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THRESHOLD BEHAVIOR OF THE SUPRAMONTE KARST AQUIFER (SARDINIA, ITALY) INFERRED FROM TRACER TEST: IMPLICATION FOR GROUNDWATER PROTECTION

ABSTRACT

The simulation of a contamination event has been explored performing an artificial tracer test in the Supramonte massif, a karst aquifer hosted in a remote area in Central East Sardinia (Italy). The experiment was carried out in July 2014 by injection of a small amount of Na-fluorescein in the lake of the Dorgheddie Cave, a shaft that opens within the fluviokarstic canyon of Gorropu, at the eastern side of the Supramonte aquifer. For its detection, charcoal bags were places in the two main accessible outflows of the karst aquifer: Gorrupu and Su Gologone springs, few hundred metres and 10 km from the cave, respectively. In winter 2015, six months later from dye injection and after few days of intense rainstorms following a very dry summer and fall, the fluorescein was detected at the Su Gologone spring. Even after several weeks of sampling, no fluorescent tracer was detected in the charcoal bags at the Gorropu spring. The tracer test has reveals a threshold in the karst aquifer that hydrogeologically controls the response of the Central-Eastern part of the karst system at least during low flow conditions as those of the hydrologic year 2014-2015. This functioning involves great challenges to the prediction of a hypothetic contaminant transport that would be detect at the spring with very long delay.

Key words: *karst hydrogeology; tracer test; threshold; pollution risk; Su Gologone; Gorropu.*

RIASSUNTO

Gli autori descrivono l'esperimento di una simulazione di contaminazione eseguito mediante un test di tracciamento artificiale nell'area centro - orientale della Sardegna, test costituito dall'immissione di Na-fluorescina nella grotta di Dorgheddie ubicata nel canyon di Gorropu - lato orientale dell'acquifero del Supramonte. I punti di captazione sono stati collocati nelle due principali sorgenti carsiche accessibili: Gorropu e Su Gologone, ubicate rispettivamente poche centinaia di metri ed una decina di chilometri dal punto di iniezione del tracciante. A distanza di sei mesi caratterizzati da siccità e dopo alcuni giorni di intense piogge, la fluorescina è stata nettamente individuata nell'acqua di Su Gologone mentre, anche a seguito di più campionamenti, nessuna traccia è stata rilevata nelle acque di Gorropu. Il tracciamento ha permesso di rilevare la presenza di una netta differenziazione idrogeologica all'interno dell'acquifero carsico. Una situazione questa che consente di prevedere, per questa area, provenienza, trasporto e tempi di percorrenza di ipotetici agenti inquinanti.

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INTRODUCTION

Karst aquifer are very susceptible to contamination and the release of pollutant might be quickly transport over large distances in high water conditions or could reach springs with long delay during dry periods. For an efficient protection of karst water against contamination it is essential to understand the characteristics of the solute transport within the aquifer in different hydrological conditions. This can be investigated performing an artificial tracer test as simulation of a contamination event. For important karst groundwater watersheds, the location of conduits system and their water flow directions should be identified using a variety of investigative techniques including dye-tracing tests. These analyses should include groundwater vulnerability evaluations (Guo et al., 2010).

