Shahrood University of Technology

Journal of Hydraulic and Water Engineering (JHWE)

Journal homepage: https://jhwe.shahroodut.ac.ir

Iranian Hydraulic Association (IHA)

Assessment of Vulnerability in the Gonabad Plain using the DRASTIC Model

Habib Lotfi [1*], Samad Emamgholizadeh [1], Sina Khoshnevisan[1], Mohammadreza Asli charandabi[1]

[1] Department of Water and Environmental Engineering, Faculty of Civil Engineering, Shahrood University of Technology, Iran.

Article Info

Article history:
Received 27 May 2025
Received in revised form 16 October 2025
Accepted 15 October 2025
Published online 18 October 2025

DOI:
10.22044/jhwe.2025.16316.1067

Keywords
Groundwater
Vulnerability
Pollution potential
Gonabad Plain
DRASTIC

Abstract

Groundwater serves as a vital resource for agricultural, domestic, and industrial purposes, particularly in arid and semi-arid regions. The increasing pressure on groundwater resources, driven by population growth, climate change, and overexploitation, has rendered them increasingly susceptible to contamination from anthropogenic activities. Excessive use of chemical fertilizers in agriculture, improper disposal of urban and industrial wastewater, and leakage of pollutants from various sources are among the primary contributors to groundwater pollution. Assessing the vulnerability of these resources is essential for ensuring their quality and sustainability. Using the DRASTIC model, this study evaluates the groundwater vulnerability of the Gonabad Plain, situated in Khorasan Razavi Province, Iran. This model incorporates seven hydrogeological parameters: depth to the water table, net recharge, aquifer media, soil media, topography, unsaturated zone, and hydraulic conductivity. The DRASTIC index calculated for the study area ranges from 63 to 193. According to the results, the pollution risk levels in the region were classified as follows: 0.65% of the area had no pollution risk, 2.06% was categorized as very low risk, 21.67% as low risk, 34.62% as low to moderate risk, 33.52% as moderate to high risk, 6.66% as high risk, 0.8% as very high risk, and 0.006% was identified as thoroughly contaminated areas. The increased vulnerability index observed in the northern parts of the plain can be attributed to factors such as a shallower water table, gentle slopes (less than 2%), and coarse-grained soils in both the aquifer and the unsaturated zone. To validate the vulnerability assessment, nitrate concentration data from wells in the region, collected in 2021, were analyzed. The findings confirmed the accuracy of the DRASTIC model in identifying areas vulnerable to contamination. This study underscores the importance of localized assessments of groundwater vulnerability. It emphasizes the need for targeted management and monitoring strategies in high-risk regions to mitigate pollution and ensure the long-term sustainability of groundwater resources.

1. Introduction

Soil Water has served as the lifeblood of human civilization (Strang, 2015). The emergence of major civilizations, from the Nile Valley to the Roman Empire, was inextricably linked to reliable access to water resources. These ancient societies recognized water not merely as a natural resource but as a cornerstone for agriculture, craftsmanship, and the very fabric of social life (Hosseiny et al., 2021). However, the advent of industrialization ushered in a new era of water consumption (Li et al., 2019). The burgeoning demands of industry placed unprecedented pressure on water resources, exceeding the limits of traditional agricultural and domestic needs. Rapid urbanization and population growth have exacerbated this pressure, transforming once-abundant water sources into increasingly scarce and vulnerable

[*] *Corresponding author: s_gholizadeh517@Shahroodut.ac.ir, Tel: +989111194389*

assets that face the threat of unsustainable exploitation and overuse.

The 20th century witnessed a confluence of challenges, including rapid population growth and the accelerating impacts of climate change, which exerted unprecedented pressure on water resources. Climate change, once an unfamiliar concern, has emerged as a defining global challenge. Rising temperatures, altered precipitation patterns, and intensifying droughts have significantly diminished the reliability of surface water resources, exacerbating water scarcity in many regions. Consequently, groundwater has assumed a critical role in sustaining human societies, particularly in arid and semi-arid regions (Ouedraogo et al., 2018). Globally, groundwater supplies a substantial portion of human water needs, especially in arid regions where water scarcity is often worsened by low and unpredictable rainfall. Groundwater emerges as a lifeline, providing a crucial source for agriculture, drinking water, and industrial activities. Groundwater quality is currently under significant threat from a combination of human activities and climate change (Aslam et al., 2018). Rapid population growth, limited access to alternative water sources, and the overexploitation of groundwater reserves have led to declines in both water quality and groundwater levels in many regions. Furthermore, aquifers worldwide are increasingly vulnerable to contamination from anthropogenic sources. Pollutants such as agricultural runoff, industrial effluents, and improperly disposed waste infiltrate the subsurface through soil absorption. This process, especially prevalent in areas with inadequate waste management practices, allows contaminants to penetrate deeper layers, accumulating within aquifers and posing a significant threat to groundwater quality (Ascott et al., 2017). The removal of pollutants from groundwater is a complex, time-consuming, and costly process. In many cases, contamination is only detected after it becomes nearly impossible to fully eliminate it from the aquifer. Major sources of groundwater pollution include the use of fertilizers and chemical pesticides in agriculture, household and industrial wastewater, and leachate from landfills (Bentekhici et al., 2024; Meegoda et al., 2025). These leachates contain high levels of chemical and organic compounds that, if not properly managed, infiltrate and contaminate groundwater reserves. A study conducted in Chandigarh, India, provides a stark example of this phenomenon. Findings from this research revealed elevated levels of arsenic and heavy metals, such as cadmium and lead, in the local aquifer, primarily attributable to pollution emanating from landfills, industrial activities, and agricultural practices. The presence of these contaminants, particularly in shallow groundwater sources, poses serious health risks to local populations, including increased susceptibility to non-cancerous ailments and various forms of cancer (Ravindra & Mor, 2019). Protecting groundwater resources from contamination is an essential and urgent measure. Preventive actions in this regard are not only simpler but also more cost-effective than attempting to remediate polluted aquifers. The concept of groundwater vulnerability gained prominence in the 1970s as a pivotal topic in hydrological literature. This significance was highlighted by the development of the first groundwater vulnerability map for France by Albinet and Margat in 1970. In 1993, the National Research Council of the United States officially defined groundwater vulnerability as: "The tendency or likelihood for contaminants to reach a specific point in the groundwater system, located above the water table."

