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Subsidence related to groundwater pumping for breweries in Merchtem area (Belgium), highlighted by Persistent Scaterrer Interferometry

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ABSTRACT

ERS, ENVISAT and TerraSAR-X Synthetic Aperture Radar scenes covering the time span 1992–2014 were processed using a Persistent Scatterer technique to study the ground movements in Merchtem (25 km NW of Brussels, Belgium). The processed datasets, covering three consecutive time intervals, reveal that the investigated area is affected by a global subsidence trend related to the extraction of groundwater in the deeper Cambro-Silurian aquifer. Through time the subsidence pattern is reduced and replaced by an uplift related to the rising water table attested by piezometers located in this aquifer. The subsidence is finally reduced to a zone where currently three breweries are very active and pump groundwater in the Ledo-Paniselian aquifer and in the Cambro-Silurian for process water for the production.

1. Introduction

Nowadays, ground movements and subsidence in particular are of major concern in terms of geological risk-hazard management for the responsible authorities. The subsidence rate of Mexico City (Strozzi et al., 2003) related to ground water extraction amounts up to −35 cm/year during the 1990s and 2000s while Cigna et al. (2012), recorded an average rate of −7–8 cm/year during the 2003–2010 period of time. Sowter et al. (2016) using 2014–2015 Sentinel-1 IW date recorded a subsidence rate up to–24 cm/year. In California, the San Joachim valley is affected by a subsidence rate of 7 cm/year between April 1992 to November 1993 (Amelung et al., 1999). In China, the city of Shanghai has suffered from subsidence since 1920 (Baeteman and Dassargues, 1992; Dassargues, 1997)t an average subsidence rate of 28 mm/year since 1976. In 2007, the estimated economic loss due to structural damage to buildings for the city of Shanghai is estimated at 13 billion US$ (Feng et al., 2008). The phenomena inducing ground deformations can arise from different sources both natural and anthropogenic. The settlement of alluvial plain deposits is a natural process due to the drainage but can be accelerated by loading of the unconsolidated sediments with constructions of buildings (Bianchini and Moretti, 2015). Furthermore, groundwater withdrawal in the alluvial plain aquifer can play a significant role in the compaction of the ground (Galloway et al., 1999; Raucoules et al., 2003). Groundwater withdrawal decreases the pore water pressure and increases the effective stress in the soils and rocks leading to the consolidation of the aquifers and thus inducing gradual land subsidence.

Conventional geodetic techniques such as optical levelling (Pissart and Lambot, 1989; Demoulin et al., 1992) and GPS devices have been used to monitor ground deformations on the field. These precise and robust techniques measure the displacement on a point by point basis. A dense network of local observations made during several field surveys is needed to be able to map a significant area. In this research, we will applyspaceborne Multi Temporal Interferometric Synthetic Aperture Radar (MT-InSAR) technique, which allows measuring area-wide ground deformations to millimetric precision. In particular, Persistent Scatterer Interferometry (PSI) (Ferreti, 2000, 2001) as implemented in Sarproz (Perissin et al., 2011) is used to process the ERS-ENVISAT Synthetic Aperture Radar (SAR) satellite images covering the Region Of Interest (ROI). MT-InSAR (PSI, SBAS, SqueeSAR) in contrast to InSAR and DInSAR techniques provides time series of displacements for each scatterer over the entire acquisition period of time. It allows the possibility to study the variation of the ground movement patterns in both time and space. The processing results revealed a previously unknown subsidence/uplift area located in Flemish Brabant around 25 km NW of Brussels in Belgium which is the central subject of this paper. The ROI

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comprises the cities of Aalst, Merchtem, Opwijk and Steenhuffel. The land subsidence with an average velocity of 2 mm/years during the time period 1991–2010 covers an area of 95 km^2. At first we will briefly characterise the geographic and geological setting of the ROI. Secondly, the PSI methodology and the processed data will be discussed. Finally, piezometric data of the different aquifers available in the ROI will be interpreted in order to characterise the evolution in time and space of the observed ground deformations.

2. Geological and hydrogeological setting

The hydrographic network of the ROI is characterised by the presence of many watercourses of which the Dender and the Scheldt rivers are the largest. The valley of the Groote Molenbeek is of particular interest as it more or less crosses the ROI from SW to NE. Its alluvial plain is typically formed by unconsolidated Holocene alluvial sediments such as sand, silt, clay and peat. The altitudes of the ROI is at 60 m in the south where a Pleistocene plateau characterise the relief. The alluvial plains of the Dender and the Scheldt are at an altitude of 5 m.

