UNIVERSITY OF SZEGED

FACULTY OF SCIENCE AND INFORMATICS
DOCTORAL SCHOOL OF ENVIRONMENTAL SCIENCES

DEPARTMENT OF PHYSICAL AND ENVIRONMENTAL GEOGRAPHY

ASSESSMENT OF GROUNDWATER VULNERABILITY FOR SUSTAINABLE WATER RESOURCE MANAGEMENT IN SOUTHEAST HUNGARY: A COMPARATIVE ANALYSIS OF METHODOLOGICAL APPROACHES

Ph.D. Thesis

FANNAKH, Abdelouahed

Supervisors:

Dr. Barta Károly

Prof. Dr. Farsang Andrea†

Szeged

2025

1 Introduction and Aims

Groundwater represents the world's largest accessible freshwater resource and sustains over half of the global population for both economic activities and daily survival. However, as global populations increase and anthropogenic activities intensify, groundwater faces significant threats from depletion and pollution, with clear detrimental effect. These challenges are compounded by the potential long-term impacts of climate change, which threaten to exacerbate these negative trends further. On top of that, aquifers in every part of the world receive today, the relentless discharge of waste and industrial effluents is overwhelming the natural purification capacities of the ecosystems, leading to the accumulation of pollutants deep within aquifers. Additionally, the widespread reliance on tube wells significantly contributes to groundwater contamination.

In the context of Southeast Hungary, which forms a part of the Great Hungarian Plain, groundwater plays an indispensable role in supporting agricultural productivity, domestic water supply, and various industrial activities, the region is characterized by its flat and fertile plains that are predominantly utilized for agriculture. This sector forms the economic cornerstone of the area, encompassing over 65% of the land dedicated to cultivating crops such as maize, sunflowers, wheat, onions, and various fruits. These agricultural activities heavily depend on groundwater for irrigation, consuming approximately 4.9 million cubic meters annually. The prevalent and intensive use of fertilizers and pesticides associated with these agricultural practices poses significant risks to the groundwater quality. Furthermore, the region is susceptible to severe and prolonged droughts, further exacerbating challenges related to groundwater depletion and influencing the dynamics of the groundwater table. These cumulative threats necessitate urgent and comprehensive groundwater vulnerability assessments, particularly to leaching contaminant from surface to subsurface. Understanding the specific vulnerabilities of aquifers is essential for crafting strategies that adeptly balance current developmental imperatives with the imperative of future resource sustainability.

While prior studies have focused on general groundwater quality and quantity in Southeast Hungary, there remains a significant gap in comprehensive, method-specific vulnerability assessments within this specific region. Previous studies, such as those by Pinke et al. (2020) on the sensitivity of wheat and maize yields to variations in groundwater levels, Gribovszki et al. (2017) on the impact of surface covers on groundwater uptake, and Barreto et al., (2017) on groundwater quality and quantity assessments, have provided foundational insights. However, these studies have not thoroughly explored the vulnerability of the aquifer system to a wide array of potential contaminants through diverse and comparative methodological frameworks. This gap highlights a critical need for an integrated approach that not only assesses but also compares the effectiveness of various vulnerability assessment methodologies in detailing specific susceptibilities of the region's groundwater system.

To address this gap, the selection of the DRASTIC, GOD, and Susceptibility Index (SI) models was guided by a systematic and comprehensive review of established groundwater vulnerability assessment approaches. This review, which formed the foundation for subsequent methodological enhancements and empirical evaluations, critically analyzed each method's theoretical basis, applicability, advantages, and limitations in different hydrogeological contexts. The review highlighted that DRASTIC is robust due to its comprehensive incorporation of seven hydrogeological parameters, yet it is limited by its reliance on static ratings and omission of anthropogenic influences like land use. Conversely, the GOD method, while simple and practical in data-scarce environments, employs equal parameter weights and omits land use, limiting its sensitivity in complex settings. The Susceptibility Index (SI), in contrast, was highlighted as particularly effective in regions with intensive agricultural activities due to its incorporation of land use parameters, thus effectively addressing human-induced contamination risks. Furthermore, this review underscored the critical role of Geographic Information Systems (GIS) and fuzzy logic integration in enhancing the precision, interpretability, and reliability of these groundwater vulnerability assessments. Accordingly, the present study formulates the following research aims:

(1) Systematically evaluate the effectiveness and suitability of conventional groundwater vulnerability assessment methods (DRASTIC, GOD, SI) within the specific hydrogeological and socio-economic context of Southeast Hungary. This includes examining how these methodologies account for local variations in geology, hydrology, and human impact.

(2) Enhance the traditional DRASTIC model through integration with a Hierarchical Fuzzy Inference System (FIS), to address uncertainties inherent in the input parameters. This enhancement aims to provide a more accurate and nuanced assessment of groundwater vulnerability.

(3) Conduct a rigorous comparative analysis of groundwater vulnerability assessment methodologies (DRASTIC, GOD, SI, and Fuzzy-enhanced DRASTIC), evaluating their predictive accuracy by correlating model outcomes with observed groundwater contamination indicators, notably nitrate concentrations. Utilize Geographic Information Systems (GIS) to produce spatially explicit vulnerability maps, facilitating clear visualization, robust interpretation, and practical application for groundwater management.

