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Land subsidence in major cities of Central Mexico: Interpreting InSAR-derived land subsidence mapping with hydrogeological data

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ABSTRACT

Significant structural damages to urban infrastructures caused by compaction of over-exploited aquifers are an important problem in Central Mexico. While the case of Mexico City has been well-documented, insight into land subsidence problems in other cities of Central Mexico is still limited. Among the cities concerned, we present and discuss the cases of five of them, located within the Trans-Mexican Volcanic Belt (TMVB): Toluca, Celaya, Aguascalientes, Morelia, and Queretaro. Applying the SBAS-InSAR method to C-Band RADARSAT-2 data, five high resolution ground motion time-series were produced to monitor the spatio-temporal variations of displacements and fracturing from 2012 to 2014. The study presents recent changes of land subsidence rates along with concordant geological and water data. It aims to provide suggestions to mitigate future damages to infrastructure and to assist in groundwater resources management.

Aguascalientes, Celaya, Morelia and Queretaro (respectively in order of decreasing subsidence rates) are typical cases of fault-limited land subsidence of Central Mexico. It occurs as a result of groundwater over-exploitation in lacustrine and alluvial deposits covering highly variable bedrock topography, typical of horst-graben geological settings. Aguascalientes and Toluca show high rates of land subsidence (up to 10 cm/yr), while Celaya and Morelia show lower rates (from 2 to 5 cm/yr). Comparing these results with previous studies, it is inferred that the spatial patterns of land subsidence have changed in the city of Toluca. This change appears to be mainly controlled by the spatial heterogeneity of compressible sediments since no noticeable change occurred in groundwater extraction and related drawdown rates. While land subsidence of up to 8 cm/yr has been reported in the Queretaro Valley before 2011, rates inferior to 1 cm/yr are measured in 2013–2014. The subsidence has been almost entirely mitigated by major changes in the water management practices of the city, i.e., a 122 km long pipeline bringing surface water from an adjacent state allowed to cease pumping in half of the wells.

1. Introduction

Unsustainable groundwater pumping is seen in several regions of the World (e.g., Wada et al., 2010). Groundwater sustainability is often defined through a water budget approach, as the balance between inputs and outputs of an aquifer system (see e.g., Alley et al., 1999). A negative water balance may imply progressive and negative impacts on the environmental equilibrium and on the communities who rely on these water resources. While the impacts should be limited to what is considered environmentally, economically, and socially acceptable, there are no obvious solutions to this problem. As it occurs globally (e.g., Famiglietti, 2014), there is an urgent need for cost-effective and globally applicable methods to study groundwater depletion and its related impacts.

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Typical water budget approaches overlook the dynamic effects of over-pumping, i.e., storage influences the governing parameters regulating inflows and outflows (Bredehoeft, 2002). Integrated flow models can be used to simulate the dynamic effects of overpumping and associated ground deformation, but have historically only been used reliably when calibrated with costly field campaigns. The lack of reliable data hinders the calibration and validation of the much-needed groundwater management models. The need for reliable data is a major challenge in hydrogeology.

Several space-borne remote-sensing techniques can be used to study groundwater overexploitation and its consequences on human settlements without having to rely on extensive field data campaigns, i.e., multispectral, radar and gravimetry, Among these, Synthetic Aperture Radar Interferometry (InSAR, Massonnet and Feigl, 1998) has been effective in studying the aquifer reaction to over-pumping (e.g., Galloway et al., 2007) and its consequence on urban infrastructures (e.g., Bru et al., 2013). InSAR uses the phase history of at least two SAR images acquired with a minimal spatial baseline to retrieve ground displacement along the satellite Line Of Sight (LOS). In the last decade, this technique was subject to major methodological developments (e.g., SBAS-InSAR: Berardino et al., 2002; PS-InSAR: Hooper et al., 2004; and Squee-SAR: Ferretti et al., 2011) and application opportunities have arisen along with the increasing availability of SAR imagery products. InSAR is particularly efficient to monitor progressive ground movements, making it an appropriate method to study depleting aquifers undergoing overexploitation and land subsidence. However, the inversion of InSAR-derived land subsidence maps into a volume of groundwater storage change is not possible without extensive lithological data and is restricted by the spatial variability of the lithological compressibility.

