DOI: 10.4408/IJEGE.2019-01.S-14

HYDROLOGICAL FEATURES OF ENDORHEIC AREAS IN SOUTHERN ITALY

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EXTENDED ABSTRACT

In questo studio sono stati focalizzati alcuni aspetti geoidrologici di alcuni massicci carsici dell'Italia meridionale (Monti Alburni, Monti del Matese, Massicci del Terminio e del Cervialto). Le forme carsiche comuni a tutte le aree investigate sono le aree endoreiche, le quali rappresentano le aree di alimentazione preferenziali per la ricarica delle sorgenti. Pur rappresentando sistemi carsici con processi idrogeologici alquanto simili, i tre massicci analizzati in realtà mostrano alcune differenze nei meccanismi di alimentazione delle sorgenti, avendo avuto origini tettoniche differenti. I massicci del Matese e dei monti Picentini mostrano una prevalenza di macro-depressioni (*polje*) rispetto alle depressioni minori le cui evidenze sono rappresentate dai *sinkholes*, mentre il massiccio degli Alburni, caratterizzato da una differente evoluzione morfostrutturale, presenta un unico vasto plateau sommitale (*internal runoff area*) butterato da un elevato numero di depressioni minori. Tuttavia il bacino del Matese è caratterizzato da una elevata presenza di *sinkholes* concentrati lungo il margine nord-occidentale del massiccio. Dall'analisi effettuata si è desunto che proprio la diversa genesi evolutiva dei massicci analizzati ha portato ad un diverso assetto giaciturale degli strati che ha condizionato profondamente l'evoluzione e lo sviluppo delle forme carsiche epigee ed ipogee. Ciò ha permesso di evidenziare un pattern idrografico per il massiccio degli Alburni che risulta profondamente diverso dall'assetto idrografico dei Monti Picentini e dei Monti del Matese. A conferma di ciò, analizzando il reticolo idrografico dei Mt. Alburni, si evidenzia una netta separazione tra il *runoff* interno impostato su pendenze lievi dell'area endoreica del plateau sommitale e il *runoff* esterno dei ripidi versanti che bordano il fitto reticolo delle aree chiuse. Dalla congiunta analisi idrogeologica e morfologica si evince come il plateau sommitale degli Alburni contribuisce alla ricarica delle sorgenti carsiche basali in misura diversa rispetto alle aree endoreiche dei massicci dei Picentini e del Matese il cui contributo alle sorgenti di base risulta essere minore. Una correlazione preliminare è stata trovata tra l'assetto giaciturale e le caratteristiche morfometriche delle aree endoreiche; questa relazione aiuta a comprendere meglio i processi di ricarica dei sistemi carsici analizzati, in particolare per alcuni massicci carsici dell'Appennino meridionale, interessati da peculiarità orografiche e geomorfologiche. Il primo step ha riguardato un'analisi dettagliata delle aree endoreiche, evidenziando la dimensione eterogenea tra le macro depressioni del Terminio, Cervialto, Matese (*polje*) e le depressioni minori dell'altopiano sommitale del Mt. Alburno caratterizzato da una elevata densità di doline. Le differenze nello sviluppo e nella evoluzione dei bacini endoreici non possono essere spiegate solo con i processi di dissoluzione delle rocce carbonatiche; diversamente la pendenza degli strati può essere considerata un ulteriore fattore che ha un forte controllo sull'evoluzione delle aree chiuse. Successivamente i massicci degli Alburni, Matese e Picentini sono stati divisi in diversi blocchi omogenei per inclinazione degli strati. L 'analisi dimostra che strati molto inclinati consentono lo sviluppo di ampie aree endoreiche (*polje*) mentre strati debolmente inclinati favoriscono lo sviluppo di depressioni di estensione limitata, in particolare depressioni minori. Le depressioni chiuse sono particolarmente sviluppate sul plateau carsico degli Alburni, dove la maggior parte dell'acqua superficiale meteorica si infiltra verso la falda. Inoltre, il rilevamento dei *sinkholes* ha permesso di definire il tipo di distribuzione statistica (normale o gaussiana) che meglio rappresenta la loro distribuzione spaziale.

