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Review Article

A Review of Methods to Assess Groundwater Vulnerability to Pollution

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Abstract

Groundwater resources that are increasingly being cherished for most socioeconomic development are exposed to varied pollutant sources. Studies have shown that they are vulnerable to various impacts such as climatic change, human impacts and also pollution from seawater intrusion in coastal areas. The susceptibility of a groundwater body to pollution indicates extent to which its quality is at risk of being compromised by contaminants. Assessments of this vulnerability are classified based on scale (site, local, regional) or objective (such as risk management or protection zoning) and also distinguish between source and resource vulnerability maps, as well as specific and intrinsic vulnerability maps. Groundwater vulnerability assessment methods differ based on several factors, including the availability and spatial distribution of quantitative and qualitative data, the objectives and scale of the mapping, the costs of model development, and the particular hydrogeological characteristics of the aquifer under investigation. The National Research Council has classified these methods into three primary categories: process-based methods, statistical methods, and overlay/index methods. Among these, the overlay/index method is widely employed for conducting large-scale assessments of aquifer sensitivity and groundwater vulnerability. It is especially advantageous in developing countries due to the easily accessible data required for its implementation.

Keywords

Statistical Methods, Process-Based Methods, Hydrogeological Setting, Overlay/Index Method, Sea-Water Intrusion

1. Introduction

Water scarcity and pollution have grown to be serious global problems in recent decades. Considering that billions of people around the world either lack access to water or face water scarcity, preserving the quality of groundwater is essential for ensuring the availability of drinking water resources [1]. Groundwater is a vital and valuable renewable resource globally, supporting human life and economic development. It makes up a significant portion of the earth's water cycle, existing in permeable geological formations known as aquifers—structures capable of storing and transmitting water at rates sufficient to supply wells with reasonable quantities. Its significance lies in its ability to serve as a large reservoir, providing "buffer storage" during drought periods [2].

Wada *et al.* [3] note that global water demand has increased sixfold over the last century and is projected to rise by 1%

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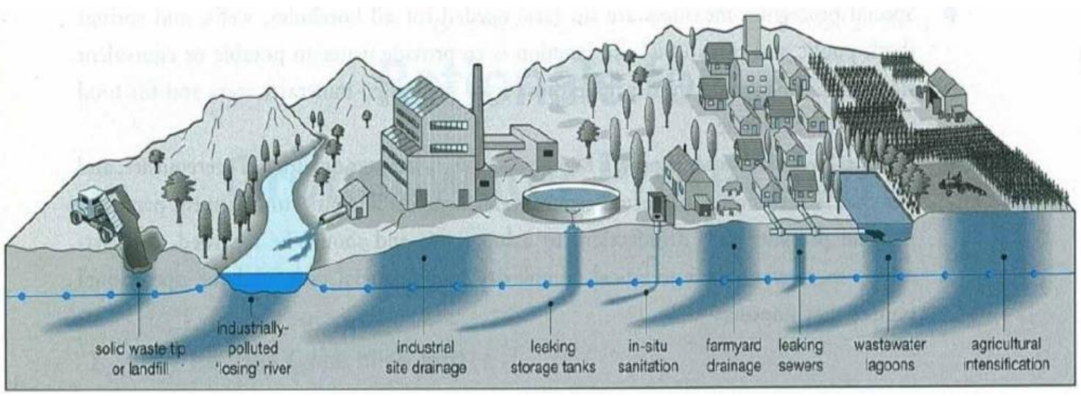
annually, driven by population growth, economic development, and shifts in water use patterns [4]. While water demand for industrial purposes (20%, with 75% used for energy production) and domestic needs (10%) is expected to keep growing, agriculture will continue to consume the largest share (70%) [4, 5]. This rising demand will be particularly significant in countries with developing or emerging economies [4]. Major rivers worldwide provide water for supply, irrigation, industrial and municipal use, waste disposal, navigation, hydroelectric power, fishing, boating, recreation, and aesthetics [6]. However, some of these services, such as irrigation, waste disposal, and industrial activities, often lead to the degradation of both water quality and quantity [6]. Consequently, groundwater has become recognized as the most vital natural resource in many countries, forming the bulk of total water resources.

