



First geomatic restitution of the sinkhole known as ‘Pozzo del Merro’ (Italy), with the integration and comparison of ‘classic’ and innovative geomatic techniques

V. Baiocchi¹ · G. Caramanna² · D. Costantino³ · P. J. V. D’Aranno¹ · F. Giannone⁴ · L. Liso⁵ · C. Piccaro¹ · A. Sonnessa¹ · M. Vecchio⁵

Received: 21 March 2016 / Accepted: 7 January 2018 / Published online: 24 January 2018
© Springer-Verlag GmbH Germany, part of Springer Nature 2018

Abstract

The sinkhole known as ‘Pozzo del Merro’ possesses unusual, geological and natural features, providing an important opportunity to study the geological and hydrological characteristics of the area, and, at the same time, to preserve an ecosystem inhabited by rare species. The site has been the object of numerous studies carried out by scholars from a wide range of disciplines, but a true morphological survey has not been performed until now due to logistical difficulties that include the lack of adequate measuring positions and the difficulty of establishing a clear view between points. The principle benefits of an accurate morphological survey include: (a) a better understanding of the geomorphological characteristics of the site, which will in turn lead to better litho-stratigraphic correlations, (b) the opportunity to obtain accurate measurements of the zero levels of several piezometric measurements, (c) the identification of any secondary cavities which might be hidden by vegetation, and (d) allowing a virtual access to the site to both researchers and general public who cannot currently visit the site due to safety issues and ecosystem vulnerability. These considerations led to the decision to undertake a detailed survey using a combination of different geomatic ‘classic’ techniques, including the use of total stations, GPS/GNSS geodetic surveying, and laser scanning. The availability of an imaging rover, an innovative photogrammetric multifocal instrument, suggests to repeat the survey to experiment this completely new technology.

Keywords Sinkhole · Merro · Laser scanner · DTM · Geomatic · GPS · Imaging rover

Introduction

The Pozzo del Merro is located in the ‘Macchia di Gattaceca e Macchia del Barco’ Nature Reserve, whose 996 ha extend into the municipal territories of Mentana, Monterotondo, and Sant’Angelo Romano.

The nature reserve was created in 1997 by a decree from the Lazio Regional Government (Legge Regionale n. 29 del 1997) and is under the tutelage of ‘Città Metropolitana di Roma Capitale.’ It was granted protected status in recognition of the presence of rare species and its vicinity to a large city like Rome, along with the many karstic phenomena within the reserve, including dolinas, pits, and grottoes. Among these, the Pozzo del Merro stands out as a prime example, since the flooded section of this dramatic sinkhole has currently the second maximum known depth in the world (Caramanna and Gary 2004) after the recent discovery of 404-m Hranice abyss (The Guardian 2016). Thus, other

✉ V. Baiocchi
valerio.baiocchi@uniroma1.it

¹ Sapienza University of Rome, DICEA, Via Eudossiana 18, 00184 Rome, Italy

² GeoAqua Consulting, 13 Pankhane Str., Oak Bluffs, MA, USA

³ Politecnico di Bari, DICATECh, Via Edoardo Orabona, 4 – 70125 Bari, Italy

⁴ Università degli Studi Niccolò Cusano, Via Don Carlo Gnocchi 3, 00166 Rome, Italy

⁵ Città metropolitana di Roma capitale, via Tiburtina 691, 00159 Rome, Italy

sinkholes are the deepest if we consider submerged and dry part together (Garasic 2000).

A rigorous topographic survey of this site will provide important information useful for geological and hydrological studies.

In fact, till now, the specific morphology of the site has made very hard to carry out an accurate topographical survey of the main geometric characteristics of the Pozzo del Merro, such as the zero level of the hydrometric staff gauge elevation, that is the reference point for all previous hydrometric measurements.

The survey planning and execution have been proved to be extremely complex; in fact, the dense vegetation and the high pit steepness make difficult the use of GPS/GNSS receivers, and aerophotogrammetric techniques, including unmanned aerial vehicles (UAV), are practically unworkable because of the tall vegetation that limit visibility and safety of UAV flights.

The specific quality of the site

The Pozzo del Merro is situated in the Cornicolani hills, whose three peaks rising above the Tivoli-Guidonia plains are part of the lower foothills of the pre-Appennini mountain

range. The Cornicolani hills are formed of carbonate sediments deposited primarily during the Mesozoic period.

The sinkhole pozzo del Merro has been studied by the scientific community for many years both for its interesting geologic features (Bono 2001) and for its unique and delicate habitat (Romano et al. 2012; Iannilli and Taglianti 2005; Giardini 2004).

The opening of the sinkhole lies at 150 m above sea level and has a roughly circular crater with a diameter of about 150 m (Fig. 1a). The interior of its crater is shaped like a funnel, becoming narrower as it descends, reaching the surface of the water 80 m down with a diameter of less than 30 m, at about 70 m above sea level (Calamita et al. 2002).

The submerged part of the sinkhole was practically unexplored until 1998 when the first scientific underwater explorations were conducted by G. Caramanna and R. Malatesta.

More explorations took place over the following years, and in 2002 a collaboration between the Province of Rome, the Diving unit of the Province of Rome Fire Brigade (Nucleo sommozzatori e SAF del Comando Provinciale di Roma dei Vigili del Fuoco), and 'La Sapienza' University of Rome, which was later substituted by the Department of Geological Sciences of the University 'Roma Tre' (Rosa 2003), allowed the use of a remotely operated vehicle (ROV)

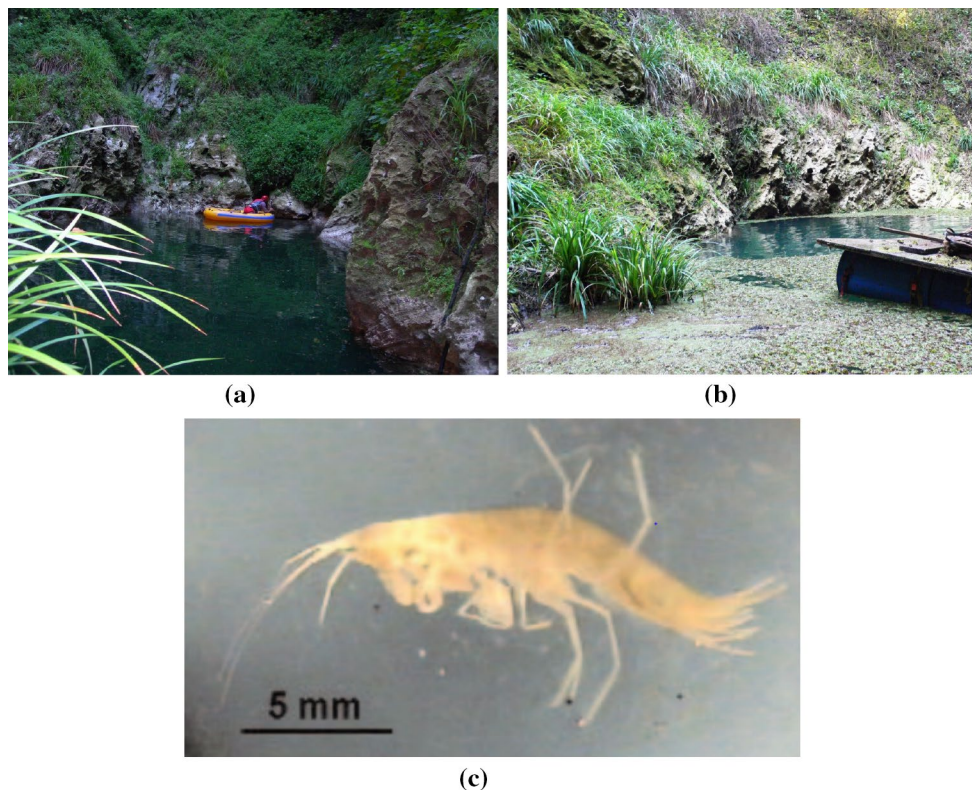


Fig. 1 The lake inside the sinkhole (a), its infestation by *Salvinia molesta* D.S. Mitch (b) which threatened the extinction of *Niphargus cornicolanus* (c)

to reach the deepest part of the sinkhole at 392 m below the surface of the water (Caramanna and Gary 2004).

The ecosystem of the Pozzo del Merro is of profound environmental interest as an unknown species (*Niphargus Cornicolanus*, Fig. 1c) was first observed here (Iannilli and Taglianti 2005), but its survival depends on a fragile equilibrium. This fragility was highlighted in 2003 when Giardini noted that the water surface had been colonized by *Salvinia molesta* D.S. Mitch, an invasive aquatic fern native to Brazil (Fig. 1b). Eventually, in 2009, a procedure was initiated to eradicate the *Salvinia Molesta* by manually removing the plants so as to return the habitat to its original state.

