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Hydrogeological investigations and groundwater vulnerability assessment and mapping for groundwater resource protection and management: State of the art and a case study

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ABSTRACT

The available literature was used in this work to review the methodologies for groundwater vulnerability mapping. The objective of the literature review was to define the vulnerability concept and to discuss the best way to establish aquifer vulnerability maps and the utilities of these maps for groundwater protection. In this study, we explore the hydrodynamic properties of the Grombalia aquifer system in north Tunisia to evaluate the vulnerability of groundwater. The established vulnerability maps are used for groundwater managing and protection. In Grombalia basin, the groundwater resource is used for agriculture and drinking purposes. The intrinsic vulnerability of the phreatic aquifer of Grombalia is mapped using the standard DRASTIC, a modified DRASTIC and a DRIST model. The adopted methodology for the intrinsic vulnerability mapping is based on the hydrogeological system properties. The vulnerability index calculation was used to establish a map with areas of vulnerability degree. This method is based on the combination of various topographical, lithological and hydrogeological data using Geobased Information System software. These methods consider the attribution of a numeric index to each considered parameter. In the established map, 26% of the aquifer extension is vulnerable according to standard DRASTIC model. The modified DRASTIC method, which considers the vadose zone heterogeneity and the aquifer geometry, showed that 17% of the studied area is occupied by a high vulnerability. The application of the DRIST model showed a high vulnerability in area covering 66% of the extension of the shallow aquifer of Grombalia. This important vulnerability is due mainly to vertical parameters implicated in the infiltration of the pollutant. The established vulnerability maps provide recommendations for groundwater resource protection in the aquifer system of Grombalia. We conclude that the three used models for vulnerability assessment and mapping reveal the susceptibility of the aquifer system to the special effects of pollutants.

1. Introduction

Because of the auto epuration function of the reservoir, groundwater is protected to the contamination. The surface water is the most sensitive to the pollution. Nevertheless, if the water resource is contaminated, it is not easy to modify its quality. Moreover, the groundwater quality is closely related to the lithology and the thickness of the vadose zone and the geometry of the reservoir. All the hydrogeological aspects of the aquifer system such as recharge zone, groundwater flow and land use must be involved in the evaluation of the water resource quality.

Assessing the vulnerability of groundwater resource is a preventive tool for controlling groundwater contamination (Farjad et al., 2012). Aquifer system protection is necessary for a sustainable use and protection of the groundwater resources (Gogu et al., 2003; Liggett and Talwar, 2009; Demiroğlu and Dowd, 2014). The aquifer protection issues are discussed using the groundwater vulnerability concept. Groundwater vulnerability to the pollution is a dimensionless parameter which is not directly measurable. The vulnerability is also identified as the hazard of the groundwater linked to the vadose zone lithology and the properties of the contaminant (Babiker et al., 2005; Musekiwa and Majola, 2013; Demiroğlu and Dowd, 2014). The vulnerability of an aquifer to the pollution is related to many parameters such as lithology of the aquifer, geometry of the reservoir and hydrogeology (Varol and Davraz, 2010; Moratalla et al., 2011). The available

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models for the assessment of the groundwater vulnerability are based on the combination of several hydrogeological parameters involved in the contamination process of groundwater.

The first use of the vulnerability concept in hydrogeology was from 1970 (Albinet and Margat, 1970). The vulnerability concept was described based on the effect of the vadose zone to protect the groundwater quality. In fact, the vadose zone can play a key role to eliminate some pollutants infiltrated from surface water. From 1980s, various models and approaches for the vulnerability assessment and mapping have been developed and tested all over the world (Haertle, 1983; Aller et al., 1987; Foster, 1987; Foster and Hirata, 1988). The process of groundwater vulnerability mapping combines hydrogeological parameters of the aquifer to establish a map with a zoning related to the susceptibility of groundwater contamination by pollutant (Foster et al., 2002).

The objectives of the manuscript are the establishment of the groundwater vulnerability map of the shallow aquifer of Grombalia and the elaboration of the groundwater contamination risk map of the aquifer system. The adopted approach is summarized in the following steps: (1) geological identification of the aquifer system; (2) geometry of the aquifer; (3) hydrodynamic characterization of the aquifer system; (4) intrinsic Vulnerability assessment and mapping (using DRASTIC model, Modified DRASTIC model and DRIST model); and (5) comparison of the 3 generated vulnerability maps and elaboration of map showing the contamination risk map of the shallow aquifer of Grombalia. The overall objective of this study was to generate and compare groundwater maps of intrinsic vulnerability and risk using 3 vulnerability assessing models, Geographical Information Systems (GIS) and available geological and hydrogeological data.

