Explaining land subsidence variation along the north coast of Java for Semarang and Pekalongan, Indonesia

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Introduction

Globally, sea-level rise is an increasing problem, enhancing inundation, salinization and potentially leading to land loss in coastal areas (Rahmawati et al., 2013). Global absolute sea-level rise is around 3 mm/year but relative sea-level rise, including vertical land motion (Esteban et al., 2020; Shirzaei et al., 2021) can be much larger (Herrera-Garcia et al., 2021). A region with high rates of relative sea-level rise is the north coast of Java (Bott et al., 2021), where coastal land subsidence occurs with rates of over 100 mm/year. This was already noted in the IPCC report of 2013 (IPCC, 2013). The cities of Semarang (population: 1.66M; BPS, 2021) and Pekalongan (population: 0.31M; BPS, 2021), located at the north Java coast, experience high subsidence rates (Sarah et al., 2021; Abidin et al., 2013). Although land subsidence is a known issue in these cities, the spatial and temporal variation and the driving processes are not well-understood and quantified. The extent and magnitude of land subsidence is often underestimated, and hazard-preventing measures mainly focus on short-term flood protection measures instead of mitigation measures to decrease subsidence rates (Bott et al., 2021). This study uses Sentinel-1 Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) data, processed by Sensar (Sensar, n.d.) to investigate the spatial and temporal variation in subsidence in the Semarang and Pekalongan regions and attempts to disentangle the various causes of the observed subsidence. The PS-InSAR vector datasets, containing spatially and temporally variable point data, cover two study areas encompassing Semarang and Pekalongan. The datasets are thoroughly analysed on their spatial and temporal variation and behaviour. The variation is expected to be induced by different subsidence drivers, both natural and human-induced. Since Semarang and Pekalongan are both largely situated on young alluvial material, natural compaction is expected (Abidin et al., 2013; Marfai & King; 2007). Human-induced groundwater extraction and land cover changes are well known to significantly affect subsidence rates (de Wit et al., 2021; Minderhoud et al., 2018; Kondolf et al., 2014; Chaussard et al., 2013). The goal of this research is gaining and improving insights on the land subsidence processes and driving forces in this study area. These insights can help to increase awareness on the extent of the land subsidence and aid the development of effective land and water management measures to reduce coastal subsidence and its impacts.

Data and methods

To gain insight in the subsidence processes and driving forces, we studied spatial and temporal correlations between the PS-InSAR data and datasets of natural and human-induced subsidence drivers. Figure 1 shows the InSAR data for the regions of Pekalongan and Semarang and their surrounding area. Data availability and methodology of analysed components are discussed below.

PS-InSAR/InSAR

The PS-InSAR vector dataset consists of a large set of PS points in the Pekalongan and Semarang regions. Each point contains a timeseries of accumulated subsidence (mm) (projected to the vertical) on its specific location, being a building, bridge or other persistent object at the surface. The timeseries range from 22nd of November 2015 until the 31st of March 2021. The Sentinel-1 images at Central-Java were taken from a descending orbit at around 22:35 UTC, with a 12-day interval. The subsidence rates were derived relative to stable reference areas (i.e. no vertical deformation) located inland on volcanic bedrock formations.

