Uncertainties in understanding groundwater flow and spring functioning in karst

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Abstract

In karst environments, typically characterized by peculiar hydrogeological features and high heterogeneity and anisotropy, the connection between the recharge areas and the springs is often not straightforward. Rapid infiltration underground, and the resulting network of karst conduits, are frequently at the origin of a lack of correspondence among topographic divides and underground watersheds. As a consequence, in many karst areas there is still much work to do to fully understand the groundwater flow, with the only "underground truth" often being provided by cave data. In this contribution we start from general considerations about the difficulty in comprehending hydrogeology in karst, and use them to analyze one of the most important karst areas of southern Italy, the Alburni Massif in Campania (Italy). In detail, we present data about the main karst features at the surface (dolines, endorheic basins, etc.), the most important cave systems (reaching maximum depth of about 450 m below the surface), and the main basal springs coming out at the massif borders. Integration of the different sources of data allows to hypothesize the main directions of groundwater flows, and to perform the first attempts in correlating recharge and discharge data, but such hypothesis then often prove to be wrong by data from cave and diving explorations.

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Abstract

In karst environments, typically characterized by peculiar hydrogeological features and high heterogeneity and anisotropy, the connection between the recharge areas and the springs is often not straightforward. Rapid infiltration underground, and the resulting network of karst conduits, are frequently at the origin of a lack of correspondence among topographic divides and underground watersheds. As a consequence, in many karst areas there is still much work to do to fully understand the groundwater flow, with the only "underground truth" often being provided by cave data. In this contribution we start from general considerations about the difficulty in comprehending hydrogeology in karst, and use them to analyze one of the most important karst areas of southern Italy, the Alburni Massif in Campania (Italy). In detail, we present data about the main karst features at the surface (dolines, endorheic basins, etc.), the most important cave systems (reaching maximum depth of about 450 m below the surface), and the main basal springs coming out at the massif borders. Integration of the different sources of data allows to

hypothesize the main directions of groundwater flows, and to perform the first attempts in correlating recharge and discharge data, but such hypothesis then often prove to be wrong by data from cave and diving explorations.

Key words: karst, springs, dolines, hydrogeology, Alburni

Introduction: peculiarities of karst hydrogeology

Karst is an extremely peculiar setting, with unique landscapes characterized by a variety of landforms (such as dolines, swallets, shafts, karrenfields, poljes, etc.), which act as sites of concentrated recharge for the aquifers and, together with the main geological and hydrogeological features of soluble materials, are at the origin of the turbulent flow of water within the karst rock masses (Worthington et al. 2001; Brinkmann and Parise 2012). Such peculiarities cause the need to approach hydrogeological studies in karst with dedicated methods and techniques, since implementation of the classical hydrogeological laws and procedures is not significant (Goldscheider and Drew 2007; Jourde et al. 2007). Starting from the non-correspondence among hydrographic boundaries at the surface and hydrogeological boundaries underground (Gunn, 2007; Parise, 2016), the whole issue of infiltration, transfer, and discharge of water in karst is extremely complex (Stevanovic, 2015, and references therein). In such a context, mapping some of the most typical karst landforms such as dolines/sinkholes, endorheic basins and poljes (Angel et al. 2004; Dorsaz et al. 2013; Miao et al. 2013; Fragoso-Servòn et al. 2014; Wu et al. 2016; Pagnozzi et al. 2019; Zumpano et al. 2019), understanding their mechanisms of formation (Waltham et al. 2005; Del Prete et al. 2010; Gutierrez et al. 2014; Parise 2019), and their hydraulic role as well (Bonacci 1995, 2001; Fiorillo et al. 2015; Parise et al. 2015), is of crucial importance to gain insights into the actual hydrogeological regime in karst areas.

In this contribution, through illustration of the Alburni case study (S Italy), one of the most significant karst areas in the country, we intend to point out to the difficulties inherent in understanding karst hydrogeology, the crucial importance to co-operate with direct explorations by cavers, and the need to approach the issue with specifically designated approaches. At this aim, we analyze the karst depressions at the summit plateau, estimate the related recharge, and compare it to the total amount coming from the main springs surrounding the massif. Then, through information derived from cave surveys, including diving explorations through some of the sumps within the cave systems, we point out to the still open problems regarding hydrogeology in the Alburni Massif.

Materials and methods

Mapping of dolines and endorheic areas on the Alburni Massif plateau was carried out through an integrated methodology, consisting of bounding their limits on 1:5000 scale topographic maps, supported by field survey, and uploading in GIS environment the geomorphological data together with those regarding strata attitude and presence of tectonic faults, as mapped from the official geological maps (Cestari 1971; Scandone 1971; De Riso and Santo, 1997).

The regional inventory of karst caves in Campania (managed by the Campanian Speleological Federation, available at http://www.fscampania.it/catasto-2/catasto/) was the starting point for the analysis of the main characters of the caves in the area: namely, through scrutiny of the individual cave surveys, in the forms of plan map and profiles, the presence of water within each inventoried cave was checked. Typically, this corresponds to stop in exploration of the cave, unless those few cases where it is possible to keep continuing through diving explorations. When the condition above (presence of water) was satisfied, its altitude within the cave system (corresponding to the maximum depth of the cave) was extracted as water level reference at the site. Collecting all these data, a preliminary attempt in reconstructing the Alburni water table was carried out. In addition, the outcomes of several tracing experiments, particularly cave-to-spring multitracer tests, carried out during the last 10 years in the area, were considered to prove some connections among caves and springs.

Data about the main springs in the area derive from detailed analysis of the existing scientific literature, but without any doubt they represent still a pitfall in the overall analysis, due to lack of continuity in recording the spring discharges. Rainfall and temperature data were taken from the official reports by the Italian Hydrography Service during the last decades.

Eventually, the groundwater recharge at the long-term scale was estimated by applying the annual model proposed by Fiorillo et al. (2015), which can be implemented especially for wide areas with strong morphological irregularities, not entirely covered by hydrological monitoring. Based on long-term mean annual data, the total amount of meteoric precipitation, runoff, and recharge are computed in GIS environment in the model, estimating the recharge and the runoff coefficient for both open and endorheic areas. The annual model provides a mean long-term estimation of the recharge.

Based on a 20 x 20 m Digital Elevation Model, the spatial annual mean rainfall and annual mean temperature have been estimated by GIS tools; temperature and rainfall data were collected for the time period 1971-1999, then a reliable correlation was found using annual mean rainfall and annual mean temperature regression lines (Pagnozzi et al., 2019). The equations provided were implemented using raster data, and raster calculator tools in GIS environment. Then, using the Turc (1954) formula, the long-term annual mean of the actual evapotranspiration was estimated; this grid has been subtracted from the annual mean rainfall distribution grid, providing the long-term annual mean effective rainfall distribution grid.

In the endorheic area, A_E, as the runoff cannot escape, the recharge amount, R, can be considered equal to the effective afflux, F_{eff}:

$$(R)_{A_E} = (F_{eff})_{A_E}$$

In the open areas, A_O, the recharge amount R can be estimated assuming that all the groundwater flow feeds the spring discharges, Q_S, and no-flow boundaries occurs towards the argillaceous, terrigenous and flysch sequences (impervious terrains). Following this assumption, the total discharge, Q_s, from springs is:

$$Q_s = (R)_{A_E} + (R)_{A_o}$$

which allows to obtain the recharge in the open areas in the case of null groundwater abstraction:

$$(R)_{A_o} = Q_s - (F_{eff})_{A_E}$$

and the total recharge on the catchment area, A_C, is:

$$(R)_{A_c} = (R)_{A_o} + (R)_{A_E} = Q_s$$

valid if no groundwater occurs in the spring catchment, as for the Alburni karst massif.

