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Spatial-temporal analysis of the subsidence in the city of Bologna

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ABSTRACT: The land subsidence induced by groundwater withdrawal is particularly troublesome, primarily because settlements develop with relatively fast rates but, moreover, because it often affects densely populated areas where exposure to risk is particularly high. In the second half of the last century, several cities of northern Italy suffered subsidence determined by an intensive exploitation of groundwater. One of the cases worthy of major attention is the city of Bologna, which holds a significant heritage of historical buildings and monuments and where settlement as high as 4 m have been recorded. This paper reports a study on the spatial distribution of the phenomenon and its evolution with time. The data recorded by a number of sequential topographical campaigns and, more recently, with satellite surveys, cover a period of more than 60 years (from 1943 to 2005) and an area of 272.25 km^2. The spatial analyses, performed with the support of a Geographical Information System, have revealed a progressive development of settlements with different time histories over the territory. The distribution of total and differential settlements is consistent with the characteristics of the subsoil, the groundwater withdrawal activity and the effects noticed on buildings.

1 INTRODUCTION

The deformation of the ground surface can be determined by different natural causes such as tectonic activity, self weight consolidation of recently deposited materials, chemico-physical transformations, volcanic activity, long term variation of the groundwater regime due to climatic changes. The incidence of these factors become particularly problematic when modifications occur in relatively short times so as to interact with the human activities or, moreover, when alterations of the natural equilibrium are compounded by anthropogenic causes. Rapid growth of population, intensive urbanization and industrialization are typical factors capable of determining deep transformations to the territory. The consequences of these processes may be particularly severe when they occur in areas particularly valuable from environmental or historical viewpoint, but also because the economic investment made to promote the development itself contribute to increase the exposure to the risk associated with the produced modifications.

Land subsidence is one of the most troublesome phenomenon which may occur when intensive extraction of groundwater is carried out in lowland areas. It may turn into a reduced functionality of buildings and infrastructures, which may reach collapse in the most severe situations, but also into changes of the natural or artificial water courses, retreat of coastlines, flooding and inundation.

The importance of the phenomenon on densely populated areas can be seen from the following list of studies retrieved from the literature:

- Mexico city (Marsal & Mazari 1962; Zeevaert 1983);
- Santa Clara valley (Poland 1958);
- Houston (Lockwood 1954);
- London (Wilson & Grace 1942);
- Japan cities (Yamamoto 1995).

The equilibrium becomes particularly delicate when subsidence affects areas where historical, cultural and monumental sites are settled. The historic centers of ancient Italian cities are acknowledged among the most relevant evidences of the contemporary civilization, not only for the presence of buildings and churches, representing authentic masterpieces from artistic and architectural viewpoints, but moreover because they have the fundamental role of preserving and passing to the new generations the memory and the culture of populations. In the present paper the attention has been focused on the city of Bologna, affected in the second half of the last century by extensive subsidence phenomena consequent to the exploitation of groundwater. The work, carried out by collecting the results of sequential topographical campaigns, is aimed to analyze the evolution with time and the spatial distribution of the phenomenon.

2 THE CASE STUDY

The city of Bologna, was settled before 1000 b.C in the southern part of the Po valley, at the foot of the Italian Apennines. It has always been an important centre, before under Etruscans (Velzna), then under Celts (Bona) and Romans. In the Middle Ages it became one of the most populated European cities. Famous for hosting the oldest university in the world, founded in 1088, Bologna has one of the largest and well-preserved historical centres in Italy, also due to the restoration and conservation policy started at the end of the last century. It has always represented an important cultural and artistic mark in the Italian landscape, thanks to a homogenous combination of monuments and architectural masterpieces including medieval towers, porticos, antique buildings and churches. The Hippodamian plant of the city, founded on the original setting of the Roman "Castrum", is a noteworthy example from the urban viewpoint.