ABSTRACT

This work focuses on hydrogeological behaviour of karst systems in southern Italy (Alburni, Matese, Termino and Cervialto massifs). The karst landform common to all areas analized is endorheic area, which may be considered the preferential vehicle for basal springs and groundwater recharge. A preliminary correlation was found between strata layout and morphometric features of endorheic areas; this relationship helps to better understand the recharge processes of karst systems analyzed, particularly for some karst massifs of southern Apennines, affected by irregular orography and geomorphological features. The first step focused on a detailed analysis of endorheic areas, highlighting the etherogeneous size between the macro depressions of Terminio, Cervialto, Matese (*polje*) and minor-depressions of Alburni summit plateau typified by high density of sinkholes. The differences among endorheic karst landforms development can't be explained only with various processes of karst rocks dissolution; otherwise the strata dip may be considered the main factor having a strong control on closed depressions evolution. Then Alburno, Matese and Picentini massifs have been split in several blocks homogeneous for strata dip. The analysis highlights that the steep slopes of strata do not allow the formation of the closed areas, whereas gentle dip of strata support endorheic areas development, especially minor-depressions. The closed depressions are especially developed on the summit areas, where most of the surface meteoric water are conveyed underground. Additionally the sinkholes detection allowed to define the kind of statistical distribution which better represent their spatial distribution.

KEYWORDS: *geomorphology, karst hydrogeology, plateau, strata dip*

INTRODUCTION

The hydrogeological analysis carried out lead to better explain the influence of endorheic areas on groundwater recharge processes (FIORILLO *et alii* 2015). Recharge can be defined as the downward flow of water reaching the water table (DE VRIES & SIMMERS, 2002). The rainfall amount which is not involved by the evapotranspiration or runoff processes or that is retained by soil, without percolating downward, constitutes the recharge. The hydrological analysis was also supported by a detailed geomorphological investigation of karst landforms as macro-depressions (*polje*) and minor-depressions (sinkholes). The correlation between two kind of analysis (hydrological and morphometric) leads to a better understanding of structural layout, karst processes and recharge phenomena on the analyzed areas. Figure 1 shows the study areas: The Alburni karst system covers a wide area of southern Italy, extending over 270 km^2 about, reaching an altitude *of 1742 m a.s.l.;* it constitutes a well-defined massif, characterized by steep slopes surrounding a horizontal undulating plateau. Two main rivers bound the karst massif: the Calore Lucano to the SW, and the Tanagro river to the NE; their valleys are filled by heterogeneous alluvial deposits, slope breccias, sand and conglomeratic deposits.

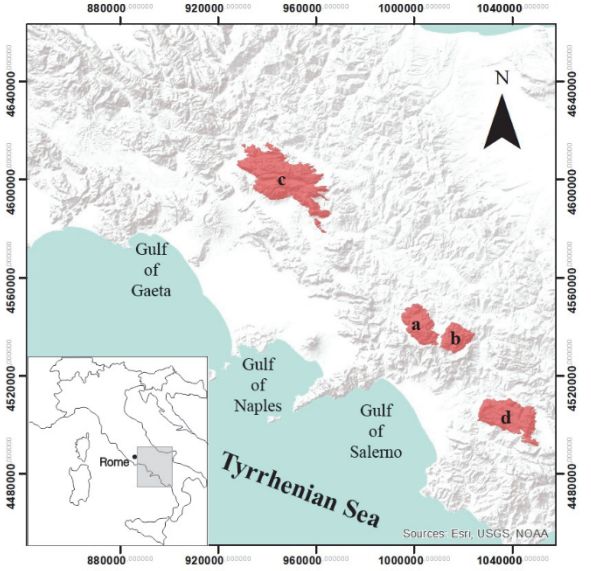

Fig. 1 - General map showing the karst systems analized: a) Terminio; b) Cervialto; c) Matese; d) Alburni