The model assumes that all the amount of recharge reaches the basal water table, even though the vadose zone may present local saturated zones (i.e., sumps within karst systems, perched water tables, etc.).

The most common hydrologic parameter used to estimate aquifer recharge is the ratio between the volume of spring discharge and the rainfall. This is computed annually, assuming that cross boundary flow does not occur (Drogue 1971; Bonacci and Magdalenic 1993; Bonacci, 2001). Such a rough estimation can be improved considering the evapotranspiration processes and distinguishing the areas characterized by different recharge conditions. Among these latter, there are endorheic basins, that are closed depressions where the runoff is completely adsorbed (internal runoff; White, 2002; Sauro 2012), and are generally hydraulically connected to one or more springs.

The recharge coefficient used is expressed in term of fraction of the effective afflux, F_{eff}, providing the effective recharge coefficient, C_R; if water pumping does not occur, the following equation can be deducted (Fiorillo et al. 2015):

$$(C_R)_{A_E} = 1;\ (C_R)_{A_o} = \frac{(R)_{A_o}}{(F_{eff})_{A_o}};\quad (C_R)_{A_c} = \frac{(R)_{A_c}}{(F_{eff})_{A_c}}$$

The same coefficients can be expressed in function of total afflux, *F,* in a generic area*, A,* the recharge coefficient is:

$$(C'_R)_A = \frac{(R)_A}{(F)_A}$$

Finally, another evaluation is the contribution of endorheic areas to spring discharge. In this case, as all the recharge amounts inside endorheic areas (minus the pumping amount, Q_P) are assumed to reach basal springs, the effective contribution to spring discharge, C_S, can be expressed by

$$(C_s)_{A_E} = \frac{(F_{eff} - Q_P)_{A_E}}{Q_s}$$

As a consequence, the effective contribution to spring discharge of open areas, A_O, is:

$$(C_S)_{A_o} = 1 - (C_S)_{A_E}$$

In terms of total afflux, *F*, the total contribution to spring discharge in a generic area, *A*, could be estimated by the following equation:

$$(C'_s)_A = \frac{(F - Q_P)_A}{Q_s}$$

Further details of the method are described in Fiorillo et al. (2015).

The Alburni Massif

The Alburni Massif (Campania region of S Italy) extends over 270 Km^2, reaching a maximum altitude of 1742 m a.s.l. It is characterized by steep slopes bounding a mostly flat and undulating summit plateau. Two rivers bound the massif: namely, the Calore Lucano to the SW, and the Tanagro river to the NE, their valleys being filled by heterogeneous alluvial deposits, slope breccias, sand and conglomeratic deposits (Fig. 1).

The massif can be described as a monoclinal SW-dipping ridge marked by faults and composed of a Mesozoic carbonate sequence of Jurassic – Cretaceous age (Sartoni and Crescenti 1962); these soluble rocks are covered by a Miocene flysch sequence consisting of clays and sandstones (Scandone 1972; Ippolito et al. 1973; Patacca and Scandone 2007). During the Pliocene and Pleistocene, several faults caused the uplift of the massif (Gioia et al. 2011; Cafaro et al. 2016), and the development of deep karst processes (Santangelo and Santo 1997). The summit plateau shows a variety of sites of concentrated water infiltration, typical of karst settings, such as dolines and shafts (Klimchouk 2000; Ford and Williams, 2007; Palmer 2007; Williams 2008), which rapidly transfer the runoff into a complex network of caves and conduits (Del Vecchio et al., 2013; Cafaro et al., 2016), and then to the saturated zone of the aquifer. This concentrated recharge occurs mainly after intense rainstorms and snowmelt, whilst during normal rainfall events the recharge shows a diffuse modality, in function of the epikarst characters at the summit plateau.

The main springs (Basso Tanagro and Pertosa on the N side, Castelcivita and Auso to the S) drain the saturated zone of the aquifer, and are distributed in the areas surrounding the massif; a systematic record of their discharge is missing, with only sporadic measurements available (Brancaccio et al. 1973; Celico et al. 1994; Ducci 2007). Overall, the total discharge can be estimated being in the order of 7-8 mc/sec (Table 1).

Other minor springs are present along the massif, and still others drain perched water tables in the unsaturated zones.

In karst settings, due to scarcity or limited length of the surface runoff, endorheic areas play a prominent role in the recharge processes (Denizman 2003; Palmer 2010; Heidari et al. 2011; Parise et al. 2015; Zumpano et al. 2019). Their size and spatial distribution is typically linked to the structural control by faults and the main discontinuity systems in the rock mass (Palmer 1991, 2007; Hauselmann et al. 1999; Parise 2011).

Mapping of dolines and endorheic areas on the Alburni Massif was carried out through an integrated approach (Fig. 2), consisting of bounding their limits on 1:5000 scale topographic maps, supported by field survey, and uploading in GIS environment the geomorphological data together with those regarding strata attitude and presence of tectonic faults, as mapped from the official geological map.

The morphometric analysis proved that closed depressions (extending up to a few square kilometers) developed on strata mostly characterized by horizontal or near-to-horizontal attitude; differently from other karst areas in Campania (Matese and Picentini Mts.) the high density of sinkholes on the Alburni karst plateau has therefore to be related to the mostly horizontal bedding.

Recharge can be defined as the downward flow of water reaching the water table (De Vries and Simmers, 2002). In order to assess the recharge on the karst system at the Alburni, the hydrological analysis was preceded by a detailed geomorphological investigation of the karst landforms (dolines and depressions) on the summit plateau; both hydrological and morphometric analyses allowed to depict a specific overview of recharge processes in which such karst landforms play a predominant role, because the effective meteoric water falling on it contributes to feed the springs.

About 400 caves, with several of them reaching depth around 450 m, and with development of some kilometres, characterize the Alburni Massif (Bellucci et al. 1991, 1995). This remarkable karst is essentially related to the presence of the wide high plateau, bounded by fault systems, and with a variety of infiltration sites, mainly corresponding to blind valleys and small catchments on the flysch deposits, which surface hydrology feeds the many swallets at the contact with the limestones (Santangelo and Santo, 1997; Del Vecchio et al. 2013; Cafaro et al., 2016). Through scrutiny of the data about the Alburni caves, all those where water was found were selected (Fig. 1 and Table 2). It must be pointed out that in these caves generally the presence of water corresponds to the end of the explorations, given the impossibility (in some cases) and the difficulty (in others) to pass the flooded passages. Further, presence of water does not necessarily mean that the saturated zone has been reached; actually, some of the water could be related to perched groundwater, due to less permeable intercalations within the stratigraphy, or to local clogging by debris and breakdown deposits. Nevertheless, we used the elevations at which water was documented into caves to build the hydrogeological profile shown in ~~figure~~ Figure 3, by assuming water as representative of the base water table.

Results

The Alburni karst massif can be considered a wide karst system, where surficial and groundwater hydrology are strictly linked, but still unclear. Surficial hydrology appears controlled by the wide summit plateau, which has been assumed as a wide closed area, where the runoff infiltrates in sinking points, providing a concentrated recharge. Outside of it, along the steep slopes bounding the plateau, the runoff can escape from the catchment and feed directly the rivers.

All karst landforms mapped and digitalized in a GIS environment provided a total number of 539 dolines, with average density of 5~~,~~.97 depressions per km^2 (Fig. 2); 62% of these close depressions has area less than 0,1 km^2 (Pagnozzi et al. 2019). Their pattern distribution highlights that the central plateau is mostly affected by dolines of small size, whilst only along the north-western, eastern and southern borders, endorheic areas are generally ≥ 1 km^2. The statistical approach adopted in the study area allowed to assess the pitting index (total karst area/plateau area) which represent a measure of superficial karst development, providing information about the extent of karstification (Denizman, 2003; Haryono et al., 2017). At Alburni the ratio between karst area and plateau is 2.96.

