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Soil uplift in the Emilia-Romagna plain (Italy) by satellite radar interferometry

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ABSTRACT Satellite radar interferometry (InSAR) data from 1992 to 2016 in Emilia-Romagna plain (about 13,000 km^2), has been represented in four maps describing vertical ground movements. The maps were created by the Regional Agency for Environmental Protection and Energy (ARPAE) on behalf of the Emilia-Romagna Region, to discover the areas mostly affected by land subsidence, and provide an opportunity to analyse its cause and find remedies. This data set is used to study positive vertical ground movements (i.e. uplifts) and their nature. Some areas are found to be constantly rising from 1992 to 2016 (Piacenza and Parma plain), others have risen in a differentiated or intermittent way (Reggio Emilia, Modena, Ferrara and Bologna plain). There are no documented uplifts in the Romagna part of the plain (Ravenna, Forlì and Rimini plain). Most of the observed uplifts are due to tectonics as they occur above active structures present in the subsoil, such as portions of the Emilian folds, Ferrara folds, and the Pede-Apennine Thrust front. Differently, the uplift observed in the Bologna plain can be considered related to anthropogenic activities, especially the strong increase of piezometric levels due to the reduction of groundwater withdrawals.

Key words: vertical soil movements, active tectonics, recovery of piezometric level.

1. Introduction and purpose

The Regional Agency for Environmental Protection and Energy (ARPAE) has produced, on behalf of the Emilia-Romagna Region, four maps that describe the vertical soil movement from 1992 to 2016 in the Emilia-Romagna plain (area approximately 13,000 km^2, Fig. 1). The maps were obtained through satellite interferometry (InSAR).

The Emilia-Romagna plain constitutes the southern part of the Po Plain, the biggest alluvial plain in Italy. The Po Plain is an active foredeep basin interposed between two chains still in formation (Fig. 1): the northern Apennines to the south and the Alps to the north (Ori, 1993). The upper part of the stratigraphic succession of the Emilia-Romagna plain is made of recent alluvial sediments (Middle Pleistocene-Holocene), which locally exceed 500 m in thickness (Di Dio, 1998). These sediments are the result of the Po River and its Apennine tributaries depositional activity, and are mainly made up of fine and unconsolidated sediments (alternation of sands, silts, and clays). Gravels are present only in the southern part of the plain, along the northern Apennine - Po Plain morphological margin (Severi and Bonzi, 2015). Because of the presence of hundreds of metres of unconsolidated sediments, this sector of the region is subject to natural subsidence, due to the compaction of these sediments (Carminati and Di Donato, 1999). The four maps of soil vertical movement were produced by the Emilia-Romagna Region to

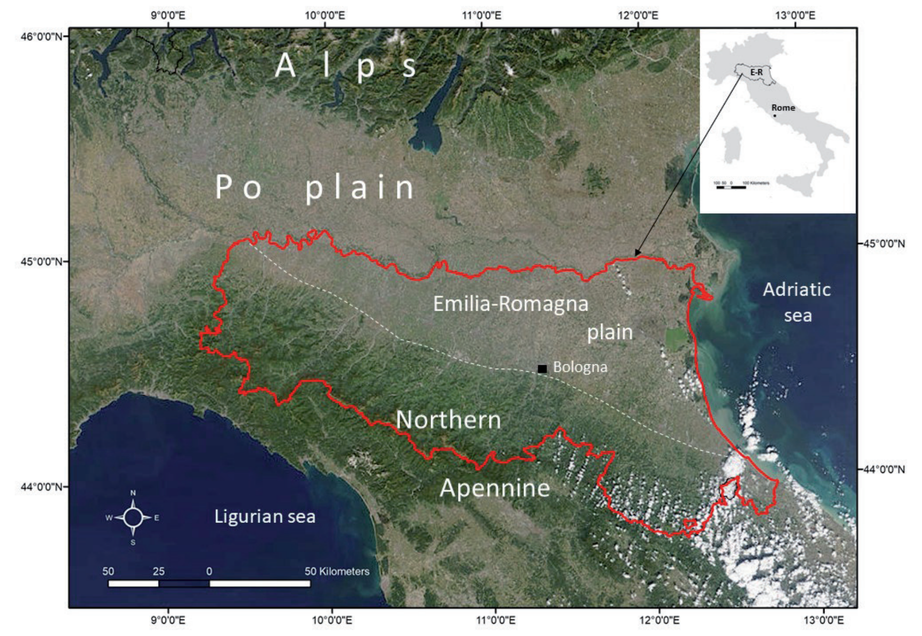

Fig. 1 - Geographical framework of the Emilia Romagna plain (red boundary: Emilia-Romagna region). In the box at the top right E-R means Emilia-Romagna region.

understand and deal with subsidence, which in the past has severely affected some parts of the plain. The main problems related to subsidence are water stagnation or flooding, due to rivers and canals flow, as well as coastal erosion.

Subsidence maps highlight the most subsident areas and offer the opportunity to analyse causes and look for remedies (Strozzi *et al.*, 2001). In addition, during the analysed period, InSAR data show how some plain sectors were stable or underwent an uplift. The present work focuses on the analysis of areas without subsidence (stable or rising soil), and on their evolution over time.

2. Maps of vertical soil movements

The analysed maps were created by elaborating InSAR data calibrated through precision topographic levelling or permanent GNSS stations (Bitelli *et al.*, 2000, 2010, 2014, 2015; ARPAE, 2012, 2018a).

The isokinetic lines on each map show the average speed of the vertical soil movement during the investigated period. The maps were made in collaboration with the Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna and with TRE ALTAMIRA S.r.l. Milano, Italy (Fig. 2).

The first map (1992-2000) was created by means of PSInSAR technique [by TRE ALTAMIRA S.r.l., Ferretti *et al.* (2001)] using data from the ERS1 and ERS2 satellites in descending geometry, on a total of 160,000 permanent scatterers (PSs). The InSAR data were calibrated through a high-precision geometric levelling based on 1,000 benchmarks (ARPAE, 2007). The second map (2002-2006) was made by PSInSAR technique using ENVISAT images in ascending