To monitor water conditions, a piezometer was installed to measure the water level and temperature changes every six hours (Buccomino et al. 2009). A new piezometer has recently been installed (February 2015) to substitute the old one that has been damaged and is no longer functioning; the height of this new piezometer was carefully surveyed during the installation.

By analyzing static water-level measurements taken at the Pozzo del Merro, recent studies have confirmed the close relationship of the aquifer that feeds water to the Merro with the aquifer underneath the Tivoli-Guidonia plains (La Vigna et al. 2012).

Safety and conservation concerns have meant that access to the Pozzo del Merro is only possible with a research permit granted by its trustee. The site's current trustee, the 'Città Metropolitana di Roma Capitale,' has promoted a number of activities and studies through the Regional Parks and Protected Areas Office of its Environmental Service for the management and monitoring of the Pozzo del Merro.

Geological context

The area of the Pozzo del Merro has been the subject of several interdisciplinary studies; the dynamic of the regional aquifer has been assessed (Brunetti et al. 2013; Capelli et al. 1987; Carucci et al. 2012; Di Salvo et al. 2013; Floris et al. 2014; La Vigna et al. 2013a, b; Maxia 1950; Baiocchi et al. 2008), as well as the structural setting (De Filippis et al. 2013a, b; Frepoli et al. 2010; Gasparini et al. 2002; La Vigna et al. 2012). Studies also focused on the formation of travertine deposits 'Lapis Tiburtinum' (Faccenna et al. 2008) and on the genesis of other sinkholes in the area (Argentieri et al. 2015; Billi et al. 2016; Ciotoli et al. 2015).

A comprehensive review of the available literature is beyond the aim of this paper which will focus on the main characteristics of the Pozzo del Merro consistent with the presented specific research activity.

The Pozzo del Merro is situated in the Monti Cornicolani Liassic limestone hills, which ridge is the westernmost edge of the Latium Apennines, to the north of Tivoli. The range

of hills reaches about 400 m altitude with an alignment of NNW–SSE and N–S (Billi et al. 2007; Caramanna et al. 2008).

Pyroclastic deposits related to volcanic activity in the Alban hills cover part of the southwestern slopes, while Pliocene alluvial layers are present on the northern edge of the carbonate structure. The principle tectonic contours are represented by three semi-vertical fault lines which are aligned NW–SE, NE–SW, and N–S and were formed during four deformative phases of the Central Apennines (Mattei et al. 1986).

- Phase 1: compressive along NE–SW (*Tortonian–Messinian*)
- Phase 2: distensive with structural axes NE–SW (*Tortonian–Messinian*)
- Phase 3: initially compressive followed by distension along NW–SE (*Messinian–Lower Pliocene*)
- Phase 4: Distensive along N 10° W and N 80° W (*Pliocene–recent*)

The limestone outcrops are fractured due to the effect of such stressors thus facilitating the circulation of water and hypogenic fluids.

To the south of the Cornicolani hills lies the Tivoli Plain containing travertine deposited during the Riss–Wurm period, the sulfuric springs of the Acque Albule and the River Aniene; the plain represents the principal catchment area for the watershed of the Cornicolani and Lucretili hills and of the southern slopes of the Tiburtini hills (Fig. 2). Rainfall varies between 1000 and 1500 mm per annum with an effective infiltration of 44% facilitated by the presence of a severely karstified and fractured carbonate substrate (Boni et al. 1986, 1988; Crema 1915).

Tectonic dislocation provides preferential routes for the flow of water far below ground and for possible geothermal and gaseous (principally CO₂) emissions connected to the nearby 'Vulcano Albano' volcanic area (Mattei et al. 1986; Salvati and Sasowsky 2002).

Morphology and hydrogeology of the Pozzo del Merro

The Pozzo del Merro is a partially submerged karstic sinkhole which extends for about 462 m below ground; a 392 m section is flooded by the regional groundwater table (Fig. 3). The sinkhole formed along a north–south discontinuity corresponds with one of the local tectonic alignments. The cavity's morphology can be divided into two sections: a funnel-shaped section above water, and a submerged semi-vertical channel. Surface erosion patterns on the rock face above the water level are evidence of the effects of epigenetic karstic phenomena. The submerged channel grows progressively

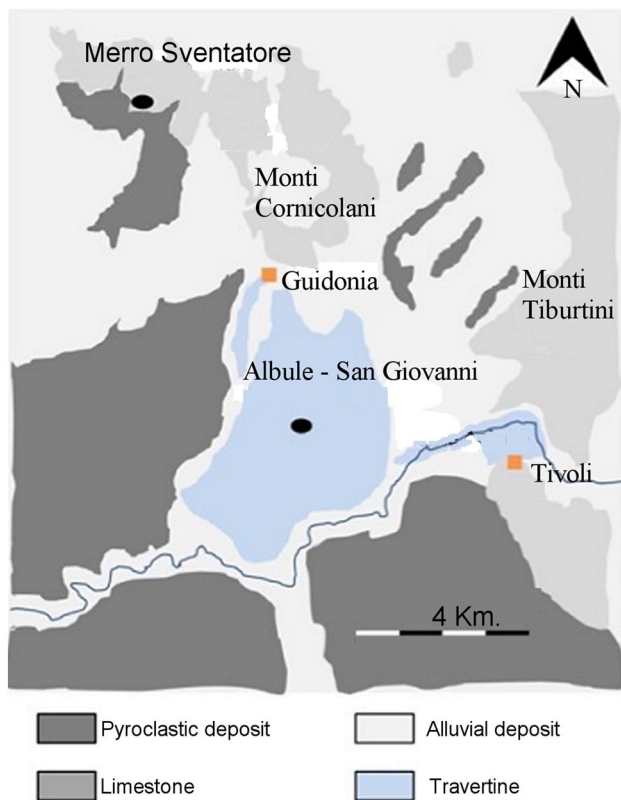


Fig. 2 Simplified geological map of the Monti Cornicolani—Piana di Tivoli system

narrower from a diameter of approximately 30 m to less than 5 m at a depth of 60 m. A series of lateral dome-shaped cavities indicate that the formation of the sinkhole is related to hypogeous karstic phenomena augmented by deep fluids that have a chemically aggressive effect on the carbonate components.

The waters that flow into the sinkhole are considered bicarbonate-calcic. The TDS is 657 mg/l and the waters are enriched in bicarbonate (957 mg/l), and sulfates (122 mg/l). Temperature in the submerged section was measured at 15 °C with no seasonal fluctuations or thermocline. The relatively high temperature and the mineral concentrations suggest that the waters of the Pozzo may receive some form of geothermic contribution.

Isotopic values ($\delta^{18}\text{O}$) registered in the water indicate an infiltration elevation of between 230 and 327 m, which is consistent with the Cornicolani hills being a source area.

The basal aquifer feeding the Merro and most of the springs in the Tivoli Plain is hosted in the Mesozoic limestone (Manfredini 1949). Until 2005 seasonal fluctuations of the piezometric surface level were in the order of 80 cm; in recent years, the water level has been observed to have fallen by a few m. The causes of this are unclear, but it may

be related to the general lowering of the regional water table, affecting the Regina and Colonnelle lakes in the Tivoli Plain which are fed from the Acque Albule (Fig. 4).

The Pozzo del Merro is thought to have been formed by deep fluids rising up and mixing with karstic ground water, resulting in hypogean hyperkarstic phenomena and the creation of a cavity growing increasingly large from below. This hypothesis is supported by morphological evidence from the nearby Pozzo Sventatore which contains a hypogean lake inside a karstic cavity and is thought to belong to an earlier phase than the Pozzo del Merro.

Methods

The design and placement of the plano altimetric network

The peculiarities of the site (Fig. 7) made it very difficult, till now, to perform an accurate topographical survey of the principle morphological characteristics of the Pozzo del Merro, which would have included a calculation of the elevation of the hydrometric staff gauge whose zero level should be the reference point for all previous hydrometric measurements and for a calculation of the zero level of the newly installed hydrometer. Such observations will be extremely useful to build a picture of the correlations between various aquifers in the area that have previously been studied for other reasons (Floris et al. 2014)

The design and execution of the survey were found to be extremely complex due to the presence of thick vegetation and to the steep incline inside the pit. These characteristics made it difficult to use GNSS instruments since it was not possible to obtain a signal inside the pit, and photogrammetry techniques from the air, including unmanned aerial vehicles (UAV), were practically unworkable because of the tall vegetation that inhibited visibility and presented safety issues with regard to UAV flights.