Since its first settlement, the city was affected by a long term deformation of the ground, induced by the self weight consolidation of the thick alluvial deposits of the Po valley. However, settlement proceeding with rates of few millimetres per year were not a serious cause of concern. In the decades after 1950, similarly to what happened to other cities of northern Italy (e.g. Milano, Venezia, Ravenna), a rapid deformation of the ground occurred in the town and the surrounding areas, developing in some cases with rates of dozens centimetres per year (Carminati & Martinelli 2002).

The Figure 1, which reports the ground deformation recorded all over the Emilia Romagna region during the period 1992–2000 (Provincia di Bologna 2012), shows a clear concentration of the phenomenon near the city of Bologna.

Damages produced by differential settlements were then noticed on several buildings of the historical centre. A noticeable attention was concentrated on the buildings of Zamboni street, a major urban artery located in the north-east side of the historical centre (Fig. 2). Displacements surveyed along this road between 1979 and 1983 (Alessi 1985) give the profiles evolution reported in Figure 3.

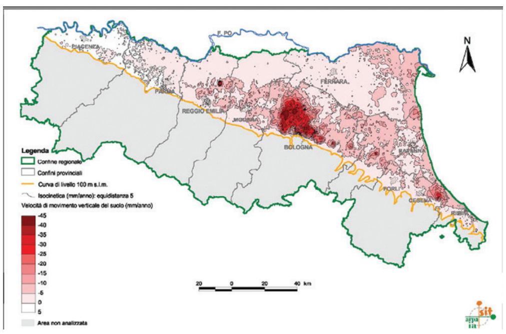

Figure 1. Map of settlements recorded during the period 1992–2000 (Provincia di Bologna 2012).

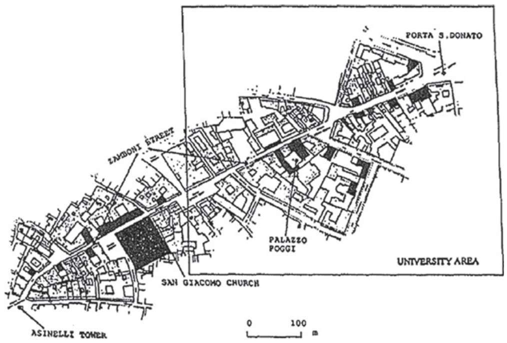

Figure 2. Map of damages buildings detected along via Zamboni (Capra & Folloni 1991).

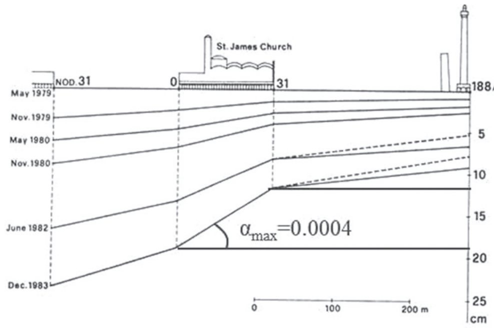

Figure 3. Settlements between the 2 towers and the University (Alessi 1985).

This new situation induced the local governmental institutions and agencies to undertake serious investigations campaigns aimed at discovering the causes of such unexpected phenomenon. Many studies have then been promoted to survey the ground deformation in the area, by means of increasingly more precise geometrical levelling networks: Pieri & Russo (1977), Pieri & Russo (1984), Pieri & Russo (1985), Arca & Beretta (1985), Folloni et al. (1996); Bondesan et al. (1997). In 2005 a campaign of satellite records was undertaken to monitor the vertical movement of the territory (Stramondo et al., 2007).

The goal of the present research is to find a mechanical explanation of the phenomenon by a quantification of the different variables (Darini et al., 2008, Modoni et al., 2012). To this aim, measures of different variables and results of numerical analyses have been merged in the same Geographical Information System, to create a comprehensive database where information of different nature can be combined.