Groundwater vulnerability can be broadly categorized into two main types: intrinsic vulnerability and specific vulnerability: a) Intrinsic Vulnerability: This type of vulnerability refers to the inherent environmental characteristics that influence the movement of contaminants toward groundwater resources, without focusing on any particular type of contaminant. It emphasizes natural factors such as geological, hydrological, and hydraulic features (Daly et al., 2002; Vrba & Zaporozec, 1994).

b) Specific Vulnerability: This category assesses vulnerability concerning a particular contaminant or a group of contaminants. It incorporates factors such as biogeochemical processes and their interactions with the components of intrinsic vulnerability (Gogu & Dassargues, 2000; Zwahlen, 2003).

Groundwater constitutes a cornerstone of sustainable development, fulfilling critical demands across sectors, including agriculture, industry, and domestic water supply. This reliance on groundwater becomes particularly pronounced in arid and semi-arid regions characterized by limited surface water availability. Within this context, identifying and mitigating vulnerabilities to groundwater contamination emerges as a paramount challenge for effective water resource management. The DRASTIC model, a widely recognized framework for assessing groundwater vulnerability, provides a robust tool for evaluating the susceptibility of aquifers to contamination. This model, pioneered by Aller et al. (1987), considers a range of hydrogeological parameters to delineate areas of potential vulnerability. Extensive research leveraging the DRASTIC model has significantly advanced our understanding of groundwater vulnerability and informed the development of effective protection strategies.

Fabrizio Rama et al. (2022) conducted a study using the DRASTIC model to assess the intrinsic vulnerability of aquifers in South America. The results of this study indicate that the majority of the continent (approximately 70%) exhibits low to moderate intrinsic vulnerability. Meanwhile, only about 10% of the area falls within the very low vulnerability range, while a small portion (approximately 0.06%) received a DRASTIC score higher than 180 (Rama et al., 2022). In a study conducted by Taghavi et al. (2023), the DRASTIC model was employed to evaluate the vulnerability of groundwater in the Bordkin Basin, Queensland, Australia. The findings indicate that 6% of the area falls under very high to high vulnerability, 25.2% shows moderate to high vulnerability, 38.4% is classified as having moderate vulnerability, 22.4% falls within low to moderate vulnerability, and 8.1% experiences low to very low vulnerability (Taghavi et al., 2023). In a study utilizing the DRASTIC model to assess the potential vulnerability of groundwater in the Asin region of Ghana, the results showed that approximately 812.78 square kilometers of the area (equivalent to 33.62%) have low vulnerability potential. In comparison, 1,604.22 square kilometers (equivalent to 66.37%) of the area was identified as regions with medium vulnerability potential (Mensah et al., 2023). In another study, the DRASTIC model, enhanced by the fuzzy AHP method and integrated into a GIS, was used to assess groundwater vulnerability in the Lake Shor Bordur basin, located in southwest Turkey. The results of this research indicated that 26.43% of the studied area falls into the very vulnerable category, 11.44% into the medium vulnerability category, and 62.13% into the low vulnerability category (Şener, 2023). In a study conducted to assess the vulnerability of the Afram Plain aquifer in Ghana using the DRASTIC model by Asante Agyare et al. (2017), the results revealed that 20.72% (1044.28 km²), 49.78% (2508.91 km²), and 29.50% (1486.80 km²) of the total area fall into the low, moderate, and high pollution categories, respectively. Additionally, the final vulnerability model was validated and confirmed with data on nitrate concentrations in the region's groundwater (Agyare et al., 2017). Mirzaei et al. (2012) used the DRASTIC model to evaluate the vulnerability of the Shahrekord Plain (Mirzaei et al., 2012). The results of this study indicated that 11.5%, 79.6%, and 8.9% of the plain's area fall into the very low, low, and moderate vulnerability categories, respectively. Similarly, in another study, Nokhostin Rouhi et al. (2017) employed the DRASTIC model to map the aquifer vulnerability of the Ajabshir Plain (Nakhostin Rouhi et al., 2017). The findings revealed that 13.48%, 55.43%, 28.69%, and 3.08% of the region's area were classified as very low, low,