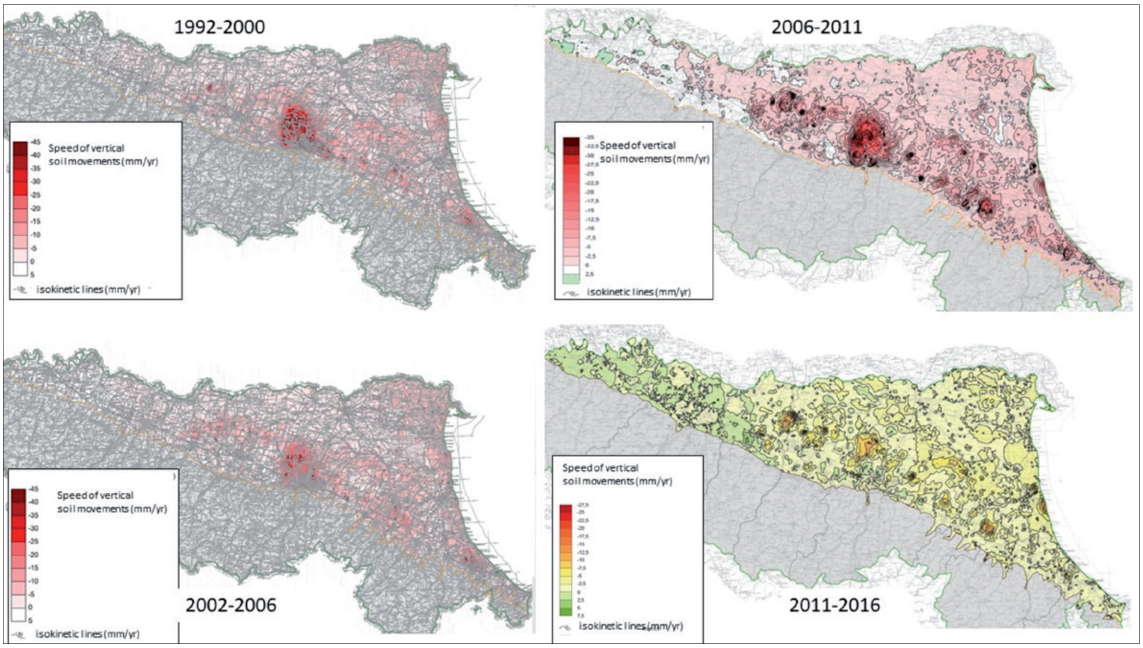

Fig. 2 - Vertical soil movements in the Emilia-Romagna plain (ARPAE, 2007, 2012, 2018a).

and descending geometry (2002-2006), and from RADARSAT-1 acquisitions in ascending geometry (2003-2005), on a total of 140,000 PSs. The InSAR data were calibrated through a high-precision geometric levelling, based on 1,000 benchmarks (ARPAE, 2007). The third map (2006-2011) was created using SqueeSAR technique (by TRE ALTAMIRA) on RADARSAT-1 images acquired in ascending geometry, on a total of 315,000 PSs and distributed scatterers (DSs). The InSAR data were calibrated with measurements from 17 GNSS permanent stations (ARPAE, 2012). The fourth map (2011-2016) was created with the SqueeSAR technique using images from RADARSAT-1 and COSMO-SkyMed ascending geometry, on a total of 1,912,781 PSs and DSs. The InSAR data were calibrated with data from 22 GNSS permanent stations (ARPAE, 2018a; Bitelli *et al.*, 2020). The evaluations reported in the following are mainly based on data indicated in the isokinetic lines reported in the cited maps. Explanation of methods in producing the maps and calibrating InSAR vs. GNSS velocity, evaluation of the errors, kind of elaborations to detect vertical movement starting from one velocity map in satellite line of sight (only in ascending geometry) are beyond the scope of the present work, and are discussed in the cited bibliography.

3. Types of vertical soil movements

The maps identify areas characterised by different velocities of vertical displacements, i.e. areas with greater or lesser subsidence, substantially stable areas, and uplift areas. The subsiding areas take up most of the Emilia-Romagna alluvial plain. Subsidence in the Emilia-Romagna plain is due to natural and anthropogenic factors (Carminati and Di Donato, 1999; Gambolati *et al.*, 2005; Cenni *et al.*, 2013; Antoncecchi *et al.*, 2021; Calabrese *et al.*, 2021); the former produce a fairly homogeneously distributed subsidence, while the latter concentrate soil lowering in localised areas (ARPAE, 2008). Natural subsidence is mainly due to sediment aedometric compaction and tectonics. Natural subsidence follows the trend of deep plain structures, with lower values on structural highs and higher ones on the synclines. They generally do not exceed 2-3 mm/yr, with the exception of the active area in the Po Delta (Fig. 3) where they can reach values over 10 mm/yr (Carminati and Di Donato, 1999; Carminati *et al.*, 2003; Teatini *et al.*, 2011).

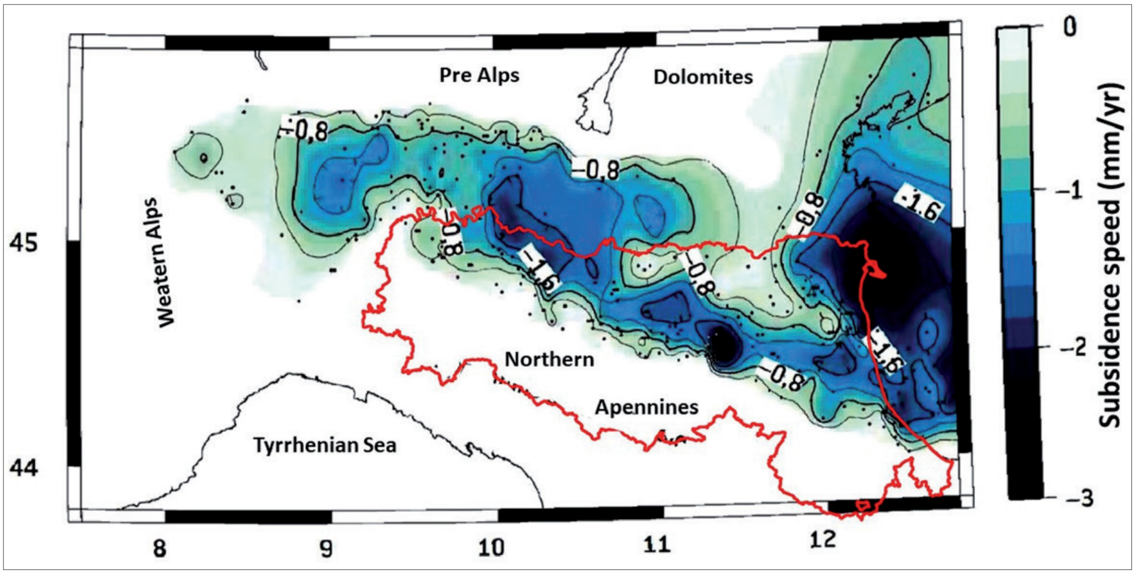

Fig. 3 - Natural land subsidence (in mm/yr) in the Po Plain (modified by Carminati and Di Donato, 1999).

Anthropogenic subsidence is largely due to underground fluid extractions (water and hydrocarbons), and can exceed natural subsidence by more than one order of magnitude (Carminati and Di Donato, 1999). There are some tens of thousands water wells on the Emilia-Romagna plain, the depth ranging from a few metres up to 500 m (Di Dio, 1998; ARPAE, 2008). Groundwater is mainly used for drinking, as well as industrial and irrigation purposes. Wells for drinking and industrial use are generally located in urban areas and are characterised by very high withdrawal rates, while irrigation wells are distributed over the entire plain with generally low withdrawal rates (Regione Emilia-Romagna, 2015). Groundwater withdrawals have decreased over the last decades in favour of surface water use, thanks to water resource management aimed at reducing anthropogenic subsidence (Regione Emilia-Romagna, 2015).