This approach was applied to the Supramonte massif, a karst aquifer hosted in a forested remote area of Sardinia (Italy), geographically isolated and unapproachable for stable human settlements. For this reason, the quality of its groundwater is still relatively high (Lai et al., 2016) and exploited for drinking purposes at the Su Gologone spring (Sanna et al., 2017). Nevertheless, due to its rapid recharge from allogenic and autogenic water, this aquifer is particularly vulnerable to an eventual toxic substance infiltrated in its underground network. The potential sources of water quality disturbance of this area are mainly (1) livestock breeding, widespread over the whole karst massif, (2) local animal farming, especially important in the southern allochthonous recharge area on the impervious catchment, (3) no-legal waste disposal in sinkhole and (4) tourism activities along climbing routes, hiking trails and caves (De Waele, 2009). Although less important than in the past, stockbreeding (primarily pigs, secondarly goats and cows) represents the major risk for groundwater contamination if sewage water is concentrated and directly injected to underground aquifer in the sinkhole zone (Barroccu et al., 2007). Even if the current polluted input is very low so far, such quantity could hardly have any influence to groundwater at middle and high water flow, but can degrade severely the aquifer properties at low water level. Considering the drought scenario projected as impact of the climate change that this region is facing (Giorgi, 2006), the plan of a proper protection measures of this karst aquifer needs to know more about the underground water flow direction and dynamic. With this purpose, a tracer test experiment was carried out in July 2014 in the central-eastern sector of Supramonte with the aim to better understand the characteristics of groundwater flow and to assess the dynamic of the possible impact of a contamination event.

HYDROGEOLOGICAL SETTING

The Supramonte massif comprises a thick Middle Jurassic – Upper Cretaceous carbonate sequence, confined at the bottom by a Palaeozoic impervious basement, consisting of metamorphic rocks intruded by granitic batholiths, and locally overlaid from Tertiary and Quaternary covers (Pasci 1997). The carbonate-crystalline bedrock transition is often characterized by siliciclastic sediments deposited in continental and/or transitional environment. This karst aquifer is composed of 4 folded and faulted lithostratigraphic units: Middle Jurassic dolostones, Upper Jurassic limestones, Lower Cretaceous Limestones and Upper Cretaceous Limestones (Fig. 1). The limestone units have high karst permeability with secondary porosity while fractured basal dolostones are less soluble and this feature is well expressed in the cave passage morphology. Although the majority of the well-karstified caves in the Supramonte massif form in limestones, the upstream underground drainage network is developed in Jurassic dolostones and follows the inclination of the basement along major faults and axes of fold (synclines of Flumineddu-Gorropu and Lanaitto). The perennial recharge of the aquifer is fed by allogenic superficial streams in the South of the massif that extend over impermeable rocks that constitute the high-elevate Gennargentu mountain belt. Primary infiltration of precipitation over carbonate outcrops usually occurs in winter. The main hydrographic network (Flumineddu River) is active only after heavy rainfall while during most of the year waters

