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### Uncertainties in understanding groundwater flow and spring functioning in karst

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Complete List of Authors:	Fiorillo, Francesco; University of Sannio, Benevento, Italy , Dipartimento di Scienze e Tecnologie Pagnozzi, Mauro; University of Sannio of Benevento, Dipartimento di Scienze e Tecnologie, Addesso, Rosangela; MIDA Foundation Cafaro, Simona; MIDA Foundation D'Angeli, Ilenia; University Aldo Moro, Earth and Environmental Sciences Esposito, Libera; University of Sannio Leone, Guido; University of Sannio Liso, Isabella; University Aldo Moro, Earth and Environmental Sciences Parise, Mario ; University Aldo Moro, Earth and Environmental Sciences
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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

	<p>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.</p>

## Uncertainties in understanding groundwater flow and spring functioning in karst

FIORILLO Francesco <sup>1</sup>, PAGNOZZI Mauro <sup>1</sup>, ADDESSO Rosangela <sup>2</sup>, CAFARO Simona <sup>2</sup>, D'ANGELI  
Ilenia Maria <sup>3</sup>, ESPOSITO Libera <sup>1</sup>, LEONE Guido <sup>1</sup>, LISO Isabella Serena <sup>3</sup>, PARISE Mario <sup>3\*</sup>

<sup>1</sup> Dipartimento di Scienze e Tecnologie, University of Sannio, Benevento, Italy

<sup>2</sup> MIDA Foundation, Pertosa, Italy

<sup>3</sup> Dipartimento di Scienze della Terra e Geoambientali, University Aldo Moro, Bari, Italy

\* corresponding author (mario.parise@uniba.it)

### 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

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

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

28

## 29 **Introduction: peculiarities of karst hydrogeology**

30 Karst is an extremely peculiar setting, with unique landscapes characterized by a variety of landforms (such  
31 as dolines, swallets, shafts, karrenfields, poljes, etc.), which act as sites of concentrated recharge for the  
32 aquifers and, together with the main geological and hydrogeological features of soluble materials, are at  
33 the origin of the turbulent flow of water within the karst rock masses (Worthington et al. 2001; Brinkmann  
34 and Parise 2012). Such peculiarities cause the need to approach hydrogeological studies in karst with  
35 dedicated methods and techniques, since implementation of the classical hydrogeological laws and  
36 procedures is not significant (Goldscheider and Drew 2007; Jourde et al. 2007). Starting from the non-  
37 correspondence among hydrographic boundaries at the surface and hydrogeological boundaries  
38 underground (Gunn, 2007; Parise, 2016), the whole issue of infiltration, transfer, and discharge of water in  
39 karst is extremely complex (Stevanovic, 2015, and references therein). In such a context, mapping some of  
40 the most typical karst landforms such as dolines/sinkholes, endorheic basins and poljes (Angel et al. 2004;  
41 Dorsaz et al. 2013; Miao et al. 2013; Fragoso-Servòn et al. 2014; Wu et al. 2016; Pagnozzi et al. 2019;  
42 Zumpano et al. 2019), understanding their mechanisms of formation (Waltham et al. 2005; Del Prete et al.  
43 2010; Gutierrez et al. 2014; Parise 2019), and their hydraulic role as well (Bonacci 1995, 2001; Fiorillo et al.  
44 2015; Parise et al. 2015), is of crucial importance to gain insights into the actual hydrogeological regime in  
45 karst areas.

46 In this contribution, through illustration of the Alburni case study (S Italy), one of the most significant karst  
47 areas in the country, we intend to point out to the difficulties inherent in understanding karst  
48 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.

