



Quantifying the Parameters Impact in Groundwater Vulnerability Assessment for Agricultural Pollution, a Review

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Abstract

This study presents a systematic review aimed at evaluating the rating schemes of modified groundwater vulnerability assessment methods, with the objective of identifying the most influential parameters and supporting mitigation strategies to reduce groundwater pressures arising from population growth, agricultural practices, industrial activities, and environmental hazards. The results confirmed that the DRASTIC methodology is the most widely used and modified approach worldwide. Parameters frequency and weights were collected and then screened using simple statistical indicators such as median and mean to properly rank their overall importance. Amongst the most widely used parameters, those representing a physical value, such as groundwater depth, morphology, recharge and hydraulic conductivity, resulted to be the most influential; while nominal parameters, such as the vadose zone, aquifer media, and soil texture, had the least effect in modified application. These differences from the standard DRASTIC approach reflect the focus of recent study on specific vulnerability to agricultural leaching and highlight the need to reconsider the weighting system when focusing on specific vulnerability. Finally, a multi-criteria decision analysis (MCDA) supported by the results of the systematic review was used to rank the most impactful parameters and assess their weight. The results confirmed that more than 70% of overall groundwater vulnerability depends on only three parameters: depth to water, recharge and morphology. These findings provide the foundation for developing more accurate and transferable methodology for evaluate the specific vulnerability assessment to agricultural leaching in porous aquifers.

1 Introduction

Groundwater is a vital source of drinking and irrigation water supply in many regions of the world. In recent decades, groundwater resources have been under increasing pressure due to rapid population growth, agricultural practices, industrial activities, and environmental hazards. Groundwater pollution from agricultural sources is a significant environmental concern, especially in arid and semi-arid regions (Lahjouj et al. 2022; Smail and

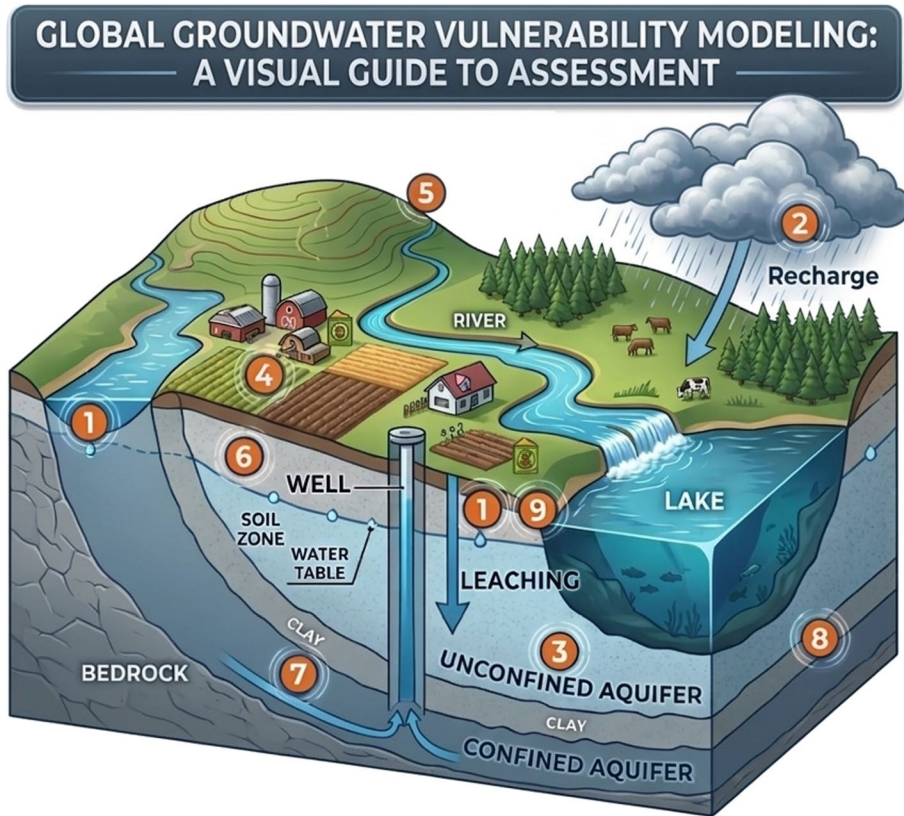
Extended author information available on the last page of the article

Dişli 2023; Torkashvand et al. 2023). Intensive agricultural practices, including the extensive use of chemical fertilizers, pesticides, and irrigation practices, have led to groundwater pollution especially by mineral nitrogen species, posing worrying effects on human health and ecosystems. Nitrate is nowadays one of the most used indicators to assess groundwater pollution worldwide due to its widespread use as fertilizer (Ascott et al. 2017; Ijlil et al. 2022). Although regulatory frameworks such as the River Basin Management Plans (RBMPs) under the European Water Framework Directive (WFD) (European Commission 2000), together with similar groundwater protection policies implemented in many regions, pressures on groundwater resources persist worldwide due to differences in policy implementation, agricultural intensity, and management practices. In this scenario, coastal alluvial aquifers are particularly prone to groundwater pollution due to a high permeability of vadose layers and shallow water tables, which in combination with the high level of anthropization that usually characterize these areas, contributes to increasing their overall vulnerability (Ourahri et al., 2024a, Busico et al. 2017).

Prevention and monitoring are so mandatory to ensure groundwater protection against pollution (Balderacchi et al. 2013; Busico et al. 2020) thus, the assessment of groundwater vulnerability to pollution stands up as an important prevention approach for the sustainable management of groundwater resources and development of mitigation strategies. This kind of approach enables policymakers to act on the prevention of groundwater pollution, evaluate the consequences of decision-making, create a comprehensive framework for groundwater resource allocation, and raise public awareness regarding the risks of groundwater pollution (National Research Council 1993).

Groundwater vulnerability is commonly divided into intrinsic vulnerability, and specific vulnerability (Gogu and Dassargues 2000). Intrinsic vulnerability refers to the inherent susceptibility of an aquifer to pollution, and it solely depends on the characteristics of the aquifer and the vadose zone, whereas specific vulnerability is used to define the vulnerability of groundwater to specific pollutants or groups of pollutants, considering their spreading properties (Kazakis and Voudouris 2015). A variety of methods have been developed to assess the vulnerability of groundwater to pollution. These approaches can be grouped into four main methods (Machiwal et al. 2018; Taghavi et al. 2022): (i) overlay and index methods, based on scores and weights; (ii) process-based methods, including simulation models; (iii) statistical methods, which analyze relationships between pollution data and environmental factors; and (iv) hybrid methods that combine two or more of the above-mentioned methods. Groundwater vulnerability assessment methods are often site or process-specific, because vulnerability depends on the characteristics of the location (e.g., geology, land use, hydrology) or the type of pollution (e.g., agricultural runoff, landfill leachate, industrial waste). Thus, the selection of the appropriate vulnerability assessment method depends on the hydrogeological regime of the study area (Saidi et al. 2014; Agossou and Yang 2021; Busico et al. 2019). The most applied GIS-based overlay and index methods are DRASTIC (Aller et al. 1987), GOD (Foster 1987; Foster and Hirata 1988), SINTACS (Civita and De Maio 2004) and AVI (Van Stempvoort et al. 1993) (Fig. 1). All aforementioned methods have been mainly applied in porous media while specific methodology have been developed and tailored for karst and fractured aquifer such as: EPIK (Doerfliger et al. 1999), COP (Vias et al., 2006) and PAPRIKA (Kavouri et al. 2011).