In the present paper attention is confined to the analysis of settlements. For this investigation, an area of 272.25 km^2 has been delimited (Fig. 4), including the city centre and the upper plain area,

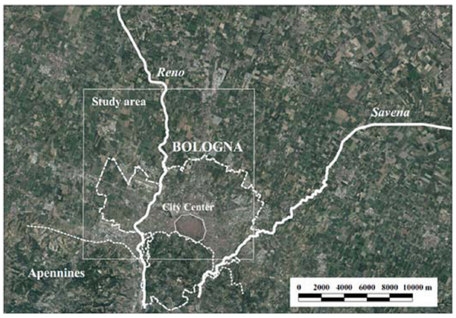

Figure 4. Plain view of the studied area.

Figure 5. Sea level in the lower Pliocene (Ricceri, 2007).

where a grid of points has been ideally superposed. The variables have been computed in each node of this grid by using a geostatistical interpolation method (Chilès & Delfiner 1999).

2.1 *Geological and hydrogeological layout*

From a geological viewpoint the Po Valley can be considered as the product of the foreland basin evolution process (Carminati & Martinelli 2002) formed at the link between the padanian-adriatic sector and the external portion of the thrust belt formed by the up-lifting tectonic units of the Upper Miocene—Quaternary (Bartolini et al., 1996).

After the middle Plio-Quaternary age, when the Po Valley formed the north-west extension of the Adriatic Sea (Fig. 5), a gradual eastward movement of the shoreline occurred thanks to a progressive deposition of marine sands and continental fine grained sediments. In the southern part, this sedimentation process is tightly interconnected with the erosion of the Apennines (Amorosi et al., 1996) resulting into two big alluvial fans, formed respectively by the Reno and Savena rivers and including predominantly gravelly and sandy materials.

The province of Bologna extends over an area of about 3702.5 km^2 and can be subdivided into the following distinct geomorphologic contexts:

- *flood plain*, consisting of alluvial materials transported by rivers and deposited in the plain mostly during floods;
- *foothill plain*, morphological connection between the hill and the alluvial plain, characterized by decreasing topographical gradients, and containing coarser materials deposited by the two major rivers (Reno and Savena);
- *hill*, characterized by a parallel to dendritic drainage system;
- *mountain*, consisting of geological units formed from chaotic complex of clay with the presence of sub-horizontal flaps of more resistant lithological units.

The investigated area can be substantially divided in the northern floodplain of continental origin and to southern chain of the Apennines. It is crossed by two rivers, Reno and Savena, flowing with torrential regime from the upper mountains to the plain.

The hydrogeological setting (RER and ENI-AGIP 1998) shows a recurrent superposition of permeable (aquifers) and semi-permeable or impermeable strata (aquitards). Three aquifer groups (named A, B and C) are classically distinguished, each of them consisting of an alternation of coarse and fine grained strata of relatively limited thickness and extension (Fig. 6). They are separated each other by thicker and widely extended layers of fine grained strata.

The upper aquifer group A, reaching depths of about 300 metres, is strongly dominated by the presence of the two alluvial fans of Reno and Savena rivers which are the most important groundwater supplies (Elmi 1984, Fava et al., 2005). These alluvial fans are present also in the upper part of the aquifer group B near the foot of Apennines. Coarse grained materials of marine origin can be found in the lower strata of aquifer group B and in Group C.

The groundwater circulation in the upper layers is mostly fed by the dispersion of the two rivers, while a secondary more limited contribution coming from remote sources can be found in the lowland area.

The withdrawal of water from wells is mostly achieved from the upper aquifer unit A, with a more limited portion extracted from the lower group B; the hydro-chemical characterization of groundwater shows the presence fossil water in the deeper group C.

The physical and mechanical characteristics of the subsoil in the whole area have been investigated by collecting the available results of fields and laboratory tests performed at different locations and depths.

