doi:10.3723/ut.31.029 International Journal of the Society for Underwater Technology, Vol 31, No 1, pp 29–41, 2012

Scientific diving techniques for the study of flooded sinkholes in Italy

G Caramanna*[1,2,3], R Malatesta[4] and MM Maroto-Valer[1]

[1]*Heriot-Watt University, Edinburgh, Scotland, UK*

[2]*Formerly at the University of Rome 'Sapienza', Rome, Italy*

[3]*Italian Association of Scientific Divers (AIOSS), Ravenna, Italy*

[4]*Scuba Team of the Italian Fire Brigade, Via del Porto Fluviale 73, Rome, Italy*

Abstract

The hydrogeology and geomorphology of some flooded sinkholes in central Italy have been studied by means of scientific diving techniques. A first group of three sinkholes is located on travertine deposits around the limestone ridge of the Cornicolani Mounts. One of these, S. Angelo Lake, is flooded by the outcrop of the regional water table. The other two, Regina Lake and Colonnelle Lake, are fed by geothermal springs with high levels of gas and are known as Acque Albule (white waters) because of the presence of cloudy layers of sulphuric water. It was possible to identify the S. Angelo Lake as a sinkhole created by the collapse of the roof of a former flooded cave. The underwater survey and water sampling of the Acque Albule sinkholes confirmed the presence of sulphuric springs emitting acidic water. The last studied sinkhole, Doganella sinkhole, is in the sedimentary cover of the Pontina Plain. It was created almost overnight by a sudden collapse in the unconsolidated sediments, and was then flooded by the local groundwater table. The S. Giovanni Lake can be classified as 'collapse sinkhole', while the Acque Albule are identified as hydrothermal-karst sinkholes. The Doganella sinkhole shows alluvial and piroclastic deposits in the submerged section, and its genesis is not totally understood yet.

Keywords: sinkholes, scientific diving, geothermal karst

1. Introduction

A sinkhole is defined as a 'circular depression in a karst area'; the term is also generally used as synonymous for doline (Bates and Jackson, 1983). The origins of such depressions are linked to different genetic factors such as chemical dissolution of calcareous bedrock, roof collapse of underground cavities or subsidence (White, 1988). When a sinkhole intercepts the groundwater level, it becomes flooded creating a small lake that can eventually be fed by submerged springs (Fetter, 2001).

Even though sinkholes are mainly an expression of superficial karst erosion, there are situations where their origins cannot be directly linked to the dissolution of outcropping calcareous deposits. Instead, they are likely due to piping processes in thick sedimentary covers overlying deep-buried carbonate bedrock. In these situations, sinkholes are usually associated with the presence of large groundwater fluxes (Newton, 1984). In Italy, karst and piping sinkholes are widely represented and are often associated with mineralised springs aligned along local and regional faults (Caramanna et al., 2008).

From the natural hazard point of view, flooded sinkholes represent a link between the water table and the external environment, and therefore can be sources of punctual pollution for the groundwater. Moreover, if the erosion process is still active, sinkholes may be enlarged by sudden rim collapses with potential damage to surrounding infrastructures (Kemmerly, 1993; Argentieri et al., 2003; Gutierrez et al., 2008).

Geophysical methods are widely used for investigating sinkholes and to identify their subterranean features and dimensions (Zhou et al., 2002; Dobecki and Upchurch, 2006; Kaufmann and Romanov, 2009). Under specific circumstances, flooded sinkholes have been studied by means of scientific diving (Jones and Dill, 2000; Caramanna and Gary, 2004), automated underwater vehicles (Gary et al., 2008) or even by coupling scientific diving with remotely operated vehicles (Caramanna, 2005).

The use of scientific diving in studying flooded sinkholes, where safety considerations allow for it, is of great advantage for the quality of data and the complexity of possible investigations, as compared with any geophysical methods or the use of remotely operated sensors.

This paper presents the results of the geomorphological and geochemical study of some flooded sinkholes in central Italy that have been investigated

* Contact author. E-mail address: g.caramanna@hw.ac.uk

by means of scientific diving techniques. Due to the characteristics of the submerged environments, such as zero visibility, overhead obstructions and the presence of potentially toxic gases, specific diving procedures and data collection techniques have been applied.

2. Methods

The studied sinkholes represent different challenges to be addressed for their safe and effective study by means of scientific diving.

The S. Giovanni Lake is a sinkhole that has overhead obstructions and potential pollution from the surrounding farming areas. Therefore, specific cave diving techniques and diver protection, such as a dry suit and full-face mask, were used. The main activity was the mapping of the submerged section of the sinkhole whose dimensions and shapes were so far unknown. A fixed reference point was deployed at the centre of the sinkhole by means of a moored buoy. From this point, a series of radial distances and bearings were measured at the surface from a small inflatable boat managed by a crew of the Italian Fire Brigade. Two main directions (north-south and east-west) were chosen to draw the underwater sections of the sinkhole. In this case, two divers operated a measured line fixed to the reference point for the horizontal dimensions and an underwater compass for the bearings.

The vertical dimensions were measured using a UWATEC Digital depth gauge (precision 0.1m as stated by the factory). The use of a AGA-Divator II full-face mask with Ocean Technology System Buddy Phone communicators allowed the divers to talk each other and with the surface team. This enhanced the overall safety of the diving operations and simplified data gathering. The full-face mask, coupled with a dry-suit, also offered some protection against potential biological pollution seepage from the surrounding farming area, although this level of protection would not be considered suitable for high levels of contamination (US Navy Sea Systems Command, 2004; Barsky, 2007).

During the underwater survey, the divers discovered along the walls of the sinkholes a cavity large enough to require some cave diving techniques, mostly the use of a safe-line, to be applied during the underwater operations. The scuba team was therefore equipped with helmet holding lights, twin-cylinder with manifold, two independent regulators and a safety reel. This equipment represents the minimum safety standards for cave diving operations (Ward et al., 2008; Caramanna et al., 2012).

Another task was water sampling from underwater springs feeding the sinkholes performed in the Regina Lake, which is fed by the Acque Albule springs. The spring is represented by a crevice in the rock at 30m of depth (Fig 1). The divers collected water samples using wide-neck half-litre plastic bottles. To avoid implosion, the bottles were carried underwater filled with deionised water. Once at the sampling spot, the bottles were opened, placed upside-down and purged with the air from the secondary regulator. The bottles were then capsized and filled with the water to be sampled.