The rapid increase in population, along with agricultural and industrial activities, has contributed to increased groundwater pollution and its over-exploitation in under-developed



PARAMETERS	ICON	DRASTIC	SINTACS	GOD	AVI
DEPTH TO WATER	1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
RECHARGE	2	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
AQUIFER TYPE	3	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
SOIL PROPERTIES	4	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
SLOPE	5	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
UNSATURATED ZONE	6	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
HYDRAULIC CONDUCTIVITY	7	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
GROUNDWATER CONFINEMENT	8	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
HYDRAULIC RESISTANCE	9	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>

Fig. 1 Conceptualization of key parameters used in groundwater vulnerability assessment models: DRASTIC, SINTACS, GOD and AVI

countries in recent decades (Maqsoom et al. 2020; Shakeri et al. 2023). In China, serious water scarcity, combined with rapid industrial development and urbanization, has escalated the demand for groundwater and caused widespread water pollution (Hu and Cheng 2013). Similarly, Iran and India face severe groundwater crisis because of population growth and higher agricultural production (Goodarzi et al. 2022; Patel et al. 2023). These real-life chal-

lenges, along with advancement and investment in research, enhance the application of index-methods for groundwater vulnerability assessment since they represent a fast way to obtain a screening of the study area and thanks to their simple implementation and easily available data retrieval over large areas.

Although these methods have been widely applied due to their simplicity, they have also limitations. A major drawback of overlay and index-based methods is the subjectivity involved in expert judgment, in the selection of parameters and in the apportionment of their relative weights and rates according to expertise and knowledge (Goyal et al. 2021; Machiwal et al. 2018). These limitations have driven many research teams to develop new methodologies to reduce subjectivity and improve weight adjustments by means of: (i) multi-criteria decision analysis (Rebolledo et al. 2016; Garewal et al. 2017; Hao et al. 2017; Mogaji and Lim 2017; Bera et al. 2022; Atenidegbe and Mogaji 2023; Baki and Ghavami 2023; Shakeri et al. 2023; Ozegin et al. 2024) (ii) statistical analysis (Antonakos and Lambrakis 2007; Liggett and Allen 2011; Mishima et al. 2011; Abbasi et al. 2013; Pacheco et al. 2013; Bonfanti et al. 2016; Jang et al. 2016; Liang et al. 2016; Luoma et al. 2017; Mfumu Kihumba et al. 2017; Pacheco et al. 2015, 2018a; Rizeei et al. 2018; Barzegar et al. 2019; Krogulec et al. 2019; Elzain et al. 2021a; Khosravi et al. 2021; Cervantes-Servin et al. 2023; Hui et al. 2023) (iii) artificial intelligence (Dixon et al. 2002; Pathak and Hiratsuka 2011; Fijani et al. 2013; Iqbal et al. 2015; Jafari and Nikoo 2016; Elçi 2017; Souleymane and Zhonghua 2017; Nadiri et al. 2018a, b) and (iv) machine learning (Baghapour et al. 2016; Jang et al. 2017; Javadi and Hashemy 2017; Bordbar et al. 2023; Elzain et al. 2023; Dasgupta et al. 2024). As a result, most of these new modifications made the procedure more data requiring and often switched the focus from intrinsic to specific vulnerability assessments to target pollutants.

Despite the development and widespread application of different groundwater vulnerability assessment methods, their reliability and use by practitioners or stakeholders without specialized scientific knowledge remain dubious (Oke and Fourie 2017). More precisely, it is uncertain whether the most widely applied methods share a standardized procedure to enable their practical use by technical or non-scientific users, especially when the user face with the necessity to rank a parameter that offer multiple rating scales and weights. The need to compare the consistency, transparency, and user-friendliness of these methods, warranted a systematic review. Specifically, this study aims to assess the weighting structure of modified groundwater vulnerability methods for agricultural leaching using index-based methods worldwide applied in porous aquifers. Specific groundwater vulnerability to agricultural leaching will be screened, where pollutant transport (e.g., nitrate) is mainly driven by water flow and related transport processes.

Accordingly, a critical review was conducted using publications included in the Web of Science and Scopus databases. Specifically, the objectives are: (i) to systematically review studies on specific groundwater vulnerability assessment to agricultural leaching, applied in porous aquifer systems, using rating indices; (ii) to identify the most important and impacted used parameters in groundwater vulnerability index-methods; (iii) to spotlight the difference in parameter weight among modified and standard methods and (iv) to provide the analysis of their relative final weight considering all the available literature. Moreover, this manuscript presents the first-ever ranking-based weighting system for specific groundwater vulnerability assessment, providing a comprehensive synthesis of all available literature on

modified vulnerability methods and establishing a robust, evidence-based framework for prioritizing influential parameters.

2 Index and overlay methods for groundwater vulnerability assessment

2.1 DRASTIC

The DRASTIC model (Aller et al. 1987) is a commonly used method for assessing groundwater vulnerability to pollution, considering seven key parameters, which are also illustrated in Fig. 1 (with numbers 1–7): Depth to groundwater (D) (1) is the vertical distance from the ground surface to the first groundwater table; Net Recharge (R) (2) is the amount of water that infiltrates and reaches the aquifer, Aquifer media (A) (3) refers to the lithology or geological composition of the aquifer; Soil media (S) (4) is the primary medium for water infiltration and movement through the vadose zone; Topography (T) (5) describes the shape and slope of the land surface; Impact of the vadose zone (I) (6) refers to the unsaturated zone between the soil surface and groundwater table; and Hydraulic Conductivity (C) (7) is the capacity of an aquifer to convey water. All DRASTIC factors are assigned a rate (r) value between 1 and 10, where higher values indicate higher vulnerability. Also, each factor is further assigned a weight (w) ranging from 1 to 5 according to their relative influence. The DRASTIC Index (DI) is determined using the following equation:

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

Due to its simplicity, the DRASTIC model is widely used in groundwater vulnerability assessment, but it has several drawbacks: (i) human subjectivity in assessing the standard rating and weighting of each parameter, (ii) inaccuracies, and (iii) limited applicability to different geological settings. A major concern is human subjectivity when assigning rating scales and weighing coefficients. This subjectivity can vary based on individual judgment and expertise, which may decrease the accuracy of vulnerability assessment (Jovanovic et al. 2006; Lathamani et al. 2015; Goyal et al. 2021; Nourani et al. 2023; Rehman et al. 2024). Such subjectivity, especially when considering the rating system, is deeply rooted in parameters A, S and I since they offer the users the possibility to choose among a range of rates or to use the average value. In both cases, the impact of these parameters can be over- or under-estimated according to user's knowledge of the area (Gogu and Dassargues 2000; Kazakis and Voudouris 2015).

Numerous research groups have modified the standard DRASTIC method to achieve higher accuracy by revising the parameter weightings and ratings, or by introducing and/or replacing some parameters. All recent modifications tried to fit the DRASTIC methodology with specific hydrogeological conditions (porous, fractured, karstic), to switch from intrinsic to specific vulnerability or to account for anthropogenic pressure on groundwater resources. Many studies have concentrated on land use, agriculture, and pollutant-specific parameters such as NO_3^- and pesticides to produce modified DRASTIC methods. DRASTIC-L (Akhavan et al. 2011; Ahmed et al. 2017; Patel et al. 2023), DRASTI-L (Lahjouj

et al. 2022), DATIL (Panagopoulos et al. 2006), DRAOTIC (Su et al. 2015), DRASTIC-LM (He et al. 2018), DRASTIC-LTPD (Zhang et al. 2022), DRASTIC-LULC (Khan and Jhariya 2019), DRASTIC-LULC-LIN (Yankey et al. 2021; Abera et al. 2022), DRASTIC-LYS (Omotola et al. 2020), DRASTIC-LY (Hui et al. 2023), and DRASTIC-L-Q (Rauf et al. 2022) have incorporated land-use (L) parameters with additional factors such as aquifer thickness (T), organic matter (O), aquifer potential (P), distance from pollution sources (D), land cover (LC), lineaments (LIN), groundwater yield (Y) and water quality index (Q). The AGRICULTURAL-DRASTIC (Sarkar et al. 2021), DRASTIC-P (Massone et al. 2010; Ncibi et al. 2018), and DRASTIC-P-L (Brindha and Elango 2015) models have adjusted weights to enhance the evaluation of pesticide pollution in agricultural areas, while DRASTIC-AgLU-CC (Persaud and Levison 2021) integrated land use (AgLU) and the impact of climate change (CC). The DRANTHVP model (Jia et al. 2019) has evaluated NO_3^- pollution in porous aquifers, and DRASTICH (Wang et al. 2022) has incorporated hydrogeochemical (H) parameters such as pH and total dissolved solids (TDS). DRICPQA (Miao et al. 2020) has integrated pollution load and aquitard retention capacity, and DRTILSQ (Wu et al. 2016) has integrated parameters such as land use (L), the impact of pollution sources (S) and groundwater value (Q).