To estimate the recharge, a preliminary delimitation of the catchment spring area, A_c, has to be provided. Definition of the spring catchment area is a challenge in karst settings (Gunn 2007; Parise 2016), especially if a wide karst system is drained by several springs, as at the Alburni Massif. A useful approach is to associate the whole mountain or karst system to a lumped system, and to consider the overall output from spring outlets, without focusing the analysis on a single spring and its relative catchment. In the Alburni case, the karst terrains are bounded by impervious terrains which make the delimitation of the lumped spring catchment easier; only along the SE sector, the spring catchment cannot be accurately defined.

Figure 3 provides the hydrogeological cross-section along the Alburni Massif considering some of the main springs (Auso, 277 m a.s.l., to the S, and Pertosa, 250 m a.s.l., to the NE); the different elevation between these springs is coherent with fault systems affecting the carbonate hydrostructure. Dolines and endorheic basins drain the meteoric water on the summit plateau through the below network of shafts and conduits. Looking at figure 3, the cave profiles, redrawn from the Regional Inventory of Caves of Campania, and adding bedding information, highlight that development of the karst systems is highly controlled by the prevailing discontinuity systems in the rock mass, both as sub-horizontal passages (bedding) and as vertical pits (fractures or faults).

However, it is very arduous to assess the groundwater flowpath in the shafts (Jouves et al., 2017), so that in many cases scholars refer to indirect methods in order to gain insights about the karst flow system (geophysics, geodesy, etc.; Martel et al., 2018). In our case, detailed studies were carried out on the Alburni catchment area, based on a methodical collection of available data about hydrology, water geochemistry and piezometric data of the aquifer with its main outflows. Being the karst environment interested by a complex system of conduits, passages and shafts (only partly known), the most reliable approach to propose a valid hydrological model is represented by tracing experiments, particularly the cave-to-spring multitracer tests (Goldscheider and Drew 2007; Filippini et al., 2018).

At Alburni, looking at the karstified limestone outcrops and at the morphological features of the calcareous area with an elevation higher than that of the springs, the estimated recharge area is 267 Km^2. This wide area includes the karst plateau, considered as a unique closed area, A_E, extended 90.09 Km^2. The catchment zones outside the internal runoff area constitute the open areas (A_O=A_C-A_E).

The main results are shown in Table 3; taking into account the effective rainfall distribution and the temperature values, the mean actual evapotranspiration at Alburni Massif can be estimated (**545 mm/year)**. This value is comparable to evapotranspiration rates for nearby karst massifs of Southern Italy (Fiorillo et al., 2015; Fiorillo and Pagnozzi, 2015), whilst the amount of recharge is higher in Alburni, due to concentrated recharge at the summit plateau and to runoff being limited along the steep slopes bounding the massif. Looking at the numbers listed in Table 3, the annual effective afflux (P_{eff}) of the whole catchment area is **246 x 10^6 m^3**, the annual spring discharge (Q) is **230.6 x 10^6 m^3**, and the ratio Q/P_{eff} provides the effective recharge coefficient of **0.94**. The difference between the effective recharge from precipitation (**7.8 m^3/s**) and the spring discharge (**7.4 m^3/s**), estimated in **0.4 m^3/s**, could be associated to runoff losses and/or to minor springs, for which discharge data are unavailable.

An high effective recharge coefficient (**C_R = 0.90**) has been found for the open area (zone outside the summit plateau), where the runoff amount is only **13.4 x 10^6 m^3**. Even if the runoff amount is believed to be a very limited component in the hydrological balance in karst areas, this value could be considered as underestimated if compared to other areas of the Southern Apennines (cf. Fiorillo et al., 2015), due to poor knowledge of the total discharge amount and spring catchment area boundaries of the Alburni massif.

Considering only the summit plateau (90 km^2), this area totally contributes to spring discharge, as all the recharge amounts inside endorheic areas are assumed to reach the basal springs; in particular it represents 34% of the total Alburni catchment, but provides about half of the effective contribution to spring discharge (C_S= 0.45), and is even higher in terms of total rainfall (C'_S=0.65).

The above estimations refer to a long-term scale (annual mean rainfall over a time span of several decades), though annual recharge changes yearly, typically concentrating in specific seasons. Kessler (1967) highlighted the role of the first four months of the year in controlling the recharge in a karst environment of Hungary, and its dependence on the amount of rainfall recorded in the previous year (during the last four months). These characteristics are even exacerbated in Mediterranean climate areas, especially within the framework of the climate changes we are experiencing. At the Alburni Massif, recharge occurs mainly during the winter and spring seasons, and depends on the previous autumn rainfall and the snowmelt as well, which are needed to satisfy the retention water of the soil cover.

Discussion and Conclusions

As repeatedly demonstrated worldwide, anthropogenic activities may produce significant changes in the hydraulic and hydrogeological regimes of karst areas (Bakalowicz, 1995, 2005; Ozanić et al. 2003; Ravbar & Sebela 2015; Chen et al., 2017; Parise et al. 2018). This occurs through a variety of human actions, ranging from land use changes (Foley et al., 2005; Quine et al., 2017; Peng et al., 2020), to quarrying and mining (Gunn 1993, 2003; Hobbs and Gunn 1993; Formicola et al. 2010; Parise 2010, 2016), variations in the amount and distribution of the natural vegetative cover (Ravbar et al. 2011; Huebsch et al. 2014), and overexploitation of groundwater resources (Hartmann et al. 2012; Finger et al. 2013; Musgrove et al. 2016; Jia et al. 2017). All these actions often lead to severe disturbance to the natural karst environment (Calò and Parise 2009), as proved through the application of the Karst Disturbance Index (Van Beynen and Townsend, 2005; North et al., 2009) to many different karst settings in the globe (Calò and Parise 2006; Day 2011). In the Alburni case study, the rural character of the area, that is a mountain setting mostly dedicated to pasture, and with a limited human presence, essentially distributed at its borders, is not considered to have in the near future a possible role in changing the hydrological regime. Nevertheless, protection and safeguard of karst groundwater, and more in general, of karst ecosystems (Bonacci et al. 2009; Fleury 2009; Gabrovsek et al. 2018) needs to be continuously pursued. This is one of the main goals of this contribution, hopefully helping to emphasize this remarkable karst area, aimed at improving and spreading its knowledge among the local inhabitants and the scientific community, in the effort to increase the awareness of the natural resources it hosts. It is also worth to mention the fact that the area is included in a National Park (*Parco Nazionale del Cilento, Alburni e Vallo di Diano*, http://www.cilentoediano.it), that was also declared Geopark by UNESCO in 2010, thus becoming member of the UNESCO network of Global Geoparks (Aloia et al. 2012; Santangelo et al. 2015).

The analysis presented in this article, based upon computation of the recharge at the summit plateau of Alburni Massif and its comparison with the total spring discharge, in spite of the many assumptions, shows a general agreement of the outcomes. Nevertheless, this cannot be considered as a definitive result, since many issues still remain to be fully examined and understood. Tracer tests in Alburni have shown in the past how the expected outcomes, in terms of sites of emergence, flow directions and velocity, and discharge values as well, have often been quite different from those forecasted on the basis of previous knowledge.

