Journal of Applied Geophysics 88 (2013) 1–11

Contents lists available at SciVerse ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Surface deformation induced by water influx in the abandoned coal mines in Limburg, The Netherlands observed by satellite radar interferometry

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ARTICLE INFO

Article history:
Received 19 April 2012
Accepted 7 October 2012
Available online 13 October 2012

Keywords:
InSAR
Persistent scatterers
Groundwater dynamics
Coal mine

ABSTRACT

The coal reserves of Limburg, The Netherlands, have been exploited until the mid-1970's, leading to significant land subsidence, a large part of which was due to ground water pumping associated with the mining activities. In 1994, when also the hydrologically-connected neighboring German mining activities ceased, all pumps were finally dismantled. This resulted in rising groundwater levels in the mining areas, continuing until today. Here we report the detection and analysis of heterogeneous surface displacements in the area using satellite radar interferometry. The lack of adequate terrestrial geodetic measurements emphasizes the value of such satellite observations, especially in terms of the temporal and spatial characterization of the signal. Since the lack of direct mine water level measurements hampers predictions on future consequences at the surface, we study the relationship between surface deformation and sub-surface water levels in an attempt to provide rough correlation estimates and map the mine water dynamics.

1. Introduction

The coal reserves of the southern Netherlands, see Fig. 1, were exploited for many centuries. Extraction at an industrial scale commenced in the beginning of the twentieth century and peaked between 1950 and 1975 (van Bergen et al., 2007). As exploitation became less economically interesting most of the Dutch mines closed during the seventies.

This long-term extraction resulted in land subsidence. The total subsidence that occurred since the beginning of 1900s is estimated to be in order of several meters (Pöttgens, 1985). Subsidence in mining areas occurred due to two different causes. First, the partial collapse of galleries after the actual extraction of coal reduced support of the upper layers producing surface deformation. Second, as the mining activities require a dry working space, groundwater was continuously pumped from the galleries and the rock layers surrounding them. The stress change due to coal extraction and pore pressure decrease produced by the pumping resulted in subsidence.

After the mines were abandoned and pumping halted, the groundwater flowed back to hydrostatic equilibrium producing the opposite effect — the land began to rise. Not anticipated at the time, first indications of uplift were observed for an incidental leveling line in 1978, four years after closure of the last mine (Pöttgens, personal communication, 2008). Pöttgens (1985) explained the uplift due to a pore pressure increase produced by the rising groundwater in the mines. To protect the neighboring German mines, still operational, from being flooded, the pump in the shaft of Beerenbosch II, near the German border, Fig. 2, remained active. Furthermore, a system of subsurface water barriers (dams) was installed by sealing most of the galleries interconnecting the mine concessions (Bekendam and Pöttgens, 1995), which were originally built as evacuation corridors for safety reasons (Wings, personal communication, 2011). However, some of the galleries were left open to control groundwater flow.

As a consequence, the coal fields were divided into a series of so-called *water basins* formed from the original concessions, which were usually delimited by natural faults. The water basins had overflowing corridors that connected them to the only remaining pump in the field, located in Beerenbosch II, i.e. southern basin. This pump was eventually disabled early 1994 (Bekendam and Pöttgens, 1995). The cease of the pumping in this year led to a rapid increase in the groundwater level in the southern basin. During 1994, the groundwater level rose from −215 m to −138 m NAP[1] and started to overflow towards the central basin. The profile A–A' in Fig. 2 shows the overflowing levels and the groundwater regime at the time when the pump in Beerenbosch II was active, (Bekendam and Pöttgens, 1995). Currently, the groundwater is still flowing back into the concession areas, bounded by the dam system (Rosner, 2011; Wings, 2006). Consequently, groundwater recharge is not synchronous throughout the region and is expected to produce a deformation pattern that changes in place and time.

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[1] NAP (Normaal Amsterdams Peil) is the vertical Dutch datum. The local topography ranges from 50 to 200 m NAP.

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http://dx.doi.org/10.1016/j.jappgeo.2012.10.003

