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Environmental Sciences Europe (2022) 34:77
https://doi.org/10.1186/s12302-022-00646-8

Environmental Sciences Europe

REVIEW **Open Access**

DRASTIC, GOD, and SI approaches for assessing groundwater vulnerability to pollution: a review

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Abstract

Over the last three to four decades, several methods for assessing groundwater vulnerability to anthropogenic pollution have been developed. Researchers and policymakers have widely used these methods for preventing groundwater pollution through knowledge about particularly vulnerable areas. This systematic review presents different and significant methods for assessing the vulnerability of aquifers for the protection of the resource. Previous studies mentioned that formulating a single technique for assessing groundwater vulnerability is difficult; thus, different methods and techniques have been proposed. Therefore, this paper presents three methods, namely, DRASTIC, GOD, and susceptibility index (SI), which will be discussed in detail, and highlights their advantages and limitations. In doing so, the study introduces the concept of aquifer vulnerability, and further discussion will be devoted to the three methods. Lastly, the study outlines the major challenges to the assessment of aquifer vulnerability. The review concludes the importance of groundwater vulnerability and strategies for preserving its quality.

Keywords: Aquifer vulnerability, Groundwater, DRASTIC, GOD, SI methods, Review

Introduction

Groundwater is an important source of water for agricultural, industrial, and domestic uses and is regarded as the largest reservoir of liquid freshwater on the planet [23]. It provides 50% of drinking water in the world [90], and 43% of global consumption for irrigation [80]. This resource has been highlighted in terms of quantity and quality [23]. Awareness of the need to protect water resources has been raised in societies for a very long time. Given this fact, technical tools are required for predicting and preserving these resources. Such tools are based on assessments of the vulnerability and sensitivity of water to pollution and on the production of maps that clearly delimit areas of vulnerability and varying degrees of sensitivity.

In recent decades, groundwater contamination has become a serious environmental issue because of increased industrial and agricultural activities. Given the increasing threat of groundwater pollution worldwide, a few researchers have emphasized the importance of assessing risk to groundwater quality to formulate effective measures for risk reduction (e.g., [45, 79, 81]) with the continued awareness that human activities are a necessity to society. One of the approaches that help in preventing groundwater pollution is the knowledge of especially vulnerable areas. The assessment of aquifer vulnerability enables policymakers to understand the impacts of decision-making [30], to adopt effective management strategies for mitigating groundwater pollution, such as modifying land use activities to reflect the potential for groundwater contamination, to guide the allocation and targeting of resources to areas where the highest levels of effort are required, and to raise public awareness about the potential for groundwater contamination [63].

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Thus, several methods for evaluating the vulnerability of groundwater to anthropogenic pollution have been developed over the past 25–30 years. The GOD, DRASTIC and SI methods are among the most popular index-based methods, over the last 25–30 years these models have been used in the estimation of groundwater vulnerability for a wide range of regions [56], due to its ease to use, much less time-consuming and suitable for use in the GIS framework; these methods are based on the assumption that certain known hydrological, geological and climatological factors control the potential impact on the groundwater contamination [48]. Hence, the current study presents a systematic review of the classification of different assessment methods for groundwater vulnerability with emphasis on DRASTIC, GOD, and SI as the pioneering approaches for resource protection. Toward the end, the study highlights the concept of aquifer vulnerability to pollution as it presents in detail the three basic categories of the existing methods for the assessment of groundwater vulnerability; discusses the DRASTIC, GOD, and SI approaches; identifies their advantages and limitations. Finally, it exposes the weaknesses of each model. The study concludes that the DRASTIC, GOD, and SI methods should be coupled with data on particular groups of polluting activities under different media systems in order to enhance the assessment groundwater vulnerability accurately and reliably.

Concept of aquifer vulnerability

Groundwater system

The groundwater resource system can be considered a set of interlinked elements, which are situated below the land surface in the pore spaces of the soil and in fractures of rock formations wherein water can be stored [83]. The flow of groundwater is mainly determined by the porosity and permeability of rocks, through which water moves from the surface of the earth into underground aquifers, where gravity plays an important role [88].

As an important element of the hydrological system, any change in groundwater and other environmental elements (e.g., amount of precipitation and land surface evaporation) will exert a direct and inevitable influence on groundwater regimes, resources, and frequently, water quality [94]. Additionally, when determining groundwater safe yield and depth, groundwater resources are dependent not only on geological/hydrogeological factors, but also on physical/geographical and anthropogenic factors. Thus, any change in water consumption leads to a change in groundwater recharge conditions, quality, and abstraction [40].

In groundwater systems, when addressing susceptibility to pollution, a deep aquifer water is generally protected from potential damage when it is not threatened by faulty drilling, injection, and other processes. By contrast, shallow aquifer systems are highly susceptible to diffusion or sudden pollution and suffer long-lasting damage (lower resistance) [12].