In the history of Alburni cave explorations, many tracer tests were addressed to prove the links among the karst systems and the basal springs (Del Vecchio et al. 2013; Parise and Santo 2017). Among the first outcomes, it has been demonstrated since the 1950's the link between the Castelcivita Caves and the Auso spring, for a total development of more than 6 km (Santo 1994). These researches were also useful to develop a first conceptual hydrogeological model along the Calore River. During the 1990's, an automatic datalogger installed at Risorgenza del Mulino provided data which indicated a deep circuit for the water at this spring (T 16,5 °C), as also proved by later cave diving explorations. Further, the delay (24 to 48 hours) in temperature changes after intense rainstorms on the Alburni highplain testified the connection between the vertical systems and the basal water table (Santangelo and Santo 1997). More recently, other tracing tests demonstrated the hydrogeological connection among the active swallow holes in Piana dei Campitelli and at Grotta del Falco with the nearby spring at Grotta dell'Acqua (Bocchino et al. 2014; Cozzolino et al. 2015). At the same time, the fluorescein was detected also at the waterfall within the Pertosa Cave and at some springs in the Tanagro River, outlining a quite complex scenario, which still needs further data to be entirely understood (Pedrali et al. 2015; Pastore 2016). In particular, cave diving explorations at Grotta del Falco proved the development of the cave system through one of the main tectonic lines of the Massif, the Vallone Lontrano – Petina (Gueguen et al. 2012; Cafaro et al. 2016), which seems to transfer the water from this system to the central part of the Alburni Massif, toward Grava del Fumo and the S. Maria karst system, and, in turn, to the Auso spring on the SW foothills of the massif. This tectonic line acts certainly as an important draining structure, as actually previously hypothesized by Bellucci and co-workers (1991).

The so far available tracer test data still hold some doubts regarding the central sector of the summit plateau: whether this is in communication with the SW or the NE side of the massif, and if there actually is the possibility of some dispersion within the groundwater network, with different functioning during the dry seasons (when the karst conduits may act independently) and during floods.

In conclusion, notwithstanding the efforts and the many continuing explorations, hydrogeology of the Alburni Massif still has several dark points, which need further work. This was also favored by high dispersion of data in the past, due to lack of communication among cave grottos, and to unpublished materials. The few available data, especially those concerning the spring discharges around the Alburni Massif, make any conclusion quite uncertain, since more detailed surveys and monitoring actions are needed.

Nevertheless, through the example of the Alburni Massif we have pointed out to some of the difficulties inherent in carrying out karst hydrogeology research, and to the need of a continuous and updated exchange of information with the cavers exploring the cave systems, since they represent the main source of new data ("the underground truth") in such settings.

References

Aloia, A., Guida, D. & Valente, A. (2012) Geodiversity in the Geopark of Cilento and Vallo di Diano as heritage and resource development. *Rend. Online Soc. Geol. It.*, 21, 688–690.

Angel, J.C., Nelson, D.O., & Panno, S.V. (2004) Comparison of a new GIS-based technique and a manual method for determining sinkhole density: An example from Illinois' sinkhole plain. *Journal of Cave and Karst Studies*, 66, 9−17.

Bakalowicz, M. (1995) La zone d'infiltration des aquifers karstiques. Methodes d'etude. Structure et fonctionnement. *Hydrogeologie*, 4, 3–21.

Bakalowicz, M. (2005) Karst groundwater: a challenge for new resources. *Hydrogeology Journal*, 13, 148–160.

Bellucci, F., Giulivo, I., Pelella, L., & Santo, A., (1991) Carsismo ed idrogeologia del settore centrale dei Monti Alburni (Campania). *Geologia Tecnica*, 3, 5–12.

Bellucci, F., Giulivo, I., Pelella, L., & Santo, A., (1995) *Monti Alburni. Ricerche Speleologiche*. De Angelis, Avellino.

Bocchino B., Del Vecchio U., De Nitto L., Lo Mastro F., Marraffa M., Maurano F., Minieri G., Parise M. & Ruocco M. (2014) Increasing people's awareness about the importance of karst landscapes and aquifers: an experience from southern Italy. In N. Kukuric, Z. Stevanovićc & N. Kresic (Eds.), *Proceedings International Conference and Field Seminar "Karst without boundaries"* (pp. 398-405).

Bonacci, O. (1995) Ground water behaviour in karst: example of the Ombla Spring (Croatia). *Journal of Hydrology*, 165, 113–134. https://doi.org/10.1016/0022-1694(94)02577-X

Bonacci, O. (2001) Monthly and annual effective infiltration coefficient in Dinaric karst: example of the Gradole karst spring catchment. *Hydrological Sciences Journal*, 46(2), 287–300.

Bonacci, O., & MagdalenićMagdalenic, A. (1993) The catchment area of the Sv. Ivan Karst spring in Istria, Croatia. *Ground Water*, 31(5), 767–773.

Bonacci, O., Pipan, T. & Culver, D.C. (2009) A framework for karst ecohydrology. *Environmental Geology*, 56, 891–900.

Brancaccio, L., Civita, M., & Vallario, A. (1973) Prime osservazioni sui problemi idrogeologici dell'Alburno, Campania. *Boll. Soc. Naturalisti Napoli*, 82.

Brinkmann, R., & Parise, M. (2012) Karst Environments: Problems, Management, Human Impacts, and Sustainability. An introduction to the Special Issue. *Journal of Cave and Karst Studies*, 74 (2), 135-136.

Cafaro, S., Gueguen, E., Parise, M., & Schiattarella, M. (2016) Morphometric analysis of karst features of the Alburni mts, southern Apennines, Italy. *Geogr. Fis. Dinam. Quat.,* 39, 121-128.

Calò, F. & Parise, M. (2006) Evaluating the human disturbance to karst environments in southern Italy. *Acta Carsologica*, 35, 47–56.

Calò, F. & Parise, M. (2009) Waste management and problems of groundwater pollution in karst environments in the context of a post-conflict scenario: the case of Mostar (Bosnia Herzegovina). *Habitat International*, 33, 63–72.

Celico, P., Pelella, L., Stanzione, D., & Aquino, S., (1994) Sull'idrogeologia e l'idrogeochimica dei Monti Alburni. *Geologica Romana*, 30, 687–698.

Cestari, G., (1971) *Note illustrative della Carta Geologica d'Italia alla scala 1:100.000. Foglio 198 Eboli.* Nuova Tecnica Grafica, Roma.

Chen, Z., Auler, A.S., Bakalowicz, M., Drew, D., Griger, F., Hartmann, J., Jiang, G., Moosdorf, N., Richts, A., Stevanović, Z., Veni, G. & Goldscheider, N. (2017) The World Karst aquifer mapping project: concept, mapping procedure and map of Europe. *Hydrogeology Journal*, 25, 771-785, 10.1007/s10040-016-1519-3.

Cozzolino, L., Damiano, N., Del Vecchio, U., Minieri, G., Testa, L., & Trifone, P. (2015) Prove di colorazione e recenti esplorazioni nell'area della Grotta del Falco - Monti Alburni. In *Proc. XXII Nat. Congr. Speleol.*, 323-328.

Day, M., Halfen, A. & Chenoweth, S. (2011) The cockpit country, Jamaica: boundary issues in assessing disturbance and using a karst disturbance index in protected areas planning. In P.E. Van Beynen (Ed.), *Karst Management.* Springer, Dordrecht (pp. 399–414).

Del Prete, S., Iovine, G., Parise, M., & Santo, A. (2010) Origin and distribution of different types of sinkholes in the plain areas of Southern Italy. *Geodinamica Acta*, 23(1/3), 113−127. https://doi.org/10.3166/ga.23.113-127

Del Vecchio U., Lo Mastro F., Maurano F., Parise M. & Santo A. (2013) The Alburni Massif, the most important karst area of southern Italy: history of cave explorations and recent developments. In M. Filippi & P. Bosak (Eds.), Proceedings 16th International Congress of Speleology, Brno, 21-28 July 2013, 1, (pp. 41-46).