54

## 55 **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):

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

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

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

121 As a consequence, the effective contribution to spring discharge of open areas,  $A_o$ , is:

122 
$$(C_s)_{A_o} = 1 - (C_s)_{A_E}$$

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

125 
$$(C'_s)_A = \frac{(F - Q_p)_A}{Q_s}$$

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

127

128 **The Alburni Massif**

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

133 The massif can be described as a monoclinal SW-dipping ridge marked by faults and composed of a Mesozoic  
134 carbonate sequence of Jurassic – Cretaceous age (Sartoni and Crescenti 1962); these soluble rocks are  
135 covered by a Miocene flysch sequence consisting of clays and sandstones (Scandone 1972; Ippolito et al.  
136 1973; Patacca and Scandone 2007). During the Pliocene and Pleistocene, several faults caused the uplift of  
137 the massif (Gioia et al. 2011; Cafaro et al. 2016), and the development of deep karst processes (Santangelo  
138 and Santo 1997). The summit plateau shows a variety of sites of concentrated water infiltration, typical of  
139 karst settings, such as dolines and shafts (Klimchouk 2000; Ford and Williams, 2007; Palmer 2007; Williams  
140 2008), which rapidly transfer the runoff into a complex network of caves and conduits (Del Vecchio et al.,  
141 2013; Cafaro et al., 2016), and then to the saturated zone of the aquifer. This concentrated recharge occurs  
142 mainly after intense rainstorms and snowmelt, whilst during normal rainfall events the recharge shows a  
143 diffuse modality, in function of the epikarst characters at the summit plateau.



144 The main springs (Basso Tanagro and Pertosa on the N side, Castelvita and Auso to the S) drain the saturated  
145 zone of the aquifer, and are distributed in the areas surrounding the massif; a systematic record of their  
146 discharge is missing, with only sporadic measurements available (Brancaccio et al. 1973; Celico et al. 1994;  
147 Ducci 2007). Overall, the total discharge can be estimated being in the order of 7-8 mc/sec (Table 1).  
148 Other minor springs are present along the massif, and still others drain perched water tables in the  
149 unsaturated zones.

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

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

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

162 Recharge can be defined as the downward flow of water reaching the water table (De Vries and Simmers,  
163 2002). In order to assess the recharge on the karst system at the Alburni, the hydrological analysis was  
164 preceded by a detailed geomorphological investigation of the karst landforms (dolines and depressions) on  
165 the summit plateau; both hydrological and morphometric analyses allowed to depict a specific overview of  
166 recharge processes in which such karst landforms play a predominant role, because the effective meteoric  
167 water falling on it contributes to feed the springs.

168 About 400 caves, with several of them reaching depth around 450 m, and with development of some  
169 kilometres, characterize the Alburni Massif (Bellucci et al. 1991, 1995). This remarkable karst is essentially  
170 related to the presence of the wide high plateau, bounded by fault systems, and with a variety of infiltration

171 sites, mainly corresponding to blind valleys and small catchments on the flysch deposits, which surface  
172 hydrology feeds the many swallets at the contact with the limestones (Santangelo and Santo, 1997; Del  
173 Vecchio et al. 2013; Cafaro et al., 2016). Through scrutiny of the data about the Alburni caves, all those where  
174 water was found were selected (Fig. 1 and Table 2). It must be pointed out that in these caves generally the  
175 presence of water corresponds to the end of the explorations, given the impossibility (in some cases) and the  
176 difficulty (in others) to pass the flooded passages. Further, presence of water does not necessarily mean that  
177 the saturated zone has been reached; actually, some of the water could be related to perched groundwater,  
178 due to less permeable intercalations within the stratigraphy, or to local clogging by debris and breakdown  
179 deposits. Nevertheless, we used the elevations at which water was documented into caves to build the  
180 hydrogeological profile shown in ~~figure~~ Figure 3, by assuming water as representative of the base water table.

## 182 Results

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

188 All karst landforms mapped and digitalized in a GIS environment provided a total number of 539 dolines, with  
189 average density of 5.97 depressions per km<sup>2</sup> (Fig. 2); 62% of these close depressions has area less than 0,1  
190 km<sup>2</sup> (Pagnozzi et al. 2019). Their pattern distribution highlights that the central plateau is mostly affected by  
191 dolines of small size, whilst only along the north-western, eastern and southern borders, endorheic areas are  
192 generally  $\geq 1$  km<sup>2</sup>. The statistical approach adopted in the study area allowed to assess the pitting index  
193 (total karst area/plateau area) which represent a measure of superficial karst development, providing  
194 information about the extent of karstification (Denizman, 2003; Haryono et al., 2017). At Alburni the ratio  
195 between karst area and plateau is 2.96.