low to moderate, and moderate to high vulnerability zones, respectively. Voudouris et al. (2010) conducted a study using the DRASTIC model to assess the vulnerability of the Kiti Plain aquifer in southern Cyprus (Voudouris et al., 2010). The results indicated that the northern areas of the plain exhibit low to very low vulnerability, whereas the southern parts of the plain fall within high to very high vulnerability zones. In another study, a modified DRASTIC model was used to evaluate the vulnerability of the Beijing Plain aquifer in China. This research integrated groundwater quality and storage as valuation criteria, alongside the intrinsic vulnerability risk, to assess the overall groundwater vulnerability. The results revealed that the northern and western areas of the plain exhibit higher vulnerability compared to other regions (Wang et al., 2012). Yibo Zhang et al. (2022) employed an improved DRASTIC model, including the DRASTIC-LTPD and AHP-DRASTIC-LTPD models, in their study to assess groundwater vulnerability in the vicinity of agricultural lands in the Shang Shan Industrial Park, Sichuan Province, China (Zhang et al., 2022). These enhanced models incorporated four additional factors: land use type (L), aquifer thickness (T'), aquifer potential (P), and distance from pollution sources (D'). The vulnerability zoning results indicated that, in the traditional DRASTIC model, the improved DRASTIC-LTPD model, and the combined AHP-DRASTIC-LTPD model, agricultural areas in the western and eastern regions exhibited lower vulnerability levels. In contrast, the industrial central regions demonstrated higher levels of vulnerability. In a study conducted in the Neyshabur Plain to investigate groundwater contamination using the DRASTIC model, the results indicated that approximately 23.55% of the area falls within the very low vulnerability class, 17.16% within the low class, 19.21% within the moderate class, 28.72% within the high class, and 11.36% within the very high vulnerability class. These findings clearly illustrated the distribution and diversity of groundwater vulnerability in the region (Amir Ahmadi et al., 2013). Other researchers, such as Asghari Moghaddam et al., evaluated the vulnerability of the Marand Plain aquifer using the DRASTIC and AVI models in their study and compared the results. The findings from the DRASTIC model indicated that 50.4%, 32.9%, and 16.7% of the area were classified as having moderate, high, and very high vulnerability, respectively. Similarly, the evaluation using the AVI method revealed that 39.13% of the area had moderate vulnerability, 6.5% high vulnerability, and 54.37% very high vulnerability (Asghari Moghaddam et al., 2016). Moreover, Nakhaei et al. conducted a study using the DRASTIC model to assess the groundwater vulnerability of the Khatunabad Plain in Kerman. The results indicated that 70% of the study area was categorized as having moderate vulnerability, while the remaining 30% fell into the low vulnerability category. To validate the final model, nitrate concentration data from the region's groundwater were utilized (Nakhaei et al., 2013).

This research aims to conduct a comprehensive vulnerability assessment of groundwater aquifers within the Gonabad Plain utilizing the established DRASTIC model. The research endeavors to provide both practical and scientifically sound solutions for enhancing groundwater resource management in arid and semi-arid regions. The findings of this investigation are expected to make a significant contribution to the development of sustainable management strategies for these critical resources. Furthermore, the research aims to establish an operational framework, aligned with international best practices, that can be effectively applied to other regions facing similar hydrogeological challenges. This research, therefore, serves as a valuable contribution to evidence-based decision-making in the field of water resource management.

2. Material and Methods

2.1. Study Area

The study area is situated in the northeastern part of Iran, within Khorasan Razavi Province, which spans an area of 111,851 square kilometers, as shown in Figure 1. It borders North Khorasan to the northwest, Semnan to the west, South Khorasan to the south, and Yazd to the southwest. The province is also adjacent to Afghanistan and Turkmenistan to the east and north. In the southern part of the province lies the Gonabad Plain, with geographic coordinates ranging from 58°19' to 59°01' eastern longitude and 34°02' to 34°22' northern latitude. The area of this plain is 1,103 square kilometers, and it is classified as a prohibited plain. The Gonabad Plain has a semi-arid climate, characterized by hot summers and cold winters. This area is particularly significant due to the presence of qanats, which have historically been the main source of agricultural water. The land use in this plain is predominantly agricultural, and, due to challenges such as water scarcity, land degradation, and the impacts of climate change, it is considered a sensitive area that requires special management.