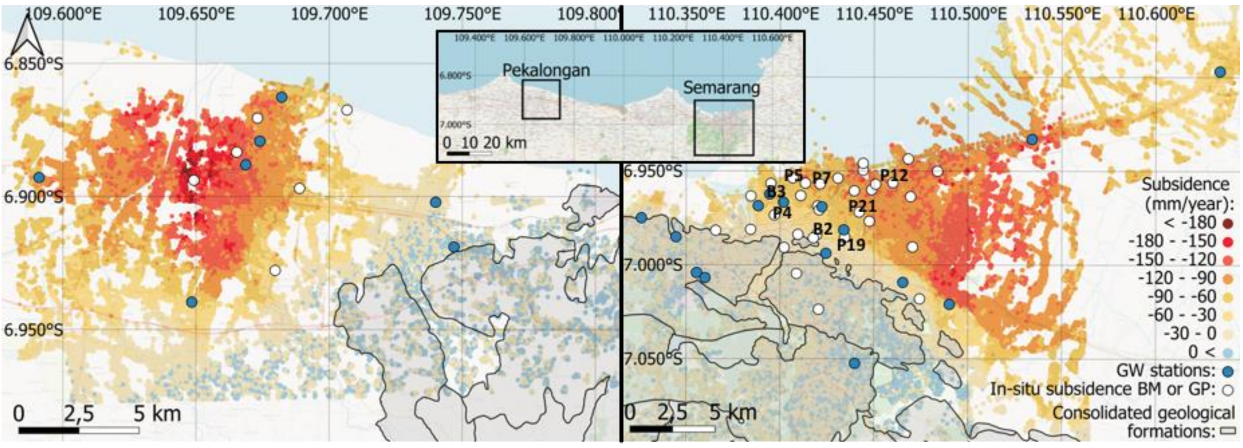

Figure 1: Study areas in Pekalongan (left) and Semarang (right). The figures show the PS-InSAR-derived subsidence rates. Locations where land subsidence is monitored by benchmarks (BM) or geodetic measuring points (GP) are shown in white. Groundwater (GW) monitoring stations containing data on hydraulic head are shown in blue. The transparent, grey polygons show the locations with more consolidated volcanic bedrock formations at the surface.

Spatial variation in the InSAR data is analysed on large scale statistical differences and local infrastructural loading. Temporal dynamics are studied by seasonality analysis.

In-situ benchmark and geodetic points

The PS-InSAR data were compared with subsidence timeseries of founded benchmarks (monitoring subsidence over the depth interval between the surface and the benchmark depth, between 67m and 110m) and geodetic point measurements (registering total surface movement) resulting from levelling surveys. As the observation could not be linked to an individual PS point, all PS points within a 10 to 40m radius around the local data points were averaged and compared with the in-situ measurement. For Semarang the timeseries for three benchmarks and 25 geodetic points range from 2011 to 2017 (data from the Ministry of Energy and Mineral Resources – ESDM, Central-Java). For Pekalongan, six recently installed benchmarks monitor from 2021/2022 to present (data acquired from the Regional Development and Planning Agency – Bappeda Pekalongan). Locations of benchmarks and geodetic levelling locations are displayed in Figure 1.

Geology

A large-scale spatial variation analysis on subsidence was done using geological data. Geological maps acquired from ESDM and Universitas Gadjah Mada (UGM Yogyakarta), show a clear division between young alluvial and coastal geological units and older, consolidated volcanic formations. The locations where these consolidated bedrock formations surface are displayed in Figure 1.

Land Cover

Open-source Land Cover (LC) data (300m resolution) from ESA CCI Copernicus (Copernicus, n.d.) was compared with the PS-InSAR data. We hypothesise an increase in median subsidence rate from natural land cover classes (e.g. tree cover) to more human-impacted land cover classes (e.g. urban), a known relationship found elsewhere in the world, for example, in the Mekong delta (Minderhoud et al., 2018).

Groundwater Extraction and Hydraulic Head

The subsidence data was compared with datasets on groundwater extraction and hydraulic head. The groundwater extraction data is only available for Semarang and shows monthly extraction volumes of businesses and catering industry, separated per districts (2018-2021). This dataset was acquired from the regional Revenue Agency (Bapenda Semarang). Timeseries of hydraulic head were obtained from groundwater monitoring stations (Fig. 1) in both Semarang and Pekalongan, acquired from the ESDM.

Results

PS-InSAR/InSAR

Land subsidence rates range up to ~180mm/year in Semarang and ~205mm/year in Pekalongan. This is up to 68 times larger than global sea-level rise, underscoring the magnitude of the challenge these coastal cities are facing. Annual seasonal variability in subsidence is clearly visible in the analysed period (2016-2020) and rates in both Semarang and Pekalongan are lowest in April-June and highest in October-December (Fig. 2). We hypothesise this is caused by the rainy season (November-March). As groundwater will recharge

