Ground Deformations Observed for Three Decades (1992–2022) above Old and Deep Coal Mines Reused for Deep Gas Storage Sites (Wallonia, Belgium) Using PS-InSAR Time-Series

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Abstract

The exploitations of the coal mines in Wallonia (Belgium) were ceased progressively till the year 1984. Groundwater pumping activities were stopped inducing a progressive groundwater rebound affecting different areas with different rates but still visible today with radar interferometry. To mitigate the threats to the environment during the post-mining period, flooding and outbreak risks, surface ground deformations and the stability of civil engineering infrastructures in the vicinity of those mined areas need to be monitored.

The persistent scatterer radar interferometry technique (PS-InSAR) revealed ground displacements during three decades above the two underground reservoirs (Peronnes to the West and Anderlues to the East) used for gas extraction and storage south of La Louvière city (Wallonia).

236 Interferograms were produced using images acquired by the ESA's satellites (ERS1/2, ENVISAT, and Sentinel-1A). Land surface displacements trends are heterogeneous both in time and space with different behaviours. During ERS1/2 (1992–2002) an uplift is visible in the western part of the Peronnes reservoir while the eastern part is still affected by subsidence while the Anderlues reservoir is affected by global subsidence. During ENVISAT (2003–2010), the uplifting conditions were stronger in the Peronnes reservoir and only the upper right corner is still affected by subsidence while the Anderlues reservoir records still a general subsidence phenomenon. The most recent data from Sentinel-1A revealed a general uplift through the Peronnes reservoir with decreasing LOS velocity towards the north and the south. The Anderlues reservoir is still affected by a subsidence phenomenon, but the LOS velocity values are reduced compared to the previous decades.

Keywords: PS-InSAR, Coal Mines, Wallonia, Gas Storage Reservoir, Ground Displacements

Introduction

Abandoned mines often pose a threat to the environment, public health, and safety (Lee and Park 2013). Many old and abandoned mines in the world, which were often mined in the shallow depth, are prone to land subsidence (Bell and Genske 2001). Various studies have demonstrated the effectiveness of InSAR technology in detecting and monitoring land surface deformations linked to mining operations (Fan *et al*. 2021; Du *et al*. 2021; Li *et al*. 2022). The use of underground gas storage (UGS) reservoirs is an important contribution to the subsurface use as a strategic gas reserve, to regulate the gas supply in a country, but also to extract remaining gas (methane) resources produced by the coal rocks still not extracted in the coal mining areas. The problems associated with the use of UGS sites are the geomechanical integrity of both the reservoir and the caprock, the reactivation of existing faults, the leakage through the caprock for example. Those elements must be considered and monitored in detail and much more when growing urbanized areas are present above those sites involving potentially civil structures and engineering infrastructures available at the surface. High-resolution satellite imagery data are needed to monitor spatially and temporally the low amplitude of deformation associated with the gas storage and extraction activities in deep geological layers. This is even more critical when the surface deformations are affecting areas where the number of PSI data is reduced implying the need to install and deploy artificial corner reflectors network (Rohmer & Raucoules 2012;). Several gas storage sites around the world are monitored using PSI (Vasco *et al.* 2018), PSI and artificial corner reflectors (Rohmer *et al.* 2015) or a combination of different geodetic techniques using GPS and PSI data (Ketelaar *et al.* 2020).

In this paper, spatiotemporal ground movement measurements and mapping were carried out over growing urbanized district areas above old coal mined deep underground exploitations in southern part of Belgium (Wallonia, South of La Louvière city). MT-InSAR technique was applied on SAR acquisitions of the satellites ERS-1/2 (1992–2006), ENVISAT (2003–2010), and Sentinel-1A (2015–2022). For three decades (1992–2022), the two underground gas storage reservoirs of Peronnes and Anderlues are monitored using PSI data and imagery from the ESA satellite datasets collection maintained at the Geological Survey of Belgium.