The Acque Albule are geothermal springs with high levels of CO_2 and H_2S, which can be potentially dangerous for divers. Full-face masks were used to reduce the exposition to the adverse environmental conditions. The divers donned all the diving gear at a safe distance from the gas emissions and breathed from the scuba gear even when at the surface. The underwater visibility was good, but the presence of a thick layer of oxidised sulphuric water at the top strongly reduced the light at depth; therefore, underwater lights were mandatory. An additional consideration was the acidity and high levels of dissolved sulphurs, which meant the water was highly aggressive and could cause an enhanced corrosion on the metal parts of the scuba gear. This is to be carefully considered for the purpose of equipment maintenance.

The last of the studied sinkholes – Doganella – was mapped with the same procedures described for the S. Giovanni Lake, and the same cave diving techniques were applied because of the presence of a large cavity along the walls. In this case, tethered diving was preferred to safety lines because of the zero visibility conditions caused by a very high load of sediments in the water. The diver was physically linked to the surface, and the line was managed by an experienced tender. The use of full-face with communicators allowed the easy exchange of information between the diver and the surface tender.

The water samples were analysed with flame-absorption and spectrum-photometric techniques

Fig 1: Spring feeding the Regina Lake

using standard laboratory equipment at the Department of Earth Sciences at the University of Rome 'Sapienza' (Italy). The vertical logs of electric conductivity, total dissolved solids and temperature were performed by operating a multi-parametric probe from the surface.

3. Results

The first three studied sinkholes (S. Giovanni Lake, Colonnelle Lake and Regina Lake) are karst cavities in the thick travertine deposit of the Acque Albule Basin in the Tivoli Plain along the Aniene River valley (Fig 2). The majority of the travertine was deposited during the II Interglacial period (Riss-Wurm), as was also inferred from the recovered fossil fauna (Maxia, 1949).

The groundwater table is fed by the regional aquifer hosted in the Mesozoic limestone of the Cornicolani and Lucretili mounts on the north, with local volcanic fluids flowing from geothermal springs linked to the volcanic activity of the Latium Volcano. It is this geothermal activity that caused the travertine deposits (Manfredini, 1949).

The active tectonic of the areas uplifted the travertine plate causing the main water flow to shift below the current surface, thus interrupting the travertine deposition (Maxia, 1949).

The S. Giovanni Lake lies about 500m north of the Acque Albule springs in the travertine deposits (Pentecost and Tortora, 1989; Pentecost, 1995). The lake is hosted in a sub-circular collapse with vertical walls. The diameter is around 60m and the maximum depth is 16m with a flat bottom covered by a thin layer of silt and organic matter (Fig 3). A few metres below the water surface, there is a cavern along the perimeter of the lake. The maximum horizontal dimension of this cave is 16m from the rim of the lake (Fig 4). Speleothems have been identified in the cave both from the ceiling and along the walls (Fig 5). These outcomes of the underwater survey indicate a roof collapse of a former cave as the probable origin of the sinkhole.

The dimensions of the submerged cavity are much wider than its visible perimeter. This presents a potential hazard for the stability of the surrounding infrastructures in case of further collapses (Fig 6). The analysis of the collected water samples highlights an enrichment in SO_4, HCO_3, Ca and Cl, with a pH of 7.30 and an electric conductivity of 1580 s/cm (Tables 1 and 2). The mineralisation of the water is likely the results of the mixing of the groundwater with the fluids linked to the geothermal activity of the area. The vertical logs of electric conductivity and total dissolved solids (TDS; see Table 3) show a constant value just below the very

Fig 2: Satellite image of the Tivoli Plain with the sinkholes of S. Giovanni Lake and Albule Springs (from Google Earth, 2011)

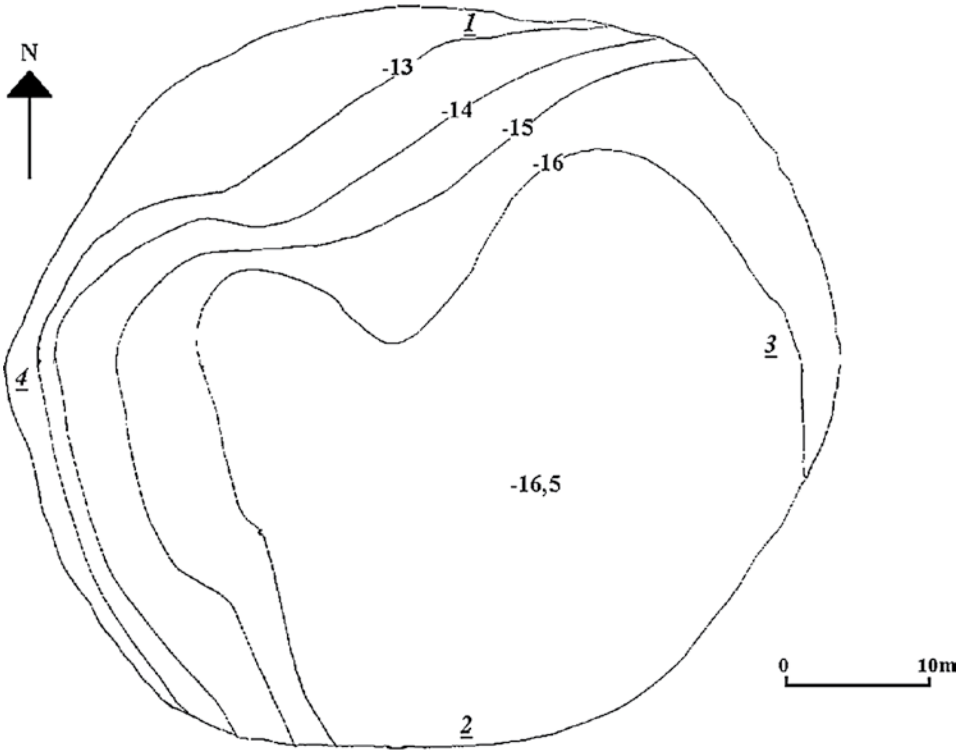

Fig 3: Bathymetric map of the S. Giovanni Lake, the numbers 1 to 4 corresponds to the vertical section in Fig 4

