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Review article

Salinization in groundwater vulnerability: A review of GALDIT-Based methods

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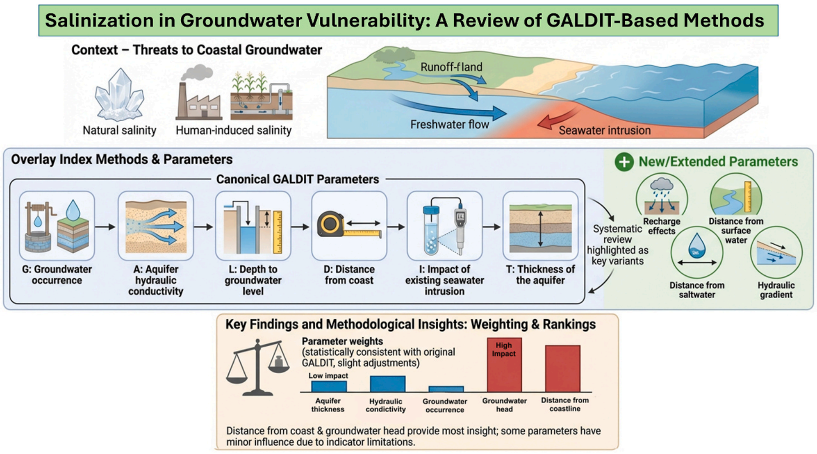
HIGHLIGHTS

- Overlay index methods to assess salinization in coastal aquifers were reviewed.
- Standard GALDIT parameters remain the most used across the reviewed literature.
- Whitin modified indices, recharge, proximity to surface waters, and topography emerged as the most impactful additions.
- Low resolution and low heterogeneous parameters need to be avoided.
- New chemical indices to identify the salinization sources must be tested.

GRAPHICAL ABSTRACT



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ABSTRACT

Groundwater quality is increasingly threatened by both natural and anthropogenic salinity, particularly in coastal aquifers where salinization represents one of the most critical challenges. In this context, a systematic review was proposed to critically analyze the most used parameters in overlay index methods for assessing groundwater vulnerability to salinity. The results highlight that the canonical GALDIT parameters remain the most widely applied, often complemented by newly introduced factors tailored to specific objectives and hydrogeological settings. Weight statistical analysis of the most frequently used parameters shows general

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consistency with the original GALDIT weighting scheme, although minor variations emerge during optimization. The proposed ranking system indicates that groundwater occurrence and the impact of existing seawater intrusion have relatively limited influence on vulnerability assessments, mainly due to constraints associated with their indicators. In contrast, distance from the coastline and groundwater head provide the most significant insights into salinity distribution and coastal aquifer vulnerability, despite some inherent limitations. Furthermore, additional parameters such as recharge effects, distance from surface water bodies (e.g., lagoons and rivers), distance from saline sources, and hydraulic gradient, show strong potential as flexible extensions for improving vulnerability mapping. This study highlights the strengths and weaknesses of GALDIT-like methodology and shows the way to improve their performance to ensure a better characterization and management of water resources in coastal aquifers all over the world.

1. Introduction

Coastal areas (CAs) are often marked by increasing population pressure and environmental hazards due to climate change. It is estimated that 2.15 billion people live within 100 km of the coast, with a forecasted increase for this century (Reimann et al., 2023). At the same time, CAs host sensitive ecosystems that provide natural resources and services (Spalding et al., 2014), e.g. fertile floodplains used for food production. In this scenario, several strategies have been employed to address the increasing water demand and enhance the availability of water resources by integrating surface and groundwater, aiming to create a buffer during drought periods (Dodd and Rishworth, 2023). However, the overexploitation of groundwater resources often leads to their salinization mainly due to seawater intrusion (SWI), upconing of deep saline water, or residual salinity in aquitards (Custodio, 2009; Cao et al., 2021; Mastrocicco and Colombani, 2021; Mastrocicco et al., 2021; Narvaez-Montoya et al., 2023). Therefore, become essential to implement efficient strategies to monitor groundwater salinization in coastal aquifers and propose suitable water management strategies.

Groundwater vulnerability (GV) assessment stands as the most common methodologies used for spotlight the protection of groundwater resources. GV was conceptualized by Vrba and Zaporozec (1994) as “the intrinsic property of the groundwater system that depends on the sensitivity to human and/or natural impacts.” This definition embeds both the intrinsic nature of the aquifer and the nature of the specific contaminants/pollutants. However, it is important to distinguish aquifer vulnerability, which is governed by natural conditions, from anthropogenic activities that can cause contamination. Accordingly, intrinsic GV refers to the inherent hydrogeological settings of the area, while specific vulnerability depends on the properties of contaminants that could interact with the groundwater system (Gogu and Dassargues, 2000). Several tools or methods have been developed to assess GV through years. Such methods are generally classified into four broad approaches (Machiwal et al., 2018): i) process-based methods; ii) statistical methods; iii) overlay or index methods, and iv) hybrid methods. Process-based methods usually refer to mathematical models that simulate groundwater flow and the behaviour of pollutants in the subsurface. These numerical models can reproduce how long a pollutant will take to reach a point and/or the amount transported within the aquifer. However, they are very intensive on input data requirements. Statistical methods are based on existing/known pollution cases in a geographic area to calculate the probability of contaminant concentration. This approach requires historical data and robust regional databases that may not always be available. Overlay and index methods combine spatial layers of various physiographic attributes (e.g., geology, soils, depth to water table), assigning a score to each attribute. The numerical ratings are combined to generate a composite sensitivity/-vulnerability score. The ratings can be considered equally essential or weighed according to the relative magnitude of their influence in the overall assessment. This method's primary limits are static results and operator subjectivity. Finally, the hybrid methods combine two or more of the previously mentioned methods to reduce drawbacks and enhance result's reliability.

Nowadays, index and overlay methods are often routinely performed within a GIS environment for spatial visualization of GV, allowing adjustments, validation, and comparison with other GV assessment approaches, allowing widespread applications and easy results dissemination, despite the limitations mentioned above. The most popular overlay and index method is DRASTIC, developed by Aller et al. (1987) to evaluate groundwater intrinsic vulnerability to pollution. DRASTIC has led to the development of other methods using a similar structure but different input parameters targeting specific problems. For example, the overlay and index method GALDIT (Chachadi and Lobo-Ferreira, 2007; Lobo-Ferreira et al., 2007) was developed to determine specific GV for SWI. Among the many existing index methods proposed in literature (Ballesteros et al., 2016; Fidelibus and Pulido-Bosch, 2019; Zeynolabedin and Ghiassi, 2019; Sbai et al., 2021; Baena-Ruiz and Pulido-Velazquez, 2021), DRASTIC and GALDIT have been the most utilized worldwide to assess intrinsic GV to pollution and specific GV to SWI, respectively (Bordbar et al., 2024). The main reason for the popularity of index-based approaches is their intuitiveness and simplicity in application. Much of the background input data required to run these methods is accessible from open-access databases offering data at different spatial levels. In addition, they are not heavily reliant on specialized field and laboratory data and apply to various scales to investigate local and regional problems (Machiwal et al., 2018; Rama et al., 2022; Taghavi et al., 2022; Huggins et al., 2025). However, index-based methods have also been criticized, primarily because of the subjective expert judgment implied in the rating and weighting system and the exclusion of some parameters that may limit their applicability in critically assessing groundwater vulnerability. Although researchers usually retain the original rating scores of these methods, a more objective weighting of hydrogeological parameters has been a matter of investigation in the literature. Weight adjustments to reduce subjectivity were obtained by applying artificial intelligence, statistical and multi-criteria decisions.

To correctly apply index methods, it is essential to understand the relevant processes, the subsurface structure, and the potential events or scenarios that influence the system's behaviour (Giambelluca et al., 1996; Soutter and Musy, 1998). In this respect, the canonical overlay index methods may not always be sufficiently comprehensive for assessing the salinization of coastal aquifers globally.

While previous reviews (Machiwal et al., 2018; Goyal et al., 2021; Banerjee et al., 2023; Taghavi et al., 2022) provide overviews of available methods or discuss commonly implemented modifications (Parizi et al., 2019; Bordbar et al., 2023b), this work tries to go further by offering an in-depth statistical analysis and parameter weight assessment. The approach aims to highlights the most impactful parameters, as well as those with minimal influence, suggesting opportunities for refinement to enhance the reliability of these methodologies or to propose new tailored ones. The proposed review rigorously screens and evaluates all relevant scientific works, filling a critical gap left by prior reviews, which often lack specificity concerning methods addressing saltwater intrusion and do not explore these aspects in detail. To identify critical knowledge gaps, a systematic literature review was conducted to critically analyze the parameters used in published index-based methods for assessing coastal aquifer salinization, including the assignment of ratings and weights. The primary objective was to address the following key questions: Are the existing rating index methods (e.g. GALDIT and its modifications) capable of spatially identifying salinized areas in coastal aquifers? And are the parameters currently used sufficient to achieve this goal? Which are the most used (frequency) and most influential (weight impact) parameters within all the assessment? All applications focusing in assessing SWI and salinization in CAs have been considered using standard or modified GALDIT methods, along with new tailored methods. Moreover, those studies which applied the DRASTIC methods in CAs to assess SWI phenomena have been also considered for this review.

