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Assessment and improvement of groundwater vulnerability mapping using the DRASTIC Model in Wadi Shuaib Sub-basin, Jordan

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Jordan, an arid to semi-arid and extremely water-scarce country, relies heavily on groundwater, rendering the Wadi Shuaib sub-basin a critical yet vulnerable resource. Contamination threats from septic-tank leakage, overflows from the Assalt and Fuhais wastewater treatment plants, and diffuse agricultural pollutants necessitated assessing and refining groundwater vulnerability via the DRASTIC index in a GIS framework. The standard DRASTIC model, utilizing seven hydrogeological parameters from hydrological, geological, soil, land-use, and well data, produced a vulnerability map classifying the 172 km² basin into five categories: very low to very high. About three-quarters of the area exhibits low to very low vulnerability, while high (6%) and very high (5%) classes concentrate in the south-western sector, driven by shallow water tables (<1.5m), permeable alluvial Entisols, and focused recharge that accelerate contaminant percolation. Validation employed a Groundwater Quality Index (GQI) for E. coli, nitrate, and turbidity against Jordanian drinking-water standards, revealing generally high GQI scores (90–99%) but post-storm deteriorations exactly in high-vulnerability zones. Sensitivity analysis (P-values <0.05, R^2) highlighted the Impact of vadose zone, net recharge, hydraulic conductivity, and topography as key contaminant transport controls, warranting higher weights for these and lower weights for depth to water, soil media, and aquifer media. The optimized DRASTIC scheme enhanced alignment between vulnerability classes and GQI distributions, offering a realistic pollution risk portrayal, particularly in recharge hotspots. The resulting maps constitute a decision support tool for delineating wellhead protection areas, prioritizing monitoring, and guiding land use planning adaptable to other semi-arid basins via local calibration and water-quality validation.

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1. Introduction

Jordan's climate is classified as dry to semi-dry, and the country is recognized as one of the most water-scarce nations worldwide, with mean annual rainfall of about 200 mm that ranges from nearly 600 mm in the highlands to around 50 mm in desert areas [14]. Groundwater basins are therefore under significant pressure from high water consumption driven by rapid population growth, which reached 5.3% between 2004 and 2015 [4].

In the Wadi Shuaib Sub-basin, several contamination issues have been reported, notably elevated concentrations of E. coli and nitrate caused by infiltration from nearby septic tanks, overflow of effluent from the Assalt and Fuhais wastewater treatment plants during winter, and diffuse agricultural inputs within the catchment. Given that many communities in and around Wadi Shuaib rely exclusively on local springs

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and wells for drinking water, even short-term contamination pulses can pose direct public-health risks, particularly after intense rainfall events.

A robust vulnerability assessment therefore provides a proactive basis for prioritizing mitigation measures such as sewer network expansion, upgrading wastewater treatment, and promoting best agricultural practices before water-quality problems become widespread or irreversible [11]. Such contamination limits the use of available water resources and increases freshwater losses in the basin, worsening Jordan's water crisis.

To safeguard groundwater basins and sub-basins and to identify potential point and non-point pollution sources, it is essential to assess groundwater vulnerability and produce vulnerability maps using the DRASTIC model [8]. The method was chosen based on area size, data availability, and expected level of detail in the results [23]. The DRASTIC model, developed by Aller et al. [3], is a standardized index method used to map intrinsic groundwater vulnerability based on seven hydrogeological parameters: Depth to water, Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, and hydraulic Conductivity. Gonçalves et al. [5] demonstrated a recent and comprehensive GIS-based application of the DRASTIC index to assess groundwater vulnerability in real conditions (cemeteries in Figueira da Foz, Portugal). Their work provided a methodological framework for data collection, GIS processing, and interpretation of vulnerability maps. Similarly, Seraiche et al. [12] applied several variations of the DRASTIC model classic DRASTIC, DRASTIC with land use, AHP-weighted DRASTIC, and fuzzy AHP–weighted DRASTIC in a semi-arid basin. They produced and compared four vulnerability maps and validated them using nitrate concentrations measured from 70 wells.

Groundwater vulnerability maps provide essential guidance for the Ministry of Water and Irrigation and the Ministry of Agriculture by delineating zones that are highly susceptible to contamination. Such maps support regulation of intensive agricultural, industrial, and urban development in vulnerable areas and delineation of wellhead protection zones. They also help prioritize monitoring efforts and supply scientific evidence for informed decision-making on sustainable land and water-resource management.

Wadi Shuaib Basin has been the focus of multiple previous studies. Ta'any [21] assessed groundwater vulnerability to pollution in the Salt urban area by calculating direct recharge across the entire Wadi Shuaib catchment using data from the main rainfall station. The subsurface zone between Wadi Shuaib and the Dead Sea in the Jordan Valley was categorized as having high vulnerability, while the middle and western parts were classified as highly to extremely vulnerable due to possible pollution from agricultural fields. Conversely, the southern part of the study area exhibited low aquifer vulnerability. Al-Kharabsheh and Al-Kharabsheh [2] investigated the effects of urbanization and population growth on the deterioration in spring water quality in northern Wadi Shuaib. Ten representative springs out of twenty-two, along with effluent from the Salt Wastewater Treatment Plant, were analysed. They found that the spring water generally met the Jordanian Standards (JS) for drinking water, except for nitrate, phosphate, lead, Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and Total Coliform concentrations. Accordingly, this study aims to (i) update groundwater vulnerability maps for the entire Wadi Shuaib sub-basin, (ii) validate groundwater quality using the DRASTIC model by comparing vulnerability classes with measured parameters from wells and springs, and (iii) refine the model by adjusting parameter weights to better represent local hydrogeological conditions

2. Material and methods

2.1. Study area

The study area is located in the Wadi Shuaib sub-basin on the eastern side of the Jordan Valley and covers about 172 km² (Fig.1). It is characterized by a steep relief with elevations ranging from -200 m in the southwest up to 1240 m in the northeast. The annual rainfall is 358 mm [10]. The population density, as well as most agricultural activities, are accumulated in the higher altitudes in the northern part of Wadi Shuaib [1].