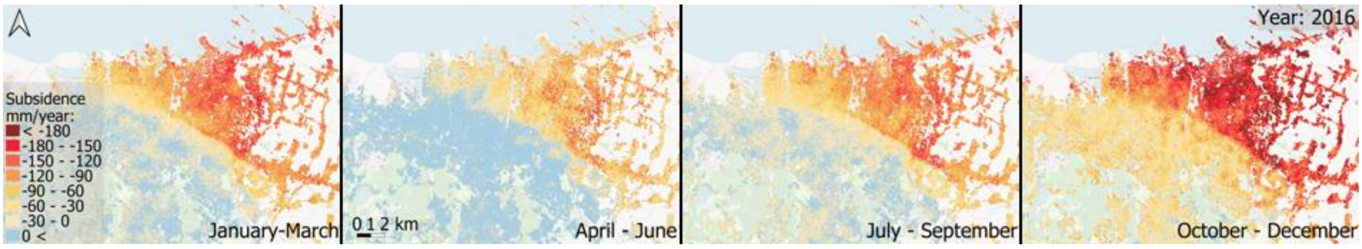

Figure 2: Seasonal variation in subsidence rate in the Semarang study area over the year 2016. The four maps show the three-month mean subsidence rate for four consecutive periods. We hypothesise that the variability is caused by the rainy season (November-March). As groundwater will recharge and at the same time its demand may decrease during and right after the rainy season, extraction-induced subsidence is expected to decrease during and shortly after the rainy season (Apr-Jun) and to increase again during dry season (Oct-Dec).

and at the same time its demand may decrease during and right after the rainy season, extraction-induced subsidence is expected to decrease during and shortly after the rainy season (Fig. 2, Apr-Jun) and to increase again during dry season (Fig. 2, Oct-Dec). To assess local and depth-dependent subsidence in the urban environment, the InSAR data from large buildings and their surrounding were analysed following the approach of De Wit et al., 2021. The majority of the selected buildings showed no to little deviation in subsidence rate with its surrounding area. This implies that most of the observed subsidence occurs below the foundation depth of these buildings, i.e. pointing to deeper-rooted subsidence processes, and that spatial variation in subsidence is not induced by individual infrastructural loading.

In-situ benchmarks and geodetic points

The PS-InSAR subsidence data is plotted against in-situ founded benchmark (Fig. 3) and geodetic point measurement (Fig. 4) data. As the benchmarks in Pekalongan were installed only recently (2021-2022), hence their data is not yet reliable and only the Semarang benchmarks were analysed. Two benchmarks in Semarang (out of the total four benchmarks, only benchmark nr. 2 and 3 were surrounded by PS data) show no subsidence occurring within the monitoring depth interval (from surface to 79 & 95m) while PS-InSAR data do show subsidence (50-70 mm/year). This would indicate that virtually all the InSAR-observed subsidence must take place below the benchmark pole depth. This is peculiar as these poles are 79m and 95m deep and stretch over the majority of the alluvial and coastal geological units (Sarah et al. 2018). From a process viewpoint it is unlikely that no compaction occurs within this depth interval, which may suggest malfunctioning or an erroneous data acquisition method of the two benchmarks, but we were unable to uncover this. For the geodetic levelling points, that follow the earth surface similar to the movements observed by InSAR, the monitored subsidence correlates well to the PS data for the majority of the points (Fig. 4 A-D), with few points showing a weaker, though still positive, correlation (Fig. 4 E-F). This underscored the reliability of the PS-InSAR data.

Geology

InSAR-derived subsidence rates and geology show a clear relation. Subsidence predominantly takes place in young alluvial/coastal plains while older volcanic formations show no or relatively low subsidence rates (Fig. 5A). Therefore, the analysis of InSAR-derived subsidence with landcover and hydraulic head were focused on the alluvial/coastal plains where high rates of subsidence occur.

Land Cover

The comparison between subsidence and land cover yields a clear trend with higher rates associated to more human-influenced land cover types. In Pekalongan such a relationship between subsidence and land cover was found (Fig. 5B).