Despite the dependence on groundwater by a great number of people, the subsurface resource over the last 50 years has not been given sufficient attention and has seen unprecedented development making it vulnerable to diverse sources of pollution. Regionally, groundwater holds significant importance in Africa, Asia, and Central and South America due to its natural protection by the vadose zone. This protection allows groundwater to respond more slowly to climate variability and drought [7]. On a national level, countries ranging from Palestine to Denmark depend on groundwater, with local examples of reliance spanning from Mexico City to small villages in Ethiopia. It is estimated that around 2 billion people globally depend on aquifers for their drinking water supply. [8].

Groundwater is often resistant to contamination from various activities and generally maintains good quality in many parts of the world. This is partly due to the natural capacity of aquifer systems to mitigate and absorb the effects of pollution. However, once groundwater is contaminated, it becomes difficult to remediate [2, 9]. Replacing a failing local aquifer is expensive, and its depletion can strain other water sources. Moreover, remediation efforts can be extremely challenging, particularly in developing countries. As a result, identifying which aquifer systems and environments are most susceptible to degradation is crucial [2, 9].

Groundwater vulnerability assessment concept emerged in the late 1960s and early 1970s through the work of researchers [9-12]. These assessments are categorized by scale (site, local, regional) or purpose (e.g., risk management, protection zoning) to distinguish between source and resource vulnerability maps, as well as between specific and intrinsic vulnerability maps. Regarding groundwater vulnerability, there are two main types: intrinsic and specific. Intrinsic groundwater vulnerability refers to the susceptibility of groundwater to contaminants resulting from human activities, while specific vulnerability pertains to the groundwater's sensitivity to certain contaminants, considering the nature of these contaminants and their relationship with various intrinsic vulnerability factors [13]. The vulnerability of an aquifer system to pollution reflects how easily it can be affected by pollutants [14, 15]. Pollution can originate from point sources (such as landfills, cemeteries, domestic or industrial wastewater discharge), linear sources (like wastewater networks, agricultural drainage systems), or diffuse sources (including chemical fertilizers, pesticides, herbicides, and domestic wastewater application) [16]. In urban or industrial areas, groundwater is at risk of being overused or contaminated. Researchers have developed tools to protect and preserve groundwater. These tools help identify areas highly vulnerable to pollution, regardless of the specific pollutant, by mapping contamination risks. Urban land use plans should, at a minimum, identify areas that require strict protection measures to prevent the spread of pollutants from development activities.

Vulnerability studies evaluate the impact of pollutant loads on water quality by examining water quality degradation. According to guidelines from the International Conference on Vulnerability of Soil and Groundwater to Pollutants [17], Lobo-Ferreira and Cabral [18] proposed that groundwater vulnerability to pollution should be defined as the sensitivity of groundwater quality to contaminants, which is influenced by aquifer characteristics. Therefore, vulnerability is determined by both the extent of pollutant presence in the subsurface environment and the inherent vulnerability of the aquifer. The severity of the impact on water usage depends on various factors, such as the magnitude of the pollution event, the importance of the groundwater resource, and the aquifer's vulnerability to contamination (Figure 1). Groundwater vulnerability can be assessed using three primary methods: process-based simulation techniques, statistical approaches, and overlay/index methods. This review aims to provide an overview of the different techniques or methods used to assess groundwater vulnerability, including the strengths and limitations of each method, and to offer recommendations for future research and practice. It also includes an overview of three selected overlay/index methods: DRASTIC, SINTACS, and GALDIT.



Source: [19]

Figure 1. *Groundwater pollution factors.*

2. Groundwater Vulnerability Assessment Methods

Margat [10] introduced the concept of groundwater vulnerability to pollution. This concept is based on the idea that the physical environment can provide some protection to groundwater from human impacts, particularly when it comes to contaminants entering the subsurface [20]. The application of groundwater vulnerability assessment varies depending on factors such as the availability and distribution of quantitative and qualitative data, the objectives and scale of the mapping, the costs of model development, and the specific hydrogeological conditions of the aquifer in question [9, 21, 22]. To evaluate groundwater vulnerability, numerous methods have been developed. The National Research Council [23] categorizes these methods into three main types: process-based methods, which use mathematical models to simulate how substances behave in the subsurface; statistical methods, which identify areas with known contamination; and overlay and index methods, which combine various physical characteristics affecting vulnerability and often assign a numerical score.

