



Small sinkhole-like features in alluvial plains

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Small sinkhole-like features in alluvial plains: the example of Paganico (Lucca Plain, Italy)

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Abstract

Paganico is a little village located in the south-eastern portion of the Lucca Plain (North Western Tuscany, Italy). Since Seventies a few square kilometres area around Paganico has been involved in opening of small cavities (sinkhole-like features – in this work named micro-sinkholes for simplification) on the land surface. At the beginning they were very small and sporadic. Then (in Eighties), the phenomenon has been characterized by a significant extension, increasing in frequency and size (up to 2 m in diameter and depth), causing inconvenience to local people, agricultural operation and sometimes damage (cracks to buildings, walls, floorings).

The cavities prevalently occur at the end of the dry season, during or immediately after the first intense rainy events, that is between the end of summer and autumn. Even so the predisposition and triggering causes are not at present completely clarified. Therefore this study is aimed at individuating the triggering and evolution mechanism of the Paganico micro-sinkholes, particularly referring to the stratigraphic, hydrogeological and geotechnical features of the involved materials.

Another important issue made clear with this research is represented by the overexploitation involving the local aquifer, characterized by particular hydro-structural conditions. In fact, the Paganico underground shows three horizons with different lithologic, hydrogeological and geotechnical properties: a superficial silty-sandy horizon (2–3 m thick), which is particularly involved in collapses; an intermediate silty-clayey horizon (2–4 m thick); a lower and thick gravel-pebbly horizon, interested by important water resources and heavy pumping. Since Seventies, such water pumping considerably rose, due to the local demographic (well-field), industrial (paper manufacture) and agricultural development.

From an hydrogeological point of view, this area is consequently characterized by two water tables: a temporary one, housed in the superficial silty-sandy horizon (aquitard), and a second one, confined, associated to the lower gravel-pebbly horizon (aquifer). Such water tables are separated by an impermeable silty-clayey horizon. According to

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the observations resulting from this study, the latter probably tends to fracture by desiccation during the dry season, originating water exchange between the two water tables during the first important autumnal rainfall, depending on the pumping conditions, which lower the piezometric surface of the confined aquifer. Cracking would interest also the superficial horizon. Thus, the water exchange would produce erosional phenomena in the superficial material, with removal of the fine fraction and collapse. This process could be at the base of the micro-sinkholes opening.

1 Introduction

Sinkholes are common in many countries and in different geological and morphological environments, involving both bedrock and cover materials (Waltham and Fookes, 2003; Waltham et al., 2005; Parise and Florea, 2008). Bates and Jackson (1987) glossary defines sinkhole as circular depression in karst areas, definition similarly proposed also by Waltham et al. (2005). The last authors, however, highlight a certain confusion in using this term, not always associated to sinks in karst areas. On the other hand, they emphasize how the term sinkhole is very descriptive, and this in a way may justify a larger use.

The Paganico holes, here named micro-sinkholes and object of this research, do not belong to karst environments. They are very small and open in an alluvial plain in which the bedrock is very deep (more than 350 m) and not necessarily carbonatic (Ghelardoni et al., 1968). Similar phenomena were observed also by Marr (1955), Warn (1966), García-Ruiz et al. (1986), Higgins and Schoner (1997), Sbrilli (2004) and Davidson (2012), not always associated to similar causes.

For the reasons just exposed, the term micro-sinkhole is probably not suitable for the case study, and sinkhole-like feature seems more proper. However, in the following we have kept the first one in order to consider its descriptive property.

Since Seventies the area round Paganico, little village in the south-eastern part of the Lucca Plain (Tuscany, Fig. 1), is involved in formation of soil collapses and small

holes. At the beginning, the phenomena were isolated and characterized by diameter and depth of only few decimetres. Inhabitants were not troubled because the zone was mainly rural, and ploughing often hid them. Since Seventies and especially since Eighties, the phenomena intensity increased: the micro-sinkholes opened more frequently, while in some cases the dimension rose up to 2 m in diameter and depth.

According to local people, they caused also problems to agricultural machinery and operators and little damage to buildings, amplified by old age and poor foundations. The opening of the micro-sinkholes seems mainly occur at the end of the dry season (September–October), during the first intense rainfall events.

The Paganico area is particularly rich of groundwater (Nardi et al., 1987; Ambrosio et al., 2010). Since remote ages, the apparently inexhaustible aquifer housed in gravel and pebbles was exposed to considerable withdrawal and several water wells-fields were carried out here since Sixties-Seventies (Fig. 1). One of these wells-fields is really located at Paganico. Moreover, in this area there are also many domestic and agricultural wells. In time, the water pumping considerably increased owing to the demographic development of the area and agricultural needs, but also in relation to the birth of one of the most important Italian and European paper industry poles. It is well known as the paper production needs of large water amount (approximately $100\text{--}200\text{ m}^3\text{ ton}^{-1}$). The considerable water demand existing in this portion of the Lucca Plain induced a strong drawdown (Ambrosio et al., 2010), with progressive aquifer impoverishment, subsidence (Salvini et al., 2004; Canuti et al., 2005), drying up of many Roman-type superficial wells, loss of several resurgences which characterized the area in the past (Nardi et al., 1987) and formation of micro-sinkholes round to Paganico. Some local geologists tried to understand the origin of the latter. For example, the thesis of Giammattei and Rossi (1999) is based on the assumption that in the past this area was characterized by resurgences, fed by the strong groundwater pressure able to go up through the fractured superficial clayey deposit. According to these authors, due to heavy pumping, the aquifer lost its strong pressure and the resurgences went

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out. Such circulation paths should be used by superficial waters going in opposite way, causing little tunnels and collapses by erosional phenomena.

This study is a contribution in order to comprehend the causes of the micro-sinkholes. Many surveys were carried out in order to provide convincing explanations on the triggering causes and developing mechanism: collecting of existing data (e.g. location of past cavities, stratigraphic and hydrogeological data), on-site survey (individuation of new cavities, acquisition of new stratigraphic data by means of two boreholes, collecting of piezometric data and soil samples), grain size analyses.

2 Geological setting

In the Lucca Plain several geological, hydrogeological and paleogeographic studies were carried out (Trevisan et al., 1971; Nardi et al., 1987; Federici and Mazzanti, 1988; Dallan, 1988; Puccinelli, 1991; Cantini et al., 2001; Sarti et al., 2001). The Lucca Plain bedrock, on which prevalently Pleistocene fluvial-lacustrine sediments lie, is formed of different tectonic units (Tuscan Nappe, Pisan Mountains Metamorphic Core Complex, Internal and External Ligurian Units). Since Upper Miocene, they were involved in extensional processes, originating large depressions (intermountain basins of Lunigiana, Garfagnana, Mugello, Florence-Prato-Pistoia, Montecatini-Lucca-Lamporecchio, etc.). In Upper Villafranchian (according to Trevisan et al., 1971; Cantini et al., 2001; Sarti et al., 2001), the Lucca depression is covered by a vast lake, with deposition of clayey-silty-sandy sediments, interbedded by fluvial pebbles in the upper portion. After the lake filling (Würm), the Lucca Plain begins to take its form, as consequence of the erosional and depositional phases of the ancient Serchio River. These alluvial deposits, mainly gravels and pebbles in sandy-silty matrix, have variable thickness and depth increasing towards south. They are covered by more recent sandy-silty deposits, locally named "*Bellettone*". The latter are recognizable as far as some hundreds meters south of Paganico, partially surmounting the lacustrine deposits of the ex-Bientina Lake.