Fig. 1. Study area.

The study area comprised several water resources, including 22 springs. The four main springs were Al-Baqouriya, Shuraia, Hazzir, and Azzraq, while the remaining springs were unused due to water quality concerns. The area also contained 32 wells, of which only 16 were operational, in addition to the treated effluent discharged from the As-Salt and Fuhais wastewater treatment plants (WWTPs) as shown in Figure 1.

2.2. Water sampling and analysis

A total of 24 Water samples were collected from these locations, which are monitored by the Water Authority of Jordan (WAJ), along with four additional sites situated along the Wadi Shuaib stream. A dam was constructed at the outlet of Wadi Shuaib in 1968 to harvest runoff water during the winter season. The baseflow of Wadi Shuaib consists of excess non-pumped spring water, treated effluent from the Salt and Fuhais WWTPs, and leakage of untreated sewage from septic tanks in the nearby villages of Ira and Yarqa. However, the flow gradually diminishes and the channel tends to dry up during the summer months. For drinking water sources, including springs and wells, samples were collected seasonally during both summer and winter to analyse Escherichia coli (E. coli), nitrate, pH, electrical conductivity (EC), sulfate, total dissolved solids (TDS), hardness, and turbidity (see Fig. 2). For treated wastewater samples, analyses were conducted once to assess total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD), E. coli, TDS, nitrate, pH, turbidity, EC, sulfate, and phosphate.

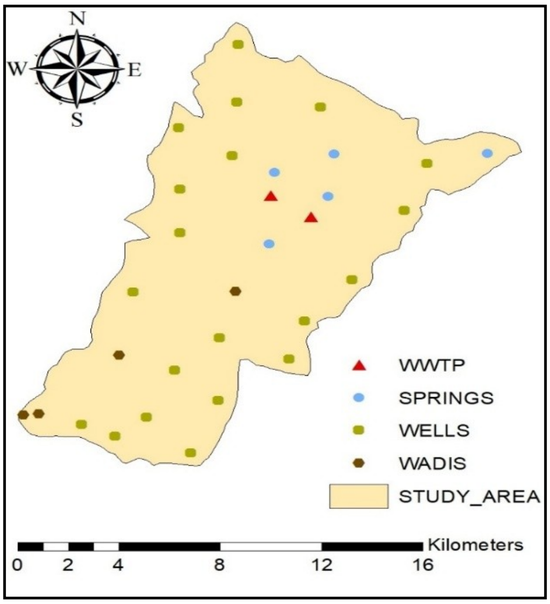

Fig. 2. Water Sample distribution

All laboratory analyses were performed at the Water Authority of Jordan (WAJ) laboratory, which is accredited by the United Kingdom Accreditation Service (UKAS). In addition, historical data from the WAJ laboratory database (2011–2015) were reviewed to obtain average values of these parameters for water facilities that are no longer operational.

2.3. DRASTIC model and GIS mapping

ArcGIS 10.8 was used to implement the DRASTIC model and generate the groundwater vulnerability map at a 25 m × 25 m resolution. Geological characteristics, particularly the impact of the vadose zone, were derived from the geological map provided by the Natural Resources Authority. Contour lines were used to generate a Digital Elevation Model (DEM), from which topography and slope were calculated. To create interpolated rainfall map by using IDW (Inverse Distance Weighting) tool within DRASTIC model as shown in Figure 3, mean annual rainfall data from six meteorological stations surrounding the study area (Assalt, Ira, South Shauna, Wadi Shuaib, Wadi Shuaib Agricultural station and Hummar) were collected for the period 1954–2018, that used to calculate Effective infiltration (Net recharge), which represents the amount of water per unit area of land which penetrates the ground surface and reaches the water table.

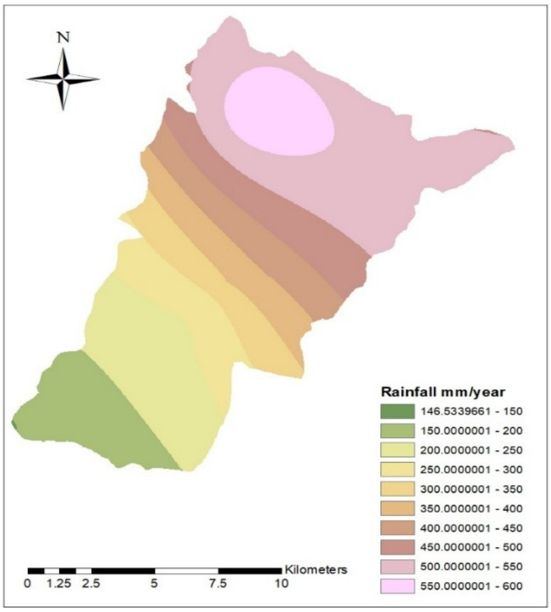

Fig. 3. Average Rainfall Isohyetal map

Thus, this recharge water might consider available to transport the contaminants vertically to the water table and horizontally within the aquifer. Therefore, Greater recharge means that the potential for groundwater pollution is higher. Variable annual recharge rates were reported in different previous studies for