4. Fluids extraction and soil movements

When groundwater withdrawal exceeds aquifer recharge, the piezometric level is lowered and fluid pressure in the subsoil decreases. Consequently, sediments are compact and the soil surface sinks. Land subsidence is mainly due to inelastic compaction and reduction of porosity of fine sediments present in the subsoil (Terzaghi and Peck, 1967; Galloway *et al.*, 1999). On the contrary, the increase in the piezometric level, for instance due to a decrease in water withdrawals, causes an increase in groundwater pressure, which in turn expands the pores of the aquifer skeleton leading to soil uplift (Galloway *et al.*, 1999).

Irreversible land subsidence is due to inelastic deformation of aquitards caused by the lowering of the piezometric level; a recoverable subsidence is due to elastic and reversible aquifer deformation caused by an increase in the piezometric level (Fig. 4). Groundwater withdrawal has been considered the main cause of subsidence that affected, especially in the past, the western part of the Bologna plain and other sectors of the Emilia-Romagna plain (Teatini *et al.*, 2006; ARPAE, 2008, 2018a; Bitelli *et al.*, 2010).

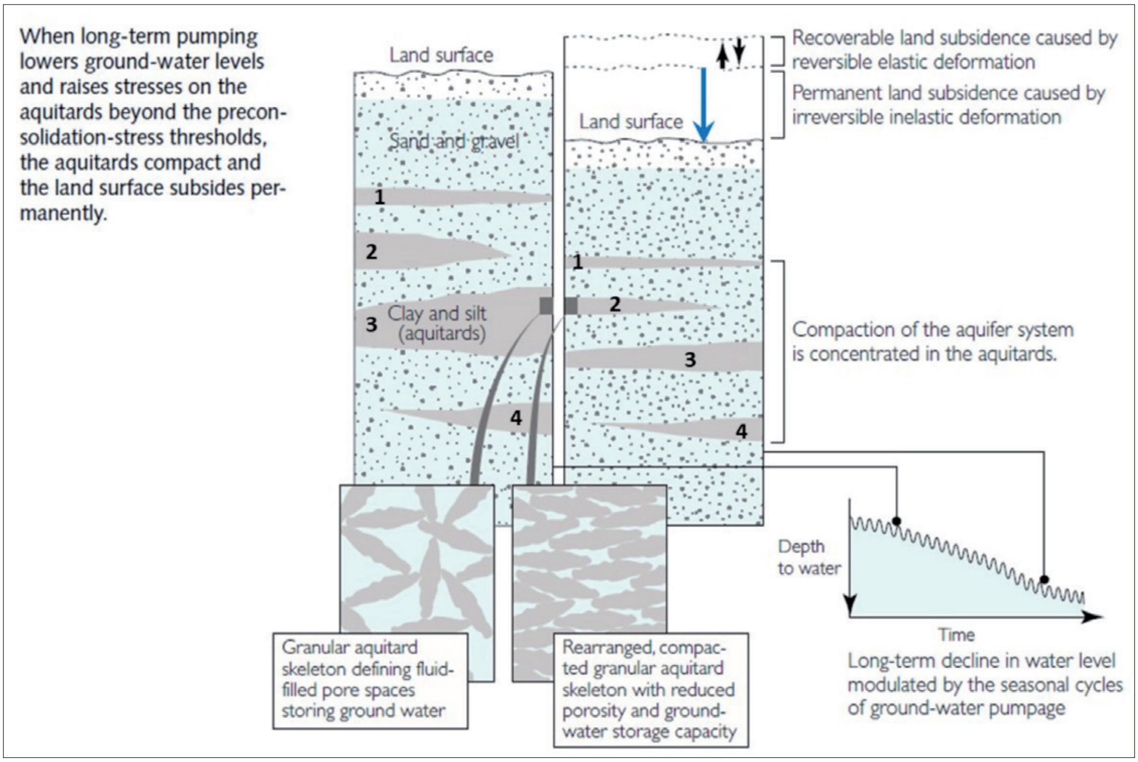

Fig. 4 - Irreversible subsidence caused by inelastic deformation (blue arrow) and recoverable subsidence (black arrows) caused by elastic deformation (Galloway *et al.*, 1999, modified).

Subsidence due to hydrocarbons withdrawal (especially methane in the Po Plain) is linked with the loss of pressure produced by gas extraction, which causes reservoir compaction. Reservoir compaction can produce effects up to the surface causing land subsidence (Geerstma, 1973; van Hasselt, 1992; Gambolati *et al.*, 1999). Production of methane in the Emilia-Romagna region reached its peak before the 1990s, therefore the regional subsidence maps do not fully describe its effects. Some current subsidence areas along the Ravenna coast can be partly attributed to methane withdrawal still on-going today (ARPAE, 2018a; Severi *et al.*, 2021).

5. Map analyses

Since natural subsidence does not exceed 2-3 mm/yr, areas where subsidence is greater than, or equal to, 5 mm/yr have been highlighted to identify places where the anthropogenic component is certainly present (Salvioni, 1957; Arca and Beretta, 1985) (Fig. 5).

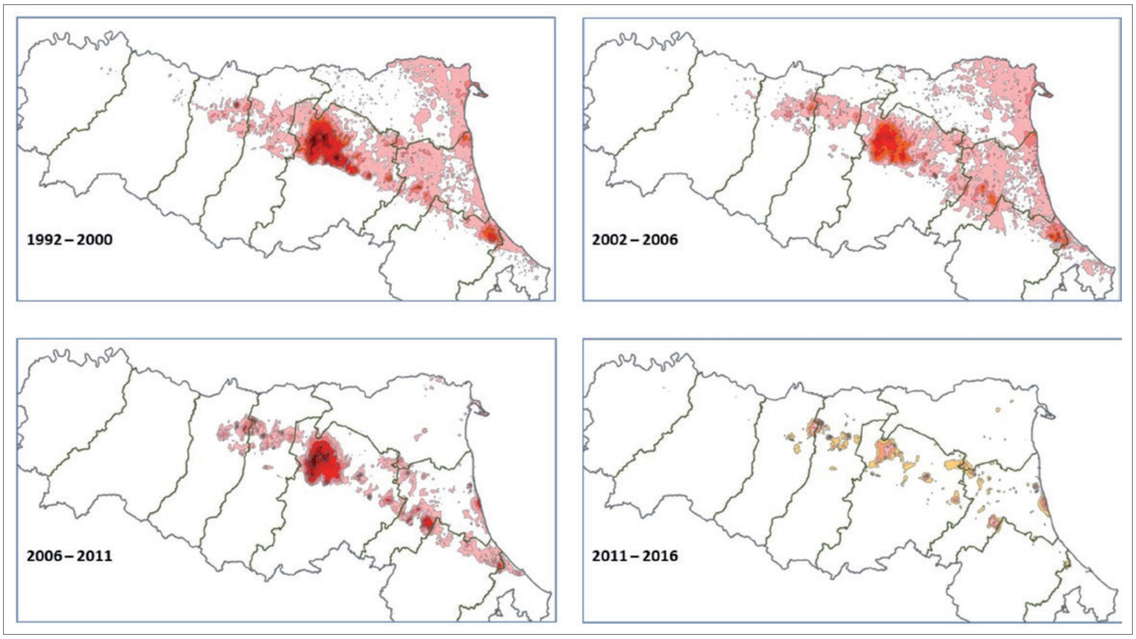

Fig. 5 - Areas with subsidence velocity greater than or equal to 5 mm/yr, from maps of Fig. 2.