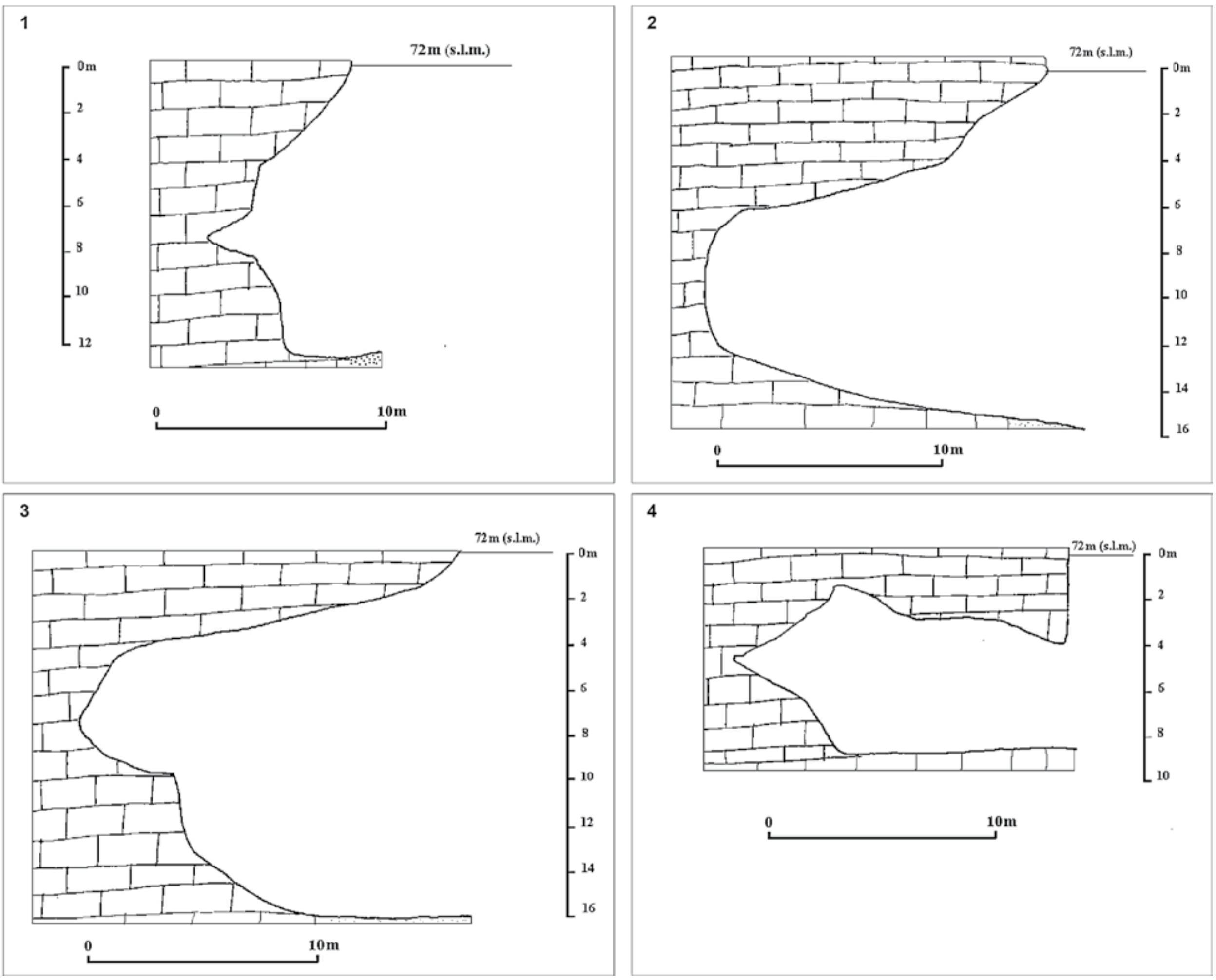

Fig 4: Vertical sections along the perimeter of the S. Giovanni Lake

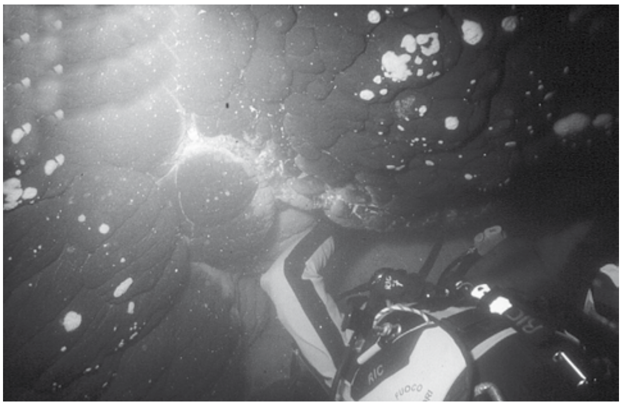

Fig 5: A diver collecting some speleothems inside the S. Giovanni Lake

top layers (Fig 7). The vertical log of temperature (Table 3) highlights two thermoclines, one at 2m and one at 8m of depth (Fig 8).

The other two studied sinkholes are the lakes of Regina and Colonnelle in the same travertine deposits hosting the S. Giovanni Lake. The lakes are fed by the highly mineralised Acque Albule springs. The Regina sinkhole has an elliptical shape with main diameter of 90m and minor of 75m. The maximum depth is 35m, and it has almost vertical walls ending on a flat bottom. At the base of the northern wall, the main spring feeding the lake is hosted in a crevice; its water flux is partially collected by a pipeline and carried to a nearby thermal spa.

Table 1: Main physical and chemical parameters measured in the studied sinkholes

	E. C. μs/cm	TDS mg/l	pH	T°C
Regina	3,180	1,813	6.25	23.0
Colonnelle	2,790	1,590	6.30	23.0
S. Giovanni	1,582	902	7.30	11.5
Doganella	392	223	7.05	9.0

Gas is emitted from the bottom and from small cracks along the walls; its composition is CO_2 mainly (90%) with a 0.6% of H_2S (Giggenbach et al., 1988). A sample of water collected from the main spring shows a higher concentration of total dissolved solids and, in particular, of SO_4 than in the S. Giovanni Lake (Table 2). The Regina Lake is likely to have originated by the progressive erosion of the travertine deposits by the aggressive (pH 6.30) waters.