Aquifer overexploitation implies changes in water levels and pore pressure. The decrease in pore pressure implies an increase in effective stress (Terzaghi, 1925; Biot, 1941). When the aquifer system contains compressible sediments such as clays and silts, an effective stress increase leads to a matrix re-configuration and land subsidence. This phenomenon varies spatially according to sediment compressibility and water pressure change patterns, leading to damages on urban infrastructures. Damages are accentuated in areas where faults and subsidence with high spatial variability occurs. It is essential to identify subsidence patterns and faulting in order to mitigate future damages and adapt groundwater management accordingly. Land subsidence also implies a largely non-recoverable physical change within the aquifer by impacting its capacity to store water for future generations.

The five central Mexican cities in this study match all criteria enumerated by Burbey (2002), who lists conditions favoring the occurrence of pumping-induced ground deformation and faulting: (1) arid to semiarid climate, (2) long-term pumping of groundwater that results in large water-level declines, (3) considerable thickness of accumulated compressible layers, (4) variable distribution of compressible layers, (5) variability in the values of the compression index of the granular material, and (6) existence of discontinuity structures such as pre-pumping faults that allows for stress accumulation.

2. Objectives

In this paper, we apply the SBAS-InSAR technique on high resolution SAR images to provide an up-to-date assessment of land subsidence in five cities of the Trans-Mexican Volcanic Belt. We reveal temporal variations over a two years period with fine spatial details. Using both geological maps and groundwater level variation data, we discuss the governing parameters explaining spatial and temporal variations of subsidence for each city. We provide an analysis of the evolution of land subsidence at a decadal time scale by comparing the results with previous studies. For changes detected, concordant water and geological data assist in identifying the causes. The study aims to contribute to future urban developments and water distribution plans.

2.1. Study area

The population density of the area and the locations of the five cities are shown on Fig. 1. The cities of Toluca, Morelia, Queretaro, Celaya and Aguascalientes (respectively, from South to North) rely mainly on groundwater to sustain both industrial and domestic water needs. Additionally, irrigation is used to sustain intensive agricultural activities in the regions of Toluca, Celaya and Aguascalientes (INEGI, 2005). While the highlands of Central Mexico are densely populated and are of major importance in the Mexican economy, precipitation is low, i.e., the cities studied rely on overexploited groundwater resources (CONAGUA, 2013; Table 1).

Among the cities within the region facing both aquifer depletion and subsidence, Mexico city has been well documented by InSAR, (e.g., Yan et al., 2012; Osmanoglu et al., 2011; Chaussard et al., 2014) but the groundwater depletion and induced land subsidence in the other cities is poorly documented. At a larger scale, land subsidence is detected by InSAR in 21 locations of Central Mexico (Chaussard et al., 2014), but there is still a need for fine-scale mapping to better understand the land subsidence arising from groundwater overexploitation in Central Mexico and provide guidance for future urban development. Geologically, the cities presented in this study are within the Trans-Mexican Volcanic Belt (TMVB), a 1000 km long Neogene continental volcanic arc (see Ferrari et al., 1994, 2012). In the five cities, the aquifer-systems from which groundwater is pumped are formed by typical layer sequences of extrusive rocks and volcanic deposits (aquifers) separated by alluvial and lacustrine deposits (aquitards). The thickness of confining alluvial and lacustrine deposits and their occurrence between volcaniclastic and basaltic sequences controls the type of aquifer confinement and, consequently, the spatial patterns of aquifer-system compaction and fracturing.

3. Material and methods

3.1. SAR datasets and InSAR processing

The InSAR dataset is composed of 69 RADARSAT-2 images and 14 ENVISAT ASAR images over the five cities, as shown in Table 2. RADARSAT-2 images were acquired from December 2012 to December 2014. Their nominal pixel footprint is approximately 1.6 m by 2.8 m (respectively Range x Azimuth) for Ultrafine acquisitions and 5.2 m by 7.7 m for Fine acquisitions (MDA, 2014). ENVISAT ASAR acquisitions were acquired in IMS mode, with a resolution of 8 m by 4 m.

The Small Baseline Subset algorithm (SBAS-InSAR; Berardino et al., 2002) integrated in ENVI through the SARScape module was used to process the images. The SBAS processing method consists in creating all possible interferograms within a temporal and a spatial baseline threshold. These interferograms are integrated in an interconnected network and inverted for the phase change through time relative to the first SAR acquisition. In this study, a total of 332 interferograms were created to build the six land subsidence time-series (Table 2). The mean connection number per image was kept above 5 to assure sufficient redundancy and connection graph density. The topographic phase was removed by using the SRTM Digital Elevation Model with a 30 m by 30 m pixel footprint (Farr et al., 2007) oversampled to 10 m $\times$ 10 m using a bilinear interpolation. The process implies the positioning of reference points with known rates