Geographical and Geological Settings

The Region of Interest (ROI) is located in the Hainaut Province of Wallonia and comprises the villages of Binche (SW of the ROI) and Anderlues (SE of the ROI) that are both located to the west of the major industrial Charleroi city. The ROI is intimately associated to the old coal mining exploitations and collieries of Wallonia that have produced different type of coals during the industrial period. The area is crosscut by small rivers and corresponds essentially to urbanized centers (like those of Binche, Leval, Anderlues) and agricultural and forest areas in between. Due to this past industrial activities, coal spoil heaps, industrial buildings of the old collieries, sealed coal mineshafts, etc. are visible in the landscape. The altitudes ranges from +47 m in the Haine valley (North of the figure 1) to >+200 m in the plateau of the Mont-Sainte Aldegonde (middle of the Figure 1, inside the Anderlues concession limits). For the citizens, a post-mining monitoring approach is necessary to follow, identify and mitigate any potential mining hazards associated to these old exploitations.

The subcrop of the ROI is composed by Paleozoic rocks folded and faulted during the Variscan orogen that are thrusted on Upper Carboniferous rocks (Silesian series including the Westphalian coal series) through the Midi-Fault. The Paleozoic rocks belongs to the Brabant Parautochton structure while those thrusted over are the Devonian series belonging to the Ardenne Allochton. The Paleozoic surface corresponds to an angular disconformity overlain by the Mesozoic cover representing the eastern extremity of the Cretaceous Mons basin. Several depressions are filled with Lower Cretaceous series (Wealdian deposits with sands, clays and gravels) in the northern areas while the southern areas begin with Upper Cretaceous series (mostly chalk with glauconite or clays). Tertiary sands and clays of the Paleogene are covering the Mesozoic sequence. Quaternary sediments of fluviatile origin are, of course, well known in the alluvial valleys.

The ROI comprises several abandoned coal concessions from which two coal concessions will be further detailed herafter. The coal concession “Bois de la Haye” located on the eastern side has a total area of 2100 hectares and was exploited by 5 extraction sites. The last extraction activities started in 1857 and stopped in 1969. An estimation of 25 millions of tons of coals have been extracted from this concession mostly in the northern area (Piessens and Dusar, 2004). The coal deposits are characterized by a very important production of gas