2.1. Process-Based Simulation Methods

Mathematical equations that describe the interconnected processes governing contaminant movement must have either analytical or numerical solutions in order to be applicable in process-based modeling approaches. Richard's equation, which accounts for variably saturated water flow, and the convection-dispersion equation, which addresses solute transport, serves as the foundation for process-based models used in simulating flow and transport in porous media [24]. This field encompasses a wide range of methods, including simple transport models, analytical solutions for pollutant movement through the unsaturated zone in one dimension, as well as linked unsaturated-saturated, multi-phase, and two- or three-dimensional models. Numerical methods are also employed to solve these problems [12]. Among these methods, MODFLOW, a three-dimensional model originally developed by the U.S. Geological Survey, is the most widely used numerical groundwater flow model [25, 26].

Lindstrom [27] conducted a study in Sweden utilizing the one-dimensional unsaturated MACRO model and the two-dimensional MOC model to assess the vulnerability of groundwater to salt contamination resulting from road de-icing practices within a water supply region. Chloride levels were employed as an indicator of the risk of groundwater contamination from road salts. The results revealed a significant increase in chloride concentrations within the aquifer due to road de-icing, and it would require several decades for these concentrations to revert back to their initial levels after the cessation of de-icing salt usage.

Simulation models based on processes are used to estimate the time it takes for a contaminant to reach a certain depth or the amount of contaminant present. These models mathematically represent the processes that affect the fate and movement of contaminants. However, the data required for these models are often not available and must be estimated using indirect methods [28, 12]. It is important to note that computer models do not directly measure vulnerability. Instead, vulnerability is assessed based on the simulations generated by the model. The complexity of these models can range from simple indicators of transport to intricate, multi-phase, multi-dimensional simulations of contaminant movement in both saturated and unsaturated zones. Furthermore, these models have limitations in understanding complex hydrogeological processes and their interactions in specific geological contexts.

2.2. Statistical Methods

Statistical methods are used to assess the presence of contaminants in groundwater by utilizing response variables such as contaminant occurrence frequency, contaminant concentration, or the probability of contamination [9]. These methods are based on the concept of uncertainty, which is represented through probability distributions for the specific variable [23]. One goal of employing statistical methods in vulnerability assessments is to identify the variables that can accurately determine the likelihood of groundwater contamination [9]. In general, the objective is to mathematically describe the relationship between water quality and both natural and human-induced factors within a defined area, either through a function or a model.

Over the years different probabilistic method is been used in these statistical methods. Evans and Maidment [29] studied the vulnerability of Texas groundwater to nitrate contamination using discrete and lognormal probability estimation methods. They used linear regression to assess the correlation between nitrate exceedance probability and between nitrate contamination patterns and nitrogen fertilizer sales. potential indicators, and also examined the relationship However, their findings did not reveal a significant relationship. Worrall & Kolpin [30] developed a logistic regression model for groundwater contamination that incorporates variations in chemical properties with land use, soil, and aquifer parameters. Statistical approaches and simulation models have shown better results compared to overlay and index methods. However, the reliance on available data, which may be limited or uncertain, presents challenges in managing these uncertainties [31].

2.3. Overlay/Index Methods (Pollution Index)

Overlay or index methods involve combining various maps that depict physiographic features such as geology, soils, and depth to the water table. Each feature is assigned a numerical index or score, making these methods relatively simple to implement. The area's physical and human-made characteristics are then mapped by assigning numerical ratings [9]. By integrating these ratings, a composite sensitivity or vulnerability score is derived [32]. The methods include DRASTIC [33], GOD [34], AVI [35, 36], SINTACS [37], GALDIT [38]. The most popular overlay and index method used all over the world is the DRASTIC method, developed by Aller *et al.* [33], for vulnerability assessments at regional scales [1]. The DRASTIC method, developed by Aller et al., is the most widely used globally for regional vulnerability assessments and has served as a basis for the creation of other similar methods with different input parameters.

In the simplest use of these techniques, all attributes are assigned equal importance, without evaluating their relative significance. However, by assigning different numerical scores and weights to these attributes, overlay and index methods attempt to create a range of vulnerability classes, which are then depicted on a map [23, 39]. The challenge with these methods lies in the difficulty of assigning appropriate weights to different parameters. These methods integrate factors that influence the movement of pollutants from the surface to the saturated zone. Overlay/index methods are often favored because they rely on data that is readily available across large areas, making them ideal for regional-scale assessments. [40].