(4) Provide scientifically informed policy recommendations and management strategies to stakeholders, policymakers, and practitioners, supporting decision-making processes aimed at sustainable groundwater resource management. This includes identifying critical areas requiring targeted protective measures and formulating guidelines for sustainable agricultural practices.

(5) Contribute to the scientific literature on groundwater vulnerability by providing insights into the application and modification of assessment methods in a specific regional context, thus offering a pathway for future research and methodology refinement.

To achieve these aims, the following research questions have been formulated:

- *What are the strengths and limitations of established groundwater vulnerability assessment methods (DRASTIC, GOD, SI) when applied to the hydrogeological context of Southeast Hungary?*
- *How effectively does the integration of fuzzy logic into the traditional DRASTIC method reduce uncertainties and improve the reliability of groundwater vulnerability assessments?*
- *Which groundwater vulnerability assessment methodology (DRASTIC, GOD, SI, or Fuzzy-enhanced DRASTIC) provides the highest predictive accuracy in correlation with observed nitrate contamination levels?*
- *What are the critical hydrogeological parameters influencing groundwater vulnerability in the region?*
- *How can the research outcomes inform sustainable groundwater management practices and policy frameworks specifically tailored to Southeast Hungary?*

Ultimately, the findings from this research will provide crucial information for stakeholders, policymakers, and scientists, enabling them to better understand the specific vulnerabilities of

Southeast Hungary's shallow aquifer. Such knowledge is crucial for developing strategic measures that effectively balance the needs of current agricultural and industrial activities with the long-term sustainability of groundwater resources. This research, therefore, provides essential information that will aid in the formulation of informed, strategic decisions aimed at protecting and managing the groundwater system more sustainably.

2 Methodology

2.1 Study area characterization

The area featured in this study located in Southeast Hungary, specifically between coordinates 46°20′–47°00′ N and 20°00′–21°00′ E, forming part of the Great Hungarian Plain (Alföld) (Fig. 1). It spans an area of approximately 8,690 km² and is characterized by a predominantly flat and fertile plain with an average elevation of around 100 meters above Baltic Sea level (MASL). The region's low-relief topography, generally under 2%, exerts a strong influence on surface water flow and land-use practices, which are overwhelmingly dominated by agriculture.

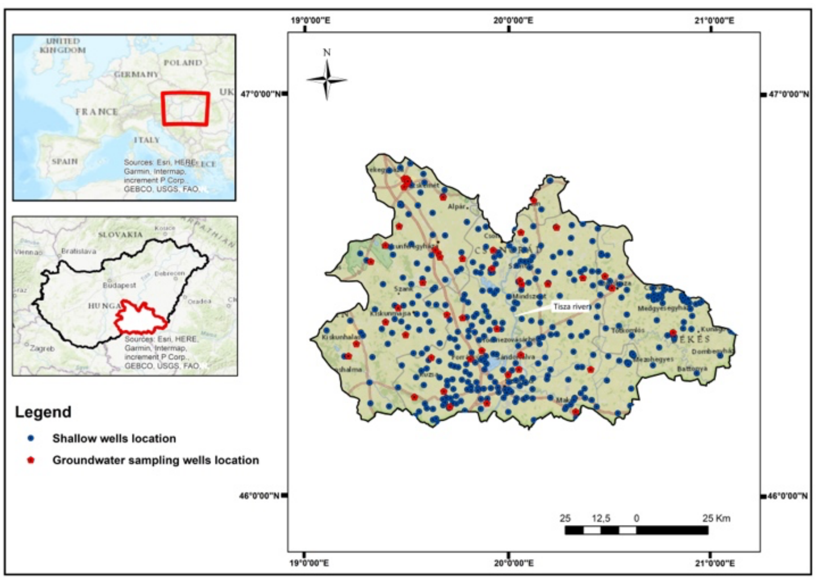

Figure 1. Location of the study area

The climate of the region is characterized as arid continental, heavily influenced by both dry continental and mediterranean air masses, resulting in marked temperature extremes and notably limited precipitation, positioning the region near the threshold of sub-humid conditions(Climate - HungaroMet, n.d.) (Mezősi, 2017). Long-term climate data from 1991 to 2020 indicate that the average annual temperature ranges between 10.5 °C and 11.5 °C, with localized southern areas occasionally exceeding 11.5 °C. Mean annual precipitation is among the lowest in Hungary, averaging between 500 and 550 mm (HungaroMet, n.d.). The Tisza River, Hungary's second-largest watercourse, bisects the region and serves as a hydrogeological boundary separating two dominant soil types: loose sandy soils to the west and finer-textured soils to the east. Along the riverbanks, the predominant soil types are clay and clay loam, which have low permeability, resulting in minimal infiltration. To the west, the terrain is primarily sandy with patches of sandy loam and loam, and the southeastern section is largely composed of loam interspersed with clay loam (European Soils Bureau Network, 2005; Farsang et al., 2017).

