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Non-permanent shallow halocline in a fractured carbonate aquifer, southern Italy

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SUMMARY

We carried out hydrogeological, geophysical, hydrochemical, isotopic, and molecular biological investigations in a fractured carbonate aquifer in southern Italy to verify if prolonged variations in groundwater salinity with depth can be due to mixing processes between fresh infiltration water and groundwater.

All investigations revealed the formation of a non-permanent halocline at the experimental site, whose thickness and shape varies over time. Variations in thickness and shape are influenced by infiltration processes. Three main types of Electrical Conductivity (EC) profiles were found during the research period. In the high-flow period, the EC profile consisted of a transition layer and a nearly homogeneous higher salinity groundwater layer, and no mixed layer was observed. A nearly-homogeneous mixed layer was detected in the low-flow period, excluding the late recession when the EC profile was characterized by a higher salinity groundwater layer and a negligible transition layer. The EC profile through the transition layer was approximately symmetric and linear, probably due to a velocity shear across this layer. The velocity shear was probably caused by the difference in opening-porosity detected between the upper and lower carbonate bedrock through geophysical investigations.

The investigated phenomenon is due to water that infiltrates very close to the observation well. In fact: (a) the isotopic composition of the lower salinity groundwater layer in early recharge 2007/2008 ($\delta^{18}O = -8.12‰$; $\delta^{2}H = -49.92‰$) is very close to the composition of rainwater collected in the same period near the observation well ($\delta^{18}O = -8.19‰$; $\delta^{2}H = -51.35‰$); (b) the C_{DIC} composition in the lower salinity groundwater layer (−15,96‰) is very close to the composition (−15.77‰) in the infiltration water collected at the bottom of the soil medium, close to the observation well; (c) the lower salinity groundwater layer is characterized by significant concentrations of acetate (up to 4.5 mg/L) as well as the saturated paste extracts obtained only from the soil medium collected close to observation well (up to 110 mg/L); (d) in the lower salinity groundwater layer acetate-assimilating bacteria belonging to *Betaproteobacteria* and *Bacteroidetes* were found, further supporting that this groundwater layer significantly interacts with the soil medium described above. Similar mean ^{3}H contents in local rainwater (4.6 TU), in the lower salinity groundwater layer (4.5 TU), in the higher salinity groundwater layer (4.5 TU) and in spring water (4.4 TU) clearly show that the halocline formation is not influenced by differences in residence times.

Introduction

In fractured aquifers, variations in groundwater salinity with depth have been observed in the proximity of more transmissive fractures (Morin et al., 1997; Cook et al., 1999). Thus, this type of geophysical logging, coupled with other field investigations, is usually used to infer the geologic structure of a fractured aquifer and to detect the types and orientations of openings that have a major control on groundwater flow.

From a theoretical point of view, variations in groundwater salinity with depth may also be due to mixing between fresh infiltration water and groundwater. This should be similar to the effect produced by rainfall on the sea surface, where haloclines can be observed due to mixing between the fresh lens and the sea water (Price, 1979; Soloviev and Lukas, 1996; Wijesekera et al., 1999). Within a fractured aquifer, this type of halocline can be theoretically produced by infiltration water that percolates diffusely through a well-developed opening network, and joins the water table with a salinity significantly lower than that of groundwater.

The main goal of this study was to verify the effectiveness of this hypothesis, analyzing variations in groundwater salinity with depth at an observation well drilled at the Acqua dei Faggi

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experimental site (southern Italy). Vertical profiles of electrical conductivity were interpreted taking into considerations the results of geophysical, hydrogeological, hydrochemical, isotopic and molecular biological investigations. The hydrogeological behavior of the site has never been influenced by pumping.

Description of the field site

The study area is a carbonate aquifer (Acqua dei Faggi, Longano, southern Italy; Fig. 1) formed predominantly of limestone (Monte Calvello and Monaci Formations; Cretaceous-Oligocene; De Corso et al., 1998) and subordinately of lower permeability rocks (Macchiagodena Formation; Oligocene-Burdigalian; De Corso et al., 1998). The Macchiagodena Formation consists mainly of marls and marly limestone. Limestone is exposed or lies below Vitric Andosols (as defined by the FAO, 1988) throughout the study site, excluding the area close to the well (P1) used to analyze variations of groundwater salinity with depth. At this site, the soil is classified as a Calcaric Cambisol (as defined by the FAO, 1988) and lies above the lower permeability marls and marly limestone.

The aquifer is bounded by fault zones that act as barriers to groundwater flow and compartmentalize the aquifer system. However, some fault zones allow significant groundwater flowthrough, and the interdependence of hydraulic heads up- and down-gradient of these faults has been observed (Celico et al., 2006). The aquifer behaves as a basin-in-series system, where seasonal springs occur along some fault zones (Celico et al., 2006). At the basin scale, the groundwater flows westwards towards the perennial spring (Fig. 1).