2. Systematic review structure

The key factor distinguishing a systematic review from a literature review is formulating a comprehensive and framed research question (Ahmadi et al., 2022). A systematic review is the most reliable and accurate method for summarizing evidence (Liberati et al., 2009; Booth, 2016). It is based on the PRISMA protocol, providing guidelines and structures for Preferred Reporting Items in Systematic Reviews and Meta-Analyses (Banerjee et al., 2023) with a 27-item checklist to reduce biases (Page et al., 2021) downloadable at https://www.prisma-statement.org/. The protocol was developed with the aim to increase the clarity, transparency, quality and value of research reports in any field of application, from medicine to ecology (Sohrabi et al., 2021; O'Dea et al., 2021; Foo et al., 2021).

2.1. Searching for articles in databases and data coding strategy

A total of 278 papers were found in Scopus (http://www.scopus.com) and 247 in Web of Science (https://www.webofscience.com), published between 2005 and 2024. Table 1 shows the search coding and Boolean operators applied to search the databases for different groups. The first and second groups show the controlled vocabulary related to salinization and CAs, respectively. The third group is related to water resources, while the fourth group considered the GV indicators. The fifth group shows the words associated with optimizing and modifying weights. In addition, groups from 6 to 9 were used to define the articles' language, the years under review, the type of documents, and subject areas. The web-based tool Rayyan (https://www.rayyan.ai) was used to screen titles and abstracts, allowing reviewers to upload RIS files and classify studies as relevant or irrelevant systematically and to identify and remove duplicate studies, ensuring the synthesis did not over-represent findings from repetitively published studies. More details are provided in Supplementary Materials (Section S1).

2.2. Article screening and study eligibility criteria

The inclusion and exclusion criteria for the searched entries were applied in three main stages. Three independent reviewers participated in all stages of the screening procedure and disagreements were resolved through discussion. Each reviewer was responsible for screening 33% of the entire database. In cases of high uncertainty, the reviewers chose inclusion rather than exclusion. The first stage considered screening gathered articles from the database to include those relevant to GV assessment and index methods, groundwater salinization in CAs, and surface water connectivity, as well as removing duplicates. During the first stage, the records identified from Scopus and Web of Science, using the Boolean string, ($n = 525$) were initially screened to remove duplicates ($n = 233$). A total of 199 records were retained and reviewed in the second stage using the Rayyan platform (https://www.rayyan.ai/). The second stage involved screening titles and abstracts to reduce the number of articles to be considered, and this was performed by defining a list of words or phrases irrelevant to the present search. The third stage included reading the full articles, including those that presented quantitative estimates of rating and weights of GV parameters at local, regional, and global scales, but only for salinization and CAs. Table 2 offer an overview of exclusion criteria along with their reasons which guided the authors in screen during the various stages. During the third stage, 7 studies that initially appeared to meet the inclusion criteria during the stage two were ultimately excluded. Ultimately, 47 articles, representing the 20% of initial screened works, were retained after reading the full articles. Fig. 1 depicts the PRISMA flow diagram.

Table 1
Search coding and Boolean operators used for the search in databases.

Keywords and Boolean operators	Group	No
(salin* OR seawater OR saltwater OR brackish water)	Groundwater salinization	1
(coast*)	Coastal areas	2
(aquifer OR groundwater OR surf* water OR interaction)	Water resources	3
(vulnerab* OR risk assessment OR GALDIT OR DRASTIC)	Vulnerability assessment	4
(rat* OR weight OR scor* OR modification OR optimization)	Scoring	5
Only English	Language	6
Article, Review, and Book	Document type	7
2005-2024	Timespan	8
Environmental Science, Earth and Planetary Sciences, Agricultural and Biological Sciences, Engineering, Multidisciplinary, and Chemical Engineering	Subject area	9

2.3. Weighting framework

As a result of applying the PRISMA protocol, the parameters frequence (v) has been calculated along with the weight general statistics. A tailored ranking system has been tested in this work to calculate the weights of each parameter and to identify the highest and lowest impacted ones among the most used. Specifically considering each statistical indicator (e.g. median, average, max and min), the parameters were ranked in ascending order, and each was assigned a score from 1 to *N*, reflecting its ranking. In this way, the value 1 represents the least important, and N represents the most important. This system created a ranking for each statistical indicator, clearly highlighting which parameters were the most impactful and which were the least influential within the overall analysis. All necessary steps are summarized in Fig. 2:

- **Step 1**: For each parameter used more than five times, calculate the maximum (Max), minimum (Min), mean (M), and median (Mdn) values.
- **Step 2**: Rank each statistical indicator in ascending order. Assign the highest-ranked parameter a score of *N* (where *N* is the total number

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

Reason for Exclusion	Exclusion criteria	Stage
Avoid using the same studies	Detect and remove duplicates from databases	Stage 1: Duplicate removal
Not focused on groundwater salinization	Studies on unrelated risks (e.g., erosion, floods, ecosystem changes)	Stage 2: Screening titles and abstracts
Different contamination processes and methodologies	Studies on non-salinization tracer (e.g., nitrates, trace metals, microplastics)	
No index-based groundwater vulnerability assessment	Studies on general water quality without vulnerability mapping	
Indirectly related, lacks vulnerability assessment methods	Studies on irrigation impacts without groundwater vulnerability focus	
No quantitative assessment	Studies lacking rating indices or vulnerability maps	Stage 3: Full text reading
Out of scope for this systematic review	Studies on inland aquifers with no connection to coastal salinization	

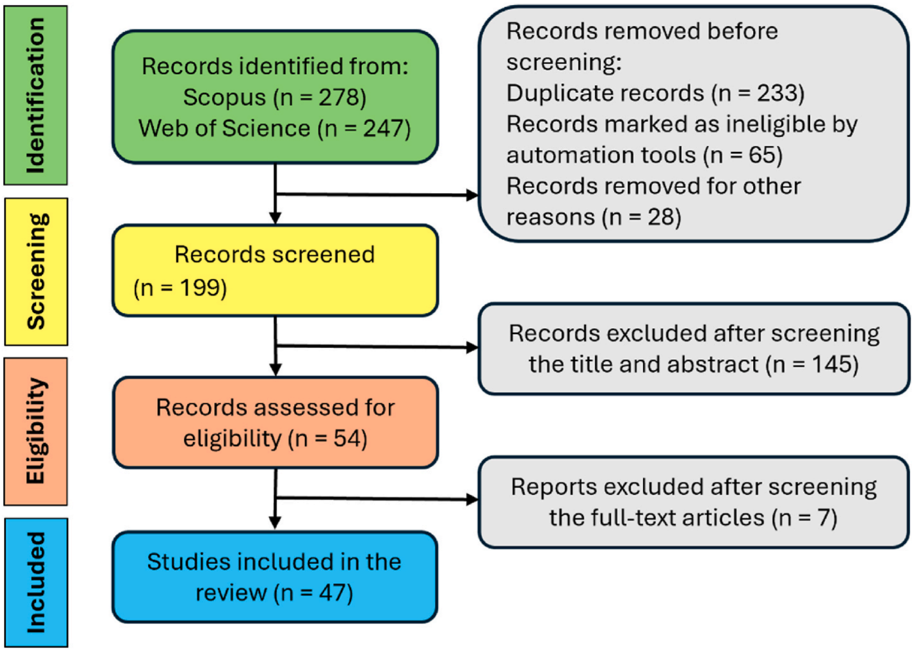

Fig. 1. The application of the PRISMA flow diagram in the systematic review and the number of articles screened at different stages are also discussed.