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The lithostratigraphic sketch map of the study area, carried out by means of surface lithostratigraphic, geotechnical data and boreholes, is shown in Fig. 2, while Fig. 3 represents a lithostratigraphic section of the area most affected by micro-sinkholes activation.

5 The underground of Paganico shows the following lithostratigraphic units (from top to bottom):

- sandy silt, 2–3 m thick, whose southern limit is included between the railway Lucca–Florence and the motorway Pisa–Florence (1 in Fig. 2); in eastern part it prevalently becomes clayey silt (2 in Fig. 2);
- 10 – clay, silty clay and clayey silt, 2–4 m thick in the Paganico area, increasing towards south; the northern limit coincides with the ancient shore of the *ex*-Bientina Lake (3 in Fig. 2);
- gravel and pebbles in sandy matrix (approximately 10 m thick), with intercalation of sandy and clayey lens (Fig. 3).

15 3 Hydrogeological characterization

Owing to grain size features and geometrical structure of sediments, in the Paganico area two water tables are recognizable, separated by an impermeable horizon (lacustrine clayey silt): the first one is superficial, unconfined and temporary, and is included in the silty-sandy level (aquitard), directly fed by local rainfall; the second one is confined, generally under pressure, housed in coarse alluvial deposits (gravel and pebbles, aquifer). This is mainly fed by water coming from Serchio River (through paleochannels) and local torrents circulating in permeable deposits, and from permeable rocks cropping out in the surrounding reliefs of the area, which are in contact with the gravelly level in the underground of the plain. Due to its high hydraulic conductivity and transmissivity ($K = 10^{-2}/10^{-4} \text{ m s}^{-1}$, $T = 10^{-2}/10^{-3} \text{ m}^2 \text{ s}^{-1}$, respectively), this aquifer

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is much exploited. Figure 4 shows the general groundwater flow direction in the aquifer of the Lucca Plain, in which the NW–SE direction (according to the ancient course of the Serchio River) is recognizable (Nardi et al., 1987; Ambrosio et al., 2010).

The unconfined aquitard has a medium-low hydraulic conductivity ($K = 10^{-6}/10^{-7} \text{ m s}^{-1}$) and consists of a temporary water table, being exclusively recharged by intense and prolonged rainfall (especially from autumn to spring). The piezometric level of the confined aquifer generally maintains a depth of about 1–3 m below the topographic surface near Paganico. The piezometric fluctuation quite rapidly follows the rainfall trend, characterized by annual maximum between autumn and winter, and a secondary one in spring. During the dry summer period, the confined aquifer tends to depressurize, suffering deficiency of water recharge and overexploitation.

According to Magazzini (1998), in dry season the impermeable level between aquitard and aquifer suffers cracking phenomena (Fig. 5), with volume variation between 3 and 12 cm m^{-1} in thickness. The author proved that cracking already begins with 30 % in soil moisture, attributing a vertic behaviour. Vertic properties are defined as soil characteristics caused by the seasonal changes in volume, or shrinking and swelling. Cracks that open and close periodically, slickensides, wedge-shaped structural aggregates that are tilted at an angle from the horizontal, vertical infillings, and high linear extensibility values are good examples of properties associated with vertic soils (Gray and Nickelsen, 1989; USDA-NRCS, 1999). Thus, water can flow through the slickensides, eroding sediments (Jones, 1994; Meisina, 2004, 2006). Tang et al. (2008) observed that this type of sediment may crack depending on temperature, thickness of soil layer, times of wetting and drying cycle, type of soil. These factors condition the number of intersections and crack segments, average cracks length and width. Similar geological situations were observed also by Higgins and Schoner (1997) in California, in which cracking reaches the gravel body as much as 10 m below the surface. Water-table lowering seems to be an important factor in development of desiccation cracks, as noticed by Neal et al. (1968), Fife (1977) and Higgins and Schoner (1997).

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Magazzini (1998) moreover observed that desiccation can produce fracturing also in the sandy silt of “*Bellettone*”, but with lower intensity: 1–3 cm per meter in thickness with moisture of 26 %. These phenomena probably have a double effect: they increase the aquitard permeability and assure hydraulic connection between aquitard and aquifer through the impermeable level.

4 Micro-sinkholes

As mentioned above, the study area is subject to micro-sinkholes activation since Sixties, but only since Eighties the collapses reached significant dimensions. The classic shape is generally circular with diameter and depth of few decimetres, but often vertical tunnels (diameter approximately within 10 cm) have been observed. The main assessed micro-sinkholes and tunnels are more than 500 (number in continuous evolution) and have been subdivided on the basis of diameter and depth (Table 1 and Fig. 6).

Vertical tunnels and micro-sinkholes (Fig. 7a) can be isolated and arranged at random, or be aligned along particular directions (usually N–S, more rarely E–W). Alternatively, they can be grouped as “swarms”, often side by side the ditches direction. This different way of distribution was observed also by Verachtert et al. (2010).

From the bottom of the micro-sinkholes, horizontal cylindrical tunnels, few centimetres large, often depart (Fig. 7b). Moreover, the micro-sinkholes can show different shapes: cylindrical, conical, truncated-conical, barrel-shape, etc. (Fig. 8).

Approximately 60 % of the Paganico micro-sinkholes is arranged in sort of “swarms”, namely in groups of cavities substantially aligned (98 %), in particular according to N–S direction. This orientation could be mainly attributable to two causes: (a) the micro-sinkholes are often near N–S oriented ditches; (b) ploughing furrows generally show this direction and could represent potential water infiltration and circulation points. Only in a few cases (2 %), different direction of the “swarms” was observed, for example E–W, again attributable to presence of ditches.

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Micro-sinkholes and vertical tunnels seem develop in lithotypes characterized by prevalent silty-sandy fraction, while tend to disappear in clayey-silty deposits. Even though the micro-sinkholes especially involve the “*Bellettone*” deposit, they always occur if this particular stratigraphic sequence is present (from top to bottom, Fig. 3): sandy silt (recent alluvial deposits of Serchio River – “*Bellettone*”); silty clay (palustrine deposits); coarse alluvial deposits (paleochannels of Serchio River). The vertical tunnels are mainly common south of Paganico (sandy silt), while the micro-sinkholes prevail in the village (Fig. 6), where the sandy fraction increases.

In order to characterize the grain size distribution of the materials involved, 26 grain size analyses were carried out on samples collected in the upper and lower parts of the micro-sinkholes and in areas not involved (at depth between 15 and 100 cm). The results (Fig. 9) confirm that micro-sinkholes and vertical tunnels mainly involve the sandy silt and tend to disappear where the cohesive fraction increases, substantially stopping in proximity of the contact between “*Bellettone*” and underlying palustrine sediments. In the zones not involved by cavities, a considerable clayey fraction was assessed.

The most involved area is located near the Paganico water well-field, where gullies were sometimes individuated (see Fig. 10e). They probably result from superficial horizontal tunnels, in which the erosional processes induced the vault thinning and collapse. As explained later, the larger dimension of these particular horizontal tunnels are probably associated to the greater erosional intensity near the well-field, resulting from the greater hydraulic gradient between the water tables housed in aquitard and aquifer. The formation of gullies was observed also by Gutiérrez et al. (1997), while Verachtert et al. (2010) attribute their formation to the progressive collapse of several contiguous cavities.