From an environmental perspective, the selected study area faces the dual pressures of water scarcity and contamination risk. It is particularly prone to severe, prolonged droughts, which exacerbate groundwater depletion and significantly affect groundwater table dynamics, influencing both the quantity and quality of groundwater (Rossi et al., 2023; Szöllősi-Nagy, 2022). The extensive use of nitrogen-based fertilizers has led to elevated nitrate concentrations in groundwater, raising serious concerns about contamination. As such, the region presents a clear case for the necessity of targeted aquifer vulnerability assessments that consider both hydrogeological variability and human-induced stressors. These assessments are critical for identifying zones at risk, as well as addressing the socio-economic demands of the region, ensuring a balanced approach to environmental sustainability and agricultural efficiency.

2.2 Methodologies for groundwater vulnerability assessment

Figure 2 illustrates the methodological workflow adopted to evaluate the selected methodologies for groundwater vulnerability assessment, including the standard DRASTIC, GOD, SI, and Fuzzy-enhanced DRASTIC model.

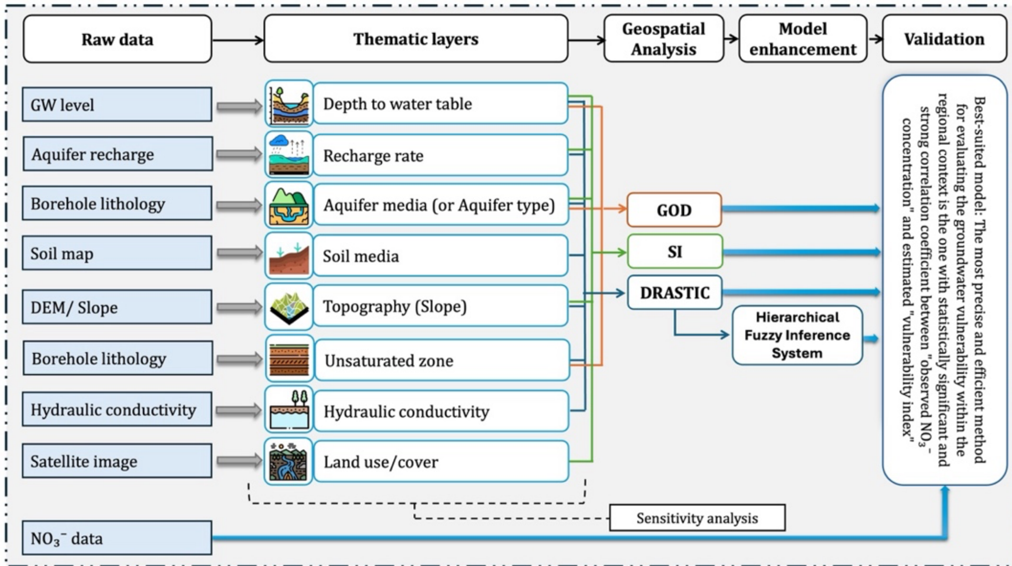

Figure 2. Methodological workflow for groundwater vulnerability analysis (GW: groundwater; DEM: Digital Elevation Model)

Each method represents a different approach to assessing vulnerability—ranging from the intrinsic, parameter-weighted frameworks of DRASTIC and SI, to the simplified parametric classification of the GOD method, and finally to the advanced Fuzzy-enhanced DRASTIC model, which addresses uncertainties associated with conventional rating systems. The selected models rely on the spatial integration of multiple thematic layers and the subjective assignment of weights and ratings based on hydrogeological significance. ArcGIS Spatial Analyst was used to process and analyze spatial data for all methods.

2.2. 1 DRASTIC method

The DRASTIC method, developed by the U.S. Environmental Protection Agency (Aller et al., 1987), assesses groundwater vulnerability through a rating and weighting system. This method involves the integration of seven critical hydrogeological factors that are considered intrinsic to the sensitivity of an aquifer to potential contaminants from the ground surface: Depth to water (D), Recharge rate (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (I), and Hydraulic conductivity (C). Each parameter is assigned a specific weight based on its relative importance in influencing groundwater vulnerability. The final vulnerability index is computed using a weighted linear combination of these parameters (Eq. 1). After calculating the vulnerability index (Vi), areas are identified as more sensitive to groundwater contamination compared with others.

$$Vi = \sum_{i=1}^{7} Wi\, Ri \qquad (1)$$

Wi and Ri weight and rating for the ith parameter, respectively (range of parameters are given by Aller et al., 1987)

2.2. 2 GOD method

The GOD method, developed by Foster (1987), employs a simplified framework focusing on three parameters: Groundwater occurrence (G), which categorizes the type of aquifer based on the degree of confinement; the Overlying lithological characteristics (O), referring to the properties of the vadose zone; and the Depth to the groundwater table (D). No weighting is applied to the parameters, as they are considered to have equal influence on aquifer vulnerability. The GOD vulnerability index (I_{vGOD}) is then calculated by multiplying the ratings of these three parameters (Eq. 2).

$$I_{vGOD} = G_R \times O_R \times D_R \qquad (2)$$

R = rating of parameters

2.2. 3 Susceptibility Index (SI) model

In Portugal, Ribeiro, (2000) introduced the SI as a specialized approach to assess groundwater vulnerability to vertical agricultural contamination, particularly with regard to nitrate and pesticides, is applied within the Southeast Hungary context to address the significant impacts of agricultural activities. The SI method considers five parameters: including: Depth to water (D), Recharge rate (R), Aquifer media (A), Topography (T), and land use/cover (LU/LC). The SI vulnerability index (IvSI) is computed by linearly combining the scores and weights of the five parameters represented by the equation 3.