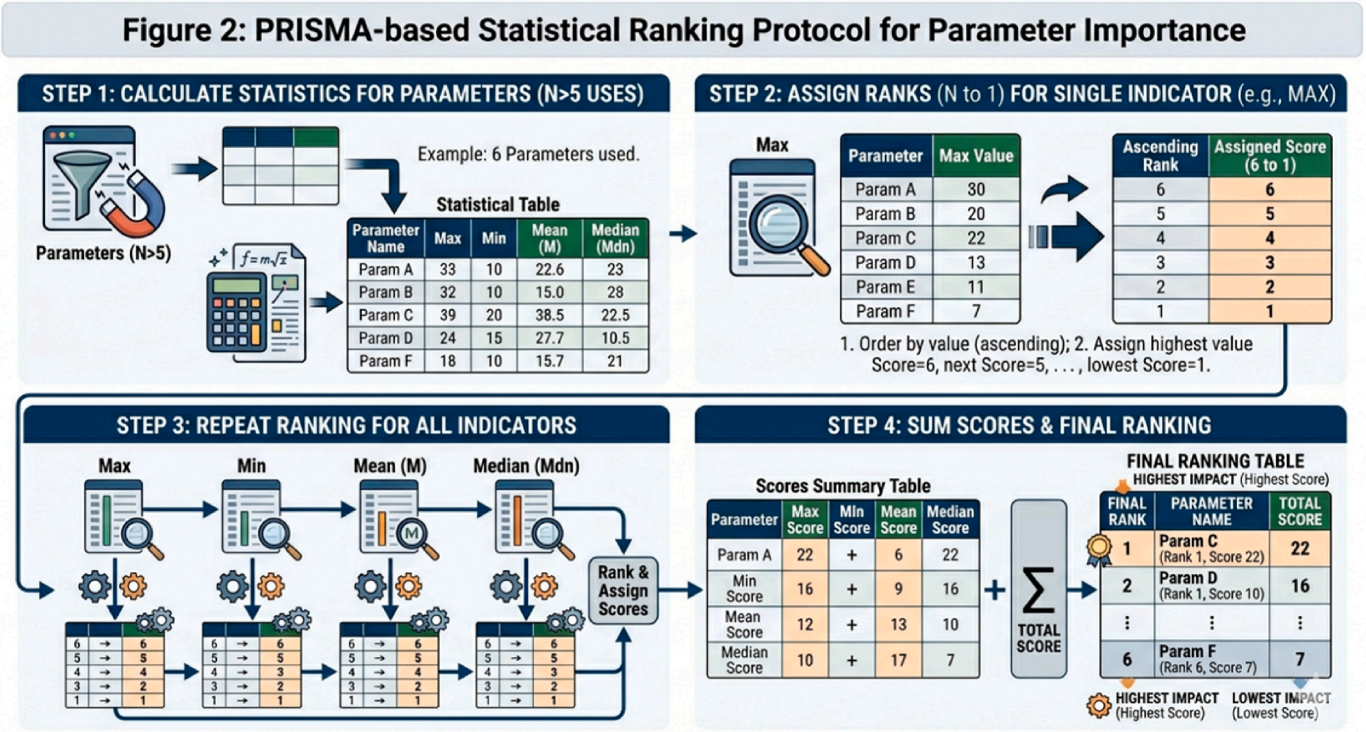

Figure 2: PRISMA-based Statistical Ranking Protocol for Parameter Importance

STEP 1: CALCULATE STATISTICS FOR PARAMETERS (N>5 USES)

Example: 6 Parameters used.

Statistical Table

Parameter Name	Max	Min	Mean (M)	Median (Mdn)
Param A	33	10	22.6	23
Param B	32	10	15.0	28
Param C	39	20	38.5	22.5
Param D	24	15	27.7	10.5
Param F	18	10	15.7	21

STEP 2: ASSIGN RANKS (N to 1) FOR SINGLE INDICATOR (e.g., MAX)

Parameter	Max Value
Param A	30
Param B	20
Param C	22
Param D	13
Param E	11
Param F	7

Ascending Rank	Assigned Score (6 to 1)
6	6
5	5
4	4
3	3
2	2
1	1

1. Order by value (ascending); 2. Assign highest value Score=6, next Score=5, . . . , lowest Score=1.

STEP 3: REPEAT RANKING FOR ALL INDICATORS

6	→	6
5	→	5
4	→	4
3	→	2
1	→	1

6	→	6
5	→	5
4	→	3
3	→	2
1	→	1

6	→	6
5	→	5
4	→	4
3	→	2
1	→	1

6	→	6
5	→	5
4	→	3
3	→	2
1	→	1

STEP 4: SUM SCORES & FINAL RANKING

Scores Summary Table

Parameter	Max Score	Min Score	Mean Score	Median Score
Param A	22	+	6	22
Min Score	16	+	9	16
Mean Score	12	+	13	10
Median Score	10	+	17	7

FINAL RANKING TABLE

HIGHEST IMPACT (Highest Score)

FINAL RANK	PARAMETER NAME	TOTAL SCORE
1	**Param C** (Rank 1, Score 22)	22
2	**Param D** (Rank 1, Score 10)	16
⋮	⋮	⋮
6	**Param F** (Rank 6, Score 7)	7

HIGHEST IMPACT (Highest Score) LOWEST IMPACT (Lowest Score)

Fig. 2. Conceptual scheme explaining the ranking of variables based on the statistical indicators Min, Max, M, and Mdn.

of parameters), the next one *N-1*, and so on, until the lowest-ranked parameter, which receives a score of 1. For example, with 6 parameters, the top parameter receives a score of 6, the second 5, the third 4, and so on, with the last one assigned 1.

- **Step 3**: Repeat Step 2 for each statistical indicator.
- **Step 4**: Sum the scores obtained for each parameter across all indicators to obtain the final ranking.

3. GALDIT method overview

GV assessment through rating indices in CAs was introduced by Chachadi (2005), who proposed GALDIT as a dedicated approach to evaluate the vulnerability to SWI. Each parameter in GALDIT is assigned a fixed rating value between 2.5 and 10, where 2.5 indicates the lowest vulnerability and 10 is the highest (Chachadi, 2005) and a weighting system where each parameter is given a fixed value from 1 to 4 based on its relative importance in GV. The hydrogeological parameters considered are: groundwater occurrence (G) which indicates the type of cell and is represented by four classes (weathered, semi-confined, unconfined, and confined aquifers); aquifer hydraulic conductivity (A) which indicates the ability of groundwater to flow through the aquifer, meaning that higher conductivity could increase the movement of saltwater into freshwater areas; depth of the groundwater level above the sea (L) which indicates the depth of the groundwater level compared to sea level and is inversely proportional to SWI; distance from the shoreline (D) which depicts the proximity of the aquifer to the coastline, with closer areas being more vulnerable; the impact of existing SWI (I) which indicates the current status of salinization of the aquifer (Revelle, 1941); and thickness of the aquifer (T) which takes into account the saturated thickness of the aquifer, thus the thicker the aquifer the more likely it is to dilute saltwater (Fig. 3).

These parameters are combined with GIS software to create the GALDIT vulnerability index. More theoretical details on the GALDIT method can be found in Chachadi (2005). The method assumes that SWI is caused by over-extraction of groundwater, sea-level rise, or both, and does not account for events such as hurricanes and tsunamis that involve the inward movement and/or mixing of seawater with freshwater (Bordbar et al., 2023b). In addition to the previously mentioned drawbacks, GALDIT neglects essential factors that affect salinity processes, such as leaching from the vadose zone, paleo-saline groundwater upconing, and salt fractionation due to over-irrigation (Fig. 3). Besides, vertical movement of saline water due to upconing or irrigation return flow is neglected (Fig. 3). This is due since the GALDIT method focus only on lateral and actual SWI. For instance, in coastal alluvial plain highly anthropized, irrigation water flow could act like a high saline water recharge increasing overall groundwater salinity (Athapattu et al., 2024; Caschetto et al., 2025; Passarella et al., 2025) and trapped paleo saline water can be responsible of high salinity also far from coastline (Schiavo et al., 2023). In fractured or karst coastal aquifers, vertical connectivity and conduits can easily move saline water from the deep aquifer (Sebben et al., 2015; Giese and Barthel, 2021). Several studies also state the necessity of GALDIT to be calibrated according to the hydrogeological features of the specific aquifer of interest to achieve a reliable assessment. Therefore, recent studies employed various techniques to optimize and modify the weights of GALDIT (Bordbar et al., 2020, 2023b).

Result validation is another fundamental step in evaluating the final performance. The most common strategies to assess model performance are the comparison among different methods, expert judgments, or the utilization of observation wells. In GV studies of coastal aquifers, when observation wells are available, the GV maps are typically evaluated using the correlation coefficient with a specific target variable (Motevalli et al., 2018; Parizi et al., 2019; Khosravi et al., 2021; Zghibi et al., 2022; Nadiri et al., 2023; Bordbar et al., 2024). Additionally, the receiver operating characteristics (ROC) curve has recently been used to estimate the accuracy of the obtained GV maps (Gharekhani et al., 2023); however, most studies did not implement a statistical validation method (Trabelsi et al., 2016; Kazakis et al., 2019; Kim et al., 2021) raising some doubts about results' reliability. It is worth noting, however, that while several studies highlight the higher reliability gained by modifying parameter weights, the post-processing of canonical GALDIT maps through AI or machine learning algorithms may sometimes force the results. This is particularly evident when using TDS or EC as dependent variables, which can bias the optimization process and lead to spatial patterns that are not fully consistent with the hydrogeological framework, thus producing unrealistic outcomes. Despite being developed to evaluate groundwater vertical pollution, several studies also tried to use DRASTIC to assess GV to SWI in coastal aquifers (Kaliraj et al., 2015; Hu et al., 2018; Hasan et al., 2023; Luo et al., 2023; Goswami and Rai, 2024a,b2025). Gharekhani et al. (2023) combined the optimized DRASTIC and GALDIT methods to create an assembled GV. Anyway, since DRASTIC lacks appropriate parameters for assessing GV of coastal aquifers, such as the groundwater head, the hydraulic gradient towards the sea or proximity to the coast, even in this case it did not provide accurate results. Although DRASTIC is not meant for GV of coastal aquifers, it should be noted that parameters such as aquifer hydraulic conductivity, recharge and slope are useful for evaluating SWI in CAs and have been combined with GALDIT to obtain a comprehensive GV assessment (Allouche et al., 2017).