Wadi Shueib [22, 25], and Riepl [18]. Riepl [18] estimated the mean annual recharge over the water years 1995/1996 to 2008/2009 to be 9.9 MCM, which represented 21% of the mean annual rainfall according to the following equation [20]:

$$R_p = O_s + O_w - R_{UR} \pm \Delta S \pm n \quad (1)$$

where:
R_p is the recharge from precipitation,
O_s is the spring discharge,
O_w is the well abstraction,
R_{UR} is the unintentional recharge from water supply pipelines, sewer canals and septic tanks,
ΔS is the change in the groundwater storage,
and n is the error term.

Awawdeh *et al.,* [15] reported that it is worth mentioning that the estimated recharge given by Riepl [18] is in good agreement with those given by Jiries et al. [7] and the Ministry of Water and Irrigation [13].

Archival soil maps (1:200,000) from the Ministry of Agriculture were used to derive soil order and texture and to build the soil-media layer, while hydraulic conductivity was defined from aquifer-test data. Land use database and published research to determine point and non-point resource of pollutants [9]. The hydraulic parameters (water depth, and Aquifer) of the study area obtained by analysing the historical data of the pumping test and well data of groundwater wells in area. These data obtained from water information system (WIS) by MWI. All these layers essential for calculating the DRASTIC index using the equation below:

DRASTIC Index = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw (2)

where:
the small letters **r** and **w** indication the rating and weight of each DRASTIC parameters [10].

The numerical relative rating (r) that indicating the relative pollution potential of that factor for Wadi Shuaib Basin varies from 1 to 10 as shown in Table1.

The weighting values (w) varies from 1-5 represents the relative importance of each factor in its ability to affect pollution transport to and within aquifer as shown in Table 2.

The higher DRASTIC index; means the greater relative pollution potential and a greater vulnerability of aquifer to contamination. The DRASTIC index could be divided into five categories: very low, low, moderate, high, and very high or extreme.

Table 1. Designated DRASTIC parameters weights (Aller et al., 1987)

DRASTIC model parameters	Weight
water Depth layer (D)	5
net Recharge layer (R)	4
aquifer layer (A)	3
soil layer (S)	2
topography layer (T)	1
impact of unsaturated zone layer (I)	5
hydraulic conductivity layer (C)	3

Table 2. DRASTIC parameters rate for Wadi Shuaib [9]

Parameters	Range	Rate	Parameters	Range	Rate
Water Depth layer (D)	0-1.5 m	10	**Topography layer (T)**	2 - 6 %	8
	1.5 – 4.6 m	9		6 - 10 %	5
	4.6 – 9.1 m	7		10 - 18 %	2
	9.1 – 15.2 m	5		> 18 %	1
	15.2 – 22.8	3			
	22.8 – 30.4 m	2	**Impact of unsaturated Zone (I)**	Wad fills: soil over bed rock	2
	> 30.4 m	1		Shuaib / Azab	3
net Recharge layer (R)	0-50 mm/day	1		Ghardan / Mwaqar Fuhais	4
	50-100 mm/day	3		Wadi-Essir / Hummar / Na'our / Kurnub	6
	100-180 mm/ day	6			
Aquifer layer (A)	**B2/A7:** chert limestone, crystalline limestone with dolomite	6		Wadi fills: land slip	8
	A4: hard dense limestone, and dolomitic limestone	6		Wadi fills: Alluvial / Gravel	10

Parameters	Range	Rate	Parameters	Range	Rate
	A1/2: limestone inter bed with thick marl limestone	6	**Hydraulic Conductivity layer (C)** (m/s)	$0.5 * 10^{-5} – 0.5 * 10^{-4}$	1
	K: massive white sandstone with reddish silt and shale	6		$0.5 * 10^{-4} – 0.15 * 10^{-3}$	2
Soil layer (S)	Entisol	6		$0.15 * 10^{-3} – 0.36 * 10^{-3}$	4
	Inceptisol	5		$0.36 * 10^{-3} – 0.51 * 10^{-3}$	6
	Alfisol	3		$0.51 * 10^{-3} – 0.10 * 10^{-2}$	8
	Vertisols	2		$> 0.10 * 10^{-2}$	10

2.4. Validation of vulnerability map

To validate the final vulnerability map, the Groundwater Quality Index (GQI) was applied, based on average concentrations of turbidity, nitrate, and E. coli in the water samples [16]. These values were compared with the allowable limits for each parameter in Jordan Standard (JS 286:2008) for drinking water by applying equations (3-5) of Babiker et al. [26] using raster calculator tool in ArcGIS 10.6.

$$C\ new = \frac{C - C\ (JS)}{C + C\ (JS)} \quad (3)$$

$$R = 0.5\ (C\ new \times C\ new) + 4.5\ (C\ new) + 5 \quad (4)$$

$$GQI = \frac{[\ \Sigma(R \times C\ new)]}{n} \quad (5)$$

where:
C is the average concentration of quality parameter,
C (JS) is maximum allowable concentration of JS of quality parameters,
R is rate of each quality parameter used to classified raster maps,
and **C** new is the concentration of the quality parameter that are obtained by equation (3),
GQI is ground water quality index,
n is the number of locations of water facilities that are monitored in the study area.