196 To estimate the recharge, a preliminary delimitation of the catchment spring area,  $A_c$ , has to be provided.

197 Definition of the spring catchment area is a challenge in karst settings (Gunn 2007; Parise 2016), especially if

198 a wide karst system is drained by several springs, as at the Alburni Massif. A useful approach is to associate

199 the whole mountain or karst system to a lumped system, and to consider the overall output from spring

200 outlets, without focusing the analysis on a single spring and its relative catchment. In the Alburni case, the

201 karst terrains are bounded by impervious terrains which make the delimitation of the lumped spring

202 catchment easier; only along the SE sector, the spring catchment cannot be accurately defined.

203 Figure 3 provides the hydrogeological cross-section along the Alburni Massif considering some of the main

204 springs (Auso, 277 m a.s.l., to the S, and Pertosa, 250 m a.s.l., to the NE); the different elevation between

205 these springs is coherent with fault systems affecting the carbonate hydrostructure. Dolines and endorheic

206 basins drain the meteoric water on the summit plateau through the below network of shafts and conduits.

207 Looking at figure 3, the cave profiles, redrawn from the Regional Inventory of Caves of Campania, and adding

208 bedding information, highlight that development of the karst systems is highly controlled by the prevailing

209 discontinuity systems in the rock mass, both as sub-horizontal passages (bedding) and as vertical pits

210 (fractures or faults).

211 However, it is very arduous to assess the groundwater flowpath in the shafts (Jouves et al., 2017), so that in

212 many cases scholars refer to indirect methods in order to gain insights about the karst flow system

213 (geophysics, geodesy, etc.; Martel et al., 2018). In our case, detailed studies were carried out on the Alburni

214 catchment area, based on a methodical collection of available data about hydrology, water geochemistry and

215 piezometric data of the aquifer with its main outflows. Being the karst environment interested by a complex

216 system of conduits, passages and shafts (only partly known), the most reliable approach to propose a valid

217 hydrological model is represented by tracing experiments, particularly the cave-to-spring multitracer tests

218 (Goldscheider and Drew 2007; Filippini et al., 2018).

219 At Alburni, looking at the karstified limestone outcrops and at the morphological features of the calcareous

220 area with an elevation higher than that of the springs, the estimated recharge area is 267 Km<sup>2</sup>. This wide area

221 includes the karst plateau, considered as a unique closed area,  $A_E$ , extended 90.09 Km<sup>2</sup>. The catchment zones

222 outside the internal runoff area constitute the open areas ( $A_O = A_C - A_E$ ).

223 The main results are shown in Table 3; taking into account the effective rainfall distribution and the  
 224 temperature values, the mean actual evapotranspiration at Alburni Massif can be estimated (**545 mm/year**).  
 225 This value is comparable to evapotranspiration rates for nearby karst massifs of Southern Italy (Fiorillo et al.,  
 226 2015; Fiorillo and Pagnozzi, 2015), whilst the amount of recharge is higher in Alburni, due to concentrated  
 227 recharge at the summit plateau and to runoff being limited along the steep slopes bounding the massif.  
 228 Looking at the numbers listed in Table 3, the annual effective afflux ( $P_{\text{eff}}$ ) of the whole catchment area is **246**  
 229  **$\times 10^6 \text{ m}^3$** , the annual spring discharge ( $Q$ ) is  **$230.6 \times 10^6 \text{ m}^3$** , and the ratio  $Q/P_{\text{eff}}$  provides the effective recharge  
 230 coefficient of **0.94**. The difference between the effective recharge from precipitation ( **$7.8 \text{ m}^3/\text{s}$** ) and the  
 231 spring discharge ( **$7.4 \text{ m}^3/\text{s}$** ), estimated in  **$0.4 \text{ m}^3/\text{s}$** , could be associated to runoff losses and/or to minor  
 232 springs, for which discharge data are unavailable.

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

238 Considering only the summit plateau ( $90 \text{ km}^2$ ), this area totally contributes to spring discharge, as all the  
 239 recharge amounts inside endorheic areas are assumed to reach the basal springs; in particular it represents  
 240 34% of the total Alburni catchment, but provides about half of the effective contribution to spring discharge  
 241 ( $C_S = 0.45$ ), and is even higher in terms of total rainfall ( $C'_S = 0.65$ ).