2.3.1. Drastic Method

A standardized model known as DRASTIC was developed in USA by Aller *et al*. [33] to assess the potential pollution of a specific area using well-established hydrogeological parameters. This model comprises three main components: hydrogeological parameters, a rating system, and parameter weights. The acronym DRASTIC represents the seven hydrogeological factors incorporated in the model: 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) [21, 41, 1]. Each factor is rated on a scale from 1 to 10, with 1 indicating the lowest vulnerability and 10 indicating the highest vulnerability, based on a range of values. Furthermore, these hydrogeological factors are assigned relative weights ranging from 1 to 5, with 5 being the most significant and 1 being the least significant (Table 1) [42, 43]. The vulnerability index is then calculated by applying a linear equation [33] to the ratings and weights of each parameter (equation (1)):

$$DR_i = D_w D_r + R_w R_r + A_r A_w + S_r S_w + T_r T_w + I_w I_r + C_w C_r \quad (1)$$

Where: DR_i = DRASTIC vulnerability index, D, R, A, S, T, I, and Cs are seven parameters of the model; w = assigned weight of DRASTIC parameter; r = assigned rate for the respective DRASTIC parameter. The benefits of the DRASTIC model include:

It offers a way to assess an area using existing conditions without requiring extensive, site-specific pollution data.

It serves as a foundation for assessing the vulnerability of groundwater resources to pollution based on hydrogeological factors.

It provides a cost-effective means of identifying areas that may require further investigation.

Despite its advantages and the widespread use of the DRASTIC technique for vulnerability mapping, this method has several limitations. The most significant drawback is its subjective nature, which raises concerns about the selection of certain factors while excluding others [44]. Due to these subjective aspects, researchers have been working in recent years to enhance the DRASTIC method for more accurate vulnerability assessments. For instance, the standard method has been refined by incorporating land use, leading to the development of the DRASTIC-LU model [45]. Additionally, combining DRASTIC with other approaches such as SINTACS, GOD, AVI, and SI has further improved the method. Below, several studies that have applied the DRAS-

TIC and enhanced DRASTIC methods in various regions of the world are reviewed.

Victorine Neh et al. [46] demonstrated the significant impact of the aquifer and soil media within the same sedimentary environment in a portion of the coastal city of Douala using the DRASTIC-GIS method.

Research conducted by Abdullah et al. [47] in the Halabja Saidsadiq Basin, Kurdistan Region, Iraq, using lineament density within the standard DRASTIC method, demonstrated that a higher concentration of lineaments enhances the likelihood of contaminant migration into the groundwater, thus impacting the vulnerability system.

Mfonka et al. [48] conducted a groundwater vulnerability assessment in the shallow aquifers of Foumban using the DRASTIC method and found that the depth to the water table and the impact of the vadose zone are the most influential factors affecting aquifer vulnerability.

Ducci & Sellerino [49] noted in a study conducted in Southern Italy that a modified AVI model used in groundwater vulnerability assessment revealed that the DRASTIC method predominantly indicated a "moderate" vulnerability level. The eastern region was identified as having a "low" vulnerability level, while only small areas were categorized as having a "high" vulnerability. The AVI method identified areas with "high" and "very high" vulnerability levels. The eastern sector's reduced vulnerability in both methods is significant, attributed to the presence of peat layers with extremely low hydraulic conductivity.

Table 1. *Standard DRASTIC parameters.*

Layer	Range	Rating	Typical rating	Weight
Depth to water (m)	0–1.5	10		5
	1.5–4.5	9		
	4.5–9	7		
	9–15	5		
	15–22.5	3		
	22.5–30	2		
	> 30	1		
Recharge (mm/y)	> 254	9		4
	178–254	8		
	102–178	6		
	51–102	3		
	0–51	1		
Aquifer media	Karst limestone	9–10	10	3
	Basalt	2–10	9	
	Sand and gravel	4–9	8	
	Massive limestone	4–9	6	
	Massive sandstone	4–9	6	
	Bedded sandstone, limestone and shale sequences	5–9	6	
	Glacial till	4–6	5	
	Weathered metamorphic/igneous	3–5	4	
	Metamorphic/igneous	2–5	3	
	Massive shale	1–3	2	
Soil media	Thin or absent	10		1
	Gravel	10		
	Sand	9		
	Peat	8		

Layer	Range	Rating	Typical rating	Weight
	Shrinking and/or aggregated clay	7		
	Sandy loam	6		
	Loam	5		
	Silty loam	4		
	Clay loam	3		
	Muck	2		
	Non-shrinking and non-aggregated clay	1		
Topography (%)	0–2	10		1
	2–6	9		
	6–12	5		
	12–18	3		
	> 18	1		
Impact of vadose zone	Karst limestone	8–10	10	5
	Basalt	2–10	9	
	Sand and gravel	6–9	8	
	Metamorphic/igneous	2–8	4	
	Sand and gravel with significant silt	4–8	6	
	Bedded sandstone, limestone and shale	4–8	6	
	Sandstone	4–8	6	
	Limestone	2–7	6	
	Shale	2–5	3	
	Silt/clay	2–6	3	
	Confining layer	1	1	
Hydraulic conductivity (m/day)	> 82	10		3
	41–82	8		
	29–41	6		
	12–29	4		
	4–12	2		
	<4	1		