$$I_{vSI} = D_nD_p + R_nR_p + A_nA_p + T_nT_p + LU_nLU_p$$

n = rating value for each parameter, p = weighting factor assigned to each parameter

2.2. 4 Fuzzy-enhanced DRASTIC approach

In addressing the limitations of static parameter ratings inherent in traditional method, this study advances the integration of a hierarchical Fuzzy Inference System (FIS) with the established DRASTIC model, thus creating a Fuzzy-enhanced DRASTIC approach. The enhanced methodology maintains the conventional DRASTIC weighting factors to preserve the model's original structure and ensure comparability with previous studies. This hybrid approach combines the strengths of the DRASTIC framework with the flexibility of fuzzy logic, providing a more refined vulnerability index without altering the fundamental principles of the original method.

This methodology incorporates a hierarchical structure composed of multi-level fuzzy inference system arranged sequentially, that processes inputs through a series of interconnected layers. The hierarchical structure organizes the DRASTIC parameters into six fuzzy inference systems (FISs), (FIS1 through FIS6), with the output of one level serving as the input of the next. For example, the parameters depth to the water table (D) and recharge rate (R) are combined to establish the first level of the hierarchy. The results of this level are then integrated with the aquifer media (A) parameter to form the second level, and this process continues sequentially.

In the application of this refined methodology, MATLAB R 2019 is utilized to develop the FIS. During fuzzification parametric values are converted into linguistic variables and assigns them trapezoidal membership functions MFs. The following phase entails constructing the conditional segment by establishing a rule that links the input parameters with the outputs analyzed by the inference engine. The Mamdani inference engine is selected in this study due to its superior capability to handle human inputs and its highly interpretable results. This engine operates on IF–THEN rules, integrating OR/AND operators to connect the input and output parameters. The final step in this process is translating the fuzzy output values back into precise real-world values.

2.2. 5 Validation and sensitivity analyses

i. Correlation analysis

In this study, nitrate (NO_3^-) concentrations were used as the primary contaminant for validation. Given its generally low natural presence in groundwater, elevated levels of nitrate often signify contamination from agricultural fertilizers or wastewater, making it a reliable indicator of anthropogenic influence (Karimzadeh Motlagh et al., 2023). A total of 46 agricultural wells were selected to assess the spatial distribution of nitrate (NO_3^-) concentrations across the study area (Fig. 1).

To evaluate the effectiveness and accuracy of the DRASTIC, GOD, Susceptibility Index (SI), and Fuzzy-enhanced DRASTIC models, a dual correlation analysis was conducted using Pearson correlation analysis and Spearman's rho correlation, performed with SPSS (Statistical Package for the Social Sciences) version 19.0. This approach is particularly suitable for environmental data, which often exhibit non-normal distributions and may contain outliers, common in studies involving natural variables (Agossou and Yang, 2021).

This dual analytical approach allows for a comprehensive evaluation of each model's accuracy in predicting groundwater vulnerability, highlighting the proportion of variance in nitrate concentrations explained by the vulnerability indices. The integration of these statistical techniques ensures a robust evaluation of the methods' effectiveness, reinforcing their utility in discerning groundwater vulnerability dynamics in Southeast Hungary, offering a reliable foundation for sustainable groundwater management strategies.

ii. Single-Parameter Sensitivity Analysis (SPSA)

Evaluating the robustness and reliability of groundwater vulnerability models requires understanding the extent to which each parameter influences the final vulnerability assessments. To address this, the present study applied Single-Parameter Sensitivity Analysis (SPSA) to identify critical parameters within the DRASTIC, Susceptibility Index (SI), and Fuzzy-enhanced DRASTIC models. While the GOD method assigns equal weighting to its parameters, the differential impact of individual parameters on the model's output is inherently assumed to be uniform (Foster, 1987).

The sensitivity of each parameter is quantified using a sensitivity index, which measures the change in the vulnerability index relative to the change in the parameter values. This approach quantitatively assesses each parameter's contribution to the model's output, identifying those with significant impacts on the final vulnerability assessment (Singha et al., 2019; Torkashvand et al., 2023). Specifically, the SPSA analysis compares the theoretical weight (assigned by the model) with the effective weight (calculated based on the parameter's actual impact) (Napolitano and Fabbri, 1996).

The effective weight (W) of each parameter is computed using the following equation:

$$W = \left(\frac{\mathrm{Pr} \times \mathrm{Pw}}{\mathrm{V}}\right) \times 100 \qquad (4)$$

Where:

- W: effective weight of the parameter,
- Pr: rating value of the parameter,
- Pw: theoretical weight of the parameter, and

- V: overall vulnerability index.