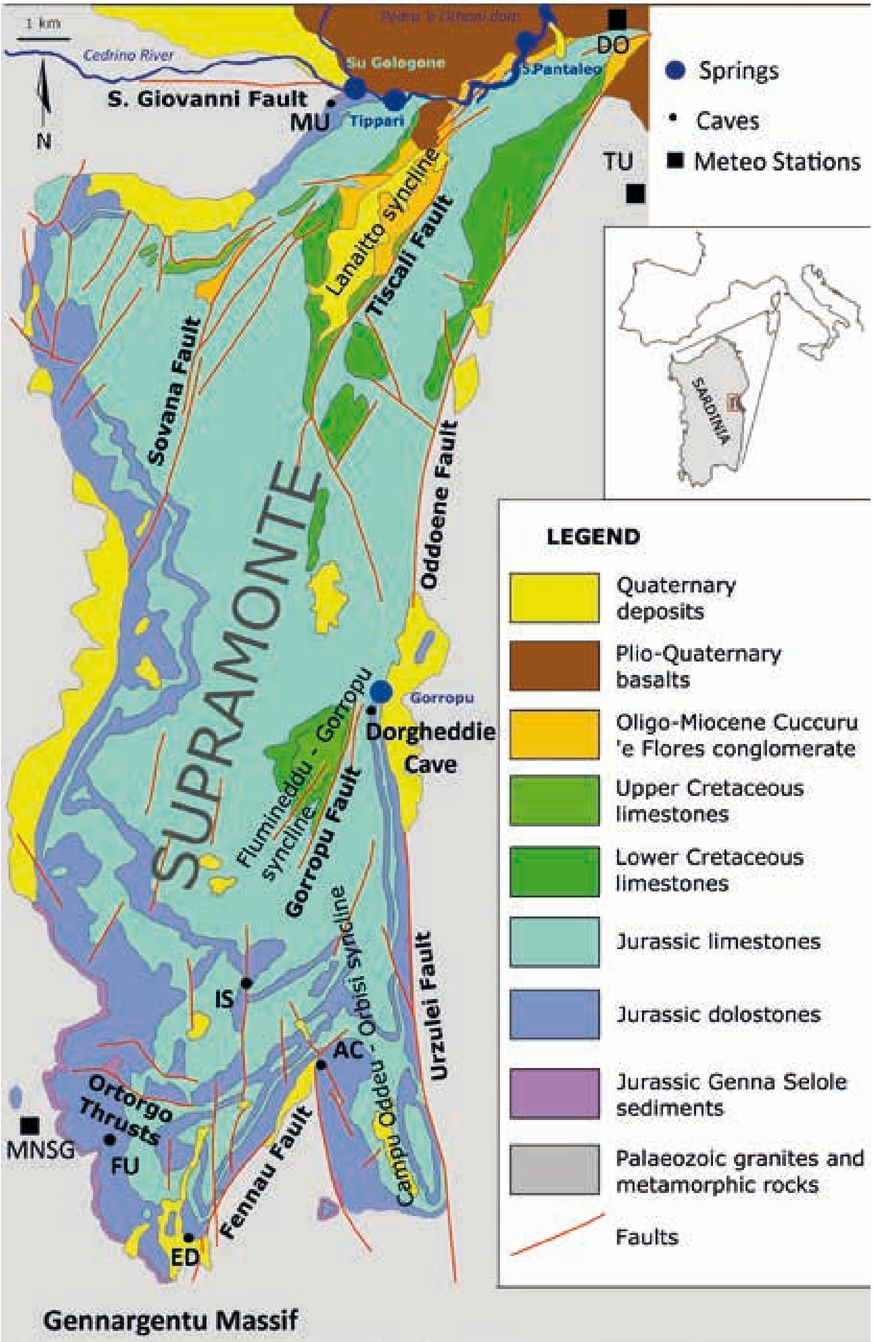

Fig. 1 - Geological sketch map of Supramonte karst massif (modified from Pasci 1997) showing the location of Dorgheddie Cave, Su Gologone and Gorropu springs and other reference points. Caves: ED: S'Edera sinkhole; FU: Sa Funga sinkhole; IS: S'Eni 'e Istettai cave; AC: Actifed cave; MU: Mussintomasu cave; Meteostations: MNSG: Monte Novo San Giovanni; TU: Tului; DO: Dorgali.

Fig. 2 - Main features of the study area: A) Su Gologone spring during the night (photo Vittorio Crobu); B) the shaft over the final lake at Dorgheddie cave (photo Vittorio Crobu); C) the steep syncline sides of Gorropu gorge where Dorgheddie entrance opens (photo Laura Sanna); D) Dorgheddie lake showing greenish fluorescent dye during the tracing experiment carried out in July 2014 (photo Laura Sanna).

flow mainly in underground conducts. The major inlets are located in the Fennau plain in the southern area (the sinkholes of S'Edera Cave, Sa Funga 'e S'Abba, etc.) while groundwater emerges 21 km far away mainly in the northern side of the karst massif along major tectonic contacts in the Cedrino valley (the main known spring are Su Gologone, Tippiri and San Pantaleo). Along the eastern edge, at the end of the Gorropu fluviokarstic canyon (where Flumineddu River leaves the carbonate plateau) there is another outlet with an average flow rate of 10 L/s. The position of the sinkholes at the altitude approximately of 950 m asl (S'Edera cave) in the southern sector and of the main spring at 104 m asl (Su Gologone spring) indicates a water gradient with North direction. This was confirmed by dye test experiment in 1999 when the water connection between S'Edera cave and Su Gologone spring was proved (Bandiera, 2000). Later, several further tracer tests have allowed to describe four routes of perennial underground streams in the Southern part of the karst plateau drainage network consisting of independent and parallel systems, without hydrogeological connections in their parts currently explored, but conveying their waters to the same main collector by supplying Su Gologone (Sanna, 2018). On the other hand, Dorgheddie cave (also known as Giuseppe Sardu cave), a 180 m-depth shaft opening in the Gorropu gorge (Fig. 2), and due to its short distance from the homonymous spring (around 300 m) it was though hydraulically connected to this outlet (Cabras et al., 2008). In fact, this cave lies exactly in the middle pathway between S'Edera sinkhole and Su Gologone spring, but very close to the eastern margin of the massif at an elevation of about 365 m asl, and represents one of the active underground conduit that drains the eastern side of the Supramonte aquifer. Taking into account the short way between these two points (Dorgheddie cave and Gorropu spring) this supposition could have suited very well as result of fracture flow through epikarst and vadose zone but this hydrogeological connection was never proved by any tracer test.