In general, the geology of the ROI consists of Tertiary (65 Ma.) and Secondary (250 Ma.) monocline layers gently dipping to the north and overlying the folded and faulted Primary (540 Ma.) bedrock.The basement of the ROI more in particular belongs to the lower Primary tectonic Massif of Brabant. This old structure consists in an ESE-WNW folded belt formed during the Primary. It is made of Cambrian (540 Ma.) to Silurian (443 Ma.) siliciclastic, often turbiditic rocks with a thickness of 13 km (Linnemann et al., 2012) that were folded into a mountain chain 400 million years ago during the Caledonian orogeny (De Vos et al., 1993; Piessens et al., 2006). The rocks are overprinted by a low-grade metamorphism that ranges from epizone in the centre of the Massif to anchizone at the borders. During its history, this chain was flattened by erosion and now stands as an ancient base of abraded hard rock in the subsoil of Flanders. The ROI was out of reach of the marine influencethe Upper Cretaceous (100 Ma.), advancing the weathering of the Primary rocks. Chalk layers were formed during this marine episode of the Cretaceous. During the Tertiary (65 Ma.) the ROI was situated on the southern edge of the North Sea Basin. The ROI was affected tectonically by alternating upward and downward vertical movements, and also by the constant fluctuation of the sea level. These alternating vertical movements of the land and the sea levels resulted in a flattening of the ROI by erosion. This started one hundred million years ago in the Upper Cretaceous period (100 Ma) and formed different series of sediment layers with a thickness of about 200 m thick in the ROI. The current morphology of the landscape has started to develop at the end of the Upper Miocene (11 Ma). after the last withdrawal of the sea that had covered the entire region.The Quaternary and Tertiary lithologies and formations until the top of the Cambrian (540 Ma) are described through the representative borehole 072E0229 (Table 1) located nearby Merchtem (Fig. 1). To the North, the "Flemish Valley" is an incised valley of mainly fluvial origin (De Moor and Heyse, 1978), with an age assigned to the Cromerian, Middle Pleistocene (0.7 Ma.) (Paepe et al., 1981). As a result of sea-level changes the river valley is now largely filled up with alluvial deposits The base of the Quaternary deposits is found close to a depth of − 20 m in Gent (Bogemans and Paepe, 1982). In the central part of the ROI, in Opwijk, the Quaternary sediments are primarily composed of aeolian silt and sand (in yellow, Fig. 1).

In the ROI, the Tertiary monocline structures forms a stack of loose and poorly consolidated sediments. From a hydrogeological point of view, this stack consists of alternating permeable and semi-permeable layers, sometimes superimposed over a large extent. These deposits overlie the Primary basement body which has been levelled, usually altered up to 20 m and fractured. The monocline structure dipping to the North leads to a superposition of captive or semi captive aquifers often well individualized but whose alimentation zones are usually completely or partially connected (Derycke et al., 1982). The Tertiary and Secondary deposits mainly have a permeability due to interstices while the Primary aquifers have permeability related to fissures and joints. In Flanders a code has been assigned to the succession/sequence of aquifers and aquitards (Dassargues and Walraevens, 2014) and is named "Hydrogeologische Codering van de Ondergrond van Vlaanderen '(HCOV, Hydrogeological Code for the subsoil of Flanders). The code is composed of three hydrogeological units: main, sub and base unit. The highest level brings together a succession of geological layers that have more or less uniform hydrogeological characteristics as the sub units. Based on the regional groundwater flow and the succession of different HCOV layers, the Flemish government has defined 6 groundwater systems. The ROI is situated in the "Centraal Vlaams System' in the river basin district of the Scheldt. Table 1 shows the different aquifers and aquitards present in the ROI.

If we consider the highest volume of groundwater extraction (DOV, 2016) the majority of the pumping sites are located in the aquifers assigned to the HCOV code 600 and named the Ledo-Paniselian aquifer. In the ROI, this aquifer is composed by the sandy part of the Formation of Maldegem, the Formation of Lede and the top sandy part of the Formation of Gent. The average thickness of the Ledo-Paniselian aquifer is ca.25 m and the hydraulic conductivity (K) ranges from 1 to 10 m/d for the coarse sandy deposits of the three formations. The Flesmish Valley in thenorth is a heterogeneous aquifer made of Pleistocene river deposits (sand, peat, clay). It is difficult to determine a representative conductivity for this unit as the lithology of the sediments changes rapidly both horizontally and vertically. The thickness of this aquifer ranges from 10 to 30 m in the ROI. The Cretaceous aquifer (HCOV 1100) in the ROI is formed by the remnants of the Cretaceous chalk deposits that were not eroded during the Tertiary. In general, the pumping wells located in this aquifer are also extracting water from the Primary basement. The Kortrijk and Tielt Formations form an impervious cover isolating the Cretaceous from the overlying Eocene aquifer layers. As the Cretaceous is mainly confined, its natural water recharge is problematic even if the outflow is high. It can only be fed by

Table 1
Quaternary and Tertiary Formations, lithologies and their tendency to act as an aquifer or aquitard. HCOV refers to the Hydrogeological Code for the Subsoil of Flanders.

Depth interval (from surface)	Formation	Chronostratigraphy	Lithology	Presence of Aquifer or Aquitard	HCOV Code
0–5 m		Pleistocene (Quaternary)	Sand, Silt, Clay, Peat	Aquifer	100
5–18 m	Sint-Huibrechts Formation	Upper Eocene (Tertiary)	Fine sand	Aquifer	600
18–36 m	Maldegem Formation	Upper Eocene (Tertiary)	Sand	Aquifer	600
36–43 m	Lede Formation	Middle Eocene (Tertiary)	Sand, Silt	Aquifer	600
43–52 m	Gentbrugge Formation	Lower/Middle Eocene (Tertiary)	Silt, Clay	Aquifer/Aquitard	700
52–71 m	Tielt Formation	Lower Eocene (Tertiary)	Silt	Aquitard/Aquifer	910
71–165 m	Kortrijk Formation	Lower Eocene (Tertiary)	Clay	Aquitard	920
165–197 m	Hannut Formation	Upper Palaeocene (Tertiary)	Sand, Clay	Aquifer	1010
197–219 m	Nevele Formation	Upper Cretaceous (Secondary)	Chalk, gravels	Aquifer	1100
219–234 m	Saint-Pierre Formation/Oisquercq Formation	Cretaceous/Cambrian (Secondary/ Primary)	Siltstone, Sand	Aquifer	1340