The Colonnelle Lake is a funnel-shaped sinkhole that has a sub-elliptical section with main diameter of 55m and minor of 40m. The maximum depth is 60m, with the bottom covered by thick layers of whitish silt originated from the dissolution of the travertine. The very high levels of $CaCO_3$ in water allow a mineral precipitation over organic matter, such as roots of plants, originating pseudo-stalactites forms (Fig 9). The water composition is similar to that of the Regina sinkhole (Table 2). The origin of this sinkhole should be the same as

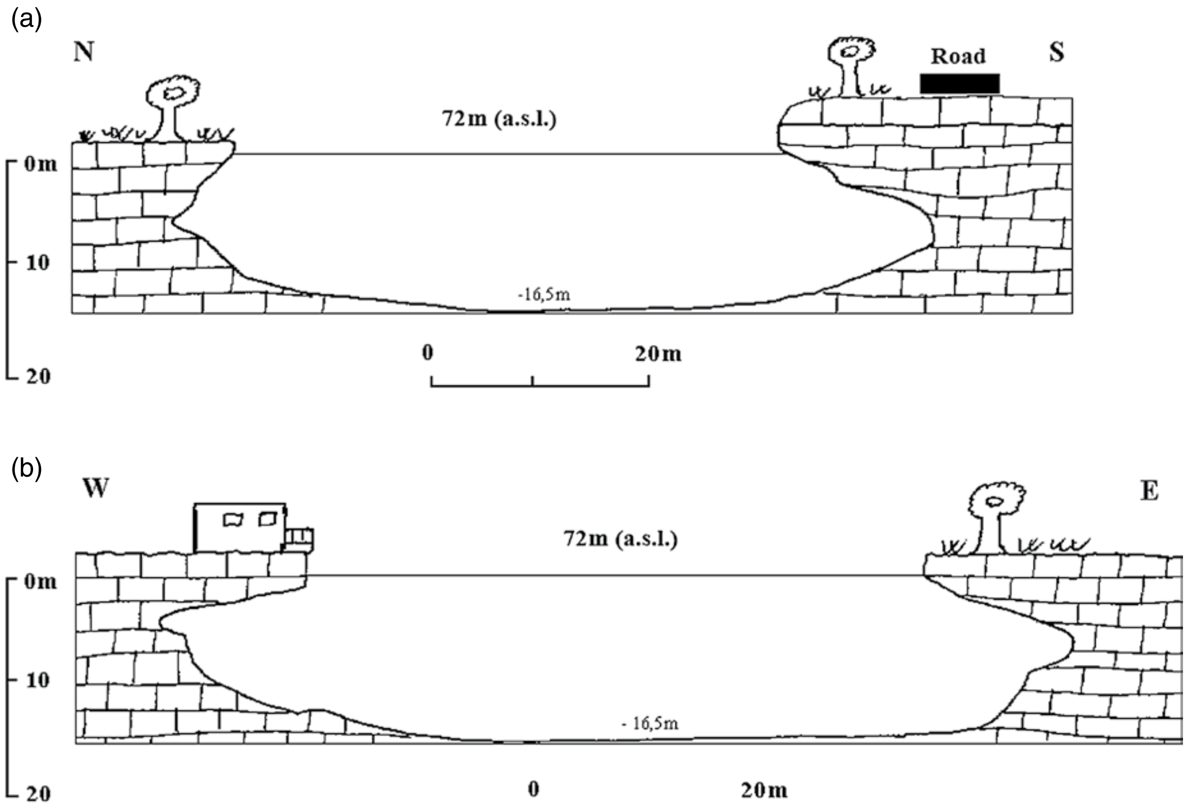

Fig 6: Vertical section along N-S (a) and W-E (b) of the S. Giovanni Lake

Table 2: Main ionic concentration in the water of the studied sinkholes

	Ca^{++} mg/l	Mg^{++} mg/l	Na^{+} mg/l	K^{+} mg/l	HCO_3^{-} mg/l	SO_4^{-} mg/l	Cl^{-} mg/l	NO_3^{-} mg/l
Regina	514.0	83.0	97.0	25.0	1,417.0	740.0	102.0	2.0
Colonnelle	517.0	80.0	88.0	26.0	1,389.0	754.0	109.0	5.0
S.Giovanni	169.0	57.0	60.0	8.0	638.0	201.0	106.0	6.0
Doganella	3.4	0.8	0.5	0.1	4.0	0.3	0.2	1.6

Table 3: Vertical log of temperature, electric conductivity and TDS along the water column in the S. Giovanni Lake

S. Giovanni Lake			
Depth M	Temperature °C	Electric Conductivity μ/cm	TDS mg/l
0	11.9	1578	899
0.5	11.8	1579	900
1	11.7	1580	901
2	11.6	1580	901
3	11.6	1582	902
4	11.6	1582	902
5	11.6	1582	902
6	11.6	1582	902
7	11.6	1582	902
8	11.5	1582	902
9	11.5	1582	902
10	11.5	1582	902
11	11.5	1582	902
12	11.5	1582	902
13	11.5	1582	902
14	11.5	1582	902
15	11.5	1582	902

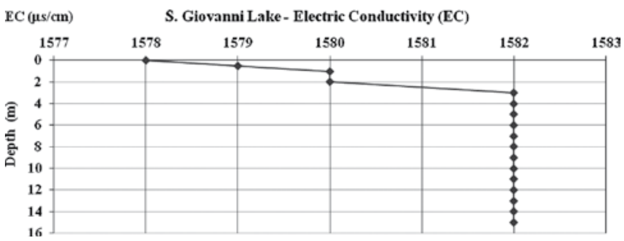

Fig 7: Vertical log of the electric conductivity in the S. Giovanni Lake sinkhole

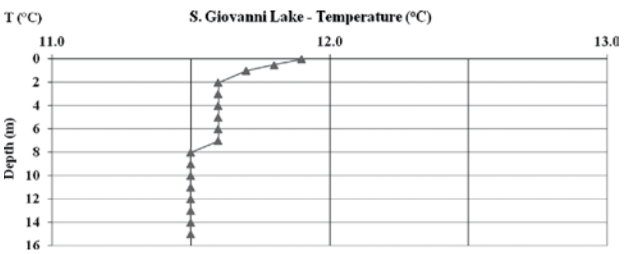

Fig 8: Vertical log of temperature in the S. Giovanni Lake sinkhole

for the nearby Regina Lake: geothermal karst erosion of the travertine bedrock.