Denizman, C. (2003) Morphometric and spatial distribution parameters of karstic depressions, lower Suwannee river basin, Florida. *Journal of Cave and Karst Studies*, 65, 29−35.

De Riso, R., & Santo, A. (1997) Geologia, evoluzione geomorfologica e frane del Bacino del T. Pietra (Campania). *Quaderni di Geologia Applicata*, 4(2), 19–33.

De Vries, J.J., & Simmers, I. (2002) Groundwater recharge: an overview of processes and challenges. *Hydrogeology Journal* 10, 5–17.

Dorsaz, J.M., Gironás, J., Escauriaza, C., & Rinaldo, A. (2013) The geomorphometry of endorheic drainage basins: implications for interpreting and modelling their evolution. *Earth Surface Processes and Landforms*, 38, 1881–1896.

Drogue, C. (1971) Coefficient d'infiltration ou infiltration eficace, sur le roches calcaires. *Actes du Colloque d'Hydrologie en Pays Calcaire*, Besancon 15, 121–130.

Ducci, D. (2007) Intrinsic vulnerability of the Alburni Karst System southern Italy. In M. Parise, & J. Gunn (Eds.), *Natural and Anthropogenic Hazards in Karst Areas: Recognition, Analysis, and Mitigation.* Geological Society, London, sp. publ. 279 (pp. 137–152).

Filippini, M., Squarzoni, G., De Waele, J., Fiorucci, A., Vigna, B., Grillo, B., Riva, A., Rossetti, S., Zini, L., Casagrande, G., Stumpp, C., & Gargini, A. (2018) Differentiated spring behavior under changing hydrological conditions in an alpine karst aquifer. *Journal of Hydrology* 556, 572-584.

Finger, D., Hugentobler, A., Huss, M., Voinesco, A., Wernli, H., Fischer, D., Weber, E., Jeannin, P.Y., Kauzlaric, M., Wirz, A., Vennemann, T., Hüsler, F., Schädler, B. & Weingartner, R. (2013) Identification of glacial meltwater runoff in a karstic environment and its implication for present and future water availability. *Hydrology and Earth System Sciences*, 17, 3261–3277.

Fiorillo, F., & Pagnozzi, M. (2015) Recharge process of Matese karst massif southern Italy. *Environmental Earth Sciences*, 74, 7557–7570.

Fiorillo, F., Pagnozzi, M., & Ventafridda, G. (2015) A model to simulate recharge processes of karst massifs**.** *Hydrological Processes*, 29, 2301–2314.

Fiorillo, F., Pagnozzi, M., & Ventafridda, G. (2019) Analysis of annual mean recharge in main karst systems of southern Italy. *Rend. Online Soc. Geol. It.*, Vol. 47, pp. 36-40. https://doi.org/10.3301/ROL.2019.07

Fleury, S. (2009) *Land Use Policy and Practice on Karst Terrains. Living on Limestone.* Springer, Dordrecht.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N & Snyder, P.K. (2005) Global consequences of land use. *Science*, 309 (5734), 570-574, 10.1126/science.1111772.

Ford, D.C., & Williams, P.W. (2007) Karst geomorphology and hydrology. 2nd ed. John Wiley & Sons, Chichester, U.K. https://doi.org/10.1002/9781118684986

Formicola W., Gueguen E., Martimucci V., Parise M. & Ragone G. (2010) Caves below quarries and quarries above caves: problems, hazard and research. A case study from southern Italy. *Geol. Soc. America Abs. with Program*, 42 (5).

Fragoso-Servón, P., Bautista, F., Frausto, O., & Pereira, A. (2014) Caracterización de las depresiones kársticas (forma, tamaño y densidad) a escala 1:50000 y sus tipos de inundación en el Estado de Quintana Roo, México. *Revista Mexicana de Ciencias Geológicas*, 31(1), 127−137.

Gabrovsek, F., Peric, B. & Kaufmann, G. (2018) Hydraulics of epiphreatic flow of a karst aquifer. *Journal of Hydrology*, 560, 56–74.

Gioia, D., Schiattarella, M., Mattei, M., & Nico, G. (2011) Quantitative morphotectonics of the Pliocene to Quaternary Auletta basin, southern Italy. *Geomorphology*, 134, 326-343.

Goldscheider, N., & Drew, D. (2007) *Methods in Karst Hydrogeology.* International Association of Hydrogeologists 26, Taylor & Francis, London.

Gueguen, E., Cafaro, S., Schiattarella, M., & Parise, M., (2012) A new methodology for the analysis of morpho-structural data of karstic caves in the Alburni Mountains of southern Italy. *Rendiconti Online Società Geologica Italiana*, 21 (1), 614-616.

Gunn, J. (1993) The geomorphological impact of limestone quarrying. *Catena*, 25, 187-198.

Gunn, J. (2003) Quarrying of limestones. In J. Gunn (Ed.), *Encyclopedia of cave and karst science*. Routledge, London (pp. 608-611).

Gunn, J. (2007) Contributory area definition for groundwater source protection and hazard mitigation in carbonate aquifers. In M. Parise, & J. Gunn (Eds.), *Natural and Anthropogenic Hazards in Karst Areas: Recognition, Analysis, and Mitigation.* Geological Society, London, sp. publ. 279 (pp. 97–109). https://doi.org/10.1144/SP279.9

Gutiérrez, F., Parise, M., De Waele, J., & Jourde, H. (2014) A review on natural and human-induced geohazards and impacts in karst. *Earth-Science Reviews*, 138, 61–88. https://doi.org/10.1016/j.earscirev.2014.08.002

Hartmann, A., Lange, J., Vivo Aguado, A., Mizyed, N., Smiatek, G. & Kunstmann, H. (2012) A multi-model approach for improved simulations of future water availability at a large Eastern Mediterranean karst spring. *Journal of Hydrology*, 468–469, 130–138.

Haryono, E., Trijuni Putro, S., & Suratman, S. (2017) Polygonal karst morphology of Karangbolong area, Java-Indonesia. *Acta Carsologica* 46-1, 63–72.

Häuselmann, P., Jeannin, P.Y., & Bitterli, T. (1999) Relationships between karst and tectonics: case-study of the cave system Northof Lake Thun Bern, Switzerland. *Geodinamica Acta*, 12(6), 377-387.

Heidari, M., Khanlari, G.R., Taleb Beydokhti, A.R., & Momeni, A.A. (2011) The formation of cover collapse sinkholes in North of Hamedan, Iran. *Geomorphology*, 132, 76–86. https://doi.org/10.1016/j.geomorph.2011.04.025

Hobbs, S.L. & Gunn, J. (1998) The hydrogeological effect of quarrying karstified limestone: options for protection and mitigation. *Quart. J. Eng. Geol.*, 31, 147-157.

Huebsch, M., Horan, B., Blum, P., Richards, K.G., Grant, J. & Fenton, O. (2014) Statistical analysis correlating changing agronomic practices with nitrate concentrations in a karst aquifer in Ireland. *WIT Transactions on Ecology and the Environment*, 182, 99–109.

Ippolito, F., Ortolani, F., & Russo, M. (1973) Struttura marginale tirrenica dell'Appennino campano: Reinterpretazione di dati di antiche ricerche di idrocarburi. *Memorie della Società Geologica Italiana* 12**,** 227-250.

Jia, Z., Zang, H., Zheng, X. & Xu, Y. (2017) Climate change and its influence on the karst groundwater recharge in the Jinci Spring Region, Northern China. *Water*, 9, 267.