3 Results and theses

1) I have identified the main "hotspots" of groundwater contamination risk in Southeast Hungary and the key contributing factors

This research precisely identified the key groundwater contamination "hotspots" in Southeast Hungary through the integrated application of four groundwater vulnerability assessment models—DRASTIC, GOD, SI, and Fuzzy-enhanced DRASTIC. While approximately 95% of the study area was classified as moderately to highly vulnerable, underscoring the pervasive susceptibility of shallow groundwater resources to contamination. Special attention was directed toward areas consistently marked as highly vulnerable across all models. The SI method indicated that 77% of the region is highly vulnerable, followed by the fuzzy-enhanced DRASTIC model (64%), GOD (45%), and conventional DRASTIC (33%). These high-risk zones across models are largely attributable to regional factors such as shallow groundwater table, high recharge rates, presence of sandy sediments, the region's gentle slope and the predominance of high agricultural activity areas in land use. These factors collectively enhance the susceptibility of groundwater to contamination from surface pollutants. Despite this general trend, notable differences in the extent and distribution of high-vulnerability zones emerged among the models, driven by differences in parameter influence observed through Single-Parameter Sensitivity Analysis (SPSA). These findings emphasize the necessity for spatially targeted and model-informed groundwater protection strategies, particularly in agriculturally dominant regions of Southeast Hungary. Establishment of a robust dual correlation validation framework.

2) The methodological comparison of four vulnerability models confirms the superior predictive accuracy of the Susceptibility Index (SI)

This research conducted a comprehensive comparative evaluation of four groundwater vulnerability assessment models: DRASTIC, GOD, Susceptibility Index (SI), and Fuzzy-enhanced DRASTIC, within the Southeast Hungary. By validating the spatial outputs of each model against measured nitrate (NO_3^-) concentrations from 46 groundwater monitoring wells, the study demonstrated marked differences in predictive performance. The Susceptibility Index (SI) outperformed all other approaches, classifying 77% of the study area as highly vulnerable and achieved the strongest statistical correlation with observed nitrate concentrations (Pearson's $r = 0.751$; Spearman's $\rho = 0.812$), underscoring its superior predictive capability in assessing contamination risk. The enhanced accuracy of the SI method is attributed primarily to its inclusion of land use/cove as a key parameter, effectively capturing direct anthropogenic impacts on groundwater quality. This inclusion facilitated the transition from intrinsic vulnerability assessment—focusing only on natural hydrogeological conditions—to a more comprehensive specific vulnerability assessment that integrates human activities, notably agricultural practices. The Single-Parameter Sensitivity Analysis (SPSA) further supported these results, revealing that aquifer media (24.19%), land use (22.87%), and depth to water table (22.15%) were the most influential factors in the SI model. These parameters closely align with the actual drivers of nitrate pollution observed in the region. In contrast, the DRASTIC models' and GOD approach exclusion of land use limited their ability to predict contamination in agricultural regions. This outcome underscores the essential role of anthropogenic considerations in accurately predicting groundwater contamination, particularly nitrate pollution in agriculturally intensive regions.

3) Advancement of intrinsic groundwater vulnerability assessment through the development and comparative evaluation of a Fuzzy-Enhanced DRASTIC Model

This research significantly advanced the assessment of intrinsic groundwater vulnerability in Southeast Hungary by developing and evaluating a Fuzzy-Enhanced DRASTIC model and comparing its performance to the conventional DRASTIC method. The conventional DRASTIC model, which integrates seven key hydrogeological parameters (depth to water table, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity) within a GIS-based weighted overlay framework, the model delineated the study area into distinct zones of low, moderate, and high vulnerability, with a predominant trend of moderate to high vulnerability, covering 5241 km² (60.32%) and 2909 km² (33.48%) of the total study area, respectively. These areas typically feature shallow water table, presence of sandy sediment composition, and high recharge rates, all of which contribute to increased vulnerability. Single-Parameter Sensitivity Analysis (SPSA) confirmed that the depth to water table and impact of the vadose zone were the most influential parameters, with effective weights of 29.56% and 21.08%, respectively. However, while the model demonstrated moderately strong correlation with observed nitrate concentrations (Pearson's $r = 0.601$; Spearman's $\rho = 0.602$), its use of fixed parameter ratings limited its predictive accuracy.

To address this limitation, a Fuzzy-Enhanced DRASTIC model was developed using a Hierarchical Fuzzy Inference System (FIS), replacing rigid parameter ratings with continuous fuzzy membership functions. This allowed for more nuanced representation of hydrogeological variability while retaining the original parameter structure and weights for comparability. The fuzzy model demonstrated superior performance, delineating 64% of the area as highly vulnerable and achieving improved correlations with nitrate concentrations (Pearson's r = 0.690; Spearman's ρ = 0.675). SPSA results also revealed a shift in parameter influence, with increased sensitivity to aquifer media (15.21%) and a more balanced distribution of effective weights, underscoring the enhanced capacity of the fuzzy model to capture lithological variability. These findings highlight the methodological value of integrating fuzzy logic into established index-overlay models, enhancing the reliability and spatial accuracy of vulnerability assessments in complex hydrogeological settings.