Furthermore, an unexpected UAV crash and fall in the lake inside the sinkhole could cause very serious problems, such as the difficult or even impossible drone recovery and the risk of obstruction of the well, with consequent contamination of its fragile ecosystem. For these reasons, *Città Metropolitana di Roma Capitale* (the Public Agency that is in charge of this site preservation) has never authorized UAV surveys up to now.

The trigonometrical survey of the Pozzo del Merro has, therefore, required the use and integration of different land- and satellite-based topographical methods.

The main factors that dictated the design of the network were the low visibility between external points in contact with the satellite receivers and the morphological features of the inside of the pit. In some cases, it was necessary

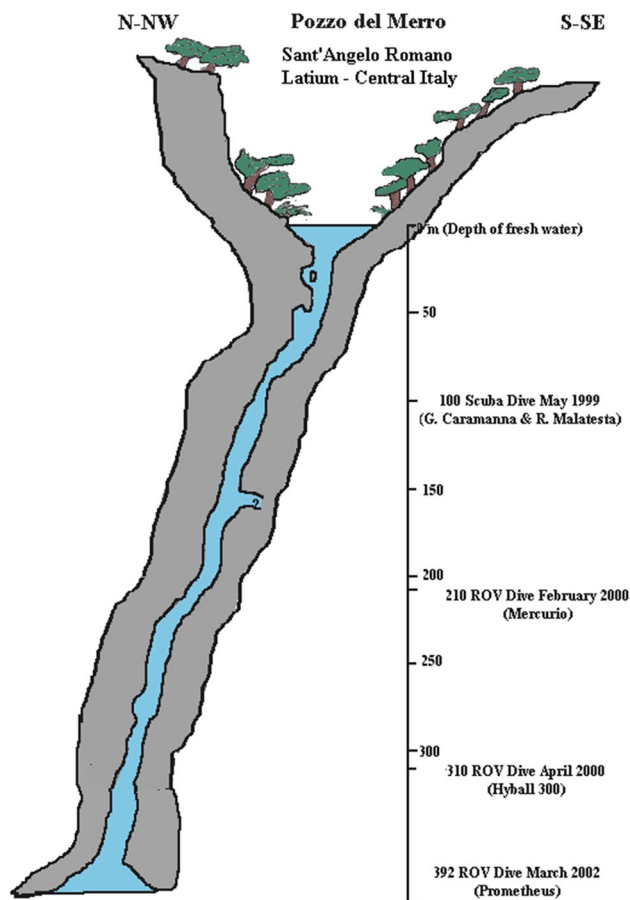


Fig. 3 Cross section of the Pozzo del Merro showing a timeline of underwater explorations. The inset shows an image of one of the lateral cavities

to create artificial platforms to support the stations and to clear the vegetation that covered the few spots from which reliable measurements could be made, these operations were made possible thanks to the staff of the ‘Città Metropolitana di Roma Capitale.’

The network (Fig. 5) included markers outside the study area which were positioned using dual-frequency GNSS receivers (Topcon Legacy E). The positions necessary for a reconstruction of the internal morphology of the pit were acquired using a total station (Leica TCR_703). All of the points thus measured were mapped out using the WGS84-ETRF2000 (EPSG: 7792) reference system because it is presently the official geodetic datum of Italy (Barbarella 2014).

An incomplete knowledge of the morphological characteristics of the site, and particularly the lack of a sufficiently precise measurement for the elevation of the hydrometric gauge reference level, made it impossible, till now, to confidently obtain a correlation between the various hydrometric measurements taken inside the pit in different time periods and using different instrumentation.

Furthermore, it was not possible, till now, to correlate such measurements with other hydrometric observations taken in the area at natural water outlets and inside artificial pits. Such observations are particularly useful in order to understand whether there are any correlations between the hydrometric levels of the pit and of known water tables in the neighborhood, like the *Acque Albule*, of which, according to some authors, the Pozzo del Merro is the primary outlet. The correlation between Merro well and *Acque Albule* will be studied from now on by the scientific community. The most complex task in what was generally a very difficult scenario was that of obtaining a measurement for the hydrometric gauge (Fig. 6). This was due to a combination of factors, including the almost vertical face of the inside of the pit and the extreme difficulty in achieving access to the zero point of the hydrometric gauge which made geometric levelling technically impossible. The hydrometric gauge was placed in correspondence with the surface level of the water at the time of installation some decades ago, but now (2017), it stands several m away from the water, on an almost vertical slope covered in vegetation.

It would, as already explained, be impossible to compute the position denominated ‘Gauge’ (the zero point of the gauge) with a GPS receiver, even if the characteristics of the entire GNSS constellation were to be used. Trigonometric levelling (by mean of a geodetic class total station) is, therefore, the only method available for the measurement of gauge absolute height. Total station measurement was also used for the survey of the ground control points coordinates for the laser survey. The LIDAR survey has made it possible, for the first time, to accurately map the morphology of the inside of the pit right down to the water level. Laser mapping also created the opportunity of being able to identify any possible cavities in the walls of the pit that had previously been hidden and unrecorded. Setting up a laser scanning survey in such a complex site requires the identification of positions that have a sufficient visibility of the site itself, and which possess characteristics that are equivalent to points employed in a trigonometric levelling network. With these considerations in mind, it was decided to begin the survey with the trigonometric levelling method; the positions identified as stations for this survey were also used as stations for the laser scanning survey.

Due to the aforementioned thick vegetation covering the entire site, the base of the pit was only visible from three positions outside of the pit, of these one is unusable, reducing the positions from which the survey could be performed to two. The first of these two, denominated ‘Station 1’ (Fig. 5), has a limited visibility of the sky and is, therefore, positionable using a GNSS receiver, but it was not possible from that position to directly collimate the ‘Gauge’ position, making it necessary to set up another station close to the

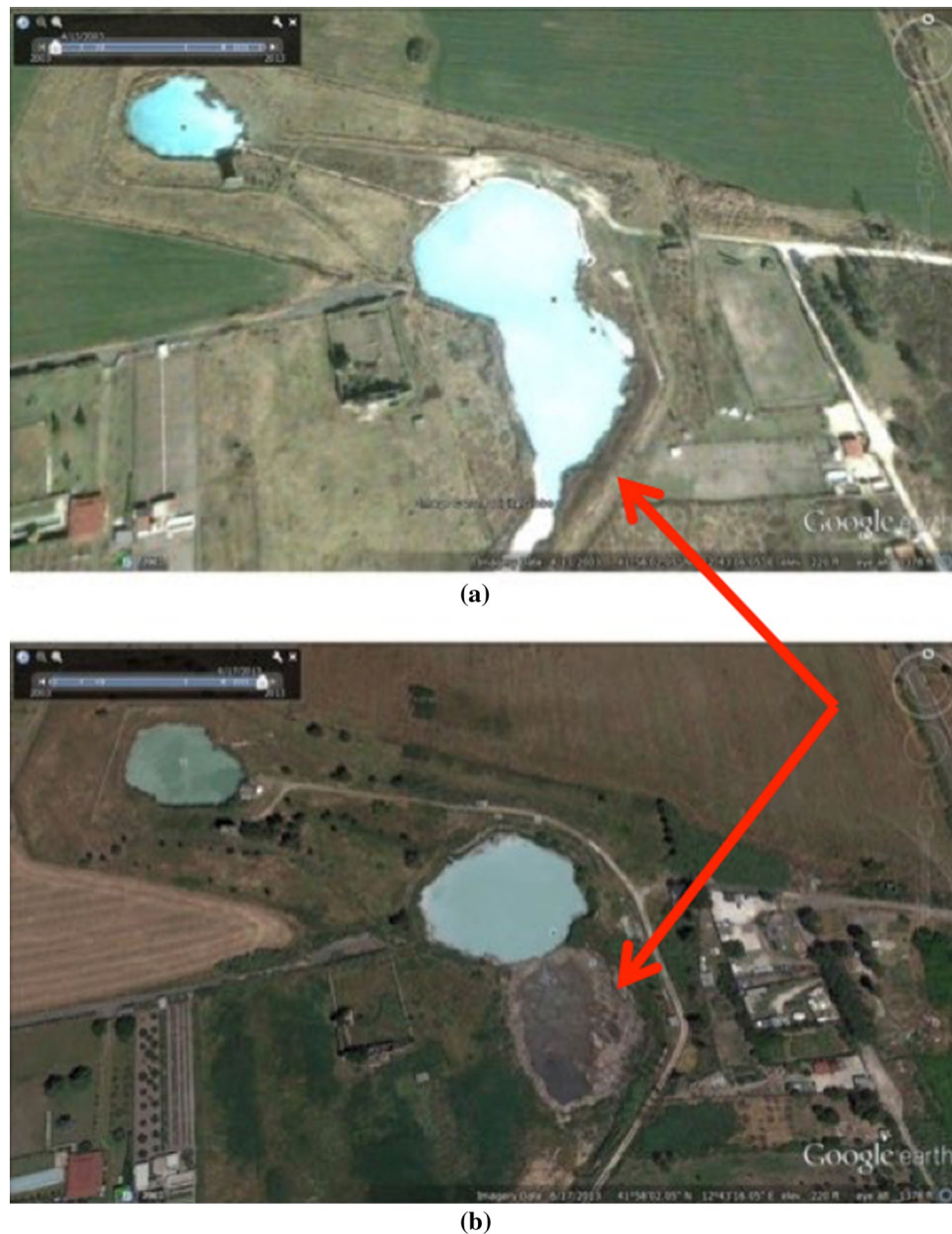


Fig. 4 Lake Colonnelle and Lake Regina in 2003 (a) and the same lakes in 2013 (b)