4. Results and discussions

4.1. Spatial distribution of GALDIT applications

The results of the systematic review revealed four main methodological approach specifically applied for assessing SWI in CAS: i) the standard application of GALDIT index ii) modified GALDIT index incorporating additional parameters, iii) GALDIT-based approaches with adjusted weights and ratings, and finally iv) a limited number of studies comparing and testing the performance of the DRASTIC index against GALDIT for SWI assessment. Fig. 4 shows the spatial distribution of the investigated studies around the world. The country-based distribution of GALDIT-based studies shows significant research in Iran, followed by India, Italy, and China. Countries including Greece, South Korea, Algeria, and Tunisia have conducted a moderate number of studies. In contrast, countries such as Bangladesh, Benin, Egypt, Portugal, the United States, Vietnam, and New Zealand have a few

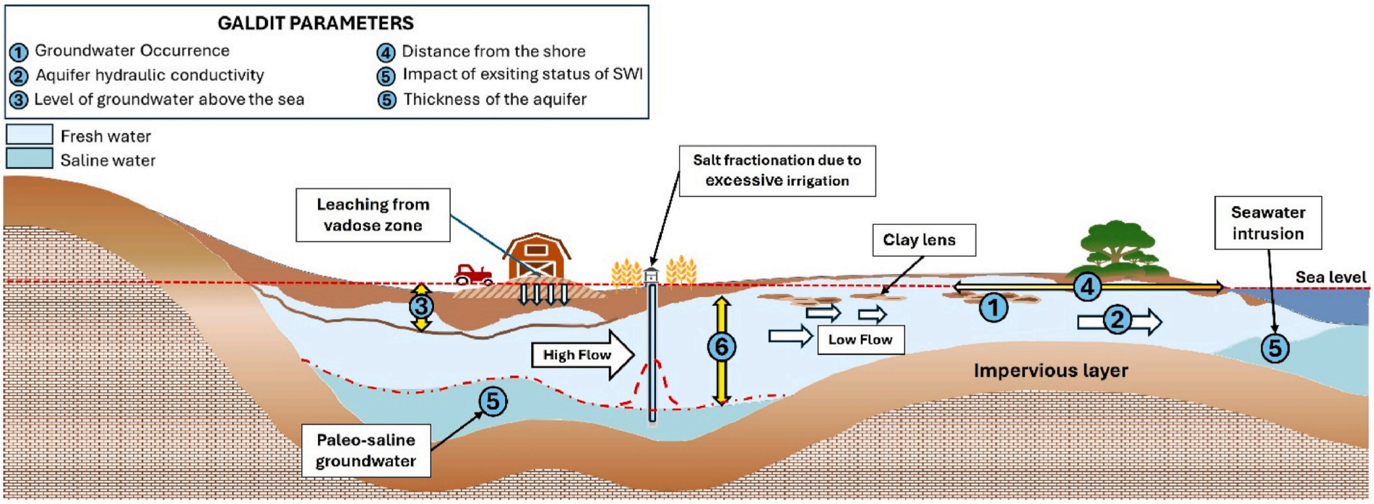

Fig. 3. A synthetic conceptual model for the GALDIT method.

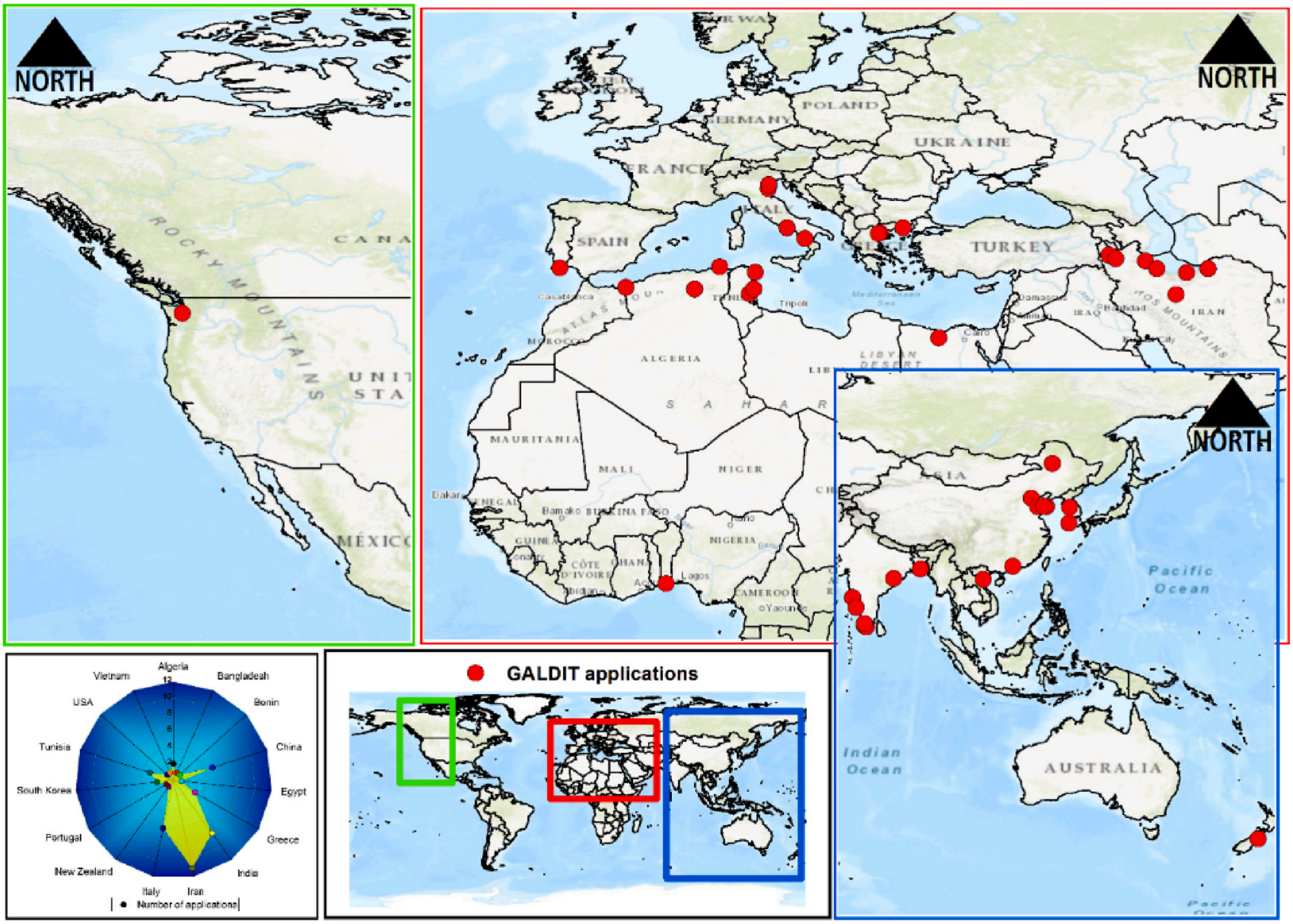

Fig. 4. Spatial distribution of investigated studies around the world.

studies. In particular, the Mediterranean region, identified two decades ago as a climate change hot spot (Giorgi, 2006), hosted many GALDIT-based studies (Mastrocicco and Colombani, 2021). Also, the northern area of Iran presents a considerable number of studies, affected by salinization processes due to increased land use and over-exploitation of groundwater for agricultural activities close to Urmia Lake (Khosravi et al., 2021). Likewise, rapid economic growth and high population density in China and India have increased the demand for groundwater and in turn, its salinization, boosting the research in the field of GV (Luo et al., 2023; Goswami and Rai, 2024a,b).

4.2. Parameters occurrency

The frequence (v) of parameters used to assess GV to salinization in CAs was analysed considering 513 records. The most frequently applied parameters, as expected, were the original GALDIT factors such as aquifer hydraulic conductivity (75/513v), distance from the shoreline (72/513v), groundwater occurrence (71/513v), thickness of aquifer (71/513v), depth of the groundwater level above the sea (71/513v), and impact of existing SWI (70/513v), confirming the popularity of the method. The other parameters introduced within the various works can be categorized into distinct groups based on their focus and frequency of use (Fig. 5).

Group 1: parameters associated with the DRASTIC method application since several researchers tried to test the suitability of the DRASTIC method to evaluate SWI (Kaliraj et al., 2015; Hu et al., 2018; Hasan et al., 2023) or coupled it with GALDIT to obtain a hybrid index to account vertical and horizontal vulnerability (Luoma et al., 2017; Luo et al., 2023). These parameters include: depth to water (3/513v), recharge (4/513v), aquifer media (3/513v), soil media (3/513v), slope (2/513v), and the impact of the vadose zone (4/513v).