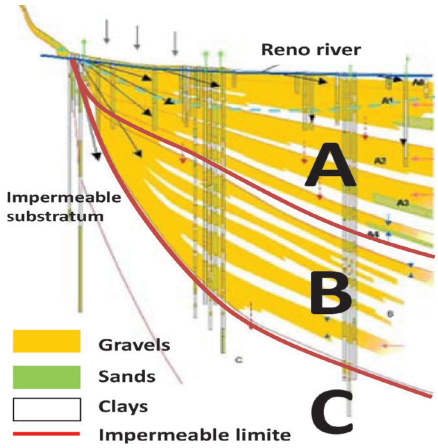

Figure 6. Longitudinal section along the Reno river (RER and ENI-AGIP 1998).

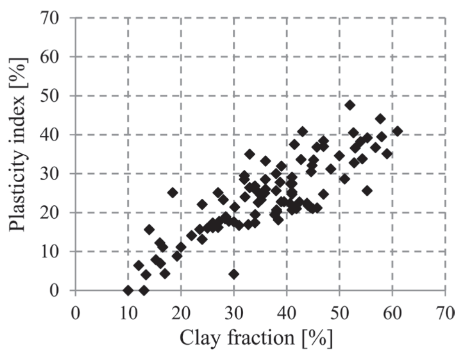

Figure 7. Activity of the finer soils. (Darini, 2007).

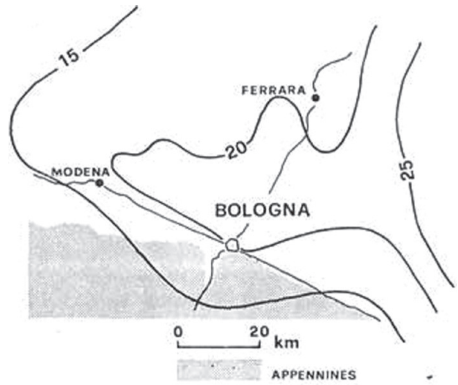

Figure 8. Contour lines (cm) of equal subsidence in the period 1897–1957 (Pieri & Russo 1984).

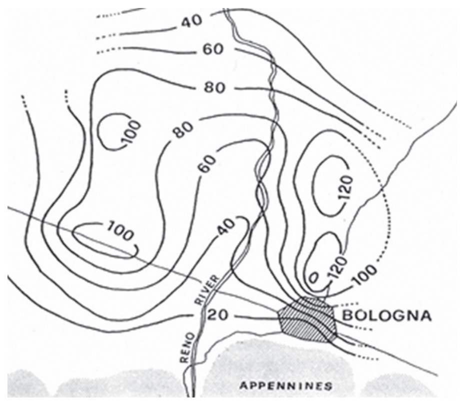

Figure 9. Contour lines (centimetres) of equal subsidence in the period 1943/1950–1970/1973 (Pieri & Russo 1984).

The grain size distributions of fine grained soils are randomly distributed over the considered area. The predominant soil fraction is made of silt (ranging between 40 and 60%) with a slightly lower content of clays (from 10 to 50%) and a small percentage of sand (from 0 to 20%). A normal activity of the clay fraction can be seen from the chart shown in Figure 7, together with a mineralogical homogeneity of the deposits. Limited differences can be seen on the dots representing samples cored at shallow (<50 m from the ground level) and deep (<300 m from g.l.) boreholes.

3 GROUND DEFORMATION

The Po Valley is known to be affected by a natural subsidence phenomenon, determined by tectonic movements and sediment compaction. In the Bologna area, this natural long-term subsidence is estimated to progress with rates ranging from 1.5 to 2 mm/year. In fact, the comparison between the levels of some benchmarks measured in the period 1897–1902 and 1947–1957 (Pieri & Russo 1977, Pieri & Russo 1984) reveal settlements ranging from 10.7 cm to 20.9 cm (Fig. 8).

Even though some works carried out in Roman times to reclaim land and reduce the swampy areas situated at the northern part of the Via Emilia (Bertoni et al., 1973) produced some limited movement of the ground surface, the subsidence in the city of Bologna area has been noticed in relatively recent times, together with the intensive exploitation of groundwater sources.