Notion of vulnerability

First, vulnerability lacks a specific definition (Vrba & Zaporožec, 1994) as well as a standard technique for estimating groundwater vulnerability, because the concept of groundwater vulnerability is not an absolute property but a complex indicator [60]. The term dates back to the 1960s and was selected to raise awareness of the fact that the notion of groundwater is associated with the image of purity. In other words, this resource is sensitive to external agents and susceptible to pollution [58]. Depending on the nature and structure of the soil and aquifer, the concept of vulnerability may take various forms and degrees to highlight the different natural resistance capacities of the media [59]. It only concerns the hydrogeological environment and excludes the mitigation of pollutants. According to Jiradech (2013), “groundwater vulnerability is defined as the tendency or likelihood of contaminants reaching the groundwater system after introduction at the surface and is based on the fundamental concept that some land areas are more vulnerable to groundwater contamination than others.” Thus, groundwater vulnerability is the tendency or likelihood of contaminants to reach the groundwater system after their introduction at the surface. This term is based on the fundamental concept that a few land areas are more vulnerable to groundwater contamination compared with others [47]. Notably, the vulnerability of an aquifer zones to contamination is a relative and not a directly measurable and dimensionless concept [72].

Principle of groundwater vulnerability

The concept of groundwater vulnerability is based on the origin–pathway–target model (Fig. 1), which is used in a European project that addresses the protection of aquifers as part of a comprehensive European research program “COST Action 620, 2004 European Cooperation in Scientific and Technology” [95]. The origin of contamination corresponds to the place of infiltration of the contaminants at the soil surface, whereas the target is the groundwater in which its protection is the main subject. This setup can be the groundwater surface or drinking water abstraction point. The pathway is the path of the contaminant through natural media (i.e., from an unsaturated zone to a saturated zone) from origin to target. Two general approaches for groundwater protection can be described. The first pertains to groundwater as a “resource” and aims to protect the aquifer storage, whereas the second denotes groundwater as a “source”

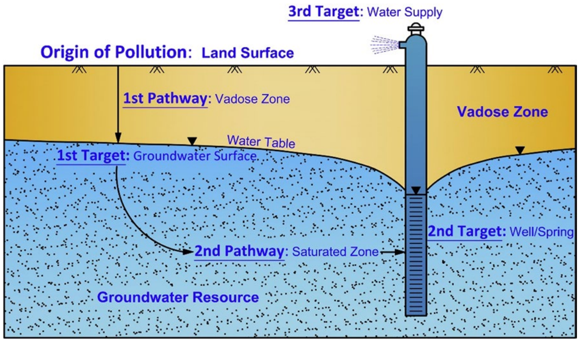

Fig. 1 Schematic of the origin–pathway–target model for the assessment of groundwater vulnerability and resource and the concept of source protection [56]

and aims to protect particular sources, such as production wells and springs [12]. The two concepts, however, are strongly related to each other in terms of protecting the source, which also typically implies the protection of the resource. Vulnerability maps of resources consider the groundwater surface as the target, whereas the vadose zone is treated as the pathway. If the object of protection is the source (i.e., a well or spring is considered the target), the pathway includes the horizontal flow path within the aquifer [38]. Quantitatively, three basic aspects of the assessment of vulnerability must be considered, namely, travel time for a contaminant from origin to target; contaminant attenuation process along the pathway; and the duration of the presence of contamination at the target.

Importance of aquifer vulnerability evaluation maps

The groundwater system is universally recognized as under increasing threat in terms of quantity and quality due to population growth, climate change, agricultural and industrial expansion [27]. In this context, it is important that measures should be taken to ensure the security and safety of groundwater. One of the approaches for preserving and optimizing water potential is the evaluation of the vulnerability of aquifers. Different models and approaches have been developed and piloted for vulnerability assessment and mapping around the world [26]. These methods combine various geological/hydrogeological parameters to produce maps that describe zones with different levels of vulnerability, which are designated by scores, patterns, or colors. The produced maps contribute in decision-making procedures regarding the monitoring and conservation of the groundwater quality [48].

Intrinsic and specific vulnerability

Specifically, the concept of vulnerability can be classified into two notions, namely, intrinsic and specific vulnerability. Intrinsic vulnerability [19] is used to represent the characteristics of the groundwater system (e.g., inherent geological, hydrological, and hydrogeological characteristics) that determine the sensitivity of groundwater to contamination generated by anthropogenic activities regardless of the nature of contaminants [92]. By contrast, specific vulnerability [77] is used to describe the vulnerability of groundwater to a particular pollutant or group of pollutants. It considers the properties of the pollutants and their relationships with the various components of intrinsic vulnerability [70].

Approaches for vulnerability evaluation

Regarding the protection of groundwater, three types of generic approaches can be differentiated in evaluating the vulnerability of groundwater to contamination [21, 56]. The first approach focuses on the evaluation of vulnerability only by considering the soil and vadose zone media and does consider the transport processes within the saturated zone. In this case, evaluation is limited to the relative possibility that contamination will reach the saturated zone. The second approach is based on the delineation of protection zones for groundwater supply systems, where groundwater flow and transport processes in the saturated zone are considered to a certain extent. The third approach is a form of a holistic approach that targets the soil and unsaturated zones as well as saturated zones. Using these three approaches, scholars have developed various methods to assess groundwater vulnerability.

CQ1

The existing methods for aquifer vulnerability can be classified into three basic categories [56]. Index-based methods (qualitative methods) remain the most commonly used models, as they are coupled with Geographic Information Systems (GIS), which makes it easier for the users to interpret the results [54]; statistical methods; and process-based methods (quantitative methods). The quantitative methods, which include simulation modeling aims to determine the "specific vulnerability" of groundwater, whereas the qualitative methods and statistical tools intend to examine "intrinsic vulnerability".

