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Research paper

Groundwater vulnerability analysis of Tunisian coastal aquifer: An application of DRASTIC index method in GIS environment

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ABSTRACT

The assessment of water resources vulnerability to human pollution has proved to be an effective means for the delineation of areas that are more susceptible to contamination from anthropogenic sources. In the peninsula of Cap-Bon (NE Tunisia), groundwater development and use for various purposes is continually increasing. These critical situation calls for urgent understanding of how the groundwater system is functioning as well as its vulnerability to contamination. In this research, the vulnerability of the groundwater resources in the Korba aquifer is evaluated and assessed with the application of the DRASTIC index method as well as using sensitivity analysis to evaluate the effect of each DRASTIC parameter on the obtained vulnerability map. Geographic Information System (GIS) application is implemented to prepare the seven layers of the DRASTIC model and to calculate the DRASTIC index. The DRASTIC index is in the range of 60–220. The highest DRASTIC index is indicated in the center part of study area due to the high pollution potential of intensive vegetable cultivation. Furthermore, the depth of water, the hydraulic conductivity and the aquifer media are responsible for the high vulnerability index in this part. However, the north and the south part exhibits low, medium to high vulnerability. This is due to the combination of deep water table, less porous vadose and hydraulic conductivity and steep topography. Hydraulic conductivity parameter inflicted the largest impact on the intrinsic vulnerability of the aquifer followed by net recharge, depth to water, soil media, topography, vadose zone media, and aquifer media. The sensitivity analysis applied in this study suggests that net recharge, hydraulic conductivity and depth of groundwater are the key factors determining vulnerability. Moreover, sensitivity analyses indicated that the removal of net recharge and depth of water causes large variation in vulnerability index. The model was validated using the simple linear regression analysis and showed a strong relationships between DRASTIC Vulnerability Index and nitrate concentrations (R^2 =0.76). These analyses confirm that the vulnerability map is quite similar that nitrate distribution. This DRASTIC study may serve as a major approach to aid in the protection and prevention of groundwater pollution in the coastal aquifer of Korba for a more effective water resource management.

1. Introduction

The most arid regions in the world are specifically dependent on groundwater as it is the only water source due to its relatively low susceptibility to pollution in comparison to surface water, and its large storage capacity. Furthermore, groundwater is the main source of drinking water, and hence its vulnerability assessment to anthropogenic contamination is very important (Ighbal et al., 2014; Ghazav and Ebrahim, 2015). However, there are significant sources of diffuse and point pollution of groundwater from land use activities, particularly agricultural practices. Thus, the nitrate pollution of groundwater caused by agricultural activity and a substantial increase in fertilizer utilization are becoming an increasing problem.

The intrusion of these pollutants to groundwater alters the water quality and reduces its value to the consumer (Melloul and Collin, 1994; Babiker et al., 2005). Therefore, the prevention of groundwater contamination is essential for effective groundwater resource management and vulnerability assessment. Groundwater contamination assessment concepts divide a geographical region into sub-areas in terms of their vulnerability to groundwater contamination; then, effective

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groundwater protection measures are conducted in the susceptible areas prone to pollution (Guo et al., 2007; Neshat et al., 2014). In general, the groundwater vulnerability is classified into intrinsic (or natural) and specific (or integrated) vulnerability. First, the intrinsic vulnerability can be defined as the ease with which a contaminant introduced into the ground surface can reach and diffuse in groundwater (Vrba and Zoporozec, 1994) generated by human activities taking into consideration the inherent geological, hydrological, hydrogeological and hydrogeochemical characteristics of the studied area. Second, the specific vulnerability is used to define the vulnerability of groundwater to particular contaminants taking into consideration the contaminant properties and their relationship with the various components of intrinsic vulnerability (Hamerlinck and Arneson, 1998; Doerfliger et al., 1999; Gogu and Dassargues, 2000; Varol and Davraz, 2010; Ghazav and Ebrahim, 2015). Most of them use overlays and index methods consisting in algebraic operations of hydrogeological parameters (Carreras et al., 2015). An overlay and index method combines factors controlling the movement of pollutants from the ground surface into the saturated zone resulting in vulnerability indices at different locations (Sener and Davraz, 2013). The main advantage is that some of the factors such as rainfall and depth to water can be available over large areas, which would make them suitable for regional scale assessments (Thapinta and Hudak, 2003). However, a major drawback is the subjectivity in assigning numerical values to the descriptive entities and relative weights for the different attributes (Babiker et al., 2005). Many simplified methods such as DRASTIC (Aller et al., 1987; Chenini et al., 2015; Anane et al., 2013; Saidi et al., 2011), GOD (Foster, 1987), EPIK (Doerfliger and Zwahlen, 1995), COP (Vias et al., 2006), SINTACS (Civita and de Maio, 1997) or CRIPTAS (IGME (Instituto Geologico y Minero de Espana), 1991) are widely used to assess groundwater vulnerability (Carreras et al., 2015). One of the most used standard groundwater vulnerability methods is DRASTIC, a method which has been developed by the United States Environmental Protection Agency (USEPA) for assessing groundwater pollution potential. This method uses seven parameters in its calculation of a 'vulnerability index' (depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity). Vulnerability maps generated by DRASTIC model show the distribution of highly vulnerable areas, in which pollution is very common because contaminants can reach the groundwater within a relatively short time. Nevertheless, the vulnerability maps established do not replace more detailed studies of the geological and hydrogeological conditions in order to ensure the suitability of a particular site for the anticipated use (Awawdeh et al., 2015; Awawdeh and Jaradat, 2010).