This subsidence has become increasingly pronounced after 1950, as brought out by the geometrical levelling carried out around 1943–1950 and some repetitions performed by I.G.M.I. (Italian Geographical Military Institute) in the period 1970–1973 (Fig. 9). The map derived from Pieri & Russo

(1984) show a concentration of settlements in two areas surrounding the Reno river (with settlements greater than 1 m), whereas less pronounced values are noticed along the course of the river.

Being aware of the uncertainty related to a limited number of benchmarks (measures from 1950 are available only on about 20 benchmarks), this map has been used in the present study, by digitalizing the curves in the Geographical Information System, to extend the analysis of subsidence to the period 1943–1973.

One of the consulted database (Fig. 10) is released by the *Autorità di Bacino del Fiume Reno*, which contains information for the period 1950–1997 and represents the first attempt to perform an extensive monitoring the subsidence phenomenon in *Emilia Romagna*. In the area of Bologna this database gathers about 200 benchmark coming from three different geometrical leveling networks previously installed by various public authorities (*Autorità di Bacino del fiume Reno, Istituto Geografico Militare Italiano, Ministry of Public Works*).

The second database (Fig. 11) was acquired by *ARPA Emilia Romagna*, in cooperation with the municipality of Bologna, and provides the localization of the 527 benchmarks and subsidence of the ground, relative to the period between 1983 and 1999. During this period more comprehensive and refined analysis could be performed on the investigated area thanks to a much higher spatial density of this network compared with the previous one (in the city center benchmarks were located at mutual distances lower than 250 m).

Subsequently, after the development of the differential interferometry synthetic aperture radar techniques DInSAR (Hanssen, 2001), a more detailed monitoring was performed for the period 1999–2005 (ARPA Emilia Romagna). It is however pointed out that a relatively limited number of benchmarks (approximately 118 mostly located along the Via Emilia and A13 motorway) were necessary to calibrate the DInSAR measurement (Fig. 12).

3.1 *Analysis of settlements*

All previous information have been combined in the Geographical Information System to compute the ground level positions and the progressive development of settlements on the studied area.

The interpolation over the studied area of the measures taken at singular points has been accomplished by performing a series of geostatistical analysis. By this method, the spatial variability of the studied quantities is evaluated considering the latter as "regionalized variables", i.e. random realizations of a space function (Matheron 1971). An experimental variogram is first plotted where the squared increments between each couple of measures are related to the distances (h) between sampling points (Fig. 13) A fitting curve (theoretical variogram) is then chosen among various possible functions. The estimate of values in unmonitored positions

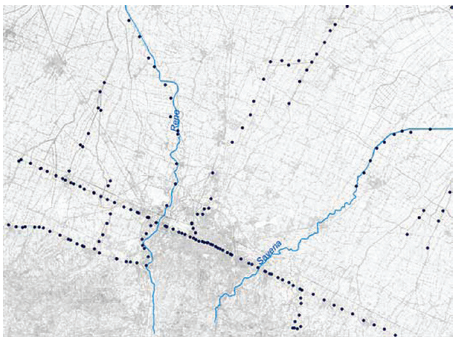

Figure 10. Monitoring network of the *Autorità di Bacino Reno* (period 1950–1997).

Figure 11. Monitoring network of the *ARPA Emilia Romagna* (period 1983–1999).

Figure 12. Network used by the *ARPA Emilia Romagna* to calibrate DInSAR measurement (2005).

is computed with a linear interpolator (Kriging), assigning a weight to each of the measured values function of the theoretical variogram. This function is found minimizing the variance of the estimation error.

Setting a zero for subsidence in the period before 1943–1950, a sequence of map has been created to reproduce with contour lines the settlements obtained in the different periods (Fig. 14).

A similar pattern of subsidence is repetitively shown by all plots with larger concentrations of settlements occurring around the alluvial fan of the Reno river.