water's edge from which both positions are visible, which was named 'Station 3.' It was possible to directly collimate the 'Gauge' position from the other position at the summit of the pit, denominated 'Station 2,' but the excessive distance, the presence of thick vegetation, and the degraded condition of the surface of the gauge itself led to uncertain measurements from the electromagnetic distance measuring (EDM), making it necessary to apply a prism to the position to be measured (Fig. 6). These operations revealed themselves to be extremely complicated due to the difficulty in gaining access to the position. The 'Station 2' position was placed on a platform built for the purpose inside a forested area on

the edge of the pit, making it necessary to create a polygon ('Station 5' and 'Station 6') so as to place it in correspondence with an area in which it was possible to make correct measurements with GNSS receivers ('Station 6' and 'Station 7'). The thick vegetation meant that it was not possible to make reciprocal collimations between the positions 'Station 1' and 'Station 2.' The survey was, therefore, performed with the use of two independent branches of trigonometric levelling which confirmed an absolute orthometric elevation of the 'Gauge' position of 79.75 m (value referred to the national heights network), with a 6-cm margin of estimated accuracy. This margin of error can be ascribed mainly to the

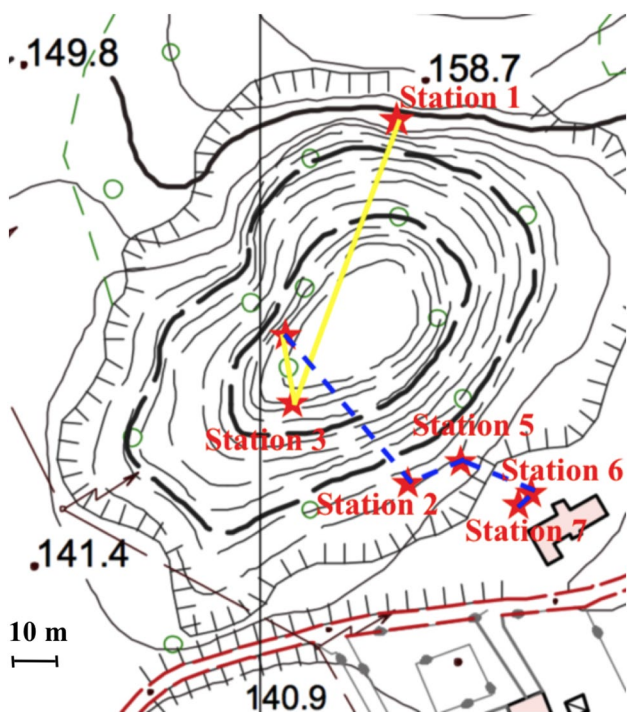
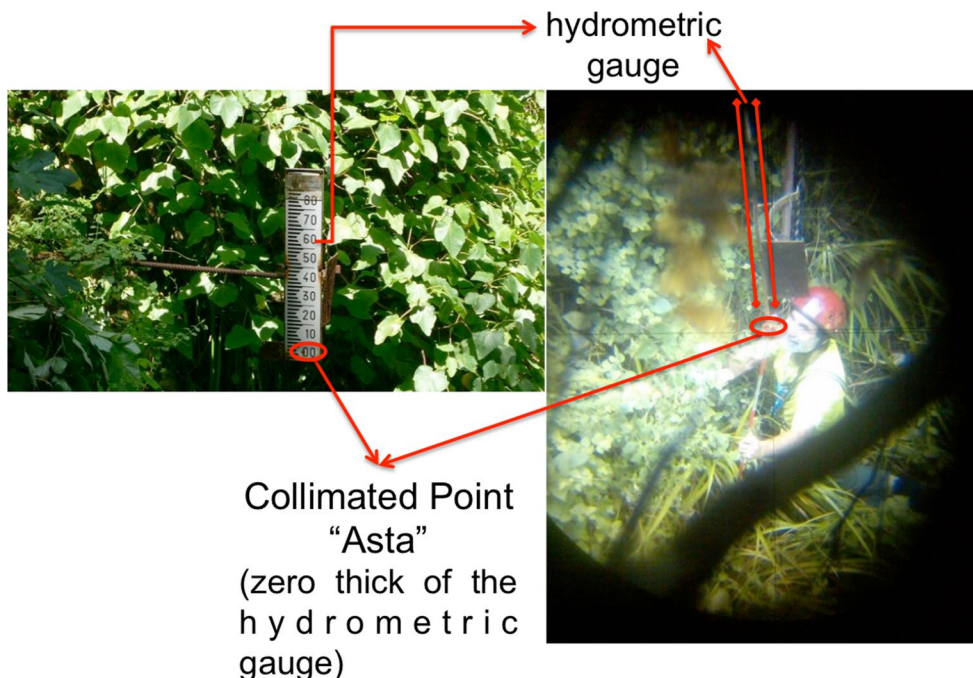


Fig. 5 The plano altimetric support network

Geoid model Italgeo05 used to convert the ellipsoid elevations of the GPS height reference points ('Station 1' and 'Station 6'). In fact the error of the total station measurement can be estimated in less than 2 cm, considering the technical characteristics of the instrument (Leica 2017), while the accuracy of 'ITALGEO05' is specified in 4 cm (IGMI 2017).

Fig. 6 The point 'Asta': the left end of the '0' thick of the old hydrometric gauge and its collimation with the total station (orthometric elevation of point 'Asta' 79.75 m)



The measurement of the orthometric elevation of the gauge agrees with the Technical Regional Map (CTR) 1:5000 scale produced by the Regione Lazio (made in 2009 from a 2003 survey flight) but it does differ by about 10 m with respect to the elevation cited in academic studies (Calamita et al. 2002; Rosa 2003). Our surveys have also confirmed the hypothesis that the zero of the automatic hydrometer installed till February 2015 is not equivalent to the zero of the 'old' hydrometric gauge. Anyway this hydrometer was not in working order so a new instrument has been installed (February 2015) and it was surveyed so the difference in elevation between the two positions was calculated and it can be used to correct all the older piezometric measurements.

Laser scanning survey

Data merging of ultra-high-resolution digital elevation model (DEM) can be used to provide geomorphological information on the geometric characteristics of the land features (Bosman et al. 2015; Giordano et al. 2015). In recent years, the laser scanner has become one of the most used technology used for massive topographic survey (Costantino and Angelini 2015; Vincia et al. 2015). The laser scanner is, in effect, a geomatic sensor capable of generating a cloud of discrete points to describe the geometry of an object or surface. Laser scanners can be grouped into three main categories according to their different modes of operation, with variations in precision, range, and acquisition methods: the triangulation laser scanner, the pulse laser scanner, and the phase laser scanner (Pirotti et al. 2013). The laser used for this survey (Table 1) belongs to the time-of-flight category

Table 1 Parameters for field data acquisition, laser scanning and imaging rover (see paragraph 5) instrument

Device	Riegl laser scanner Z210ii	Trimble imaging rover V10
Field of view V/H	80°/360°	93.1°/360°
Accuracy (declared)	0.015 m @ 50 m	0.02 m @ 20 m 0.05 m @ 50 m 0.1 m @ 100 m
Average point cloud spacing	0.02 m (x and y directions)	Depending on distance
Weight (declared)	13.0 kg	0.9 kg
Number of scans (for this test site)	8	5 (3 actually used)
Total time for the survey (on site)	4 days	5 h
Total time for elaboration	2 days	1 day

of laser scanners, with a range up to a few km, and a precision estimated in a few cm. These scanners calculate the geometry of a surface by measuring the distance between the surface and the sensor. For this survey, the instrument was used in conjunction with a digital camera, so it was also possible to associate radiometric information with each point (RGB).