METHODS

To demonstrate the hypothesis that Gorropu spring was the probable outlet of the eastern side of Supramonte, a tracer test was carried out at the end of July 2014 in Dorgheddie cave. Based on the supposed distance the tracer had to travel, 150 g of Na-fluorescein was diluted in the sinking lake just below the waterfall within the Dorgheddie Cave (Fig. 2). The same day, the charcoal bags for tracer detection (captors) were placed into the water of Gorropu and Su Gologone springs. Later these captors were collected at various intervals. At the injection time, springs discharge was calculated as an average of 10 measurements at a weir point at Gorropu and from measured water level and discharge curve at Su Gologone.

The water physical parameters at the injection and sampling points were determined with a portable Hanna HI991301 sensor measuring pH, temperature (T) and electrical conductivity (EC). The range of this probe is between 0.00 and 14.00 for pH (resolution: 0.01; accuracy: ± 0.01), between 0.0 and 60.0 °C for the temperature (resolution: 0.1 °C; accuracy: ± 0.5 °C) and 0.00 to 20.00 mS/cm for EC (resolution: 0.01 mS/cm; accuracy: ± 2%). The alkalinity was determined in situ by titration with methyl orange and hydrochloric acid, as bicarbonate ion concentration (HCO_3^-).

Daily precipitation data were available online from the local meteorological stations (Monte Novo San Giovanni - MNSG, Tului - TU and Dorgali - DO weather stations) supplied by the Department of Meteorology and Climatology of the Environmental Protection Agency of Sardinia (ARPAS).

The charcoal-bag analyses were carried out after alcoholic potash extraction using a Turner Designs Digital fluorimeter equipped with a UV photomultiplier detector tube armed with fluorescein filters (E_{ex}=520 nm and E_{em}= 550 nm) with a detection limit 0.01 ppb. For the fluorescence measurement about 1.5 g of charcoal from the bag were treated, in duplicate, by extraction with about 50 mL of 10% KOH in methanol under stirring for 30 minutes. The solutions were then filtered and diluted to 100 mL again with 10% KOH in methanol. A certain quantity of both filtered solutions was diluted in 100 mL of distilled water and its absorbance measured respect to a standard of pure fluorescein of known concentration (about 0.1 ppm) prepared for each analysis. The reference standard was obtained by weighing about 0.5 g of sodium fluorescein to which was added 1 g of sodium decahydrate tetraborate and diluted to 1

L with distilled water. Breakthrough curve of the tracer was also recorded at the Su Gologone spring by a continuous monitoring system of the Nuoro Province.

RESULTS

The main physico-chemical parameters of groundwater at the outlet points and cave are reported in Table 1. Both cave and spring groundwater were near neutral in pH (7.06-7.38) reflecting their dominant circulation in carbonate rocks. The salinity was low in all monitoring points with conductivity (EC) <1 mS/cm, ranging between 0.30 to 0.37 mS/cm (the lowest values was observed in Su Gologone spring water), and with total dissolved solid (TDS) around 0.2 g/L. The alkalinity was higher in cave water (244 mg/L) and lower at the Su Gologone spring. Water temperature was 13.1 °C in cave and 13.0 to 14.5 °C at the Su Gologone and Gorropu springs, respectively. This large difference among waters in Dorgheddie cave and Gorropu spring represents the first clue that refutes the hypothesis of a hydraulic connection of these water points.