Index-based methods

This type of methods can be further classified into two groups according to applicability, namely, methods for porous aquifers or methods for karst aquifers [46]. The first step is to determine the soil, hydrogeological, hydrographical, and morphological characteristics that match each zone within a vulnerable range. Subsequently, the entire zone is examined and divided according to the established criteria [3]. After the development of GIS technology (since the 1990s), the majority of qualitative methods can be used in the GIS framework and can easily perform map overlaying and indexing operations in the spatial domain [49]. These methods can be used to produce maps of medium-to-large areas with different hydrographic and morphostructural fractures. The three methods, which are the subject of this paper, are DRASTIC [5], GOD [31], and SI [69] methods used to assess aquifer vulnerability, are the widely used GIS-based overlay and indexing methods. Table 1 presents the other significantly used methods for vulnerability assessment.

Statistical methods

Statistical methods provide a viable means for assessing aquifer vulnerability when groundwater quality data are linked to media data (e.g., hydrogeological data, soil properties, land use, etc.) [76]. These methods can range from simple descriptive statistics of the concentrations of contaminants to more complex regression analyses that incorporate the effects of several explanatory variables [56]. In the majority of rigorous statistical analyses, such as logistic regression (which intends to account for potential explanatory variables), additional information and data are frequently included as potential sources of contamination and factors that influence the intrinsic susceptibility of resources [76]. According to [56], the most commonly used statistical techniques in the evaluation of vulnerability are (i) logistic regression or binary logistic regression, which are useful methods for assessing the vulnerability of aquifers to pollution by different pollutants, such as nitrate, chloride, and pesticides [34], and (ii) multiple linear regression (MLR), which is similar to the logistic regression method. The MLR method conceptually evaluates the relationships between a dependent factor and several independent factors and predicts the concentration of contamination instead of the probability of pollution [84]. It is useful for comparing drinking water standards. Lastly, (iii) artificial intelligence (AI) models include fuzzy logic, artificial neural networks, and neuro-fuzzy modeling, which have been applied in the prediction of groundwater vulnerability [25]. Fuzzy logic and fuzzy set theory are mainly used in fuzzy input modeling, because they account for imprecision and uncertainty and reduce information loss when coupled with GIS-based methods [93]; other (AI) models that are powerful soft-computing methods and are highly limited in water resources studies [73], such as Random Forest [14], and Support Vector Machine (SVM) [24].

Process-based methods (quantitative methods)

Contrary to the qualitative approaches, quantitative or process-based methods, these methods can be used to assess the vulnerability (typically, specific vulnerability) of aquifers using natural processes that occur in the hydrogeological parameters of underlying unsaturated and saturated zone systems [30]. This type of method

Table 1 Significant methods for evaluating groundwater vulnerability to contamination for resource protection (adapted from [56])

Methods	Equation	Parameters	Aquifer type	Source
DRASTIC	$\text{DRASTICIndex} = \sum_{i=1}^{7} W\text{iRi}$	Wi and Ri weight and rating for the ith parameter, respectively (range of parameters are given [5]		[5]
GOD	$\text{IvGOD} = G_R \times O_R \times D_R$	G = groundwater type, O = lithology for unsaturated zone, D = depth of groundwater, R = rating of parameters		[31]
SI	$\text{IvSI} = \text{DnDp} + \text{RnRp} + \text{AnAp} + \text{TnTp} + \text{LUnLUp}$	D = depth to water table, R = net recharge, A = water ground media, T = topography, LU = land use, n = score for each parameter, p = weighting factor given to each parameter		[69]
SINTACS	$Iv = \sum_{i=1}^{7} \sum_{j=1}^{n} (\text{Pi} \times \text{Wi})$	Pi = rating for the ith parameter, and Wj = associated weight for the jth weight classification	Porous media aquifers	[18]
GALDIT	$I_{GALDIT} = \frac{\sum_{i=1}^{6} (Wi \times Ri)}{\sum_{i=1}^{6} Wi}$	Wi = weight of the ith indicator; Ri = rating of the ith indicator		[16]
AVI Rating system	$c = \sum_{i=1}^{n} \frac{dj}{ki}$	n = number of sedimentary layers above the aquifer; d = thickness of each sedimentary unit, and k = estimated hydraulic conductivity of each sedimentary unit		[85]

mainly involves simulation models that integrate various physical, chemical, and biological processes to predict the transport of contaminants on the spatial and temporal scales [1]. Moreover, this type emphasizes the protection of the source and resource. Process-based methods generally range from relatively simple functional models to complex models dependent on data requirements and the level of complexity [56]. Complex models can solve equations that control for flow and transport processes in vadose zones or aquifer porous media. Furthermore, such models can consider the stochastic nature of specific system parameters. For models intended to assess intrinsic vulnerability, the thickness and site-specific hydrological regime can be used [44]. In the literature, some of the quantitative models include: the Soil and Water Assessment Tool (SWAT) [4, 8]; Pesticide Analytical (PE- STANS) [28]; Root Zone Water Quality Model (RZWQM) [22, 55]. A complete description of the process-based methods and their applications can be found in reference [56].