4) **Identification of limitations in the GOD method for complex agricultural regions**

This research critically evaluated the performance and methodological constraints of the GOD vulnerability assessment method in the context of Southeast Hungary, an area characterized by intensive agricultural activity and hydrogeological complexity. The GOD method, while recognized for its simplicity and rapid applicability, demonstrated comparatively lower predictive accuracy (Pearson's r = 0.592; Spearman's ρ = 0.583). This reduced effectiveness is largely attributable to the method's equal weighting of parameters: groundwater occurrence, overlying lithology, and depth to groundwater, which limits its sensitivity to critical variations in hydrogeological factors. Moreover, the GOD method omits land use/cover as a parameter, a key anthropogenic driver of contamination risk in agricultural landscapes. The research thus emphasizes that although GOD is practical for preliminary or broad-scale assessments, it may not reliably capture subtle vulnerability distinctions essential for precise management and remediation strategies in agriculturally intensive regions.

5) **Quantitative identification of influential parameters through Single-Parameter Sensitivity Analysis (SPSA)**

This thesis significantly advanced the understanding of groundwater vulnerability modeling by employing a comprehensive Single-Parameter Sensitivity Analysis (SPSA) across the DRASTIC, SI, and Fuzzy-enhanced DRASTIC models. By comparing theoretical weights with effective weights, SPSA enabled a quantitative evaluation of each parameter's relative influence on the final vulnerability indices. The analysis revealed that the parameters "depth to water table (D)," "impact of the vadose zone (I)," "aquifer recharge (R)," and "aquifer media (A)" exerted the most significant influence across the models, with "land use/land cover (LU/LC)" emerging as a particularly critical parameter in the SI model. These findings underscore the limitations of conventional, uniform weighting schemes, as seen in the GOD method. Recognizing these parameters' critical roles will informs targeted data collection, future model refinement, and practical groundwater management decisions. This precise identification of influential parameters significantly advances methodological rigor and practical applicability in vulnerability assessment research.

6) Establishment of a robust dual correlation validation framework

This research introduced and operationalized a dual correlation validation framework combining Pearson's and Spearman’s correlation analyses to evaluate the predictive performance of four groundwater vulnerability assessment models (DRASTIC, GOD, SI, and Fuzzy-enhanced DRASTIC) against nitrate concentrations from 46 agricultural wells. The dual approach enabled the assessment of both linear and monotonic relationships between computed vulnerability indices and observed nitrate levels. While Pearson’s correlation tested the models' performance under assumptions of linearity and normal distribution, Spearman’s rho accounted for non-parametric data trends and potential outliers, offering complementary insights. The results revealed that the SI and Fuzzy-enhanced DRASTIC models exhibited the strongest correlations with observed nitrate concentrations, underscoring the importance of integrating anthropogenic factors, such as land use/cover, and advanced modeling techniques, including fuzzy logic, into groundwater vulnerability assessments. Nevertheless, the nitrate dataset, though geographically representative, is based on a limited number of sampling points (n = 46), this sampling density may not fully capture the spatial variability in contamination levels, particularly in a heterogeneous aquifer system. Additionally, correlation does not confirm causality, and nitrate levels may be temporally and spatially variable due to complex hydrogeological or anthropogenic factors not fully captured by the models.

4 A doktori értekezés magyar nyelvű összefoglalása

A felszín alatti vizek kiemelt jelentőségű erőforrást jelentenek Délkelet-Magyarországon, elsősorban az ivóvízellátás, az ipari vízhasználat és különösen a mezőgazdaság szempontjából. Az alföldi termékeny táj intenzív mezőgazdasági művelést tesz lehetővé – a térség több mint 65%-át szántóföldi növénytermesztésre (kukorica, napraforgó, búza) használják, ami jelentős műtrágya- és növényvédőszer-felhasználással jár. E mezőgazdasági gyakorlatok, valamint a térségre jellemző súlyos és hosszan tartó aszályok együtt komoly veszélyt jelentenek a felszín alatti vízkészlet mennyiségére és minőségére egyaránt. Ennek következtében a térség vízadó rétegeit folyamatos szennyezési és túlhasználati kockázat fenyegeti. Bár korábbi kutatások foglalkoztak a régió vízminőségi és vízmennyiségi problémáival, átfogó, módszertani összehasonlításon alapuló sérülékenységi értékelés nem állt rendelkezésre.

A jelen doktori kutatás ezt a hiányt kívánja pótolni azáltal, hogy több különböző értékelési módszer (DRASTIC, GOD, Susceptibility Index – SI –, valamint a fuzzy logikával bővített DRASTIC) összehasonlító elemzésével átfogó felszín alatti víz sérülékenységi értékelést végez Délkelet-Magyarországon. A kutatás elsődleges célja a legmegfelelőbb módszer azonosítása a sérülékenységi mintázatok feltárására, valamint olyan tudományosan megalapozott eszköztár előállítása, amely támogatja a fenntartható vízgazdálkodást, területrendezést és szakpolitikai döntéshozatalt.