Usually, when reconstructing complex geometries, numerous scans need to be made from different stations, which are then combined in a common reference system. This operation, known as registration, is carried out by placing a series of targets inside the scanning area to be visible from all stations. At sites like this, ground cover vegetation causes a series of echoes during each measurement. The handling and filtering of these echoes have been investigated by numerous authors (Raber et al. 2002; Costantino and Angelini 2011; Munaretto and Roggero 2013); attempts were made to take advantage of this characteristic to estimate the thickness of the vegetation, as described below. The model extracted from the point cloud will serve as a basis for geological/geotechnical investigations and constitute a complete documentation of the site making it possible to perform a series of subsequent analyses (cross sections, slope map, and depth measurements).

Results

Eight scans were made from two different positions during the survey, with variations in resolution and in the vertical inclination of the sensor. Scans were made on two different days from the positions indicated in Fig. 5 as ‘Station 1’ and ‘Station 3,’ which were chosen in order to allow a complete reconstruction of the site and of its morphology.

The first survey, based on WGS84-ETRF2000 (EPSG:7792) geodetic datum and reusing the previously surveyed points (Fig. 5), served as a frame of reference, while the second scan was subsequently registered with

the first by calculating a roto-translation matrix against a portion of the survey common to both measurements. This procedure was made necessary by the impossibility of using automatic registration systems, since it was not possible to position targets that were visible from both measuring positions due to the thick vegetation and the inaccessible nature of the area.

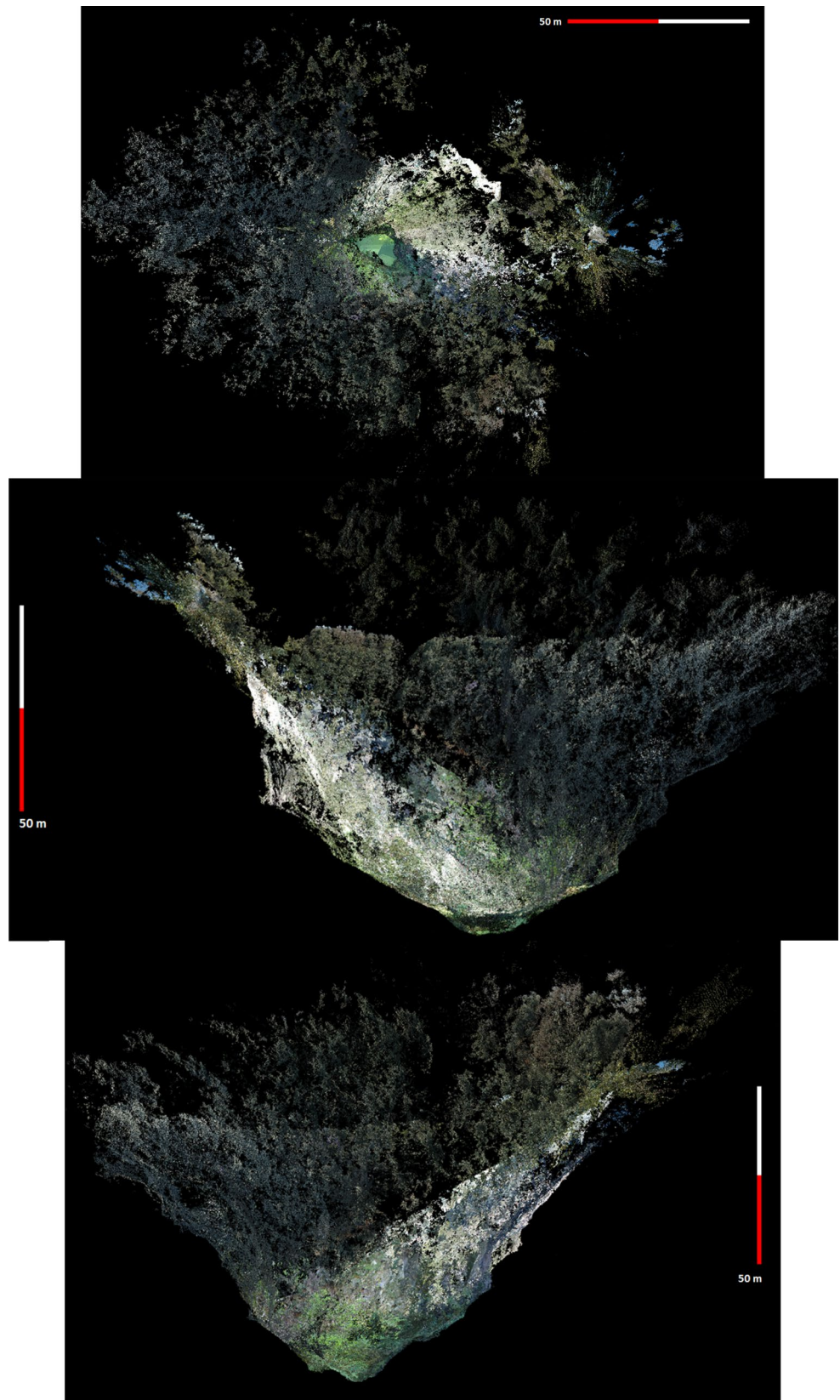
The resulting point cloud was then filtered in order to separate the surface points from those of the vegetation, enabling a sufficiently accurate reconstruction of the morphology of the pit. This advanced application was achieved through a differentiation of successive scans, using alternate pulse settings of the ‘first’ and ‘last.’ Apart from the information regarding the number of echoes, the additional access to RGB information associated with the cloud was of fundamental importance (Fig. 7). The data obtained from a subsequent editing phase have and will be used to build a number of three-dimensional models of the Pozzo del Merro at different scales according to their intended use. These data will also facilitate the creation of morphological profiles. Two of these profiles are illustrated here (Fig. 8), one with a north–south orientation, the other oriented east–west.

The features of the Pozzo del Merro (Table 2) are here compared with the depth and the volume of the main sinkholes in the world (Table 3). The other sinkholes are the biggest and deepest if both submerged and dry part are considered, but the flooded part of the ‘*Pozzo del Merro*’ is currently the second deepest measured in the world.

The imaging rover panoramic acquisition and its results

Together with the ‘classic’ laser scanning acquisition, a totally new instrument has been tested in this peculiar and specific site to verify and compare capabilities of the new methodology and assess the potentiality for the survey in these unusual morphologies. The instrument tested is a ‘Trimble V10 Imaging Rover’ (IR) (Fig. 9) that

Fig. 7 The Pozzo del Merro represented as a point cloud, the depth of the cavity is approximately 80 m



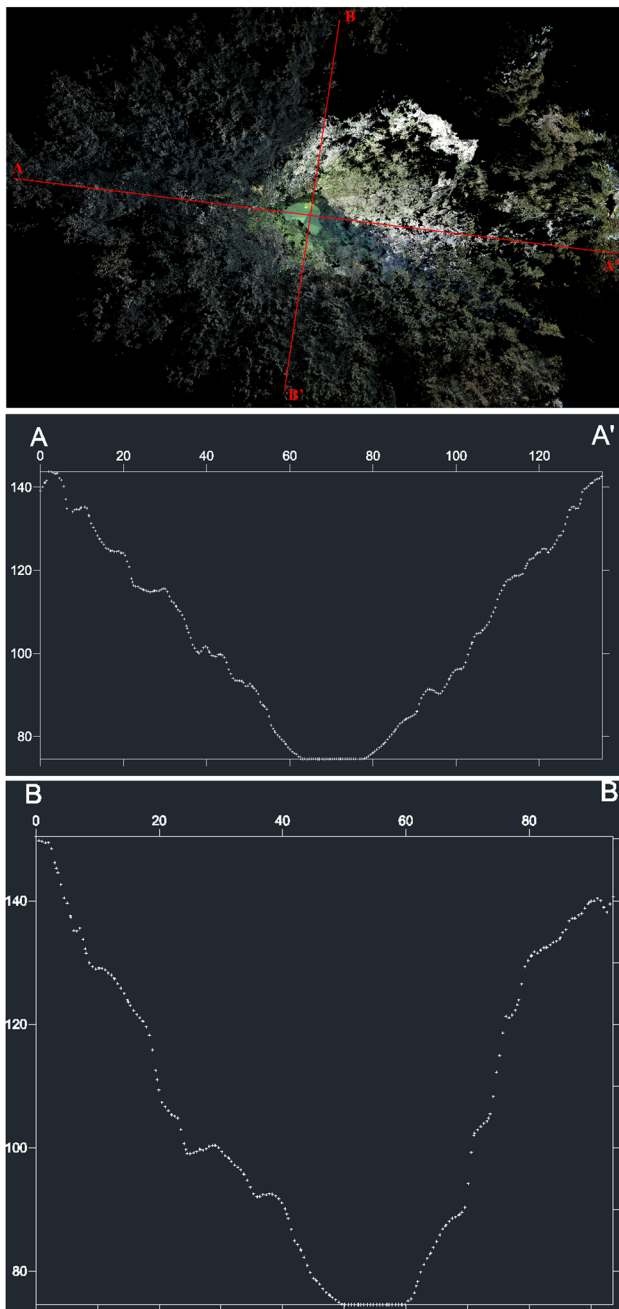


Fig. 8 Northeast–southwest and northwest–southeast profiles of the site obtained from the filtered point cloud (AA' profile length = 158.55 m, BB' profile = 115.50, heights are in the same scale of planimetric coordinates: m)

consists of an integrated camera system that captures a 60 MP 360-degree digital panoramas; each acquisition is performed with a total of 12 calibrated photogrammetric cameras—seven panorama and five downward-looking (Fig. 10). The new methodology is based on a classical photogrammetric approach that has been widely tested for environmental and historical sites (Balletti et al. 2015;