It is interesting to notice the complete absence of micro-sinkholes and vertical tunnels to the north of the Pisa–Florence motorway (Fig. 6), where superficial clayey deposits, directly lying on the gravelly deposits, are present (eastern part in section of Fig. 3).

5 Development mechanism

The development mechanism originating the micro-sinkholes seems follow two possible ways. The first one concerns the cavities far from ditches. In this case, the origin is probably associated to leakage between aquitard and aquifer. In fact, leakage should induce erosional phenomena through the desiccation cracks of the silty-clayey level. The second mechanism regards the micro-sinkholes close to ditches, in which the possible causes that come into play are the superficial water table and the ditches water, as better explained in the following paragraphs.

Analysing the various shapes individuated on-site, both as precursory events and intermediate steps determining the formation of the micro-sinkholes, it is possible to hypothesize the evolutionary process:

1. at the beginning of the rainy period the formation of micro-holes occurs along the vertical fractures produced by soil desiccation (Fig. 10a);
2. inflow of water causes erosional phenomena, originating a little hollow on the surface (Fig. 10b);
3. the percolating water increases the erosional power, enlarging the micro-holes which become vertical tunnels (sometimes in groups); moreover water tends to circulate also in the horizontal cracks, enlarging them due to hydraulic gradient and mechanical erosion. This phenomenon especially occurs along the contact between sandy silt and underlying clayey deposits, forming from centimetric to metric horizontal tunnels (Fig. 10c).
4. the intersection between horizontal and vertical tunnels determines a soil structural fragility, and the collapse can occur, originating a micro-sinkhole (Fig. 10d);
5. in some cases, actually not frequent in the study area, the collapse of superficial large horizontal tunnels forms gullies (Fig. 10e).

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Some camera videos carried out by the Capannori Municipality seem confirm the proposed developing model. The images show (a) the presence of underground horizontal tunnels, containing debris deposits, probably attributable to previous falls (Fig. 11a), (b) the tunnels shape, rounded at the vault and “v-shape” at the base, indicating water runoff (Fig. 11a); (c) the presence of fractures and micro-holes on the cavities vault, proving their vertical continuity (Fig. 11b). Moreover, the images show the presence of abundant radical apparatuses (Fig. 11a). According to Sanglerat et al. (1984), vegetation is important in raising the erosional processes rate in swelling clay, favouring soil desiccation and cracking by suction. If cavities and horizontal tunnels are large, the roots become hanging and unable to absorb water. In time this induces the plant to wither and this may be considered as premonition of cavities in the ground.

As mentioned above, the micro-sinkholes phenomena mainly develops from September/October to March, after long rainy periods or during heavy rainstorms (in the study area they are common in autumn).

The model proposed for Paganico cavities presents analogies with that suggested by Higgins and Schoner (1997), studying cavities in silty-sandy sediments in Central California. In the same way, analyzing piping phenomena in several regions of Britain, Jones et al. (1997) ascribe the evolution from desiccation cracks to piping to water erosion. Soil subject to piping lies on clayey deposits, characterized by vertic properties and high shrinkage potential, likewise at Paganico.

5.1 1st development mechanism – micro-sinkholes associated to water flow between aquitard and aquifer

The sequence (Fig. 12) begins at the end of the dry season (step a), when the piezometric surface of the gravelly confined aquifer is low (not in pressure), while the silty-sandy unconfined aquitard water table is absent. In summer the superficial sediments desiccate (the desiccation cycle time generally lasts two months, July and August). In autumn the rainy periods come back, and the piezometric levels of aquifer and aquitard

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grow (b). In relation to different hydraulic conductivity, the reaction time to rainfall of the two levels is different (short for gravelly aquifer, longer for silty-sandy aquitard). However, the unconfined piezometric level, if present, is always upper than the confined one. As consequence, hydraulic flow from aquitard to aquifer can occur through desiccation cracks, which are developed both in intermediate clayey horizon and in superficial silty-sandy sediments. The presence of water in the aquitard induces the soil volume increase, closing the cracks (b). The same phenomenon was observed also by Van Breemen and Buurman (1998) and Tang et al. (2008) in other geographical environments. Contemporaneously, water involved in leakage exerts erosional actions along the fractures, opposing to the complete closing.

At the end of the rainy period (b1) the superficial water table slowly reaches the maximum level, with a certain time lag as regards the piezometric level of the confined aquifer (reached previously, b). During the b1 phase, leakage is intense, due to the greater difference of height between the piezometric levels. Thus cracks are further eroded, becoming little vertical tunnels (b1, b2). Not all the desiccation cracks become vertical tunnels, but only those in which the erosional power is greater. A superficial predisposing factor is for example the presence of local ground depressions (associated to ploughing), which can intercept the runoff.

Moreover, it is possible (but actually not proved) that cracks in silty-sandy deposits do not join the cracks in clayey sediments. This fact, together with a light slope of the contact between sandy silt and clay, probably favour a sub-horizontal movement of water along the contact, considering the different hydraulic conductivity of the two sediments. This erosional power of water flow should slowly produce horizontal tunnels (b2, b3). The intersection between vertical and horizontal tunnels causes portions of structural weakness, in which underground collapses may occur (hypogean cavity, b3). The evolution of horizontal tunnels and cavity may stop when the aquitard water table disappears and resumes in the following rainy period (c, c1, d). On-site surveys really allow at observing that, despite the return of rainy periods, tunnels preserve their features due to sediments plasticity.

The erosional process involving the superficial sandy silt may be quickened by leakage when the piezometric levels allow it. In time, sequences of rainy periods imply the progressive increase of the hypogeal cavities size till the collapse (d_1 , d_2). The material eroded is then probably dispersed by water flow.

Therefore, the erosional processes are activated by leakage phenomena. This is not a simple particles capture under pumping effects (Panno et al., 2003; Leake, 2004) or subsidence induced by compacting (Rosepiler and Reilinger, 1977; Melidoro et al., 1996; Galloway et al., 1999).

In order to individuate the area most exposed to leakage, a schematic and simplified map of the hydraulic gradients (i) between water table and piezometric surface was carried out (Fig. 13) making two assumptions: (1) since direct measures of the superficial water table fluctuation are not available, it was considered at the topographic surface; (2) the confined aquifer piezometric surface, stressed by intense pumping, was considered at the minimum level, namely below the gravelly aquifer roof (testified by several piezometric surveys in dry seasons). This approach lets to individuate in the study area four classes of micro-sinkholes susceptibility:

- class I ($i = 0$): area lacking in micro-sinkholes and tunnels, where lacustrine clayey deposits are present);
- class II ($0.1 < i < 0.6$): area with sporadic micro-sinkholes and tunnels, where clayey silt is present);
- class III ($0.6 < i < 1.0$): area with large number (70 % of total) of micro-sinkholes (diameter and depth < 1 m) and tunnels (diameter < 4 cm), where sandy silt is present);
- class IV ($1.0 < i < 1.9$): area located close to the Paganico groundwater well-field, characterized by the remaining 20 % of phenomena including larger micro-sinkholes (diameter from 0.7 to 2.8 m, depth from 0.6 to 2.0 m), vertical tunnels (diameter from 4 to 8 cm), and gullies, where sandy silt is present.