The Alburno massif belongs to the Alburno-Cervati Unit (SCANDONE, 1972; IPPOLITO *et alii*,1973; PATACCA & SCANDONE, 2007); it is characterized by monoclinal ridge, inclined to the SW), it is marked by fault systems and characterized by a Mesozoic carbonate sequence (Jurassic – Cretaceous); these soluble rocks are bounded by a flysch sequence constituted by argillaceous and sandstone series (Burdigalian –Serravallian); during the Pliocene and Pleistocene, several faults have caused the uplift of the massif (GIOIA *et alii*, 2011; CAFARO *et alii*, 2016), with the development of deep karst processes (SANTO 1988, SANTO 1991; SANTANGELO & SANTO 1997). The perimeter steep slopes of the massif are associated to main fault scarps, and the plateau is a consequence of the geostructural setting, affected by a sub-horizontal layout. This wide summit area, in the following called plateau, has induced the formation of numerous points of concentrated water infiltration, such as dolines and shafts (Ford and Williams, 2007), which rapidly transfer the runoff into a wide and complex systems of caves and conduits (CAFARO *et alii*, 2016), and then to the saturated zone of the aquifer (figure 2).The large springs (Pertosa, Castelcivita, Basso Tanagro) can be considered the main outflows of the karst system,, draining the saturated zone of the aquifer; a systematic record of their discharge is missing, and only sporadic measurements can be

found in the technical reports and literature (BRANCACCIO *et alii* 1973; CELICO *et alii*, 1994; DUCCI, 2007). Other minor springs drain perched water tables of the unsaturated zones. This karst massif can be considered as a hydrogeological structure with independent groundwater flow (CELICO, 1978), whose hydrogeological Units have different permeability features (CELICO *et alii*, 1994). DUCCI *et alii* (2008) analyzed the vulnerability and contamination aspect of this karst system (DUCCI 2007; DUCCI *et alii* 2008). Hydrogeological features of Matese, Terminio and Cervialto massifs with their relative endorheic areas are detailed in FIORILLO & PAGNOZZI (2015) and FIORILLO *et alii* (2015) respectively.

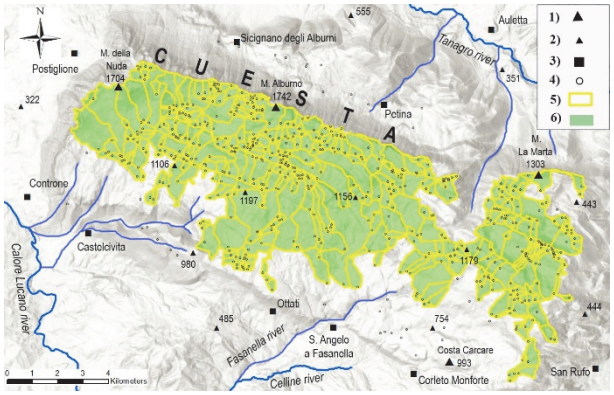

Fig. 2. - Map of karstic depressions on Alburni plateau
Legend: 1) mountain peak; 2) elevation point; 3) village; 4) sinkhole; 5) sinkhole's catchment area; 6) plateau. The relief base map allowed to point out the plateau watershed (Cuesta) splitting the internal runoff from external runoff area marked by main river and their relative streams.