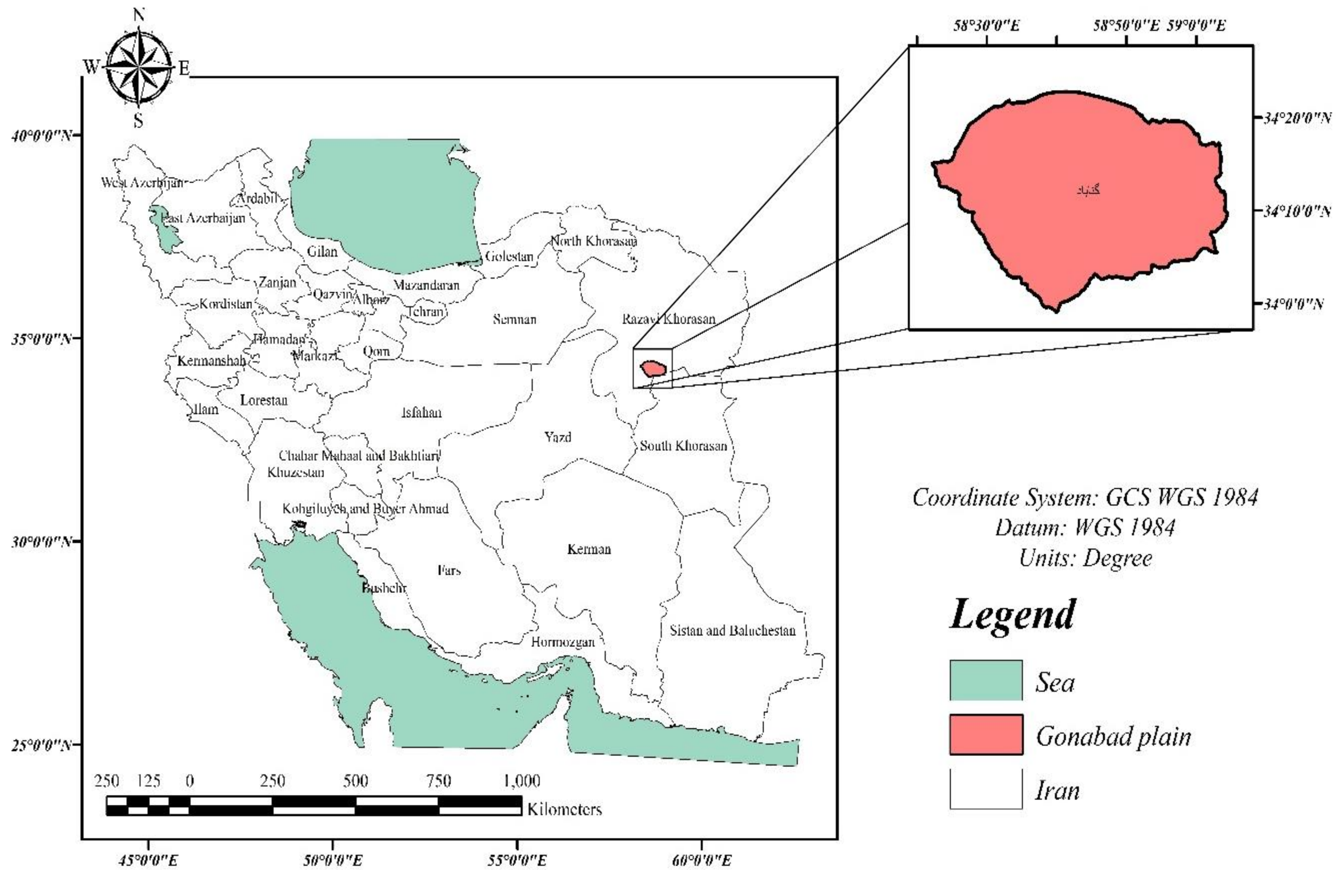


Figure 1. Map of the plains of Khorasan Razavi and the location of Gonabad plain

2.2. Research Method

The DRASTIC model is one of the most widely used methods for evaluating aquifer vulnerability. This method was introduced by the United States Environmental Protection Agency (EPA) as a standardized system for assessing the vulnerability of groundwater resources to pollution. The primary goal of this method is to prioritize activities related to groundwater management. Additionally, it can be employed to regulate and guide operations in groundwater monitoring. For example, in areas where aquifer vulnerability is higher and land use has a high potential for polluting water resources, a denser and more precise monitoring system should be established. The aforementioned organization developed this method to identify the potential for groundwater pollution. In this approach, the vulnerability index is calculated as the sum of the products of the weight and rating of seven parameters. Each parameter is assigned a weight (ranging from 1 to 5) based on its significance, and the ratings of DRASTIC parameters range from 1 to 10. A rating of 1 indicates the least risk, while a rating of 10 signifies the highest risk of groundwater contamination. After calculating the index, it can be determined which areas are at risk of pollution, as a higher index value corresponds to a greater risk of contamination. The output of the DRASTIC model is a numerical index derived from the weights and ratings of the parameters used. The DRASTIC index is calculated using Equation (1).

$$\text{DRASTIC Index} = D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_{W+} C_R C_W \quad (1)$$

In Equation 1, the letters D, R, A, S, T, I, and C represent the parameters of Depth to Water, Net Recharge, Aquifer Media, Soil Media, Topography, Vadose Zone (Unsaturated Zone), and Hydraulic Conductivity of the Aquifer, respectively. The symbols r and w denote the rating and weight assigned to each parameter, respectively.

The DRASTIC model operates under four primary assumptions:

1. The pollutant originates at the ground surface and enters the groundwater system.
2. The pollutant is transported to the groundwater through infiltrating precipitation.
3. The transport capabilities of the pollutant and water are identical.
4. The study area has a minimum size of 4 square kilometers.

2.3. Mapping Hydrogeological Parameters for Groundwater Vulnerability Assessment

2.3.1. Depth to Water Table (D):

The depth to the water table refers to the thickness of the unsaturated zone that contaminants must traverse to reach the aquifer surface. A greater saturated zone thickness increases the time required for pollutants to reach the aquifer, thereby reducing the risk of contamination. This parameter is derived through interpolation of groundwater level data collected from piezometer wells. To create a depth-to-water table map, data from observation wells in the studied plain must be utilized.

2.3.2. Net Recharge (R)

Net recharge controls the volume of water that dilutes and disperses pollutants within the unsaturated and saturated zones. Generally, the greater the net recharge, the higher the potential for groundwater contamination. A net recharge map is produced using the Piscopo method. In this approach, net recharge is calculated based on precipitation, slope, and soil permeability, following the equation below:

Net Recharge Rating Map = Slope Rating Map + Precipitation Rating Map + Soil Permeability Rating Map

Slope, precipitation, and permeability maps can be created using specific datasets. Slope maps are derived from a digital elevation model (DEM), precipitation maps are prepared using annual rainfall statistics from regional stations, and permeability maps are generated by interpolating permeability data from field measurements. These maps are then converted to raster format. By overlaying the three raster maps, the net recharge layer is created.

2.3.3. Aquifer Media (A)

Aquifer media represents the capacity of the aquifer environment to facilitate pollutant movement, which largely depends on soil composition and grain size. Generally, coarse grains or open structures, such as fractures and fissures within the aquifer, accelerate contaminant transfer, increasing the potential for groundwater pollution. Data related to this parameter can be obtained from exploratory studies, geophysical surveys, and observation wells in the targeted plain.

2.3.4. Soil Media (S)

The soil media refers to the layer above the unsaturated zone, typically ranging in thickness from 0.5 to 2 meters. This layer is microbiologically active and has a significant capacity to reduce pollutant concentrations through filtration and biodegradation. A soil map of the area can be prepared using semi-detailed or detailed soil survey reports of the plain. In some cases, national soil maps or datasets provided by the Agricultural Organization can also be utilized to create the soil media layer.

2.3.5. Topography (T)

Topography refers to variations in slope across the land surface. Steeper slopes decrease the interaction time between surface water and pollutants with the ground surface, which reduces the potential for contaminants to infiltrate the aquifer. Slope data is derived from the region's digital elevation model (DEM) and is used to generate the topographic map.

2.3.6. Unsaturated Zone (I)

The unsaturated zone is the soil layer located between the water table and the soil media, which is either unsaturated or intermittently saturated. This zone plays a crucial role in controlling the transport and dilution of pollutants as they move toward the saturated zone. To create the map of the unsaturated zone, exploratory data and observation well records of the targeted plain are used, focusing on soil grain size and characteristics between the ground surface and the water table.

