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Abstract. Pollution of groundwater is a primary issue because aquifers are susceptible to contamination from land use and anthropogenic impacts. Groundwater susceptibility is intrinsic and specific. Intrinsic vulnerability refers to an aquifer that is susceptible to pollution and to the geological and hydrogeological features. Vulnerability assessment is an essential step in assessing groundwater contamination. This approach provides a visual analysis for helping planners and decision makers to achieve the sustainable management of water resources. Comparative studies are applying different methodologies to result in the basic evaluation of the groundwater vulnerability. Based on the comparison of methods, there are several advantages and disadvantages. SI can be overlaid on DRASTIC and Pesticide DRASTIC to extract the divergence in sensitivity. DRASTIC identifies low susceptibility and underestimates the pollution risk while Pesticide DRASTIC and SI represents better risk and is recommended for the future. SINTACS method generates very high vulnerability zones with surface waters and aquifer interactions. GOD method could be adequate for vulnerability mapping in karstified carbonate aquifers at small–moderate scales, and EPIK method can be used for large scale. GOD method is suitable for designing large area such as land management while DRASTIC has good accuracy and more real use in geoenvironmental detailed studies.

1. Introduction

Pollution of groundwater is a basic issue because aquifers and the contained groundwater are inherently considerate to contamination from land use and other anthropogenic impacts [1]. Vulnerability has been defined as a relative evaluation of the potential exposure of a groundwater resource to contamination from various human activities [2]. The usefulness of comparative vulnerability assessment is generally regarded as having two functions: providing information to regulators and increasing on groundwater quality monitoring [3].

Groundwater susceptibility is intrinsic and specific. Intrinsic vulnerability refers to the aquifer that is susceptible to contamination and attaches to the geological and hydrogeological features. Specific susceptibility defines the susceptibility of aquifers to a group of pollutants or to only one particular contaminant [4]. The intrinsic vulnerability depends on three main factors:

- Absorption process and fluid contaminant travel time;
- The fluid contaminant flow dynamics in the saturated zone;
- The residual concentration of the contaminant as it reaches the saturated zone.

Groundwater vulnerability assessments are usually represented using a map displaying zones where the resource is vulnerable to contamination from some sources. Vulnerability mapping is a suitable technique for assessing hydrogeological factors. The groundwater for potential contamination in a specific region is shown on a map [5].

What we review here is the available approaches, and we discuss the groundwater vulnerability assessment techniques with the main focus on overlay method. We also present updated information by using comparative and evaluative analysis. The overall objective is to produce a process of applicable vulnerability assessment, using available information from existing or planned databases.

2. Overview of methodology

There are three groups of Groundwater vulnerability assessment method; subjective rating methods, statistical method, and process-based methods [6]. Index and overlay method are based on combining maps of various physiographic attributes (geology, soil, aquifer media, depth to water) controlling groundwater vulnerability of the region by assigning a numerical score or rating to each attribute. Statistical method ranges from descriptive statistics of the concentration of a contaminant to more complex regression analysis. Incorporation data on known pollutant and their distribution areas provide information on potential contamination for the specific geographic area from the data. Additional information on factors affecting the intrinsic vulnerability of the resource can be obtained by using logistic regression [7]. The importance of GIS-based mapping comes from its ability to produce geodatabases and to create vulnerability maps [8]. The evaluation of groundwater vulnerability in this study was carried out using several methods, each one adopting a specific set of parameters:

- DRASTIC considers seven parameters: depth to water (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I), and hydraulic conductivity (C) [9];
- SINTACS was created for vulnerability assessments and mapping in medium and large scale maps, and the multiplier weights of normal string were used [10];
- AVI, which is a measure of groundwater vulnerability based on two physical parameters. i) thickness (d) of each sedimentary layer above the uppermost, saturated aquifer surface, and ii) estimated hydraulic conductivity (K) of each of these sedimentary layers [11];
- GOD is a classical system for quick assessment of the aquifer vulnerability to pollution. Three main parameters are considered: the groundwater occurrence, the lithology of the overlying layers, and the depth to groundwater [12];
- SI involves five layers which are: Depth to water, Net Recharge, Aquifer media, Topography and Land Use (LU) [13].