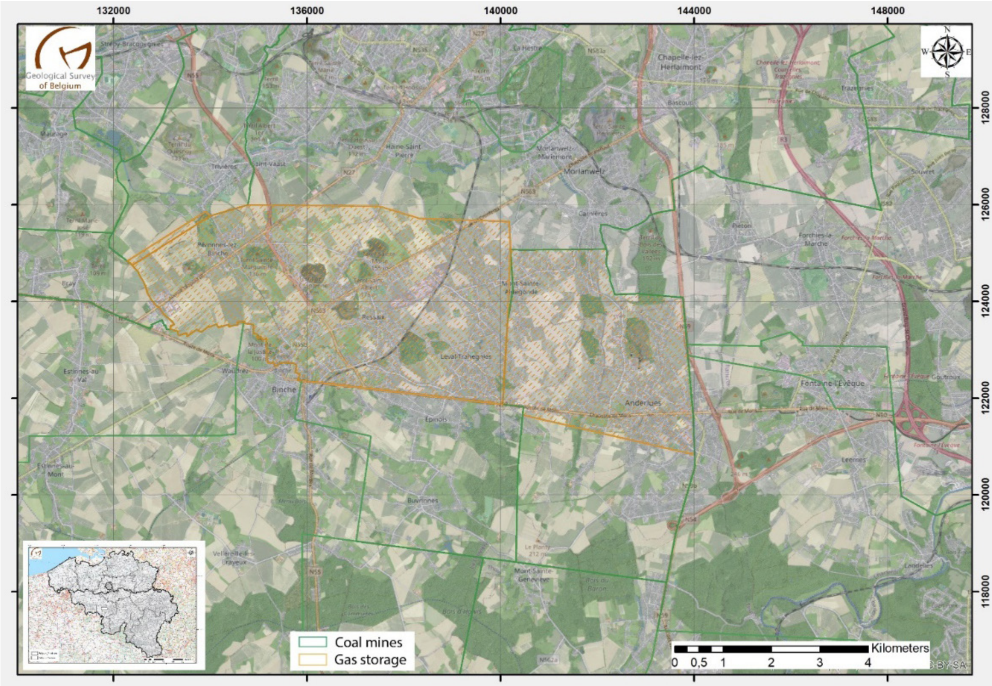

__Figure 1__ Geographic locations of the ROI inside Wallonia (Belgium) including two old coal mines used as gas storage reservoirs (orange polyline for Peronnes on the western side and Anderlues on the eastern side) vs all the other coal mines exploited in the area (green polylines) till the second half of the 20th century. The coal concession limits are based on WMS data provided by the Walloon Administration, the background map is a transparent superimposition of the 2020 version of the aerial Ortophotos of the Walloon Region (also available as WMS data provided by the Walloon Administration on the OpenStreetMap data available in ArcGIS basemap). The map provided contains X and Y Belgian Lambert 72 coordinates.

(methane) from the coal seams, which were partly captured during and after the colliery exploitation activities till 1975. During the period 1975–2004, the northern part of this coal concession was transformed into the underground natural gas storage reservoir (UNGSR) of Anderlues given by the federal government to an industrial company called formerly Distrigaz and now Fluxys. The exploitation activities by the company as a natural gas storage reservoir were possible after the sealing of several mineshafts at different depths. All these operations were possible without any groundwater pumping activities due to the fact that the mine was dry in the deeper exploitation levels between 600 m and 1100 m. The shallow mined workings were isolated from the deeper ones due to the thrust faults acting as primary hydrogeological barrier. The coal seams were essentially exploited in one specific thrusted serie called the Massif du Carabinier bounded by two major faults. Three thrusted sequences are superimposed to each other in that area, the one exploited for coal is in the middle. The difference in pressure from the end of the gas storage use in the mine with the values measured more recently indicates a pressure increase from 700 hPa (2004) to 1250 hPa. The sealing rocks covering the gas storage reservoir are water-saturated and nine piezometers were installed to monitor the piezometric levels and to detect any gas contamination due to any gas leaking. The use of the gas reservoir (injection or production) has never changed the piezometric levels in the superficial aquifer and gas was never detected in the piezometers neither (Piessens and Dusar, 2004). The sealing system used in Anderlues was thus well maintained.

The second coal concession is the one of "Ressaix-Mariemont-La Louvière" is located on the northern and western side. It has been exploited since 1790 by 230 mineshafts and the exploitation activities stopped in 1978. The coal seams were exploited into two coal sequences separated by an intermediate sterile zone (80 m thick at a depth of about 500 m) that has not been exploited and bounded by thrust faults. The uper sequence belongs to the "Massif de Masse" and was water-saturated while the lower sequence belongs to the "Massif du Poirier" and was considered as dry due to the sealings of the mineshafts (Piessens and Dusar, 2004). A part of the "Ressaix-Mariemont-La Louvière" coal concession and a small area from another contiguous coal concession named "Bois du Luc, La Barette et Trivières" were joined together to create the underground natural gas storage reservoir (UNGSR) of Peronnes exploited by the industrial company formerly called Distrigaz and lately Fluxys. The subsurface use of the underground gas storage started in 1982 till 1991. The injection of gas and the gas exraction were made possible using two main mine shafts thanks to the continous groundwater pumping activities to maintain the piezometric level at the depth -350 m from the surface.

After the cease of the groundwater pumpings, the piezometric water levels have risen to a depth of -150 m from the surface that are known more recently. Fron the end of the gas storage subsurface use, the gas pressure was of about 790 hPa in 1999 and has increased to 1180 hPa in 2008. To maintain dry the underground gas storage of Peronnes, the Fluxys company has pumped continuously the groundwater level of the