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Comparing the hydraulic gradient map (Fig. 13) with the micro-sinkholes distribution (Fig. 6), an increase in number and dimension of phenomena is recognizable where the hydraulic gradient is higher. Micro-sinkholes developing far from ditches preferentially originate where pumping is stronger, determining higher drawdown of the confined aquifer, as close to the Paganico well-field.

5.2 2nd development mechanism – micro-sinkholes “swarms” associated to water flow between aquitard water table and ditches

Several micro-sinkholes (“swarms”) may be aligned along the same direction (Fig. 14a) and connected by horizontal tunnels (Fig. 14b). Approximately 60% of identified cavities belong to N–S oriented “swarms”. This fact should be in relation to several reasons: (1) the contact between sandy silt (“*Bellestone*”) and silty clay (lacustrine deposits) slopes to the South; (2) the ploughing furrows, which direct the superficial water and increase infiltration rate and erosion, are N–S oriented; (3) ditches and canals are mainly N–S oriented. Bryan and Jones (1997) and García-Ruiz et al. (1997) considered furrows as the main predisposing factor as well.

Figure 15 synthesizes the mechanism of water flow between ditches and water table. In summer, the silty-sandy sediments tend to dry and crack (Fig. 15a). Autumnal rainfall rapidly recharges ditches, which drain the fields, while the aquitard water table has longer response time (Fig. 15b). This determines water flow between ditch and sides, with alternate direction basing on the water level variation (Fig. 15bc). The phenomenon continues until reaching a substantial equilibrium (Fig. 15d). These flows likely produce erosional phenomena in particular weakness zones of soil, originating vertical (along the vertical cracks) and horizontal (along the horizontal plain, where flow is more lasting) tunnels.

Actually, this model should be more complex, because in some situations and in consideration of the hydro-stratigraphic conditions, the two developing mechanisms should be coexisting.

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6 Conclusions

The study carried out in the Paganico area allowed at individuating some important factors in inducing micro-sinkholes. If the triggering cause is basically certain (rain-fall intense and prolonged, able to originate water table and water flow in ditches), uncertainty regards the predisposing factors. One of the most important is surely the lithostratigraphic-hydrogeological structure. This consists of superficial silty-sandy levels (medium-low hydraulic conductivity), lying on almost impermeable clayey-silty sediments. Below, a very permeable gravelly level is present. The latter houses a considerable water circulation, which feeds the confined aquifer. The Paganico well-field, the wells of several paper-factories of national importance, and numerous domestic wells draw water from this aquifer, determining a strong drawdown. The piezometric level sometimes gets down below the aquifer roof. On the other hand, the superficial silty-sandy sediments may occasionally house a temporary water table, during intense and prolonged rainfall (whose importance is at this moment not quantifiable).

It has been hypothesized that at the end of the dry season, both the superficial silty-sandy horizon and the clayey-silty below may suffer desiccation phenomena, originating vertical and horizontal cracks. During rainfall following the dry season, such cracks favour water circulation, saturation and formation of a temporary water table, which is involved in vertical leakage. This induces erosional phenomena in the superficial level (*"Bellettone"*), formation of vertical and horizontal tunnels and collapse of the weaker areas.

The micro-sinkholes seem more frequently open near to ditches limiting fields, in which the erosional processes are probably associated to water flow between water table and ditches water during intense rainfall.

The lithostratigraphic-hydrogeologic structure of Paganico seems therefore represent the most important factor in developing micro-sinkholes. In fact, in spite of the presence of paper-factories and water wells, there are not cavities either to the North (lacking the intermediate clayey-silty lacustrine deposit) or to the South (lacking the

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Alternative water supplying should be individuated also for paper-factories (e.g., water recycling, external derivation), which is a problem discussed since many years but not solved yet.

Apart from only few cases, the problem of damage to buildings is also attributable to clay swelling/shrinkage phenomena and general subsidence (however linked to over-exploitation) rather than micro-sinkholes. The pumping reduction certainly will benefit also this phenomenon.

Acknowledgements. The authors are grateful to the Geotechnical Laboratory of the Civil Engineering Department (University of Pisa) and in particular to Stefano Giusti, for the grain size analyses carried out under the supervision of Diego Lo Presti and Nunziante Squeglia.

References

- Ambrosio, M., Del Sordo, A., Fagioli, M. T., Giannecchini, R., Puccinelli, A., and Sartelli, A.: Analisi dell'evoluzione piezometrica nel periodo 2007–2008 nel settore meridionale della Piana di Lucca (Toscana), area di crisi idrica conclamata. Proc. Congr. Codice Armonico 2010, Castiglioncello, Italy, 11–13 March 2010, 224–234, 2010.
- Bates, R. L. and Jackson, J. A.: Glossary of geology, American Geological Institute, 3rd ed., Alexandria, VA, 788 p., 1987.
- Bryan, R. B. and Jones, J. A. A.: The significance of soil piping processes: inventory and prospect, *Geomorphology*, 20, 209–218, 1997.
- Cantini, P., Cavallini, R., Testa, G., and Zanchetta, G.: The Plio-Pleistocene evolution of extensional tectonics in northern Tuscany, as constrained by new gravimetric data from the Montecarlo basin (lower Arno Valley, Italy), *Tectonophysics*, 330, 25–43, 2001.
- Canuti, P., Casagli, N., Farina, P., Ferretti, A., Marks, F., and Menduni, G.: Land subsidence in the Arno river basin studied through SAR Interferometry, Proc. 7th Int. Symp. on Land Subsidence, Shanghai, China, 23–28 October 2005, 1, 407–416, 2005.
- Dallan, L.: Ritrovamento di *Alephys lyrix* nelle argille della serie lacustre di Montecarlo (Lucca) e considerazioni stratigrafiche sui depositi continentali dell'area tra il Monte Albano e il Monte Pisano, *Atti Soc. Tosc. Sc. Nat. Mem. Ser. A*, 95, 1–17, 1988.

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- Davidson, G. R.: Micro-sinkhole development from groundwater pumping in a non-karst system. *Geol. Soc. Am. Abstracts with Programs*, 44, p. 11, 2012.
- Federici, P. R. and Mazzanti, R.: L'evoluzione della paleogeografia e della rete idrografica del Valdarno inferiore, *Boll. Soc. Geogl. It., Ser. XI*, 5, 573–615, 1988.
- 5 Fife, D. L.: Engineering geologic significance of giant desiccation polygons, Lucerne Valley playa, San Bernardino County, California, *Geol. Soc. Am. Spec. Pap.*, 252, 1–28, 1977.
- Galloway, D., Jones, D. R., and Ingebritsen, S. E.: Land subsidence in the United States, U.S.G.S., Circular, 1182, <http://pubs.usgs.gov/circ/circ1182/> (last access: January 2013), 177 pp., 1999.
- 10 Garcia-Ruiz, J. M., Lasanta-Martinez, T., Ortigosa-Izquierdo, L., and Arnànez-Valdillo, J.: Pipes in cultivated soils of La Rioja: origin and evolution, *Z. Geomorphol.*, 58, 93–100, 1986.
- Garcia-Ruiz, J. M., Lasanta, T., and Alberto, F.: Soil erosion by piping in irrigated fields. *Geomorphology*, 20, 269–278, 1997.
- Ghelardoni, R., Giannini, E., and Nardi, R.: Ricostruzione paleogeografica dei bacini neogenici e quaternari nella bassa Vale dell’Arno sulla base dei sondaggi e dei rilievi sismici, *Mem. Soc. Geol. It.*, 7, 91–106, 1968.
- 15 Giammattei, L. and Rossi, F.: Indagini geologico-geotecniche ed idrogeologiche relative a cavità che si riscontrano nell’abitato di Paganico, Conclusive Report, Capannori Municipal Administration, unpublished technical report, 16 pp., 1999.
- 20 Gray, M. B. and Nickelsen, R. P.: Pedogenetic slickensides, indicators of strain and deformation processes in redbed sequences of the Appalachian foreland, *Geology*, 17, 72–75, 1989.
- Gutiérrez, M., Sancho, C., Benito, G., Sirvent, J., and Desir, G.: Quantitative study of piping processes in badland areas of the Ebro Basin, NE Spain, *Geomorphology*, 20, 237–253, 1997.
- 25 Higgins, C. G. and Schoner, C.: Sinkholes formed by piping into buried channels, *Geomorphology*, 20, 307–312, 1997.
- Jones, J. A. A.: Soil piping and its hydrogeomorphic function. *Cuaternario y Geomorfología*, 8, 77–102, 1994.
- Jones, J. A. A., Richardson, J. M., and Jacob, H. J.: Factors controlling the distribution of piping in Britain: a reconnaissance, *Geomorphology*, 20, 289–306, 1997.
- 30 Leake, S. A.: Land subsidence from ground-water pumping, USGS, <http://www.savethesantacruz aquifer.info/Land%20Subsidence.htm> (last access: January 2008), 2004.