Many researchers have considered the impact of human activities, including population density, urban development, and groundwater exploitation. The DRAIA model (Vaezihir and Tabarmayeh 2015) integrated population density, recharge by rivers, abstraction, and agricultural and industrial activities. Anthropogenic impacts have been integrated into urban and irrigated areas within the DRASTICA model (Rehman et al. 2024; Gharekhani et al. 2023; Zare et al. 2022; Zare et al. 2023). The DRASTIC-FM and the adapted DRASTIC-FM-URBAN (Denny et al. 2007; Freitas et al. 2023) have been enhanced by including fracture media (FM), hydraulic and sanitary features in conjunction with land use/cover. In addition, DRSIHVL (Huan et al. 2012), DRASTICLE (Liu et al. 2022), DRMSICEL (Hao et al. 2017), and DRSTIC-LE (Liang et al. 2019) have incorporated aquifer thickness (H), groundwater velocity (V), groundwater exploitation (E), and land use (L) to evaluate the pressures of human intervention on groundwater resources. The DRASTIC MINE model (Krogulec et al. 2023) included parameter Z that considers the specific characteristic of the areas in which underground mining is performed.

Models have also been developed that integrate the geological, geomorphological and structural characteristics. The FRASTIC model (Hamza et al. 2017) and the DRASTIC-Fr model (Msaddek et al. 2022) introduced fractures (Fr), while DRASTIC-Sg model (Hernández-Espriú et al. 2014) integrated the subsidence gradient parameter (Sg) to account for ground deformation. The SIN-DRASTIC model (Taheri et al. 2023) includes the distance to the sinkholes (SIN), and the DRISTPI model (Jiménez-Madrid et al. 2013) incorporates preferential infiltration zones. The DRASHCL model (Yu et al. 2022) replaced standard parameters with aquifer thickness (A) and hydraulic resistance of the vadose zone (H), while the DIRTWS model (Li et al. 2017) also added aquifer thickness (A) and water yield capacity (W).

2.2 SINTACS

The SINTACS method is an advanced groundwater vulnerability assessment model developed by Civita and De Maio (2004). It is based on the same seven hydrogeological param-

eters as in the case of DRASTIC but it was especially created for Mediterranean regions (Busico et al. 2017). The acronym SINTACS is derived from the initials of Italian words representing the seven parameters of the method: Soggiacenza (depth of water) (1), Infiltrazione efficace (effective infiltration) (2), Non saturo (vadose zone) (6), Tipologia della copertura (soil media) (4), Acquifero (aquifer media) (3), Conducibilità idraulica (hydraulic conductivity) (7) and Superficie topografica (slope) (5). Each parameter in the SINTACS method is assigned a specific weight (w), and the rating (r) value depends on the impact of potential pollution. The formula for the equation is the following:

$$SINTACS = S_r S_w + I_r I_w + N_r N_w + T_r T_w + A_r A_w + C_r C_w + S_r S_w \quad (2)$$

The SINTACS method has been applied and modified by many researchers to create vulnerability maps or to compare with commonly used models such as DRASTIC (Al-Amoush et al. 2010; Ramos Leal et al. 2012; Noori et al. 2019; Busico et al. 2019; Awawdeh et al. 2020; Chamanehpour et al. 2020; Jahromi et al. 2021; Larva et al. 2023; Abduljaleel et al. 2024). The standard SINTACS method differs from DRASTIC because it includes the dilution role of recharge and it offers 5 sub-sets of weights for each parameter according to specific hydrogeological conditions which increase the overall applicability of the methods without forcing modifications.

2.3 GOD

The GOD method was developed by Foster (1987) to characterize aquifer vulnerability to pollution. This method considers three specific factors to determine aquifer pollution vulnerability: Groundwater hydraulic confinement (G) (8), Overlying lithology of the aquifer (O) (4), and Depth to groundwater table (D) (1). Each parameter is assigned a value from 0 (least vulnerability) to 1 (highest vulnerability) based on the degree of vulnerability. The GOD index is calculated using the following equation:

$$GOD = G * O * D \quad (3)$$

The GOD index is then classified into five classes: negligible (0–0.1), low (0.1–0.3), moderate (0.3–0.5), high (0.5–0.7), and extreme (0.7–1) (Foster and Chilton 2021). The practical application of the GOD method allows a quick assessment of groundwater vulnerability, and it therefore constitutes a useful tool for initial vulnerability assessments (Mehta et al. 2024; Atashi Yazdi et al. 2023; Busico et al. 2019; Boufekane and Saighi 2018; Hirata et al. 1991). The main difference between the GOD method and other index-methods is that it employs a limited number of parameters without the need to assign them a score.

2.4 AVI rating system

The Aquifer Vulnerability Index method (Van Stempvoort et al. 1993) is based on two physical parameters to assess the vulnerability of an aquifer: the thickness (d) of each sedimentary layer above the uppermost aquifer and the estimated hydraulic conductivity (k) of each

of these sedimentary layers. The hydraulic resistance (c) (9) is calculated using equation below:

$$c = \sum_{i=1}^n \left(\frac{d_i}{K_i} \right) \quad (4)$$

The AVI method can be effectively applied to regional scale groundwater vulnerability mapping in areas with limited detailed hydrogeological data. It has been used standalone or to substitute the role of vadose zone parameter within other rating indices such as SINTACS or DRASTIC (Agossou and Yang 2021; Busico et al. 2017; Kazakis and Voudouris 2015; Ducci and Sellerino 2013). In comparison to DRASTIC, the AVI method does not assign subjective weights. It is based on the physical relation between layer thickness and permeability to determine groundwater vulnerability. However, the use of the AVI method has several drawbacks. It assumes vertical flow, and it does not account for lateral groundwater movement, preferential flow paths or heterogeneity in subsurface materials.

3 Systematic Review Framework

Systematic reviews aim at summarizing existing knowledge in a specific field, enabling the identification of future research priorities (Nourani et al. 2024). The rationale of a systematic review, as suggested by the Center for Evidence-Based Conservation (CEBC), is to combine evidence considering the purpose of answering a fixed question (Pullin et al. 2022). In this context, the current systematic review established a structured framework for evaluating previous articles while defining inclusion and exclusion criteria. The systematic review was conducted following Cochrane protocols (Keramati et al. 2019) and a search strategy in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines (Liberati et al. 2009).

PRISMA includes four important steps. First, all publications related to the subject under investigation are identified and specific search criteria are defined. Next, the entries are filtered and selected based on pre-defined criteria aligned with the research objectives. During the screening step, the publications are selected based on the inclusion criteria (identifying eligible studies) (Afrifa et al. 2022). This step ensures transparency and reduces bias in the selection process of articles. In the next step, relevant entries are extracted from the final set of articles. Finally, all findings are analyzed and summarized (Nourani et al. 2024).

The stepwise procedure of the systematic review is shown in Fig. 2 (Aromataris and Pearson 2014). The flowchart provides a visual overview of the methodological process, including the definition of the study objectives, the identification of relevant publications, and the determination of inclusion and exclusion criteria to establish study eligibility. It also details the evaluation of the quality and validity of the selected studies, the extraction and synthesis of the data from the research, and the reporting of the methods used to perform the review.