Explanation to this result can be given considering that the largest part of groundwater is extracted for civil purpose in the upper part of the Reno river (Vassena, 2003). Interception of such a large amount of water coming from the mountains prevents the feeding of water bearing strata in the lower plain and causes a significant lowering of the hydraulic heads. Although the drop of water head is maximum in the alluvial fan, where the most active wells are located, the subsidence is not particularly high in this zone due to the predominance of coarse grained materials in the subsoil strata.

The maximum observed settlements occur in the surrounding zone, where thicker strata of fine grained soils are present. Finally, the development of settlement with time for two points representative of different locations (Fig. 14) is plotted in Figure 15.

Both curves show the maximum rate in the period between 1970 and 1980, i.e. when groundwater extraction reached its peak. However, it is worth observing that the curve representative of the situation in the city centre shows an almost stable phenomenon. On the contrary, a further increase of settlements must be expected in the surrounding area, being the rates computed in 2005 still significantly high.

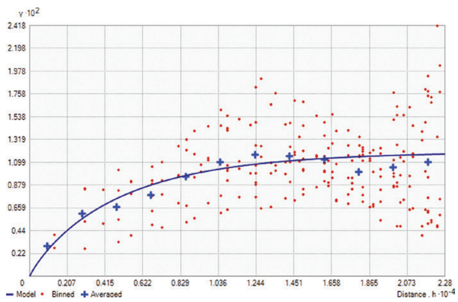

Figure 13. Experimental and theoretical variograms for settlements in the period (1983–1987).

3.2 *Damage on buildings*

As shown by literature, damage of buildings, ranging from the formation of small fissures to complete collapse, can be correlated with the development of angular distortion (e.g. Skempton & Mc Donald 1956) or tensile strain (Burland & Wroth 1974). Limiting values depends on the type of structure (open framed structures may tolerate higher defor-

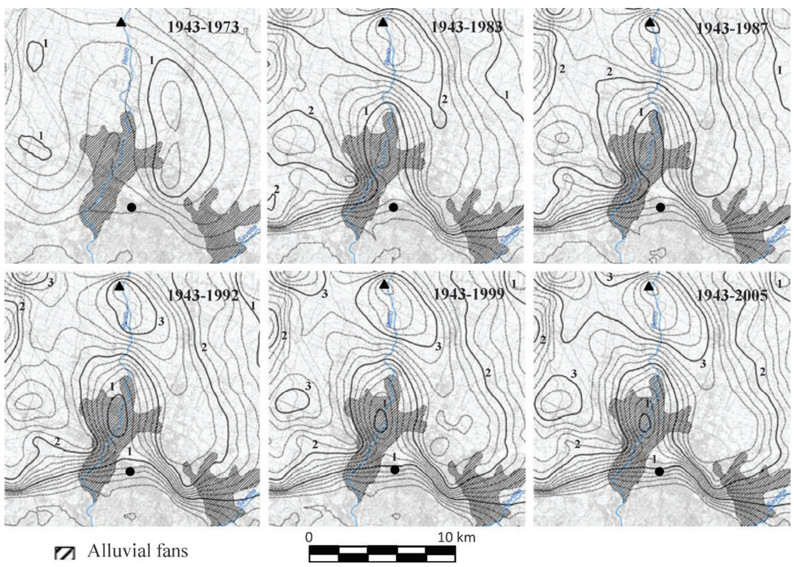

Figure 14. Settlements cumulated in different periods from 1943.

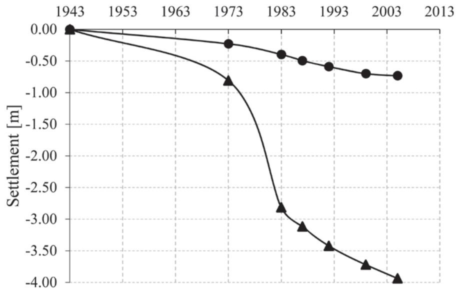

Figure 15. Settlements time histories for two positions of the city and surrounding area.

mation compared with load bearing walls) and on the deformation mode (sagging or hogging). Irrespective of the assumed criterion, angular distortion ranging between 0.5 and $1 * 10^{-3}$. have been observed to produce cracks in continuous walls (Sowers 1962; Burland & Wroth 1974).