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- Magazzini, P.: Indagini sull'idrologia sotterranea e sulla crepacciabilità di un suolo mediante utilizzo di traccianti e misure di estensibilità lineare (COLE) in località Paganico (Comune di Capannori), Capannori Municipal Administration, unpublished technical report, 16 pp., 1998.
- Marr, J. C.: Sinkholes in irrigated fields, *Calif. Agr.*, 9, 6–7, 1955.
- 5 Meisina, C.: Swelling-shrinking properties of weathered clayey soils associates with shallow landslides, *Q. J. Eng. Geol. Hydrogeol.*, 37, 77–94, 2004.
- Meisina, C.: Characterisation of weathered clayey soils responsible for shallow landslides, *Nat. Hazards Earth Syst. Sci.*, 6, 825–838, doi:10.5194/nhess-6-825-2006, 2006.
- Melidoro, A., Melidoro, N. L., and Simeone, V.: Primi casi di subsidenza in Puglia prodotta da emungimento d'acqua da pozzi, *Mem. Soc. Geol. It.*, 51, 49–12, 1996.
- 10 Nardi, R., Nollodi, G., and Rossi, F.: Geologia ed idrogeologia della pianura di Lucca, *Geogr. Fis. Din. Quat.*, 10, 132–160, 1987.
- Neal, J. T., Langer, A. M., and Kerr, P. F.: Giant desiccation polygons of Great Basins playas, *Geol. S. Am. S.*, 252, 77–110, 1968.
- 15 Panno, S. V., Wiebel, C. P., Heigold, P. C., Reed, P. C.: Formation of regolith-collapse sinkholes in southern Illinois: interpretation and identification of associated buried cavities, *Environ. Geol.*, 23, 214–220, 1994.
- Parise, M., Florea, L. J.: I sinkholes nella letteratura scientifica internazionale: una breve rassegna, con particolare riferimento agli Stati Uniti d'America, *Mem. Descr. Carta. Geol. d'It.*, 85, 427–450, 2008.
- 20 Puccinelli, A.: Nuovi aspetti dell'evoluzione paleogeografia e tettonica al Plio-Quaternario della piana di Lucca (Toscana), *Geogr. Fis. Din. Quat.*, 14, 171–177, 1991.
- Rosepiler, M. and Reilinger, R.: Land subsidence due to water withdrawal in the vicinity of Pecos, Texas, *Eng. Geol.*, 11, 295–304, 1977.
- 25 Salvini, R., Disperati, L., Zuccaro, M., Anselmi, M., and Viridis, S.: Monitoring the anthropogenic land subsidence in the Lucca plain (Italy) by means of differential SAR interferometry, 32nd International Geological Congress, Florence, Italy, 20–28 August 2004, Abstract, 2004.
- Sanglerat, G., Olivari, G., and Cambou, B.: Practical Problems in Soil Mechanics and Foundation Engineering, 2, Elsevier, 283 pp., 1984.
- 30 Sarti, G., Zanchetta, G., Mazza, P., and Grassi, R.: Sedimentological and palaeontological features of an ancient alluvial plain in the Lucca Basin (Central Italy), *Eclogae Geol. Helv.*, 94, 107–117, 2001.

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Sbrilli, L.: Fenomeni diffusi di sinkholes nella Pianura del Fiume Cornia soggetta a subsidenza, Proc. Congr. “Stato dell’Arte sullo studio dei fenomeni di sinkholes e ruolo delle amministrazioni statali e locali nel governo del territorio”, ARPAT, Rome, 20–21 May 2004, 639–649, 2004.

5 Tang, C., Shi, B., Liu, C., Zhao, L., and Wang, B.: Influencing factors of geometrical structure of surface shrinkage cracks in clayey soils, *Eng. Geol.*, 101, 204–217, 2008.

Trevisan, L., Brandi, G. P., Dallan, L., Nardi, R., Raggi, G., Rau, A., Squarci, P., Taffi, L., and Tongiorgi, M.: Note illustrative della Carta Geologica d’Italia alla scala 1 : 100.000 – Foglio n. 105 (Lucca), Min. Ind., Comm., Artig., Roma, 1971.

10 USDA-NRCS (United States Department of Agriculture-Natural Resources Conservation Service): Soil taxonomy, a basic system of soil classification for making and interpreting soil survey, *Agricultural Handbook*, 436, 871 pp., 1999.

Van Breemen, N. and Buurman, P.: “Formation of vertisols”, *Soil Formation. Earth and Environmental Book, Part C*, 233–244, 1998.

15 Verachtert, E., Van Den Eeckhaut, M., Poesen, J., and Deckers, J.: Factors controlling the spatial distribution of soil piping erosion on loess-derived soil: a case from central Belgium, *Geomorphology*, 118, 339–348, 2010.

Waltham, T. and Fookes, P. G.: Engineering classification of karst with respect to the role and influence of caves, *Q. J. Eng. Geol. Hydroge.*, 36, 101–118, 2003.

20 Waltham, T., Bell, F., and Culshaw, M.: Sinkholes and subsidence: karst and cavernous rocks in engineering and construction, Springer, 382 pp., 2005.

Warn, F.: Sinkhole development in the Imperial Valley, in: *Engineering Geology in Southern California*, edited by: Lung, R. and Proctor, R., Association of Engineering Geologists, Los Angeles Section, 144–145, 1966.

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Table 1. Morphometric features of the Paganico micro-sinkholes and relative distribution.