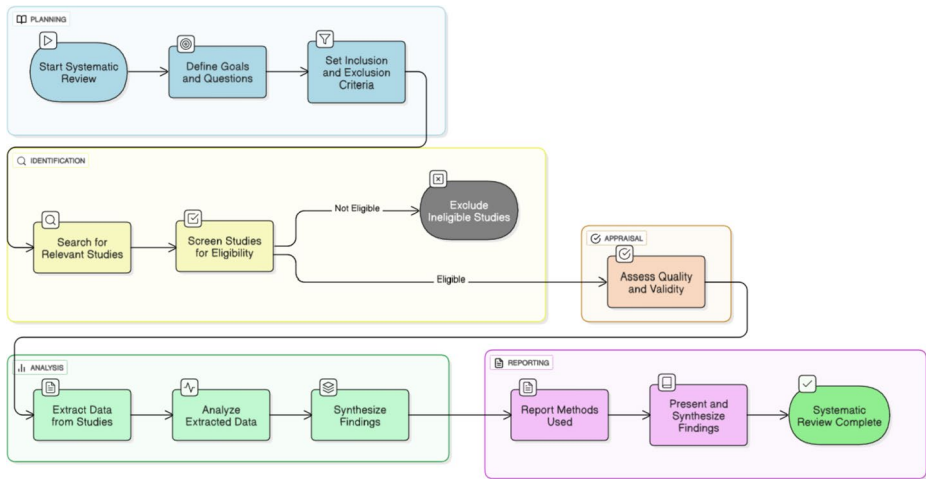


Fig. 2 Systematic review methodology followed in the current study

3.1 Searching for Articles in Databases and Data Coding Strategy

In this work, a systematic review of previous publications was conducted on the topic of agricultural leaching and aquifer vulnerability assessment using index-methods in porous aquifer worldwide. The systematic review made use of a comprehensive search with a set of vocabularies grouped into categories. Group 1 included terms related to agricultural leaching processes and potential pollutants such as ‘salin*’, ‘pollut*’, ‘leach*’, ‘nitr*’, ‘nutrient*’ and ‘contamin*’, while Group 2 referred to the target of pollution, including ‘aquifer’, ‘groundwater’, ‘vadose’. In addition, Group 3 included terms related to vulnerability assessment methods, such as ‘vulnerable*’, ‘risk assessment’, ‘hazard’, ‘sintacs*’, ‘drastic*’, ‘god’, ‘avi’. Scoring terms and the optimization and modification of weights were integrated in Group 4. Moreover, restrictions were applied in Groups from 5 to 8 for the language of the articles (English), the years under review (1990–2024), the types of documents (article, review and book) and the subject areas (Environmental Science, Earth and Planetary Sciences, Agricultural and Biological Sciences, Engineering, Multidisciplinary, and Chemical Engineering). Table 1 illustrates the search codes and Boolean operators used in the database searches.

3.2 Screening and Eligibility Criteria

The screening process was conducted twice for two principal academic databases, Web of Science and Scopus (Fig. 3), by making use of the Rayyan platform (Ouzzani et al. 2016), a web-based tool designed to support systematic and literature reviews. Rayyan facilitates the efficient screening of large numbers of studies by allowing rapid inclusion and exclusion decisions based on titles and abstracts, while providing features such as tagging and filtering. In this study, Rayyan was used to organize the retrieved records, identify and remove duplicates, and apply the predefined inclusion and exclusion criteria during both the title/abstract and full-text screening stages. The platform was selected because of its user-

Table 1 Search codes and Boolean operators employed for querying the Web of Science and Scopus databases

Group 1	(salin* OR pollut* OR leach* OR nitr* OR nutrient* OR contamin*)
AND	
Group 2	(aquifer OR groundwater OR vadose)
AND	
Group 3	(vulnerab* OR risk assessment OR hazard OR sintacs* OR drastic* OR god OR avi)
AND	
Group 4	(rat* OR weight OR scor* OR modification OR optimization)
Language	
Group 5	English
Document type	
Group 6	Article, Review, and Book
Timespan	
Group 7	1990–2024
Subject area	
Group 8	Environmental Science, Earth and Planetary Sciences, Agricultural and Biological Sciences, Engineering, Multidisciplinary, and Chemical Engineering

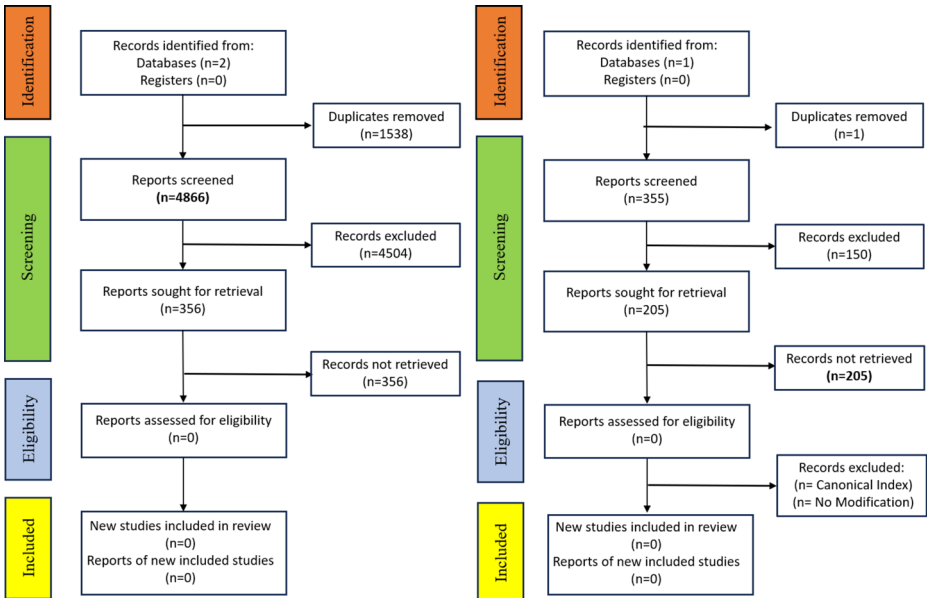


Fig. 3 Application of PRISMA flow diagram in the systematic review and number of articles screened at different stages

friendly interface and its ability to simplify and accelerate the screening process. In addition, its widespread use in systematic review studies supports transparency and improves the reproducibility of the selection process. During the first stage of identification, 1538 duplicate records were removed before screening. The remaining manuscripts were 4866 before screening. In the first screening, 4504 records were excluded based on the title and abstract using the filter in Rayyan. Articles unrelated to vulnerability were eliminated, resulting in 356 entries that could not be retrieved. In the second screening, one duplicate entry was further removed. Manuscripts related to index-overlay methods without any modifications were further eliminated (150), since the aim of this review was to analyze only those studies where weight optimization and modification were adopted to compare the result with the standard methods. Finally, 205 entries addressed adequately the criteria of the systematic review. Table 2 summarizes the pre-defined inclusion and exclusion criteria that were applied from the first screening of abstracts to full text articles to ensure that the selected articles were relevant to the research objectives.

The screened entries were stored in a Spreadsheet. Data provided for each entry were: (1) title, (2) authors, (3) DOI number, (4) year published, (5) domain, (6) countries in which research was conducted, (7) the groundwater vulnerability assessment method applied, (8) the method used to assign or classify parameter weights, and (9) the validation variables. The two spreadsheets containing modified (considered in this study) and standard applications are available in supplementary to this manuscript.

3.3 Parameter's Ranking System

To calculate the parameter ranking upon the modified methodology the Analytical Hierarchy Process (AHP) method has been implemented. The AHP is an MCDA technique proposed by Saaty (1980) and used in many applications to solve complex problems. This technique breaks down decision issues hierarchically, enabling decision-makers to assess the relative weights of multiple factors using the pairwise comparison matrix. It has been chosen despite the others classification methodologies since it does not rely on a dependent variable (i.e.

