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A global risk approach to assessing groundwater vulnerability

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ABSTRACT

This research provides a new approach to assess groundwater vulnerability to contamination from anthropogenic activities and sea water intrusion. The DRASTIC and GALDIT parametric methods were then linked to a novel land use index to create a more robust "global risk index", useful for assessing aquifer vulnerability to pollution and seawater intrusion risk.

In addition, sensitivity analysis was used to evaluate the effect of each individual parameter on the final models.

The vulnerability to pollution and the seawater intrusion contamination maps show three classes of water resources degradation: low, moderate and high, relating to the intrinsic properties. In addition, the global risk map shows three risk classes': low (25%), moderate (64%) and high (11%) depending on the hydrogeological characteristics, land use, distance from the coast and human impacts in most of the study area. The modified models were statistically compared with the nitrate concentration and the water resistivity values for validation.

These maps are considered indispensable for sustainable land use planning and groundwater management of the shallow aquifer.

1. Introduction

The protection and conservation of groundwater resources is very important, particularly in arid and semi-arid regions where water resources are limited. The effects of rapid population growth, rapid urbanization and diversification of economic and agricultural activities contribute to the quantitative (scarcity, overexploitation) and qualitative degradation of groundwater (pollution, chemical degradation). Moreover, the extensive pumping of coastal wells contributes to the intrusion of seawater into the mainland freshwater porous aquifer and the contamination by *sebkhas* are additional factors in the degradation of the quality of groundwater (Carrey et al., 2014; Pedreira et al., 2014), particularly in the Sfax region of Central-Eastern Tunisia in Africa, the subject of this study (Trabelsi et al., 2005, 2008).

Additionally, there are significant sources of groundwater pollution from land use activities, particularly agricultural practices, with an increasing consumption of chemical fertilizers, and urbanization. The intrusion of pollutants into groundwater affects the water quality (Melloul and Collin, 1994).

Many other studies have proved that overexploitation of aquifers may impair groundwater quality and increase salinization (Trabelsi et al., 2005; Ben Hamouda et al., 2010). In 2012, the exploitation was estimated at $53.6 \cdot 10^6$ m^3/year relative to $39.28 \cdot 10^6$ m^3 for the potential resources of the aquifer (Khanfir and Obey., 2013). This may cause the degradation of water resources due to anthropogenic and seawater intrusion. Parametric methods such as DRASTIC and GALDIT were developed to assess groundwater vulnerability including the overlay and index method, which is the simplest and most popular (Beaujean et al., 2013).

DRASTIC assessment is the indexing method most widely used to evaluate areas that are more vulnerable to different sources of pollution, such as urban (Hentati et al., 2010), agricultural (Yin et al., 2013; Neshat et al., 2014), industrial (Johansson et al., 1999) and other general human activities (Baalousha, 2006; Pathak et al., 2008).

The DRASTIC method is chosen because it is simple and all the parameters needed to compute the model are either readily available or easy to obtain (Yin et al., 2013; Shekhar et al., 2014).

Furthermore, the GALDIT method represents the unique model to determine the vulnerability of groundwater to seawater

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intrusion. It has been the subject of analysis in several studies (Chachadi et al., 2002; Lobo-Ferreira et al., 2005; Sundaram et al., 2008; Saidi et al., 2013; Kura et al., 2014).

This study aims to assess groundwater vulnerability in the shallow aquifer of Sfax, Central Eastern Tunisia, by determining the regions that are more vulnerable to anthropogenic and seawater intrusion. DRASTIC and GALDIT methods are applied using a Geographic Information System (GIS) in combination with hydrogeological data.

The results were used to create a cumulative risk map based on the DRASTIC, GALDIT and land use indices, resulting in the creation of a more robust global risk index for assessing aquifer vulnerability to pollution and seawater intrusion risk.

2. Study area

The study area is located on the east coast of Tunisia (Fig. 1) between 34°00′- 35°30′N and 9°30′-11°30′E. It covers an area of around 6848 km^2 (4.6% of the total land area) with a coastline extending 180 km. It is characterized by a semi-arid to arid Mediterranean climate with irregular temperature and rainfall. Average annual precipitation, temperature and humidity are around 230 mm, 19.3 °C and 64.8%, respectively (INM, 2014).

On the plain of Sfax, the altitude rarely exceeds 200 m. It presents a monotonous topography with mounds of large radius separated by vast basins, generally subsiding, and occupied by sebkhas (a smooth flat often saline plain sometimes occupied after a rain by a shallow lake until the water evaporates), named from north to south: S. El Ghorra; S. El Jem; S. Bou Jmel; S. Mechiguigue; S. Noual (Maliki, 2000).