Vertical logs of electric conductivity performed in both lakes (Tables 4 and 5) show almost constant values (Fig 10). The temperature of Colonnelle

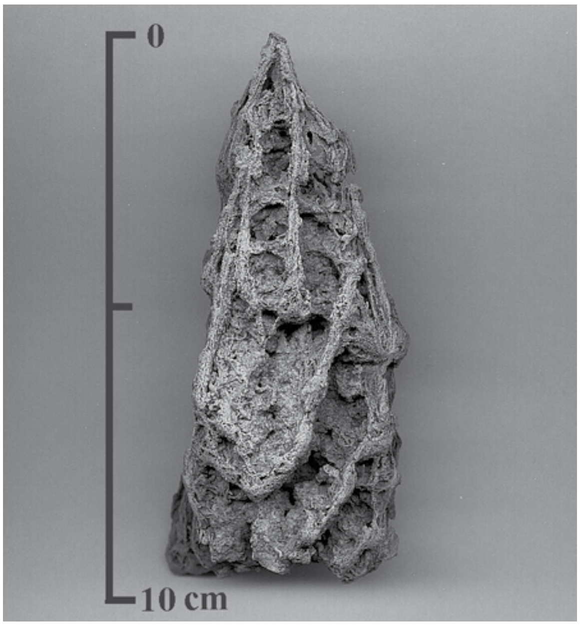

Fig 9: Pseudo-stalactite formed by the deposition of $CaCO_3$ over vegetal matter (from Caramanna and Gary, 2004)

Lake is stable around 23°C (Table 4). In Regina Lake it slightly increases with depth (Table 5), as the main geothermal emission is from the bottom of the lake (Fig 11). The values of *T*, electric conductivity and TDS of these sinkholes are clearly different from the ones in a nearby lake, which is used as reference showing that the chemistry of the waters in the sinkholes is influenced by the presence of geothermal fluids (Table 6). The reduced, or absent, stratification of the lake water is likely caused by the mechanical effect of the rising bubbles and the convection cell trigged by the warm water emissions. In summer, a certain level of stratification is observed in the upper layers, which are heated by the sun above the geothermal values. This stratification causes the sulphur content of the top layers to be oxidised from contact with the atmospheric oxygen, thus creating a 'milky' level (from which came the original Latin name of Acque Albule).

In recent years, the level of both lakes has been steadily dropping (Fig 12). This is very likely caused by the large amount of groundwater that is pumped into the nearby travertine quarries in order to exploit the deposits that lie well below the water

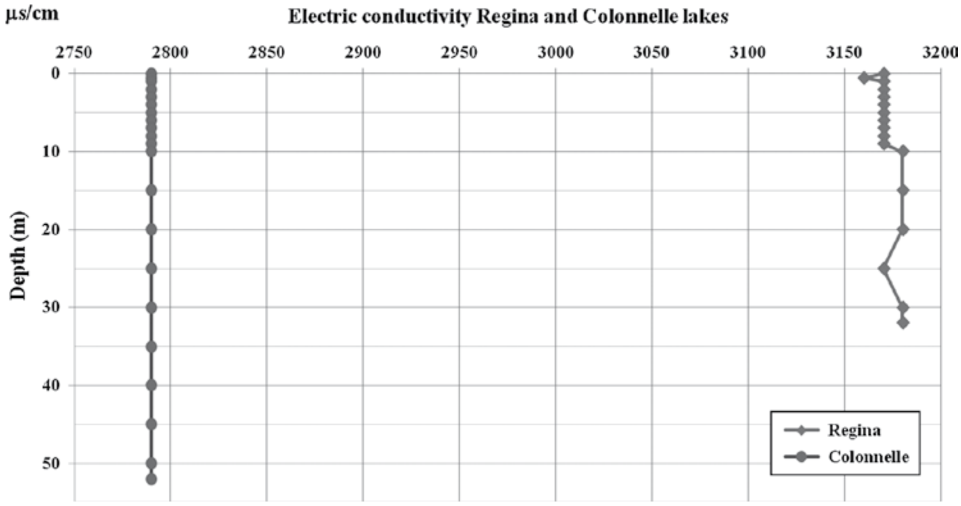

Fig 10: Vertical log of the electric conductivity in the Regina and Colonnelle sinkholes

Table 4: Vertical log of temperature, electric conductivity and TDS along the water column in the Colonnelle Lake

Colonnelle Lake (Acque Albule)			
Depth M	Temperature °C	Electric Conductivity µ/cm	TDS mg/l
0	22.8	2790	1590
0.50	23.1	2790	1590
1	23.1	2790	1590
2	23.1	2790	1590
3	23.1	2790	1590
4	23.1	2790	1590
5	23.1	2790	1590
6	23.1	2790	1590
7	23.1	2790	1590
8	23.1	2790	1590
9	23.1	2790	1590
10	23.1	2790	1590
15	23.1	2790	1590
20	23.1	2790	1590
25	23.1	2790	1590
30	23.1	2790	1590
35	23.1	2790	1590
40	23.1	2790	1590
45	23.1	2790	1590
50	23.1	2790	1590
52	23.1	2790	1590

Table 5: Vertical log of temperature, electric conductivity and TDS along the water column in the Regina Lake

Regina Lake (Acque Albule)			
Depth m	Temperature °C	Electric Conductivity µ/cm	TDS mg/l
0	23.0	3170	1807
0.50	23.3	3160	1801
1	23.3	3170	1807
2	23.3	3170	1807
3	23.3	3170	1807
4	23.3	3170	1807
5	23.3	3170	1807
6	23.3	3170	1807
7	23.3	3170	1807
8	23.3	3170	1807
9	23.3	3170	1807
10	23.4	3180	1813
15	23.4	3180	1813
20	23.4	3180	1813
25	23.4	3170	1807
30	23.5	3180	1813
32	23.5	3180	1813

table level (Fig 13). The long-term effects of such dropping on the stability of the sinkholes, and on one of the other underground voids that could potentially be hosted in the travertine, have not yet been completely clarified (Salvi et al., 2004).

The last studied sinkhole is called Doganella from the name of the nearest village Doganella di Ninfa in the Pontina plain. The sinkhole lies on clastic sediments composed of sand, gravel, pebbles, clay and pyroclastic deposits. The latter are originated by the quaternary eruptions of the closer Latium Volcano area. Three buried travertine horizons mark the end of three different volcanic cycles (Bono, 1995).