Table 2 Exclusion criteria for the systematic literature review based on PRISMA

Stage	Exclusion criteria	Reason for Exclusion
Stage 1: Duplicate removal	Detect and remove duplicates from databases	Avoid using the same studies
Stage 2: Screening titles and abstracts	Studies unrelated to groundwater vulnerability (e.g., erosion, floods, soil ecosystem changes)	Not focused on groundwater vulnerability
	Studies that applied statistical approaches or complex modelling	Not index-based groundwater vulnerability assessment
	Studies on general water quality without vulnerability mapping	Not index-based groundwater vulnerability assessment
Stage 3: Full text reading	Studies on irrigation impacts without groundwater vulnerability focus	Indirectly related, lacking index-methods
	Studies applying standard index-based groundwater vulnerability assessment	No rate and weight modification

NO_3^- , TDS, EC, Cl) which can limit their applications. The AHP is based on Saaty's rating scale from 1 to 9 to assign priority values according to the importance of multiple factors to the overall objective (Şener et al. 2010). A rating of 1 indicates equal importance between factors, and a rating of 9 indicates their extreme importance. In an AHP pairwise comparison matrix, the number of rows and columns is equal to the number of parameters, and all elements on the main diagonal are equal to 1, since each parameter is compared with itself. The consistency of the AHP matrix can be calculated using the Consistency Ratio (CR) (Saaty 1990) according to the following formula:

$$CR = CI/RI$$

where RI is the random index, and CI is the consistency index. CR should be less than 0.1, indicating a sufficiently consistent matrix suitable for weight analysis. However, the need to establish a preliminary ranking reintroduces intrinsic subjectivity into AHP, a method designed to minimize it. This occurs because, in most cases, expert opinion or a limited number of prior applications are used as reference points. To overcome this limitation, the present study replaces individual "expert judgment" with the collective evidence from the entire body of literature on modified applications of rating indices. Standard methods are excluded from this step to prevent weight convergence toward standard values.

To define a variable hierarchy, a preliminary weight was assigned to each parameter according to its relative impact. This initial weighting, meant to distinguish the most and least influential parameters, was derived from the modified weights identified in the systematic review through a multi-step procedure. First, a Python script was used to determine the rank position of the seven most frequently adopted parameters in each manuscript, based on their assigned weights. This provided, for each parameter, a percentage of occurrences in the first, second, third, and subsequent positions up to the seventh. These percentages were then multiplied by a ranking factor (7 for first position and 1 for seventh), and the resulting values were summed for each parameter (Fig. 4). This procedure produced a ranked list of the seven parameters quantified in terms of their final score which will be the reference point to build the AHP matrix.

4 Results and Discussions

The worldwide spatial distribution of studies related to the application of the modified models to evaluate the vulnerability of aquifers is presented in Fig. 4. The map includes only those studies that have proposed modifications to the standard index-methods. As shown in Fig. 5, a significant number of studies have been conducted in Iran (Javadi et al. 2011; Sadeghfam et al. 2016; Nadiri et al. 2017a; Bordbar et al. 2019; Jafari and Nikoo 2019; Rezaei et al. 2017; Yousefi et al. 2021; Bahrami et al. 2022), China (Huicheng et al. 1999; Qian et al. 2012; Yu et al. 2012; Zhang et al. 2013; Yan et al. 2019; Li et al. 2020; Dong et al. 2020), and India (Brindha and Elango 2015; Kumar and Krishna 2020; Saravanan et al. 2020; Rajput et al. 2021; Ganwer et al. 2024). Additionally, countries where a moderate number of studies were conducted are: Tunisia (Saidi et al. 2011a, b; Ncibi et al. 2018), Algeria (Bensenane et al. 2011; Boufekane et al. 2022b), Morocco (Lahjouj et al. 2022; Ourarhi et al. 2023, 2024a, b), Nigeria (Oke et al. 2016; Chukwuma et al. 2023), Italy (Spandre et al. 2001; Busico et al.

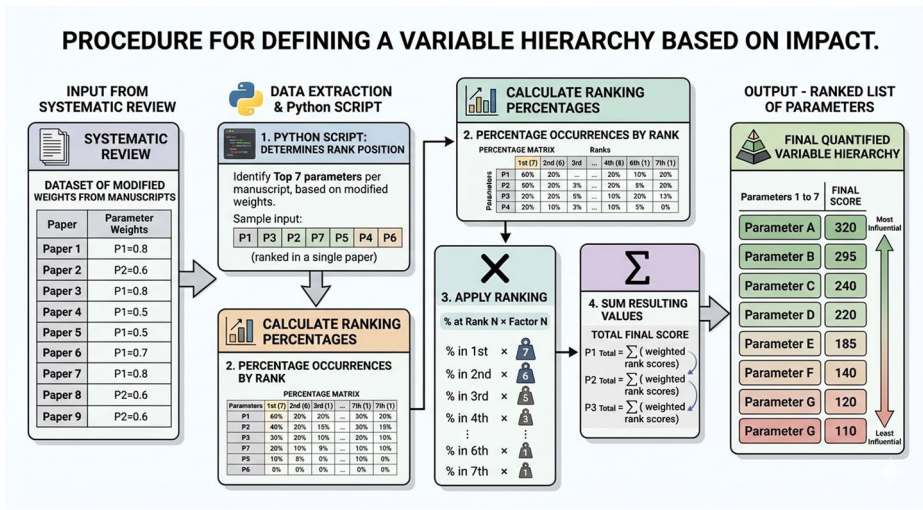


Fig. 4 Conceptual flow for the applied ranking system

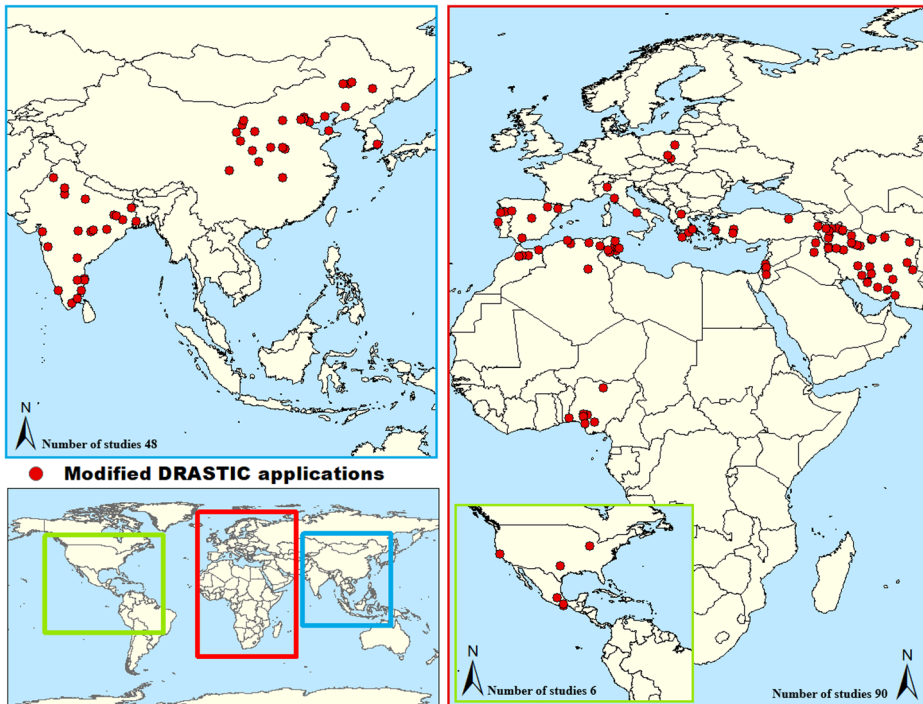


Fig. 5 Spatial distribution of studies on DRASTIC-based methods with modified parameter weights (1990 and 2024). The number of studies is shown in each region, based on the systematic review

2019), Portugal (Valle et al. 2015; Pacheco et al. 2018b), Spain (Uzcategui-Salazar and Lillo 2022; Arauzo 2017) the United States (Fritch et al. 2000; Cepelcha et al. 2004), and Greece (Kazakis and Voudouris 2015; Tziritis et al. 2021). Country such as South America do not provide any study with substantial modification but only few applications of DRASTIC and GOD in Brazil, Colombia, Chile and Argentina as reported by Rama et al. (2022).