Dominici et al. 2013) and to reconstruct models between submerged and emerged morphologies (Menna et al. 2015). This new instrument was scientifically tested, till now only for a few experimentations on historic heritage sites (Park et al. 2015; Baiocchi 2017a, b; Cera and Campi 2017), but never on natural heritage sites like in this research. The IR provides photogrammetric site documentation that can be used to make true photogrammetric restitution. The instrument can be integrated with a GPS/GNSS double-frequency real-time receiver: while the photogrammetric acquisition is being performed, the center of the instrument is positioned using the GPS [Horizontal 8 mm + 1 ppm, Vertical 15 mm + 1 ppm; ppm is calculated considering the distance to the nearest GPS permanent station- Trimble (2017)]. With this configuration, after a single photogrammetric acquisition, the position of the instrument is given, but not its azimuth. The provider of the instrument suggests at least three acquisitions (but also more, if it is possible) of the area of interest, the acquisitions must be mutually visible to perform a correct mutual orientation with redundant observations. After the stations orientation, an automatic photogrammetric algorithm can extract the cloud of points with their three-dimensional coordinates.

The possibility to have each station already georeferenced is a strength point of this methodology, because no topographic network is needed if the GPS/GNSS visibility is given. On the other hand, the instrument reconstructs the morphology only using photogrammetric algorithm and, as a consequence, the penetration of foliage is not possible. Considering these features and the differences with respect to a laser scanner technique, a totally independent survey with the IR was performed in order to check its possibilities in an actual survey of a sinkhole. The survey was completed during a day without previous planning, the weight of the instrumentation is noticeably lighter consequently its stationing is easier. Due to the specific morphology of the sinkhole, only five points fitted the visibility/safety requirements (Fig. 10) and from each of these points a panoramic acquisition with GPS/GNSS positioning was performed (Fig. 11a).

All the images acquired from the different five stations are jointed and elaborated with the specific software (Fig. 11b), *Trimble Business Center v. 3.7*. To link each panorama to the others, so to estimate the orientation of the instrument at every single station, some tie points (TP) can be found automatically by the software but we observed that if some additional TPs (MTP in Fig. 11b) are collimated manually the correlation and so the estimation of orientation improve. Starting the adjustment of the whole block of photogrammetric data, we found that two of the five stations failed in achieving sufficient correlation with other three stations so their data couldn't be used for the cloud point extraction. The photogrammetric automatic algorithm has extracted

Table 2 Main morphological characteristics of the site from this survey (emerged part)

Volume (the emerged part):	335,341 m ³
Depth	74.85 m
Length (W–NW/S–SE direction)	158.55 m
Width (N–NE/S–SW direction)	115.50 m

almost completely the parts of sinkhole without foliage cover that represents a very small area with respect to the whole sinkhole. Even if the point cloud cover a small area of the whole sinkhole, a comparison with the laser scanner survey was performed on the common extracted part; the fitting of the two point cloud (Laser cloud and V10 cloud) was compared using a specific open source package (Cloudcompare 2017), reporting absolute differences mostly lower than 0.05–0.06 m, totally compatible with the declared accuracy of both instrumentations (Table 1, Fig. 12).

Discussions

The unusual morphology of the Pozzo del Merro required attentive planning and exploration of the surrounding areas for the ‘classic’ survey. The purpose of this type of survey is the calculation of the orthometric elevation of the hydrometric gauge that is the reference point for all hydrometric readings measured over the recent decades. A difference of about 10 m was discovered between the current height measurement and those which appear in previous studies. It is important to highlight that all previous hydrometric measurements are now being corrected and properly correlated with the measured values in the near piezometer.

The zero of the existing hydrometric gauge, now with a rigorous height value referred to the national vertical datum, can

**Fig. 9** The imaging rover combined with GPS/GNSS receiver (on top)

be used as a common and unambiguous reference for all future measures automatically made by the new instrument installed (in February 2015) or by other temporary instruments.

It will, therefore, be possible to refer all the historic measurements surveyed so far to their absolute elevation, and correlate them with high precision to other hydrometric surveys in the area.

Table 3 Main morphologic characteristics of some of the deepest sinkhole of the world (wondermondo 2017)

Sinkhole	Location	Depth ^a	Volume
Andros Black Hole	Bahamas, South Andros	47 m	–
Crveno Jezero—Red Lake	Croatia, Split-Dalmatia	530 m	30 million m ³
Dean’s Blue Hole	Bahamas, Long Island	202–203 m	1.1 million m ³ ?
El Zacatón sinkhole	Mexico, Tamaulipas	339 m	10 million m ³
Great Blue Hole	Belize, Belize District	124 m	–
Hranice abyss (Hranicka propast)	Czech Republic, Olomouc Region	known: 473.5 m waterbody: 404 m	–
Minyé sinkhole and cave	Papua New Guinea, East New Britain	510 m	26 million m ³
Sima Humboldt	Venezuela, Bolívar state	314 and 248 m	21 million m ³
Sótano de las Golondrinas—Cave of the Swallows	Mexico, San Luis Potosí	372 m	5 million m ³
Teiq sinkhole	Oman, Dhofar Governorate	250 m	90 million m ³
Xiaozhai tiankeng	China, Chongqing Municipality	662 m	119,349 million m ³

^aDepth: on the ‘wondermondo’ Web site is not specified if the depth includes submerged and dry part for all the reported sinkholes but, as an example, for Zacaton, the depth reported is the total



Fig. 10 Schematic reconstruction of the twelve simultaneous acquisitions of a *panorama*

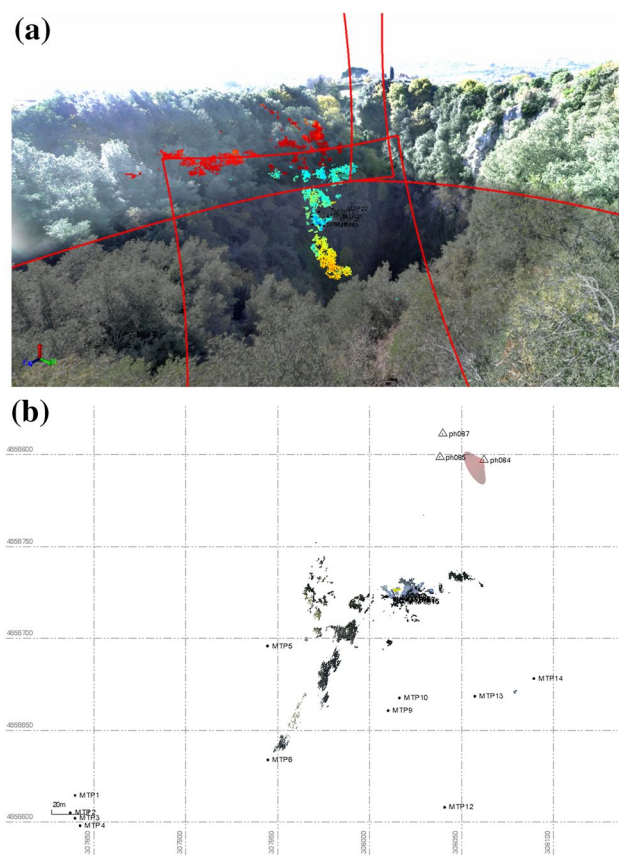


Fig. 11 Part of a ‘panorama’: in red the border between an image and the other (a), the same results of the matching between the three panoramic acquisitions (b)

Both the independent three-dimensional reconstructions (laser scanning and photogrammetric) of the morphology of the pit did not identify secondary emerged cavities or tunnels that had been hypothesized on the basis of those found above water. Nonetheless, due to the specific morphology of the site, the presence of other undiscovered morphological characteristics cannot be

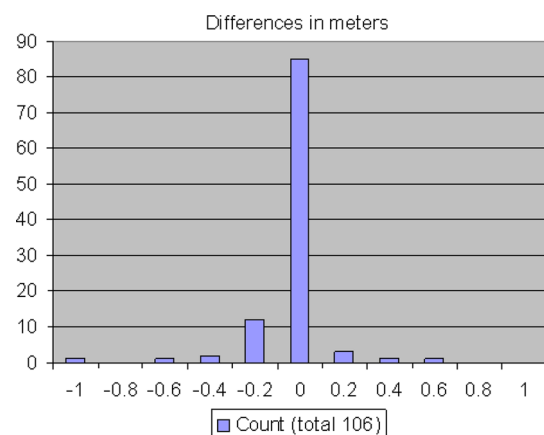


Fig. 12 Differences along normal direction in m between lidar survey and photogrammetric survey in a bare area

ruled out. The laser survey has also made it possible to evaluate the location and consistence of the vegetation cover, and to carry out the first complete reconstruction of the site with the use of precise geometric data. The comparison with the innovative IR instrumentation showed that the accuracy of the two methodologies is similar, the imaging rover has a wider vertical field of view, it is logistically much more versatile, and it can be of strategic importance in such sites with complex morphologies. On the other hand, IR has no capabilities of penetrating foliage that is a drawback, particularly in some periods of the year.