A dolgozat első lépésben áttekinti a felszín alatti víz sérülékenységének értékelésére szolgáló leggyakoribb módszereket, kitérve azok elméleti alapjaira, térbeli modellezési technikáira, valamint gyakorlati alkalmazási korlátaira. E szakirodalmi alapozás alapján három hagyományos index-overlay típusú modellt (DRASTIC, GOD, SI), illetve egy fuzzy logikával továbbfejlesztett DRASTIC modellt választottam ki a vizsgálathoz. A klasszikus DRASTIC modell hét hidrológiai-paramétert – talajvízmélység, utánpótlódási ráta, vízadó kőzet típusa, talajtípus, lejtés, telítetlen zóna jellemzői és hidraulikus vezetőképesség – integrál súlyozott pontozási rendszerben. Az így kapott DRASTIC index alapján térben explicit sérülékenységi térkép hozható létre. A GOD modell ezzel szemben leegyszerűsíti a folyamatot, csupán három paraméterrel számol (víztartó előfordulása, fedőréteg litológiája, vízszintmélység), és azok egyenlő súlyozását feltételezi, ezáltal könnyebb alkalmazhatóságot, de korlátozott rugalmasságot kínál. Az SI módszer újszerűsége a földhasználat bevonásában rejlik, így nemcsak a természeti, hanem az antropogén tényezők is megjelennek az értékelésben.

A módszertani korlátok leküzdése érdekében egy fuzzy logikán alapuló, hierarchikus Fuzzy Inference System (FIS) alkalmazásával továbbfejlesztett DRASTIC modellt dolgoztam ki. Az eredeti paraméterek és súlyok megtartása mellett a diszkrét pontszámokat folytonos fuzzy tagsági függvényekkel helyettesítettem, lehetővé téve a folyamatos átmenetek pontosabb leképezését a sérülékenységi indexben. Mind a négy modellt ugyanazon vizsgálati területen alkalmaztam, a bemeneti adatok tematikus GIS rétegek formájában kerültek feldolgozásra. A modellek érvényességét 46 mezőgazdasági terület alatti talajvízből származó nitrátkoncentrációs adatokkal (2022 novembere – 2023 áprilisa között) teszteltem. Az összefüggések kvantifikálásához Pearson- és Spearman-féle korrelációs elemzést, továbbá egyparaméteres érzékenységvizsgálatot (SPSA) is végeztem a DRASTIC, SI és fuzzy-DRASTIC modellek esetén.

Az eredmények jelentős térbeli változékonyságot mutattak ki a régió sérülékenységében, a közepes és magas kategóriák dominanciájával. E tendencia a sekély talajvízszint, a homokos üledékek jelenléte, a magas utánpótlódási ráta, valamint a domináns mezőgazdasági földhasználat együttes hatásának tudható be. Ugyanakkor a magas sérülékenységű zónák kiterjedése jelentősen eltért az egyes modellek között, amit az SPSA eredmények által feltárt paraméterérzékenység magyaráz. A klasszikus DRASTIC modell a terület ~33%-át sorolta a magas sérülékenységi kategóriába (Pearson $r = 0{,}601$; Spearman $\rho = 0{,}602$). A GOD modell hasonlóan ~45%-ot jelölt ki, de a leggyengébb korrelációs értékekkel ($r = 0{,}592$; $\rho = 0{,}583$). Ezzel szemben a földhasználatot is figyelembe vevő SI modell a legnagyobb prediktív teljesítményt nyújtotta ($r = 0{,}751$; $\rho = 0{,}812$), a terület ~77%-át jelölve magas sérülékenységűként. A fuzzy-DRASTIC modell szintén kedvező eredményeket mutatott ($r = 0{,}690$; $\rho = 0{,}675$), a paraméterértékelések finomításának köszönhetően. Az eredmények egyértelműen alátámasztják, hogy az antropogén hatások (különösen a földhasználat) és a fejlettebb modellezési módszerek (pl. fuzzy logika) integrálása jelentősen növeli a sérülékenységi értékelések pontosságát.

Az SPSA vizsgálatok további betekintést nyújtottak a paraméterek hatékonyságába. A DRASTIC modellben a vízmélység (29,56%) és a telítetlen zóna jellemzői (21,08%) voltak a legmeghatározóbb tényezők, míg a fuzzy változatban az utánpótlódás szerepe csökkent, a víztartó réteg fontossága nőtt (15,21%). Az SI modellben a vízmélység, a víztartó és a földhasználat közel azonos súllyal járultak hozzá az indexhez (~22–24%). A GOD modell paramétereinek egyenlő súlyozása ugyan egyszerűsíti az alkalmazást, de a hidrogeológiai különbségek hatását nem képes megfelelően leképezni, ezáltal pontatlanságokat eredményezhet.

Ez a kutatás tehát elméleti és gyakorlati szinten is hozzájárul a felszín alatti víz sérülékenységi értékelések továbbfejlesztéséhez. Rámutat a regionális sajátosságokhoz igazított, rugalmas, antropogén tényezőket is figyelembe vevő módszerek fontosságára. A kutatás eredményei gyakorlati eszközként szolgálnak a fenntartható vízgazdálkodás, területrendezés, monitoringhálózatok kialakítása és szabályozási beavatkozások tervezése terén. A magas kockázatú területek azonosításával lehetőség nyílik a beavatkozások priorizálására, a földhasználati gyakorlatok optimalizálására és a hosszú távú vízbázis-védelem megerősítésére. A dolgozat javasolja, hogy az eredmények épüljenek be a szakpolitikai és területi tervezési dokumentumokba, különösen a földhasználati szabályozás és az érintettek bevonása révén. A kutatás jövőbeli irányokat is kijelöl: (1) nagyfelbontású távérzékelt adatok integrálása a földhasználat, talajtípusok és utánpótlódás pontosabb térképezésére; (2) a nitrát-adatsor térbeli és időbeli kiterjesztése a validációs megbízhatóság növelése érdekében; (3) gépi tanulási módszerek (pl. neurális hálók, SVM, random forest) alkalmazása paraméter-súlyozás optimalizálására; (4) hosszú távú vizsgálatok lefolytatása a földhasználat és klímaváltozás hatásainak nyomon követésére; valamint (5) numerikus áramlás- és transzportmodellek (MODFLOW, MT3DMS) bevonása a szennyeződés terjedésének pontosabb leírására.