Principle of application of the DRASTIC, GOD, and SI approaches for assessing groundwater vulnerability

The DRASTIC approach of mapping groundwater vulnerability

Theory

This method was developed in 1987 under a cooperative agreement between the United States Environmental Protection Agency and the National Water Well Association [5]. The approach considers seven parameters, whose first letters compose the name of the method. Each thematic layer or factor is ranked ranging from 1 to 10. Each of the seven parameters is assigned a multiplication factor that increases from 1 to 5 according to the importance of the parameter for the vulnerability estimate. The result is a vulnerability index (the DRASTIC index), which is a weighted sum of the seven parameters. Table 1 summarizes the details of the DRASTIC index for vulnerability assessment. For conditions with intense agricultural activities, DRASTIC weights are modified to relatively high weights and assigned to soil and slope factors. This modified form of DRASTIC is called pesticide DRASTIC (DRASTIC-P) [5] and represents a specific approach to vulnerability assessment [9]. Table 2 presents the seven parameters and the weight factors for the DRASTIC and DRASTIC-P indexes. After calculating the DRASTIC index, areas are identified as more sensitive to groundwater contamination compared with others. For further interpretation, [20] developed a vulnerability classification that divides the final index into very low, low, medium, high, and very high vulnerability potential (Table 3). [5] hypothesized that the contaminant mimics the mobility of groundwater, whereas the study area considered has a surface area of more than 40 ha. In other words, it is considered the probability of contaminants released from the surface to reach the groundwater. It focuses on contamination from anthropogenic sources and does not assess pollutants introduced into the shallow or deep subsurface by certain processes, such as leakage from underground storage tanks, animal waste lagoons, or injection wells.

Advantages

Evidently, DRASTIC is one of the most widely known and used methods for the assessment of aquifer vulnerability. It has been applied from municipal, such as National Capital Territory, Delhi, India [89] to the continental scale, where the study developed by [68] uses a critical application of the DRASTIC method to assess the intrinsic vulnerability of South American groundwater.

The main strength of the DRASTIC method is the possibility of including or eliminating parameters or factors from the model to adapt to different problems, such as the conditions in the area of study and availability of data [45, 75, 82]. Alternatively, the weight and rate scores can be modified depending on the field measurement data, whereas susceptibility and risk maps can be combined to provide better results using DRASTIC [51].

Over the past decade, several scientists have modified the original DRASTIC model by modifying the scoring ranges and relative weights and by including or omitting certain factors. However, [42] demonstrated that all parameters exert an equal influence on groundwater contamination, where each factor indicates a situation where it has exerted the greatest impact regardless of the weight assigned to the parameters. To effectively manage groundwater contamination, decision-makers and researchers should not only rely on the assumed weight of a given factor when evaluating the vulnerability of groundwater, but also conduct a thorough scientific analysis.

The DRASTIC approach is a useful tool for assessing groundwater vulnerability, because it is relatively low-cost and simple and uses data that are widely available or estimated, and its application with GIS integration provides a map that is easily understood and integrated into the decision-making process [61].

Applications

As previously discussed, DRASTIC is one of the widely used methods for assessing the vulnerability of groundwater resources due to its performance and ease of applicability. According to local needs and to improve the results of the DRASTIC method, two principal approaches for modifying the DRASTIC method are possible:

Table 2 Parameters, class/rating, and weight factors for the DRASTIC-P and DRASTIC indexes and SI (adapted from [5, 69]

	Parameter	Class	Rating	P-DRASTIC weight	DRASTIC index weight	SI weight
D	The depth to water table (m)	0–1.5	10	5	5	0.186
		1.5–3	9			
		3–4.5	8			
		4.5–9	7			
		9–15	5			
		15–22.5	3			
		22.5–30	2			
		Up to 30	1			
R	Net recharge (mm)	> 250	9	4	4	0.212
		180–250	8			
		100–180	6			
		50–100	3			
		0–50	1			
A	Aquifer media	Karst limestone	10	3	3	0.259
		Basalt	9			
		Sand and gravel	8			
		Massive sandstone and limestone	7			
		Bedded sandstone and limestone	6			
		Glacial	5			
		Weathered metamorphic/igneous	4			
		Metamorphic/igneous	3			
		Massive shale	2			
S	Soil media	Thin or absent, gravel	10	5	2	–
		Sandstone and volcanic	9			
		Peat	8			
		Shrinking/aggregate clay/alluvium	7			
		Sand loam, schist, sand, karst volcanic	6			
		Loam	5			
		Silty loam	4			
		Clay loam	3			
		Muckacid, granitoid	2			
		Non-shrink and nonaggregate clay	1			
T	Topography (slope) (%)	0–2	10	3	1	0.121
		2–3	9			
		3–4	8			
		4–5	7			
		5–6	6			
		6–10	5			
		10–12	4			
		12–16	3			
		16–18	2			
		> 18	1			

Table 2 (continued)

	Parameter	Class	Rating	P-DRASTIC weight	DRASTIC index weight	SI weight
I	Impact of the unsaturated zone	Karst limestone	10	4	5	–
		Basalt	9			
		Sand and gravel	8			
		Gravel, sand	7			
		Limestone, gravel, sand clay	6			
		Sandy silt	5			
		Metamorphic gravel and sandstone	4			
		Shale, silt, and clay	3			
		Silt clay	2			
		Confining layer, granite	1			
C	Hydraulic conductivity	$> 6.5e^{-4}$	10	2	3	–
		$5e^{-4} - 9.5e^{-4}$	8			
		$33e^{-5} - 5e^{-4}$	6			
		$15e^{-5} - 33e^{-5}$	4			
		$5e^{-5} - 15e^{-5}$	2			
		$1.5e^{-7} - 5e^{-5}$	1			
LU	Land use	–	–	–	–	0.222