Source: [33, 50]

2.3.2. SINTACS Method

The SINTACS method is an adaptation of the DRASTIC method, which was developed in the early 1990s to address Italy's extensive hydrogeological diversity [33, 51, 52]. It falls under the category of point count system models, such as SINTACS, where each factor is assigned a score and an additional weight to adjust its significance in the analysis. This weight is modified based on environmental conditions, such as significant dispersion from surface water to groundwater or widespread pollution sources [53]. The key vulnerability parameters identified by this method include the depth of water (S), effective infiltration (I), unsaturated zone (N), soil media (T), aquifer media (A), hydraulic conductivity (C), and topographic slope (S).

Civita [54] emphasized the importance of considering various factors when choosing a method to assess groundwater vulnerability. These factors include the density of observation points, availability and completeness of data, reliability of the data, and the uniformity of the study area. A critical review of existing methods has identified several concerns that need to be addressed in order to improve the evaluation of groundwater vulnerability. These concerns include the need to integrate the influence of soil with the surrounding system, to consider the impact of climatic factors on the water system, to develop methods that are applicable in different local contexts, and to ensure that vulnerability maps are based on a thorough understanding of contaminant production mechanisms and associated risks [55].

The SINTACS framework is more intricate than the DRASTIC model due to the distinct ways its parameters are evaluated and weighted. In SINTACS, the rates and weights are meticulously allocated to consider all environmental factors associated with the seven variables in the model [54, 56], and they vary according to local hydrogeological conditions. Consequently, SINTACS provides more adaptability in parameter scoring and weighting compared to the DRASTIC model [57]. SINTACS vulnerability index (SIv) is computed using Equation 2, which involves summing the ratings for each of the seven parameters along with their respective weights.

$$SI_v = \sum_{i=1}^{7} (P_i W_j \qquad (2)$$

Where: Pi is assigned a rating for the ith parameter; W_j is assigned a weight of the jth weight classification. The higher the SIv value, the higher the vulnerability.

Aboulouafa *et al*. [58] applied the DRASTIC and SINTACS methods along with GIS and remote sensing techniques in the Berrechid basin. Both methods produced nearly identical maps, but a sensitivity analysis revealed that the highest risk of groundwater contamination in the Berrechid plain is primarily influenced by "topography," "aquifer media," and "hydraulic conductivity" according to the DRASTIC method. For the SINTACS method, the factors indicating greater risk of contamination were "depth to water level" (S) and "aquifer media."

Corniello et al. [59] observed that lithological and morphological factors play a crucial role in the creation of vulnerability maps using SINTACS. In a comparative analysis of three methods [60] carried out in a Mediterranean region, it was found that climatic conditions have a significant impact on the effectiveness of these methods. Specifically, DRASTIC outperformed both SINTACS and AVI. Furthermore, a comparison of the vulnerability maps generated by DRASTIC and SINTACS for an Algerian aquifer [61] showed that the results are statistically consistent.

By comparing the results of the DRASTIC, SINTACS, and GOD methods applied to a database from Central Romania [62], it is evident that the maps produced by the DRASTIC and SINTACS methods are quite similar, despite some differences in the areas classified as having low vulnerability. In regions with minimal variation in vulnerability, the GOD method was less effective. Thus, GOD should be employed primarily in areas with significant variations in vulnerability.

Secunda et al. [63] and Noori et al. [64] applied a modified version of the SINTACS method known as SINTACS-LU in their studies. This updated method incorporated a new factor, LU, similar to DRASTIC-LU, to account for the impact of land use on groundwater vulnerability. The SINTACS-LU and DRASTIC-LU approaches demonstrated superior performance compared to the original SINTACS method in case studies from Israel and Iran. Both methods effectively identified areas significantly influenced by human activity [63]. Sensitivity analysis of SINTACS-LU [64] revealed that the vadose zone had the greatest impact, followed by land use. Furthermore, the correlation between the vulnerability index and field-recorded nitrate values was highest for SINTACS-LU (0.75), compared to DRASTIC-LU (0.68) and SI (0.64).