While in the first two maps the extent of these areas remains approximately the same, in the third and fourth map the surfaces affected by anthropogenic subsidence drastically decrease (Table 1).

At the same time, maximum subsidence rates significantly decrease, and uplift areas increase. In each of Fig. 2 maps there are uplifting areas; an increase in total uplift surface is observed over time, which culminates in 2006-2011 (Fig. 6 and Table 1).

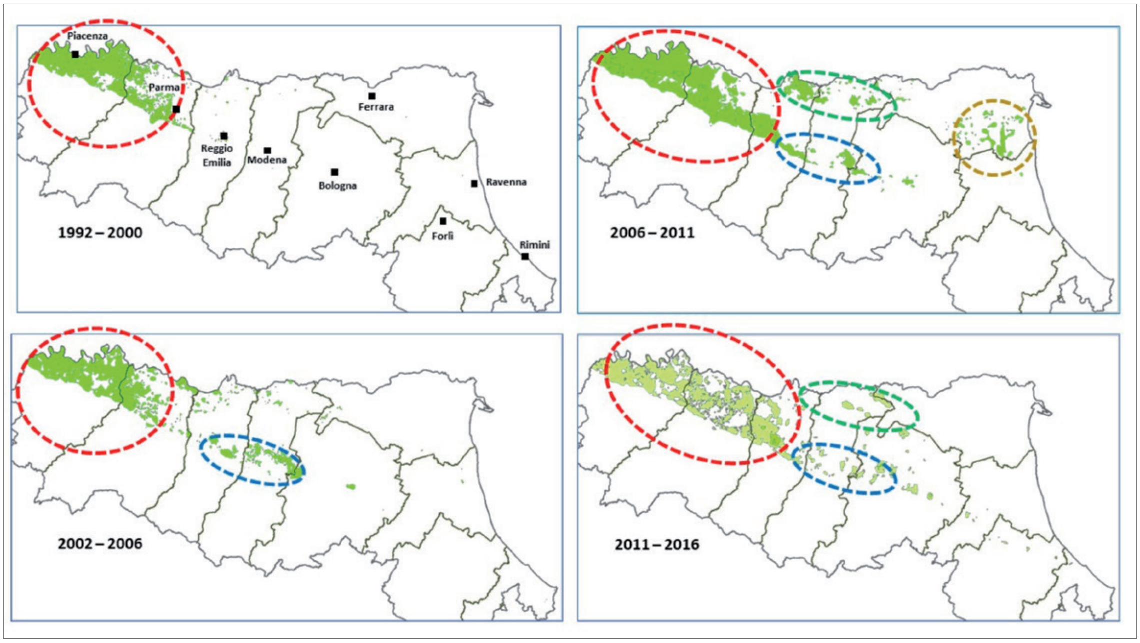

Fig. 6 - Uplift areas, with boundaries and names of Emilia-Romagna provinces (see the text for the explanation of the colours).

Table 1 - Extension of areas with subsidence and uplift: A = areas with subsidence rates greater than, or equal to, 5 mm/yr (Fig. 5); B = uplift areas (Fig. 6).

Areas/Years	1992-2000	2002-2006	2006-2011	2011-2016
A (km^2)	4,075	4,244	1,935	637
B (km^2)	978	1,142	1,911	1,525

Uplift of the plain is observed in four areas of the Emilia-Romagna region. The western plain area (Piacenza and Parma provinces) shows an uplift pattern from 1992 to 2016 (red ellipse in Fig. 6), over time the uplift expands to also affect the Reggio Emilia province in 2011-2016. The widespread uplift of western Emilia-Romagna is well documented by GNNS measurements in 2001-2013 (Cenni *et al.*, 2013). Previously (1897-1957) an area characterised by land uplift was documented west of Piacenza city (Arca and Beretta, 1985). It, therefore, appears that the uplifting area is expanding eastwards over time. The southern part of Reggio Emilia, Modena and Bologna plain uplifted from 2002 to 2016 (blue ellipse in Fig. 6). The northern part of Modena and Reggio Emilia plain and the western sector of Ferrara province uplifted during 2006-2016 (green ellipse in Fig. 6). It should be noted that coseismic elevation changes recorded in the southern Modena area during the 2012 earthquake are removed from the 2011-2016 map, since mechanism and amplitude [over 20 cm: Bignami *et al.* (2012) and Pezzo *et al.* (2013)] of these uplifts are different from those normally recorded (ARPAE, 2018a). The south-eastern area of Ferrara province only uplifted during 2006-2011 (brown ellipse in Fig. 6). The uplifted areas in Emilia-Romagna plain highlighted during the analysed periods are located above buried tectonic structures considered active or potentially active (Fig. 7): the Emilia folds, the Pede-Apennine thrust front at Reggio Emilia, Modena and Bologna plain, and in some sectors of the Ferrara folds (Emilia-Romagna Region, 2017).