The GQI was expressed as a percentage. Rahmani et al. [17], divided values of GQI into 3 categories; less than 60% that represent the poor water quality 60% to 80% considered as moderate water quality, and more than 80% as good water quality.

2.5. Sensitivity analysis

Sensitivity analysis was performed using an exploratory regression approach to evaluate all possible combinations of input explanatory variables, following the criteria of P-values < 0.05 and R^2, as suggested by Gonçalves et al. [5]. Sensitivity analysis was carried out to evaluate the accuracy of vulnerability maps resulted by using DRASTIC model [27]. They showed a deviation in the effective weights of the DRASTIC parameters from "theoretical" weights in the vulnerability assessment, depth to water table, land use impact and hydraulic conductivity, but in the remaining parameters as, net recharge, aquifer media, soil media and impact of vadose zone represent low "effective" weights as compared to their "theoretical" weights. This methodology enabled us to identify which parameters had the most significant effect on the model and to adjust their weights accordingly for application in Jordan

3. Results and Discussion

The assessment of groundwater vulnerability to pollution in the Wadi Shuaib Basin was conducted using the DRASTIC model. The results of all model parameters were presented and discussed in detail as follows:

3.1. Depth of water

As illustrated in Figure 4, the depth to groundwater in most parts of the study area exceeds 30.4 m, indicating a lower potential for contamination. This zone corresponds to a low rating (r = 1) within the rating range shown in Table 1. In contrast, the highest rating (r = 10) is observed in the southwestern part of the study area near the dam, where the groundwater depth is less than 1.5 m. A shallow water table indicates proximity to the surface, which increases the likelihood of pollutant infiltration and vice versa. These conditions contribute to the dominance of low to very low vulnerability classes over much of the basin.

3.2. Net recharge

The net recharge was calculated for the study area as a percentage of annual rainfall. It was estimated to be 21% of annual rainfall [18]. The average annual rainfall of study area is 358 mm/year calculated from different stations distributed around study area. As shown in Figure 5 the amount of net recharge represented in 3 categories, the lowest net charge in the southwest region, but the highest net recharge in the north of study area related to highest rainfall in these regions, and the middle region which is the most area of the study area equal (50-100 mm/year).

3.3. Aquifer media

The domain aquifer formations were B2/A7, A4, A1/2, and K. And the dominant rock was crystalline, dolomitic, and interbed limestone with some marl, reddish silt, extensive white sandstone, and shale. According to Table 2, the rate of all Aquifer media have is (6) as shown in Figure 6. The aquifer parameter had limited influence, being mostly uniform across the study area.

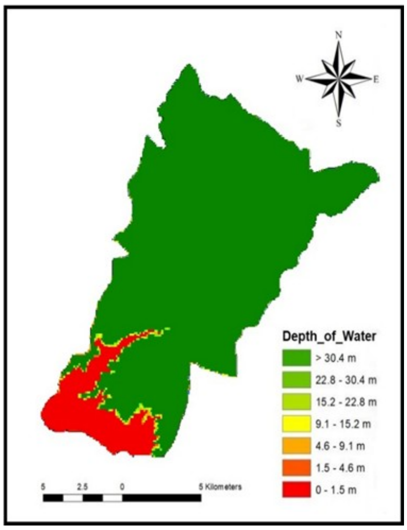

Fig. 4. Depth of water

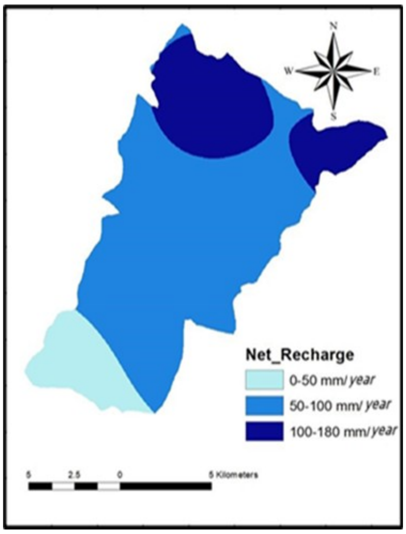

Fig. 5. Net recharge

Fig. 6. Aquifer media

3.4. Soil media

The soil map issued by the Ministry of Agriculture and based on the USDA taxonomy (Fig. 7) identifies Entisols, Vertisols, and Inceptisols as the main soil orders controlling the DRASTIC soil factor in the basin. The spatial distributions of these soils in Figure 7, and their correspondence with slope and rainfall patterns in the accompanying maps, explain the observed gradient in groundwater vulnerability.

Entisols occur mainly on steep slopes and over shallow bedrock, where profiles are shallow and weakly developed, with coarse structure and abundant macropores (cracks, root channels, voids among coarse fragments). This results in high permeability, a thin unsaturated zone, and rapid vertical flow of water and dissolved contaminants toward the water table. Chemically, these soils are generally poor in clay, secondary oxides, and organic matter, so they have low cation-exchange capacity and weak sorption capacity. Under relatively low but stormy and erosive rainfall, the combination of steep topography, high permeability, and limited sorption produces very high leaching potential and high groundwater vulnerability, consistent with assigning Entisols the highest DRASTIC soil rating (6) and with their occurrence in the most vulnerable zones on the maps.