In recent years various methods of vulnerability assessment of groundwater have been developed with different approaches. Various classic vulnerability methods are available such as GOD and AVI; empirical vulnerability methods such as DRASTIC, SINTACS, and SI that based on overlay and indexing techniques, depends on the type of aquifer, the type of pollutant and the availability of data.

2.1. DRASTIC

DRASTIC is a standardized system for evaluating the intrinsic vulnerability of groundwater [9]. The DRASTIC system parameters are depth to water (D), net recharge (R), aquifer media (A), soil media (S), topography (T), the influence of the vadose zone (I), and hydraulic conductivity of the aquifer C). The final vulnerability index (*Di*) is a weighted sum that can be computed using the formula;

DRASTIC Index (Di) = DrDw+RrRw+ArAw+SrSw+TrTw+IrIw+CrCw
Where, w -Weight factor for parameter, r- Rating for parameter
Over the times, DRASTIC has been modified into several methods (Table 1):

Table 1. Several methods modified DRASTIC.

Reference	Modification	Extension method
[14]	DRASTIC-LU	Modified DRASTIC by introducing Land use as a parameter and applied to categorized Indo gangetic plains into vulnerability Zones.
[15]	DRASTIC-sensitivity analysis	Assessed groundwater pollution risk by applying the DRASTIC model along with sensitivity analysis to evaluate the relative importance of the model parameters for aquifer vulnerability.
[16]	Pesticide DRASTIC-DRASTIC-LU	Employing both Generic and Pesticide DRASTIC method for assessing groundwater vulnerability to non point source pollution under conflicting land use pattern. Correlation analysis showed a significant association between high groundwater NO3--concentration and distance between LULC types.
[17]	DRASTIC-geostatistical techniques	Modified DRASTIC model by incorporating simple statistical and geostatistical technique. Correlation coefficient with the nitrates concentration and landuse included as additional factor. The correlation coefficient between groundwater pollution risk and nitrates concentration found to be higher than the original method.
[18]	DRASTIC-Fm	Modified version of DRASTIC of fissured hard-rock aquifers. The fractured was derived from the map of tectonic lineaments density.

2.2. SINTACS

The SINTACS method involves seven parameters and its name is derived from the initial of each parameter such as static level depth, net recharge, non-saturated zone, soil type, aquifer type, hydraulic conductivity and topographic slope [19]. The weight of each variable will be different depending on the hydrogeologic scenario. It can be calculated by following equation:

$$SINTACS = Sr1Sw1 + IrIw + NrNw + TrTw + ArAw + CrCw + SrSw$$

S = static level depth, I = net recharge, N = non-saturated zone, T= soil type, A = aquifer type, C = hydraulic conductivity and S = topographic slope, w =Weight factor for parameter, r= Rating for parameter

Presently, SINTACS has been modified into several methods (Table 2):

Table 2. Several methods modified SINTACS.

Reference	Modification	Extension method
[20]	SINTACS-source contaminant	Established a cause and effect relationship between potential source of contamination and water quality indices
[21]	SINTACS-nitrate	Result in a high correlated between measured concentration of nitrate and parameters of SINTACS. Sensitivity analysis showed soil overburden attenuation capacity parameter (T) and the depth to the groundwater parameter (S) were the most sensitive parameters to SINTACS exposure model.

2.3. AVI (The Aquifer Vulnerability Index method)

AVI method measures groundwater vulnerability based on two parameters: i) thickness (d) of each sedimentary layer and ii) estimated hydraulic conductivity (K) [11]. Based on the two physical parameters, d and K, the hydraulic resistance "c" can be calculated.