2.3.7. Hydraulic Conductivity (C)

Hydraulic conductivity refers to the ability of an aquifer to transmit water and dissolved contaminants. Higher hydraulic conductivity facilitates the faster movement of pollutants within the aquifer. Consequently, the higher the hydraulic conductivity, the lower the aquifer's resistance to pollution. The hydraulic conductivity value is obtained by dividing the aquifer's transmissivity, measured through pumping tests, by the saturated thickness of the aquifer.

The DRASTIC method derives from the integration of seven parameters based on the vulnerability index equation. The classification and valuation of the classes associated with each parameter are conducted according to the standard DRASTIC methodology within a GIS environment. By integrating these parameters, the resulting output is a grid that is ranked based on the criteria outlined in the table below. In this layer, cells with higher numerical values indicate areas where groundwater has a higher intrinsic vulnerability to contamination. Conversely, cells with lower numerical values correspond to regions with lower intrinsic vulnerability. (Guide to Risk Management for Pollution Hazards in Surface and Groundwater Resources).

2.4. Validation of the DRASTIC Model

Groundwater in the Gonabad plain plays a vital role in agricultural activities, leading to the widespread use of chemical fertilizers in the region. These fertilizers can therefore be identified as a primary source of groundwater contamination. Since nitrate is not naturally present in groundwater under normal conditions and is typically transported from surface layers, it serves as an effective indicator for assessing the actual vulnerability of the region. In this study, nitrate concentration data collected from 29 wells in the plain were used to validate the DRASTIC model.

3. Results and Discussion

3.1. Water Table Depth

The depth-to-water table layer derived using ArcMap reveals that the most significant groundwater depths in the Gonabad plain are found in the central and southwestern regions, with a range exceeding 75 meters. Conversely, areas with a groundwater depth of less than 75 meters are primarily located in the northern and northeastern parts of the plain. The aquifer depth values are categorized into six classes, assigned rankings of 1, 2, 5, 7, 9, and 10. In this classification, a value of 10 indicates a high impact on pollution potential, while a value of 1 reflects the lowest impact, as shown in Figure 2(a).

3.2. Net Recharge

The net recharge map generated using the Piscopo method incorporates layers of rainfall, slope, and soil permeability in the plain. Recharge values range from less than 15 cm per year in the southern regions and certain parts of the east and west to more than 25 cm per year in the central and northern areas. This map is classified into five categories with rankings of 1, 3, 6, 9, and 10. As shown in Figure 2, the central and northern regions, due to their higher recharge rates, exhibit a greater potential for pollution, as shown in Figure 2(b).

3.3. Aquifer Media

The characteristics of aquifer media and the composition of its materials determine the flow path and length of water movement. According to research, coarser-grained aquifer materials have a higher potential to transmit contamination to groundwater. Therefore, a class with coarse-grained soil, due to its higher permeability, is assigned a value of 10. In contrast, a class with fine-grained soil (such as clay, which restricts the infiltration of contaminated flows due to its fine texture) is given a value of 1, as shown in Figure 2(c).

3.4. Soil Media

The soil media layer plays a significant role in contamination transfer based on properties such as texture and permeability. This layer was derived from the soil formation map of Iran (https://esdac.jrc.ec.europa.eu/content/soil-map-iran) and is categorized into four classes. The soil media parameter map is shown in Figure 5, with classes ranked as 4, 5, 7, and 10, as depicted in Figure 2(d).

3.5. Topography

This map was generated using the Digital Elevation Model (DEM) layer obtained from the Khorasan Razavi Regional Water Authority. Since materials tend to accumulate in low-slope areas, these regions play a more significant role in groundwater contamination. The Gonabad plain, except for the southern, western, and small eastern parts, is largely flat with low slopes. The slope layer is classified into five categories with rankings of 1, 3, 5, 9, and 10, as shown in Figure 2(e).

3.6. Unsaturated Zone

This layer was created based on data from drilling wells and the composition of the unsaturated zone. It includes three classes: 3, 6, and 8. The highest rank (8) is assigned to areas with sandy soil, covering the eastern, western, and major northern parts of the plain, which exhibit relatively high permeability, as shown in Figure 2(f).

3.7. Hydraulic Conductivity

This layer was developed using piezometric well data within unsaturated zone formations. Each formation was assigned a numerical value based on its hydraulic conductivity. The layer is categorized into four classes: 1, 2, 4, and 10. Higher hydraulic conductivity corresponds to greater contamination potential, resulting in a higher ranking. The northern, eastern, and western parts of the region, predominantly composed of sand and gravel, exhibit the highest vulnerability levels, as shown in Figure 2(g).

The ranking and weighting of DRASTIC parameters are provided in Table 1. This table outlines the classification and associated weights for each parameter, which are essential for assessing the vulnerability of groundwater to contamination. The weights reflect the relative importance of each parameter in influencing the overall vulnerability index.

Table 1. Ranking and Weighting of DRASTIC Parameters

Depth to Water Table		Net Recharge	
Class Range	Rank	Class Range	Rank
Less than 15	10	Less than 10	1
15-30	9	10-15	3
30-50	7	15-20	6
50-75	5	20-25	9
75-100	2	More than 25	10
More than 100	1		
Aquifer Media		Soil Media	
Class Range	Rank	Class Range	Rank
Clay	1	Saline Sediment	10
Clay-Sand	2	Limestone Lithosol	7
Cemented Particles	3	Desertized Saline and Soils	5
Sand-Clay	4	Desert and Regosol	4
Gravel-Clay	4		
Sand-Silt-Gravel	5		
Marl	7		
Gravel-Sand	8		
Coarse Sand-Silt	10		
Topography		Unsaturated Zone	
Class Range	Rank	Class Range	Rank
Less than 2	10	Clay	3
2-6	9	Sand	6
6-12	5	Sand-Gravel	6
12-18	3	Gravel	8
More than 18			
Hydraulic Conductivity		Parameter	Weight
Class Range	Rank	Depth to Water Table	5
Clay	1	Net Recharge	4
Sand	3	Aquifer Media	3
Sand-Gravel	5	Soil Media	2
Gravel	7	Topography	1
	10	Unsaturated Zone	5
		Hydraulic Conductivity	3