242 The above estimations refer to a long-term scale (annual mean rainfall over a time span of several decades),  
 243 though annual recharge changes yearly, typically concentrating in specific seasons. Kessler (1967) highlighted  
 244 the role of the first four months of the year in controlling the recharge in a karst environment of Hungary,  
 245 and its dependence on the amount of rainfall recorded in the previous year (during the last four months).  
 246 These characteristics are even exacerbated in Mediterranean climate areas, especially within the framework  
 247 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 & Sebelja 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).

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

280 In the history of Alburni cave explorations, many tracer tests were addressed to prove the links among the  
281 karst systems and the basal springs (Del Vecchio et al. 2013; Parise and Santo 2017). Among the first  
282 outcomes, it has been demonstrated since the 1950's the link between the Castelcivita Caves and the Auso  
283 spring, for a total development of more than 6 km (Santo 1994). These researches were also useful to develop  
284 a first conceptual hydrogeological model along the Calore River. During the 1990's, an automatic datalogger  
285 installed at Risorgenza del Mulino provided data which indicated a deep circuit for the water at this spring (T  
286 16,5 °C), as also proved by later cave diving explorations. Further, the delay (24 to 48 hours) in temperature  
287 changes after intense rainstorms on the Alburni highplain testified the connection between the vertical  
288 systems and the basal water table (Santangelo and Santo 1997). More recently, other tracing tests  
289 demonstrated the hydrogeological connection among the active swallow holes in Piana dei Campitelli and at  
290 Grotta del Falco with the nearby spring at Grotta dell'Acqua (Bocchino et al. 2014; Cozzolino et al. 2015). At  
291 the same time, the fluorescein was detected also at the waterfall within the Pertosa Cave and at some springs  
292 in the Tanagro River, outlining a quite complex scenario, which still needs further data to be entirely  
293 understood (Pedrali et al. 2015; Pastore 2016). In particular, cave diving explorations at Grotta del Falco  
294 proved the development of the cave system through one of the main tectonic lines of the Massif, the Vallone  
295 Lontrano – Petina (Gueguen et al. 2012; Cafaro et al. 2016), which seems to transfer the water from this  
296 system to the central part of the Alburni Massif, toward Grava del Fumo and the S. Maria karst system, and,  
297 in turn, to the Auso spring on the SW foothills of the massif. This tectonic line acts certainly as an important  
298 draining structure, as actually previously hypothesized by Bellucci and co-workers (1991).