The sinkhole collapsed in August 1989 and since then its dimensions have progressively become enlarged up to the current 25m diameter and 35m depth (Fig 14). The sudden collapse involved a rural street, Via Lunetto, that was swallowed by the enlarging cavity (Fig 15). The sinkhole flooded, creating a pond of 30m of depth. The vertical section of the sinkhole shows vertical walls ending in a bell-shaped form at the bottom. The lithology is represented by volcano-clastic deposits and clay from the rig down to 15m below the water surface. From this depth down to the bottom, the walls are composed of harder tuff; on the bottom, a thick layer of silt and organic matter overlays compact

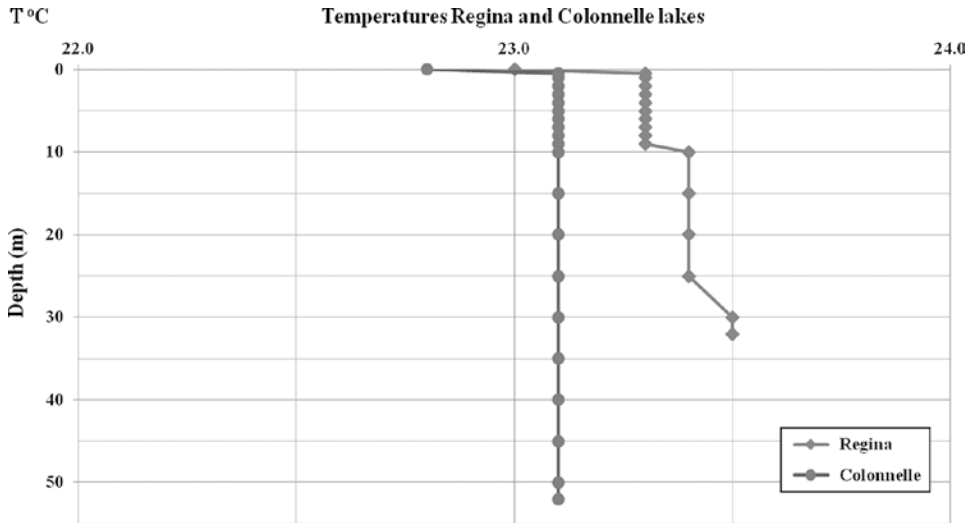

Fig 11: Vertical log of temperature in the Regina and Colonnelle sinkholes

Table 6: Vertical log of temperature, electric conductivity and TDS along the water column in the Albano Lake

Albano Lake			
Depth M	**Temperature °C**	**Electric Conductivity μ/cm**	**TDS mg/l**
0	18.7	505	288
0.50	18.7	506	288
1	18.6	506	288
2	18.6	509	290
3	17.7	509	290
4	17.7	509	290
5	17.5	509	290
6	17.5	509	290
7	17.5	509	290
8	17.5	509	290
9	16.8	509	290
10	16.6	512	292
15	16.6	512	292
20	16.6	513	292
25	13.1	515	294
30	13.1	520	296
35	12.9	520	296
40	10.4	525	299
45	9.4	525	299
50	9.4	532	303
55	9.3	550	314
60	9.2	557	317

clay deposits (Fig 16). The observed lithology is in good accordance with the stratigraphic data available from a nearby borehole where travertine deposits were found below 60m from the terrain surface (Italian Web Sinkhole Database (IWSD), 2011).

The sinkhole acts as a natural piezometer on the groundwater hosted inside the alluvial and pyroclastic cover of the Pontina Plain. The water of the sinkhole is bicarbonatic–calcic, with pH 7.05 and electric conductivity of 392 s/cm (Table 1; Fig 17). The high levels of NO_3 indicate probable pollution seeping from the surrounding farming area (Table 2). The temperature trend highlights a progressive reduction in water temperature with a shallow thermocline at about 5m of depth. Below this level, the temperature of the water column is stable (Fig 18). The presence of such stratification will likely reduce the mixing of the water inside the sinkhole, with increased anoxic conditions in the bottom layers leading to conditions favourable for the accumulation of organic matter that was observed during the dives.

The chemistry of the water inside the sinkholes is compared in a Chebotarev diagram (Fig 19). This diagram shows that the lakes of Regina and Colonnelle can be described as sulphur-chlorine waters, and that instead S. Giovanni Lake and mostly the Doganella sinkhole are filled by carbonate waters.

4. Conclusions

The studied sinkholes can be clustered into three categories. The S. Giovanni Lake is clearly a karst sinkhole originated by the roof collapse of a former cave and therefore is to be considered a 'collapse sinkhole'. The lakes of Regina and Colonnelle are karst sinkholes originated by the progressive dissolution of travertine deposits by the aggressive fluids of geothermal origin mixed with the water of the springs feeding the lakes.

The sinkhole of Doganella is the more problematic in regard to determining its origin. The sedimentary cover (alluvial and pyroclatsic deposits) is not prone to karst erosion, and the water filing the sinkhole does not highlight any specific aggressive chemistry. From borehole data, the presence of lenses of travertine is identified in the area; therefore, a hypothesis on the origin of the sinkhole is

Fig 12: Shrinking in the dimensions of the Regina and Colonnelle lakes from 2003 (top) to 2009 (bottom) caused by the reduced flux from the Albule springs (from Google Earth, 2011)

Fig 13: The studied area of the Albule springs with the nearby travertine quarries (from Google Earth, 2011)

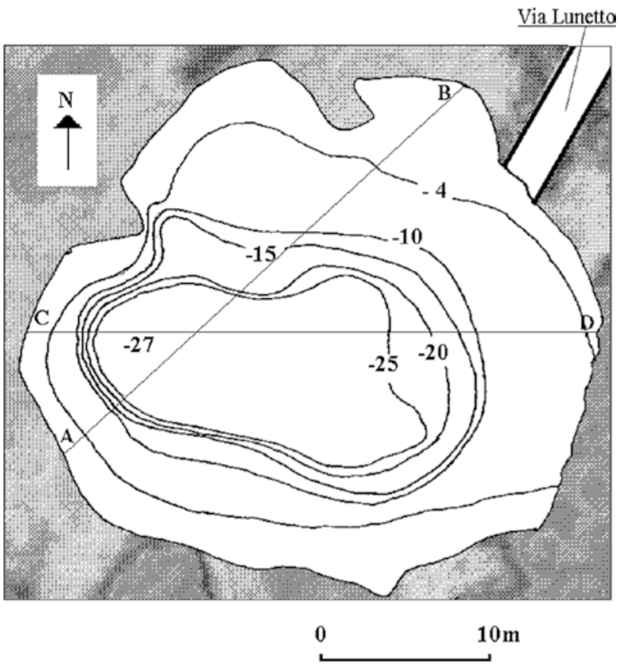

Fig 14: Bathymetric map of the Doganella sinkhole with traces of the vertical sections (from Caramanna and Gary, 2004)

the dissolution of one of such lenses and the subsequent collapse of the overlying deposit.

In all of the presented cases, the sinkholes are a contact point between the local and regional aquifer and the external environment, therefore representing a potential preferential path for pollutants to contaminate the groundwater. The authorities should adopt specific procedures in order to avoid the contamination of the water inside the sinkholes.

In two of the three presented cases (S. Giovanni Lake and Doganella sinkhole), the underwater morphology is characterised by the presence of large voids which extend far beyond the perimeter of the sinkhole, thus representing a hidden hazard for the stability of the surrounding infrastructures.