The geographical distribution of published studies reflects the widespread use of index-based methods for groundwater vulnerability assessment, as these approaches provide a rapid screening of the study areas (Fig. 5). The most frequently used index-methods (48% of reviewed studies) were the standard methods such as DRASTIC, DRASTIC-L, DRASTIC-P, SINTACS, GOD and AVI methods. In most of the reviewed studies, the standard methods were consistently compared to the modified approaches for validation purposes, which explains their high frequency of occurrence. Considering the modified methods, the most frequently used methodologies to modify standard weights were Multi-Criteria Decision Analysis MCDA (21%), Statistical Analysis (19%), Artificial Intelligence and Machine Learning with 11% and 2%, respectively. The Analytical Hierarchy Process (AHP) was the most frequent technique used in MCDA (Thirumalaivasan et al. 2003; Asefi et al. 2014; Neshat et al. 2014a; Murtadha et al. 2015; Sahoo et al. 2016b; Saida et al. 2017; Aydi 2018; Abu-Bakr 2020; Ojeda Olivares et al. 2020; Olaseeni et al. 2021; Ma et al. 2021; Li et al. 2023; Luo et al. 2023; Metwally et al. 2023; Ourarhi et al. 2023; Saranya and Saravanan 2023; Saravanan et al. 2023; Yildirim 2023; Wang et al. 2023; Wei and Chi 2023). The most used statistical techniques cited in the literature were sensitivity analysis (Saidi et al. 2011a, b; Neshat et al. 2014a; Kura et al. 2015; Abdullah et al. 2016; Sahoo et al. 2016a; Ncibi et al. 2018; Rajput et al. 2020; Wu et al. 2014; Gazal and Eslamian 2022), frequency ratio (Neshat and Pradhan 2014b; Shrestha et al. 2018; Lakshminarayanan et al. 2023), and the Wilcoxon rank-sum test (Kang et al. 2017; Barzegar et al. 2020; Balaji et al. 2021; Boufekane et al. 2022a). Within the domain of artificial intelligence, fuzzy logic (Dixon et al. 2002; Nadiri et al. 2017a, b; Baalousha et al. 2021; Hassanzadeh et al. 2021; Maleki et al. 2023; Nourani et al. 2023) and genetic algorithms (Nadiri et al. 2019; Norouzi et al. 2021; Siarkos et al. 2023) have been utilized. Mean decrease accuracy and information gain ratio (Bordbar et al. 2019) were amongst the most applied machine learning techniques. Furthermore, many authors applied hybrid methods that combine two or more methods as to increase the reliability of groundwater vulnerability results (Shahmaleki et al. 2013; Ki and Ray 2014; Neshat and Pradhan 2015; Şener and Şener 2015; Barzegar et al. 2016; Asadi et al. 2017; Yang et al. 2017; Khosravi et al. 2018; Jesiya and Gopinath 2019; Lad et al. 2019; Elzain et al. 2021b; Saranya and Saravanan 2021; Torkashvand et al. 2021b; Gharakezloo et al. 2022; Lakshminarayanan et al. 2022; Mohammaddost et al. 2022; Şener 2022; Umar et al. 2022; Shaheen et al. 2023; Mohammad et al. 2024). The results of the analysis indicate that MCDA is the most utilized modification method.

4.1 Frequency and Statistics of Parameters

The frequency of the parameters used to evaluate groundwater vulnerability to agricultural leaching was analysed. It is worth to stress that “most frequently” not mandatory means “most important” since data availability, resolution and quality can influence the possibility to use/not use a specific parameter. The most frequently used parameters to assess groundwater vulnerability to agricultural leaching are those that feature in the original DRASTIC

method which are the same used also for the SINTACS methodology and partially by the GOD index : depth to water ($n=425$), recharge ($n=410$), impact of vadose media ($n=399$), topography ($n=392$), aquifer media ($n=385$), soil texture ($n=381$), and hydraulic conductivity ($n=375$). Land use ($n=129$) is the most frequent parameter that features in modified models, as it is considered a critical factor in groundwater vulnerability assessments commonly introduced to switch from vulnerability to risk assessment. In addition to these core parameters, numerous studies have added parameters such as aquifer thickness ($n=20$), aquifer potential/yield ($n=7$), hydraulic resistance/travel time ($n=6$), groundwater occurrence ($n=6$), and rainfall ($n=6$), water abstraction ($n=6$), fine sediment percentage ($n=5$), lineament density ($n=5$), infiltration condition ($n=5$), aquifer transmissivity ($n=4$) and soil organic matter ($n=4$). Furthermore, sporadically used parameters were pollution source distance ($n=4$), groundwater quality ($n=4$), population density ($n=3$), well density ($n=3$), hydraulic and sanitary features ($n=1$), sinkholes ($n=1$), marginalization index ($n=1$), runoff ($n=1$), irrigation ($n=1$), fertilizer/manure ($n=1$), groundwater value ($n=1$), flow accumulation ($n=1$), and soil pH ($n=1$). The parameter frequency is summarized in Fig. 6.

4.2 Statistical Results for Parameter Weights

A descriptive statistical analysis was conducted to analyze the weights of the parameters used in all manuscripts within the systematic review. The minimum (Min), maximum (Max), median (Mdn), and average (Avg) values were calculated for the five identified group of manuscript. The first group contains “All manuscript” used in this review while the other group were created according to the method used to modify the standard weight: (i) MCDA, (ii) Statistical Analysis and (iii) Artificial Intelligence (Fig. 7). A final group includes all the case studies that researchers usually employ to highlight the performance of the modified methods with respect to the classical methodologies. The results revealed considerable amplitudes in the weights of parameters, while the Mdn and Avg values presented close alignment with the classical DRASTIC method. Depth to water, impact of