3.8. Final DRASTIC Index Map

Considering the ranks and weights of the layers and their integration, the DRASTIC index for the entire plain was determined to range from 63 to 193 units. Based on this range and established standards for the DRASTIC index, the aquifer was classified in terms of contamination risk, ranging from no risk to highly contaminated. The distribution of the plain's area across each classification is as follows: 0.65% falls under no contamination risk, 2.06% has very low contamination, 21.67% has low contamination, 34.62% falls within low to moderate contamination, 33.52% falls under moderate to high contamination, 6.66% is classified as having high contamination, 0.8% has very high contamination, and 0.006% is in thoroughly contaminated areas, as illustrated in Figure 2(h).

3.9. DRASTIC Model Validation

To validate the final DRASTIC index, nitrate concentrations measured in 2021 in the wells of the Gonabad plain were used, based on previous research findings in this field. Nitrate concentrations range from 0.04 to 3.16 milliequivalents per liter, as shown in Figure 2(i), and their distribution across different sections of the Gonabad plain is illustrated in Figure 10. The majority of the plain has nitrate concentrations below 1.08 milliequivalents per liter, while in parts of the central, northern, and northeastern areas, the nitrate concentration varies from 1.43 milliequivalents per liter to the highest value of 3.18 milliequivalents per liter, indicating contamination in these areas. This confirms that the DRASTIC index accurately reflects the vulnerability of the Gonabad plain.

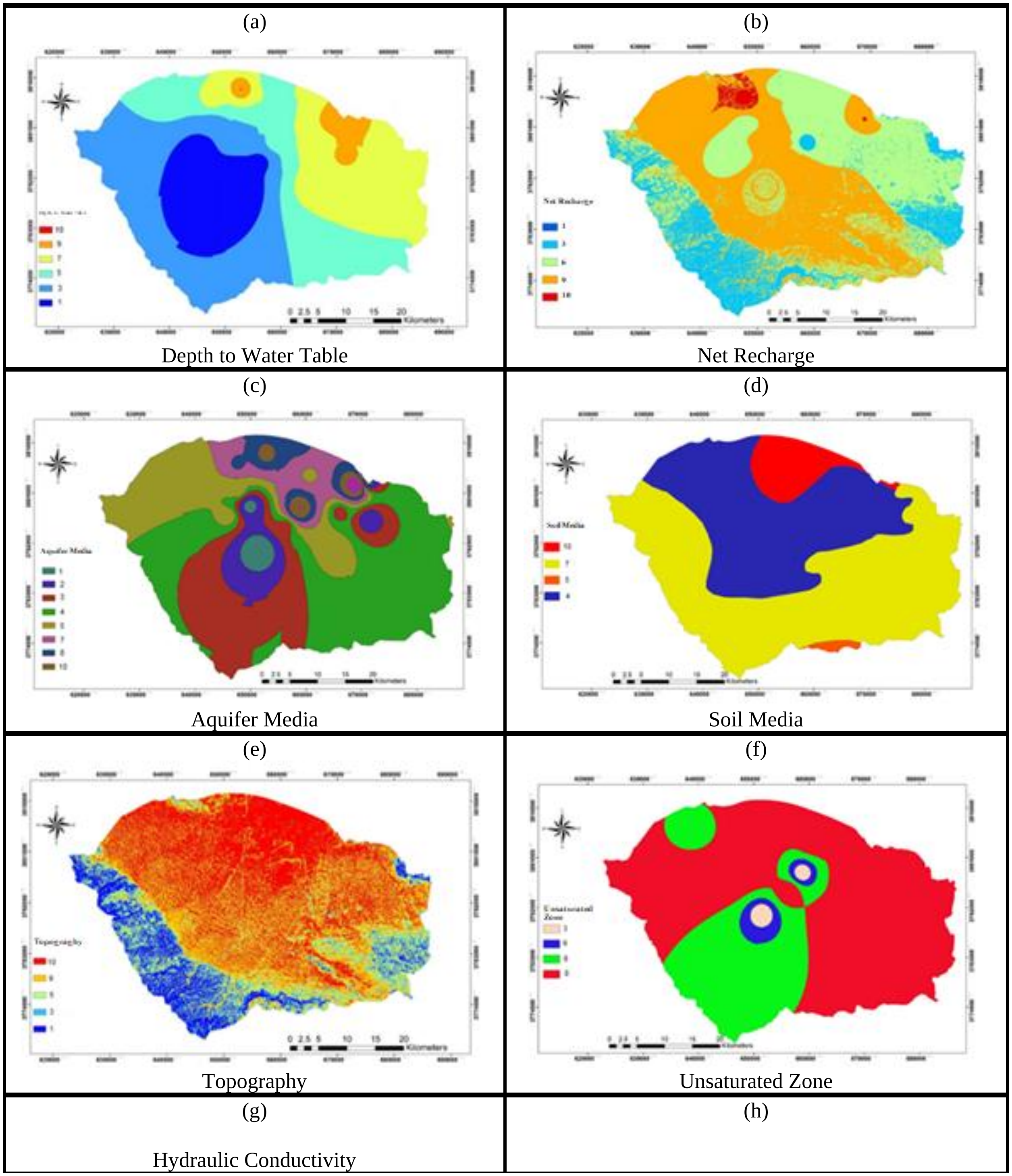
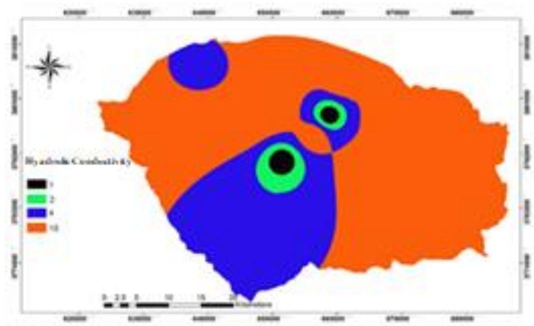