	Diameter (m)	Depth (m)	No.	Distribution (%)
Big micro-sinkholes	0.7–2.8	0.6–2.0	10	2
Medium micro-sinkholes	0.3–0.7	0.3–0.6	76	15
Little micro-sinkholes	0.1–0.3	0.1–0.6	207	41
Vertical tunnels	0.01–0.1	0.3–0.5	213	42

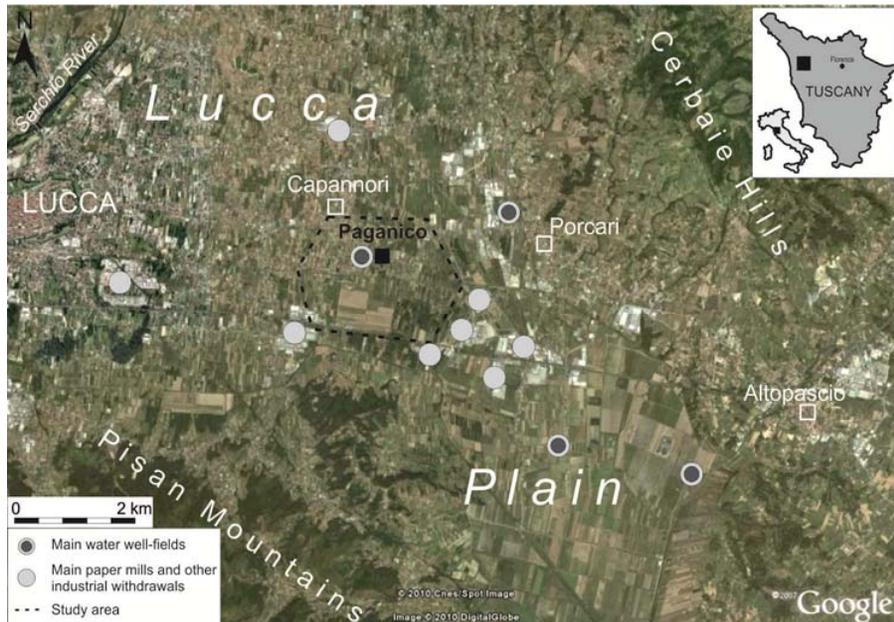


Fig. 1. Location map of the study area and main groundwater withdrawals.

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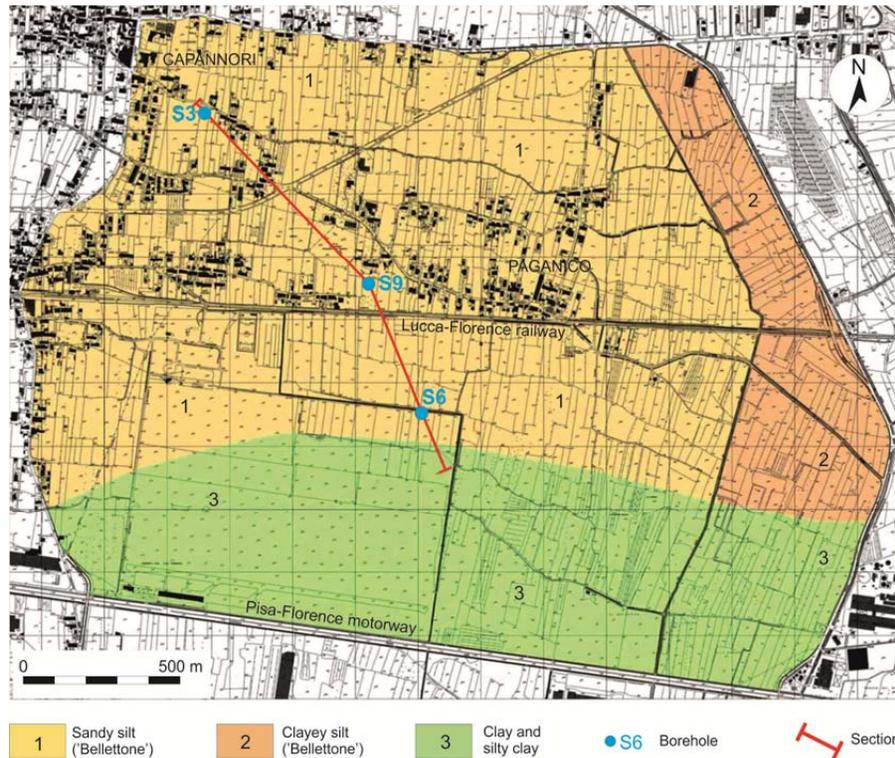


Fig. 2. Litostratigraphic sketch map of the study area.

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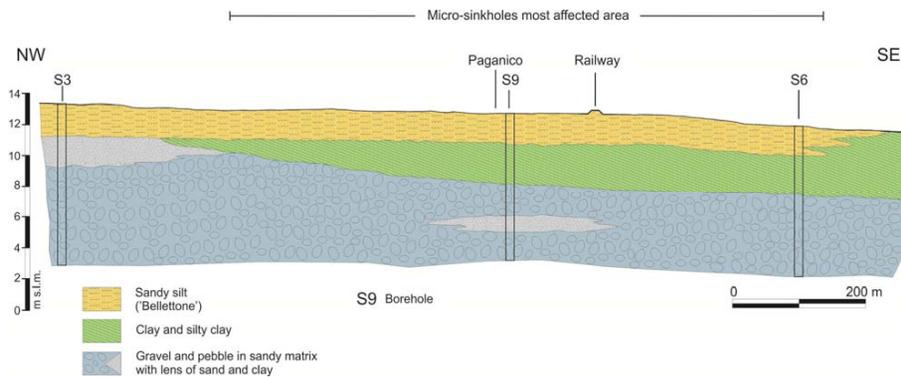


Fig. 3. Lithostratigraphic section of the area most affected by micro-sinkholes.

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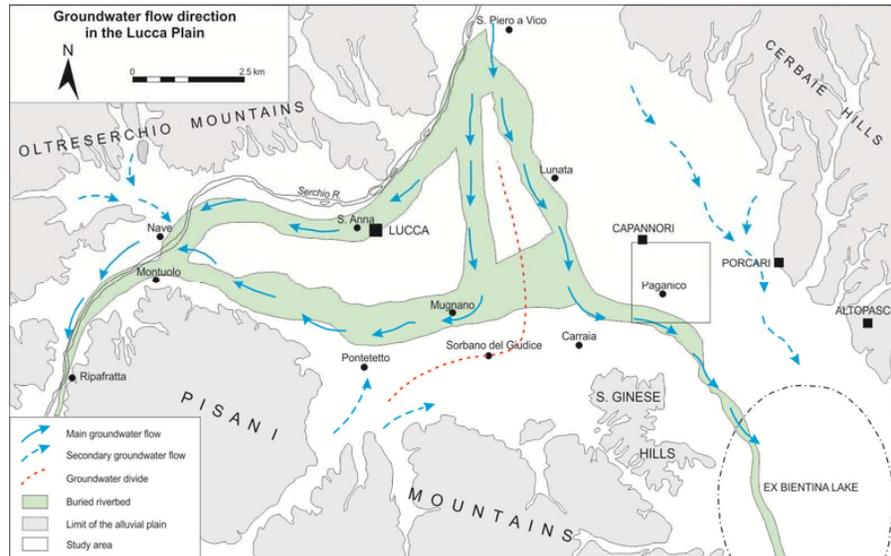


Fig. 4. Chief and secondary groundwater flow directions in the Lucca Plain (after Nardi et al., 1987, modified).

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Fig. 5. An example of deep soil cracks affecting clay deposit near Paganico (the scarp is approximately 2 m high).