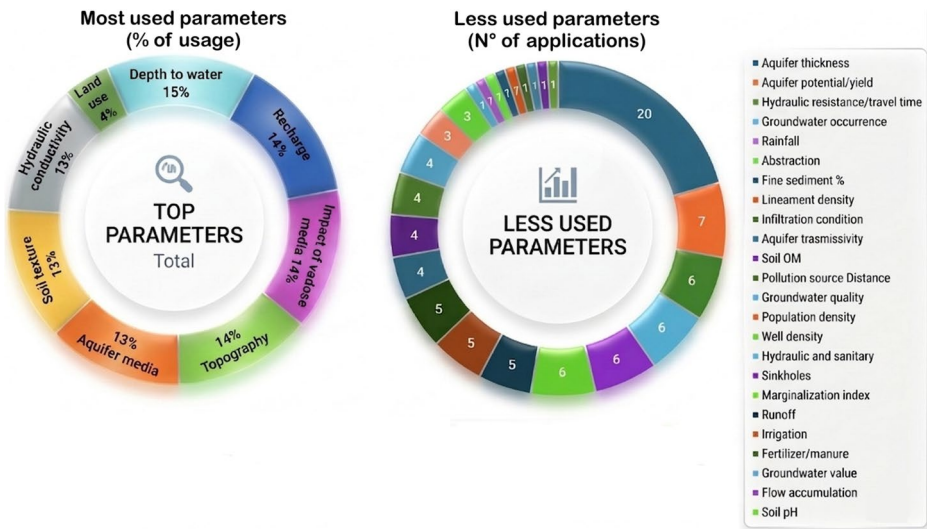


Fig. 6 Frequency of most used parameters to assess groundwater vulnerability

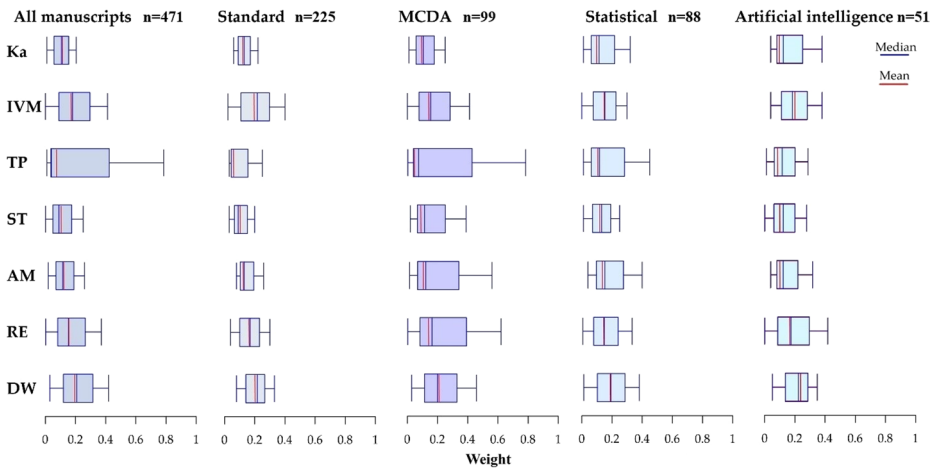


Fig. 7 Statistical analysis of parameter weights for all manuscripts and for each group of methods (Standard, Multi-Criteria Decision Analysis MCDA, Statistical Analysis and Artificial Intelligence) separately. Ka: Hydraulic conductivity; IVM: Impact of vadose media; TP: Topography; ST: Soil texture; AM: Aquifer media; RE: Recharge; DW: Depth to water

vadose media, and recharge are identified as the most impactful parameters to the final score according to the weight analysis, while aquifer media, hydraulic conductivity, soil texture, and topography were the least impactful parameters (Fig. 7). The statistical comparison of the parameter weights among the four categories (Standard, MCDA, Statistical Analysis and Artificial Intelligence) indicates significant differences between methods. In the first and second groups (All and Standard), the parameters' weights remain close to the original values proposed by Aller et al. (1987), since, as previously mentioned, approximately 48% of the case studies correspond to the classical DRASTIC method, which is often used as a comparative framework to evaluate and highlight the performance of modified methodologies. Consequently, the median weight values and the parameter importance ranking within these two groups closely align with those of the original DRASTIC index. The MCDA group exhibits the greatest variability in parameter weights while Statistical and AI groups display low to moderate variation in their weights. Moreover, significant differences in Mdn weights, compared to classical methods, can be observed in in these groups that also suggest a shift in position in parameters ranking.

4.3 Probability Distribution of Parameter Weights

To further analyze the probability distribution of parameter weights, the statistical distribution of data is shown (Fig. 8). The shape of the curves, obtained considering all the manuscripts, shows that an important division can be done considering quantitative and qualitative parameters: the first such depth to water and recharge show a more normal like distribution with low skewness (0.09 and 1.41, respectively), while the second parameters, such as aquifer media and vadose zone media, display bimodal or stretched patterns with high (2.68) and negative skewness (−0.31) respectively. Topography also exhibits a huge variability with a skewness of 2.04, likely due to differences in spatial resolution, which can alter its relative influence. Compared to standard DRASTIC weights, modified methods

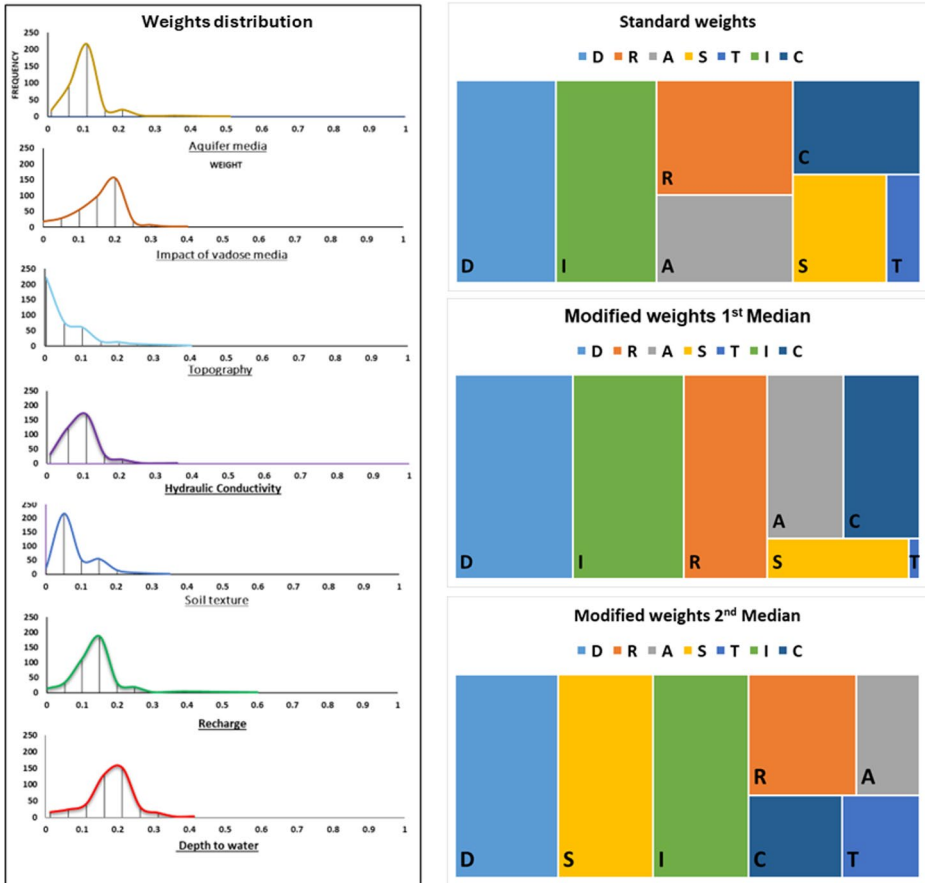


Fig. 8 Probability distribution of parameters weights

generally increase the importance of slope, soil, and recharge, while reducing that of aquifer and vadose zone media (tree diagrams in Fig. 8).

4.4 Parameters Ranking

The results obtained using the proposed ranking procedure indicate that depth to water, topography, recharge, and hydraulic conductivity consistently occupy the top ranks, whereas impact of vadose media, aquifer media, and soil texture appear most frequently in the lower ranks (Table 3). As previously described in paragraph 3.3, the preliminary rank shown in Table 3 was derived from the frequency results. A Python script identified the ranking positions of the seven most frequently used parameters across studies, calculating how often each appeared in positions from first to seventh. These frequencies were weighted (7 for first, 1 for seventh) and summed up to produce a final score for each parameter.

The parameters impact of vadose media, aquifer media, and soil texture were found to be the least significant in modified groundwater vulnerability assessments due to their limited spatial variability, redundancy with more influential parameters, and methodological as

Table 3 Final ranking of Parameters

Parameters	Ranking	Final score
Depth to water	1	561.19
Topography	2	500.55
Recharge	3	487.76
Hydraulic conductivity	4	484.39
Impact of vadose media	5	476.63
Aquifer media	6	460.56
Soil Texture	7	448.55

well as data-related constraints. It is important to emphasize that these results are specific to groundwater vulnerability assessments focused on agricultural leaching, particularly in relation to nitrate transport. In such contexts, parameters that directly control water movement and pollutant transport such as depth to water, recharge, topography, and hydraulic conductivity, are expected to exert a stronger influence on vulnerability outcomes. This does not imply that the conceptual framework of intrinsic vulnerability methods, such as DRASTIC, is flawed; rather, lithological and soil-related parameters remain essential for controlling contaminant attenuation independently of pollutant type. Instead, the observed weighting reflects the characteristics of the target pollutant, the structure and availability of input datasets, and the modeling approach adopted. In many study areas, these parameters were homogeneous (i.e., composed of similar materials throughout), and their spatial variability was diminished. The uniformity of these layers reduces their role as significant barriers or enhancers of pollutant transport. As a result, these parameters show limited influence on vulnerability assessment methods in the study area, and statistical approaches assign them lower weights (Torkashvand et al. 2021a; Ma et al. 2023; Nguyen and Tat 2024).