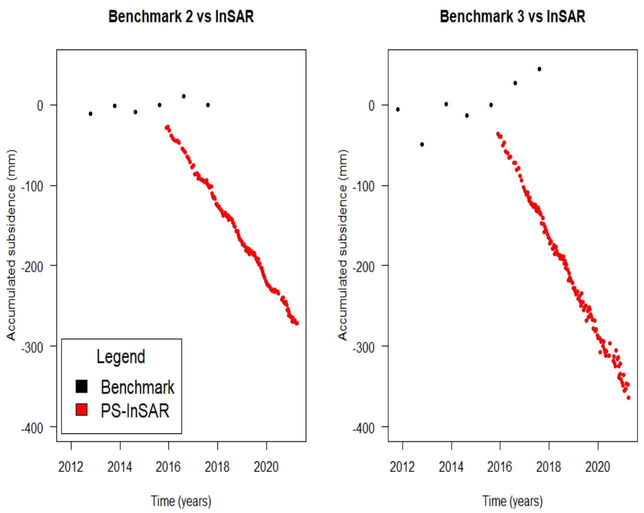

Figure 3: Accumulated subsidence (mm)registered by benchmarks for their respective depth intervals, 79m and 95m, and mean accumulated subsidence derived from the PS-InSAR data in a 40m radius around the benchmark location. See Fig. 1 for benchmark locations (B2 and B3).

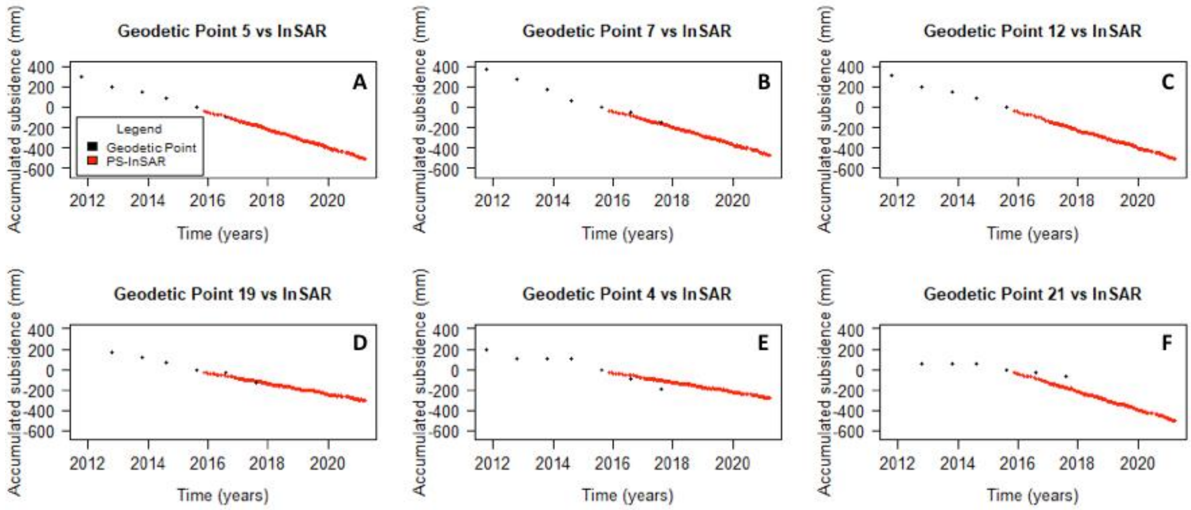

Figure 4: Accumulated subsidence (mm)measured at geodetic monitoring points (black dots) and mean accumulated subsidence derived from PS-InSAR data in a 40m radius around the geodetic point. The measuring point locations are shown in Figure 1 (P5, P7, P12, P19, P4 & P21).

Urban areas have a high subsidence rate, Crop and Mosaic Crop lower, but still high and the natural land cover classes show barely any subsidence. This is as would be expected since urban areas consist of higher population and therefore more human activities driving subsidence (e.g. groundwater extraction), resulting in higher subsidence rates. For Semarang a similar clear relation was not present in the studied data. This might be due to the strong spatial relation between geology and subsidence and to the 'patchiness' (i.e. many classes with small areas close to each other), of agricultural land cover classes in strongly subsiding areas. As for example groundwater extraction-induced subsidence affects a larger area, correlations to individual landcover classes will be weaker.