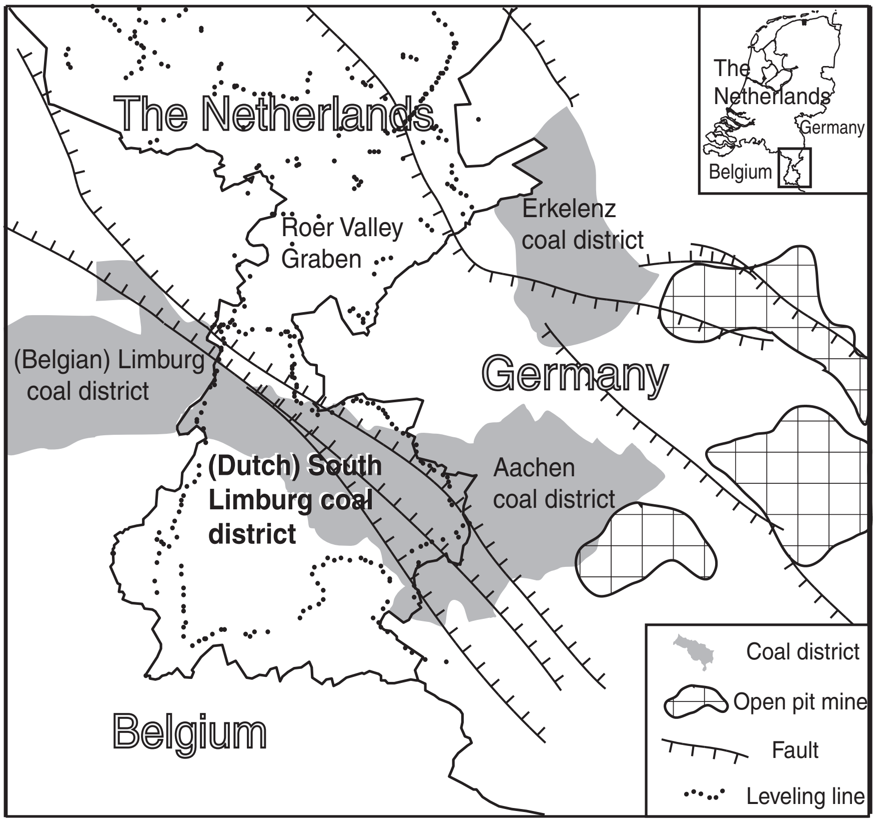

Fig. 1. Coal fields in the southern Netherlands and adjacent regions, after (Devleeschouwer et al. (2008), Heitfeld et al. (2002) and TNO (1999)). German open pit lignite mines are also shown, as water pumping in these areas influences the surface motion. Reliable leveling benchmarks that were measured at least three times during the period 1992–2009 are also displayed.

Until now, the mines have been monitored mostly with leveling. Unfortunately, to study the whole deformation process with this technique is difficult because leveling campaigns are rather limited in extent, spatially sparse and have a low measurement frequency, see Fig. 1.

In depth comprehension of mine water dynamics can also help to predict hazardous situations derived from mine water flow and consequent surface motion, such as building or pipe damage. In the German city of Wassenberg, near Limburg, the cessation of pumping in abandoned mines led to infrastructure damage, nine buildings were reported to be strongly affected (Caro Cuenca and Hanssen, 2011; Heitfeld et al., 2006). Satellite-based radar measurements provide a spatio-temporally dense network of observations that can be used to aid the analysis of such complex deformation mechanisms. In contrast to conventional Synthetic Aperture Radar Interferometry, (InSAR), which estimates deformation and height from two images acquired at different times (Hanssen, 2001), persistent scatterer interferometry (PSI) utilizes a time series of spaceborne radar acquisitions to identify objects whose scattering properties remain stable over time. The pixels representing these objects are electromagnetically coherent and referred to as persistent scatterers (PS). The phase information obtained from their radar returns can be reliably used to infer surface deformation time series (Ferretti et al., 2001; Hooper et al., 2004; Kampes, 2006). Most PS are related to anthropogenic constructions, with a common density about 100 PS per km^2 in urban environments for the C-band sensors (ERS1/2 and Envisat). The detection and use of coherent scatterers aids phase unwrapping (unfolding the phase outside its natural range of $(-\pi,\pi]$) and the estimation of atmospheric signals, which are the dominant error sources when estimating surface deformation.

We employ PSI to measure surface displacements in the Dutch coal region, potentially subject to mine water recharge. The total study area is 50×45 km^2. The deformation time series is obtained with the Delft implementation of PSI (DePSI), with the unwrapping algorithm of Caro Cuenca et al. (2010) where the solutions of most stable PS are used to constrain and weigh the solution space of the rest of detected PS using Bayesian inference. The interferograms are created with the Doris software (Kampes et al., 2003).

Two data sets are used in this study. The first one was acquired by the ERS1/2 satellites between April 1992 and December 2000, yielding 74 radar images. The second set includes 59 images provided by the Envisat satellite and acquired from December 2003 to October 2009. Satellite precise orbits are provided by the Delft University of Technology, (Scharroo and Visser, 1998), and by ESA (European Space Agency).

In Section 2, we apply PSI to the mines in Limburg and report cumulative displacements and time series analysis. We estimate total displacements and describe the spatio-temporal behavior of the signal in Section 3, by analyzing how the deformation changes in time and space. We model the volume increase suffered by the mines from the total surface displacements in Section 4.

2. Surface displacements observed by PSI

We processed almost 18 years of radar acquisitions to produce line of sight (LOS) displacement time series. We projected the LOS direction to vertical assuming vertical-only displacements. The whole time span was initially divided into two stacks as provided by the European satellites ERS1/2 and Envisat. These two sets of displacement time series were low pass filtered in time and space to reduce noise. The time series were merged to produce longer time series from April 1992 to October 2009 (Caro Cuenca and Hanssen, 2010). The procedure to join time series assumes that the displacements in ERS1/2 and Envisat