Water points	T (°C)	pH	EC (mS/cm)	TDS (g/L)	Alkalinity (mg/L HCO_3^-)
Dorgheddie cave	13.1	7.06	0.37	0.18	244
Gorropu spring	14.5	7.06	0.36	0.18	238
Su Gologone spring	13.0	7.38	0.33	0.16	170

Table 1 - Main physico-chemical parameters of groundwater at the karst spring and within the studied cave.

In autumn and winter 2014-15 an extraordinary dry period lasted a few months. At the time of injection water levels at the springs were low and discharge was at a minimum base flow. In the four months after the injection only one efficacious rain event occurred and it was not sufficient for the mobilization of the tracer toward the spring. At the beginning of February 2015, six months later from dye dilution and after few days of intense rainstorms and

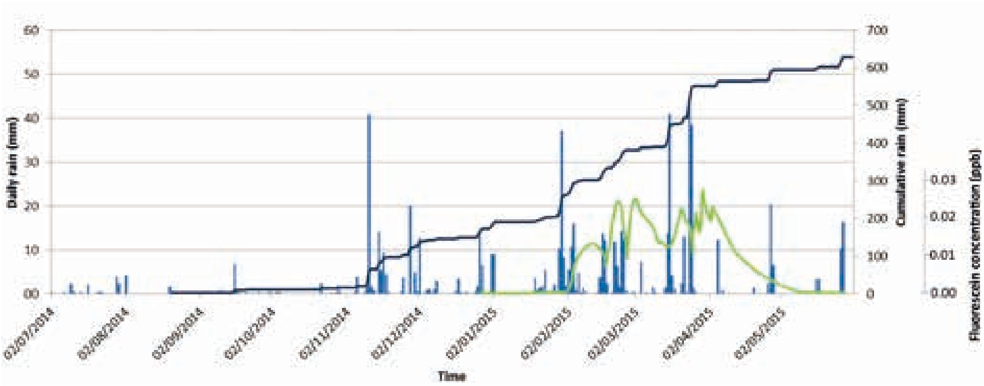

Fig. 3 - Relationship between cumulative rainfall vs breakthrough curve at the Su Gologone spring. Daily rain is also reported (data supplied by the Department of Meteorology and Climatology of the Environmental Protection Agency of Sardinia).

snow melting in the highest mountain belt, the fluorescein was detected at the Su Gologone spring. Figure 3 shows the relationship between cumulative rainfall at the MNSG meteorological station versus breakthrough curve at the Su Gologone spring. The cumulative rainfall graph shows that approximately 28 mm of rain were recorded in the period from November 11th 2014 to January 31st 2015. Additionally, precipitation was detected during the beginning of the next month, partly in the form of snow but this cover melted very fast with the rain contribution of 14 mm on February 3rd and 20 mm on February 5th. The breakthrough curve indicates that fluorescein was first detected the January 31st 2015, approximately 180 days after the injection, and the maximum concentration of 0.03 ppb was measured 25 days later of the first appearance. The interval time among the first detection and the maximum concentration of the tracer indicates strong dilution effects from important inflow of water without tracer which significantly diluted it. From this result it can be inferred that the recharge of the spring from other part of the catchment is significantly, namely at lower water level the inflow from Dorgheddie cave is negligible. The concentration temporary stagnated and further increased to the maximum value again at the end of March. Then the concentration slightly decreased and the detection limit was reached at the beginning of May 2015. Dye permanence at the Su Gologone spring lasted 3 months and in the time of tracing water, discharge ranged between 0.85 L/s and 5,000 L/s. Even after several weeks of sampling, no fluorescent tracer was detected in Gorropu spring.