Conclusions and future developments

The surveyed data cannot be reported here in their completeness due to representation limits caused by page size, but detailed images and geometric characteristics surveyed

are available in full resolution on the web or by direct request to the authors.

The local administration plan to use the surveys in their three-dimensional full resolution allows a virtual visit to researchers all over the world overcoming the safety and environmental preservation problems.

This improved geometric understanding of the pit's morphology will also make it possible to plan a future photogrammetric survey using a drone, a plan which till now was difficult to put into action due to the geomorphic conditions of the site.

The eventuality of the presence of secondary emerged cavities can be further explored by future surveys taking new measurements from fixed station ('Station 1', 'Station 2', and 'Station 3'), permanently realized on the ground during the first survey. The future surveys should ideally be done during the winter season, when vegetation is at a minimum.

Acknowledgements The authors would like to thank Computer Graphic Technologies company (CGT s.r.l.) for the kind availability of 'Trimble V10' Imaging rover. The project has been partially funded by MIUR-PRIN project: 'Tecniche geomatiche innovative ed emergenti di rilievo, telerilevamento (da aereo, satellite, UAV) e Webgis per la mappatura del rischio in tempo reale e la prevenzione del danno ambientale,' number 20107XJHCC_004.

References

- Argentieri A, Carluccio R, Cecchini F, Chiappini M, Ciotoli G, De Ritis R, Di Filippo M, Di Nezza M, Marchetti M, Margottini S, Materni V, Meloni F, Nardi A, Rotella G, Sapia V, Venuti A (2015) Early stage sinkhole formation in the acque albule basin of central Italy from geophysical and geochemical observations. *Eng Geol* 191:36–47. <https://doi.org/10.1016/j.enggeo.2015.03.010>
- Baiocchi V, Bozzano F, Floris M, Prestininzi A (2008) Strappavercia C (2008) An evaluation of anthropic pressure increase in a subsidence area near Rome (Italy). *Rend Online Soc Geol Italiana* 3(1):48–49
- Baiocchi V, Barbarella M, Del Pizzo S, Giannone F, Troisi S, Piccaro C, Marcantonio D (2017a) Augusto's sundial: image-based modeling for reverse engineering purposes. *Int Arch Photogramm Remote Sens Spatial Inf Sci*. <https://doi.org/10.5194/isprs-archives-XLII-2-W3-63-2017>
- Baiocchi V, Giammarresi V, Ialongo R, Piccaro C, Allegra M, Dominici D (2017b) The survey of the Basilica di Collemaggio in L'Aquila with a system of terrestrial imaging and most proven techniques. *Eur J Remote Sens* 50(1):237–253. <https://doi.org/10.1080/22797254.2017.1316523>
- Balletti C, Guerra F, Scocca V, Gottardi C (2015) 3D integrated methodologies for the documentation and the virtual reconstruction of an archaeological site. *Int Arch Photogramm Remote Sens Spat Inf Sci—ISPRS Arch*. <https://doi.org/10.5194/isprs-archives-XL-5-W4-215-2015>
- Barbarella M (2014) Digital technology and geodetic infrastructures in Italian cartography. *Citta e Storia*, N°1/2014 gennaio-giugno Anno IX
- Billi A, Valle A, Brilli M, Faccenna C, Funicciello R (2007) Fracture-controlled fluid circulation and dissolutional weathering in sinkhole-prone carbonate rocks from central Italy. *J Struct Geol* 29:e385–e395. <https://doi.org/10.1016/j.jsg.2006.09.008>
- Billi A, De Filippis L, Poncia PP, Sella P, Faccenna C (2016) Hidden sinkholes and karst cavities in the travertine plateau of a highly-populated geothermal seismic territory (Tivoli, central Italy). *Geomorphology* 255:63–80. <https://doi.org/10.1016/j.geomorph.2015.12.011>
- Boni C, Bono P, Capelli G (1986) Schema idrogeologico dell'Italia Centrale. *Mem Soc Geol Italiana* 35:991–1012
- Bono P (2001) Is the "Merro Well" the deepest karst cenote explored in the world? *Environ Geol* 40(6):787–788
- Bosman A, Casalbore D, Anzidei M, Muccini F, Carmisciano C, Chiocci F (2015) The first ultra-high resolution marine digital terrain model of the shallow-water sector around Lipari Island (Aeolian archipelago, Italy). *Ann Geophys* 58:2–2015. <https://doi.org/10.4401/ag-6746>
- Brunetti E, Jones JP, Petitta M, Rudolph DL (2013) Assessing the impact of large-scale dewatering on fault-controlled aquifer systems: a case study in the Acque Albule basin (Tivoli, central Italy). *Hydrogeol J* 21:401–423. <https://doi.org/10.1007/s10040-012-0918-3>
- Buccomino G, Capecchi P, Vecchio M, Vinci M, Cazzella R (2009) Monitoraggio Idrogeologico ed Ambientale del Pozzo del Merro (Roma). *Atti 2° Workshop Internazionale. I Sinkholes. Gli sprofondamenti catastrofici nell'ambiente naturale ed in quello antropizzato*. ISPRA, 903–911. ISBN 978-88-448-0400-8
- Calamita U, Caramanna G, Giardini M (2002) Il Pozzo del Merro: un gioiello naturale tra Tevere e Aniene. *Tor San Lorenzo Informa XL*, Settembre 2002:11
- Capelli G, Cosentino D, Messina P, Raffi R, Ventura G (1987) Modalità di ricarica ed assetto strutturale dell'acquifero delle sorgenti Capore-S. Angelo (Monti Lucretili-Sabina meridionale). *Geol Romana* 26:419–447
- Caramanna G, Gary M (2004) Applicazioni di metodologie di immersione scientifica e ROV (Remote Operated Vehicle) nello studio comparato dei due sinkholes allagati più profondi del pianeta: Pozzo del Merro (Lazio, Italia Centrale), El Zacaton (Tamaulipas, Messico). *Atti Primo Seminario Stato dell'arte sullo studio dei fenomeni di sinkholes e ruolo delle amministrazioni statali e locali nel governo del territorio APAT*, pp 211–227
- Caramanna G, Ciotoli G, Nisio S (2008) A review of natural sinkhole phenomena in Italian plain areas. *Nat Hazards* 45(2):145–172. <https://doi.org/10.1007/s11069-007-9165-7>
- Carucci V, Petitta M, Aravena R (2012) Interaction between shallow and deep aquifers in the Tivoli Plain (Central Italy) enhanced by groundwater extraction: a multi-isotope approach and geochemical modelling. *Appl Geochem* 27:266–280. <https://doi.org/10.1016/j.apgeochem.2011.11.007>
- Cera V, Campi M (2017) Evaluating the potential of imaging rover for automatic point cloud generation. *Int Arch Photogramm Remote Sens Spatial Inf Sci*. <https://doi.org/10.5194/isprs-archives-XLII-2-W3-147-2017>
- Ciotoli G, Di Loreto E, Finoia MG, Liperi L, Meloni F, Nisio S, Sericola A (2015) Sinkhole susceptibility, Lazio Region, central Italy. *J Maps*. <https://doi.org/10.1080/17445647.2015.1014939>
- Costantino D, Angelini MG (2015) Three-Dimensional Integrated Survey for Building Investigations. *J Forensic Sci* 60(6):1625–1632. <https://doi.org/10.1111/1556-4029.12915>
- Costantino D, Angelini MG (2011) Features and ground automatic extraction from airborne LIDAR data. *Int Arch Photogramm Remote Sens Spat Inf Sci—ISPRS Archives*, 38: 19–24. <http://www.isprs.org/proceedings/XXXVIII/4-W15/>
- Crema C (1915) Improvvisa formazione di una dolina presso Montecelesio. *Boll Soc Geol Italiana* 34:273–276