<u>Groundwater Extraction and Hydraulic Head</u>

Groundwater over-extraction is a well-known driver of high rates of subsidence (e.g. Minderhoud et al. 2017; Shirzaei et al., 2021). Unfortunately, detailed groundwater extraction data in Semarang and Pekalongan is hard to obtain since many groundwater extractions (e.g. households and agricultural wells) are not monitored. The available data on extracted volumes (total volume per district) only includes data from registered businesses and catering industry and no clear correlation was found with observed subsidence. The hydraulic head timeseries from groundwater monitoring stations are fragmented and show inconsistent patterns. We compared the median hydraulic head (in m below surface) per station to InSAR-derived subsidence. For Semarang (10 monitoring stations on alluvial plain) we found no correlation between subsidence rates and median hydraulic head (R^2=0.01), for Pekalongan hydraulic heads measured at seven groundwater monitoring stations do reveal some correlation (R^2=0.46) with InSAR-derived subsidence, indicating the occurrence of extraction-induced subsidence.

Preliminary conclusions

Subsidence in both the Semarang and Pekalongan study areas show a clear relation with geology, with high rates (>10 cm/yr) occurring in unconsolidated coastal geological units. In Pekalongan subsidence rates and patterns strongly correlate to anthropogenic activities. In Semarang this correlation is less strong, presumably due to the profound geological division between subsidence prone geological units overprinting the InSAR signal, however the high rates of subsidence and their spatial occurrence clearly indicate also human-induced subsidence in the Semarang study area and will be studied in more detail.

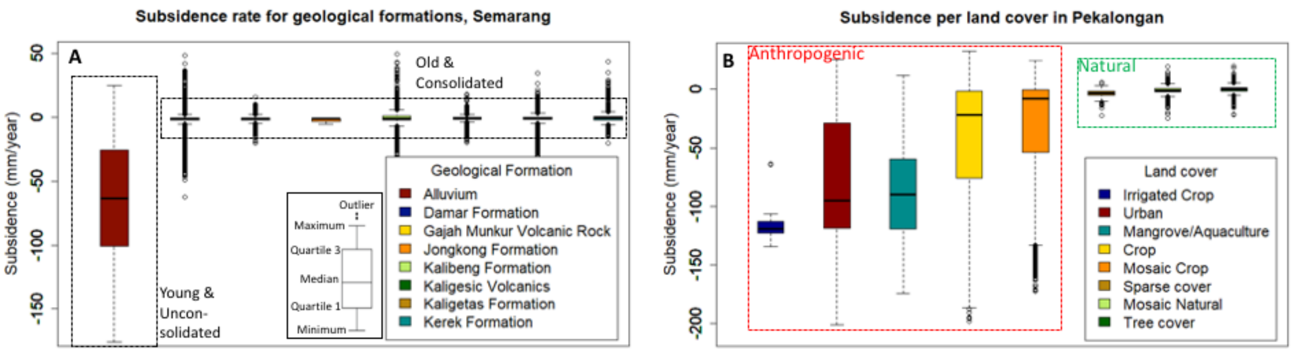

Figure 5: Figure 5A shows boxplots for subsidence rates on different geological formations in the Semarang study area. Figure 5B shows boxplots for subsidence rates on different land cover classes in the Pekalongan study area.

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References

Abidin, H. Z., Gumilar, I., Andreas, H., Murdohardono, D., & Fukuda, Y. (2013). On causes and impacts of land subsidence in Bandung Basin, Indonesia. *Environmental Earth Sciences*, *68*(6), 1545–1553. https://doi.org/10.1007/s12665-012-1848-z

Bott, L. M., Schöne, T., Illigner, J., Haghshenas Haghighi, M., Gisevius, K., & Braun, B. (2021). Land subsidence in Jakarta and Semarang Bay – The relationship between physical processes, risk perception, and household adaptation. *Ocean and Coastal Management*, 211. https://doi.org/10.1016/j.ocecoaman.2021.105775

Chaussard, E., Amelung, F., Abidin, H., & Hong, S. H. (2013). Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction. *Remote Sensing of Environment*, *128*, 150–161. https://doi.org/10.1016/j.rse.2012.10.015

De Wit, K., Lexmond, B. R., Stouthamer, E., Neussner, O., Dörr, N., Schenk, A., & Minderhoud, P. S. J. (2021). Identifying causes of urban differential subsidence in the Vietnamese Mekong delta by combining InSAR and field observations. *Remote Sensing*, *13*(2), 1–33. https://doi.org/10.3390/rs13020189