2.3.3. GALDIT Method

GALDIT is an open-ended additive model with six parameters that was designed by Chachadi and Lobo Ferreira [38]. It is known to be particularly effective for coastal regions [65]. The model includes the following parameters: Groundwater occurrence (aquifer type: unconfined, confined, or leaky confined) (G), aquifer hydraulic conductivity (A), depth to the groundwater level relative to sea level (L), distance from the shore (perpendicular distance inland from the shoreline) (D), effect of current seawater intrusion in the area (I), and thickness of the aquifer (T).

GALDIT factors are quantifiable parameters, and data for these factors can typically be accessed from multiple sources [66]. Each of the six indicators has a fixed weight assigned to it, which reflects its significance in relation to seawater intrusion [65]. These weights are presented in Table 2. The GALDIT Index is calculated by evaluating the scores for each indicator and summing them, using the formula provided in equation (3).

$$\text{GALDIT} - \text{index} = \frac{\sum_{i=1}^{6}\{(W_i)R_i\}}{\sum_{i=1}^{6} W_i} \qquad (3)$$

Where: W_i is the weight of the ith indicator and R_i is the rating of the ith indicator

Several researchers have used this method to assess seawater intrusion in coastal areas. Some researchers have also improved the rating system to make it more effective [67]. For example, Sujitha *et al.* [65] applied the GALDIT method to evaluate aquifer vulnerability on the west coast of Gao State, India. They found moderate to low levels of pollution and noted that the northern region was more susceptible to pollution than the southern region. Bordbar *et al.* [68] enhanced the GALDIT framework by integrating statistical and entropy models. This improved the accuracy of the method in mapping groundwater vulnerability to seawater intrusion in the eastern Alborz Mountains. In another study, Mirzavand *et al*. [66] used the AHP-GALDIT method in the Kashan Plain aquifer in Iran. They identified that the northeastern section of this inland coastal aquifer is experiencing saltwater intrusion. This is primarily due to the groundwater table in the northeastern region being below sea level, which allows saltwater to enter.

Table 2. *Rating for Indicators for the GALDIT method.*

Indicators	Weight	Indicator Variables: Class	Indicator Variables: Range	Importance rating
Groundwater occurrence/ Aquifer type	1	Confined Aquifer		10
		Unconfined Aquifer		7.5
		Leaky confined Aquifer		5
		Bounded Aquifer (recharge and/or impervious boundary aligned parallel to the coast)		2.5
Aquifer Hydraulic Conductivity (m/day)	3	High	> 40	10
		Medium	10 – 40	7.5
		Low	5 – 10	5
		Very low	< 5	2.5
Height of groundwater Level above msl (m) Distance	4	High	< 1.0	10
		Medium	1.0 – 1.5	7.5
		Low	1.5 – 2.0	5
		Very low	> 2.0	2.5
Distance from shore / High Tide (m)	4	High	< 500	10
		Medium	500 – 750	7.5
		Low	750 – 1000	5
		Very low	> 1000	2.5
Impact of existing seawater intrusion	1	High	> 2	10
		Medium	1.5 – 2.0	7.5
		Low	1 – 1.5	5
		Very low	< 1	2.5
Aquifer thickness (saturated) in meters	2	Large	> 10	10
		Medium	7.5 – 10	7.5
		Small	5 – 7.5	5
		Very small	< 5	2.5

Source [65]

2.4. Sensitivity Analysis

To assess groundwater vulnerability, sensitivity analysis is conducted to determine the most significant and pertinent variables. Two methods are utilized: single parameter sensitivity and map removal sensitivity analyses. These methods analyze the impact of each parameter on the final vulnerability maps.

2.4.1. Single Parameter Sensitivity Analysis (SPSA)

Napolitano & Fabbri [69] presented the SPSA method, which compares the theoretical weight of each parameter with its actual or effective weight. The effective weight is determined using equation (4).

$$W = \frac{P_r P_w}{V} \times 100 \quad (4)$$

In this context, W represents the effective weight of each parameter, Pr stands for the rating value of each parameter, Pw indicates the weight of each parameter, and V refers to the overall vulnerability index. [70].

