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Vulnerability mapping and protection zoning of karst springs. Validation by multitracer tests

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HIGHLIGHTS

- An approach for protection zoning has been proposed based on vulnerability mapping.
- Three source vulnerability methods, specifics for karst aquifers, are compared.
- The vulnerability map of the spring, by COP+K method, is used as protection tool.
- The protection zoning levels are proposed according to vulnerability classes.
- The validation by multi tracer tests, required step, supports the results obtained.

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ABSTRACT

Protection zoning of karst springs and wells used for water supply is a key aspect in many countries, calling for specific methodologies adapted to the particular characteristics of karst media. This work presents a new approach, in view of the present state of the art and based on experiences with contamination vulnerability mapping at the pilot site of the Villanueva del Rosario karst system (southern Spain). Source (intrinsic) vulnerability maps were prepared and compared using three European procedures for karst aquifers. The vulnerability maps were then tested using dye tracers. The COP + K method and Slovene Approach appear to provide reliable results in terms of intrinsic vulnerability mapping. Nevertheless, all the methods have a margin of error. The COP + K map is adopted as the baseline to delineate the protection zones, through the conversion from vulnerability classes to degrees of protection.

1. Introduction

Delineating protection zones for water supply and implementing proper land-use practices in surrounding areas are crucial aspects for a sustainable use of valuable drinking water resources (Adams and Foster, 1992; Foster et al., 2013). To prevent groundwater pollution, mostly owing to human activity, it is necessary to find a balance between socio-economic development and reasonable land-use planning.

According to Guidance Document No. 16 of the Water Framework Directive (WFD) on groundwater (European Commission, 2007), addressing Drinking Water Protected Areas (DWPAs) defined under Article 7 (European Commission, 2000), protection measures should be focused on (but not necessarily restricted to) zones around current or planned abstractions (safeguard zones or protection zones) in order to comply with Article 7 and Article 4.2.

In the context of delineating protection perimeters for groundwater sources for human supply, policy and standards vary from country to country (SAEFL, 2004; DVGW, 2006; DELG-EPAGS, 1999). This disparity is reflected in the number of zones established, the requirements concerning minimum dimensions, and the regulations regarding potentially polluting land-use activities. Yet vulnerability mapping, together with travel-time methods, is already used in many Member States as the approach for delimiting safeguard zones (European Commission, 2007).

In Europe, carbonate terrains occupy 35% of the land surface, and contribute up to 50% of the drinking water in some countries (European Commission, 1995). Freshwater from karst springs is a very important renewable natural resource. One obvious way of wasting this resource is through groundwater contamination. Karst aquifers are particularly sensitive to contamination, having a very low self-cleaning capacity due

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to their structure and hydrological behavior (Ford and Williams, 1989; Dörfliger and Zwahlen, 1997; Zwahlen, 2004), the flow concentration in the epikarst, a rapid recharge of infiltrating water underground and its fast distribution over large distances, high flow velocities and short residence time, etc. Consequently, the methodologies applied to delineate protection zones in karst aquifers call for additional, more specific considerations (Dörfliger and Zwahlen, 1997; Zwahlen, 2004; European Commission, 2007; Goldscheider, 2010). In acknowledgement of these issues, the Directorate General for Science, Research and Development of the European Commission supported the COST Action 620: "Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers".

Following official guidance documents on groundwater in drinking water protected areas (European Commission, 2007), the protection zones in karst aquifers may need to be defined using vulnerability maps as the tool.

The concept of vulnerability to contamination has been defined and developed by many researchers (Margat, 1968; Foster, 1987; Zaporozec, 1994; among others). European COST Action 620 (Zwahlen, 2004) aimed for consensual guidance about vulnerability and risk mapping for the protection of karst aquifers. Accordingly, 'intrinsic vulnerability' was described as the sensitivity to contamination of an aquifer, taking into account its geological, hydrological and hydrogeological characteristics, regardless of the nature and scenario of the contamination.

A European Approach was proposed within the COST Action framework for groundwater vulnerability mapping: the origin-pathway-target model (Daly et al., 2002), which discerns resource and source vulnerabilities, depending on the target or the receptor of potential contamination. In the case of resource vulnerability, the target to protect is the top of the saturated zone; the pathway is mainly through the layers above the groundwater surface. For source vulnerability assessment, in turn, the target is the karst water supply (borehole or spring), and consequently the pathway should include the unsaturated and saturated zones. The two concepts are very closely related, as it is impossible to protect a source without protecting the resource.

Several methodologies to assess vulnerability to pollution in karst aquifers have been evolved over the past two decades. Based on COST Action 620 recommendations and EPIK, the first method specifically designed for karst vulnerability mapping, (Dörfliger and Zwahlen, 1997), many other methods for vulnerability assessing and mapping have been developed, such as: PI (Goldscheider et al., 2000), KARSTIC (Davis et al., 2002); COP and COP + K methods (Vías et al., 2006; Andreo et al., 2009), the Slovene Approach (Ravbar and Goldscheider, 2007), or PaPRIKa (Kavouri et al., 2011). Geographic information systems and GIS-based approaches are widely used for the intrinsic vulnerability mapping of karst aquifers, although there are also relevant advances in geological and hydrogeological modeling for karst systems (Jeannin et al., 2013; Hartmann et al., 2014; Turk et al., 2014).