By contrast, Vertisols, mapped mainly in the more humid north-western part of the basin (Fig. 7), have very high clay content and pronounced shrink–swell behaviour, forming dense blocky to wedge-shaped structures dominated by fine pores and few effective macropores. Their saturated hydraulic conductivity is therefore low, and vertical water movement is slow. Mineralogically, Vertisols are rich in expansive clays (e.g., smectites) with clay coatings and oxides on ped surfaces, which confer high cation-exchange capacity and strong sorption of many cationic pollutants and nutrients. Even under higher rainfall, these properties lead to long residence times of water and solutes in the soil profile, low effective leaching of contaminants to the aquifer, and a protective role of the soil. This justifies assigning Vertisols the lowest DRASTIC soil rating (2) and their appearance in the vulnerability maps as belts of relatively low groundwater vulnerability.

Inceptisols, which cover most of the basin area according to Figure 7, represent an intermediate case in both physical and chemical behaviour. Structurally and texturally, they are more developed and finer than Entisols but less dense and restrictive than Vertisols, resulting in moderate permeability and intermediate rates of vertical percolation. They commonly have appreciable clay content and reasonable cation exchange capacity, making them relatively fertile; however, their low organic matter and high carbonate content limit sorption of some organic and anionic contaminants. Under the intermediate rainfall regime where they predominate, contaminants migrate more slowly than in Entisols but are less strongly retained than in Vertisols, producing moderate leaching potential and groundwater vulnerability. Accordingly, Inceptisols receive a medium DRASTIC soil rating and appear on the interpretive maps as zones of moderate vulnerability between the highly and weakly vulnerable areas. Together, the contrasts in structure and permeability, sorption capacity, and local rainfall response among Entisols, Vertisols, and Inceptisols provide a coherent physical and chemical rationale for the assigned DRASTIC ratings and for the spatial pattern of groundwater pollution vulnerability inferred from the soil map (Fig. 7).

3.5. Topography

Topography is related with the graduate slope percentage over the study area. The highest slope has lowest rate (1) because it has low effect in pollution and the lowest slope has a high rate (8) because the opportunity of pollution will increase. Figure 8 shows the variation in slope over study area.

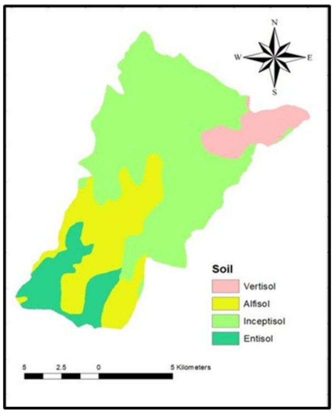

Fig. 7. Soil media

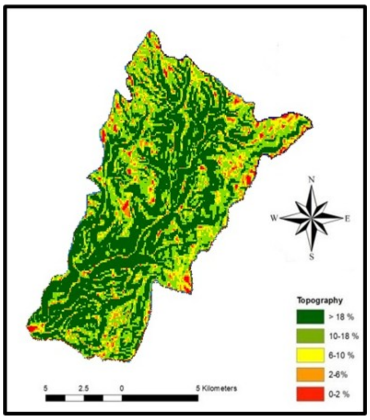

Fig. 8. Topography of study area

3.6. Impact of vadose

The results were shown in Figure 9, indicate a sharp hydrogeological variation in groundwater vulnerability to contamination. The Shuaib Dam area is classified as a maximum risk zone with a rating of (10) due to the nature of the wadi deposits composed of gravel and alluvium, which lack filtration capacity and allow pollutants to pass through at high speeds. This vulnerability decreases to a moderate level (6) across most of the study area, consisting of the Wadi Essir and Hummar formations, due to the structural characteristics of the limestone that provide partial protection. Vulnerability reaches its lowest levels (2) in the northern and eastern parts and around springs, where soil layers over the bedrock act as a protective cover with low permeability that impedes pollutant infiltration, making the geological formation represented by the Aquifer Media parameter the essential driver in identifying the spatial risk zones in your study.

3.7. Hydraulic conductivity

Most of the study area as shown in Figure 10 was characterized by a high hydraulic conductivity rating of 10, which correlates with high permeability geological formations such as sand and gravel or highly fractured rock. This indicates that these zones are highly vulnerable, as contaminants can move rapidly from the surface into the groundwater system with minimal natural attenuation or filtration.

