Monitoring land subsidence induced by groundwater change using satellite gravimetry and radar interferometry measurements. Case study: Surabaya city, Indonesia

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Abstract. Land subsidence is considered a potential hazard often occurring in densely populated urban areas due to increasing freshwater demands from groundwater pumping. The Gravity Recovery and Climate Experiment (GRACE) satellite gravimetry combined with Sentinel 1 interferometric satellite radar measurement has provided the possibility to monitor land subsidence induced by groundwater change. This study monitored land subsidence induced by groundwater change through satellite observations over Surabaya City, Indonesia, from 2014 to 2019. Persistent Scattered InSAR (PSInSAR) measurement was used to monitor land subsidence by using 114 SLC pairs. As for the groundwater perspective, Global Land Data Assimilation System (GLDAS v.2.2), which contains the Groundwater Storage Anomaly (GWS) derived from GRACE satellite observation, was used to understand groundwater's spatial and temporal variation. The results show a satisfactory agreement of satellite radar measurement with ground measurement ($R = 0.96$, RMSE = 4.92cm), while satellite gravimetry measurement showed reasonably good agreement with radar measurement as well ($R = 0.25$). Regarding the magnitude and occurrence of land subsidence over Surabaya City, the result shows that, over the past 5 years, the southern part of the city had the highest subsidence ranging from -10 mm/year to -40 mm/year. Therefore, the results conclude the capability of both satellite gravimetry and radar measurements to monitor land subsidence over an urban area. Thus, this information could be considered as an important decision-making process for disaster management purposes.

1. Introduction
Surface deformation, especially land subsidence, results in the gradual sinking of the earth's surface due to the compaction of land [1]. One of the potential causes that could induce land subsidence is groundwater extraction due to urban development, which further increases the demand for freshwater as the population and the economic activities grow [2]. Therefore, a precise monitoring framework to monitor land subsidence in a dense urban area should be carried out to mitigate the potential of such disaster.

Earth observation satellite has many advantages in regards to its kind, especially for environmental monitoring purposes. For example, an active remote sensing satellite known as Synthetic Aperture Radar (SAR) is a radar sensor mounted in an earth-orbiting satellite that produces its own signal with microwave spectrum. Thus, it can measure both phase (distance of signal return) and amplitude (strength of signal return) [3]. In addition to that, Interferometry Synthetic Aperture Radar (InSAR) is known as a technique to utilize the phase signal for measuring the surface deformation over time by calculating
the phase differences between two or more satellite radars’ acquisitions. One of the global and free public access of SAR satellite is Sentinel 1, managed by the European Space Agency (ESA) along with its capability of 6 to 12 days revisit time in C band (5.6 cm wavelength) [4].

Another kind of earth observation satellite is satellite gravimetry, known for its primary mission to measure earth's gravity variation through the change of earth's mass that is mainly caused by the change of water stored in the earth system. The Gravity Recovery and Climate Experiment (GRACE) satellite is satellite gravimetry managed by the National Aeronautics and Space Administration (NASA) with monthly global coverage and free public access with its main missions to monitor earth’s water storage, ice sheets and glaciers, sea level and the solid earth [5]. Many studies have already incorporated both InSAR and GRACE to monitor both land subsidence and groundwater depletion in agricultural areas [6],[7], as well as urban areas within a basin [8].

On the contrary, no specific study has ever been conducted in Surabaya City to monitor land subsidence with groundwater depletion as its potential cause. Several previous studies of land subsidence in Surabaya City, as it is explained in Figure 1, were mainly conducted only using ground measurements (Kurniawan 2010) or InSAR measurements [10],[11],[12] with no sufficient validation with ground measurement, and without the investigation of its potential causes, for instance, groundwater depletion. The interferometry phase measurement to monitor ground movement has a long observation period with non-obvious deformation in a short time, thus consistent and precise measurements have to be considered.

The electromagnetic wave from the SAR satellites for performing the InSAR measurement has an inherent limitation of the signal delay issue due to the troposphere effect [13]. It is revealed that this issue could cause 10 to 14 cm error measurements for monitoring surface deformation [14]. In addition to that, the global water vapor content has been revealed to increase for few decades (1979-2014), especially over the tropical climate region [15]. Therefore, these two issues highlight the importance of performing the atmospheric phase screen (APS) correction for InSAR measurement in the tropical region to ensure the precision of the obtained subsidence information.

The purpose of this study is to precisely monitor land subsidence induced by groundwater change through InSAR and satellite gravimetry observations over Surabaya City, Indonesia, from 2014 to 2019. Thus, the results could be considered during important decision-making processes for disaster management purposes.