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

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

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

312

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For Review Only



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## 540 Figures

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

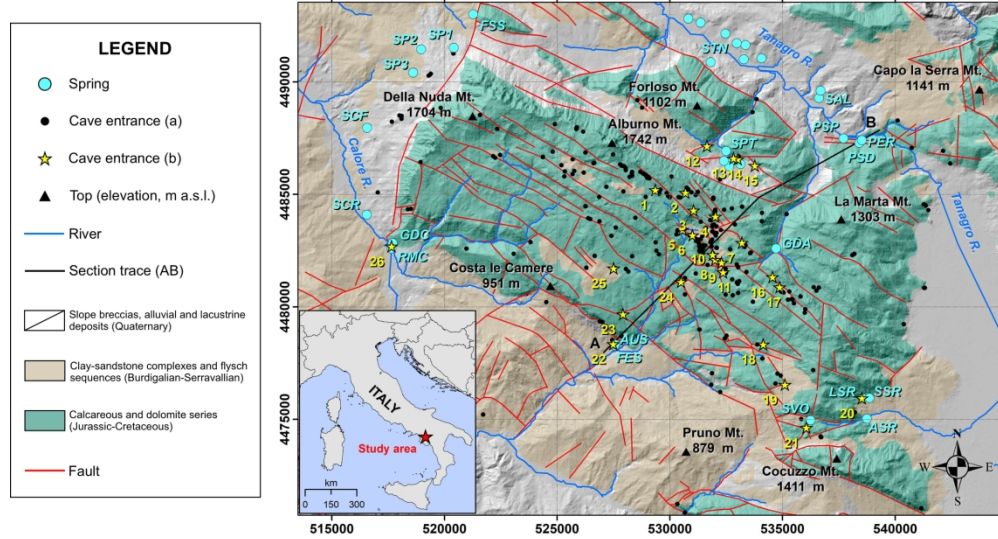
552

## 553 Tables

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

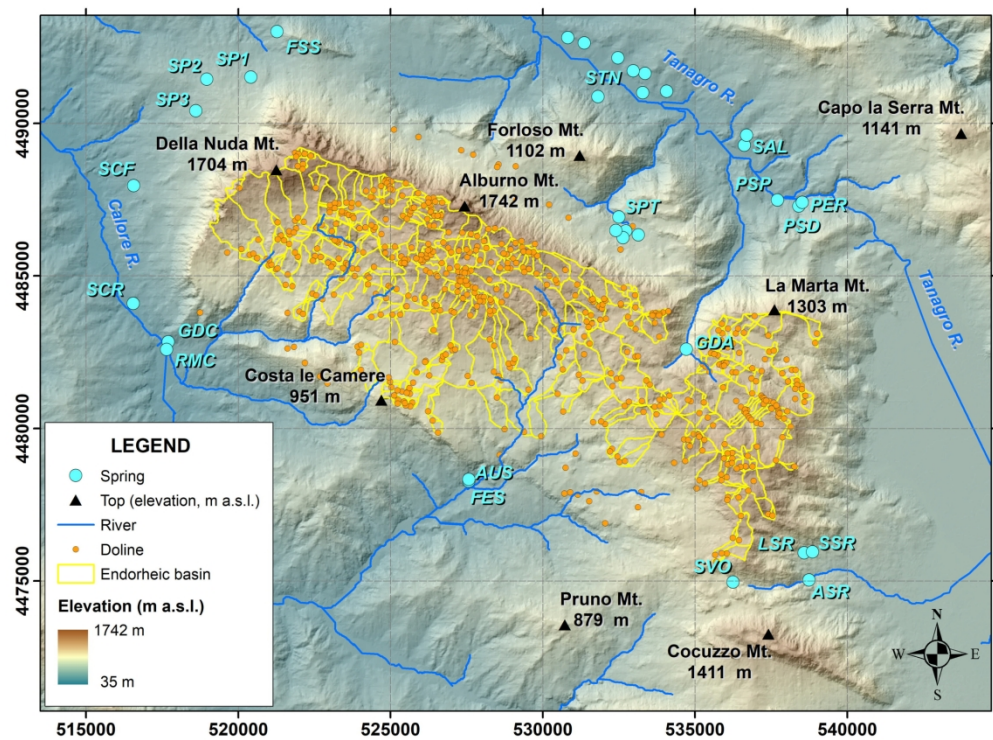
561 effective recharge coefficient;  $C'_R$ , total recharge coefficient;  $C_s$ , effective contribution to  
562 spring discharge;  $C'_s$ , total contribution to spring discharge.

For Review Only



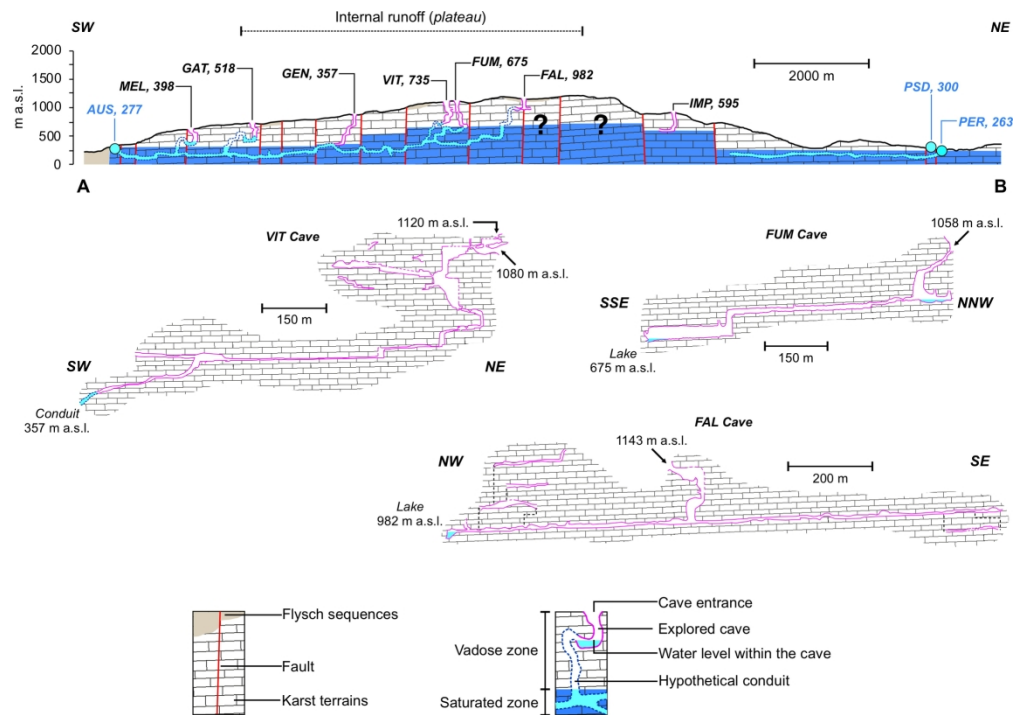
Geological map of the Alburni Massif.