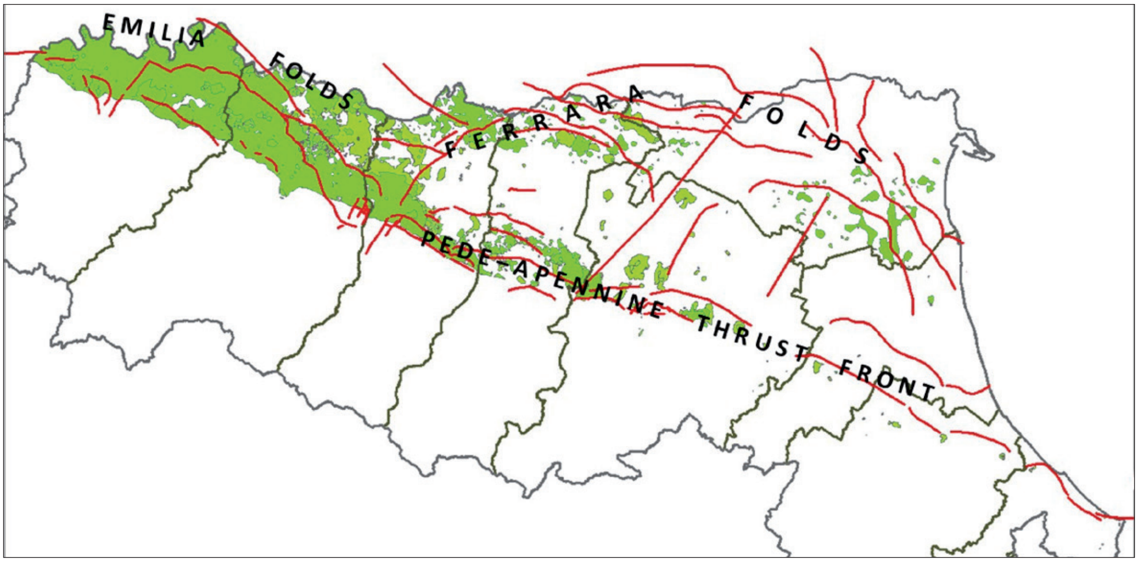

Fig. 7 - Uplifted areas during 1992-2016 (green areas) and active or potentially active structures in the Emilia-Romagna plain (red lines, from Regione Emilia-Romagna, 2017).

Therefore, the information deduced from the maps shown above seems to indicate that these tectonic structures produced constant uplifts throughout the 1992-2016 period (the Emilia folds), or intermittent vertical moments (Ferrara folds, Pede-Apennine thrust front). The uplift in 2006-2011 in the north part of Modena province and the western part of Ferrara province could indicate a triggering of the compressive tectonics, which culminated with the 2012 earthquakes. No uplifts were recorded in tectonic structures in the Romagna portion (Ravenna, Forlì and Rimini plain).

What is stated above should be considered a first hypothesis. In fact, the variations in velocity over time that distinguish the uplifted areas and the subsidence areas are very low, and perhaps further investigations, also with different methodologies, would be needed.

6. The uplifts in the Bologna plain

The 2011-2016 map indicates uplifted areas in some sectors of the Bologna plain (Fig. 6). Uplifts were previously observed (Severi *et al.*, 2009, 2010) in some areas of the Reno River alluvial fan (Fig. 8), which in recent decades has been affected by strong subsidence, recording the highest subsidence values in the Emilia-Romagna region (Fig. 2). The Reno River alluvial fan is one of the largest in Emilia-Romagna, and consists of an alternation of coarse gravels passing undercurrent to sand and fine clay and silt deposits, for a thickness of several hundred metres (Severi *et al.*, 2009; Severi and Bonzi, 2015). Gravel thickness is maximum at the end of the valley (section L10 in Fig. 8), and decreases laterally to it (sections L7 and L15 in Fig. 10). Drinking water withdrawal for the Bologna metropolitan area is concentrated in the Reno River alluvial fan aquifer.

The most marked decrease of land subsidence rates and the most significant ground uplifts were observed in areas where fine sediments prevail (sections L7 and L15 in Fig. 8).

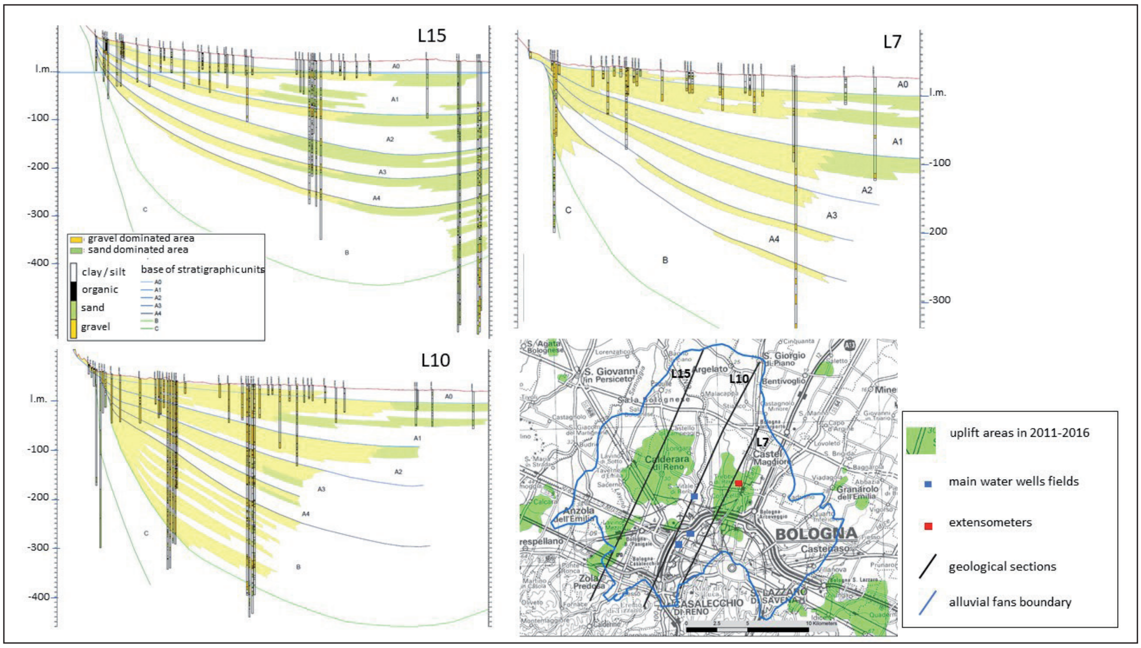

Fig. 8 - Reno River alluvial fan (amalgamated with the minor alluvial fans of the Samoggia, Lavino, and Savena rivers), uplifted areas in 2011-2016, main water well fields, extensometers and geological sections (as reported in https://ambiente.regione.emilia-romagna.it/it/geologia/cartografia/webgis-banchedati/sezioni-geologiche-prove-geognostiche-pianura).

The reversed ground movement trend observed in this area is quite surprising, and is shown well by the comparison between 2006-2011 and 2011-2016 subsidence maps. The Bologna area recorded a very strong slowdown in subsidence velocity (Fig. 9), with peaks of decrease of 30 mm/yr (Bitelli *et al.*, 2020).