Figure 1. Known research of land subsidence in Surabaya compared to our research

2. Methods
We used the InSAR technique and satellite gravimetry product to monitor land subsidence and the groundwater change over the study area. In regards to the InSAR technique, 114 SLC products of Sentinel 1 were used along with the Persistent Scatterer Interferometry Synthetic Aperture Radar (PSInSAR) technique to precisely monitor land subsidence, which was later validated with the ground measurement from Continuous Operating Receiver Station (CORS) in Surabaya City (CSBY) to ensure its accuracy, represented in root mean square error (RMSE) and correlation coefficient (R). In general, the phase measurements in InSAR contain multiple sources (equation (1)) [3] that need to be addressed
individually to derive the exact product depending on the purpose. The phase from deformation is the main interest of this study, and the other phase information should be retrieved individually and removed from the equation. Thus the PSInSAR technique could effectively remove the phase from flat earth, topography, and atmosphere. At the same time, the other two sources for orbital error have already been fixed from ESA’s precise orbit product of Sentinel 1. The other potential noises have yet to be considered in this study (difference in object scattering properties, thermal expansion, and other potential noises).

\[
\Phi = \Phi_{\text{flat}} + \Phi_{\text{deformation}} + \Phi_{\text{topography}} + \Phi_{\text{atmosphere}} + \Phi_{\text{orbital}} + \Phi_{\text{noise}} \quad (Eq.1)
\]

In regards to the satellite gravimetry product, we used the groundwater storage anomaly product (GWS) from Global Land Data Assimilation System (GLDAS) version 2.2 [16] [17]. The GRACE Satellite has the main capability to measure the Total Water Storage (TWS), which consists of total water in soil, snow, surface, and lastly, the groundwater (Equation (2)). Therefore, once the other components besides groundwater have already been calculated through the data assimilation process in GLDAS v2.2, it is possible to retrieve the daily groundwater storage anomaly product (GWS) by substracting the TWS with the other identified components.

\[
TWS = W_{\text{soil}} + W_{\text{snow}} + W_{\text{surface}} + W_{\text{groundwater}} \quad (Eq.2)
\]

Furthermore, we investigated whether the surface deformation or land subsidence was caused by the groundwater change using the correlation coefficient (R). In addition to that, to ensure that the InSAR measurements were accurate, we validated the PSInSAR results with the available ground measurements of CSBY CORS using the root mean square error (RMSE).

3. Results and Discussion
The land subsidence map derived from the PSInSAR technique over Surabaya City from 2014 to 2019 in Figure 2 indicates that the magnitude and occurrence in the southern part of the city have the highest subsidence rate, ranging from -10 mm/year to -40 mm/year. Furthermore, both surface deformations from InSAR measurements and ground measurements from GPS stations and the groundwater storage anomaly product showed a consistent declining trend throughout the period, as explained in Figures 2 and 3. Regarding the accuracy of the PSInSAR measurements, it has R = 0.96 and 4.92 cm of RMSE compared with the ground measurement, which is quite a good result. However, it has yet to reach millimeter accuracy. Moreover, Figure 4 explains that the agreement of both PSInSAR measurements and groundwater change from GRACE has reached R = 0.25, which is quite a typical value in InSAR and GRACE studies due to the difference in revisit time and spatial resolution. Therefore, it is revealed that the subsidence event was caused by declining groundwater content over the study area.

The results showed the historical, consistent, and precise capability of satellite gravimetry and satellite radar measurements to monitor land subsidence over an urban area. Figure 5 shows the proposed workflow of the study to monitor urban land subsidence, along with some considerations of four possible observations. The proposed method in our research could be a potential consideration for the related stakeholders to define disaster management policy for the government, urban planner, or other related parties. For instance, historical and consistent observation from the satellite could be used as scientific evidence of how the urban development over Surabaya City affects the subsidence caused by the declining groundwater content over time. It is understandable that the growing population of Surabaya City would eventually lead to more groundwater extraction to fulfill the clean water demand. Additionally, monthly observation of surface deformation and groundwater variability measured from earth observation satellites may indicate whether the mitigation attempt to combat the land subsidence is effective or not. Moreover, the global and consistent coverage of observations could be an effective tool to implement the related spatial policies based on the magnitude and occurrence of land subsidence over the region, such as the regulation of groundwater extraction and the promotion of the use of surface water or piped water provided by local freshwater authority instead.
Despite the fact that there is only one available CGPS Station to monitor surface deformation and no available observation well to monitor the groundwater level over Surabaya City, it is still necessary to perform ground measurement over satellite observations. The theoretical and physical limitations of satellite observations remain a challenge to be further studied. For instance, the coarse spatial resolution of GRACE to monitor groundwater variability would hinder specifically the identification of the corresponding area with severe groundwater depletion on the city scale. Another major limitation is the phase measurement of satellite radar interferometry, which contains multiple phase budgets that need to be addressed carefully if the phase from the surface deformation is the main interest. Therefore, the availability of ground measurement would be beneficial for confirmation as to whether the processed and analyzed satellite observations could precisely measure the land subsidence induced by the groundwater change.

