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Monitoring land subsidence in Yangon, Myanmar using Sentinel-1 persistent scatterer interferometry and assessment of driving mechanisms

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ABSTRACT

Inhabitants and ecosystems in delta areas are becoming increasingly vulnerable to the effects of subsidence, caused by anthropogenic activities. Yangon is a city on the periphery of the Irrawaddy delta in Myanmar where little is known about the true extent of this hazard, while its effects can potentially harm millions of its inhabitants. This research presents the magnitude and extent of the subsidence hazard in Yangon through a Persistent Scatterer Interferometry (PSI) time-series analysis on the Sentinel-1 data archives in the period of December 2015 through April 2017. The PSI analysis revealed four distinct zones of varying sizes where vertical velocity differences over 20 mm/yr were found, locally exceeding 110 mm/yr. The significant subsidence zones are exclusively located in young Alluvium deposits and 95% of velocity differences over 10 mm/yr are found at Quaternary age deposits. The addition of loads, such as buildings, predominantly affect subsidence rates in the first decade after placement. Estimates of groundwater extraction for domestic supply, used by more than 2 million inhabitants, correlate with the township average subsidence rates which shows that most subsidence in Yangon can be explained by groundwater extraction. Current operation of groundwater extraction wells induces an aquifer volume loss of 5.5 million cubic meter per year in the aquifer system of Yangon city. Unless groundwater extractions are mitigated, Yangon will be increasingly vulnerable to infrastructural damages, flooding events, and degrading aquifer quality.

1. Introduction

Many delta areas in the world are experiencing the consequences from subsiding land surface (Syvitski, 2008). Human-induced land subsidence is mainly caused by extraction of resources from the subsoil, such as groundwater and hydrocarbons, and can outpace natural subsidence or sea-level rise by one or two orders of magnitude (Higgins, 2015; Minderhoud et al., 2017). Among the problems resulting from subsidence are an increased vulnerability to flooding events, infrastructural damages or failures, and permanent geological deformation (Syvitski et al., 2009; Wang et al., 2013). Deltas that accommodate mega-cities in Asia are especially affected, as large populations and rapid urban growth development have profound impacts on their environment (Syvitski et al., 2009).

Yangon city is an example of such a delta city where 5 million inhabitants are confronted with the negative effects of groundwater extraction such as seen in cities such as Bangkok (Phien-wej et al., 2006), Shanghai (Chai et al., 2004), the Hong Kong surroundings (Chen et al., 2012), and Ho Chi Minh City (Thoang and Giao, 2015). In Yangon City, groundwater is the most significant source of water supply (JICA, 2014b) which means that subsidence can be expected. Although the potential for subsidence has been reported before (RVO Netherlands, 2014), until now no preventive or even monitoring measures have been taken (Aobpaet et al., 2014; personal communication surveying department, 31 July 2017).

Subsidence is usually caused by compaction of aquitards through an increase in effective stress. An increase in effective stress in the soil skeleton follows from drawdown of the water table or an addition of load on top of the soil. This results in elastic strain, inelastic strain, and consolidation of compressible layers for effective stresses larger than the historical stress (Galloway et al., 1998; Verruijt, 2012). The major part of the fine-grained silt and clay layer compaction is an irreversible rearrangement of the pore structure while a significantly smaller elastic strain rebounces after recovery of the initial groundwater level (Motagh et al., 2017). The severity and irreparable nature of the consequences of subsidence essentially require monitoring and mitigation for sustainable development.

Satellite based Interferometric Synthetic Aperture Radar (InSAR) has shown great capability in detecting and monitoring subsidence hazards over the past decades, especially when applied with a

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Persistent Scatterer (PS) time-series analysis (Ferretti et al., 2000, 2001; Hanssen, 2001; Hooper et al., 2012; Van Leijen, 2014). This technique enables the monitoring of large-scale deformation patterns at sub-centimeter precision on a very dense grid (Ferretti et al., 2001; Sousa et al., 2011). The new Sentinel-1 (S1) satellites which are systematically observing the Earth's surface, offer valuable data for deformation monitoring (Berger et al., 2012). They provide C-band data continuity at a swath width of 250 km for the main acquisition mode (Wegmuller et al., 2015). The data is provided free of charge and the sensor system repeat time of 6 days greatly improves the temporal coverage with respect to alternative datasets in the scientific community.

The use of InSAR, in particular Persistent Scatterer Interferometry (PSI) time-series, is especially useful in areas such as Yangon, where other means of monitoring subsidence have never been employed. Aobpaet et al. (2014) show that InSAR-derived vertical velocities can be extracted at the vast majority of the city extent, and that there are velocity differences of several centimeters per year within the city limits in the period of November 2012 until April 2014. The number of used images in this research was enough to identify a network of PS measurement points, but as only 16 Radarsat-2 images—acquired in the dry season—were used, the reliability of the results could be significantly improved. An update of the surface deformation using the S1 datasets is necessary to show the most recent and accurate situation regarding subsidence in Yangon City.