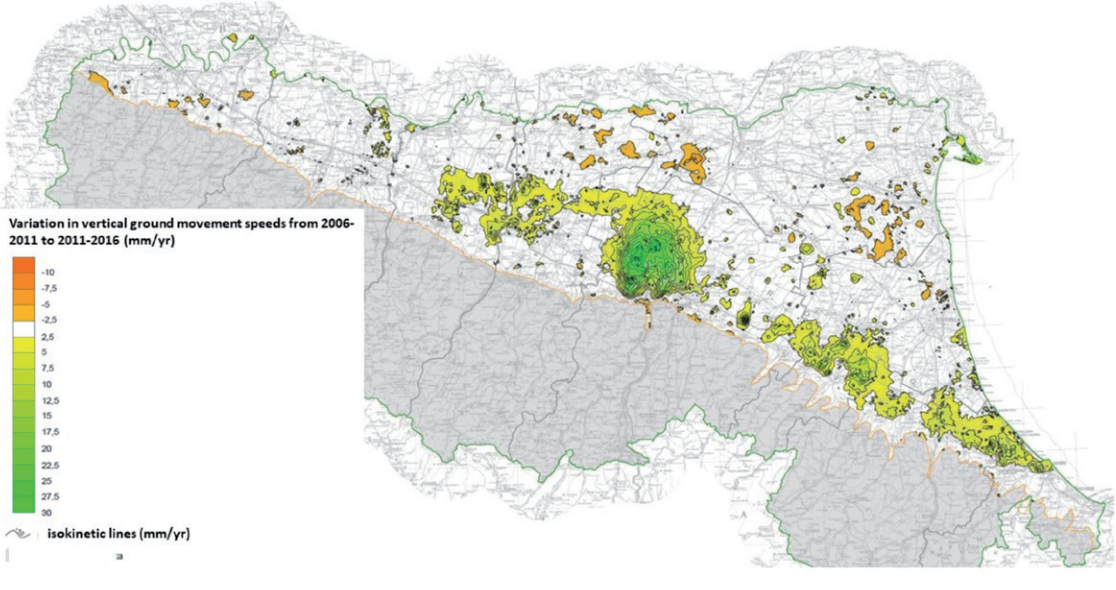

Fig. 9 - Variation in vertical ground movement rate from 2006-2011 to 2011-2016 (ARPAE, 2018a).

The sharp land subsidence decrease and the presence of areas characterised by land uplift were accompanied by a widespread recovery of the piezometric level in the Reno alluvial fan, as highlighted by the regional groundwater monitoring network (ARPAE, 2018b). Over the last few decades, total groundwater withdrawal (drinking, industrial and irrigation use) significantly decreased from over 90 million m^3/yr in 1976 to less than 50 million m^3/yr at the end of 2010. The decrease mainly concerned drinking water withdrawal, which accounts for most of the total, and was largely due to surface water use (from the Setta stream, a tributary of the Reno River) instead of groundwater. This decrease (Fig. 10) clearly influenced the trend of subsidence in the Bologna plain (ARPAE, 2018a).

The largest decrease in groundwater pumping rates occurred over the period 1972-2000, but slowed in 2000-2011, and increased again in 2011 to 2016. The subsidence velocity trend shows a very similar pattern, highlighting an evident correlation between groundwater withdrawal and ground displacements. Thus, the aquifer exploitation can be realistically considered a significant factor causing the soil subsidence (Fig. 10a).

The sharp reduction of groundwater withdrawal during 2010 (Fig. 10b), related to the increase in the use of surface water, resulted in an evident recovery of the groundwater levels that is clearly visible in the regional groundwater network (Fig. 11). It should be noted that a previous reduction of the pumping rates (between 1976 and 2000) did not cause any increase in piezometry. This probably means that only from 2011 the amount of withdrawal become smaller than the aquifer recharge, favouring the rise of the groundwater levels.

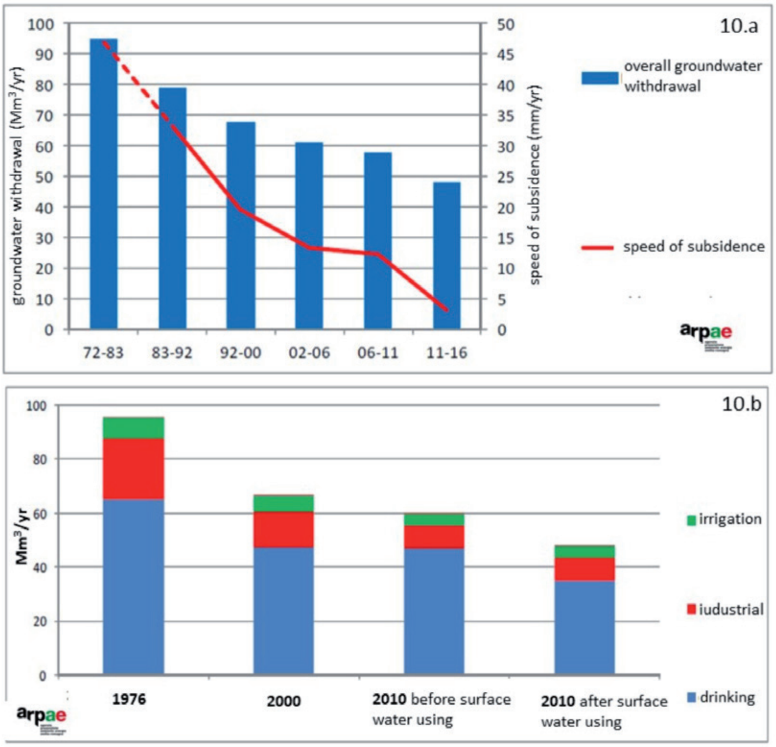

Fig. 10 - Trend of groundwater withdrawals in the Reno alluvial fan and simultaneous decrease in subsidence (a). Different components of groundwater withdrawal (b) (ARPAE, 2018a, modified).

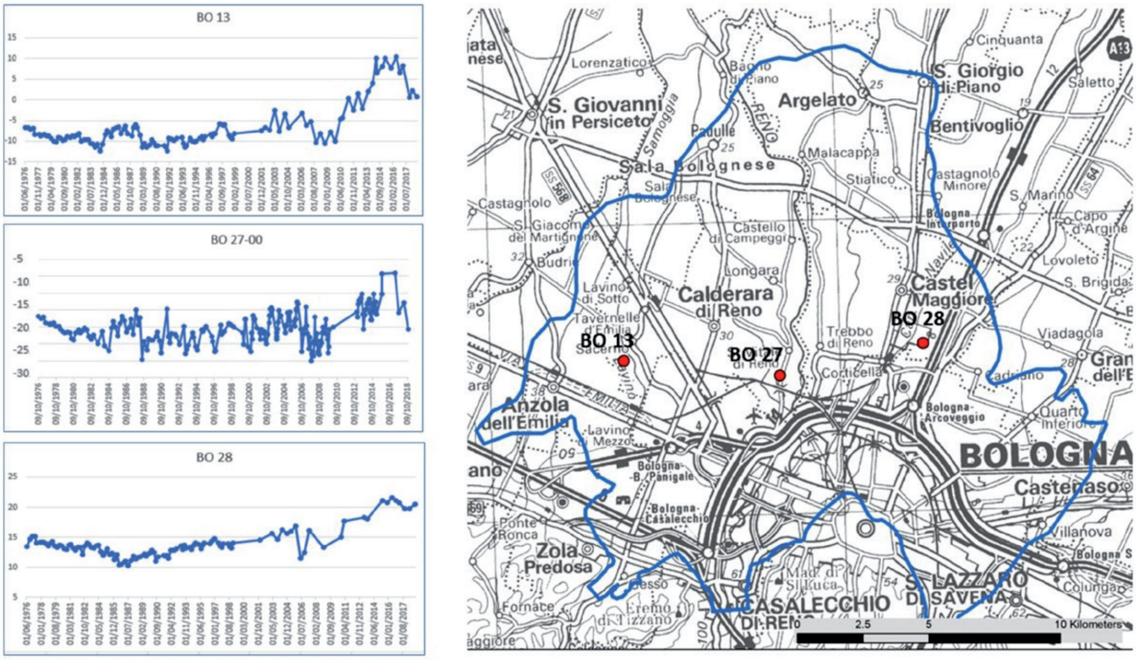

Fig. 11 - Piezometer levels versus time in three representative monitoring wells of regional groundwater network (data in https://www.arpae.it/elenchi_dinamici.asp?tipo=dati_acqua&idlivello=2020).

