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Groundwater vulnerability and risk mapping using GIS, modeling and a fuzzy logic tool

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Abstract

A groundwater vulnerability and risk mapping assessment, based on a source–pathway–receptor approach, is presented for an urban coastal aquifer in northeastern Brazil. A modified version of the DRASTIC methodology was used to map the intrinsic and specific groundwater vulnerability of a 292 km^2 study area. A fuzzy hierarchy methodology was adopted to evaluate the potential contaminant source index, including diffuse and point sources. Numerical modeling was performed for delineation of well capture zones, using MODFLOW and MODPATH. The integration of these elements provided the mechanism to assess groundwater pollution risks and identify areas that must be prioritized in terms of groundwater monitoring and restriction on use. A groundwater quality index based on nitrate and chloride concentrations was calculated, which had a positive correlation with the specific vulnerability index.

Keywords: Aquifer vulnerability; Groundwater contamination; Risk assessment; Fuzzy logic

1. Introduction

The exploitation of urban aquifers has been historically undertaken without proper concern for environmental impacts or even the concept of sustainable yield. In Brazil, for example, this attitude is no longer acceptable and the concept of groundwater vulnerability is now increasingly being used to evaluate risks to groundwater. The concept involves hydrogeologic and climatic variables, pedology, land use and land cover (LULC), potential contaminant sources, and an estimate of well capture zones. Due to the complexity involved in this assessment, the use of mathematical tools such as analytical or numerical modeling, along with geographic information systems (GIS), is essential to manipulate the large amounts of spatial data.

Existing methods to assess groundwater vulnerability can be classified into three categories (National Research Council, 1993): i) overlay and index method; ii) process-based methods that apply deterministic models based on physical processes; and iii) statistical models. These methods are typically intended to provide a comparative evaluation of areas related to the potential for groundwater contamination.

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The overlay and index methods result from the intersection of maps on a regional basis and the qualitative interpretation of the data by indexing the parameters and assigning appropriate weights. The maps have both physical and climatic attributes that are assigned numerical indices for each attribute. The DRASTIC system (Aller et al., 1987), which falls under the index category, is the best known of these methods. It was developed in the United States with the support of the U.S. Environmental Protection Agency (EPA) and was designed to be a standardized system for evaluating the groundwater vulnerability for a variety of land areas. It was not intended to produce an absolute measure of vulnerability, but can be one of many criteria used in decision making (Aller et al., 1987). Parallel with the development of DRASTIC, the GOD method (Foster, 1987) was developed in Europe, which consists of three parameters: Groundwater occurrence, Overall aquifer class and Depth to watertable. The Aquifer Vulnerability Index (AVI) method (Van Stempvoort et al., 1992) developed in Canada, which considers depth and hydraulic conductivity of each sedimentary layer above the groundwater level and the vertical hydraulic gradient. The U.K. vulnerability system (Palmer and Lewis, 1998) identifies three important components of groundwater vulnerability: soil type, the presence/absence of drift and the nature of the aquifer.

The DRASTIC method has received much criticism due to lack of proper validation. For example, a positive correlation between the model results and field data was reported by Baker (1990) and Kalinski et al. (1994), while others have reported little correlation (Holden et al., 1992; Maas et al., 1995). Despite these concerns DRASTIC has been applied worldwide with adaptations on the procedures to elaborate thematic maps and the use of different ratings criteria (Napolitano, 1995; Melloul and Collin, 1998; Pizani et al., 2002; Thirumalaivasan et al., 2003; Babiker et al., 2005).

Deterministic methods to assess groundwater vulnerability use mathematical models to simulate the complex phenomena of flow and contaminant transport in the subsurface. These methods require a good hydrogeologic and geochemical database coverage. Due to the lack of these data at the regional scale, it is common to use models in a one-dimensional sense (e.g., Schlosser et al., 2002; Connell and Daele, 2003). Statistical methods depend on extensive databases and were created to identify priority pollutants to be used in monitoring soil and groundwater remediation projects. Vulnerability to groundwater is calculated directly from monitoring data and is frequently coupled with contaminant characteristics (typically organic carbon partition coefficient and half-life) (Chowdhury et al., 2003). Worrall and Kolpin (2003) suggest that for pesticide issues the interaction between the contaminant and medium is more significant than considering these two factors separately and conclude that vulnerability systems based on indices do not fit well into risk assessment studies. This implies that aquifer vulnerability cannot be calculated independently of the contaminant in question. There are also some methodologies that integrate various elements of the index methods with other information, such as contaminant loading and LULC to estimate the expected risk to groundwater contamination on a regional scale (Secunda et al., 1998; Tait et al., 2004).

This paper presents a new methodology to assess groundwater vulnerability and risk mapping based on an index methodology and source–pathway–receptor risk chain analysis using GIS and process-based modeling. This methodology is an advance over other existing methods since it integrates the controlling features that interfere along the contaminant pathway from source to receptor such as recharge, natural attenuation, soil, aquifer media, LULC and wells distribution. It uses a fuzzy hierarchy model to evaluate source hazard potential, which is an adequate procedure to incorporate subjective reasoning and an extensive database into the calculations and rank the importance of each class of contaminant to groundwater impact. Since it is not possible to validate this kind of model, a procedure for model testing is presented, an essential requirement to vulnerability assessment, not always addressed in most publications. In addition, the available methods do not evaluate the regional risk within the perspective of the well capture zone and hence fail to predict the implications that high vulnerability areas have on the future performance of abstraction wells and their water quality. In the methodology presented here, on the other hand, it is possible to search for areas within the well capture zones with the highest risk indices and expected impact to the receptor/well. These areas are subject to further evaluation or intensive groundwater monitoring and more restrictive land use criteria. This methodology constitutes an important tool for managing water resource systems, as well as for land-use planning in a city that uses groundwater to supply approximately 80% of its water demands. This proposed new methodology will also aid in the evaluation of wellhead protection areas (WHPA) based not only on the conventional time-of-travel concept but also on potential contaminant sources and land use practices within the capture zone, a new concept that has been discussed in the recent literature (for example Frind et al., 2006).