The carbonate medium is laterally and vertically well-connected in the subsurface, and the fracture spacing is sufficiently dense to apply the continuum approach to describe groundwater flow at the metric scale (Petrella et al., 2007). A significant vertical heterogeneity of the carbonate bedrock has been found, due to differences in fissuring and karstification with depth (Petrella et al., 2007). Darcy's law can be applied in epikarstic horizons with some karstification, and groundwater flow is also expected to be laminar in diffusely karstified epikarst and in the underlying fractured bedrock (Petrella et al., 2008).

The fractured limestone responds rapidly to recharge events, due to fast and diffuse rainwater infiltration. The funneling effect into larger shafts does not play an important role in the hydrogeological behavior of the aquifer (Petrella et al., 2007).

Materials and methods

Geophysical investigations

One Schlumberger Vertical Electric Sounding (VES) was performed to define the shallow underground resistivity distribution close to observation well P1 (Fig. 1). The electrode distance (AB/2 = 300 m) was limited by local morphological features, but was enough to obtain information up to a depth of several tens of meters. The soundings were modeled using a simple one-dimensional (1D) terrain structure. Due to the roughness of the topography, it was not possible to do 2D profiling. However, several 1D inversions were performed, using different initial models, to check the consistency and uniqueness of the solution. Moreover, using an existing model (Petrella et al., 2007) to compute the expected resistivity curves, an "a posteriori" check of the validity of the suggested models was performed.

Hydrogeological investigations

The hydraulic head was measured at well P1 (130 m deep and fully screened; Fig. 1) on an hourly basis, from January 2007 to April 2008. The head was recorded with a pressure transducer. Precipitation was recorded at a meteorological station on an hourly basis.

Water sampling

Rainwater

Rainwater samples for isotopic analyses were collected at two rain samplers, RWS1 and RWS2, located within the aquifer system, at 1150 and 1014 m above sea level (m asl), respectively (Fig. 1). The sampling at RWS2 was carried out on a weekly basis, from January 2007 to April 2008. RWS1 was used to collect rainwater

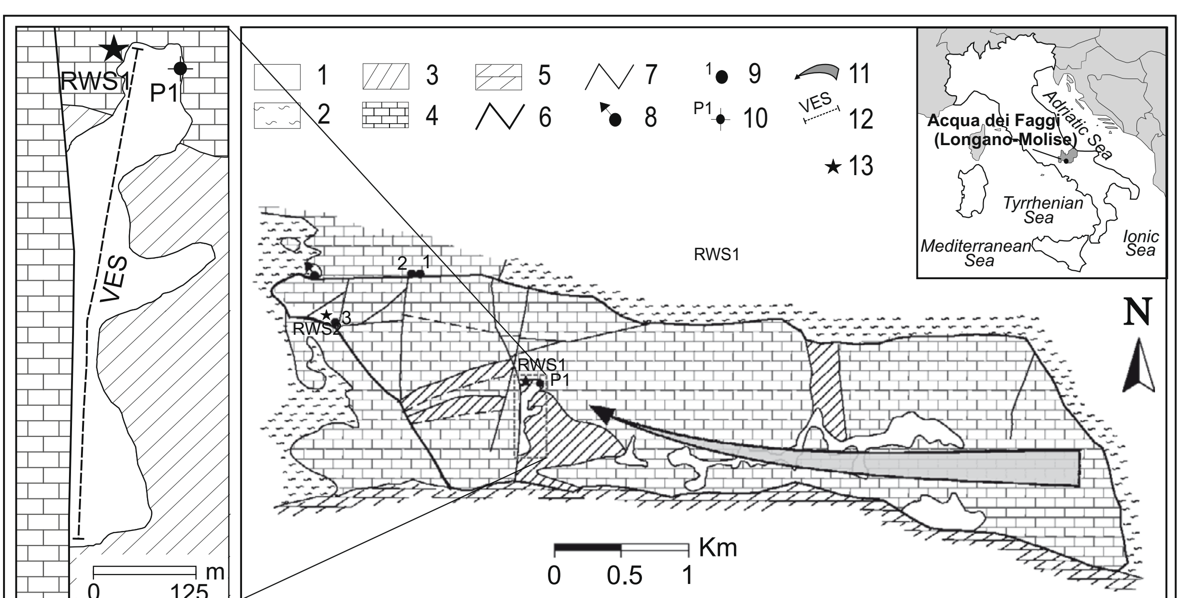

Fig. 1. Hydrogeological map (1 quaternary deposits; 2 marls and clays; 3 marls and marly limestone; 4 limestone; 5 dolostone; 6 aquifer boundary; 7 fault; 8 perennial spring; 9 seasonal spring; 10 well; 11 main groundwater flow direction; 12 Vertical Electric Sounding [VES]; 13 Rain Water Sampler [RWS]).