2.4.2. Map Removal Sensitivity Analysis (MRSA)

Lodwick *et al*. [71] introduced this method, which operates on the principle of assessing the sensitivity of each parameter by individually omitting one parameter at a time. This calculation is performed using equation (5) [70].

$$S = \frac{\left(\frac{V}{N}\right) - \left(\frac{V'}{n}\right)}{V} \times 100 \quad (5)$$

Where V' represents the adjusted vulnerability index, while V refers to the overall vulnerability index. The variables n and N indicate the number of input layers utilized for computing V' and V, respectively. Additionally, S signifies the sensitivity value.

In recent years, researchers have conducted sensitivity analyses on various overlay-indexed methods to improve the accuracy and reliability of assessments. Ganesh Babu *et al*. [72] performed sensitivity analyses in the Tirupur Block in India and found that the most sensitive parameters were depth to the water table, net recharge, and impacts of vadose zone parameters. On the other hand, aquifer media, soil media, topography, and hydraulic conductivity were found to be less sensitive. Pacheco *et al*. [73] applied the modified DRASTIC technique to analyze 26 aquifer systems in Portugal. They found that vulnerability indices derived from the modified technique were, on average, 20% lower than those derived from the original DRASTIC values [73]. Abouloufa *et al.* [58] conducted sensitivity analyses on both DRASTIC and SINTACS in the Berrechid Plain. They observed that topography, aquifer media, and hydraulic conductivity were key factors in contamination risk for DRASTIC, while depth to water level and aquifer media were more critical for SINTACS. Yang *et al*. [67] utilized the GALDIT method for sensitivity analysis in southern Benin. Their findings revealed that three parameters—distance from shoreline, height of groundwater level above mean sea level, and thickness of the saturated aquifer—significantly influenced the overall vulnerability map. These parameters are crucial for assessing the vulnerability to seawater intrusion in the region, and understanding their variations is essential for accurately interpreting the vulnerability map derived from GALDIT.3. Strengths, Weaknesses and Possible Recommendations of the Various Methods

3. Strengths, Weaknesses and Possible Recommendations of the Various Methods

3.1. Process-Based Simulation Method

This method for assessing groundwater vulnerability offers numerous advantages, including clear physical interpretation, high reliability, low subjectivity, predictive capabilities, comprehensive analysis, and broad applicability [74]. However, there are limitations to this method. These limitations include the requirement for long-term groundwater flow and transport data, as well as the difficulty in obtaining quantitative parameters for contaminant fate and transport [74]. Another limitation is the complexity and expertise required, as these models demand specialized knowledge and skills in hydrogeology, mathematics, and modeling, which can be a barrier to implementation. Furthermore, computational resources are needed as simulation models often require significant computational power and time, especially for high-resolution or large-scale assessments, which could limit their practical use.

In order to address these limitations, it is recommended that future research place emphasis on investigating the behavior and movement of pollutants within the vadose zone. Additionally, the development of an integrated model encompassing both vadose and saturated zones is crucial, while incorporation of GIS into groundwater flow and pollutant migration models should be considered [74]. Furthermore, the method should take into account the impact of surface runoff and lateral contamination of groundwater [75]. It is also advisable to consider leveraging advanced technologies, such as artificial intelligence, to tackle challenges and foster sustainable development [76]. Model simplification for practical use is also recommended, which entails the development of simplified versions of complex models made for specific applications to reduce the barrier of entry and increase usability. Integrated monitoring and model validation are recommended as well, which entails implementing robust monitoring programs alongside modeling efforts to validate and refine simulation outputs continuously.

3.2. Statistical Method

Assessing groundwater vulnerability is crucial for understanding and managing potential risks to groundwater quality. Statistical methods play a significant role in this assessment, as they provide a systematic and quantitative approach to evaluating groundwater vulnerability [77]. They enable the examination of intricate datasets, revealing patterns and connections, and integrating various factors like geology, hydrogeology, land use, and soil properties into vulnerability assessments [78]. This comprehensive approach enhances the accuracy of vulnerability predictions. Additionally, statistical methods leverage historical and spatial data to gain insights into vulnerability patterns, facilitating evidence-based decision-making for groundwater protection and management.

However, there are limitations to this method. Firstly, statistical methods often assume that relationships between variables remain constant over time, which may not always be the case due to changes in environmental conditions and land use patterns. Secondly, some statistical models may struggle to capture non-linear relationships or sudden changes in vulnerability factors, which can affect the accuracy of long-term predictions [79]. Furthermore, effective statistical analysis requires high-quality data, including accurate measurements of groundwater properties and environmental variables. Obtaining and maintaining such data can be challenging and expensive [80]. Additionally, these methods are often specific to certain regions and not easily applicable to other areas [70]. Lastly, statistical outputs can be complex and require expertise to interpret correctly. Misinterpretation of results can lead to inaccurate vulnerability assessments and subsequent management decisions.