Table 3 Vulnerability assessment criteria for the GOD, DRASTIC, and SI methods [20, 31, 69]

	Vulnerability index		
	DRASTIC	GOD	SI
Very low	< 80	–	–
Low	80–120	0.1–0.3	< 45
Moderate	121–160	0.3–0.5	45–64
High	161–200	0.5–0.7	65–85
Very high	> 200	0.7–1	> 85

(1) Modifying the weights and ratings on the basis of the thorough scientific analysis of data and the combination of the risk and vulnerability maps. [74] identified three methods, namely, entropy information method (E-DRASTIC), fuzzy pattern recognition method (F-DRASTIC), and single-parameter sensitivity analysis (SA-DRASTIC), and applied them to Kanpur City, India. Furthermore, the authors changed the weights of the initial DRASTIC parameters to obtain the corresponding vulnerability index and compared the performance of the subjective (DRASTIC and SA-DRASTIC) and objective (E-DRASTIC and F-DRASTIC) weighting-based methods. The authors concluded that the objective approaches were suitable for vulnerability assessment in the study area. The effectiveness of E-DRASTIC and F-DRASTIC is based on the modification of the weights of only those parameters that are essential in the vulnerability estimation process, as well as the objective methods assigning weights to features according to their relative importance in the final vulnerability assessment. Grey incidence analysis models have been used to evaluate the effectiveness of the modified DRASTIC methods. To improve the reliability of the model, [43] modified the DRASTIC model by adjusting the rating and weighting scores using Wilcoxon's rank-sum test and the fuzzy optimization model for groundwater risk assessment and by considering the nitrate concentration. The results demonstrate that the correlation coefficient between the original and improved DRASTIC models and nitrate concentration indicates that this approach is effective in improving the accuracy of the assessment of groundwater risk (i.e., the correlation coefficient increased significantly from 0.573 to 0.789).

(2) Altering the original DRASTIC parameters, such as subtracting parameters, or including other parameters, such as land use and irrigation type. Under the conditions of intense agricultural activities in Tiruchirappalli district, India, [45] modified the

original DRASTIC and DRASTIC-P models by introducing two extra parameters, namely, land use or land cover (LU) and lineament density (LD), and compared them with six modified forms of these models, namely, DRASTIC-LD, DRASTIC-LU, DRASTIC-LDLU, DRASTIC-P-LD, DRASTIC-P-LU, and DRASTIC-P-LDLU. The results of the vulnerability maps generated by the eight vulnerability models were verified using a single water quality parameter (NO_3^- -N, F^- and Cl^-) individually. The performance of DRASTIC-P-LDLU indicated that the model is the most accurate one with accuracies of 61% and 68% for nitrate and chloride concentrations, respectively, followed by DRASTIC-LDLU with accuracies of 59% and 61% for the same concentrations. Other comparative studies conducted worldwide are presented in Table 5.

Limitations

The major limitations of the DRASTIC method are (i) the reliability of the different parameters used by the approach is dependent on data used in their realization. Typically, information related to parameters, such as net recharge, hydraulic conductivity, water body depth, unsaturated zone impact [53], and the penetration of contaminants through the vadose zone, are influenced by its lithology and determined through interpolation [10]. This aspect leads to faults in the generation of parameter values because it is only accurate in the intervals delimited by the point data [33]. Thus, the DRASTIC model can only be used as a relative assessment tool and is not designed to provide an absolute assessment of groundwater vulnerability [66]. (ii) The one-dimensional DRASTIC approach may be sufficient for assessing the vulnerability of an aquifer in porous media, where water and contaminants penetrate vertically from the soil surface to the water table. Nevertheless, the opposite is true for karst aquifers, where water and contaminants bypass the protective function by flowing laterally through shallow holes [65]. (iii) A few factors are overlapping, such as aquifer media and hydraulic conductivity, which is directly dependent on aquifer media [65].

GOD method

Theory

[31] developed the GOD method in England in 1987. It was originally formulated for use in areas with limited data availability. It uses an empirical approach, where the vulnerability of aquifers is defined as a function of the inaccessibility of a saturated zone, in the sense of pollutant penetration, and the attenuation capacity of the layer above the saturated zone. The GOD scheme considers three parameters, namely, the type of Groundwater occurrence (**G**; the Overlying (**O**) lithological characteristics of the aquifer in terms of lithology and porosity, such as loam, gravel, sandstone, and limestone; and the Depth to groundwater table (**D**). Table 1 defines the vulnerability index (IvGOD).

The result of the values is assigned to these three parameters, which consequently range from 0.0 (negligible) to 1.0 (extreme). The empirical methodology involves several steps in making the map. (i) Factor (G): identify the aquifer type according to its degree of confinement using a scale of 0–1. The (ii) Overlying lithology rating is multiplied as well as with the (iii) depth to water table factor rating. According to [21], the parameters may range from 0 to 1, where the calculated GOD index is generally one value less than the score assigned to each parameter. In the case where two parameters obtain a rating of 1, the vulnerability index is the same as the score of the third parameter.

The GOD values for aquifer vulnerability are grouped into four types that correspond to four levels of vulnerability (Table 3).

Advantages

This approach is less widely popularized compared with DRASTIC. However, it remains one of the best GIS-based overlay and indexing methods, mainly used in data-limited regions that require a rapid assessment of the groundwater situation [39]. A limited number of studies address this method, such as [2, 62], and [53]. The major advantage of the GOD method is that it can be applied to any type of aquifer, except for those in karst regions. Moreover, it is most suitable for large spatial scales [54].

