shoreline changes and urban expansion. There is land loss along the entire coastline and is best seen close to Semarang. Even with the eroding shoreline there is urban expansion occurring in similar areas. There has been a boom of housing along the coastal area as well as land conversion in surrounding agricultural areas. Such housing booming and expansion relies heavily on groundwater abstraction for urban, industrial and agriculture uses. Recent studies [5] have shown that the increased exploitation of the confined groundwater under the city is reducing the piezometric stress of the aquifer-aquitard system, making it very easy for clayey soils to be compacted by building loads and infrastructural expansion which ultimately contribute to rapid land subsidence. The geology of the coastal flats in and around Semarang City plays an important role in land subsidence [6]. Within the city perimeters there runs an E-W boundary between unconsolidated marine sediments and relatively solid volcanic rocks (Figure 1). This boundary demarcates where most wells are preferentially located, with groundwater pumping occurring mostly in the flat and soft sediments. Similarly subsidence rates change significantly across this boundary with strong subsidence occurring in the alluvial coastal sediments (thick layers of calcareous and shell-bearing clay), less subsidence in the consolidated Damar Formation (tuffaceous sandstone, conglomerate, and volcanic breccia) and no subsidence in the sedimentary rocks of the Kerek (sand/claystones, marls) and Kaligetas Formations (clastic sediments) [6]. Both Quaternary marine and volcanic rock formations contain multi-layered aquifer systems with highly compressible clay layers separating them. The most exploited aquifer is the deeper Damar Formation aquifer due to its fresh water quality and excellent transmissivity. However, the exploitation of this deeper aquifer has caused a depression of the piezometric contours which exerts additional pressure on the overlying aquitard. This has led to a compaction of the aquitard which causes land subsidence [5]. In this geological setting, the expansion and density of building loads and infrastructure development over highly compressible sediment layers plays an important role in accelerating surface subsidence. Correlation of the urban area classification, land conversion change map, and Sentinel-1 derived subsidence map indicates some significant spatial relationship between urban zones (building density), flood extent (shoreline retreat) and subsidence rates. Furthermore, land conversion (agriculture to aquaculture and vice versa) along the shoreline shows some important differences with land loss mostly occurring east of and land gain west of

Semarang City (Figure 2). This pattern is corroborated by the subsidence rate map where the western coastal area shows little to no subsidence (green color) and the eastern part shows significant subsidence (red color).

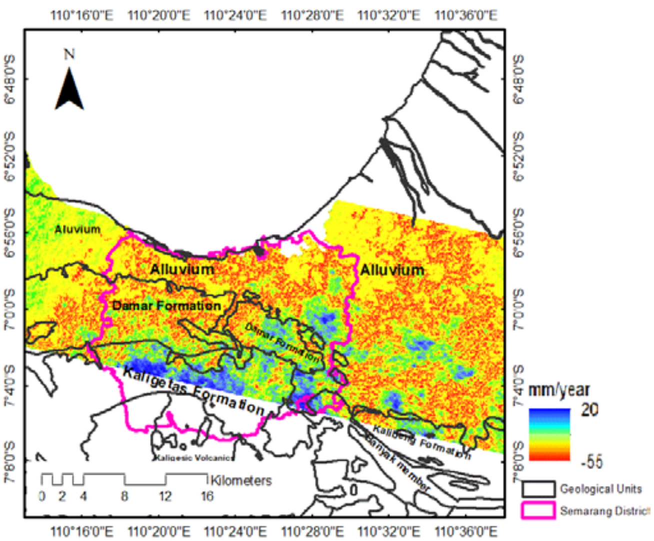

Figure 1. Sentinel-1 derived subsidence map of Semarang City and coastal area with geological units overlaid.

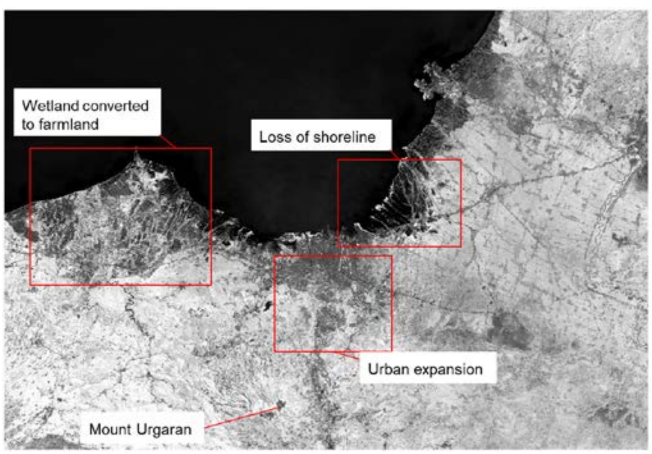

Figure 2. NDVI change map of Landsat images (2002-2017) showing land loss and gain along the coast.

4. CONCLUSIONS

Land subsidence and flooding events in coastal Semarang has had severe impacts on the region's population and economy. The quality of life in the region has been affected by continued and devastating coastal flooding and subsidence events. The combined use of InSAR and optical change detection methods is an efficient and effective way to monitor severity of the phenomena and vulnerability of coastal urban areas.

5. REFERENCES

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