Group 2: to characterize the susceptibility of coastal aquifers to saltwater intrusion via surface drainage of saltwater bodies or to account the dilution factor of freshwater superficial resources, several new parameters were added to enhance the standard GALDIT application (Kazakis et al., 2019; Busico et al., 2021; Tosi et al., 2021) such as distance from torrents (2/513v), distance from wetlands (2/513v), distance from rivers and lagoons (5/513v), distance from salt sources (1/513v), ground elevation (3/513v), potential runoff (1/513v), vadose zone hydraulic conductivity (2/513v), distance from freshwater sources (1/513v) and subsidence (1/513v).

Group 3: site specific hydrogeological features related to saltwater up-coning and aquifer characteristics were also introduced (Motevalli et al., 2018; Parizi et al., 2019), including bedrock topography (3/513v), cross-resistance (3/513v), the impact of the existing status of saltwater up-coning (3/513v), permeability of the shallow aquifer (1/513v), hydraulic gradient (2/513v), and clay content (2/513v).

Group 4: anthropogenic impacts parameters such as land use (3/513v), well density (3/513v), and pumping rate (1/513v), relative ground level change (1/513v), groundwater level decline (3/513v) were considered highlighting human-induced factors affecting

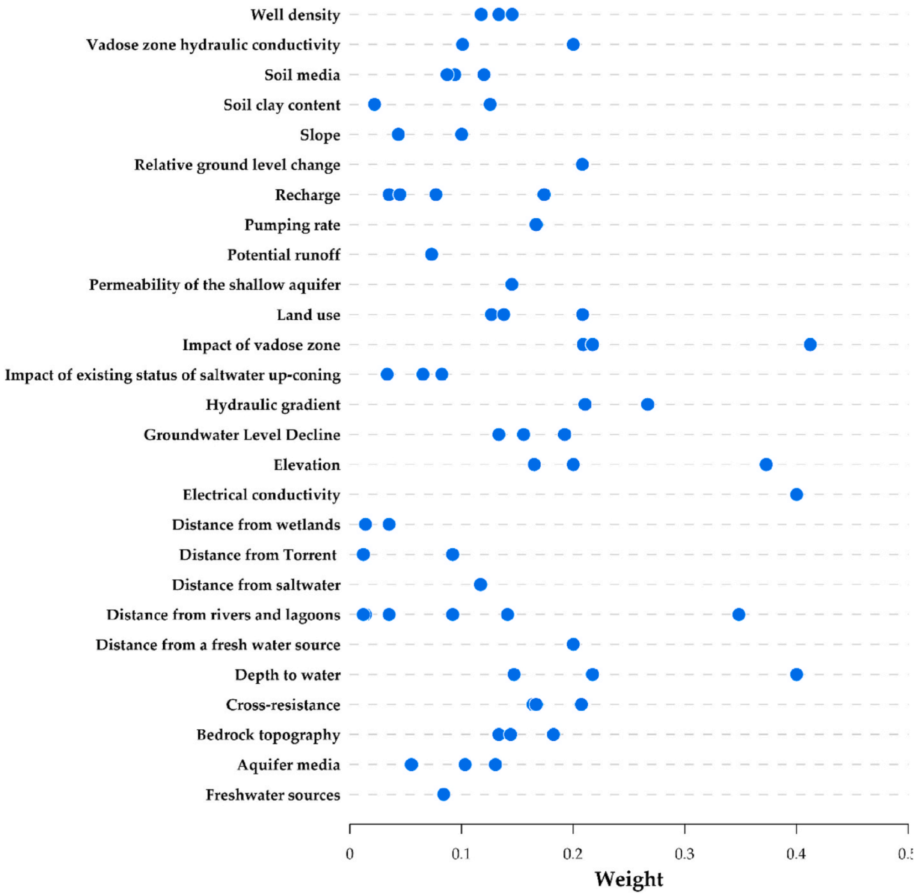

Fig. 5. Occurrence and weights of parameters used to assess GV to salinization in Cas out of GALDIT.

groundwater vulnerability (Sadeghfam et al., 2020; Mahmoudpour et al., 2023).

Recharge, morphological parameters, and distance from rivers and torrents were the most frequently used parameters among the additional ones. It is worth noting that high-frequency parameters should not automatically be considered more important than low-frequency ones. A high frequency of use may often reflect inertia in methodology, ease of data acquisition, or even citation copying, rather than true physical relevance. Anyway, it is clear from the frequence analysis how the GALDIT method and its derivation represent the only ratings and weights methodology tailored for assessing coastal salinization despite its well-known limitations.

4.3. *Statistical analysis*

All manuscript collected following the PRISMA protocol were divided into three main groups and separately investigated: a) a group including all 47 identified manuscripts, b) a subset of manuscripts (35) where validation procedures were applied, and c) a group containing manuscripts (15) with weights optimization. The remaining works (7) simply applied the GALDIT methods without any sort of modification or validation procedure. For all three groups, the Max, Min, M, and Mdn values were computed for those parameters used at least more than five times ($v > 5$) to determine their relative contribution to GV to salinization. This step aimed to observe the statistical changes in the weights of single parameters within the three groups and to compare the weight obtained during the various modification procedure with the GALDIT standard weights.

According to the statistical results obtained considering all the studies selected with the review criteria (group 1), the depth of the groundwater level above sea and distance from the shoreline had the most significant impact on the final assessment. Conversely, groundwater occurrence and the effect of existing SWI were the parameters with the least impact. Aquifer hydraulic conductivity and aquifer thickness ranked the most and the least essential parameters. While there are huge differences among Min and Max weights across the application, the Mdn value is close to the standard value applied by the GALDIT method (Fig. 6).

In the second step, only those studies using validation methods to evaluate the accuracy of GV assessment were considered (group 2). The Mdn and Min weights were comparable to the first group's result. At the same time, slight differences were notable considering the Max and M results (Fig. 6). Also, in this case, the Mdn values are comparable to the standard GALDIT weights. The last analysis involved only the studies that applied optimization methods to enhance the accuracy and reliability of GV assessments both in weight optimization and spatial data distribution (group 3). Again, the two most influencing parameters were the depth of the groundwater level above sea and distance from the shoreline, which showed the highest weights. In this group, some differences were notable when comparing all parameters' Mdn values and the standard GALDIT weights especially for the highest-ranking parameters which saw decrease their overall impact (Fig. 6).

A synthesis of studies using the original GALDIT showed that most of the studies maintained methodological rigor according to the standard framework, but they suffered from moderate to high risk of bias due to the absence of validation methods (such as ROC curves or correlation analyses), which could limit the reliability of the results. It is also worth noting that some studies have emphasized limited data sets or, in some cases, omitted critical parameters, increasing the likelihood of error in estimating salinity dynamics.