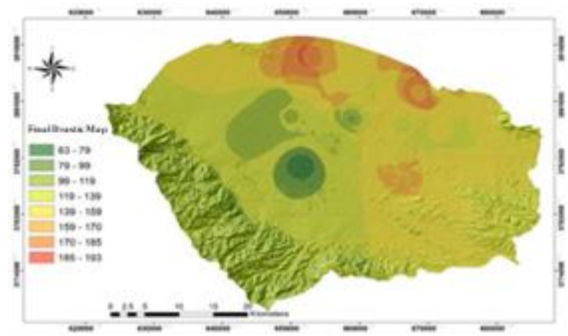
Figure 2. Maps illustrating the indices and the DRASTIC method. All units are in meters (depth), mm/year (recharge), percent (slope), and m/day (hydraulic conductivity

(g)



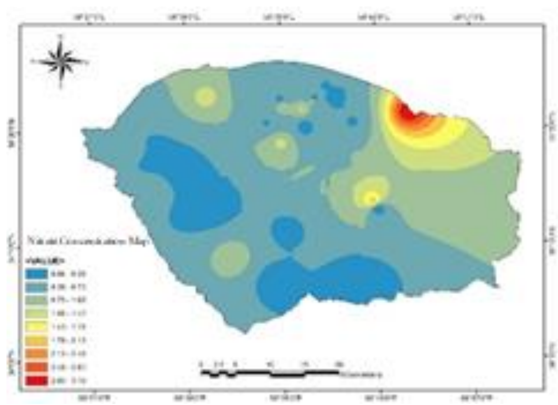
Hydraulic Conductivity

(h)



DRASTIC

(i)



Nitrate Concentration Map

Figure 2 (continued). Maps illustrating the indices and the DRASTIC method. All units are in meters (depth), mm/year (recharge), percent (slope), and m/day (hydraulic conductivity)

4. Conclusion

The vulnerability index for the Gonabad Plain, calculated using the DRASTIC model, ranged from 63 to 193. Based on the model's classification, 0.65% of the plain was categorized as having no pollution risk. In comparison, 2.06%, 21.67%, 34.62%, and 33.52% fell into the very low, low, low-to-moderate, and moderate-to-high pollution risk categories, respectively. Additionally, 6.66% of the area exhibited high pollution risk, 0.8% showed very high pollution risk, and 0.006% was identified as thoroughly polluted. These findings underscore the significant variability in pollution vulnerability across the plain and highlight the necessity of targeted management strategies for groundwater resources.

The heightened vulnerability observed in the northern parts of the plain can be attributed to environmental factors, including shallow water tables, gentle slopes of less than 2%, and coarse-grained soil in the aquifer, unsaturated zone, and soil media. These characteristics facilitate rapid infiltration and contaminant transport, making these areas particularly susceptible to groundwater pollution. The results of this study demonstrate the critical need for refined vulnerability assessments tailored to local conditions. Incorporating site-specific contaminants and environmental factors into the DRASTIC model would enhance the accuracy and reliability of pollution risk evaluations. High-risk zones identified in the plain require stricter regulations to mitigate contamination, including controlling human and agricultural activities. Regular monitoring of groundwater quality is crucial for identifying emerging risks and ensuring the long-term sustainability of water resources.

Additionally, implementing restrictions on groundwater extraction in vulnerable areas can prevent overexploitation and further degradation of water quality.

This research provides a practical framework for managing groundwater resources in the Gonabad Plain and similar arid and semi-arid regions. By focusing on the interaction between environmental parameters and groundwater vulnerability, the study offers valuable insights for policymakers and resource managers. It also lays the groundwork for future studies that could integrate advanced technologies, such as machine learning and remote sensing, to enhance the precision and scalability of groundwater vulnerability assessments.

The present study successfully evaluated groundwater vulnerability in the Gonabad Plain using the DRASTIC model, revealing that shallow water tables and coarse alluvial deposits in the northeastern zones pose the highest pollution potential. Nevertheless, several scientific directions are proposed for future research to overcome the model's conceptual and contextual limitations. First, the DRASTIC framework should be regionally adapted for arid, irrigation-dominated aquifers. Since recharge and nitrate transport in such environments are primarily driven by irrigation return flow rather than rainfall, redefining the recharge component as effective recharge (R_{eff} = rainfall + α × irrigation) can significantly improve model accuracy.

Moreover, incorporating multi-criteria decision-making and data-driven methods, such as the Analytic Hierarchy Process (AHP), Fuzzy Logic, and Machine Learning models (e.g., Random Forest, XGBoost), is recommended to enable adaptive parameter weighting and better capture nonlinear interactions among DRASTIC factors. Future work should also explore land-use change and groundwater abstraction scenarios to assess temporal variations in vulnerability and the potential impacts of human activities on nitrate dynamics. Integrating the DRASTIC index with additional groundwater quality indicators (such as nitrate, phosphate, EC, and TDS) and performing sensitivity and uncertainty analyses can enhance the robustness and interpretability of the results.

Ultimately, developing hybrid vulnerability models that dynamically integrate hydrogeological, climatic, and land-use data will provide a robust framework for sustainable groundwater quality monitoring and management in Iran's arid regions.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

References

Agyare, A., Anornu, G. K., & Kabo-bah, A. T. (2017). Assessing the vulnerability of aquifer systems in the Volta river basin: a case-study on Afram Plains, Ghana. *Modeling Earth Systems and Environment*, *3*, 1141-1159.