The influence of aquifer media is often captured by more direct indicators, such as hydraulic conductivity, which quantifies groundwater flow more accurately. Similarly, the effects of soil texture and the impact of vadose media can be indirectly represented by recharge and depth to water table, as a result their contribution to vulnerability assessment methods is weak (Jang et al. 2017). Statistical, MCDA, Machine Learning, and Artificial Intelligence methods frequently assign these parameters as less important due to weak correlations with observed pollution data (i.e., NO_3^- concentrations or EC) (Saidi et al. 2014; Dizaji et al. 2020; Bera et al. 2022; Abduljaleel et al. 2024). Furthermore, the lack of high-resolution data for soil texture and the impact of vadose media reduces their influence on the model score when compared to well-documented parameters supported by more comprehensive datasets, such as recharge or depth to water table (He et al. 2018).

It is worth stressing and highlighting the differences in data type between the top-ranked and bottom-ranked parameters. The parameters identified as significant with this procedure, namely recharge, slope, and depth to water, are typically represented as physical raster that display continuous data across the territory with a defined spatial resolution. These datasets are generally produced from monitoring field points collected in a geodatabase and then interpolated using various algorithms, allowing for reliable spatial distribution if data density and coverage are adequate. In some cases, they may also be derived from remotely sensed products following specific post-processing steps. In contrast, parameters such as vadose zone media, aquifer media, and soil texture often ranked among the least significant are, in most cases, obtained from polygon shapefiles converted into raster format. While the resulting raster shares structural similarities with the physical raster, its informational

content differs substantially. During polygon-to-raster conversion, large contiguous areas of pixels inherit the same attribute value, reflecting the uniform classification of the original polygon. This process reduces spatial variability and may mask small-scale heterogeneities, potentially limiting the parameter's influence in modelling processes (Li et al. 2000; Acero Triana et al., 2024).

These fundamental differences in data structure and variability may partly explain the systematic review findings, which are in contrast with the standard ranking of parameters (i.e. DRASTIC, SINTACS) since parameters derived from high-resolution continuous datasets are easily handled by algorithms, and they were consistently allocated higher weights, while those based on generalized polygon data tended to be assigned to lower significance.

Furthermore, the results of all the weight modification methods were used to evaluate the performance of the AHP method in reducing the subjectivity of modeling. In this regard, the weights obtained from all modification methods were used as inputs for the AHP method.

To achieve this, the minimum and maximum final scores obtained from the ranking were divided into nine classes using a Natural Breaks classification to categorize performance for use in the AHP method. The Natural Breaks algorithm is a data classification method that partitions values into distinct groups by minimizing within-class variance and maximizing between-class variance, thereby revealing inherent patterns in continuous data. This method was selected because the relatively small differences among ranked values required an approach capable of effectively highlighting subtle distinctions between classes (Gui et al. 2025). Pairwise comparisons were then organized in a 7×7 matrix, where the diagonal elements are equal to one. The values in each row represent the relative importance between pairs of parameters. The Jenks natural break classification method was applied to categorize subclasses into separate groups (Jenks 1967). This approach ensures that differences in final scores translate into appropriate relative weights. For example, the parameter Depth to Water, with a final score of 561, was classified as having a strong to very strong importance compared with Morphology, which obtained a final score of 500 reflecting a difference of 60 points that places them in different Natural Breaks classes (Table 4).

Table 5 shows a pairwise comparison of the significance of criteria and their weights.

According to the results, depth to water accounts for 54.4% of the vulnerability score, followed by topography (12.5%), recharge (9.2%), hydraulic conductivity (8.7%), impact of vadose media (7.2%), aquifer media (4.6%), and soil texture (3.4%) (Table 5). The four most impactful parameters (depth to water, topography, recharge and hydraulic conductivity) constitute 84.4% of the groundwater vulnerability score. The results clearly show a distinct division between numerical parameters (e.g., Depth to Water, Topography, Recharge, Hydraulic Conductivity) and qualitative factors (e.g., Impact of Vadose Media, Aquifer

Table 4 Reference interval for the AHP matrix construction

Level of importance	Value	Reciprocal	Class range
Extreme importance	9	1/9	81–90
Very strong to extreme importance	8	1/8	72–81
Very strong importance	7	1/7	63–72
Strong to very strong importance	6	1/6	55–63
Strong importance	5	1/5	47–55
Moderate to strong importance	4	1/4	38–47
Moderate importance	3	1/3	28–38
Equal to moderate importance	2	1/2	20–28
Equal importance	1	1	10–20

Table 5 Pairwise comparison of the modified weights. Ka: Hydraulic conductivity; IVM: Impact of vadose media; TP: Topography; ST: Soil texture; AM: Aquifer media; RE: Recharge; DW: Depth to water

PARAMETES	DW	TP	RE	Ka	IVM	AM	TP	WEIGHT (%)
DW	1	6	8	9	9	9	9	54.4
TP	1/6	1	1	1	2	4	5	12.5
RE	1/8	1	1	1	1	2	4	9.2
Ka	1/8	1	1	1	1	2	3	8.7
IVM	1/9	1/2	1	1	1	1	3	7.2
AM	1/9	1/4	1/2	1/2	1	1	1	4.6
ST	1/9	1/5	1/4	1/3	1/3	1	1	3.4

Media, Soil Texture) for assessment of vulnerability to agricultural leaching when modification occur. Numerical parameters represent continuously defined quantities across the territory, measurable in the field and expressed as objective numerical values. On the other hand, qualitative factors describe categorical characteristics such as geological classifications. Their evaluation heavily depends on the operator's knowledge and interpretation of the study area.

5 Conclusions

This systematic review analysed 205 screened studies related to groundwater vulnerability assessment methods in the context of agricultural leaching. Through this analysis, the most frequently applied methods and parameters that are commonly used in groundwater vulnerability studies were identified. Based on the analysis, the following considerations can be obtained:

- Standard DRASTIC methods, including DRASTIC, DRASTIC-L, DRASTIC-P, SINTACS, GOD, and AVI, have been reported as the most frequently used methods because of their widespread acceptance and have consistently been used as baseline methods for comparing modified methods.
- The results of the statistical analysis of the standard DRASTIC parameters indicate that depth to water, topography, recharge, and hydraulic conductivity are the most important parameters for assessing groundwater vulnerability to pollution from agricultural sources. The quantitative nature of these parameters increases their influence when optimization techniques are applied. These parameters are often simple to characterize with available open-access datasets except for hydraulic conductivity. Moreover, their accessibility allows government agencies, policymakers, technical offices, and local stakeholders to easily apply them in original vulnerability assessments.
- On the other hand, aquifer media, soil media, and the impact of the vadose zone constitute qualitative parameters that have the least impact when optimization techniques are applied. These parameters can still be included to improve the accuracy of vulnerability assessment. However, the contributions of aquifer media, soil media, and the impact of the vadose zone are important in site-specific studies when detailed hydrogeological data and resources are available.
- Although numerous modifications and optimizations have been proposed in the literature, the site- or process-specific nature of the existing methods indicates the necessity

of a simplified groundwater vulnerability index that shall include the most influential parameters. To address the complexity and specificity of existing methods, the development of a user-friendly groundwater vulnerability index for agricultural leaching is needed. This new index will facilitate its broader use by policymakers, local stakeholders, and non-specialist users in groundwater protection and land use planning.

The results of this study could be used to support the development of a new index. Future research needs will need to focus on the development, calibration, and validation of this user-friendly vulnerability index under different hydrogeological and climatic condition.

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Data Availability The datasets and materials generated during the current study are available in Supplementary.

Declarations

Competing interests The authors declare no competing interests.

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