Jourde, H., Roesch, A., Guinot, V., & Bailly-Comte, V. (2007) Dynamics and contribution of karst groundwater to surface flow during Mediterranean flood. *Environmental Geology*, 51(5), 725–730. https://doi.org/10.1007/s00254-006-0386-y

Jouves, J., Viseur, S., Arfib, B., Baudement, C., Camus, H., Collon, P., & Guglielmi, Y. (2017) Speleogenesis, geometry, and topology of caves: A quantitative study of 3D karst conduits. *Geomorphology* 298, 86 –106.

Kessler, H. (1967) Water balance investigations in the karstic regions of Hungary. In *Proceedings of the Symposium "Hydrology of fractured rocks"*. Dubrovnik, October 1965, vol. 1, Int. Ass. Scientific Hydrology, UNESCO (pp. 91–105).

Klimchouk, A.B. (2000) The formation of epikarst and its role in vadose speleogenesis. In A.B. Klimchouk, D.C. Ford, A.N. Palmer, & W. Dreybrodt (Eds.), *Speleogenesis. Evolution of Karst Aquifers* (pp. 91–99). National Speleological Society, Huntsville, Alabama, USA.

Martel, R., Castellazzi, P., Gloaguen, E., Trépanier, L., & Garfias, J. (2018) ERT, GPR, InSAR, and tracer tests to characterize karst aquifer systems under urban areas: The case of Quebec City. *Geomorphology* 310, 45-56.

Miao, X., Qiu, X., Wu, S.-S., Luo, J., Gouzie, D.R., & Xie, H. (2013) Developing efficient procedures for automated sinkhole extraction from Lidar DEMs. *Photogrammetric Engineering Remote Sensing*, 79(6), 545–554. https://doi.org/10.14358/PERS.79.6.545

Musgrove, M., Opsahl, S.P., Mahler, B.J., Herrington, C., Sample, T.L. & Banta, J.R. (2016) Source, variability, and transformation of nitrate in a regional karst aquifer: Edwards aquifer, central Texas. *Science of the Total Environment,* 568, 457–469.

North, L.A., Van Beynen, P.E. & Parise, M. (2009) Interregional comparison of karst disturbance: west central Florida and southeast Italy. *Journal of Environmental Management*, 90, 1770–1781.

Ozanić, N. & Rubinić, J. (2003) The regime of inflow and runoff from Vrana Lake and the risk of permanent water pollution. *RMZ - Materials and Geoenvironment*, 50, 281–284.

Pagnozzi, M., Fiorillo, F., Esposito, L., Leone, G. (2019) Hydrological features of endorheic areas in Southern Italy. *Italian Journal of Engineering Geology and Environment*, Special Issue 1, 85-9. DOI: 10.4408/IJEGE.2019-01.S-14

Palmer, A.N., (1991) Origin and morphology of limestone caves. *Geological Society of America Bulletin*, 103, 1-25.

Palmer, A. N. (2007) *Cave Geology*. Cave Books.

Palmer, A.N. (2010) Understanding the hydrology of karst. *Geologia Croatica*, 63, 143−148. https://doi.org/10.4154/gc.2010.11

Parise, M. (2010) The impacts of quarrying in the Apulian karst. In F. Carrasco, J.W. La Moreaux, J.J. Duran Valsero & B. Andreo (Eds.), *Advances in research in karst media*. Springer (pp. 441-447).

Parise, M. (2011) Surface and subsurface karst geomorphology in the Murge (Apulia, southern Italy). *Acta Carsologica*, 40(1), 79-93.

Parise, M. (2016) Modern resource use and its impact in karst areas – mining and quarrying. *Zeitschrift fur Geomorphologie*, 60 (X), 199-216.

Parise, M. (2016) How confident are we about the definition of boundaries in karst? Difficulties in managing and planning in a typical transboundary environment. In Z. Stevanovic, N. Kresic, & N. Kukuric (Eds.), *Karst without boundaries* (pp. 27−38). IAH-Selected Papers on Hydrogeology, 23, ISBN 9781138029682, CRC Press. https://doi.org/10.1201/b21380-4

Parise, M. (2019) Sinkholes. In W.B. White, D.C. Culver & T. Pipan (Eds.), *Encyclopedia of Caves* (pp. 934-942). Academic Press, Elsevier, 3rd edition, ISBN ISBN 978-0-12-814124-3.

Parise, M. & Santo, A. (2017) Tracer tests history in the Alburni Massif (Southern Italy). *IOP Conference Series: Earth and Environmental Science*, 95, 062006, doi :10.1088/1755-1315/95/6/062006

Parise, M., Ravbar, N., Živanović, V., Mikszewski, A., Krešić, N., Mádl-Szőnyi, J., & Kukurić, N.~~Živanovic, V., Mikszewski, A., Kresic, N., Mádl-Szo˝Nyi, J., & Kukuric, N.~~ (2015) Hazards in karst and managing water resources quality. In Z. Stevanović~~e~~ (Ed.), *Karst Aquifers – Characterization and Engineering* (pp. 601−687). Professional Practice in Earth Sciences, Springer. https://doi.org/10.1007/978-3-319-12850-4_17

Parise, M., Gabrovsek, F., Kaufmann, G. & Ravbar, N. (2018) Recent advances in karst research: from theory to fieldwork and applications. In M. Parise, F. Gabrovsek, G. Kaufmann & N. Ravbar (Eds.), *Advances in Karst Research: Theory, Fieldwork and Applications*. Geological Society, London, Special Publication 466 (pp. 1-24), https://doi.org/10.1144/SP466.26.

Pastore, C. (2016) *Analisi idrogeologica dell'area carsica dei Monti Alburni Salerno, Campania*. Master Thesis, Univ. Alma Mater, Bologna, Italy.

Patacca, E., & Scandone P. (2007) Geology of the southern Apennines. *Italian Journal of Geosciences*, Special Issue 7, 75-119.

Pedrali, L., Buongiorno, V., Antonini, G., Cafaro, S., & De Nitto, L. (2015) Convergenza di dati per l'esplorazione della Grotta del Falco sul Massiccio degli Alburni (Campania). In *Proc. XXII Nat. Congr. Speleol.*, 537-542.

Peng, J., Tian, L., Zhang, Z., Zhao, Y., Green, S.M., Quine, T.A., Liu, H. & Meersmans, J. (2020) Distinguishing the impacts of land use and climate change on ecosystem services in a karst landscape in China. *Ecosystem Services*, 46, 101199, https://doi.org/10.1016/j.ecoser.2020.101199.

Quine, T., Guo, D., Green, S.M., Tu, C., Hartley, I., Zhang, X., Dungait, J., Wen, X., Song, Z., Liu, H., Buss, H., Barrows, T., Evershed, R., Johnes, P. & Meersmans, J. (2017) Ecosystem service delivery in karst landscapes: Anthropogenic perturbation and recovery. *Acta Geochimica*, 36 (3), 416-420, 10.1007/s11631-017-0180-4

Ravbar, N. & Šebela, S. (2015) The effectiveness of protection policies and legislative framework with special regard to karst landscapes: insights from Slovenia. *Environmental Science Policy*, 51, 106–116.

Ravbar, N., Engelhardt, I. & Goldscheider, N. (2011) Anomalous behaviour of specific electrical conductivity at a karst spring induced by variable catchment boundaries: the case of the Podstenjšek spring, Slovenia. *Hydrological Processes*, 25, 2130–2140.

Santangelo, N., & Santo, A. (1997) Endokarst processes in the Alburni massif Campania, Southern Italy: Evolution of ponors and hydrogeological implications. *Zeitschrift fur Geomorphologie*, 41(2), 229-246.

Santangelo, N., Romano, P. & Santo, A. (2015) The Geo-itineraries in the Cilento Vallo di Diano Geopark: A Tool for Tourism Development in Southern Italy. *Geoheritage* 7, 319-335.