Conversely, the lowest rating of 1 found in a small area of the southern part of the study area signifies a very low hydraulic conductivity. This indicates the presence of low-permeability materials, likely clay or unfractured shale, that function as effective aquitards (confining layers), severely restricting groundwater flow and acting as a strong natural barrier against pollution

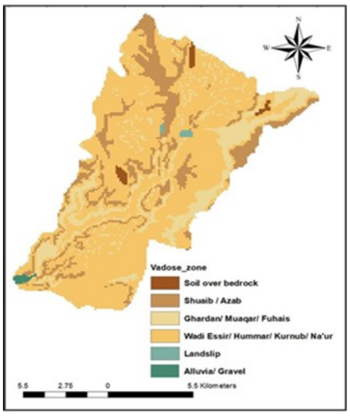

Fig. 9. Impact of vadose

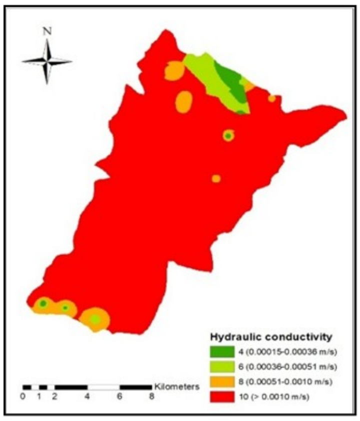

Fig. 10. Hydraulic Conductivity

3.8. Vulnerability map

The final map of vulnerability (Fig. 11) showed 5 categories: very low, low, moderate, high, very high. The very low has yellow colour and the very high has red colour. The very high to high vulnerability concentrated in the southern west part of study area and they had 5% and 6% respectively. A 52% of area showed a low vulnerability and 22% was very low. A moderate vulnerability to contamination located in northwest and north east and had 15% of study area. Table 3 shows area and percentages of each category. The large area was for low vulnerability (88.87 Km^2) and lowest area for very high vulnerability (8.77 Km^2). So, it could be classified as low to very low in general.

By reviewing to overall results, it showed that the main reasons of increasing the vulnerability in the southern west part of study area was related to shallow water depth (<1.5 m) that mean increasing opportunity to polluted by agriculture activity, especially with existing of Entisol group which have alluvial deposit around dam, which is high permeability, and limited sorption produces very high leaching potential and high groundwater vulnerability, consistent with their occurrence in the most vulnerable zones on the maps.

Table 3. Area and percentage of each category derived from attribute table of vulnerability map (GIS)

Category	Severity	Description	Area (Km^2)	percentage
78 - 98		very low	38.64	22
98 - 110		low	88.87	52
110-125		moderate	25.91	15
125-142		high	9.97	6
142-174		very high	8.77	5
Total		----------	172.16	100

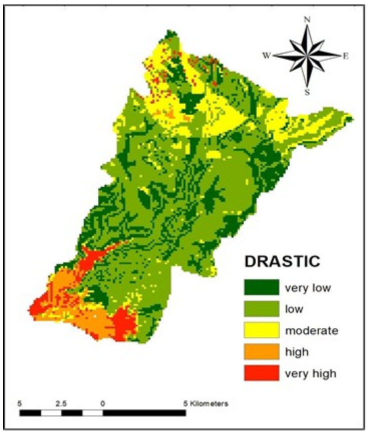

Fig. 11. Final vulnerability map

3.9. Validation of vulnerability map assessment and Groundwater Quality Index (GQI)

To validate vulnerability assessment map of Wadi Shuaib sub-basin and verify water quality, water samples were collected twice annually from drinking water resources in February and August, besides once in February for the source from wastewater treatment plant as shown in Tables 4 and 5 respectively; to calculate groundwater quality index method (GQI) that depended on average concentrations of some pollution indicators; like turbidity, nitrate and *E. coli* as shown in Table 6, to create GQI map by using Arc GIS 10.6.

Table 4. Results of water samples from drinking water resources

Sampled date	Location Description	Escherichia coli	Nitrate	Sulfate	Electrical Conductivity	pH	Turbidity	Hard	TDS
13-FEB-2019 09:50:00.00	Baqouriyyeh Spring Feb	24.6	0.11	34.6	711	7.61	0.22	282	455
3-AUG-2018 09:20:00.00	Baqouriyyeh Spring Aug	8.6	0.095	35.2	803	7.45	0.084	297	514
13-FEB-2019 08:30:00.00	Hazzir Spring Feb	68.3	0.35	63.7	1054	7.36	0.35	358	675
3-AUG-2018 08:20:00.00	Hazzir Spring Aug	920.8	3.50	66.3	1117	7.13	3.60	371	715
13-FEB-2019 09:45:00.00	Shoreai Spring Feb	1.0	0.06	22.1	603	7.53	0.055	251	405
3-AUG-2018 09:15:00.00	Shoreai Spring Aug	8.4	0.09	24.6	633	7.37	0.085	251	413
13-FEB-2019 11:30:00.00	Azraq (Fuheis) Spring Feb	4.1	0.08	20.2	646	7.45	0.07	262	443
3-AUG-2018 11:15:00.00	Azraq (Fuheis) Spring Aug	93.3	0.41	23.3	677	7.30	0.42	279	433
13-FEB-2019 10:00:00.00	WADI JREA'A NO 1 N.R.A Feb	1.0	0.06	29.2	1216	7.40	0.055	258	778
3-AUG-2018 10:00:00.00	WADI JREA'A NO 1 N.R.A Aug	7.6	0.085	25.9	1196	7.21	0.08	238	765
13-FEB-2019 10:35:00.00	WADI JREA'A NO 3 Feb	10.8	0.10	28.6	1208	7.31	0.10	184	773
3-AUG-2018 11:00:00.00	WADI JREA'A NO 3 Aug	3.2	0.07	20.1	1919	6.92	0.05	222	728
13-FEB-2019 11:40:00.00	Yazidiyya No.5 Well Feb	1.0	0.06	43.1	625	7.60	0.065	267	497
3-AUG-2018 09:30:00.00	Yazidiyya No.5 Well Aug	0.0	0.0	31.6	641	7.50	0.01	278	470
13-FEB-2019 11:35:00.00	Fuhais Municipality um alfash Feb	45.0	0.21	63.2	680	8.30	0.26	363	985
3-AUG-2018 12:00:00.00	Fuhais Municipality um alfash Aug	91.4	0.4	58.9	644	7.90	0.41	320	476
13-FEB-2019 12:00:00.00	Wadi Shuaib NRA 11 Feb	468.0	1.7	95.6	1984	8.10	2.0	430	1120
3-AUG-2018 11:00:00.00	Wadi Shuaib NRA 11 Aug	1178.0	4.2	90.1	1773	8.30	4.1	468	1135