The general rise in piezometric levels in the Bologna plain has also formed a lake in a sunken quarry area immediately west of Bologna (Fig. 12).

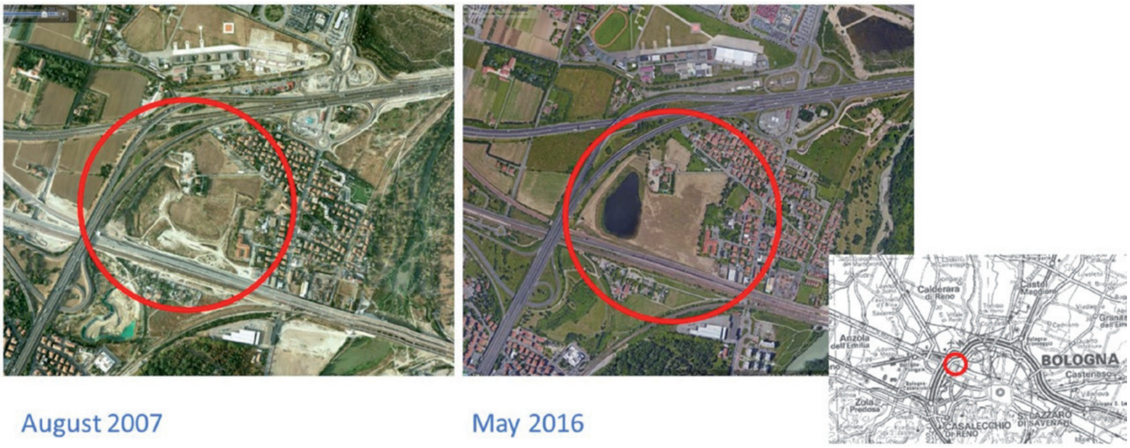

Fig. 12 - Piezometric level rise in the Reno alluvial fan has caused flooding of a former quarry in a sunken area, creating a lake (note that in 2007 the sunken area contained no water).

7. Relationship between piezometry and soil deformation in Castel Maggiore (Bologna province)

The rise of the groundwater level in the Bologna area was also recorded in a continuous piezometry monitoring point in Castel Maggiore, a municipality immediately north of Bologna (underlined in Fig. 13) and one of the formerly most subsident areas in Emilia-Romagna. A 60-m deep piezometer (Fig. 13) was positioned in the first confined aquifer A1 (Di Dio, 1998) and is located near two 100- and 200-m deep extensometers (Bonsignore *et al.*, 2010; ARPAE, 2018a). Monitoring started in spring 2005 (extensometers) and autumn 2007 (piezometer).

The recorded piezometric level shows an evident sinusoidal trend with seasonal frequency, characterised by lowering in summer-autumn and uplift in winter-spring, consistent with the recharge and withdrawal regime (purple arrows in Fig. 14). Furthermore, some minor daily oscillations, due to water well withdrawal near the piezometer are recorded (orange circle in Fig. 14). The 100-m deep extensometer, which intercepts the same portion of the sedimentary sequence as the piezometer (Fig. 13), records a similar sinusoidal trend in phase with the groundwater level, with subsidence in summer-autumn and uplift in winter-spring (brown arrows in Fig. 14). The extensometer records some small daily variations, just like those of the piezometer (grey circle in Fig. 14). There is a clear and immediate relationship between the seasonal trend of the groundwater level and soil deformation: when the piezometric level decreases the deposits compact, and when the level rises the soil expands (Galloway *et al.*, 1999).

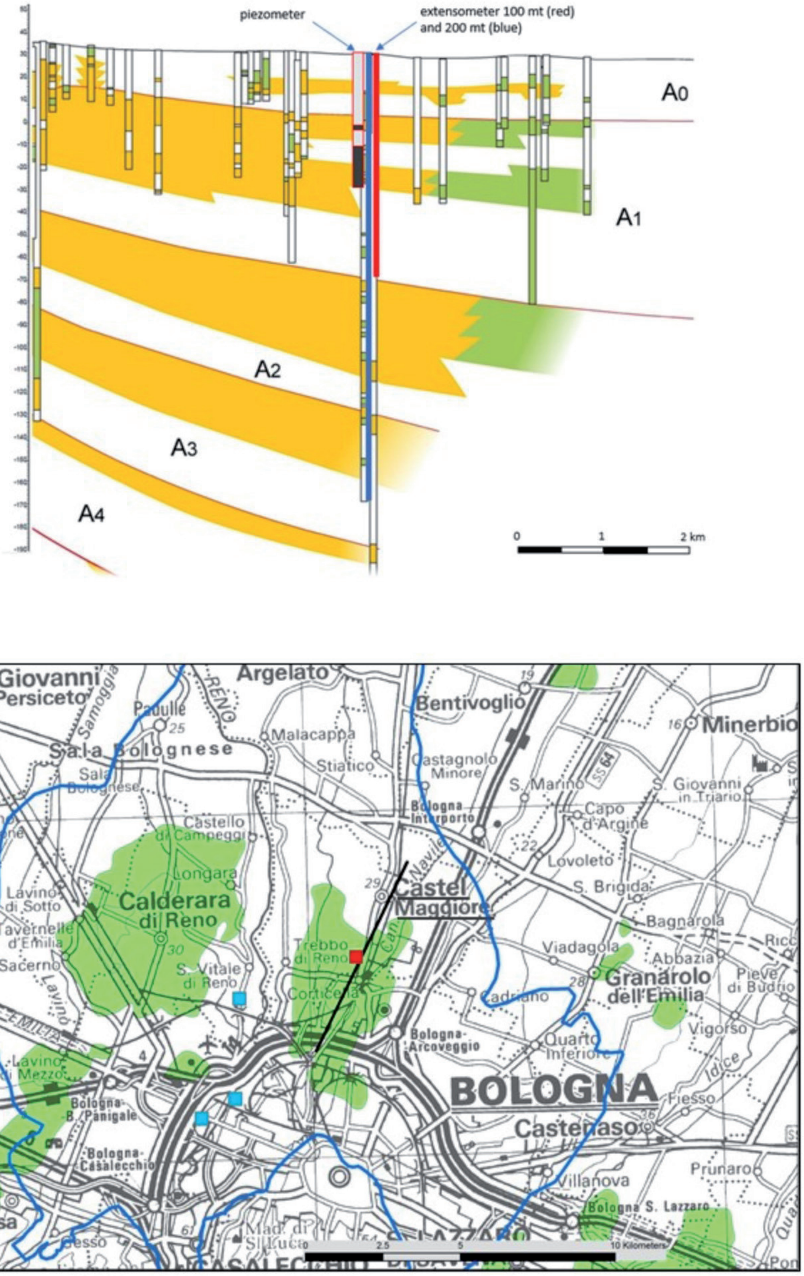

Fig. 13 - Detailed geological section (above) and piezometer and extensometers locations (below). Legend as in Fig. 8 (ARPAE, 2018a, modified).