Applications

Compared with the DRASTIC model, this method is less widely popularized [56]. Thus, studies that utilize this method are limited. [36] investigated an Abarkooh aquifer located in the south-eastern part of Yazd province, Iran, and applied the DRASTIC and GOD models to evaluate the vulnerability of the aquifer to pollution. The authors used nitrate concentration as the primary pollution parameter to validate the results obtained using the two vulnerability maps generated by the models. The study concluded that the DRASTIC method was more appropriate for the assessment of the potential for contamination in the study area compared with the GOD method. The correlation coefficient between the DRASTIC index and nitrate content was 68%, which is clearly exceeded the 28% obtained using the GOD method. In the alluvial aquifer of the Florina basin, Northern Greece, [50] compared among three methods, DRASTIC, GOD, and AVI. Nitrate concentrations in groundwater were examined to

Table 4 Principal types of land use and their assigned ratings and weight provided by the Instituto Geogràfico Português (2001)

Land use parameter	Rating	Weight
Agricultural areas		0.222
Irrigation perimeters (annual crops), paddy fields	90	
Permanent crops (orchards, vineyards)	70	
Heterogeneous agricultural areas	50	
Pastures and agro-forested areas	50	
Artificial areas		
Industrial waste discharges, landfills	100	
Quarries, shipyards, open-air mines	80	
Continuous urban areas, airports, harbors, (rail)roads, areas with industrial or commercial activity, laid out green space	75	
Discontinuous urban areas	70	
Natural area		
Aquatic environments (salt marshes, salinas, intertidal zones)	50	
Forests and semi-natural zones	0	
Water bodies	0	

verify the results obtained. The study concluded that the GOD approach displayed a correlation higher than those of the two other approaches, whereas the vulnerability maps produced are generally comparable with the DRASTIC and AVI methods. List of some comparative studies conducted worldwide is given in Table 5

Limitations

The GOD method has its limitations. In regions with moderate variations in the level of vulnerability, the GOD method can provide homogeneous distributions of values. Thus, using this method in areas with high contrasting vulnerability is preferable [21]. Another limitation is the neglect of the inherent heterogeneity of underground systems, whereas the nature of the subcutaneous zone and vertical wells are additional problems when applying this method in karst areas [56, 65]. Hence, [32] suggested particular strategies to follow in any assessment, such as using the predominant lithology of the layers above the aquifer; considering aquifers as unconfined in the case of doubts about the continuity and properties of the confining beds; and using shallow aquifers to assess pollution risk, except in the case of small-perched aquifers.

SI method

Theory

In Portugal, [69] developed SI as a specific method for vulnerability assessment, especially with respect to nitrates. The model considers five parameters (Table 2) and is an adaptation of the DRASTIC method with the omission of three parameters, namely, soil medium, unsaturated zone, and hydraulic conductivity of the aquifer. Instead, it incorporates an additional parameter, namely, land use, which is based on the classification provided by a team of Portuguese scientists. Table 4 presents the main types and classification of land use. In recent studies, the integration of the land use factor in the assessment of groundwater quality is a key issue that should be considered in predicting the effect of anthropogenic activities on groundwater quality [15, 87]. According to [31], the two factors, namely, the lithology of aquifer media and soil media exert no significant impact on the pollutant movement to the groundwater table. Additionally, aquifer media and hydraulic conductivity are two overlapping factors [65]. Hydraulic conductivity is directly dependent on aquifer media because of the difficulty of evaluating it [29]. The vulnerability index (IvSI) is obtained using a linear combination of ratings and weights of the five parameters. Similar to the GOD approach, Table 3 presents the four degrees of vulnerability assigned to each interval of the SI value according to the equation highlighted in Table 1.

Advantages

The main advantage of the SI method is that it can be combined with GIS and remote sensing to develop an integrated approach, especially for heterogeneous media that consider geological, hydrological, and geochemical data to improve the reliability of risk assessment [6, 11]. Similar to the DRASTIC and GOD methods, the SI approach was developed to assess the vulnerability of aquifers on large and medium scales.

Applications

In recent years, aquifer vulnerability assessed using the SI model has many applications. For example, the SI