Publications related to the scientific topic of the dissertation

Hungarian Scientific Bibliography (MTMT) identifier: 10081888

1) **Fannakh, A.,** Farsang, A. DRASTIC, GOD, and SI approaches for assessing groundwater vulnerability to pollution: a review. Environ Sci Eur 34, 77 (2022). https://doi.org/10.1186/s12302-022-00646-8

   IF_{2024} = 6.0

2) **Fannakh, A.,** Károly, B., Farsang, A. et al. Evaluation of index-overlay methods for assessing shallow groundwater vulnerability in southeast Hungary. Appl Water Sci 15, 118 (2025). https://doi.org/10.1007/s13201-025-02463-9

   IF_{2024} = 5.7

3) **Fannakh, A.,** Károly, B., Fannakh, M., & Farsang, A. (2025). Assessment and Validation of Shallow Groundwater Vulnerability to Contamination Based on Fuzzy Logic and DRASTIC Method for Sustainable Groundwater Management in Southeast Hungary. Water, 17(5), 739, https://doi.org/10.3390/w17050739

   IF_{2024} = 3.0

Conference Lectures and Posters

Lecture:

1) **Abdelouahed Fannakh**, Barta Károly, Mhamed Fannakh, *Assessment and Validation of Shallow Groundwater Vulnerability to Contamination Based on Fuzzy Logic and DRASTIC Method for Sustainable Groundwater Management, Southeast Hungary*
   IAH World Groundwater Congress
   8th - 13th September 2024, Davos, Switzerland

2) **Fannakh Abdelouahed,** Barta Károly, Farsang Andrea
   Evaluation of shallow groundwater vulnerability to pollution using three different methods - Application to the shallow aquifer of Southeastern Hungary
   18th Carpathian Basin Conference for Environmental Science
   17th - 19th May 2023, Szeged, Hungary

3) **Abdelouahed Fannakh,** Andrea Farsang†,
   GIS-Based DRASTIC Method for Assessing the Vulnerability of Shallow Groundwater to Pollution - Application to the Shallow Aquifer of Southeast Hungary
   Mediterranean Geosciences Union Annual Meeting (MedGU-22),
   27th – 30th November 2022, Marrakech, Morocco

Posters:

1) **Abdelouahed Fannakh,** Barta Károly, Andrea Farsang†,
   Comparative evaluation of index-overlay models for mapping the vulnerability of shallow groundwater to pollution in southeast Hungary
   International Riverbank Filtration Conference,
   16th – 18th October 2023, Dresden, Germany.

2) **Fannakh Abdelouahed,** Farsang Andrea†,
   DRASTIC versus SI methods for assessing groundwater vulnerability to agricultural pollution: A systematic comparison
   25. Spring Wind Conference – 2022
   May 6-8, 2022, Pécs, Hungary.

Co-authors' waivers

I, Dr. Károly Barta, as co-author of the publications entitled *"Assessment and Validation of Shallow Groundwater Vulnerability to Contamination Based on Fuzzy Logic and DRASTIC Method for Sustainable Groundwater Management in Southeast Hungary"* (published in *Water, MDPI, 2025*) and *"Evaluation of Index-Overlay Methods for Assessing Shallow Groundwater Vulnerability in Southeast Hungary"* (published in *Applied Water Science, 2025*), hereby officially declare that the results jointly published in these works are substantially and primarily contributed by the doctoral candidate, Abdelouahed Fannakh. Furthermore, I confirm that these results have not been and will not be used, either in the past or in the future, by myself or any other co-author for the purpose of acquiring an academic degree or title.

Date: 09/09/2025

Name and signature of co-author:

Károly Barta

Co-authors' waivers

I, Dr. Fannakh Mhamed, as co-author of the publication entitled " Assessment and Validation of Shallow Groundwater Vulnerability to Contamination Based on Fuzzy Logic and DRASTIC Method for Sustainable Groundwater Management in Southeast Hungary" published in the journal " Water, MDPI" officially declare that the jointly published results in the thesis and the publication are greatly contributed by the candidate and was not or will not be used in the past or in the future, respectively, for the purpose of acquiring an academic degree or title.

Date: 09/09/2025

FANNAKH Mhamed

Co-authors' waivers

I, Dr. Ben Ali Mohammed, as co-author of the publication entitled " Evaluation of index-overlay methods for assessing shallow groundwater vulnerability in southeast Hungary" published in the journal " Applied Water Science " officially declare that the jointly published results in the thesis and the publication are greatly contributed by the candidate and was not or will not be used in the past or in the future, respectively, for the purpose of acquiring an academic degree or title.

Date: 09/09/2025

Name and signature of co-author: Dr. Ben Ali Mohammed