The angular distortion is correctly computed as the ratio between maximum differential settlement and distance of two contiguous points, provided rigid tilting of the structure is discounted. Being the decoupling of tilting and distortion meaningless at the very large scale of the present work, rotation has been herein assumed as indicator of the damage on buildings.

The analysis has been restricted to the historical centre of the city, superposing an ideal grid of points (nodes are positioned at a mutual distance $\Delta = 60$ m). and computing settlements at each node (i, j) with the previously described geostatistical method. Rotation in each node $\alpha_{i,j}$ has been then computed with the following relation:

$$\alpha_{i,j} = \sqrt{\left(\frac{w_{i+1,j} - w_{i-1,j}}{2\Delta}\right)^2 + \left(\frac{w_{i,j+1} - w_{i,j-1}}{2\Delta}\right)^2} \quad (1)$$

Calculation of these values over the studied area (Fig. 16a) show that the largest rotations occur in the central part of the city. Focusing the attention on Zamboni street, the road where noticeable cracks were recorded (Figs. 2 and 3), it is worth noting that the curvature (either concavity or convexity) of the deformed ground (given by the gradient of rotation) is maximum along the direction of this road. The maximum rotation computed in this area for the period 1943–2005 is equal to about 0.002, which five times larger than the one (0.0004) calculated by Alessi (1985) for the period May 1979–Dec 1983 (Fig. 3). The settlement profiles traced along this road with the present analysis (Fig. 16b) are fully consistent with the profiles (reported in the same plot with a shaded area) derived by Alessi (1985).

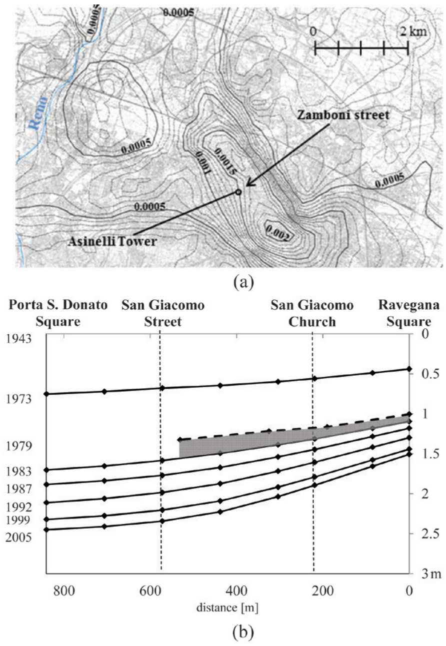

Figure 16. Map of rotations computed for the period 1943–2005 in the historical centre of Bologna (a) and settlement profiles along Zamboni road (b).

4 CONCLUSION

The settlements induced in the area of Bologna by an intensive groundwater extraction carried out in the second part of the last century have been quantified by combining information reported in the literature with results of topographical investigations and satellite records. The patterns reconstructed for different time lengths (from 1943 to 2005) show a recurrent situation with larger settlements (up to a maximum cumulated values of 4 m) in the area surrounding the alluvial fan of Reno river, i.e. the countryside part of the city. Nevertheless, high cumulated settlements have been recorded in the central part of the city. Additionally, relative large rotations have been computed in this area consistently with the damages observed on the buildings of Zamboni street. The rotation computed for the period 1943–2005 is about five time larger than the one observed by previous authors during the period 1979–1983. Luckily, the evolution of subsidence with time shows an almost stable condition for the historical centre, while relative fast rates are observed in the outer part of the city. It is finally worth considering that the computed distribution of settlement is fully consistent with the causes determining the phenomenon combined with the mechanical characteristics of the subsoil. In fact, the largest observed settlements have been recorded where the water table lowering induced by groundwater extraction matches with the compressibility of fine grained materials.

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