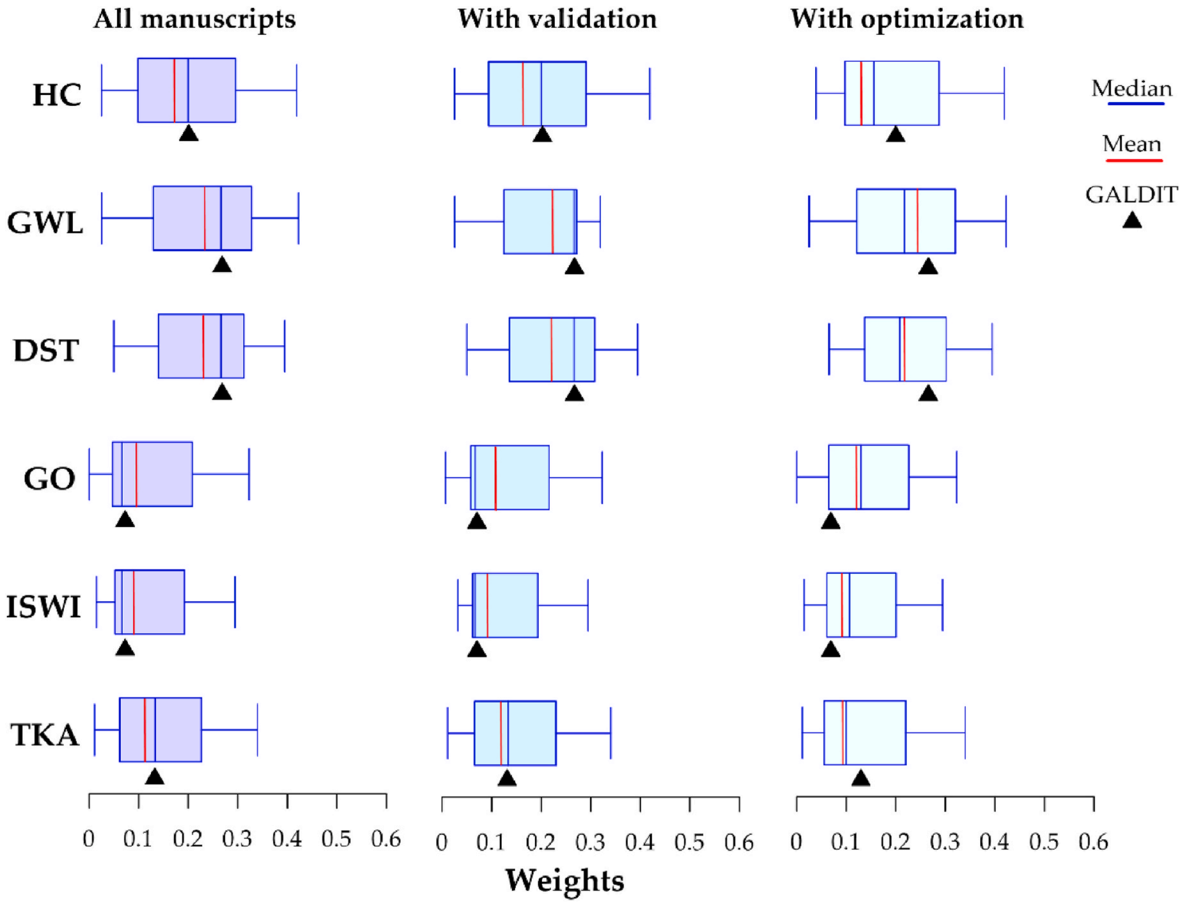

Fig. 6. Statistical analysis of all manuscripts from systematic review, validation, and optimization. HC: Hydraulic conductivity; GWL: depth of the groundwater level above sea; DST: Distance from the shoreline; GO: Groundwater occurrence; ISWI: Impact of SWI; TKA: Thickness of the aquifer.

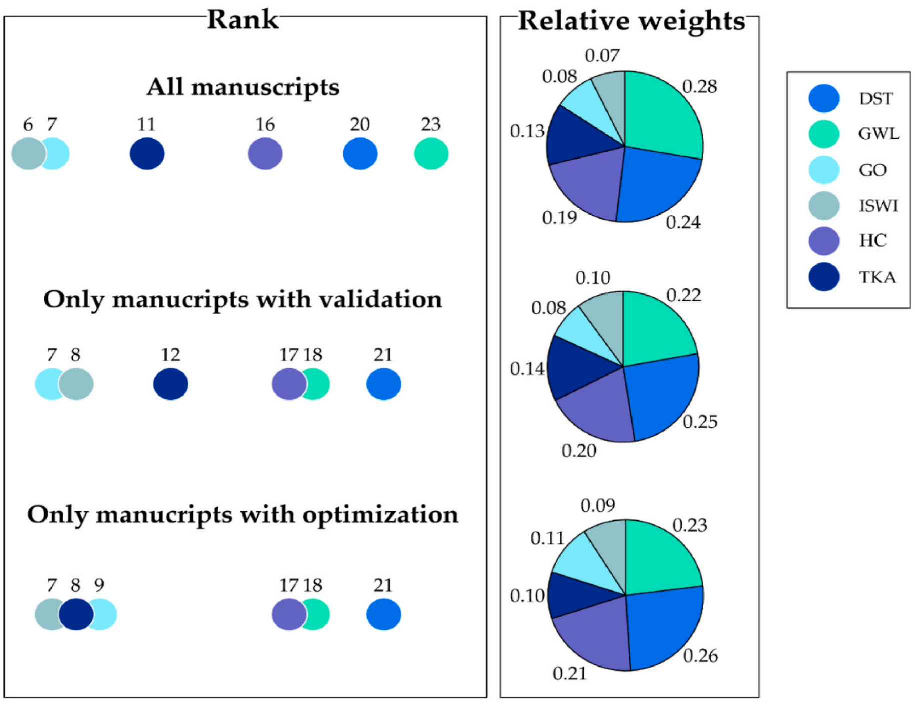

Fig. 7. The weighted sum for all manuscripts from a systematic review, with validation and optimization. HC: Hydraulic conductivity; GWL: Depth of the groundwater level above the sea; DST: Distance from the shoreline; GO: Groundwater occurrence; ISWI: Impact of existing SWI; TKA: Thickness of the aquifer.

4.4. Parameters ranking

The results of the weighted analysis for all group are shown in Fig. 7. The overall analysis indicated that the parameters “depth of the groundwater level above sea”, and “distance from the shoreline” compete for the top spots in the ranking of the most significant parameters, alternating between groups. In contrast, “groundwater occurrence” and “impact on existing SWI” consistently occupy the lowest positions (Fig. 7). Additionally, “aquifer hydraulic conductivity” carries substantial importance, closely following the two primary impact parameters, while the significance of “aquifer thickness” ranks near the bottom. From Fig. 7, it is also possible to see that the first three parameters have a significantly greater impact in magnitude compared to the last two, with a weighted sum that is four times greater. This underscores the significant impact of the first three parameters on the overall assessment.

4.5. Parameters advantages and drawbacks

Given the results, the role of parameters “groundwater occurrence” and “impact of the existing SWI” were investigated in more detail in all the studies to find the reason behind their low rank. According to GALDIT, aquifers can be classified into four groups (weathered, semi-confined, unconfined, and confined), depending on their geological nature. As shown in Fig. 8, 62%, 17%, 20%, and 1% of investigated studies reported one, two, three, and five aquifer classes, respectively. Based on the statistical analysis, most of the studies have only one aquifer class, confirming that this parameter retains the least sensitivity in assessing GV of coastal aquifers since multiplying all the areas for the same value everywhere has no real impact on GV results. The homogeneity of this parameter shows limited influence on the overall vulnerability assessment methods in the study areas, and consequently all kinds of modification algorithms assigns them the lowest weights. The “impact of existing SWI” is commonly utilized in GALDIT to assess the degree of salinization of an aquifer. According to the results, the three most frequently used parameters- Revelle index, TDS, and EC-present various drawbacks. The Revelle index (1941), which considers the ratio of $Cl/[HCO3+CO3]$ as a chemical indicator to evaluate the extent of SWI in coastal aquifers (Chachadi, 2005), has been employed in most studies.

The main disadvantage of the Revelle index is its limited range, making it unsuitable for preparing a schematic map and unable to consider the impact of the frequent reactions (precipitation/dissolution of carbonates and biogeochemical reactions, such as organic matter oxidation) that usually occur in coastal aquifers. TDS is the second most frequently used indicator to validate the extent of SWI in CAs. Simple indicators such as TDS and EC act as the first quick screening of salinity not providing information to its source (Rachid et al., 2017). One of the advantages of TDS is the ease in data collection, but TDS is often estimated based on its linear relationship with EC that may be less meaningful because of other components dissolved in groundwater, such as nitrates and phosphates. Parizi et al. (2019) used EC and Cl, as chemical parameters for preparing the “impact of existing SWI” map. Anyway, also the use of Cl alone as indicator of groundwater salinization is not enough in distinguish the different source of salinization which can have a different order of magnitude in influencing groundwater quality.

Another issue that emerged from the critical review of each study is that GALDIT, alone, cannot always show the actual extent of GV of coastal aquifers since also the three most impacted parameters: “depth of the groundwater level above sea”, “distance from the shoreline”, and “aquifer hydraulic conductivity” suffer of numerous drawbacks. For example, the parameter “distance from the shoreline”, which has the most weight in GALDIT, can only show actual SWI up to 1-2 km from the shoreline. Meanwhile, other sources of superficial salinity, including rivers, lagoons, or lakes, may contribute to the salinization process. For instance, Emara et al. (2024) used GALDIT to assess the GV of the Moghra aquifers in the Desert of Egypt. The study area is far from the Mediterranean coast, which indicates that the parameter “distance from the shoreline” is not applicable. Therefore, the “distance from the shoreline” will not be relevant to GV assessment to salinization, leading to erroneous evaluation. In this case, GALDIT users should consider the distance from the saltwater source, such as lakes, lagoons, rivers, wetlands, and coastline itself, in assessing the GV to salinization. The importance of lakes as significant sources of salinity has been intensely investigated, for example, in Urmia Lake (Sadeghfam et al., 2020; Barzegar et al., 2021; Nourani et al., 2024) and Namak Lake (Hosseini and Kerachian, 2023) in Iran. Additionally, other studies conducted in Italy (Kazakis et al., 2019; Busico et al., 2021), Greece (Kazakis et al., 2019), and New Zealand (Setiawan et al., 2024) have investigated the importance of superficial saline water on the salinization of coastal aquifers.

Therefore, despite the distance from the shoreline being significant for assessing GV in CAs, the saltwater source may not necessarily be the sea. This holds even in the path of autonomous salinization (Oude Essink et al., 2010), where the source of salinity consists of buried saline layers, such as deposited during the last marine transgression, that may be located far from the shoreline, but which can cause widespread salinization of groundwater resources via upcoming, especially in reclaimed agricultural areas situated below the actual sea level (Colombani et al., 2016, 2024; Yu et al., 2023; Seibert et al., 2023). This phenomenon is totally neglected in GALDIT though it effects large delta areas all over the world (Fig. 3).