The presence of such voids was clearly detected only after the underwater survey of the sinkholes by means of scuba diving techniques. The same techniques allowed the identification of speleothems in the S. Giovanni Lake, classifying the origin of the cavity as collapsed sinkhole originating from the roof failure of a former cave. In the Regina Lake of the Acque Albule springs, samples of water were collected by the divers directly from the main spring, whose position inside a lateral crevice at the bottom of the cavity did not allow any surface sampling techniques.

Scientific diving has been demonstrated to be a valuable tool for the scientists to study environments, such as the presented flooded sinkholes, the characteristics of which would otherwise not be possible to fully appreciate without the use of this scientific tool.

Fig 15: The Doganella sinkhole and the track of the damaged road (from Google Earth, 2011)

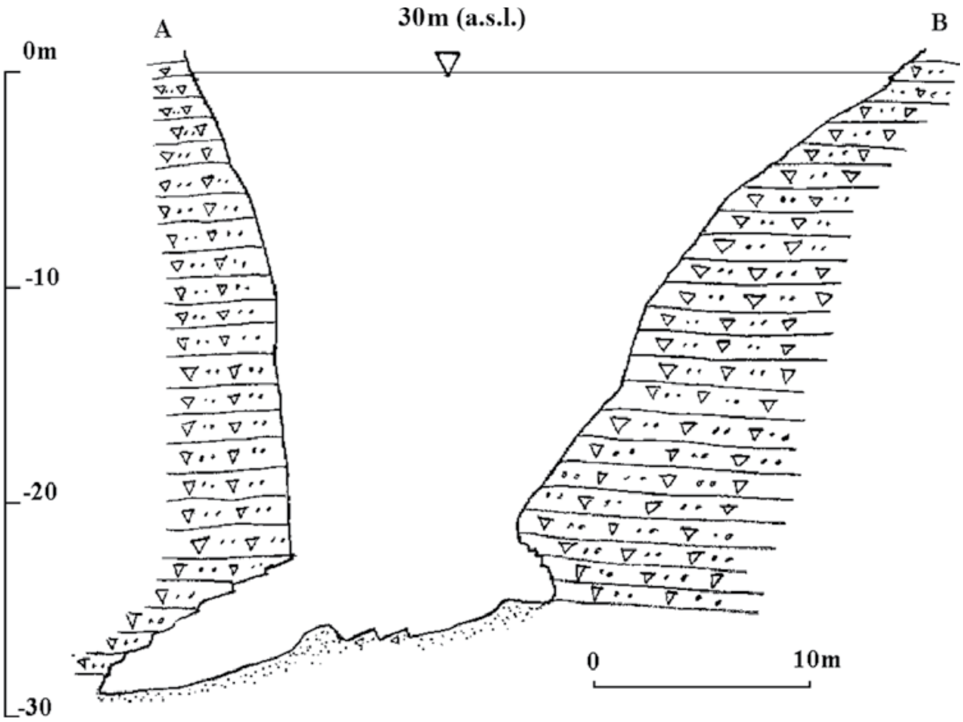

Fig 16: Vertical section of the Doganella sinkhole along SW–NE direction (mod. from Caramanna and Gary, 2004)

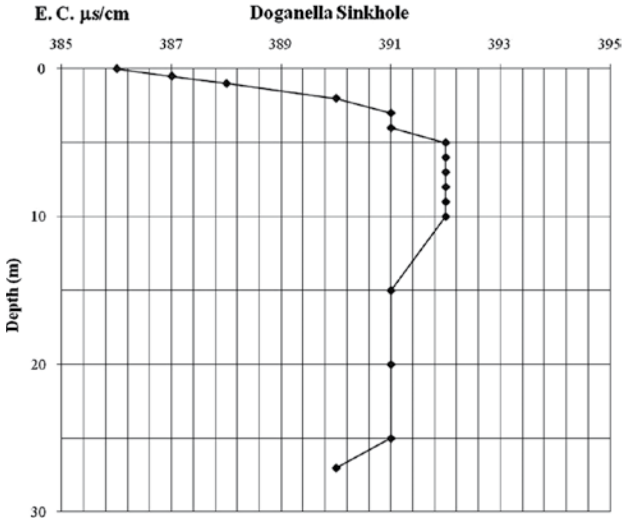

Fig 17: Vertical log of electric conductivity in the Doganella sinkhole

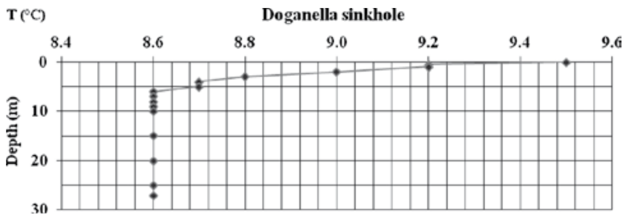

Fig 18: Vertical log of temperature in the Doganella sinkhole

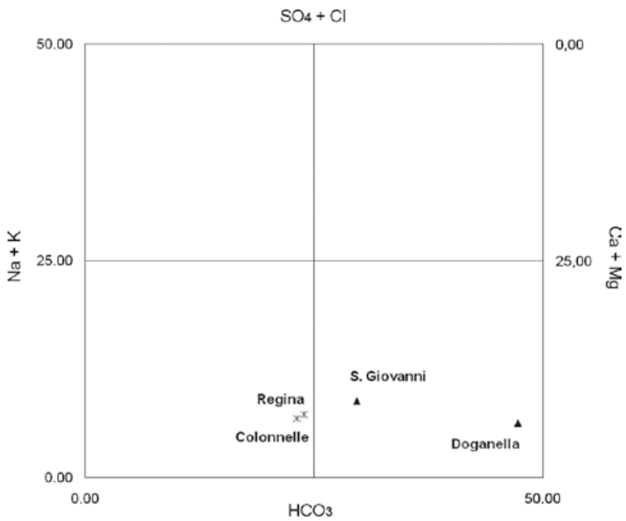

Fig 19: Chebotarev diagram showing the chemical characterisation of the studied sinkholes

Acknowledgments

The authors acknowledge the Centre for Innovation in Carbon Capture and Storage, Engineering and Physical Sciences Research Council (EPSRC) grant EP/F012098/1, for supporting the diffusion of the results of this research. The Italian Fire Brigade Scuba Team is gratefully acknowledged for the major operative support given to the authors for the fulfilment of the fieldwork activity. The Department of Geology at the University of Rome 'Sapienza', where most of the laboratory work was conducted, is also acknowledged. The Acque Albule spa is acknowledged for giving the authors special authorisation to dive in the Regina and Colonnelle sinkholes. The landlord of the S. Giovanni Lake is acknowledged for giving the authors special authorisation to dive on his property. Simone Formica is gratefully acknowledged for collaborating on many dives in very hostile environments. Dr Carlo Percopo and Dr Marco Giardini are acknowledged for their scientific support to part of the research. The RAI National Italian Television, along with Pippo Cappellano and Marina Cappabianca of Capmar Studios, are acknowledged for their efforts in producing a documentary on the topics of this research, often working in very difficult environmental conditions.