- De Filippis L, Anzalone E, Billi A, Faccenna C, Poncia PP, Sella P (2013a) The origin and growth of a recently-active fissure ridge travertine over a seismic fault, Tivoli, Italy. *Geomorphology* 195:13–26. <https://doi.org/10.1016/j.geomorph.2013.04.019>
- De Filippis L, Faccenna C, Billi A, Anzalone E, Brillì M, Soligo M, Tuccimei P (2013b) Plateau versus fissure ridge travertines from Quaternary geothermal springs of Italy and Turkey: interactions and feedbacks among fluid discharge, paleoclimate, and tectonics. *Earth Sci Rev* 123:35–52. <https://doi.org/10.1016/j.earscirev.2013.04.004>
- Di Salvo C, Mazza R, Capelli G (2013) Gli acquiferi in travertino del Lazio: schemi idrogeologici e caratteristiche chimico-fisiche. *Rend Online Della Soc Geol Italiana* 27:54–76. <https://doi.org/10.3301/ROL.2013.20>
- Dominici D, Rosciano E, Alicandro M, et al. (2013) Cultural heritage documentation using geomatic techniques: Case study: San Basilio's monastery, L'Aquila. In: *Proceedings of the digital heritage 2013—federating the 19th Int'l VSM, 10th Eurographics GCH, and 2nd UNESCO Memory of the World conferences, plus special sessions from CAA, Arqueologica 2.0 et al.* vol 1. pp 211–214. <https://doi.org/10.1109/digitalHeritage.2013.6743735>
- Faccenna C, Soligo M, Billi A, De Filippis L, Funicello R, Rossetti C, Tuccimei P (2008) Late Pleistocene depositional cycles of the Lapis Tiburtinus travertine (Tivoli, Central Italy): possible influence of climate and fault activity. *Global Planet Change* 63:299–308. <https://doi.org/10.1016/j.gloplacha.2008.06.006>
- Floris M, Bozzano F, Strappaveccia C, Baiocchi V, Prestinzi A (2014) Qualitative and quantitative evaluation of the influence of anthropic pressure on subsidence in a sedimentary basin near Rome. *Environ Earth Sci* 72(11):4223–4236. <https://doi.org/10.1007/s12665-014-3317-3>
- Frepoli A, Marra F, Maggi C, Marchetti A, Nardi A, Pagliuca NM, Pirro M (2010) Seismicity, seismogenic structures, and crustal stress fields in the greater Rome area (central Italy). *J Geophys Res* 115:B12303. <https://doi.org/10.1029/2009JB006322>
- Garasic PM (2000) Spelohydrogeological research of Crveno jezero (Red Lake) near Imotski in Dinaric karst area (Croatia). In: Vlahovic I, Biondic R (eds) *Proceedings of the second croatian geological congress, Dubrovnik, Croatia*. Institut za Geološka Istrazivanja, Zagreb
- Gasparini C, Di Maro R, Pagliuca NM, Pirro M, Marchetti A (2002) Recent seismicity of the “Acque Albule” travertine basin. *Ann Geophys* 45:537–550
- Giardini M (2004) *Salvinia molesta* D.S. Mitchell (Salviniaceae): seconda segnalazione per l'Italia (Lazio) e considerazioni sul controllo di questa specie infestante. *Webbia J Plant. Taxon.* <https://doi.org/10.1080/00837792.2004.10670778>
- Giordano F, Mattei G, Parente C, Peluso F, Santamaria R (2015) Integrating sensors into a marine drone for bathymetric 3D surveys in shallow waters. *Sensors (Switzerland)*. <https://doi.org/10.3390/s16010041>
- Iannilli V, Taglianti AV (2005) New data on the genus *Niphargus* (Amphipoda, Niphargidae) in Italy, with the description of a new species of the orcinus group. *Crustaceana* 77(10):1253–1261. <http://doi.org/10.1163/1568540043166029>
- IGMI www.igmi.org/it/descrizione-prodotti/elementi-geodetici-1/prodotto-e-servizi-per-il-passaggio-tra-sistemi-geodetici-di-riferimento, last visited July 14 2017
- La Vigna F, Carucci V, Mariani I, Minelli L, Pascale F, Mattei M, Mazza R, Tallini M (2012) Intermediate-field hydrogeological response induced by L'Aquila earthquake: the Acque Albule hydrothermal system (Central Italy). *Italian J Geosci* 131:475–485. <https://doi.org/10.3301/IJG.2012.05>
- La Vigna F, Mazza R, Capelli G (2013a) Detecting the flow relationships between deep and shallow aquifers in an exploited groundwater system, using long-term monitoring data and quantitative hydrogeology: the Acque Albule basin case (Rome, Italy). *Hydrol Process* 27:3159–3173. <https://doi.org/10.1002/hyp.9494>
- La Vigna F, Mazza R, Capelli G (2013b) Le risorse idriche nei travertini della piana di Tivoli-Guidonia. La modellazione numerica come strumento di gestione degli acquiferi. *Rend Online Della Soc Geol Italiana* 27:77–85. <https://doi.org/10.3301/ROL.2013.21>
- Leica <http://hds.leica-geosystems.com/en/15434.htm>, last visited July 14 2017 www.cloudcomapre.org, last visited July 14 2017
- Manfredini M (1949) Alcuni dati sulla falda idrica che alimenta le sorgenti delle Acque Albule” *Boll. Srv Geol D'Italia* 71:107–113
- Mattei M, Montone P, Salvini F (1986) Analisi strutturale dei rilievi del margine appenninico intorno a Tivoli (Roma). *Memorie Soc Geol Italiana* 35:579–589
- Maxia C (1950) Il Bacino delle Acque Albule (Lazio). *Contributi di Scienze Geologiche, Supplemento Ricerca Scientifica* no. 27. Università di Roma La Sapienza, Rome
- Menna F, Nocerino E, Troisi S, Remondino F (2015) Joint alignment of underwater and above-the-water photogrammetric 3D models by independent models adjustment. *Int Arch Photogramm Remote Sens Spat Inf Sci* 40(5):143. <https://doi.org/10.5194/isprsarchive-s-xl-5-w5-143-2015>
- Munaretto D, Roggero M (2013) Solid image extraction from lidar point clouds. *Int Arch Photogramm Remote Sens Spat Inf Sci—ISPRS Arch.* <https://doi.org/10.5194/isprsarchives-XL-5-W1-189-2013>
- Park JK, Lee JS, Yun HC (2015) Efficient construction of 3D modeling data using panoramic scene. *Adv Sci Technol Lett* 89:156–159. <https://doi.org/10.14257/astl.2015.89.32>
- Pirotti F, Guarnieri A, Vettore A (2013) State of the art of ground and aerial laser scanning technologies for high-resolution topography of the earth surface. *Eur J Remote Sens* 46:66–78. <https://doi.org/10.5721/EuJRS20134605>
- Raber GT, Hodgson ME, Jensen JR, Tullis JA, Tullis Thompson G, Davis B, Schuckman K (2002) Comparison of LIDAR data collected leaf-on vs. leaf-off for the creation of digital elevation models. In: *Proceedings of the ASPRS 2002 annual convention, Bethesda, Maryland: ASPRS*. 19–26 April 2002, Washington, DC, CD-ROM
- Romano A, Salvidio S, Palozzi R, Sbordoni V (2012) Diet of the newt, *triturus carnifex* (laurenti, 1768), in the flooded karst sinkhole pozzo del merro, central Italy. *J Cave Karst Stud* 74(3):271–277. <https://doi.org/10.4311/2011JCKS0208>
- Rosa C (2003) Il Pozzo del Merro. *Rivista ufficiale dei Vigili del Fuoco* 3:11–15
- Salvati R, Sasowsky ID (2002) Development of collapse sinkholes in areas of groundwater discharge. *J Hydrol* 265:1–11. [https://doi.org/10.1016/S0022-1694\(02\)00062-8](https://doi.org/10.1016/S0022-1694(02)00062-8)
- Vincia AA, Brigante R, Todisco F, Mannocchi F, Radicioni F (2015) Measuring rill erosion by laser scanning. *CATENA* 124(2015):97–108. <https://doi.org/10.1016/j.catena.2014.09.003>
- www.trimble.com, last visited July 14 2017
- www.theguardian.com/world/2016/sep/30/worlds-deepest-underwater-cave-found-czech-republic-hranice-abyss, last visited July 14 2017
- www.wondermondo.com/Best/World/Sinkholes.htm, last visited July 14 2017