Groundwater contamination vulnerability mapping has implicit weaknesses, most notably residing in the subjectivity of its application. Nevertheless, it remains a tool with great potential for groundwater quality protection. It is relatively simple to apply, if supported by appropriate hydrogeological studies and baseline maps, and its implementation within land-use planning policies is intuitive, as the outcome is a map that shares a common territorial basis with the working environment.

The main aim of this work is to propose an approach for protection zoning karst springs based on the application and the comparison of results from contamination vulnerability methods, with validation of results by dye and natural tracers.

Despite increasing scientific contributions in terms of vulnerability mapping and groundwater protection, even in karst aquifers, there is still a need for new ideas, methods and strategies when facing the practical challenges of karst spring protection. The present work provides orientation in delineating protection zones for public drinking-water supplies in karst Drinking Water Protected Areas. The approach described here may serve to control diffuse pollution and prevent further deterioration of the environment (Water Framework Directive Guidance Document No. 16; Nitrates Council Directive 91/676/EEC; COST Action 620, European Commission, 1991). In view of the European guidelines for the protection of karst groundwater, the present proposal involves the application of pollution vulnerability assessment as a referential map to delineate protection zones. To this end, three methods for source vulnerability mapping were applied and compared, not only resource vulnerability maps, as in majority of previous studies (Vías et al., 2005; Neukum and Hötzl, 2007; Marín et al., 2012). As the final step, this work highlights the need to validate results obtained in karst aquifers where high anisotropy and heterogeneity can limit the extrapolation of data. Vulnerability maps and protection zoning should be validated to ensure their adequacy for land use management and groundwater protection (Andreo et al., 2006; Goldscheider, 2010). Validation may involve a wide range of methods and techniques (dye tests, natural responses of springs, environmental tracers, etc.), allowing for the characterization of fast and slow flows within the system, aquifer responses for high and low water conditions, the global response of the system, or the response to any short-term signal. The present study applies artificial dye tracers specifically tested for the identification of recharge areas and flow velocities, to assess and validate pollution vulnerability maps (Käss, 1998; Andreo et al., 2006; Benischke et al., 2007; Goldscheider, 2008; among others).

2. Pilot site: background and previous works

The case study is the catchment area of Villanueva del Rosario spring (14 km^2), largely responsible for drainage of the Sierra Camarolos and Sierra del Jobo aquifer (28 km^2), located 30 km north of the city of Malaga, Southern Spain (Fig. 1). The relief is rugged, with altitudes ranging from 600 to 1640 m a.s.l. The climate is temperate Mediterranean, with a mean historic annual precipitation of 760 mm, highly influenced by the altitude (below 600 mm in the lower sectors and up to 900 mm in the higher areas). The precipitation regime is associated with wet winds coming from the Atlantic Ocean in autumn, winter and, to a lesser extent, in springtime. The mean annual temperature is around 14 °C, but there are only temperature records for lower areas of the aquifer. The prevailing vegetation is Mediterranean scrubland with forest patches (Mediterranean forest and pines from reforestation).

Geologically, the test site is situated within the Betic Cordillera and is made up of Jurassic carbonate rocks, with a maximum total thickness of 400–450 m (Peyre, 1974). The base of the stratigraphic series is constituted by Upper Triassic clays with evaporite rocks (mainly gypsum). Above these lies a dolomite formation followed by limestones; at the top, there are Cretaceous–Paleogene marly-limestones and marls. To the north and south of Alta Cadena, Flysch-type rocks crop out, including Tertiary clays and sandstones. The geological structure of the aquifer is characterized by a severe degree of deformation: ENE-WSW lying folds, from which overthrusts developed, with S-SE vergence (Figs. 1 and 2). The whole structure is affected by more recent fractures (faults and joints) in a mainly NW-SE direction (Figs. 1 and 2; Martín-Algarra, 1987). This geological complexity causes hydrogeological heterogeneity.

Two main soil types can be distinguished. The carbonate outcrops are covered by patchy leptosols (thickness <30 cm), whereas less permeable soils with a thickness of 10–70 cm and a silty–clayey texture overlie the Cretaceous marls.

Karst features are developed mainly on Jurassic limestones, with large karrenfields, dolines and uvalas. There are also some karst swallow holes (Fig. 1) which become active during storms or heavy rainfall. No evidence of caves exists in the study area, despite the activity of speleological groups.

From a hydrogeological standpoint, the aquifer is constituted by fractured and karstified Jurassic carbonate rocks, limited along almost all their borders of a tectonic nature by low permeability materials (Triassic and Flysch clays and Cretaceous–Paleogene marls). The boundaries and recharge area of the system were outlined taking into account the results obtained from hydrogeological studies and multitracer tests