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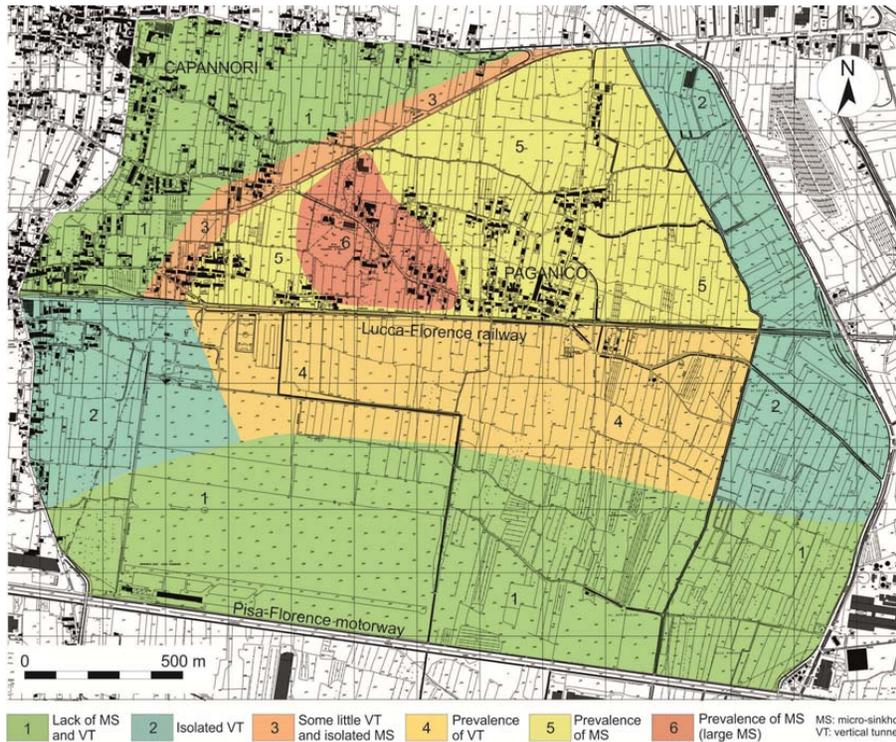


Fig. 6. Distribution of the micro-sinkholes in the Paganico area.

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Fig. 7. (a) vertical tunnel (left) and micro-sinkhole (right); (b) sub-horizontal tunnels departing from the bottom of the micro-sinkholes.

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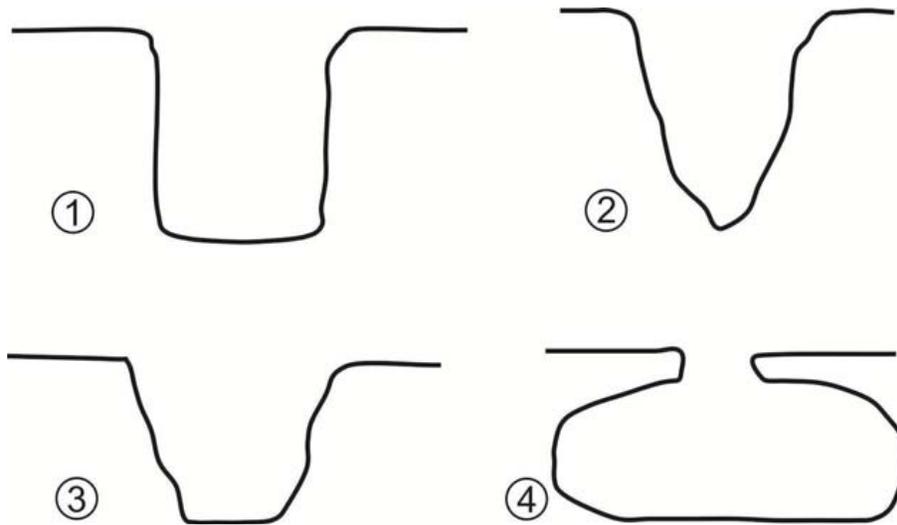


Fig. 8. Schematic sections of micro-sinkholes individuated in the Paganico area: (1) cylindrical, (2) conical, (3) truncated-conical, (4) barrel.

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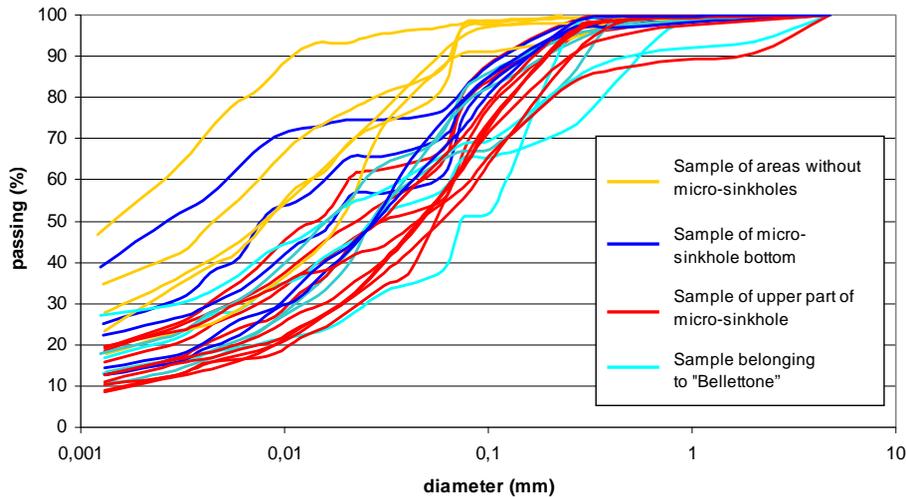


Fig. 9. Grain size distribution of the samples collected in the Paganico area.

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Fig. 10. Supposed evolution steps in micro-sinkholes formation: **(a)** little holes of water circulation along soil fractures; **(b)** partial hollow zone; **(c)** vault fall showing horizontal tunnels; **(d)** horizontal tunnels; **(e)**: gully.

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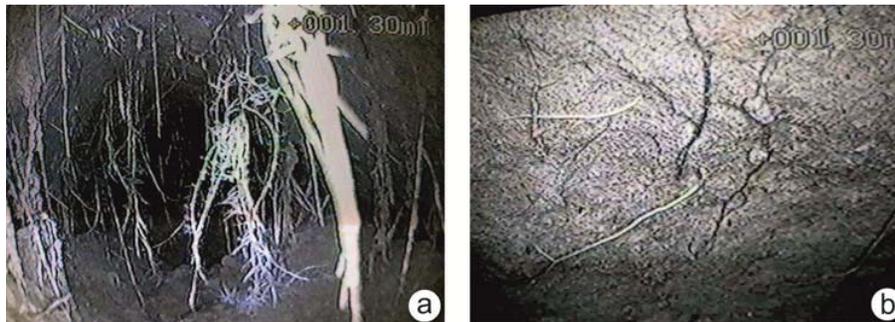


Fig. 11. Videocamera images (courtesy of Capannori Municipality). **(a)** internal part of horizontal tunnel; **(b)** detail of tunnel vault in which fractures, roots and micro-holes are recognizable.