DISCUSSION

Since 1999 thanks to results of various fluorescein tracer tests, it was clear that the Supramonte karst aquifer has a dominant drainage system, whose main collector drains groundwater from South to North (Bandiera, 2000; Cabras et al., 2008; De Waele & Sanna, 2008; Sanna, 2018). The stream that disappears within the S'Edera sinkhole passes through a large and intricate karst network, of which S'Eni 'e Istettai represents a median segment, before emerging from the North side of the Mesozoic massif, mainly through Su Gologone spring (deeper than 135 meters). The relationships with the recharge area and the northern sector are still not entirely clear, especially as some outflow points are inaccessible and cannot be investigated (such as the San Pantaleo spring, currently below the spillway level on the Pedra 'e Othoni dam), while in other active caves an anomalous response to tracer test was observed (lack of correspondence of green colour in the waters of Mussintommasu cave, near Su Gologone when the latter was visually positive to the fluorescein) (Sanna et al., 2017). The most important lateral leakage of the system was thought to be the Gorropu spring which, being negative to this and all previous dye tracer studies, is probably independent from the main flow path and drains the thick slope deposits on the eastern edge of karst massif. A recent dye test within the stream at the Actifed cave in Televai zone (Southern Supramonte) has also ruled out a feeding of Gorropu spring from this area (Cabras & Sanna, 2016).

The residence time of Supramonte groundwater varies naturally with discharges, over 70 days of transit time for the S'Edera-Su Gologone tracer test during the drought in 1999 and less than a month for the same distance in the spring of 2002. Usually travel time in this aquifer has an average of 300 m/day (Sanna & Cabras, 2015). The increased travel time during the dye tracing from Dorgheddie cave to Su Golgone and the analysis of this spring response reveal that the hydraulic connection among the eastern side of the aquifer and the emergence occurred at high discharge. The water level within the karst system needs to be sufficiently high to cause the overflow of a hypothetical hydrogeological barrier represented by geological structures such as faults and folds systems between Gorropu canyon and Lanaitto valley. This overflow could be explained with a functional threshold crossed after winter precipitation and snow melting at an equivalent groundwater level over the minimum base flow corresponding to a cumulative rainfall of around 200 mm.

This obviously poses great challenges to the prediction of flow and transport phenomena of a pollutant in this type of setting. Accidental contamination of Supramonte groundwater with a toxic substance could be detected several months later its release and could reach the spring with subsequent peaks lasting different days, jeopardizing public health. This has already been experienced in this area by the detection of tinopal (another artificial tracer contained in detergents) which reached the spring during a flash flood after a dry season.

Considering that Su Gologone spring is an important source of drinking water and of strategic importance in particular during dry periods (ensuring habitat preservation and water supply to the local communities), an adequate understanding of processes and response threshold should be employed for the hydrogeological characterisation of the karst system, for the assessment of its dynamic and vulnerability, and for the planning of a proper protection measures. Additional tracer tests should be performed to reach this goal.

CONCLUSIONS

During recent decades, the use of artificial tracers has given an important input to assess the impact of contamination events in karst aquifers. In this framework, this study has contributed to the hydrogeological knowledge of Supramonte karst area determining a new underground water flow connection. The catchment area of the Su Gologone spring has also been delineated at the eastern margin of the aquifer and the hydrodynamic behaviour of groundwater in the saturated zone in low flow conditions has been determined. The results of this tracer test experiment have also showed that at low water discharge a hydrogeological threshold avoids groundwater from the central-eastern part of the aquifer to tribute the main drainage system. Moreover, the hydraulic independence of Gorropu spring from the main cave system has been established. It was also highlighted the groundwater vulnerability of this karst system to a hypothetic contaminant transport during flash flood if the spring is recharged by polluted water from broader part of the aquifer. Additional research with tracer test at low and high water level should be carried out to test the hydrogeological function and the threshold behaviour also at higher discharge for better define the complicate geometry of this aquifer.

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