Table 5. Results of water samples from wastewater resources

Sampled date	Location Description	Escherichia coli	Nitrate	Sulfate	Electrical Conductivity	pH	Turbidity	TDS	TSS	PHOSPHATE	COD	BOD
13-FEB-2019	Fuheis Wastewater Treatment Plant Effluent	24000	38	69.2	416	7.12	192	279	49	6.1	96	22
13-FEB-2019	Salt Wastewater Treatment Plant Efffluent	170000	110	68.7	1358	7.26	580	910	34	12	132	58
13-FEB-2019	Seil Shueib / sea level	92000	60	56.3	881	8.50	419	590	125	8.2	115	37
13-FEB-2019	Seil Shueib / under bridge	160000	100	52.7	1113	8.50	503	746	450	9	127	49
13-FEB-2019	Shueib Dam Influent	54000	48	60.5	731	8.34	343	490	388	10.3	110	33
13-FEB-2019	Shueib Dam Effluent	7900	16	65.9	460	8.18	52	308	22	3.7	82	12

Table 6. The result of equations of QGI for E. coli, Nitrate and Turbidity as pollution indicator for water sample location

Location Description	Escherichia coli	Cn (E.coli)	R (E.coli)	R*Cn (E.coli)	Nitrate	Cn (NO_3)	R (NO_3)	R*Cn (NO_3)	Turbidity	Cn (Turb.)	R (Turb.)	R*Cn (Turb.)	GQI
Fuheis Wastewater Treatment Plant Effluent	202700.0	0.951853635	9.74	9.27	280.33	0.697272425	8.00	5.84	790.9	0.987439476	9.93	9.81	98.2
Salt Wastewater Treatment Plant Effluent	366000.0	0.973045822	9.85	9.59	185.64	0.575623833	8.35	4.80	602.6	0.983542346	9.91	9.75	98.3
Seil Shueib / sea level	169925.0	0.942832643	9.69	9.13	108.33	0.368407756	7.06	2.64	580.2	0.982911135	9.91	9.74	98.5
Seil Shueib / under bridge	83900.0	0.887514061	9.33	8.83	56.34	0.059620087	5.00	0.30	454.1	0.978216717	9.88	9.67	98.7
Shueib Dam Effluent	15505.0	0.512314070	7.44	3.81	33.71	0.194600406	6.00	1.17	311.3	0.968384545	9.83	9.52	99.0
Shueib Dam Influent	31175.5	0.723569472	8.52	6.16	45.22	0.001995538	6.50	0.01	413.3	0.976096246	9.87	9.63	98.9
Baqouriyyeh Spring	1962.5	0.436272698	7.06	3.08	5.56	0.799856010	9.00	7.13	197.5	0.950267037	9.73	9.25	98.5
Hazzir Spring	390.3	0.855170546	9.21	7.88	1.35	0.947419669	10.00	9.50	50.6	0.820521728	9.10	7.43	98.3
Shoreai Spring	203.2	0.921894015	9.57	8.83	0.88	0.965480805	10.50	9.07	32.5	0.733411342	8.57	6.28	98.2
Azraq Spring	447.3	0.835780330	9.11	7.61	1.90	0.926872274	10.00	9.27	67.3	0.861704948	9.25	7.98	98.7
Shurayah Drinking Water Treatment Plant	1077.1	0.645519730	8.11	5.24	3.80	0.853760590	9.00	7.68	95.8	0.900793651	9.46	8.52	98.8
Yazidiya No.5 Well	8.5	0.996592482	9.98	9.95	0.09	0.996406408	10.00	9.96	13.7	0.465288289	7.20	3.38	98.3
WADI JREA'A NO 1 N.R.A	0.6	0.999743366	10.00	10.00	0.05	0.998001998	10.00	9.98	2.1	0.408450704	6.92	2.83	98.4
WADI JREA'A NO 3	0.6	0.999760029	10.00	10.00	0.05	0.998001998	10.00	9.98	1.8	0.474998809	7.27	3.49	98.3

GQI results indicated a high groundwater quality, with a total values ranging from 98 to 99% for all pollution indicators combined as shown in Table 6, in agreement with the annual water quality reports of the Water Authority of Jordan [14], despite episodic deterioration in some parameters, particularly turbidity and E.coli, which was mainly following winter rainstorms, or flooding of overloaded effluents from wastewater treatment plants into downstream along the wadis feeding the main springs such as Baqouriya, Shuraia, and Azraq. GQI values differed among the individual contamination indicator. GQI values ranging from approximately 90 to 97% for E. coli and turbidity, and about 90 to 99% for nitrate. The maps in Figure 12 show that the GQI for each individual parameter still falls within the good quality class, while Figure 14 presents good overall water quality based on the combined GQI