Another highly sensitive GALDIT parameter is “groundwater level above sea”. This parameter is a proxy that indicates seaward and landward hydraulic head or potentiometric surface. So, the fluctuations of the hydraulic gradient caused by changes in the temporary supply and discharge components are essential in increasing groundwater salinity,

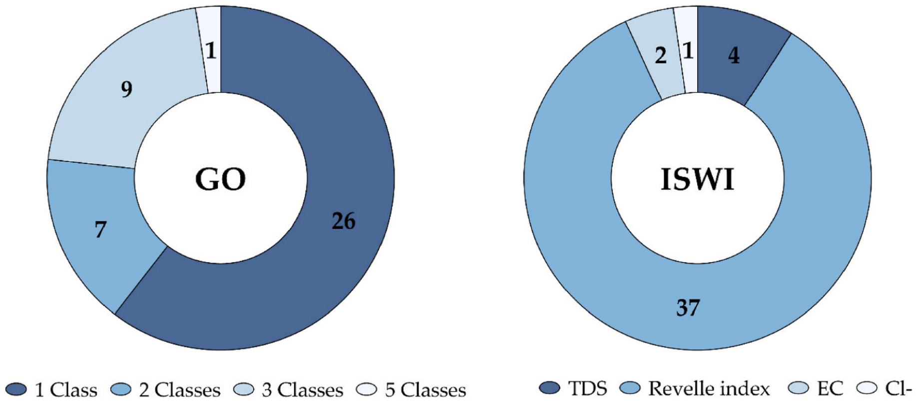

Fig. 8. Number of studies related to the “groundwater occurrence” classes and to the approach used to estimate the “impact of existing SWI.”

especially along the shoreline. Anyway, in CAs where groundwater is overexploited, the hydraulic gradient toward the sea is a more relevant parameter controlling the location of the seawater interface. It provides the primary mechanism of fresh groundwater discharge to the sea (Parizi et al., 2019). Therefore, the hydraulic gradient should be considered for evaluating GV to salinization in CAs, as it was confirmed in the study by Parizi et al. (2019).

4.6. *Modifications for GV in CAs*

What clearly emerged from this review is that researchers generally follow two main approaches when assessing salinization in coastal aquifers (CAs) through rating and weighting methods (Fig. 9).

- The first approach consists of the straightforward application of the standard GALDIT method, without any modification or adaptation to the specific hydrogeological setting. In most of these cases, validation procedures are either missing or only superficially addressed (Mahesha et al., 2012; Trabelsi et al., 2016; Seenipandi et al., 2019; Sujitha et al., 2020; Muzzillo et al., 2022; Yang et al., 2022; Zghibi et al., 2022; Lyu et al., 2024).
- The second approach encompasses the different types of modifications applied to GALDIT. These modifications can be grouped into two main pathways: i) Adjustment of rates and weights without introducing new parameters and ii) adding new specific parameters.

In the first case, the objective is to better emphasize the relative importance of existing parameters under specific conditions (Gontara et al., 2016; Kazakis et al., 2018; Bordbar et al., 2019, 2020, 2024; Reshma and Sindhu, 2019; Sadeghfam et al., 2020; Barzegar et al., 2021; Khosravi et al., 2021; Wei et al., 2021b; Chronidou et al., 2022; Faal et al., 2022; Gharekhani et al., 2023; Hosseini and Kerachian, 2023; Luo et al., 2023; Mahmoudpour et al., 2023; Pham et al., 2023; Goswami and Rai, 2024a,b; Huang et al., 2024; Nourani et al., 2024). Two main strategies are typically adopted:

- MCDA based approaches (e.g., AHP): weights are modified starting from expert judgment, which is then refined through a pairwise comparison matrix to reduce subjectivity.
- ML and AI based approaches: these require a dependent variable (e.g., TDS, EC, Cl) to calculate the parameter ranking. In many cases, GALDIT maps are first produced and then optimized according to the spatial distribution of the chosen dependent variable.

The second type of modification involves the introduction of new parameters into the GALDIT framework, with the choice of parameters strongly influenced by the hydrogeological setting of the study area (Gorgij et al., 2017; Motevalli et al., 2018; Kazakis et al., 2019; Parizi et al., 2019; Sadeghfam et al., 2020; Boufekane et al., 2022; Mahmoudpour et al., 2023; Bordbar et al., 2024; Goswami and Rai, 2024a, b).

- In alluvial floodplains, depressions, or areas with extensive natural or artificial drainage networks, parameters related to the presence of canals, rivers, and wetlands have proven to provide valuable insights for the final assessment. Similarly, subsidence rate analysis and vadose zone characteristics have been incorporated as additional parameters to improve the representation of local vulnerability. An example is represented by the GALDIT-Superficial Seawater Intrusion (SUSI), proposed by Kazakis et al. (2019) with the aim of providing a flexible and convenient tool to investigate actual SWI into CAs. The modification relies on the assumption that the intrusion of superficial seawater through rivers, canals and lagoons is a crucial process in GV (Busico et al., 2021; Setiawan et al., 2024). Tosi et al. (2021) introduced several parameters to prepare a hazard index for SWI in farmland areas. Potential runoff was used to identify sectors with varying capacities to recharge the aquifer from rainfall and distance from saltwater was used to distinguish between rivers stretches close or far from the shoreline.
- In contrast, when dealing with coastal zones heavily influenced by anthropogenic pressures, parameters such as hydraulic gradient,

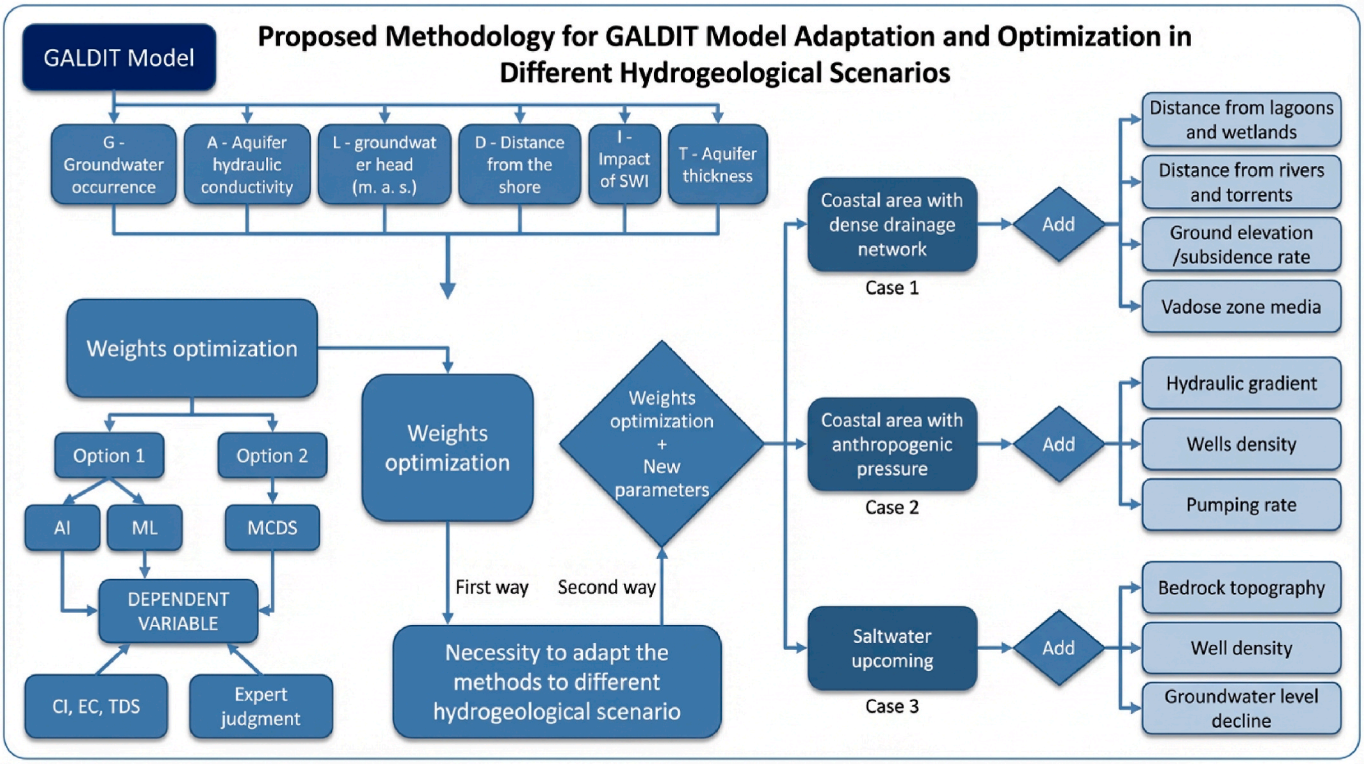

Fig. 9. Conceptual scheme of GALDIT modifications.

well density, and pumping rates have been introduced to better capture the impact of human activities on salinization processes. Parizi et al. (2019) modified GALDIT introducing the GAiDIT and GALDIT-i indices for mapping the vulnerability of coastal aquifers to SWI where the hydraulic gradient was combined as an additional parameter into the GALDIT method. Moreover, anthropogenic parameters such as well density, pumping well and land use have been used in many case studies to enhance the performance of GALDIT method (Gorgij et al., 2017; Motevalli et al., 2018; Sadeghfam et al., 2020; Mahmoudpour et al., 2023; Bordbar et al., 2024; Goswami and Rai, 2024a,b).

