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Cross comparison of five popular groundwater pollution vulnerability index approaches

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SUMMARY

Identification of a suitable overlay and index method to map vulnerable zones for pollution in weathered rock aquifers was carried out in this study. DRASTIC and four models derived from it, namely Pesticide DRASTIC, modified DRASTIC, modified Pesticide DRASTIC and Susceptibility Index (SI) were compared by applying them to a weathered rock aquifer in southern India. The results were validated with the measured geochemical data. This study also introduces the use of temporal variation in the groundwater level and nitrate concentration in groundwater as input and for validation respectively to obtain more reliable and meaningful results. Sensitivity analysis of the vulnerability index maps highlight the importance of one parameter over another for a given hydrogeological setting, which will help to plan the field investigations based on the most or the least influential parameter. It is recommended to use modified Pesticide DRASTIC for weathered rock regions with irrigation practises and shallow aquifers (<20 m bgl). The crucial input due to land use should not be neglected and to be considered in any hydrogeological setting. It is better to estimate the specific vulnerability wherever possible rather than the intrinsic vulnerability as overlay and index methods are more suited for this purpose. It is also necessary to consider the maximum and minimum values of input parameters measured during a normal year in the models used for decision making.

1. Introduction

Groundwater, a much needed fresh water source is susceptible to contamination due to natural and anthropogenic sources. Degradation of groundwater quality due to contamination is of serious concern as nearly half of the world's population depends on groundwater sources for drinking water supply and other uses (Oki and Kanae, 2006). Use of polluted groundwater for domestic purposes is of risk as it will affect human health. The prevention of groundwater contamination is always preferred than attempting to remove once it has entered the aquatic environment (WHO, n.d.). Hence, it is very crucial to delineate regions that are vulnerable to groundwater contamination, which will enable to take suitable precautionary measures to locate public wells.

Regional vulnerability mapping can be made for geogenic and anthropogenic sources of contamination depending on the need and data availability. Aquifer vulnerability is termed as the possibility of percolation and diffusion of contaminants from the ground surface into natural water table reservoirs under natural conditions (Albinet and Margat, 1970). Vrba and Zaporotec (1994) define vulnerability as an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts. This leads to distinguishing vulnerability as 'intrinsic' and 'specific' vulnerability. 'Intrinsic' or 'natural' vulnerability is a function of hydrogeological conditions and 'specific' or 'integrated' vulnerability addresses the vulnerability to a particular contaminant of interest or from specific source. Specific vulnerability assessment is complex compared to intrinsic vulnerability because of the wide range of pollutants and the variation in its sources. Vulnerability should not be mistaken as a synonym for 'pollution risk' which depends not only on vulnerability but also on the existence of significant pollutant loading entering the sub-surface environment as a result of human activity (Foster, 1987).

Mapping vulnerable zones can be done by many approaches such as process based, statistical, overlay and index methods. These methods are discussed elaborately in the report of the United States National Research Council (1993). Process based approach capture the physical, chemical, and biological reactions that occur from the surface through the groundwater regime by

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modelling to estimate the extent of contaminant plume and its transport but resourceful results depend on intensive field work and collection of primary and secondary data. Regression analysis, linear modeling, principle component analysis, fuzzy models, analytical hierarchical process, kriging are some of the statistical methods to expresses vulnerability in terms of probability of contamination (National Research Council, 1993). However, these statistical methods demand large amount of reliable data in order to obtain meaningful results.

On the other hand overlay and index methods are comparatively simpler and are based on geological, hydrogeological settings and other factors which control the groundwater vulnerability in a region. Basic steps of these methods include analysis of raw data, ranking of features on a map, integration of maps and classification of the integrated map based on an index. This method is applicable from regional to global scale and should be supplemented with field visits and validation to produce reliable results. Some examples of overlay and index method are GOD (Groundwater occurrence, Overall lithology of aquifer and Depth to groundwater level) (Foster, 1987), AVI (Aquifer Vulnerability Index) (van Stemproot et al., 1993), SEEPAGE (System for Early Evaluation of Pollution Potential of Agricultural Groundwater Environments) (Navulur, 1996), SINTACS (S – soggiacenza (in Italian) i.e. aquifer depth, I – infiltrazione i.e. seepage water input, N – non saturo i.e. unsaturated zone features, T – tipologia della copertura i.e. soil type, A – acquifero i.e. aquifer hydrogeological features, C – conducibilità i.e. aquifer hydraulic conductivity, S – superficie topografica i.e. roughness of land surface) (Civita, 1994), EPIK (Epikarst, Protective cover, Infiltration conditions and Karst network development) (Doerfliger et al., 1999), RISKE (Rock of aquifer media, Infiltration, Soil media, Karst, and Epikarst) (Petelet-Giraud et al., 2000), EPPNA (Equipa de Projecto do Plano Nacional da Água) (EPPNA, 1998), SI (Susceptibility Index) (Riberio, 2000) and DRASTIC (D – aquifer depth, R – recharge rate, A – aquifer lithology, S – soil type, T – topography, I – impact of vadose zone, C – aquifer hydraulic conductivity) (Aller et al., 1987). While all these methods have their pros and cons, adapting these methods with minor modifications based on the local needs may provide better results.