To enhance predictive accuracy and robustness in assessing groundwater vulnerability, it is recommended to employ ensemble methods [81]. These methods involve combining regression models, machine learning algorithms, and other statistical techniques. Moreover, it is crucial to consider and communicate uncertainty associated with statistical predictions, enabling informed decision-making. Incorporating spatial analysis is also essential. It allows for the utilization of geospatial statistical methods, which can account for spatial autocorrelation and variability in vulnerability across landscapes. Regularly validating statistical models using independent datasets is a vital step to assess their reliability and generalizability. Stevenazzi [82] presents a time-dependent Bayesian spatial statistical method that can project groundwater vulnerability in future scenarios, providing a comprehensive assessment.

3.3. Overlay/Index Methods

These approaches are commonly employed to assess the vulnerability of groundwater to contamination by combining various spatial layers or indices. They have been proven to be dependable and flexible, particularly when conducting assessments on a regional level [82]. One of the key strengths of overlay-index methods is their integrative approach. They enable the integration of multiple factors, including geology, land use, soil properties, and hydrological characteristics. By considering all these factors together, these methods provide a comprehensive and holistic view of vulnerability. Another advantage of overlay-index methods is that they often produce maps that visually represent groundwater vulnerability. This visual representation makes it easier to communicate with stakeholders and decision-makers [83]. Additionally, overlay-index methods can be relatively simple to implement, especially with the use of GIS tools. They do not always require complex modeling techniques and can utilize existing spatial datasets. Several methods, including DRASTIC, SINTACS, GALDIT, and GOD, have been found to be effective in identifying vulnerable zones [84]. It is worth noting that these methods also have limitations. For example, they often lack a numerical basis and may require dynamic links with numerical models (Gogu & Dassargues, 2000) [85]. Furthermore, the effectiveness of overlay-index methods is largely influenced by the accessibility and quality of the input data. Any inaccuracies or gaps in the data can lead to misleading vulnerability assessments. Lastly, assigning weights to different layers or indices and determining how to combine them can introduce subjectivity and uncertainty. The choices made in terms of weighting and scaling can significantly impact the results.

To address these limitations, it is recommended to improve the quality and availability of data. Invest in collecting high-quality and up-to-date data for input layers. Use field surveys and monitoring programs to validate and supplement existing datasets. Additionally, treat vulnerability assessment as an iterative process, continuously updating input data, refining methodologies, and incorporating new knowledge to enhance the robustness of overlay-index methods over time. Moreover, conduct sensitivity analyses to understand how changes in input data or weighting schemes affect vulnerability assessments [71]. This can help identify critical factors and reduce uncertainty. Furthermore, a hybrid approach has been proposed, integrating overlay and index methods with a streamlined process-based technique designed specifically for the groundwater component [86].

4. Conclusion

Aquifer vulnerability evaluation techniques have been created in many different ways. Methods that are process-based Mathematical equations that reflect coupled processes regulating contaminant transport can have analytical or numerical solutions, but the data needed by these methods are sometimes unavailable and must be approximated indirectly. Statistical methods are utilized to ascertain correlations between spatial characteristics and the presence of contaminants in groundwater. However, these methods are typically region-specific and not transferable to other regions. While location-specific vulnerability indices are developed using overlay and index methods. These indices are based on the factors that influence the movement of pollutants from the ground surface to the saturated zone. Since the data can be easily obtained, the overlay/index methods have been the most commonly used of the three major methodologies for large-scale aquifer sensitivity and groundwater risk studies, making them relatively affordable in underdeveloped nations. From the overview of the various methods and limitations the following are recommended for future research: interdisciplinary collaboration between hydrogeologists, statisticians and GIS experts to develop integrated methodologies that leverage the strengths of each approach, promotion of open data initiatives and establish centralized data bases for groundwater related information to facilitate standardized input data for vulnerability assessment and stakeholder engagement that involve local communities and stakeholders in the vulnerability assessment process to incorporate valuable local knowledge and ensure the relevance of results.

Abbreviations

AVI	Aquifer Vulnerability Index
GIS	Geographic Information System
GOD	Groundwater Occurrence, Overlying Materials, and Depth to Water Table
USA	United States of America

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Conflicts of Interest

The authors declare no conflicts of interest.

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Research Fields

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