$c = \Sigma d/Ki$

This parameter c is a theoretical factor used to describe the resistance of an aquitard to vertical flow. The c or log (c) value is related to a qualitative Aquifer Vulnerability Index by a relationship table.

2.4. GOD method

GOD is a classical system for quick assessment of the aquifer exposure to contamination. There are three main parameters to be considered: the groundwater occurrence, the lithology of the overlying layers, and the depth to groundwater [12]. Currently, GOD has been modified into several methods (table 3). The Vulnerability index can be calculated by following formula:

GOD vulnerability index = Gr x or x Dr

Where; G = Rating for groundwater occurrence
O = Rating for overlaying lithology of unsaturated zone
D = Rating for depth to groundwater

Table 3. Several methods modified GOD.

Reference	Modification	Extension method
[12]	GOD-S	Evolution of GOD index, considering soil media properties

2.5. Susceptibility Index (SI)

SI involves five layers, which are: Depth to water, Recharge, Aquifer media, Topography and Land Use (LU) [13]. SI system contains three significant parts: ratings, weights and ranges.

SI Index= DrDw+RrRw+ArAw+TrTw+LUrLU

D = Depth to water, R = Recharge, A = Aquifer media, T = Topography, L = Land Use
r = Rating for parameter w = Weight factor for parameter

3. Review of Some Comparative Studies

This paper discuses some of the important cases in which an attempt has been made to compare several vulnerability methods (Table 4).

Table 4. Several comparison vulnerability methods.

Reference	Comparison method	Comparative Studies	Result Research
[22]	DRASTIC, SINTACS, GOD, AVI	Assess the vulnerability of the aquifer.	SINTACS method generates very high vulnerability zones in the areas concerned with surface waters and aquifer interactions.
[23]	GOD, AVI, DRASTIC, EPIK	Study a diffuse flow carbonate associated with the rainfall variations	Resulting that the GOD method could be adequate for a vulnerability in karstified carbonate aquifers at small–moderate scales. EPIK method could be used for large scale.
[24]	DRASTIC, Pesticide DRASTIC,SI	A Study in potential of shallow aquifer.	Result of study revealed that DRASTIC identified low vulnerability and underestimated the pollution risk.
[25]	GOD,	Assess urban areas	GOD method is best suitable for large design while DRASTIC has good accuracy and effectively used in

DRASTIC	geoenvironmental studies.

Comparison vulnerability method has shown that GOD method generates some zones aquifer with medium to high vulnerability. The AVI method assigns high to very high vulnerability. DRASTIC method assigns a high vulnerability to a larger area. A sensitivity analysis of DRASTIC suggests that depth to water table is the key factor determining vulnerability, followed by impact to the vadose zone and soil type. It has been concluded that pesticide DRASTIC and GOD provide similar results, but DRASTIC may be considered more reliable based on hydrogeological parameters. However, for reconnaissance studies, AVI and GOD methods provide good preliminary tools.

4. Conclusions

Comparative studies apply different methodologies to result from the effective evaluation of the groundwater vulnerability. SI could be overlaid on DRASTIC and Pesticide DRASTIC to extract the divergence in vulnerability. DRASTIC identified low vulnerability and underestimated the pollution risk. SI represents better risk and it is recommended for the future. SINTACS method generates very high vulnerability zones in the areas concerned with surface waters and aquifer interactions. GOD method could be adequate for vulnerability mapping in karstified carbonate aquifers at small–moderate scales. EPIK method could be used for vulnerability mapping in karstified carbonate aquifers at a large scale. Both the DRASTIC and GOD methods were compared qualitatively and statistically. GOD method was relatively close to DRASTIC, and as a simpler method can be used in areas with limited information, it is suitable for designing large area such as land management. DRASTIC has good accuracy and more effectively used in geoenvironmental detailed studies. Comparison of the vulnerability methods can be used to estimate their efficiency for vulnerability of the study area.

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