Santo, A. (1994) Idrogeologia dell’area carsica di Castelcivita (M. Alburni – SA). *Geologia Applicata e Idrogeologia*, 28, 663-673.

Sartoni, S., & Crescenti, U. (1962) Ricerche biostratigrafiche nel Mesozoico dell'Appennino meridionale. *Giornale di Geologia*, **2**, Bologna.

Sauro, U. (2005) Closed depressions. In D.C. Culver & W.B. White (Eds.), *Encyclopedia of Caves* (pp. 108-127). Elsevier, Amsterdam.

Scandone, P. (1971) *Note illustrative della Carta Geologica d’Italia alla scala 1:100.000. Fogli 199 e 210 Potenza e Lauria.* Nuova Tecnica Grafica, Roma.

Scandone, P. (1972) Studi di geologia lucana: carta dei terreni della serie calcareo-silico-marnosa e note illustrative. *Boll. Soc. Nat. Napoli*, 81, 225-300.

Stevanoviće, Z. (Ed.) (2015) *Karst Aquifers – Characterization and Engineering*. Professional Practice in Earth Sciences, Springer.

Turc, L. (1954) Le bilan d’eau des sols. Relations entre les precipitations, l’evaporation et l’ecoulement. *Ann. Agric.*, 5, 4-24.

Van Beynen, P.E. & Townsend, K. (2005) A disturbance index for karst environments. *Environmental Management*, 36, 101–116.

Waltham, T., Bell, F., & Culshaw, M. (2005) *Sinkholes and subsidence. Karst and cavernous rocks in engineering and construction*. Springer Praxis.

White, W.B. (2002) Karst hydrology: recent developments and open questions. *Engineering Geology*, 65, 85–105. https://doi.org/10.1016/S0013-7952(01)00116-8

Williams, P.W. (2008) The role of the epikarst in karst and cave hydrogeology: a review. *International Journal of Speleology*, 37, 1−10. https://doi.org/10.5038/1827-806X.37.1.1

Worthington, S., Ford, D., & Beddows, P. (2001) Characteristics of porosity and permeability enhancement in unconfined carbonate aquifers due to the development of dissolutional channel systems. In G. Gunay, D. Ford, P.

Williams, & K. Johnson (Eds.), *Present state and future trends of karst studies* (pp. 13–29). Technical Documents in Hydrology. UNESCO, Paris, 49.

Wu, Q., Deng, C., & Chen, Z., (2016) Automated delineation of karst sinkholes from LIDAR-derived digital elevation models. *Geomorphology*, 266, 1−10. https://doi.org/10.1016/j.geomorph.2016.05.006

Zumpano, V., Pisano, L., & Parise, M. (2019) An integrated framework to identify and analyze karst sinkholes. *Geomorphology*, 332, 213-225.

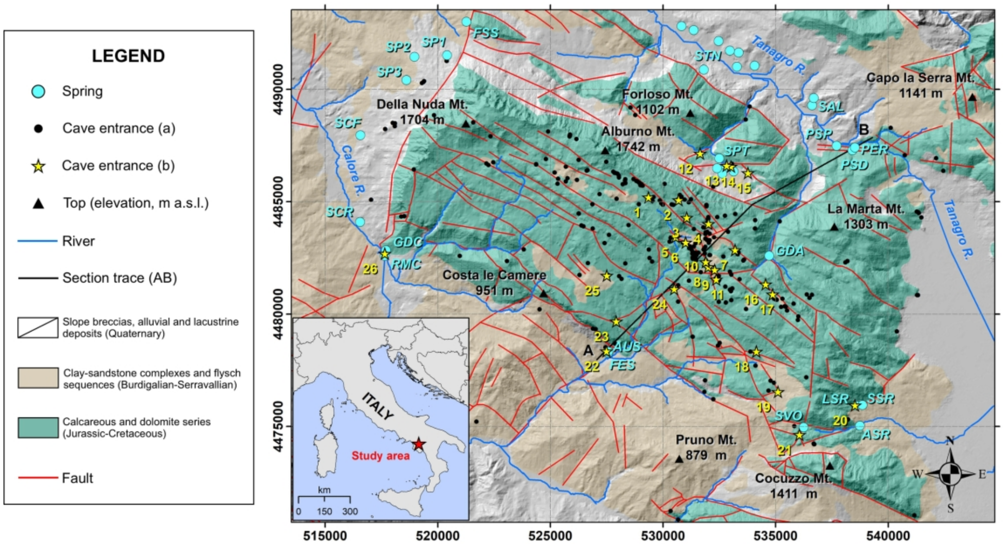
Figures

1) Geological map of the Alburni Massif.
2) Map showing dolines and endorheic basins on the summit plateau of the Alburni Massif.
3) Hydrogeological schematic cross-section across the Alburni Massif, based upon speleological data from the Regional Inventory of Caves of Campania, managed by the Campanian Speleological Federation. Trace of section in figure 1. Some profiles of selected caves are also shown, after the surveys from Campanian Speleological Federation (http://www.fscampania.it/catasto-2/catasto/), with addition of the strata attitude.
4) Karst features of the Alburni Massif: A) the sump at Grotta del Falco (photo: GSAVD); B) view of the shafts in the Parchitiello system (photo: GSAVD); C) downhill sump in the Grave del Minollo (photo: GSAVD); D) Auso spring, at the S foothills of the massif (photo: F. Fiorillo).

Tables

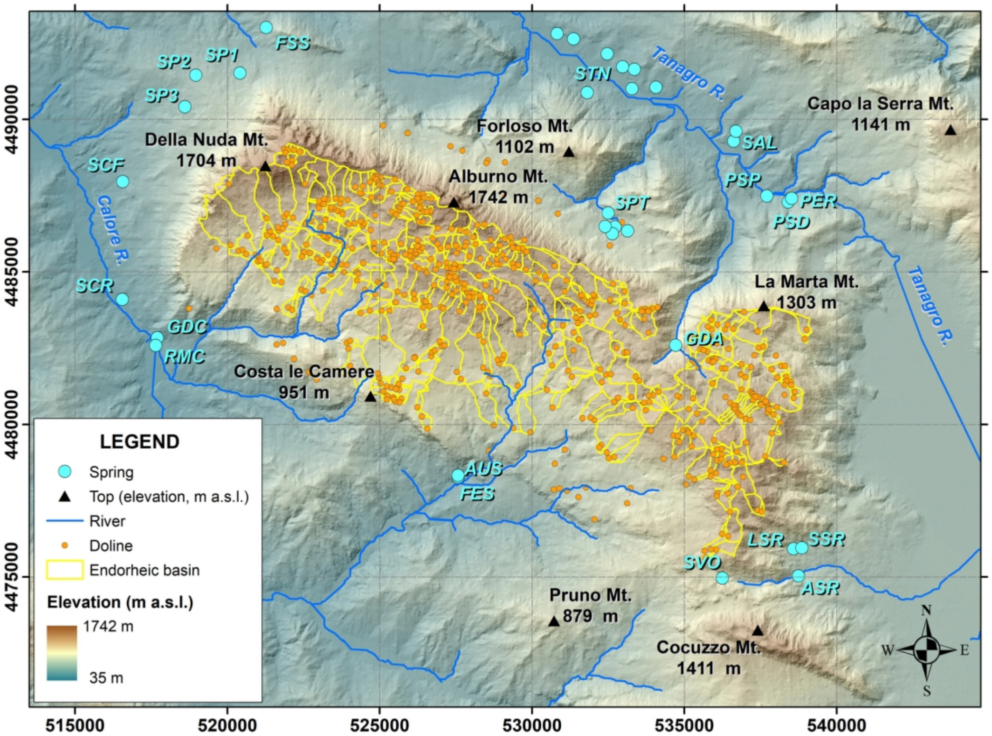
1) Springs surrounding the Alburni Massif, and related discharge values (if available).
2) Caves (yellow stars in figure 1) where water has been found within the karst systems. Labels as in figure 3.
3) Hydrological parameters obtained from the recharge analysis for the Alburni Massif (modified after Fiorillo et al. 2019). Key: *F*, afflux (mean precipitation on the catchment); T, temperature; AET, actual evapotranspiration; F_{eff}, effective afflux (mean effective precipitation on the catchment); *RO*, runoff; Q_P, groundwater abstracted; R, recharge; C_R,

effective recharge coefficient; C'_R, total recharge coefficient; C_s, effective contribution to spring discharge; C'_s, total contribution to spring discharge.