MATHERIAS AND METHODS

Endorheic areas are closed depressions (SAURO 2005; 2012), where runoff is completely adsorbed (internal runoff; WHITE, 2002). These areas constitute important recharge zones of karst aquifers and generally are hydraulically connected to one or more springs. Outside endorheic areas, runoff can escape from the spring catchment, especially during intense storms; these areas are here named 'open areas' (FIORILLO *et alii,* 2015) constituting the external runoff zone. On the Alburni karst plateau the runoff can be considered as *internal* runoff (WHITE, 2002) as it ends in a shafts or dolines system; a similar consideration can be assumed for the snowmelt in this area. Thus the entire karst plateau can be considered as a wide closed area, where the runoff cannot escape from the catchment and must infiltrate in sinking points, providing a concentrated recharge. Outside the karst plateau, in the open areas characterized by steep slopes, the runoff can escape from the catchment and feed the rivers directly. FIORILLO *et alii* (2015) and FIORILLO & PAGNOZZI (2015) highlight the predominant role of endorheic areas in recharge processes of karst massifs, representing internal runoff structures where rainfall amount is completely adsorbed, recharging karst springs; nevertheless closed areas development is not only linked to karst processes of limestone dissolution but there is a strong structural control. After a preliminary step regarding the closed areas assessment using 1:5000 scale topographic maps supported by field survey, all strata dip of the study areas marked on 1:100000 scale geological maps, were uploaded in the GIS environment. Then a blocks network was built, where each block is characterized by similar strata dip. To map the closed depressions, a preliminary phase regarded endorheic areas detection and their uploading in a GIS database. All karst landforms were mapped using topographic map at different scale and digitalized in a GIS environment. In a typical karst environment, closed areas, characterized by karst shafts and water drainage point (swallow holes), drains surface water towards the aquifer; additionally the presence of other karst landforms such as karrenfield allow the seasonal storage of snow amount (Williams, 2008); for Terminio and Cervialto massifs were identified n. 7 and n. 5 closed areas respectively (Fiorillo *et alii*, 2015) whereas n.539 closed depressions were mapped on Alburni karst plateau, allowing to carry out a statistical distribution.

RESULTS

Table 1 shows the relationship found between strata dip and the development of endorheic areas. Morphometric analysis proves that closed depressions (wide until to few square kilometers) developed on strata characterized by horizontal or closed-to-horizontal layout; the strata slopes greater than 10° favor only the formation of *polje* (endorheic areas larger than several square kilometers).The high density of sinkholes on Alburni karst plateau is favored by horizontal and closed-to-horizontal framework of strata which allow the development in depth of dolines while the Matese and Picentini massifs are generally affected by *poljes* (orizzontal strata are absent), micro depression are almost missing because the strata dip is high.

The relationship found between endorheic area/sinkhole and strata dip lead to consider the presence of a thresholds for endorheic area size under which only the karst dissolution processes affect depression development, whereas the endorheic areas greater than thresholds size are strongly conditioned by tectonic activity which is predominant on karst processes in depressions evolution. The analysis of Matese massifs allowed to detect n. 15 macro-depressions (*polje*); whereas n. 130 minor-depressions (sinkholes) has been founds, particularly distributed along north-western sector of catchment area uphill Gallo and Letino lakes; an average density of 0.97 sinkholes/km^2 has been estimated; The analysis points out how more than 70% of Matese sinkholes are

embedded in lowest range size (0-0.1 km^2). Figure 2 provides an overview of karstic closed depressions with their relative catchment perched on Alburni plateau; pattern distribution highlights that the central sector of plateau is affected by minor-depressions; only along the north-western, eastern and southern borders, endorheic areas are ≥ 1 km^2; otherwise for Matese and Picentini the majority of closed depressions are > 2 km^2 (table 1). The statistical approach adopted in the study area allowed to assess the karst index (total catchment area/endorheic area) which represent a measure of superficial karst development, providing information about the extent of karstification (DENIZMAN, 2003; HARYONO *et alii*, 2017); the ratio between Alburni karst area and plateau is 2.96; the karst indexes, founds for nearby massifs are 4.07 (Cervialto), 2.37 (Terminio) and 4.45 (Matese) proving the high karstification rate for all massifs analyzed.The recharge processes were described for some karst massifs in southern Italy as Picentini (FIORILLO *et alii*, 2015; PAGNOZZI *et alii*, 2017) and Matese (FIORILLO & PAGNOZZI, 2015) providing simulation models at different time scale to analyze recharge processes of karst aquifers. Nevertheless the assessment of flow in karst shafts towards basal springs is very harduous to pinpoint, especially if continuous springs discharge data are not available as in the case of the Alburni basal springs (FIORILLO *et alii*, 2019).