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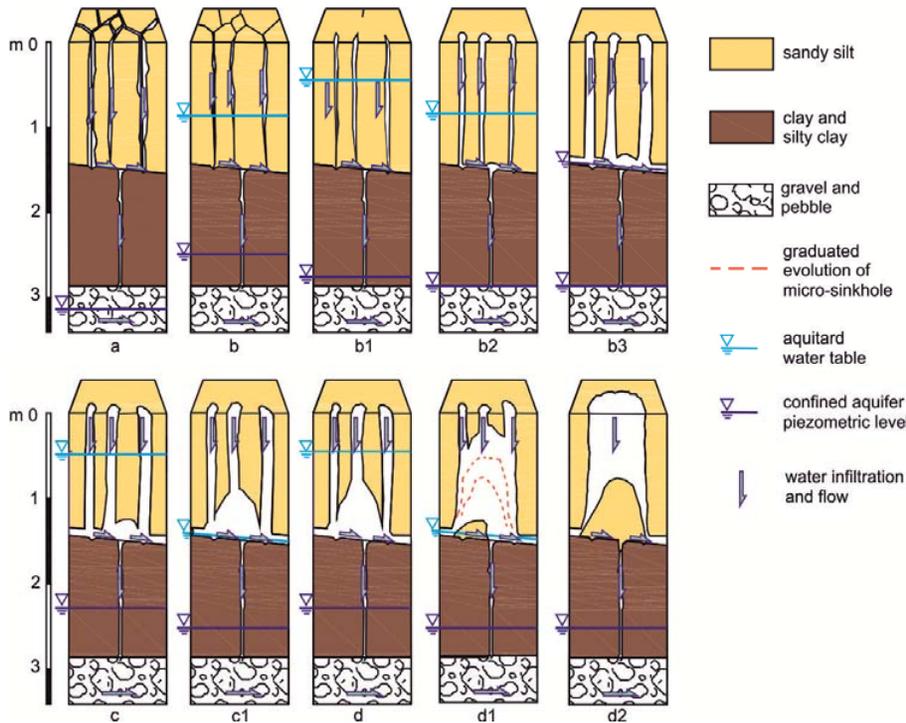


Fig. 12. Evolution sequence of micro-sinkholes produced by water flow between aquitard and aquifer: a, dry period; b, during and after rainy periods; c, following rainy cycle; d, collapse.

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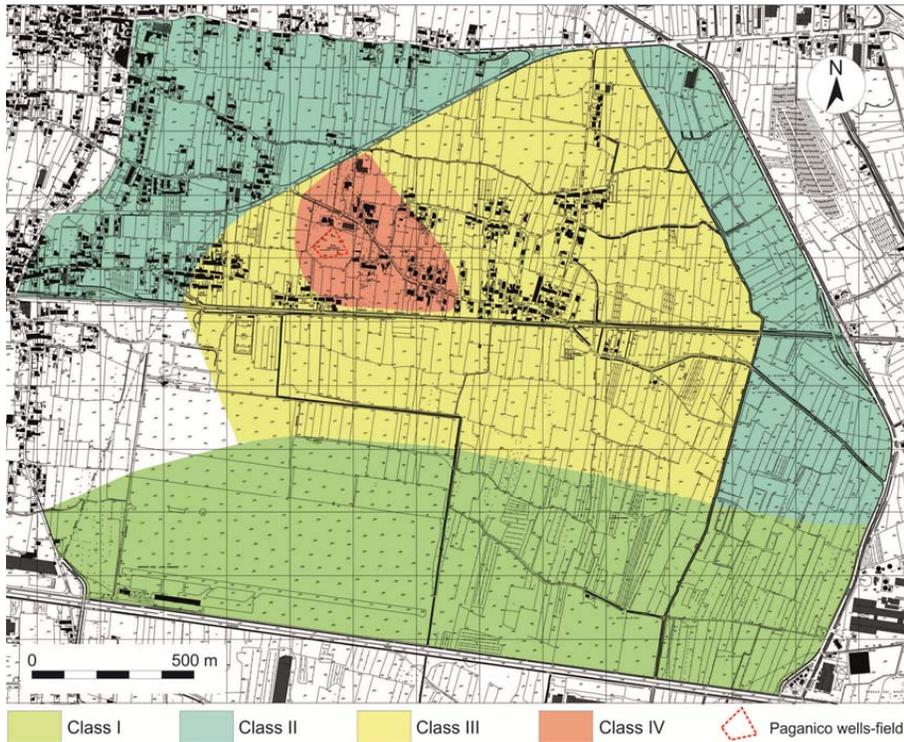


Fig. 13. Hydraulic gradient (i) map (class I ($i = 0$): lack of micro-sinkholes and vertical tunnels; class II ($0.1 < i < 0.6$): sporadic phenomena; class III ($0.6 < i < 1$): 70 % of identified phenomena (micro-sinkholes: diameter and depth < 1 m; vertical tunnels: diameter < 4 cm); class IV ($1 < i < 1.9$): 20 % of identified phenomena (micro-sinkholes: diameter 0.7–2.8 m, depth 0.6–2 m; vertical tunnels diameter: 4–8 cm).

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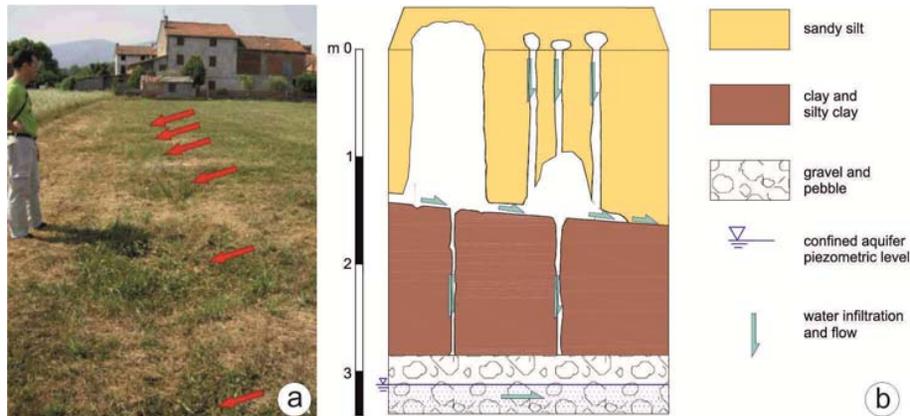


Fig. 14. (a) “Swarm” of filled micro-sinkholes N–S oriented (micro-sinkholes are recognizable by more green grass, due to greater moisture). (b) Sketch of micro-sinkholes connected by sub-horizontal or lightly sloping tunnels.

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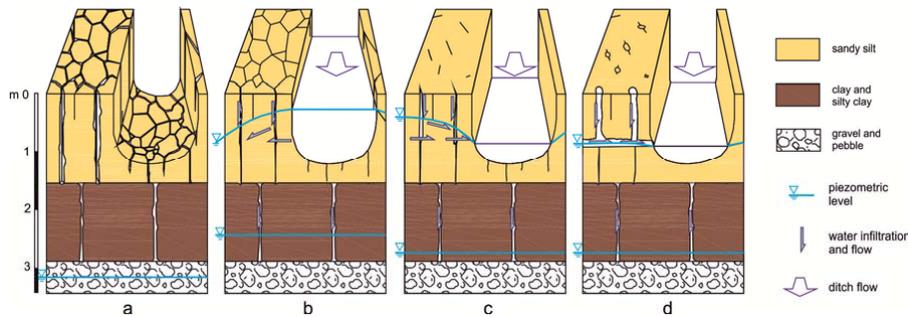


Fig. 15. Supposed developing sequence for micro-sinkholes caused by flows between water table and ditches. **(a)** dry period; **(b)** beginning heavy rainfall; **(c)** just after rainfall; **(d)** approximately 10–15 days after the rainfall period.

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