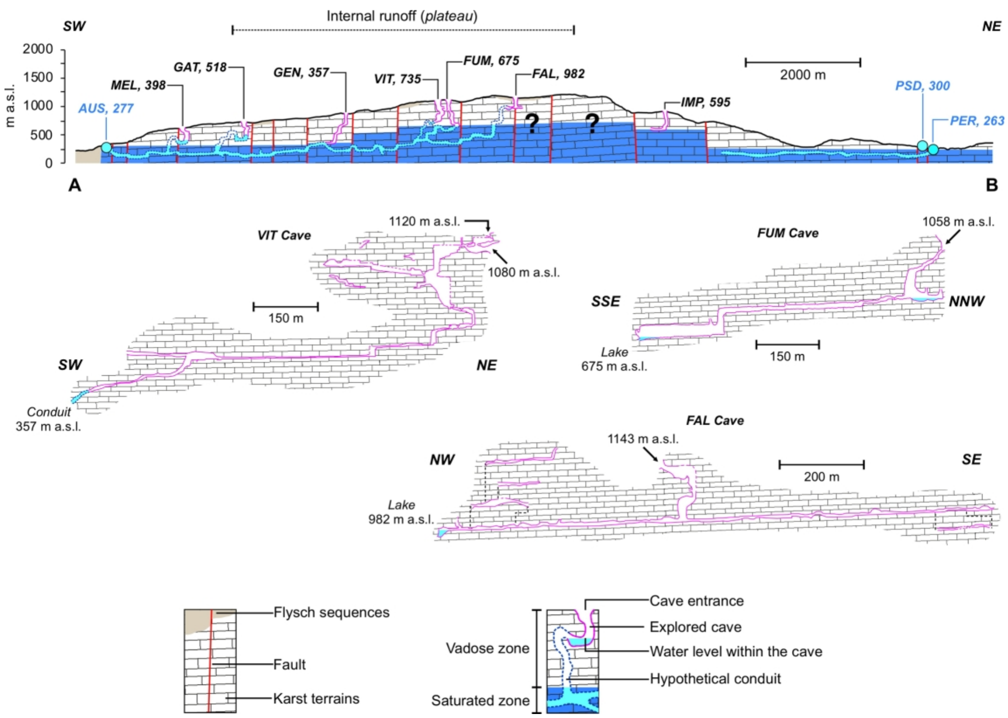
Geological map of the Alburni Massif.

200x108mm (300 x 300 DPI)



Map showing dolines and endorheic basins on the summit plateau of the Alburni Massif.

184x136mm (300 x 300 DPI)



Hydrogeological schematic cross-section across the Alburni Massif, based upon speleological data from the Regional Inventory of Caves of Campania, managed by the Campanian Speleological Federation. Trace of section in figure 1. Some profiles of selected caves are also shown, after the surveys from Campanian Speleological Federation (http://www.fscampania.it/catasto-2/catasto/), with addition of the strata attitude.

193x136mm (300 x 300 DPI)

4) Karst features of the Alburni Massif: A) the sump at Grotta del Falco (photo: GSAVD); B) view of the shafts in the Parchitiello system (photo: GSAVD); C) downhill sump in the Grave del Minollo (photo: GSAVD); D) Auso spring, at the S foothills of the massif (photo: F. Fiorillo).

289x202mm (300 x 300 DPI)

Table 1

LABEL	*SPRING NAME*	*Elevation (m a.s.l.)*	*Mean annual discharge (m^3/s)*
RMC	Risorgenza del Mulino di Castelcivita	65	nd
GDC	Grotta di Castelcivita	94	1.50
SCR	Controne	100	0.10
SP1	Postiglione1	570	0.10
SP2	Postiglione2	570	0.10
SP3	Postiglione 3	570	0.10
SCF	Sorgenti Cafaro	180	nd
FSS	Fontana Scorzo Sicignano	363	0.01
STN	Sorgenti del Tanagro	204	3.5
SAL	Sorgenti Auletta	235	nd
PSP	Polle sorgive Pertosa	195	nd
SPT	Sorgenti Petina	647	0.10
PSD	Polle Santa Domenica	243	nd
PER	Grotta di Pertosa	263	1.10
LSR	Lavatoio San Rufo	669	0.01
SSR	Sorgente San Rufo	636	nd
ASR	Abbotituro San Rufo	672	0.01
SVO	Sorgente Valetorno	848	nd
AUS	Risorgenza dell'Auso	280	1.00
FES	Sorgente Festola	280	nd
GDA	Grotta dell'acqua	875	nd

Table 2

ID	*LABEL*	*CAVE NAME*	*Cave entrance ELEVATION (m a.s.l.)*	*WATER ELEVATION (m a.s.l.)*
1	MAR	Grava di Maria	1300	1097
2	VEN	Grava del Vento	1270	1231
3	ISC	Inghiottitoio sotto Serra Carpineto	1230	1076
4	INV	Grava d'Inverno	1150	949
5	VIT	Grotta dei Vitelli	1120	735
6	FUM	Grotta del Fumo	1058	615
7	PAR	Grava II del Parchitiello	1112	907
8	SM2	Inghiottitoio Piani di Santa Maria II	1096	1094
9	SM3	Inghiottitoio Piani di Santa Maria III	1076	656
10	SM1	Inghiottitoio Piani di Santa Maria I	1086	807
11	OSS	Grava delle Ossa	1060	769
12	LAU	Grotta del Lauro	550	532
13	POE	Grava del Poeta	635	590
14	MIL	Grotta Milano	640	600
15	IMP	Inghiottitoio di Mastro Peppe	680	595
16	FAL	Grotta del Falco	1105	944
17	CAM	Grotta II di Campitelli	1099	993
18	MIN	Grava del Minollo	888	577
19	SER	Grava del Serrone	970	754
20	GSR	Grotta di san Rufo	698	672
21	GPA	Grotte del Piano di Allaga	912	870
22	GAO	Grotta dell'Auso di Ottati	280	260
23	MEL	Grava di Melicupo	674	415
25	GEN	Grava dei Gentili	841	404
24	GAT	Grava dei Gatti	943	541
26	GAU	Grotta dell'Ausino	69	49

Table 3

Category	Mean elevation	Area	F		T	AET	F_{eff}		RO	Q_p	R	C_R	C'_R	C_s	C'_s
	m a.s.l.	Km[2]	m^3x10^6/y	mm/y	°C	mm/y	m^3x10^6/y	mm/y	m^3X10^6	m^3X10^6/y	m^3X10^6/y				
Plateau area, A_E	1175	90	149	1658	7,.9	500	104	1157	0,0	0,.0	104	1,00	0,.69	0,.450	0,.646
Open area, A_O	828	177	243	1375	10,.5	569	142	805	13,.4	0,.0	128,.6	**0,.90**	0,.53	0,.550	0,.354
Alburni, A_C	945	267	392	1470	9,.6	545	246	923	13,.4	0,.0	232,.6	0,.94	0,.59	1,.000	1,.000