Massif	Dip strata range (°)	n. blocks	n. closed depressions	Endorheic areas (Km^2)
MATESE	0 – 10	7	1	0 – 2,5
	10 – 45	30	14	2,5 – 45
	45 - 90	-	-	-
PICENTINI	0 – 10	3	2	0 - 2
	10 – 45	14	10	2 - 50
	45 - 90	3	-	-
ALBURNI	0 – 10	17	538	0 - 2
	10 - 45	12	1	2 - 4
	45 - 90	1	-	-

Tab. 1 - Main results obtained by correlation found between the homogeneous blocks analysis and morphometric features of closed depressions

The relevant role of Alburni karst upland (internal runoff area) is further highlighted by high effective contribution to spring discharge (FIORILLO *et alii*, 2019) although the plateau (90 km^2) represents only 34% of the Alburni catchment. The hydrological analysis provides a high effective recharge coefficient (FIORILLO *et alii*, 2019) for open area, assuming that annual runoff amount is only 13.4 x 10^6 m^3. The analysis of karst landforms, highlights that the karst plateau is a flat area (gentle slope) affected by karst shaft and sinkholes representing predominant features of the drainage system; slope angle highlights that the karst plateau, characterized by a mean ground-elevation of 1175 m a.s.l. is bounded by steep slopes; in any case the karst upland is affected by gentle slope. Particularly, sinkholes are aligned according to faults distribution (HÄUSELMANN *et alii*, 1999); the main depressions trend is NW – SE, with short alignments NE –SW. Considering the effective rainfall distribution, the regression line of temperature (table 2) allowed to estimate, using formula by TURC (1954), the mean actual evapotranspiration on Alburni catchment area, (545 mm/year) comparable to actual evapotranspiration found for other nearby karst massifs in southern Italy (529 mm/year and 587 mm/year for Cervialto and Terminio catchments respectively; PAGNOZZI *et alii*, 2013); the regression lines of temperature founds for Matese, Termino and Cervialto massifs are further described by FIORILLO & PAGNOZZI 2015, and Fiorillo *et alii,*2015. The recharge amount is higher than other nearby karst massifs in southern Italy (Picentini massifs; FIORILLO *et alii*, 2015; FIORILLO & PAGNOZZI, 2015) because Alburni mountains are characterized by a wide internal runoff area which allows rainfall to infiltrate quickly through sinkholes; runoff only occurs along the short steep slopes which bound karst plateau.

Massif	REGRESSION LINE				
	Temperature		Rainfall		
MATESE	y = -0.0070x + 16.43	R = 0.96	**(a)**	y=0.729x + 1105	R=0.97
			(b)	y=0.381x + 1067	R=0.65
PICENTINI	y = -0.0066x + 16.28	R= 0.96		y= 0.753x + 1207.1	R= 0.97
ALBURNI	y= -0.0078x + 17.09	R= 0.80		y= 0.814x + 703.3	R=0.75

Tab. 2 - Regression lines equations of temperature and rainfall obtained for karst massif analyzed; for Matese massif two different regression lines of rainfall were found for upwind zone (a) and downwind zone (b) of catchment area.

Alburni analytical outcomes confirm the recharge observations above-mentioned; considering volumetric amounts, the annual effective afflux (F_{eff}) of catchment area is 246 x 10^6 m^3, the annual spring discharge *(Q)* > 230 x 10^6 m^3; the ratio between Q and F_{eff} provides the effective recharge coefficient >0.90 (FIORILLO *et alii*, 2019), even if this value, differently to Matese, Terminio and Cervialto massifs, needs to further improvement monitoring Alburni basal springs, whose data are too discontinuous. The difference between effective meteoric afflux (7.8 m^3/s) and spring discharge (7.4 m^3/s) estimated as 0.4 m^3/s could be associated to runoff loss and other minor springs (FIORILLO *et alii*, 2019). The different recharge coefficient found in open areas between Picentini and Alburni can also be explained with different infiltration processes due to different morphometric and lithostratigraphic features of closed areas.