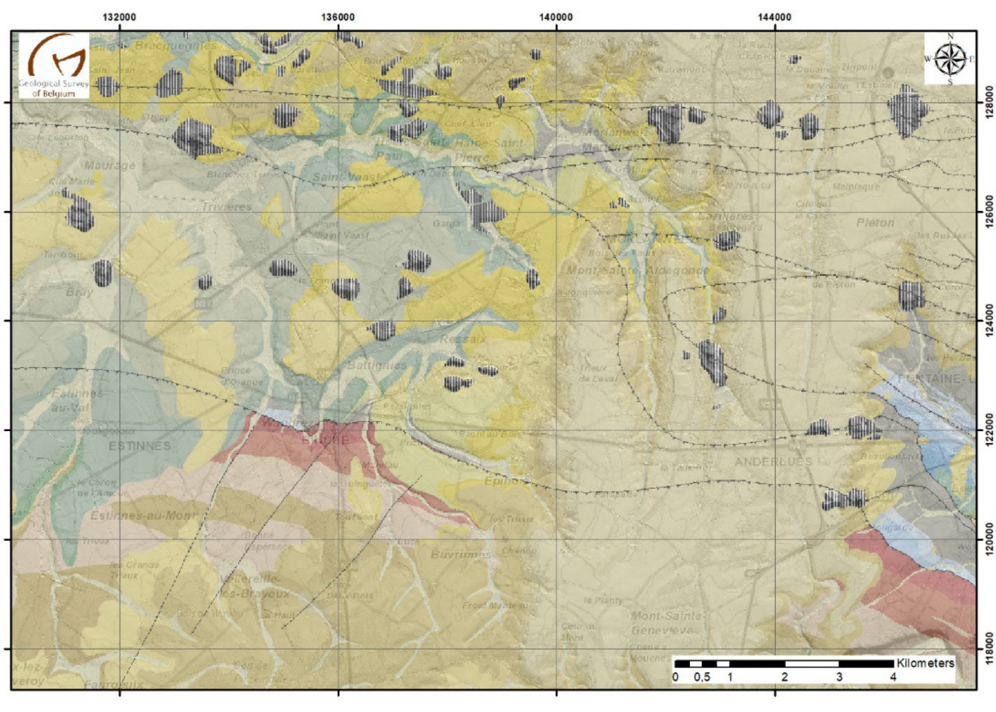

Figure 2 Geological map of the ROI inside Wallonia from the Binche-Morlanwelz 1:25,000 geological scale-map across the urbanized areas of Binche to Anderlues along West-East direction. The two underground gas storage sites of Peronnes and Anderlues are stored inside the area. The geological data of the geological maps are provided using WMS data provided by the Walloon Administration, the background map is a transparent superimposition of the DEM of the Walloon Region in hillshade mode (also available as WMS data provided by the Walloon Administration on the topographic data provided by the WMS topographic data of NGI). The ROI is associated with Belgian Lambert 72 coordinates.

shallower aquifer till 1998 using an immerged pump in the main mineshaft (Saint-Albert I) at a depth of -417 m in betwee, 1970 and 1982 and at -222 m from 1982 to 1998. Since the end of the groundwater pumping activities in 1998, the groundwater level has risen from 8 m per month in 1998 to about 2.5 m per year in 2010.

Data and Methodology

To calculate the ground movements using PSI, more than 170 C-Band SAR images from ascending and descending tracks of different satellites were used, providing a good coverage in time and space of the ROI. The average acquisition sampling time is 35 days for ERS-1/2 and ENVISAT and 12 days for Sentinel-1A. The list of the processed data is given in the Table 1. ERS-1/2, ENVISAT data were processed using Doris-StaMPS suite (Kampes and Usai 1999; Hooper 2008) while the recent Sentinel-1A data were done by InSAR Scientific Computing Environment (ISCE, Rosen *et al.* 2012) and StaMPS (Hooper 2008). During the processing, the external Digital Elevation Model (DEM) data from the Shuttle Radar Topography Mission (SRTM 3-arc second) with a 90 m horizontal resolution (Farr *et al.* 2007) was used to remove the topographic component of the interferometric phase. StaMPS was used afterwards to finalize the PSI processing. After the processing, only Persistent Scatterer (PS) points characterized by a temporal coherence greater than 0.7 were selected, a common value in radar interferometry studies (Chaussard 2014).