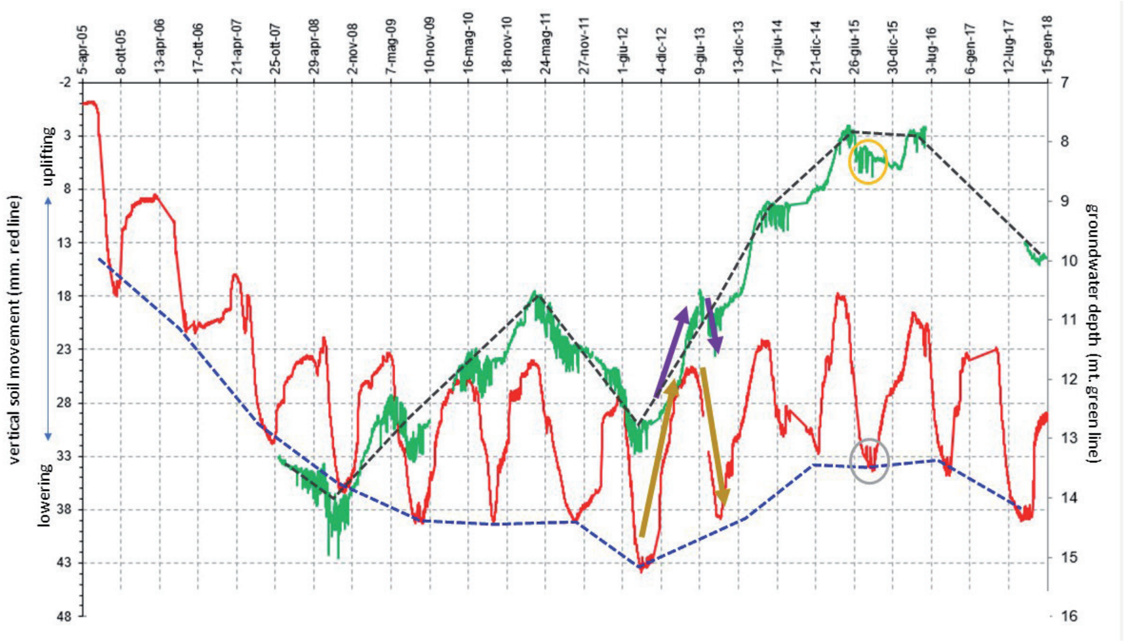

Fig. 14 - Piezometric level (green line) and soil movements (red line). Dashed black and blue lines indicate overall trend, purple and brown arrows seasonality variations, orange and grey circles daily variations (ARPAE, 2018a, modified).

While the amplitude of seasonal piezometric variations is rather variable, the positive and negative seasonal variations recorded by the extensometer are very regular, with an amplitude of about 15 mm. Although the two phenomena are temporally correlated, they do not have a direct proportionality, that is, the amount of soil deformation is not strictly proportional to the piezometric variations. In fact, seasonal soil deformation also depends on other factors, such as soil humidity and the piezometric behaviour within the other aquifers here monitored. Beyond seasonal fluctuations, similarly to what has been observed in other places in Bologna plain (Fig. 11), the piezometric level rose over time (about 6 m in 9 years, from October 2007 to June 2016, dashed black line in Fig. 14). This increase is likely related to the overall decrease in groundwater withdrawal rates from the Reno aquifer (Fig. 10). The pressure recovery occurred in two distinct phases, interrupted by a period in which the piezometry decreased (Fig. 14). The level rises from spring 2008 to spring 2011, and in this period the subsidence rate slows down to zero. The level decreases from spring 2001 to August 2012, and at the same time subsidence began to increase again. The level, then, rises from August 2012 to May 2014, and at the same time the ground expands. The level rises (less quickly than before) from May 2014 to July 2016 and the ground is essentially stable. The level decreases from July 2016 to the end of the monitoring (January 2018) and subsidence increases. A clear relationship is, therefore, observed between the piezometric level trend and the soil deformation (black and blue dashed lines in Fig. 14). As already observed for seasonal oscillations, the piezometric level elevation is simultaneous with the slowing down and zeroing of subsidence and to ground uplift. It is, therefore, likely that the general increase in the piezometric level starting from 2010 is causing the topographical rises highlighted in the Bologna plain in the 2011-2016 map (Figs. 6 and 9). The uplift of Bologna plain would seem to have, at least in part, a man-induced cause because of the reduction of groundwater withdrawal. This raising of the Bologna plain has, therefore, an anthropogenic cause, different from those described above (see Fig. 7) whose origin is of tectonic nature.

8. Conclusions

InSAR-based measurements are available from 1992 to 2016 in the Emilia-Romagna plain (about 13,000 km^2). The data set, once properly processed and calibrated with precision topographic levelling and GNSS, represent significant and good information to analyse ground movements. Four maps of the average rate of land displacement over the periods 1992-2000, 2002-2006, 2006-2011, and 2011-2016 have allowed making some interesting considerations on positive ground vertical movements (i.e. uplifts) and their nature. Some areas are constantly rising from 1992 to 2016 (Piacenza and Parma plain), while others show intermittent uplift (Reggio Emilia, Modena, Ferrara and Bologna plain). Most of the observed uplifts are due to tectonics, with the uplifts recorded above active structures present in subsoil, such as portions of the Emilian folds, of the Ferrara folds, and of the Pede-Apennine Thrust front. The uplift recorded in the north-western part of the Ferrara fold, in 2006-2011 could indicate the triggering of the compressive tectonics, which, then, culminated with the May 2012 earthquakes. There are no documented uplifts in the Romagna part of the plain.

The uplift observed in the Bologna plain (NW of Bologna city) can instead be considered man-induced, owing to a significant recovery of piezometric levels due to a reduction in groundwater withdrawals.

Since these statements derive exclusively from INSAR data, they should be considered a first hypothesis that could be verified with different methodologies and approaches.

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