- Finally, in cases of saline upconing from deeper aquifers, parameters including well density, groundwater decline, and bedrock topography have been considered essential to represent vertical flow dynamics and structural controls. The TAWLBIC method, suggested by Motevalli et al. (2018), tried to address saltwater up-coning from deep saline aquifer far from the shoreline. To achieve that, the index focuses on parameters related to internal saltwater dynamics such as cross-resistance, bedrock topography and well density.

To summarize, advantages of some factors along with the corresponding rating criteria, are described in Table 3.

5. Limitations and future recommendations

The results of this study, while valuable, have several limitations that should be acknowledged. The first major issue is inherently tied to the current literature on rating indices applied for salinization of groundwater resources. Despite this phenomenon is becoming a critical global challenge, there are relatively few applications of these methods documented in the literature. Consequently, the statistical analysis conducted suffers from a limited dataset (47 applications), which could constrain the robustness of the conclusion. Another significant limitation is that the dataset collected for this manuscript is largely dominated by standard GALDIT applications. As a result, the statistical analysis aligns closely with the original GALDIT weights, with notable differences primarily observed in studies that applied modifications using optimization algorithms. However, this raises a crucial question: in how many of these studies was GALDIT successfully used to assess SWI? This distinction is critical for evaluating the method's reliability and practical utility. The systematic review revealed that 12 out of 47 studies did not apply any form of validation, making it difficult to assess the robustness of their findings. Another drawback of this study is that the use of Boolean search techniques may have excluded some relevant research. As a result, certain applications of the GALDIT method beyond the scope of this systematic review were not selected. These studies might not apply the exact terms included in the search string. Notable examples include studies conducted in the Baltic Sea region (Luoma et al., 2017; Potrykus et al., 2018; Winid and Maruta, 2025), Brazil (Lima et al., 2024), Mexico (Trejo-Albuerne and Canul-Macario, 2024), and Kenya (Idowu et al., 2022). Specifically, Luoma et al. (2017) successfully applied AVI, modified SINTACS and GALDIT to identify the degree of groundwater vulnerability in southern Finland. Anyway, none of those deeply modified the original GALDIT. The study by Winid and Maruta (2025) was published after our search and was so excluded from our systematic review. They employed the GALDIT model validated with groundwater chemical indices, including EC, seawater mixing index (SMI), $rHCO_3/rCl$, rNa/rCl, and the of Cl^- and Br^- concentrations. They found that the ratios of $rHCO_3/rCl$, rCa/rMg, and Cl/Br had significant roles in risk assessment compared to the others confirming that Cl/Br ratio can be considered as a quality parameter, instead of the Revelle index. This ratio is employed as a tracer to identify the origins of underground and surface water with low to medium salinity (Alcalá and Custodio, 2008). Cl/Br ratio (salinity ranges) in groundwater can be divided into different groups based on the origin, including paleo SWI, actual SWI, recharge waters, volcanic activities, agricultural impacts, anthropogenic factors, industrial activities (Alcalá and Custodio, 2008). Despite these limitations, the findings of this systematic review provide a comprehensive understanding of the current drawbacks and extensive advances in groundwater salinization studies and management, pointing out that future studies should focus on improving data quality, exploring new and alternative approaches (Table S2). Future assessment frameworks should minimize or avoid the use of qualitative parameters characterized by low spatial variability, such as groundwater occurrence, as these provide limited discriminatory capability in vulnerability mapping. Instead, research efforts should prioritize the development and validation of quantitative indicators that can reliably differentiate salinity sources across diverse hydrogeological settings. The integration of hydrochemical tracers, and high-resolution monitoring datasets

Table 3

New parameters with ameliorations and rating criteria.

SOURCE	RATING CRITERIA	ADVANTAGES	PARAMETERS
Kazakis et al. (2019) Busico et al. (2021) Setiawan et al. (2024) Bordbar et al. (2023a)	Vulnerability increase approaching to the superficial bodies	Include the role of superficial water bodies as a SWI pathways	Distance from lagoons Distance from rivers Distance from torrents Distance from wetlands
Kazakis et al. (2019) Busico et al. (2021) Setiawan et al. (2024) Bordbar et al. (2023a) Tosi et al. (2021)	Ground elevation below or close to zero metres upon sea level spotlight higher vulnerability to SWI	Easily available with DTM, it accounts the role of depressed area in triggering SWI	Ground Elevation
Motevalli et al. (2018)	Higher is the depth of this formation, lower is the possibility of saltwater upconing	Obtained making a difference among DTM and aquifer thickness. Specific for aquifers hosted in bedrock brine	Bedrock topography
Motevalli et al. (2018)	Low resistance values indicate either thin aquifers or high salinity/ contamination	Obtained by multiplying the thickness of the aquifer and specific resistivity of the rock	Cross resistance
Parizi et al. (2019)	Lower hydraulic gradient indicates higher risk of SWI	Accounts the role of climate change, such as sea level rise and droughts	Hydraulic gradient
Tosi et al. (2021)	Vulnerability increase approaching to the saltwater source	Allow to consider any known source of saltwater such as rivers, or lagoon and not only the shoreline as reference point of SWI	Distance from saltwater
Tosi et al. (2021)	Higher runoff potential can indicate higher risk of salinity	Used to identify preferable recharge zone where salinity could be mitigated	Runoff potential
Sadeghfam et al. (2020) Mahmoudpour et al. (2023) Gorgij et al. (2017) Motevalli et a,l. 2018	High value of well density and pumping rate usually express higher risk of SWI	Used when heads data are lacking, to express the pressure on groundwater head due to over pumping	Pumping rate, well density
Tosi et al. (2021) Busico et al. (2021)	Higher subsidence rate or risk reflects higher risk of SWI	Used to forecast future morphology and change in groundwater level	Subsidence rate

represents a promising strategy to improve both the accuracy and the transferability of groundwater vulnerability assessments. Additional research is required to better quantify the dual influence of surface water bodies, including lagoons and rivers, which may function as either freshening or salinizing drivers depending on local hydrological conditions, seasonal dynamics, and anthropogenic stressors. From a management perspective, policy strategies should prioritize sustained monitoring programmes and targeted research initiatives aimed at enabling early detection and mitigation of salinization in coastal aquifers. Furthermore, the establishment of standardized and broadly applicable methodologies for groundwater vulnerability assessment is needed to enhance cross-site comparability and to support evidence-based management of coastal groundwater resources. The outcomes of this review will support the systematic identification of eligible parameters and the definition of their relative weighting within vulnerability assessment methodologies.

6. Conclusions

The proposed critical review is a comprehensive analysis of groundwater vulnerability assessment methods using overlay indices to represent salinization processes of coastal aquifers, with an emphasis on the parameters (and weights) chosen to perform the assessment. The analysis revealed that:

- The original GALDIT parameters have been applied most frequently to assess groundwater vulnerability to salinization in coastal aquifers, while recharge and surface slope have been the most used parameters among the new ones.
- Considering the calculated weights within all GALDIT applications it is evident how the original weights align with the Mdn value calculated considering all studies (group 1) and only studies with validation (group 2). Slight differences appear when considering only optimized methodology since the availability of chemical data along with the specific site conditions are responsible for some change in weight, always considering the Mdn value (group 3).
- The statistical analysis of the original GALDIT parameters indicated that “groundwater occurrence” and “impact of existing SWI” have the least influence on assessing the vulnerability of coastal aquifers due to some clear limitation of the used indices.
- Rather than the distance from the shoreline, the distance from saltwater (whether it is hosted in the sea, in coastal lagoons, in river mouths) could provide a better representation of the salinization of coastal aquifers. In addition, the recharge and the hydraulic gradient also proved to be key parameters in mapping groundwater vulnerability of coastal aquifers.

The results of this systematic review provided a deeper understanding of salinity-related vulnerability of groundwater systems. Moreover, this study not only offered a detailed analysis of past research but also suggested valuable subjects for future studies, which could contribute to better management strategies of groundwater resources hosted in coastal aquifers.

CRediT authorship contribution statement

Mojgan Bordbar: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Gianluigi Busico:** Conceptualization, Data curation, Investigation, Validation, Writing – original draft, Writing – review & editing. **Nebojsa Jovanovic:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Beata Jaworska-Szulc:** Formal analysis, Writing – review & editing. **Simona Castaldi:** Writing – review & editing. **Konstantinos Chalikakis:** Writing – review & editing. **Ricardo Hirata:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsd.2026.101626.

Data availability

Data will be made available on request.

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