DISCUSSION

The lithostratigraphic analysis pointed out that the closed depressions affected by micro-areas (generally dolines and sinkholes) ranging between few hundreds of square meters until 2.5 km^2 are matched with gentle strata dip (0°-10°). Otherwise endorheic areas typified by a wide surface (*polje*) can be perched on structures with strata slope greater than 10°.The density and the size of endorheic areas in a karst environment provide precious information also about the age of karst

landform evolution. This point of view allows to enhance the geomorphological knowledge about the origin and evolution of closed areas with surface magnitude ranging from few square kilometers (doline, sinkholes) to several tens of square kilometers (*polje)*. For this reason the gentle strata dip of the Alburni plateau allows the evolution of micro depression as sinkholes, having meteoric water and weathering agent more time to interact with carbonatic structure. The karst massifs characterized by higher strata dip as Terminio, Cervialto and Matese massifs allow only the develop of wide endorheic areas (*polje*) typified mostly by tectonic activity which caused, through fault system, horst and graben structures. The analysis points out how Alburni massif shows specific geomorphological features and hydrological behavior that can't be found in other nearby karst environments in southern Italy (FIORILLO *et alii*, 2015; FIORILLO & PAGNOZZI, 2015). For Matese, Termino and Cervialto massifs, the catchments are characterized by concentrated infiltration phenomena occurring specially on endorheic catchment area, where swallow holes (Bocca del Dragone for Terminio; Brecce and Scennerato for Matese massif) drain meteoric water; however concentrated infiltration is particularly predominant on the Alburni karst plateau, whose flat area, characterized by gently inclined strata, allows sinkholes and dolines development; in this case diffuse infiltration is substantially reduced and can be neglected.

The distribution of the closed areas for different classes, A_i, is shown in Figure 3.a; the sum of all closed areas is 90.3 km^2, with mean 0.17 km^2 and standard deviation 0.33 km^2. The distribution of the number of closed areas, N_i, in each class is shown in Figure 3.b, where n. 539 closed areas of the Alburni plateau are plotted; the distribution highlights that most closed areas (62%) lie in the smallest class (0.0 ÷ 0.1 km^2), with rapid decrease according to a power with negative exponent of second order. The mean median and modal value are duly shown in figure 3c.

To highlight the distribution of closed areas in the smaller classes, the logarithmic plot is shown in Figure 3.c; the distribution of the closed areas appears likely gaussian or gamma in this case, which seems better to explain the distribution of closed areas for each class. These characteristics of the distribution of closed areas indicate that the natural tendency of a closed area to englobe the adjacent one by enlarging its boundary (water divide), appears weaker of the tendency to develop a new closed area. Of course, this morphological evolution depends on the karst characteristics of the area, which allows a rapid formation of sinkholes; in other karst environments of the Apennines, there are few closed areas but with wide extension (tens of km^2) where only few sinkholes control the drainage of large portions of karst catchments. Geological factors, as fractures and faults density, strata thickness and their attitude, appear important factors controlling landscape evolution.

High recharge coefficient affecting Alburni open area is an annual mean estimation on groundwater catchment, based on a overestimation of spring outlets (FIORILLO *et alii*, 2019); to compare the recharge volumes of Alburni with nearby karst massifs (Terminio, Cervialto and Matese) the availability of continuous discharge data is needed, quantifing also minor springs output.