Results and Discussions

Satellite observations revealed various surface displacement patterns during the last three decades. During the satellite image acquisitions made by ERS1 and 2 (1992 to 2006), the LOS velocities reported in the Peronnes UNGSR are characterized by: 1°) a west to east trend showing a decrease of the LOS velocity values from positive values to the west in the village of Péronnes-lez-Binche to negative values in the villages of Leval and la Jonquière villages; and 2°) a north to south gradient surface displacements either from positive LOS velociy values either from negative LOS velocity values towards relatively stable LOS velocity values in between -0.5 and 0.5 mm/a mapped either in Binche and Battignies to the Trahegnies village. The southern urbanized areas inside the Peronnes UNSGR and those below to the south outside the limits are all characterized by very stable LOS velocity values. The LOS velocity values reported in the Anderlues UNGSR are indicative of: 1°) negative LOS velocities inside a relative elliptic area centred on the northern part of Anderlues with an axis oriented WNW to ESE. A symmetric gradient towards higher LOS velocity values is present in the urbanized areas located directly to the south (city centre of Anderlues) and to the North. It has also to be noticed that positive LOS velocity values are present in the urbanized areas located to the North from Maurage-Trivières to the West towards Morlanwelz and Carnières with the highest positive LOS values around the villages of Saint-Vaast, Haine-Saint-Paul and Haine-Saint-Pierre while the LOS velocity values are clearly decreasing towards the West, the North and the East. Far more to the East in the Piéton urbanized areas north of Fontaine-l'Evêque, positive LOS velocity values are also observed (Figure 3).

During the second period of satellite image acquisitions of Envisat (2003–2010), the following behaviours can be noticed in the Peronnes UNSGR: 1°) the LOS velocity values were higher and more positive with a WNW

Table 1 *Characteristics of the SAR image datasets used for studying the Binche-Anderlues region*

Satellite	Number of interferograms	Start date of spanning	End date of spanning
ERS1/2	74	26/04/1992	04/10/2006
ENVISAT ASAR	73	19/03/2003	13/10/2010
Sentinel-1A	179	02/04/2015	31/01/2022

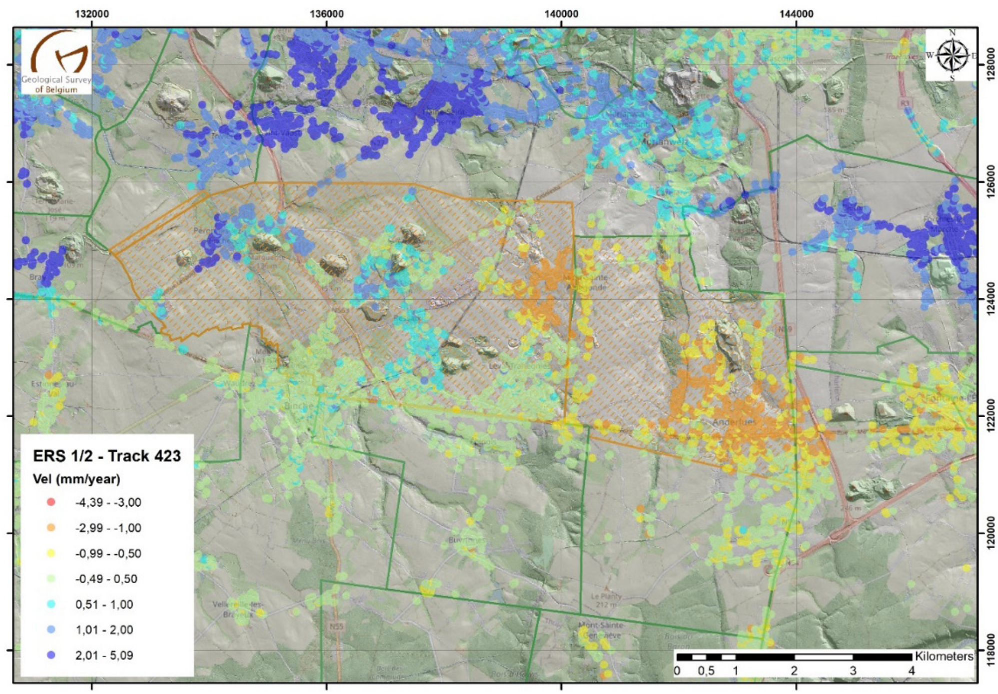

Figure 3 *LOS velocity map of PS points distributed over the ROI derived from ERS1/2 radar data (1992-2006).*