This research presents the results of a PSI analysis applied on Yangon city to assess recent surface deformation using S1. The aim is to detect subsidence areas and identify the most likely driving mechanisms.

2. Study area

Yangon, or Rangoon, shown in Fig. 1 is the old capital and the largest city in Myanmar in terms of population and urbanized area. An estimated 5.2 million people currently inhabit the urbanized area of Yangon region, and this number is expanding with more than 20% each decade (Department of Population, 2015). The same expansion rate is also observed in the extent of the city's urban environment (Morley, 2013).

The city of Yangon requires sufficient inhabitable area for its increasing population. The population density increased by building more high-rise buildings in existing urban areas. Spatial limits of the city were extended by creating new urban land, which can be easily observed from historic Google Earth optical imagery. Agricultural land, mostly flooded for half of the year, is replaced by impervious plots, improved drainage, and external loads of housing, industrial sites, and roads. The decrease of the phreatic surface level, and the addition of loads on the soil lead to an increase in effective soil stress, locally exceeding historic values. This triggers consolidation of the layers beneath, eventually leading to subsidence.

Water supply in Yangon city is partially managed by the Yangon City Development Council (YCDC), responsible for water supply, which supplies less than half of the city with reservoir water via pipes. The other inhabitants rely on private or shared water supply consisting mostly of tube wells (YCDC, 2015) that account for the major part of the groundwater extraction in Yangon. Moreover, many inhabitants who receive water supply via pipes, occasionally also extract groundwater during periods of unavailable reservoir water as the supply availability varies between 6 and 24 h across the city (JICA, 2014b). Additionally, the YCDC extracts water from the ground for 10% of their total water supply (Mon et al., 2013). Finally, water is extracted for industrial

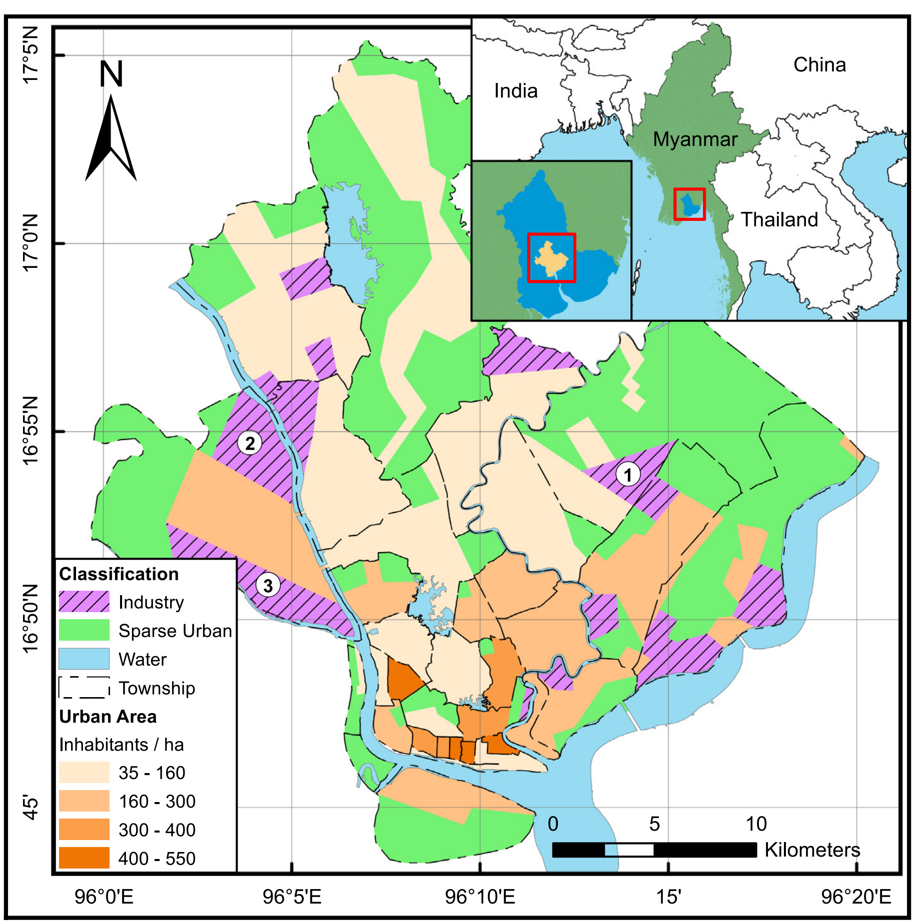

Fig. 1. The top right shows the location of Myanmar and the outline of Yangon city within the Yangon Region. On the left, a map of the study area—Yangon City—showing its 33 townships classified into industrial zones, sparsely urbanized areas with low population density, and urban areas colored by population density. Labels 1 through 3 refer to the industrial zones in Fig. 4. The land-use classification was manually derived from optical satellite imagery.