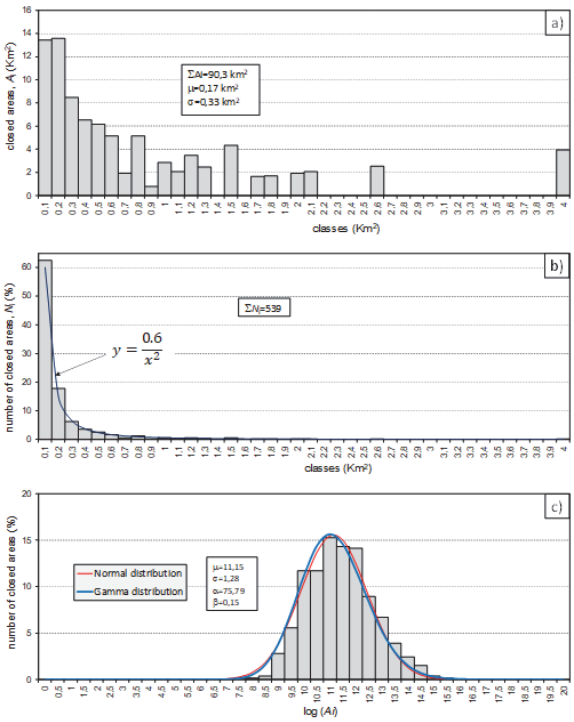

Fig. 3 - a) Distribution of Alburni closed areas for different classes; b) distribution of the number of closed areas, Ni*, in each class; c) the logarithmic plot highlights the distribution of closed areas in the smaller classes.*

CONCLUSIONS

The analysis carried out highlights how the recharge processes of karst massifs are connected to strata layout undergone to endorheic areas which are considered the main recharge zone of basal springs. Then several analyses were carried out on Alburni massif in order to better understand the overall recharge phenomenon on catchment affected by geomorphological complexity given by high density of sinkholes, dolines and karst shafts characterizing the internal runoff area (karst plateau). Even if the recharge simulation models were tested on Picentini and Matese providing valuable hydrological results, for Alburni the recharge parameters obtained need further in-depth analysis, planning an efficient field monitoring. In order to analyze the recharge phenomenon, the groundwater recharge analysis was integrated with a karst

geomorphological study which allowed to digitalize in GIS environment n. 539 sinkholes and their relative closed areas on summit plateau. A statistical approach was adopted in order to get a specific overview of karst landform perched on plateau, which can be considered a relatively young karst surface due to presence of minor-depressions which were predominant compared to wide endorheic areas characterizing nearby karst massifs (Termino, Cervialto and Matese). For this reason it was assumed that karst plateau (internal runoff area) is a lumped recharge system (unique closed area) and external runoff can be occur only along lateral steep slope bounding the upland. A brief comparison was carried out between the karst systems analyzed proving that Matese and Picentini massifs are strongly affected by *polje*, the presence of minor-depression is weak, while Alburni massif is affected by high density of closed areas which play a predominant role in recharge processes of the system, diversifying it from other carbonatic structures as concern the recharge coefficient. On Alburni, the hydrological analysis underlines how the ground-elevated flat area plays an important role in karst aquifer hydrological behavior, being the hydrogeological structure that mainly contributes to basal springs discharge through a well –developed karst shafts and conduits. The sporadic springs discharge data and the piezometric level data in karst shafts detected by previous studies allow to depict a generic overview of the groundwater flowpath in the conduits and the assessment of the contribution of karst shafts to discharge of each basal springs However from the hydrological and hydrogeological analysis carried out in this work, the predominant role of karst plateau on recharge of basal springs is highlighted. Moreover, because on the plateau the predominant kind of recharge is that provided by concentrate infiltration it could be mainly vulnerable to water contamination risk, overall considering that the sinkholes may be considered preferential vehicles for a generic polluting; then this karstic plateau should be preserved in order to reduce quality water contamination optimizing groundwater management.

ACKNOWLEDGEMENTS

Authors are grateful to anonymous reviewers for their helpful advice in the manuscript improvement.

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