to ESE axis across the urbanized areas of Péronnes-les-Binche, Ressaix and Trahegnies. A gradient towards more stable LOS velocity values (green/ -0.5 to 0.5 mm/a) is present to the south towards the limits of the Peronnes UNSGR while most of the Binche city centre is now characterized by negative LOS velocity values including all the other urbanized areas south of the Peronnes UNSGR. 2°) more negative LOS velocity values are extremely well mapped in the north-eastern corner of the Peronnes UNSGR inside the Leval and la Jonquière villages. The ground displacements observed at the surface have thus evolved oppositely towards more higher positive LOS velocity values in most of the Peronnes UNSGR while the NE area is experiencing more negative LOS velocity values. A localized elliptical surface with a main axis oriented WSW to ESE is clearly visible from the northern part of Leval, across la Jonquière and towards Mont-Sainte-Aldegonde. For the Anderlues UNSGR, most of the area is characterized by more negative LOS velocity values extending towards all directions outside the UNSGR. It has also to be noticed that positive LOS velocity values are maintained in the urbanized areas located to the North around the villages of Saint-Vaast, Haine-Saint-Paul and Haine-Saint-Pierre while the LOS velocity values are clearly decreasing towards stable values (green) to the West, the North and the East. Far more to the East in the Piéton urbanized areas north of Fontaine-l'Evêque, positive LOS velocity values are still observed (Figure 4).

During the Sentinel-1A interval (2015–2022) of satellite imagery, the following observations are noticed in the Peronnes UNSGR: 1°) the LOS velocity values were higher and more positive with a WNW to ESE axis across the urbanized areas of Péronnes-les-Binche, Ressaix and Trahegnies. A gradient towards more stable LOS velocity values (green) is present to the south towards the limits of the Peronnes UNSGR while most of the Binche city centre is now characterized by very stable LOS velocity values (-0.5 to 0.5 mm/a) including all the other urbanized areas south of the Peronnes

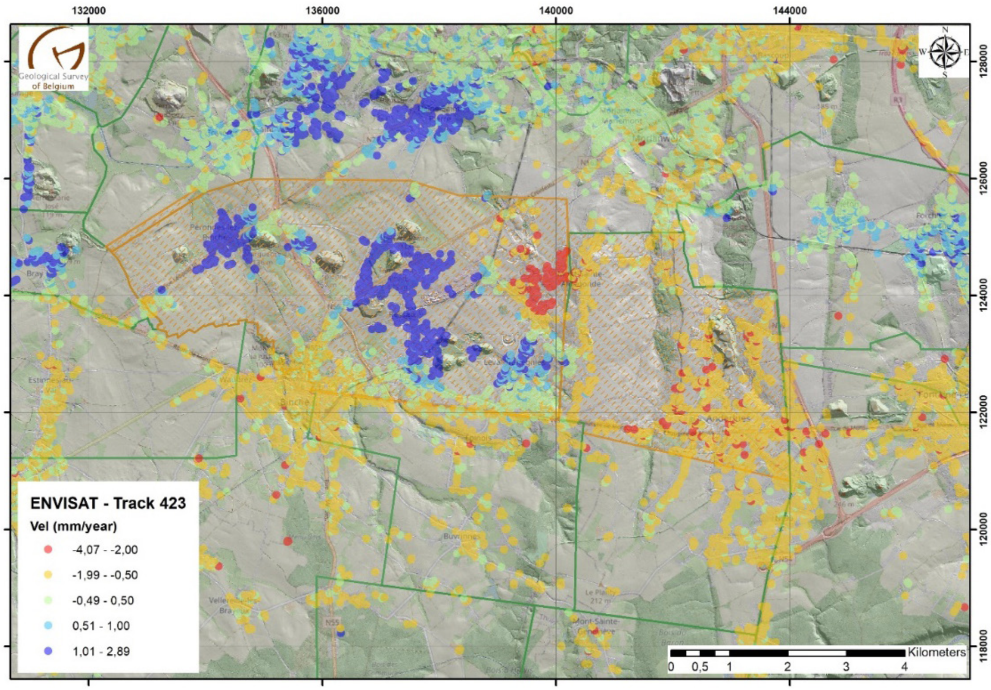

Figure 4 *LOS velocity map of PS points distributed over the ROI derived from Envisat ASAR radar data (2003-2010).*