Figure 2. Land subsidence map from 2014 to 2019 of Surabaya City
Figure 3. Temporal variation of surface deformation measured from ground measurement (CSBY GPS Station) VS PSInSAR measurements in Line of Sight (LOS) direction

Figure 4. Temporal variation of PSInSAR measurements VS GRACE groundwater storage anomaly in CSBY GPS Station
Figure 5. Proposed framework to monitor land subsidence

4. Conclusion
The capability of satellite gravimetry and satellite radar measurements to monitor the land subsidence over an urban area has proven to provide historical, consistent, and precise information regarding the scientific evidence for disaster management purposes. However, the major limitation of expensive and limited coverage of ground measurement such as GPS station to monitor surface deformation and the observation wells to monitor groundwater level have proven to be quite scarce crucial instruments to monitor the land subsidence in Surabaya City. It is also worth mentioning that the research framework could be further implemented as a critical indicator of related disaster management policy over a particular region with excessive and growing groundwater withdrawal issues.

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References
[1] Gambolati G, Teatini P, Ferronato M 2005 Anthropogenic Land Subsidence Encycl Hydrol Sci.
[2] Abidin H Z, Andreas H, Gumilar I, Gamal M, Yoichi F, Deguchi T 2009 Land Subsidence and Urban Development in Jakarta (Indonesia) Spat Data Serv People L Gov Environ - Build Capacit 5–16
[3] Hanssen R F 2001 Radar Interferometry (Springer Netherlands)
[4] ESA 2021 Sentinel 1 ESA’s radar observatory mission for GMES operational services [Internet]. Vol. 1, ESA Special Publication
[5] NASA-JPL 2020 Gravity Recovery and Climate Experiment Follow-on (GRACE-FO) Level-3 Data Product User Handbook
[6] Liu Z, Liu P, Massoud E, Farr TG, Lundgren P, Famiglietti J S 2019 Monitoring Groundwater Change in California’s Central Valley Using Sentinel-1 and GRACE Observations
[7] Vasco D W, Farr T G, Jeanne P, Doughty C, Nico P 2019 Satellite-based monitoring of
groundwater depletion in California's Central Valley. Sci Rep [Internet] 9(1):1–14

[8] Castellazzi P, Martel R, Galloway D L, Longuevergne L, Rivera A 2016 Assessing Groundwater Depletion and Dynamics Using GRACE and InSAR: Potential and Limitations Groundwater 54(6):768–80.

[9] Kurniawan A 2010 Studi Penelitian Penurunan Tanah Kota Surabaya Menggunakan Global Positioning System

[10] Chaussard E, Amelung F, Abidin H Z 2011 Sinking cities in Indonesia: space-geodetic evidence of the rates and spatial distribution of land subsidence Proc 'Fringe 2011 Work (Frascati, Italy)

[11] Aditiya A, Takeuchi W, Aoki Y 2017 Land Subsidence Monitoring by InSAR Time Series Technique Derived from ALOS-2 PALSAR-2 over Surabaya City, Indonesia IOP Conf Ser Earth Environ Sci 98(1) 0–8

[12] Anjasama I M, Yulyta S A, Cahyadi M N, Khomsin, Taufik M, Jaelani L M 2018 Land subsidence analysis in Surabaya urban area using time series InSAR method AIP Conf Proc.

[13] Massonnet D, Feigl K, Rossi M, Adragna F 1994 Radar interferometric mapping of deformation in the year after the Landers earthquake Nature 369(6477) 227–30

[14] Zebker H A, Rosen P A, Hensley S 1997 Atmospheric effects in interferometric synthetic aperture radar surface deformation and topographic maps J Geophys Res Solid Earth 102(B4) 7547–63

[15] Chen B, Liu Z 2016 Global water vapor variability and trend from the latest 36 year (1979 to 2014) data of ECMWF and NCEP reanalyses, radiosonde, GPS, and microwave satellite J Geophys Res Atmos 121(19)

[16] Li B, Rodell M, Kumar S, Beaudoin H K, Getirana A, Zaitchik BF, et al 2019Global GRACE Data Assimilation for Groundwater and Drought Monitoring: Advances and Challenges Water Resources Research Vol. 55 7564–7586

[17] Li B, Beaudoin H, Rodell M 2020 GLDAS Catchment Land Surface Model L4 daily 0.25 x 0.25 degree GRACE-DA1 V2.2, Greenbelt, Maryland, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC) Goddard Earth Sci Data Inf Serv Cent (GES DISC) 16(1) 1–32