Amir Ahmadi, A., Ebrahimi, M., Zanganeh, M., & Akbari, E. (2013). Investigation of DRASTIC model on GIS. *Journal of Geography and Environmental Hazards*, *2*(6), 37-56.

Ascott, M., Gooddy, D. C., Wang, L., Stuart, M. E., Lewis, M., Ward, R., & Binley, A. M. (2017). Global patterns of nitrate storage in the vadose zone. *Nature Communications*, *8*(1), 1416.

Asghari Moghddam, A., Fakhri, M. S., & Najib, M. (2016). Zoning of Groundwater Pollution Potential of Marand Plain Aquifer Using from AVI, DRASTIC and Methods at GIS Environment. *Journal of Geography and Planning*, *19*(54), 19-41.

Aslam, R. A., Shrestha, S., & Pandey, V. P. (2018). Groundwater vulnerability to climate change: A review of the assessment methodology. *Science of the Total Environment*, *612*, 853-875.

Bentekhici, N., Benkesmia, Y., Bouhlala, M. A., Saad, A., & Ghabi, M. (2024). Mapping and assessment of groundwater pollution risks in the main aquifer of the Mostaganem plateau (Northwest Algeria): utilizing the novel vulnerability index and decision tree model. *Environmental Science and Pollution Research*, *31*(32), 45074-45104.

Daly, D., Dassargues, A., Drew, D., Dunne, S., Goldscheider, N., Neale, S., Popescu, I., & Zwahlen, F. (2002). Main concepts of the" European approach" to karst-groundwater-vulnerability assessment and mapping. *Hydrogeology Journal*, *10*, 340-345.

Gogu, R. C., & Dassargues, A. (2000). Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. *Environmental geology*, *39*, 549-559.

Hosseiny, S. H., Bozorg-Haddad, O., & Bocchiola, D. (2021). Water, culture, civilization, and history. In *Economical, Political, and Social Issues in Water Resources* (pp. 189-216). Elsevier.

Li, B., Yang, Z., & Xu, X. (2019). Examining China's water pressure from industrialization driven by consumption and export during 2002–2015. *Journal of Cleaner Production*, *229*, 818-827.

Meegoda, J. N., Chande, C., & Bakshi, I. (2025). Biodigesters for Sustainable Food Waste Management. *International Journal of Environmental Research and Public Health*, *22*(3), 382.

Mensah, D. O., Appiah-Adjei, E. K., & Asante, D. (2023). Groundwater pollution vulnerability assessment in the Assin municipalities of Ghana using GIS-based DRASTIC and SINTACS methods. *Modeling Earth Systems and Environment*, *9*(2), 2955-2967.

Mirzaei, S., Naderi Khorasgani, M., Beigi, H., & Mohammadi, G. (2012). Vulnerability assessment of the Shahrekord plain groundwater using DRASTIC model. *Iranian Water Researches Journal*, *6*(2), 143-151.

Nakhaei, M., Amiri, V., & Rahimi-Shahrebabaki, M. (2013). Assessment of groundwater vulnerability and sensitivity analysis in Khatoon Abad aquifer using a GIS based DRASTIC model. *Advanced Applied Geology*, *3*(2), 1-10.

Nakhostin Rouhi, M., Rezaei Moghaddam, M. H., & Rahimpour, T. (2017). Groundwater vulnerability zonation using DRASTIC and SI models in GIS (Case Study: Ajabshir Plain). *Iranian journal of Ecohydrology*, *4*(2), 587-599.

Ouedraogo, I., Defourny, P., & Vanclooster, M. (2018). Application of random forest regression and comparison of its performance to multiple linear regression in modeling groundwater nitrate concentration at the African continent scale. *Hydrogeology Journal*.

Rama, F., Busico, G., Arumi, J. L., Kazakis, N., Colombani, N., Marfella, L., Hirata, R., Kruse, E. E., Sweeney, P., & Mastrocicco, M. (2022). Assessment of intrinsic aquifer vulnerability at continental scale through a critical application of the drastic framework: The case of South America. *Science of the Total Environment*, *823*, 153748.

Ravindra, K., & Mor, S. (2019). Distribution and health risk assessment of arsenic and selected heavy metals in Groundwater of Chandigarh, India. *Environmental pollution*, *250*, 820-830.

Şener, E. (2023). Appraisal of groundwater pollution risk by combining the fuzzy AHP and DRASTIC method in the Burdur Saline Lake Basin, SW Turkey. *Environmental Science and Pollution Research*, *30*(8), 21945-21969.

Strang, V. (2015). *Water: Nature and culture*. Reaktion Books.

Taghavi, N., Niven, R. K., Kramer, M., & Paull, D. J. (2023). Comparison of DRASTIC and DRASTICL groundwater vulnerability assessments of the Burdekin Basin, Queensland, Australia.

Science of the Total Environment, *858*, 159945.

Voudouris, K., Kazakis, N., Polemio, M., & Kareklas, K. (2010). Assessment of intrinsic vulnerability using the DRASTIC model and GIS in the Kiti aquifer, Cyprus. *European water*, *30*(1), 13-24.

Vrba, J., & Zaporozec, A. (1994). Guidebook on mapping groundwater vulnerability.

Wang, J., He, J., & Chen, H. (2012). Assessment of groundwater contamination risk using hazard quantification, a modified DRASTIC model and groundwater value, Beijing Plain, China. *Science of the Total Environment*, *432*, 216-226.

Zhang, Y., Qin, H., An, G., & Huang, T. (2022). Vulnerability assessment of farmland groundwater pollution around traditional industrial parks based on the improved DRASTIC Model—A case study in Shifang City, Sichuan Province, China. *International Journal of Environmental Research and Public Health*, *19*(13), 7600.

Zwahlen, F. (2003). *Vulnerability and risk mapping for the protection of carbonate (karst) aquifers*. Office for Official Publications of the European Communities Luxembourg.