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

<i>LABEL</i>	<i>SPRING NAME</i>	<i>Elevation (m a.s.l.)</i>	<i>Mean annual discharge (m<sup>3</sup>/s)</i>
RMC	Risorgenza del Mulino di Castelcivita	65	nd
GDC	Grotta di Castelcivita	94	1 <sub>-1</sub> 50
SCR	Controne	100	0 <sub>-1</sub> 10
SP1	Postiglione1	570	0 <sub>-1</sub> 10
SP2	Postiglione2	570	0 <sub>-1</sub> 10
SP3	Postiglione 3	570	0 <sub>-1</sub> 10
SCF	Sorgenti Cafaro	180	nd
FSS	Fontana Scorzo Sicignano	363	0 <sub>-1</sub> 01
STN	Sorgenti del Tanagro	204	3 <sub>-1</sub> 5
SAL	Sorgenti Auletta	235	nd
PSP	Polle sorgive Pertosa	195	nd
SPT	Sorgenti Petina	647	0 <sub>-1</sub> 10
PSD	Polle Santa Domenica	243	nd
PER	Grotta di Pertosa	263	1 <sub>-1</sub> 10
LSR	Lavatoio San Rufo	669	0 <sub>-1</sub> 01
SSR	Sorgente San Rufo	636	nd
ASR	Abbotituro San Rufo	672	0 <sub>-1</sub> 01
SVO	Sorgente Valetorno	848	nd
AUS	Risorgenza dell'Auso	280	1 <sub>-1</sub> 00
FES	Sorgente Festola	280	nd
GDA	Grotta dell'acqua	875	nd

Table 2

<i>ID</i>	<i>LABEL</i>	<i>CAVE NAME</i>	<i>Cave entrance ELEVATION (m a.s.l.)</i>	<i>WATER ELEVATION (m a.s.l.)</i>
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 elevatio n  m a.s.l.	Area  Km <sup>2</sup>	F		T  °C	AET  mm/y	F <sub>eff</sub>		RO  m <sup>3</sup> X10 <sup>6</sup>	Q <sub>p</sub>  m <sup>3</sup> X10 <sup>6</sup> /y	R  m <sup>3</sup> X10 <sup>6</sup> /y	C <sub>R</sub>	C' <sub>R</sub>	C <sub>s</sub>	C' <sub>s</sub>
			m <sup>3</sup> x10 <sup>6</sup> /y	mm/y			m <sup>3</sup> x10 <sup>6</sup> /y	mm/y							
Plateau area, A <sub>E</sub>	1175	90	149	1658	7 <sub>±</sub> 9	500	104	1157	0,0	0 <sub>±</sub> 0	104	1,00	0 <sub>±</sub> 69	0 <sub>±</sub> 450	0 <sub>±</sub> 646
Open area, A <sub>O</sub>	828	177	243	1375	10 <sub>±</sub> 5	569	142	805	13 <sub>±</sub> 4	0 <sub>±</sub> 0	128 <sub>±</sub> 6	<b>0<sub>±</sub>90</b>	0 <sub>±</sub> 53	0 <sub>±</sub> 550	0 <sub>±</sub> 354
Alburni, A <sub>C</sub>	945	267	392	1470	9 <sub>±</sub> 6	545	246	923	13 <sub>±</sub> 4	0 <sub>±</sub> 0	232 <sub>±</sub> 6	0 <sub>±</sub> 94	0 <sub>±</sub> 59	1 <sub>±</sub> 000	1 <sub>±</sub> 000