The geology of the study area (Fig. 1) is dominated by outcrops of the Mio–Pliocene and Quaternary deposits, which are constituted mainly by current and recent alluvial deposits: conglomerates, gravels, sands, and silts, calcareous with high permeability (Bouaziz, 2002). The Sfax Shallow aquifer is composed by sands and silty clay of Mio-Plio-Quaternary age which are characterized by high permeability (Maliki, 2000; Allouche et al., 2015). The aquifer layers, characterized by productive horizons, are separated by sandy clay intercalations allowing their communication. The aquifer is generally recharged by direct infiltration of rain waters and. Mediterranean Sea and Sebkhas represent the discharge areas.

The population growth in the region of Sfax, with the rapid development of different economic sectors (agriculture, fisheries and industry), has contributed to a more intensive use of land and a greater pressure on natural resources and ecosystems. The economy of the region is mainly based on agriculture (olives, representing the principal activity, vineyards, greenhouse crops, fodder and vegetables) and livestock. Agricultural land occupies almost (90%) of the area: 639,000 ha of arable land, consisting of 326,000 ha of olive trees and 87,000 ha of almond trees.

Industrial activities are represented essentially by chemical fertilizers and other chemical products, textiles, the production and storage of olive oil, food, construction materials and ceramics (Fig. 1).

3. Methodology

3.1. Data set

Data sources were provided by the Regional Agency of Agriculture of Sfax (CRDA-Sfax). Data base was obtained by digitizing the existing maps of the study area, with a scale of 1:50000 collected from the (CRDA-Sfax). Groundwater samples were collected from water supply wells. Chemical analysis was processed in Chemical analysis Laboratory of the CRDA-Sfax. Different analytical methods were used to estimate the water chemical composition, as Atomic absorption spectrometer ($NO3^+$ and Na^+), titration with AgNO3 (Cl^-), Chromatography liquid-phase ($SO42^-$) and Ec meter.

3.2. Intrinsic vulnerability mapping (the DRASTIC model)

The DRASTIC method was developed by the US Environmental Protection Agency to evaluate the groundwater pollution potential for the entire USA (Aller et al., 1987). It considers the hydrogeological pattern, which depends on the major geological and hydrological factors that affect and control the groundwater circulation (Aller et al., 1987; Babiker et al., 2005; Saidi et al., 2013).

DRASTIC is the acronym of seven hydrological parameters: **D**epth to water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of the vadose zone and hydraulic **C**onductivity. It is based on the following assumptions: the area evaluated by DRASTIC has a surface area greater than 0.40 km^2, the pollutant is initiated at the ground surface and the pollutant infiltrates the groundwater by precipitation (Aller et al., 1987; Kura et al., 2014; Pedreira et al., 2014).

This method generates an index for the pollution potential of groundwater resources that is derived from ratings and weights assigned to each parameter (Table 1). This index can be calculated using the following equation:

$$\text{DRASTIC index} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r D_w \tag{1}$$

where D, R, A, S, T, I, and C are the seven parameters, r is the rating value, which varies from 1 to 10 based on their relative effect on aquifer vulnerability, and w is the weight associated with each parameter reflecting their relative importance. It ranges from 1 to 5 (Table 2).

The D, R, A, I and C maps relative to these five parameters were established using the inverse distance moving average interpolation technique (Babiker et al., 2005). However, the soil type and topography maps are geo-referenced and digitized from different data files. In order to produce the final DRASTIC map, all the thematic maps relating to the seven parameters were converted to raster format then overlaid, after assigning a weight to each layer based on Equation (1) and using the spatial analyst extension of ArcGis 10.1 software (Fig. 2).

3.3. Seawater intrusion risk mapping (the GALDIT model)

The GALDIT method was created by Chachadi and Lobo-Ferreira (2001) to evaluate the vulnerability of coastal aquifers to sea water intrusion. It was chosen because it takes into account the physical characteristics affecting seawater intrusion potential, which are also inherent in each hydrogeological setting (Saidi et al., 2013). The most important factors that control seawater intrusion are found to be the following. GALDIT is the acronym of six physical and chemical parameters believed to be the most significant variables controlling seawater intrusion: **G**roundwater occurrence, **A**quifer hydraulic conductivity, depth to groundwater **L**evel above sea, **D**istance from the shore, **I**mpact of existing status of seawater intrusion and **T**hickness of the aquifer.

Each of these six parameters has a fixed weight (varying from 1 to 4) that reflects its relative importance to seawater intrusion and it was carried out by ratings ranging from 1 to 10 (Table 3). They were then employed to develop the GALDIT index using the following equation:

$$\text{GALDIT index} = (1 \times G) + (3 \times A) + (4 \times L) + (4 \times D) + (1 \times I) + (2 \times T) \tag{2}$$