Esteban, M., Takagi, H., Jamero, L., Chadwick, C., Avelino, J. E., Mikami, T., Fatma, D., Yamamoto, L., Thao, N. D., Onuki, M., Woodbury, J., Valenzuela, V. P. B., & Crichton, R. N. (2020). Adaptation to sea level rise: Learning from present examples of land subsidence. *Ocean and Coastal Management*, *189*(July 2018), 104852. https://doi.org/10.1016/j.ocecoaman.2019.104852

Herrera-García, G., Ezquerro, P., Tomas, R., Béjar-Pizarro, M., López-Vinielles, J., Rossi, M., Mateos, R. M., Carreón-Freyre, D., Lambert, J., Teatini, P., Cabral-Cano, E., Erkens, G., Galloway, D., Hung, W. C., Kakar, N., Sneed, M., Tosi, L., Wang, H., & Ye, S. (2021). Mapping the global threat of land subsidence. Science, 371(6524), 34–36. https://doi.org/10.1126/science.abb8549

IPCC. (2013). CLIMATE CHANGE 2013 Climate Change 2013. In *Researchgate.Net*. https://www.researchgate.net/profile/Abha_Chhabra2/publication/271702872_Carbon_and_Other_Biogeochemical_Cycles/links/54cf9ce80cf24601c094a45e/Carbon-and-Other-Biogeochemical-Cycles.pdf

Kondolf, G.M., Rubin, Z.K., Minear, J.T. (2014). Dams on the Mekong: Cumulative sediment starvation. *Water Resources Research*. 50, 5158–5169. https://doi.org/10.1002/2013WR014651

Marfai, M. A., & King, L. (2007). Monitoring land subsidence in Semarang, Indonesia. *Environmental Geology*, *53*(3), 651–659. https://doi.org/10.1007/s00254-007-0680-3

Minderhoud, P. S. J., Erkens, G., Pham, V. H., Bui, V. T., Erban, L., Kooi, H., & Stouthamer, E. (2017). Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. Environmental Research Letters, 12(6), 64006. https://doi.org/10.1088/1748-9326/aa7146

Minderhoud, P. S. J., Coumou, L., Erban, L. E., Middelkoop, H., Stouthamer, E., & Addink, E. A. (2018). The relation between land use and subsidence in the Vietnamese Mekong delta. *Science of the Total Environment*, *634*, 715–726. https://doi.org/10.1016/j.scitotenv.2018.03.372

Rahmawati, N., Vuillaume, J. F., & Purnama, I. L. S. (2013). Salt intrusion in coastal and lowland areas of Semarang city. *Journal of Hydrology*, *494*, 146–159. https://doi.org/10.1016/j.jhydrol.2013.04.031

Sarah, D., & Soebowo, E. (2018). Land subsidence threats and its management in the North Coast of Java. *IOP Conference Series: Earth and Environmental Science, 118(1).* https://doi.org/10.1088/1755-1315/118/1/012042

Sarah, D., Soebowo, E., & Satriyo, N. A. (2021). Review of the land subsidence hazard in Pekalongan delta, central Java: Insights from the subsurface. Rudarsko Geolosko Naftni Zbornik, 36(4), 163–176. https://doi.org/10.17794/rgn.2021.4.13

Shirzaei, M., Freymueller, J., Törnqvist, T.E. et al. Measuring, modelling and projecting coastal land subsidence. Nat Rev Earth Environ 2, 40–58 (2021). https://doi.org/10.1038/s43017-020-00115-x

URL:

BPS (2021):

Kepadatan-Penduduk @ Semarangkota.Bps.Go.Id. (n.d.). https://semarangkota.bps.go.id/indicator/12/48/1/kepadatan-penduduk.html

population-by-sex-in-pekalongan-municipality @ pekalongankota.bps.go.id. (n.d.). https://pekalongankota.bps.go.id/indicator/12/177/1/population-by-sex-in-pekalongan-municipality.html

Copernicus (n.d.):

esa-cci-open-data-portal-project @ www.copernicus.eu. (n.d.). https://www.copernicus.eu/en/documentation/research-projects/esa-cci-open-data-portal-project

Sensar (n.d.):

index @ www.sensar.nl. https://www.sensar.nl