Most of these models are applicable to specific geological terrains as GOD is suitable for sedimentary aquifers and EPIK and RISK are suited for karst aquifers. However, Vias et al. (2005) reported that GOD is adequate to assess vulnerability of flow carbonate aquifers while AVI is not. DRASTIC has been very popular and also applied more widely than other models to map vulnerability in basaltic (Al-Adamat et al., 2003), karstic (Mimi et al., 2012), sedimentary (Rodney, 2006; Bai et al., 2012), carbonate (Hussain et al., 2005; Vias et al., 2005), hard rock (Prasad et al., 2011) and coastal (Almasri, 2008) aquifers. All these methods are useful for groundwater resource management and land use planning (Rupert, 2001; Connell and Daele, 2003; Anane et al., 2013). It is understandable from these studies that selection of a particular overlay and index method out of the several available methods to map the vulnerability of aquifers for pollution is very tricky and complicated. Application of different methods may give significantly different and surprising results. Hence, it is challenging to decide about the proper measures of aquifer pollution prevention and land use planning based on the outcome of a particular overlay and index method.

Researchers have compared Generic and Pesticide DRASTIC (Ahmed, 2009), six different methods: AVI, GOD, DRASTIC, SI, EPPNA and SINTACS (Artuso et al., 2002), DRASTIC/EGIS (Kim and Hamm, 1999), GOD, DRASTIC and AVI (Kazakis and Voudouris, 2011) to test the superiority of one model over the other. Murat et al. (2004) compared a few methods and inferred that vulnerability maps for any hydrogeological setting vary significantly with the type of vulnerability evaluation method selected. Anane et al. (2013) showed that SI helped in contamination prevention but Pesticide DRASTIC are better suited to select the best sites for specific on-the-ground practice or future land use. More reliable results were obtained from SI method than DRASTIC though the vulnerability was overestimated in many areas as reported by Stigter et al. (2006). Nevertheless, no studies have been carried out so far to compare the modified DRASTIC and modified Pesticide DRASTIC along with DRASTIC, Pesticide DRASTIC and SI. Such a study is very vital as several researchers seem to be biased to the use of DRASTIC.

In general, groundwater occurring in weathered rock aquifers is highly susceptible to pollution due to the poor filtering process during percolation of recharging water and shallow aquifers are eventually more susceptible to pollution due to surface contaminants than the deeper aquifers. Hence, it very much necessary to identify a proper overlay and index method among the available methods for assessing the vulnerability of weathered rock aquifers to pollution. None of the existing methods consider the seasonal variation in the groundwater level as an input, which is important as the use of the data measured in different times of the year will give completely diverse results. So, it is necessary to study the applicability of the various methods by incorporating temporal variation in the input parameters. Such a study need to be carried out for the same site and the outcome of various models has to be validated with the observed temporal data. An attempt was made in the present study with the objective of evaluating popular overlay and index methods and to identify a suitable method for highly weathered shallow aquifers. This study also introduces the possibility of incorporating temporal variation of input parameters in the existing models, as the rainfall and the groundwater table varies with respect to time.

2. The approach

2.1. Mapping vulnerable zones

Index and overlay methods are based on three critical factors assigned to each parameter: range, rating and weight. DRASTIC (Aller et al., 1985) identifies vulnerable zones based on seven unique features of an area (Fig. 1). Pesticide DRASTIC also uses the same parameters (Fig. 1) but the relative weights that range from 1 to 5 differ from the DRASTIC model (Table 1). Most significant parameters are assigned a weight of 5 and the least significant factor is assigned 1. Similarly a rating from 1 to 10 is assigned to each factor within a parameter depending on the potential to cause pollution (Table 2). DRASTIC index (DI) was proposed as Aller et al., 1985:

$$\text{DRASTIC index (DI)} = (Dr \times Dw) + (Rr \times Rw) + (Ar \times Aw) + (Sr \times Sw) + (Tr \times Tw) + (Ir \times Iw) + (Cr \times Cw) \quad (1)$$

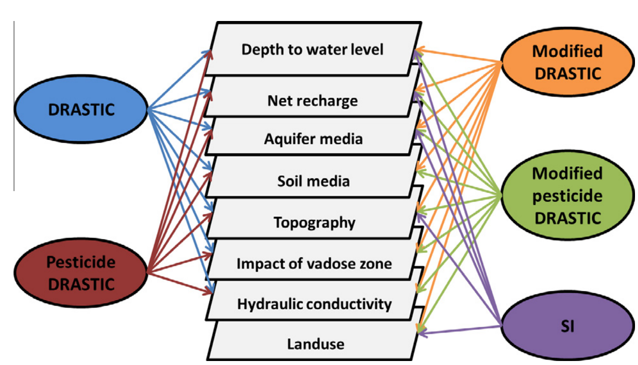

Fig. 1. Various input layers for different vulnerability models.