The objective of this paper is to design and implement an assessment tool controlling the groundwater vulnerability of Korba area using DRASTIC model combined with a geographic information system (GIS). This study also aims at evaluating the relative importance of the DRASTIC parameters for assessing aquifer vulnerability through sensitivity analysis.

2. Study area

The study area which the DRASTIC index was applied is located in the eastern part of Cap-Bon peninsula, in the north of Tunisia (Fig. 1a) and it has a surface of approximately 438 km^2 (Fig. 1b). It extends from Nabeul in the south to the city of Kélibia, and is bounded by the Mediterranean sea in the east and the Djebel Sidi Abderrahmen anticline in the west. The Korba area is characterized by a semi-arid climate with an average annual precipitation of 425 mm and an annual mean temperature of 17 °C. According to the Korba station data and from the climatologic reports of the National Institute of Meteorology (I.N.M. Institut National de la Météorologie, 2015), approximately 60% of the annual precipitation is concentrated between November and January, and the climatic deficit (Rainfall–Evapotranspiration) covers a period of about nine months, reaching its maximum (150 mm) in June and July (Fig. 2). The coastal area is quite flat and covered by thin layers of sandstones and of conglomerates marine terraces of Tyrrhenian age (Bensalem, 1998). The sand dunes extend up from 1 to 3 km inland and are wider especially in the north and in the south. The greater part is covered essentially by a mixing of sand, clay and sandy loam intercalations of Pliocene age and recent alluvial deposits (Fig. 3a). The main hydrographic network consists of three rivers (Chiba, Lebna and Bouliddine) with irregular flows which are completely dry during summer. The outcropping formations of the study area are represented by Mio-Plio-Quaternary deposits (Fig. 3b). The lower part of the Middle Miocene corresponds to detrital deposits known as the Beglia Formation (Bensalem, 1995). These geological formation processes correspond to an alteration of continental sand and sediments resulting from the erosion of the top of the Djebel Sidi Abderrahmen anticline with frequent clay lenses and were found only to the south of the study area (Bensalem, 1992, 1995, 1998). Thus, the thickness of this detritus layer is nearly 450 m. The second main geological unit is the Pliocene formation. This layer corresponds to the sandstone facies "Astien or Porto Farina", whose outcrops are deposited on these folded and eroded formations, which are mainly composed of sandstone-sand-marl alternations topped by sandstones and sand. The thickness of this formation depth is highly variable, ranging from 150 m in the south to 30 m in the north, and decreasing from 6 m in the east to nearly vanish at the Djebel Sidi Abderrahmen anticline. Finally, the Quaternary deposits are usually composed of two units: the lower unit of marine facies corresponds of the Tyrrhenian outcrops along the east coast formed by the superposition of two cycles represented by marine sandstone limestone and sandstone dunes (Abbes and Polak, 1981). The upper unit is mainly composed of the Quaternary continental formed of a crust of white limestone more or less thick (Ennabli, 1980). The hydrogeological settings of the study area are well presented and discussed by many authors especially by Kerrou (2008) and Ennabli (1980). Thus, Fig. 3b shows an idealized west-east geological cross-section through the aquifer system visualizing the three hydrogeological units (Kerrou et al., 2010). It is composed of deposits from the quaternary, Pliocene and upper Miocene laying unconformity on middle Miocene (sandstones and marls formations) that constitute the basis of this aquifer. The Korba aquifer was formed during the Pliocene and Quaternary ages by sedimentation of eroded products from Djebel Sidi Abderrahmen anticline. This hydrogeological system is layered, consisting of an upper, unconfined, alluvial aquifer separated from a lower, confined aquifer by Pliocene marls. Thus, the impermeable layer underlying the aquifer is the lacustrine marls of the Miocene marl formation as it can be seen in the geological cross-section of Fig. 3b.

The mean annual precipitation for the period 1975–2012 is 425 mm, which corresponds to the mean annual rainfall water volume of 183.96×10^6 m^3. The water balance parameters have been computed based on the procedures described by Thornthwaite and Mather (1955). A big part of the annual volume of precipitation namely 124.54×10^6 m^3 (67.7%) is lost via evapotranspiration, while 33.30×10^6 m^3 (18.1%) infiltrates and recharges groundwater. The rest 26.12×10^6 m^3 (14.2%) discharges to the Mediterranean sea as surface runoff (Zghibi et al., 2011). The 3D numerical model, presented and developed by Zghibi et al. (2011), allowed to estimate the areal recharge in the range of 5–8% of the average annual precipitation (21–34 mm/year), a transmissivity ranging from 5×10^{-5} to 10^{-2} m^2/s and an average porosity of 0.12. These values, together with an estimated seasonal head variation of 0.88 m, allowed a first estimation of the groundwater regulatory reserve and limited to about 68 Mm^3.

The Korba area was selected since it has been subjected to permanent settlement and significant agricultural expansion since the early 1960 s, growing from a cultivated area of only 20 ha in 1960 to nearly 7200 ha in the year 2013. The irrigated area located mainly between Korba, Diarr El Hojjaj, El Mida and Menzel Horr. A major part