Table 5 List of some of the comparative studies conducted around the world

Authors	Study area	Year	Methods used	Type of aquifer system	Results
[67]	Apulia, southern Italy	2009	GOD, DRASTIC, SINTACS, EPIK, PI, and COP	Karstic aquifer	The GOD model gives an underestimation of vulnerability and a low sensitivity to spatial variation in key hydrogeological features. The DRASTIC and SINTACS approaches chose limitations in applications to karst aquifer systems. However, the methods EPIK, PI and COP, developed for application to carbonate or karst aquifers, provide cost-effective results, highly consistent with karst and hydrogeological characteristics
[57]	Miopliocene sandy aquifer, Biskra, Algeria	2016	DRASTIC and SI	Porous media aquifer	By integrating the land use parameter, the results obtained with the SI model were more reliable compared to the DRASTIC model. The vulnerability maps produced were tested and validated by the distribution of groundwater nitrates in the study area. The correlation coefficient between the SI and the nitrate concentrations was 85%, which is higher than the 75% obtained with the DRASTIC method
[13]	The aquifer of the city of Meknes, Morocco	2013	DRASTIC and GOD	Porous media aquifer	The analysis of the results obtained from the DRASTIC and GOD approaches indicated three spatial distributions of vulnerability categories, low, medium and high, with 85% of similarity between the two methods for the medium vulnerability category
[53]	Ghiss-Nekkour aquifer, Northeast of Morocco	2020	DRASTIC, GOD and SI	Porous media aquifer	The application of the DRASTIC, GOD and SI methods shows a range of intervals divided into categories corresponding to fluctuating degrees of vulnerability ranging from "very low" to "extreme". The validation of the mapping result was carried out using the nitrate concentrations measured in April 2017. The most reliable results were obtained with the SI method in comparison with DRASTIC and GOD
[79]	Shallow groundwater aquifer of the Kathmandu Valley, Nepal	2022	DRASTIC, GOD and SI	Porous media aquifer	The DRASTIC and SI models are similar for the vulnerability assessment because both methods identify about 80% of the groundwater basin area under the highly vulnerable zone. By contrast, in the GOD model, vulnerability assessment identify areas with "low" and "moderate" vulnerability categories are 24% and 76%, respectively. The correlation between the estimated risk and the measured nitrate concentration was performed to validate the resulting mapping. Comparing with DRASTIC and GOD, the authors conclude that the SI method has more reliable results

Table 5 (continued)

Authors	Study area	Year	Methods used	Type of aquifer system	Results
[52]	Nea Moudania aquifer, Chalkidiki, Greece	2022	DRASTIC, pesticide DRASTIC, SINTACS, nitrate SINTACS, GOD, AVI, and SI,	Porous media aquifer	As the study area is marked by intensive agricultural activities. The authors confirm that DRASTIC Pesticide and SINTACS Nitrate were the more precise and efficient methods for evaluating the groundwater vulnerability in the study area. Using the coefficient of correlation (R^2), the authors validated the results obtained by the seven methods using the nitrate concentrations from 23 observation wells. The most efficient and accurate approaches were pesticide DRASTIC and nitrate SINTACS with $R2 = 0.6475$ and 0.6438, respectively. The two methods have a slightly higher coefficient of determination compared to DRASTIC and normal SINTACS. Besides, AVI, GOD methods were the less reliable, with correlation coefficients of GOD ($R2 = 0.5348$), AVI ($R2 = 0.5045$); SI method, which incorporates the land use parameter exhibited a greater R2 of 0.6084

approach was used to assess the vulnerability of groundwater in the Takelsa phreatic aquifer, north-east of Tunisia. The resulting vulnerability maps were validated by comparing areas at high risk of salinity with their relative vulnerability index. Moreover, [37] demonstrated that 50% of the study area is characterized by areas of high to very high levels of vulnerability. The main reasons for these high-vulnerability areas are the presence of high recharge rates, sandy soils, shallow water tables, and areas with high levels of agricultural activity in land use. Hence, results that were more reliable were obtained using the SI method in comparison with DRASTIC by [53] and [41]. Moreover, the vulnerability classes mapped are higher with the application of the SI approach, which supports the idea that the SI method was designed to consider the properties of nitrates and the relationship between them and intrinsic vulnerability. By contrast, the DRASTIC model ignores the nature of contaminants and focuses solely on hydrogeological parameters. The LU parameter incorporates land use categories, which enables the integration of various special features. List of some comparative studies conducted worldwide is given in Table 5.

Limitations

In Tunisia, [6] applied this method in combination with consistency, where contamination by nitrate has occurred. Data on vulnerability exhibited certain limitations in assessing groundwater vulnerability. The first is that the application of the SI model displayed an overestimation of vulnerability as a result of the impact of dilution, which reduced the level of contamination. Moreover, [64] highlighted the difference between the most vulnerable and most contaminated areas. The second limitation is that the SI method overlooks the recycling process of groundwater that contributes to the accumulation of pollutants. This tendency leads to an underestimation of vulnerability due to the failure to consider two factors, namely, soil media and unsaturated zone [6].

Discussion

A simple mapping of vulnerable areas is prepared by overlaying a series of features that exhibit the areal distribution of attributes considered significant to the characterization of the potential of groundwater contamination (e.g., soil type, depth to groundwater, and unsaturated zone). Each feature is assigned a weight relative to the other in order of importance, whereas areas with different vulnerability scores are defined by ranges on the basis of their impact on the pollution potential in the area. Typically, the product is a vulnerability map that describes different levels of vulnerability, which are designated by scores, patterns, or colors. The assessment of groundwater vulnerability is frequently a difficult task, such that an oversimplification or inadequate description of the geological, hydrological, and hydrogeological characteristics of the media can compromise the reliability of the resulting maps. The reliability of the different parameters used can also be a serious limitation of the assessment of groundwater vulnerability, which can influence the reliability of the vulnerability maps.

Different circumstances may justify the modification of the original DRASTIC approach by changing the weights and ratings of different features or by subtracting/including other parameters according to specific case studies [78]. However, [42] proved that all parameters all exert an equally significant influence on groundwater pollution, whereas each factor indicates a particular situation, where it exerted the most impact regardless of their assigned weights.

According to[86] , the best method for increasing confidence in vulnerability mapping is to compare the results of different tools and analyze their consistency by conducting case studies on areas, where contamination occurred.

