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Accidental contamination during hydrocarbon exploitation and the rapid transfer of heavy-mineral fines through an overlying highly karstified aquifer (Paradiso Spring, SE Sicily)

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ABSTRACT

The area around Ragusa in Sicily is well known for the exploration of petroleum deposits hosted in Mesozoic carbonate rocks. These reservoirs are overlain by less permeable rocks, whereas the surface geology is characterized by outcrops of Oligo-Miocene carbonate units hosting important aquifers. Some of the karst springs of the area are used as drinking water supplies, and therefore these vulnerable aquifers should be monitored and protected adequately.

In the early afternoon (14:00) of 27 May until the late evening (19:30) of 28 May 2011, during the construction of an exploitation borehole (Tresauro 2), more than 1000 m^3 of drilling fluids were lost in an unknown karst void. Two days later, from 06:30 on 30 May, water flowing from Paradiso Spring, lying some 13.7 km SW of the borehole and 378 m lower, normally used as a domestic water supply, was so intensely coloured that it was unfit for drinking.

Bulk chemical analyses carried out on the water have shown a composition that is very similar to that of the drilling fluids lost at the Tresauro borehole, confirming a hydrological connection. Estimations indicate that the first signs of the drilling fluids took about 59 h to flow from their injection point to the spring, corresponding to a mean velocity of ~230 m/h. That Paradiso Spring is recharged by a well-developed underground drainage system is also confirmed by the marked flow rate changes measured at the spring, ranging from a base flow of around 10–15 l/s to flood peaks of 2–3 m^3/s.

Reflecting the source and nature of the initial contamination, the pollution lasted for just a few days, and the water returned to acceptable drinking-water standards relatively quickly. However, pollution related to heavy-mineral fines continues to be registered during flooding of the spring, when the aqueducts are normally shut down because of the high turbidity values. This pollution event offers an instructive example of how hydrocarbon exploitation in intensely karstified areas, where natural springs provide domestic water supplies, should be controlled effectively to prevent such disasters occurring. This pollution incident is also a useful example of how such "accidental" tracer tests can identify rapid karstic flow-paths over long distances.

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1. Introduction

Although karstic rocks cover only about 12% of the Earth's ice-free land surface, around a quarter of the world's population relies upon water flowing out of karst aquifers (Ford and Williams, 2007). The largest fresh water springs flow out of carbonate areas, with flow rates that are often greater than several cubic metres per second. Carbonate rock outcrops are particularly widespread around the Mediterranean Sea, representing around 15% of the total catchment area, and supplying around 25% of the total domestic water supply (Bakalowicz, 2015). Unfortunately, karst aquifers are also much more vulnerable to contamination compared to other aquifer types because of: (1) rapid infiltration through fissures (more or less opened by dissolution) and swallow holes, as well as the direct input of sinking streams, all providing low resistance pathways for

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contaminated water and hence reducing the time available for biological purification processes; (2) soil cover is generally thin or absent hardly inhibiting flow, and enhancing rapid infiltration; (3) absence of granular rock texture, reducing natural filtration as a self-purification mechanism; (4) occurrence of zones with turbulent flow enhances transport of fine particles and contaminants (Drew and Hötzl, 1999; Daly et al., 2002; White, 2002; Pronk et al., 2006, 2009; Goeppert and Goldscheider, 2011; Marín and Andreo, 2015).

It is well-known that, from a hydrogeological point of view, karst aquifers are characterized by a dual or even triple porosity and permeability, always with flow through more or less open fractures and open conduits (Gabrovšek et al., 2004) and in some lithologies also through intergranular pores (White, 2002). This inposes high levels of heterogeneity and complexity upon the groundwater flow, which is thus almost impossible to understand on the basis of standard hydrogeological investigation methods such as borehole monitoring and pumping tests. In one sense the most suitable methodology of studying a karst aquifer resembles the approach used in surface hydrology (Bakalowicz, 2005), and a combined view of the three types of flow, conduit, fracture and matrix, generally seems to produce the best results (White, 2002).

Understanding the aquifer geometry is of primary importance in evaluating its vulnerability to contamination, and this can be achieved by various methods (Perrin and Luetscher, 2008). The more important methods include hydraulic and physico-chemical monitoring of springs, especially their response to storms, and tracer tests (Goldscheider, 2015).

Pollution of karst aquifers has been reported repeatedly, and incidents have shown that most pollutants travel very quickly through well-karstified systems: detection of such polluting events is therefore highly challenging (Ryan and Meiman, 1996). This means that many accidental pollution events pass unnoticed, especially if the contaminated springs are not used as drinking water supplies or are located in scarcely visited areas of difficult access. When, instead, the contamination involves springs that are used as drinking water sources, the same type of polluting event and successive artificial tracer tests can shed light on the structure and behaviour of the aquifer (Magal et al., 2013).