2. Review of methodologies for aquifer vulnerability mapping

The vulnerability to contamination of an aquifer system is a concept directly related to its sensitivity to pollutant (Vrba and Zaporozec, 1994). The vadose zone has an important function in the pollution of groundwater. It is the part of aquifer where the infiltration and the transport of the contaminant take place. Thus, the integration of the vadose zone in the vulnerability evaluation becomes with higher importance to have idea about the groundwater contamination susceptibility. As presented and defined in previous sections, the groundwater vulnerability can be assessed and mapped in two manners:

- The intrinsic vulnerability is assessed and mapped based on the hydrogeological properties of the aquifer system (Civita, 1994).
- The specific vulnerability is related to some specific pollutants. It characterizes the sensitivity of groundwater to be contaminated by a specific contaminant (Schnebelen et al., 2002).

The evaluation of the intrinsic vulnerability is the result of the superimposition of many maps reflecting hydrogeological parameters. The resulting map of the vulnerability mapping process is a zoning of the aquifer extension with specific degree of vulnerability (Farjad et al., 2012). A variety of models are available to assess and map the groundwater vulnerability. We can distinguish the following methods for the vulnerability assessment: (1) an approach using the vulnerability index; (2) a computer aided vulnerability mapping approach (Marcolongo and Pretto, 1987; Schnebelen et al., 2002); and (3) methods based on the statistical treatment (Antonakos and Lambrakis, 2007).

The mapping method based on the intrinsic vulnerability index is applied using Geobased Information System software to assess and map all hydrogeological parameters considered in the vulnerability evaluation. This method consists on the attribution of an index to each hydrogeological parameter. The simulation methods take into account all the physical and dynamic properties of the aquifer. It is based on the resolution of the equations of pollutant transfer process. This method involves several hydrogeological data that are not usually available.

The intrinsic vulnerability assessment and mapping considers the physical properties of the reservoir and the hydrodynamism of the groundwater in the aquifer system. The most common models for vulnerability mapping are (1) DRASTIC, (2) SINTACS, (3) GOD, (4) AVI, (5) SYNTACS, (6) SI, and (7) EPIK. Some specific methods of intrinsic vulnerability mapping are applied to coastal aquifers such as GALDIT model (Chachadi and Lobo-Ferreira, 2005). For vulnerability mapping in karst aquifer, EPIK model is applied (Doerfliger et al., 1999). The vulnerability map in fractured aquifer can be established using the DRASTIC-Fm model (Denny et al., 2007).

The intrinsic vulnerability of groundwater and the susceptibility of the aquifer system to the pollution are presented in a map. The zoning map of the aquifer extension according to the vulnerability index is used by planners and decision makers to establish the policy of water resource protection and management. These vulnerability maps are used to establish a scenario to avoid groundwater pollution process and to protect and manage the available water resource.

It is important to evaluate the reliability of the established maps by the application of more than two models and by the analysis and the validation of the quality of used data for hydrogeological parameter's mapping (Stigter et al., 2006). We give below some examples from the literature to demonstrate the process of the vulnerability map's validation:

- Banton and Villeneuve (1989) used the DRASTIC rating system and the PRZM model to simulate the vulnerability. The established maps of the vulnerability were analyzed to explore the relationship between the DRASTIC index and the PRZM approach.
- Antonakos and Lambrakis (2007) applied 3 models to establish the vulnerability of the aquifer to the nitrates using modified DRASTIC approaches.
- Ravbar and Goldscheider (2009) used 4 methods to elaborate the groundwater vulnerability map in a Slovene karstic aquifer catchment.
- Jose et al. (2012) attempt to assess the groundwater vulnerability in the Oaxaca Central Valleys by the application of the SINTACS model. The second method used is the geographic weighted regression method. A comparison between the two approaches is then presented and discussed.
- Abbasi et al. (2013) propose the application of DRASTIC model based on the Analytic Element Method. The statistical modeling of the hydrogeological data by the application of the Weights of Evidence method is used to elaborate the groundwater vulnerability.
- Yu et al. (2014) propose the vulnerability assessment using transport modeling and groundwater age modeling with an application to the Beijing Plain in China.

3. Utilities of vulnerability maps for groundwater protection and management

The management of water resources is a policy promoting the sustainable use by the economy of water resources to promote a good quality and significant quantity of water to the future generations. The main strategy of the water resource management is to support universal access to the water. The interpretation of the vulnerability map helps in identifying the basic of the strategy that will be adopted by planner to avoid the groundwater resource