The DRASTIC and SI methods are based on the concept of parametric methods with a weighted class system. The different parameters used by the two approaches have different weights. Thus, their contribution to the final intrinsic vulnerability also varies. Alternatively, the GOD method is based on the concept of the parametric class system [17]. The different parameters used in the approach are assumed to exert the same effect in terms of vulnerability, which leads to the lack of weighting.

The GOD approach adopts a multiplicative combination approach, given that the intrinsic vulnerability of groundwater to contamination is dependent on a conditional probability concept. In this case, groundwater contamination risk can be defined as the probability of a contaminant particle to reach a given compartment of the lithological section through soil surface activities. Moreover, the risk may be a result of the interaction between the vulnerability of the aquifer and the contaminant load applied at the location concerned[17]; [31]. Conversely, the DRASTIC and SI methods adopt an additional model, which refers to a concept of unconditional probability. According to these approaches, the pollution of a given layer through a given pollutant can occur even if the soil surface is not contaminated.

The literature review of different methods, namely, modified DRASTIC, modified SINTACS and SI methods [64]; DRASTIC, P-DRASTIC, and the SI approach [6]; GOD, DRASTIC, and AVI [50]; and DRASTIC, GOD, and SI [53]. The results reveal that the boundaries of the standard categories do not always correspond to the actual situation of a study area because these classes can always group into different entities within them. Hence, the clustering of dimensions, as well as the vulnerability indices, may not always be the same as those defined by the DRASTIC, GOD, or SI approach. According to [33], the different categories are not absolute but relative values. These limits may then vary across studies and regions. Alternatively, [71] compared several approaches in porous media aquifers and in a fractured rock aquifer system, and concluded that the vulnerability maps for a given hydrogeological system considerably vary according to the type of the selected method for vulnerability assessment.

[86] applied the DRASTIC and SI methods relative to groundwater salinization and levels of nitrate contamination in two agricultural regions in the south of Portugal. In the karstified limestone aquifers of Campina da Luz, the results revealed an overestimation of vulnerability even with the low degree of contamination as a result of dilution. The DRASTIC and SI methods overlooked this aspect. These methods assume that attenuation capacity was extremely low under the conditions in question, such that vulnerability to contamination is, therefore, high. The DRASTIC method does not consider the dilution of groundwater although it has a strong control on the levels of contamination, which may lead to erroneous results [5]. By omitting the impact of the vadose zone, SI minimizes the error of DRASTIC. Moreover, it integrates land use, which adds valuable information. However, the SI approach tends to overestimate vulnerability, which is preferable to underestimating it, in that it implies the safety of uncertainty [27].

In agricultural regions in the southern Tehran aquifer, Iran, [64] demonstrated that the SI model was a useful tool for evaluating specific vulnerability and examined the benefit of integrating the land use factor into the SI index to predict nitrate contamination in groundwater.

The literature review revealed that index-based methods, such as DRASTIC, GOD, and SI, are suitable for incorporation with GIS tools [56].

For aquifer vulnerability mapping, the protective impact of the above aquifer layers presents a semiquantitative value and gives weights to different parameters in order of importance by controlling for the migration of pollutants [35]. This aspect includes the possibility of including or excluding parameters according to the availability of information and the requirements of the study area. Therefore, GIS-based integration provided a satisfactory assessment of groundwater vulnerability in the study area. Moreover, it is cost-effective and consumes less time [26].

Conclusion

This study presents a review of three methods, namely, DRASTIC, GOD, and SI, which are used for assessing aquifer vulnerability in relation to resource protection.

The three approaches are based on the subjective weighting and rating of relevant parameters and are suitable for porous media aquifers. Nevertheless, they have been proven adequate for fractured/fissured and karst aquifer systems, where groundwater flow typically exists.

All vulnerability assessment methods have their pros and cons. Despite the complex aspects, however, the major limitation of GIS-based methods, such as DRASTIC, GOD, and SI, is the limited availability of the necessary geological, hydrological, and hydrogeological data sets that influence groundwater vulnerability. The problem of data availability is complicated from the perspective of spatial variability and scale problems associated with media systems. Alternatively, the assignment of weights and ratings to each parametric map leads to significant uncertainties and the lack of strong criteria for the classification of vulnerability. However, validating the vulnerability maps must be a required step and can be conducted using the water quality parameter. To reduce the risk of incorrect decisions, the objective of groundwater value assessment should always be as rigorous as possible.

Notably, assessing vulnerability is an efficient tool for groundwater management policies if it concentrates on particular groups of pollutants and polluting activities. [7] suggested that the evaluation of vulnerability must focus on factors such as the clean-up capacity of the soil and restoration capacity of the aquifer instead of other parameters, such as the impact of unsaturated zones and the depth to groundwater. However, the rapid influx of pollutants into the aquifer should not necessarily be associated with high vulnerability, as implied by the DRASTIC, GOD, and SI methods.

We have critically examined the DRASTIC, GOD and SI approaches to understand their challenges and the research needs to advance the framework of these methods. Our future work will focus on the practical aspects of these three approaches to evaluate and compare the findings of this systematic review.

Acknowledgements
Not applicable.

Author contributions
FA: conceptualization, investigation, data analysis, methodology, writing the original draft. AF: supervision, data curation, resources, project management, and editing. All authors read and approved the final manuscript.

Funding
Open access funding provided by University of Szeged. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Availability of data and materials
The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Received: 22 March 2022 Accepted: 17 July 2022

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