UNSGR. 2°) a switch towards positive and high LOS velocity values is now mapped in the north-eastern corner of the Peronnes UNSGR inside the Leval and la Jonquière villages. The ground displacements observed at the surface have thus a global and more uniform evolution across the entire Peronnes UNSGR. A gradient towards positive but lower LOS velocity values is observed to the western and northern areas. For the Anderlues UNSGR, most of the area is characterized by negative LOS velocity values extending towards more stable LOS velocity values (green) in every directions outside the UNSGR. It has also to be noticed that positive LOS velocity values are maintained in the urbanized areas located to the North around the villages of Saint-Vaast, Haine-Saint-Paul and Haine-Saint-Pierre while the LOS velocity values are clearly decreasing towards stable values (green) to the West, the North and the East. Far more to the East in the Piéton urbanized areas north of Fontaine-l'Evêque, weak positive LOS velocity values are still observed (Figure 5).

Conclusions

This study attempted to illustrate the necessity of a long-term monitoring of the surface deformations encountered in old coal mining districts associated to growing urbanized areas. The type of activities of the subsurface has changed with the needs of finding and exploiting reservoirs for gas extraction and storage. Geothermal approach and the use of the underground water aquifers related to the underground coal exploitations is another possibility. These new industrial activities of the subsurface can be extremely well monitored using mm-scale radar satellites to detect, estimate and cartography the ground deformations seen at the surface. Those highlighted in this study have shown that (1) the ground deformations are not homogeneous neither in space neither in time, (2) urbanized areas are affected by cm to several cm of deformations during the 30 years of the study, (3) the potential causes of these ground deformations need additional data both from the underground water levels

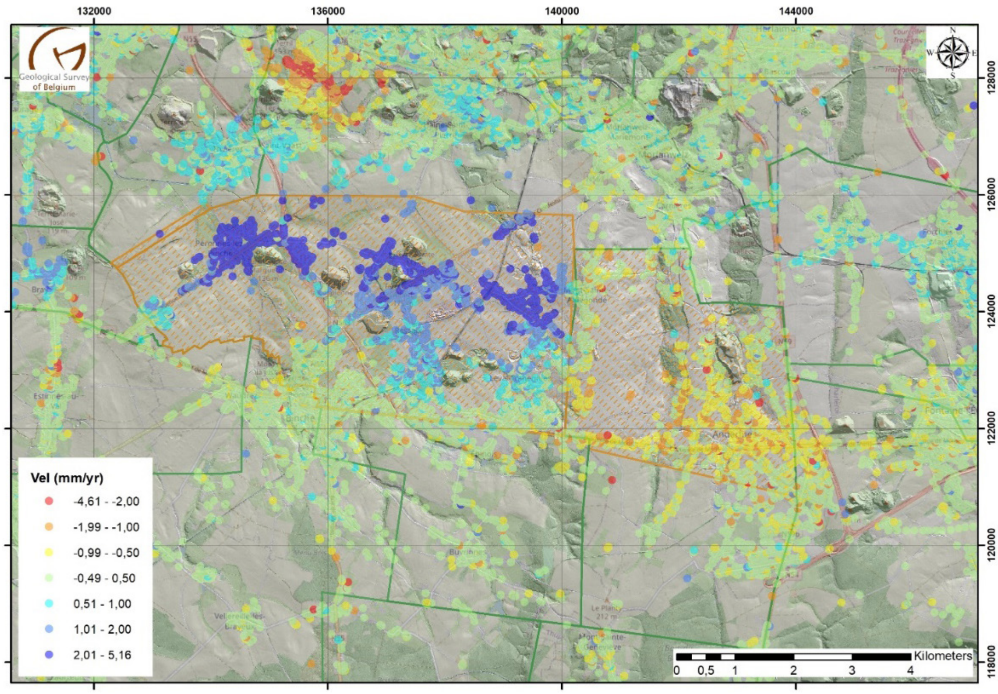

Figure 5 LOS velocity map of PS points distributed over the ROI derived from Sentinel-1A (2015-2022).

monitoring and from the industrial activities in terms of volume of gas extraction and/or storage through time.

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