Pollution of surface aquifers by hydrocarbons has been reported in many areas around the world (i.e. Nadim et al., 2000; Jerez Vegueria et al., 2002; Ma et al., 2012), and is related mainly to leakage from waste disposal sites and storage tanks, accidental spills due to breakage of pipelines or during war (e.g. in Kuwait, Al-Sulaimi et al., 1993), and the disposal of oilfield wastewater. Aquifer pollution can also occur before the hydrocarbons production begins, during exploratory or infrastructure drilling operations.

Contaminants are often transported in the form of fines (which commonly sorb different chemical and bacterial pollutants) that are flushed out of the aquifer in high-flow conditions. Many such contaminated sediment plumes are short-lived (often no more than 2–3 days), and have shown pollutants to arrive at springs after delays of several hours, or even days, depending upon the aerial extent of the recharge basin (Mahler and Lynch, 1999). Such rapid transfer of polluted water to springs does not allow time for pollutants to transform completely into innocuous substances by processes such as biodegradation, although attenuation rates can be significant for some of the more typical compounds present in wastewaters (e.g. paracetamol, caffeine) (Hillebrand et al., 2015). It has been shown, however, that whereas turbidity is a good indicator of contamination, the lack of suspended material does not necessarily mean that there is no contamination (Dussart-Baptista et al., 2003). The initial flow conditions of the aquifer greatly influence the quantity of contaminant that will be released (Mahler and Massei, 2007), and so does the nature of the pollutant (Vesper et al., 2001). However, fine particles that transport pathogens also travel through karst aquifers under low flow conditions, though arriving at lower concentrations, indicating that karst aquifers are vulnerable to pollution no matter what the flow condition is (Goeppert and Goldscheider, 2008).

This study relates to an exceptional case of pollution of a karst aquifer by drilling fluids in an exploration borehole (Pozzo Tresauro 2) for hydrocarbons in Sicily's Ragusa oilfield (Ruggieri, 2015). Observations of this event has allowed some conclusions to be drawn about the hydrogeological structure of the polluted karst aquifer, and about the mode of contaminant transport of heavy-mineral fines from the accidental injection site to the karst spring.

1.1. Regional geological and hydrogeological setting

The contamination with drilling fluids occurred in the Pozzo Tresauro 2 borehole, located some 5 km west of the city centre of Ragusa, in Central-South Sicily (Italy) (Fig. 1). Tresauro 2 is an exploration borehole, one of many in the area, drilled from 509 m a.s.l. in the Ragusa oilfield. This exploration borehole had intercepted the deep oil reservoir and was to be converted into a production borehole by enlarging its diameter. Contaminants lost from the borehole were detected at the Paradiso spring, which lies 13.7 km to the southwest at an altitude of 67 m a.s.l. Flow rates from the spring are estimated to vary between 10 and several m^3/s.

Geologically, the central southern Hyblean platform is characterized by outcrops of carbonate- and volcanic-dominated rock sequences of Late Cretaceous-Late Miocene age (Grasso et al., 2000). Older underlying rocks are known from many deep boreholes (e.g. the Vizzini I borehole of 5.5 km depth, King, 1968), comprising dolostones and limestones of Triassic-Early Cretaceous age (Bianchi et al., 1987). These deeply buried Mesozoic carbonates are the main reservoir rocks for the important oil deposits of the Ragusa oilfield (Kafka and Kirkbride, 1959; Grasso et al., 2000; Granath and Casero, 2004).

The main geological structures affecting these sequences display a generally NE-SW trend, intersected by younger N-S lineaments (Grasso and Lentini, 1982; Grasso et al., 2000). The widespread occurrence of carbonate rocks together with their favourable structural setting has allowed the development of a karstic network with a clearly dominant NE-SW direction (Ruggieri, 2015). Karstification commenced after the emergence of part of the carbonate sequence, at the end of the Miocene, and is continuing at present. Rapid uplift, combined with Quaternary climatic cyclicity, has allowed the development of a series of stacked cave levels, connected by vertical percolation pathways (shafts) (Ruggieri and Grasso, 2000). The long period of karstification has created a highly vulnerable carbonate aquifer with a particularly high permeability due both to fissures and to karstic voids (Aureli, 1993; Ruggieri, 2005). Many karst springs in the area are used as sources of drinking water (e.g. the domestic supply of Ragusa city).

The presence of many caves and vadose shafts clearly indicates that this limestone is strongly karstified. Intense subsurface karstification is also confirmed by numerous examples of the loss of heavy drilling fluids at depths up to 70 m below the surface in the area. Some of the heavy fluid losses were far greater than that which occurred at Tresauro 2; as reported by the Regional Office of Hydrocarbons and Geothermal Energy (U.R.I.G.) in official documents: boreholes Ragusa 17 (795 m^3 of fluid), Ragusa 19 (692 m^3), Ragusa 57 (4568 m^3), Ragusa 58 (7155 m^3), and Ragusa 63 (1030 m^3) (Fig. 1). Because of this vulnerable karst aquifer overlying the oil reservoirs, the regional authorities have made prescriptive recommendations for the construction of new boreholes, asking the companies to use water as the only fluid

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