References

Argentieri A, Vecchia P, Salvati R, Capelli G and Loretelli S. (2003). La pericolosita' da sinkhole nel territorio della provincia di Roma: il caso di Marcellina. *Thalassia Salentina* **26**: 95–105.

Barsky S. (2007). *Diving in High-risk environments.* Ventura, CA: Hammerhead Press, 196pp.

Bates RL and Jackson J. (1983). *Dictionary of geological terms, 2nd edition.* Falls Church, VA: American Geological Institute, 571pp.

Bono P. (1995). The sinkhole of Doganella (Pontina Plain, central Italy). *Environmental Geology* **26**: 48–52.

Caramanna G. (2005). Scientific diving and ROV techniques applied to the geomorphological and hydrogeological study of the world's deepest karst sinkhole (Pozzo del Merro, Latium, Italy). Diving for Science 2005 – Proceedings of the American Academy of Underwater Sciences 24th Annual Symposium, Groton, Connecticut, USA, 233–238.

Caramanna G and Gary M. (2004). Applicazioni di immersione scientifica e ROV (Remotely Operated Vehicle) nello studio geologico comparato dei due sinkholes allgati piu' profondi del pianeta: Pozzo del Merro (Lazio, Italia Centrale), El Zacaton (Taumalipas, Messico). Atti del workshop Stato dell'arte nello studio dei fenomeni di sinkholes e ruolo delle amministrazioni locali nel governo del territorio, 221–228.

Caramanna G, Ciotoli G and Nisio S. (2008). A review of natural sinkhole phenomena in Italian plain areas. *Natural Hazards* **45**: 145–172.

Caramanna G, Kekäläinen P, Leinikki J and Maroto-Valer M. (2012). Scientific diving techniques in restricted over-head environments. *Underwater Technology* (in press).

Dobecki TL and Upchurch SB. (2006). Geophysical applications to detect sinkholes and ground subsidence. *The Leading Edge* **25**: 336–341.

Fetter CW. (2001). *Applied hydrogeology.* Upper Saddle River, NJ: Prentice Hall, 598pp.

Gary M, Fairfield N, Stone W, Wettergreen D, Kantor G and Sharp J. (2008). 3D mapping and characterization of Sistema Zacaton from DEPTHX (Deep Phreatic Thermal eXplorer). *Proceedings of KARST08: 11th sinkhole conference ASCE*, 1–11.

Giggenbach WF, Minissale AA and Scandiffio G. (1988). Isotopic and chemical assessment of geothermal potential of the Colli Albani area, Latium region, Italy. *Applied Geochemistry* **3**: 475–486.

Google Earth. (2011). On-line images catalogue. Available at www.google.com/earth/index.html, accessed on 18 August 2012.

Gutierrez F, Guerrero J and Lucha P. (2008). Quantitative sinkhole hazard assessment: A case study from the Ebro Valley evaporite alluvial karst (NE Spain). *Natural Hazards* **45**: 211–233.

Italian Web Sinkhole Database (IWSD). (2011). Italian Web Sinkhole Database. Available at http://host.uniroma3.it/laboratori/idrogeologia/stratigrafie_1.php?cod=S40, accessed on 19 October 2012.

Jones A and Dill R. (2000). Great Blue Hole of Lighthouse Reef Atoll, Belize, Central America: deep technical diving to collect sea-level records. In: Jackson T. (ed.). *Caribbean Geology into the third millennium. Transaction of the 15th Caribbean Geological Conference*. Kingston, Jamaica: University of the West Indies Press, 279pp.

Kaufmann G and Romanov D. (2009). Geophysical investigation of a sinkhole in the northern Harz foreland (North Germany). *Environmental Geology* **58**: 401–405.

Kemmerly PR. (1993). Sinkhole hazards and risk assessment in a planning context. *Journal of the American Planning Association* **58**: 221–229.

Manfredini M. (1949). Alcuni dati sulla falda idrica che alimenta le sorgenti delle Acque Albule. *Boll. Serv. Geol. d'Italia* **71**: 107–113.

Maxia C. (1949). Studi geologici sui Monti Cornicolani (Lazio). *La Ricerca Scientifica Roma* **18**: 387–399.

Newton JG. (1984). Natural and induced sinkhole development in the Eastern United States. In: Johnson AI. (ed.). *Land Subsidence, Proceedings of the Second International Symposium on Land Subsidence*, Venezia, 323–331.

Pentecost A. (1995). The Quaternary Travertine deposits of Europe and Asia Minor. *Quaternary Science Reviews* **14**: 1005–1028.

Pentecost A and Tortora P. (1989). Bagni di Tivoli, Lazio: a modern travertine depositing site and its associated microorganisms. *Boll. Soc. Geol. It.* **108**: 315–324.

Salvi S, Pirro M, Gasparini C, Stramondo S, Pagliuca NM, Atzori S, Colini L, Tolomei C, Doumaz F, Ferretti A and Allievi J. (2004). Le deformazioni del suolo ricavate da dati satellitari in un settore a rischio sinkhole del bacino delle Acque albule (Lazio). In: *Apat-Dipartimento Difesa del Suolo - 1° Workshop 'Stato dell'arte sullo studio dei fenomeni di sinkholes e ruolo delle amministrazioni statali e locali nel governo del territorio'*. Roma, 20–21 Maggio 2004.

US Navy Sea Systems Command. (2004). Guidance for diving in contaminated waters. SS521-AJ-PRO-010. Direction of Commander, Naval Sea Systems Command, 35pp.

Ward A, Hayward C, Brock D and Cordingley J. (2008). *The Cave Diving Group Manual*. Somerset, UK: Cave Diving Group, 224pp.

White WB. (1988). *Geomorphology and hydrology of karst terrains*. Oxford: Oxford University Press, 464pp.

Zhou W, Beck BF and Adams AL. (2002). Effective electrode array in mapping karst hazards in electrical resistivity tomography. *Environmental Geology* **42**: 922–928.