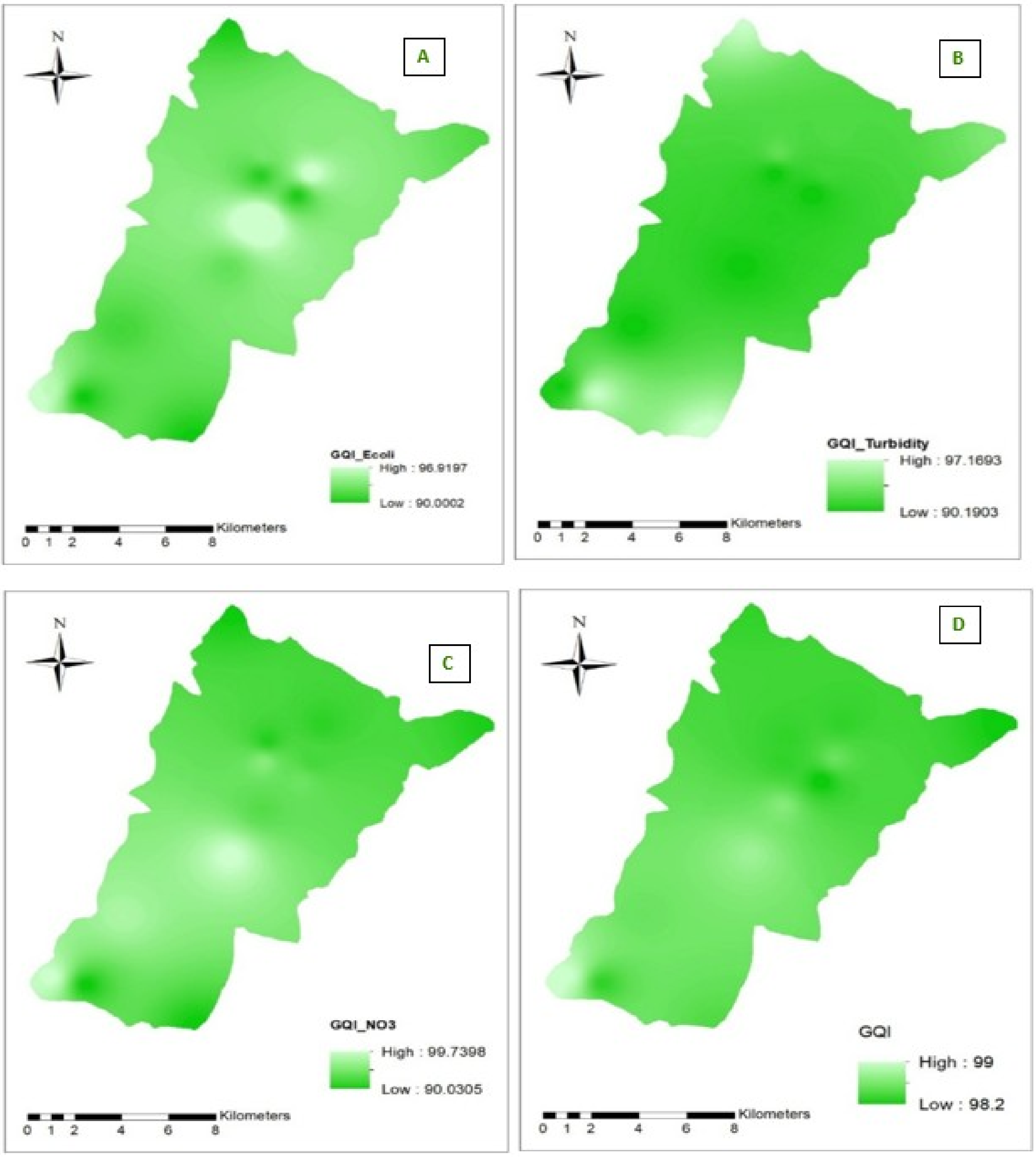

Fig. 12. GQI for A: E. coli, B: turbidity, C: nitrate and D: all quality indicators

3.10. Sensitive analysis

Sensitive analysis was used to determine the role of each parameter of DRASTIC model and its effect on the result of vulnerable maps. It examined the effect of all parameters on final vulnerability map of DRASTIC model. Table 7 showed that all parameters have a statistically significant effect on the vulnerability index at a significance level of $P < 0.05$. The depth-to-water (D) parameter was significant in 98.05% of the tested cases and exhibited a predominantly negative influence (84.38%), with a very low coefficient of determination ($R^2 = 0.01$), indicating that small variations in depth can strongly reduce the calculated vulnerability. In contrast, net recharge (R), topography (T), impact of the vadose zone (I), and hydraulic conductivity (C) were significant in 100% of the cases, had an entirely positive effect (100%), and showed R^2 values of 0.12, 0.07, 0.18, and 0.04, respectively, confirming that increases in these parameters systematically lead to higher vulnerability scores. The aquifer media (A) parameter was also highly influential, being significant in 91.41% of the tests with a predominantly positive impact (83.59%) and a low R^2 of 0.001, while soil media (S) was significant in 96.09% of the cases and showed a mixed but mainly negative effect (55.08%) with $R^2 = 0.03$, suggesting that finer or less permeable soils contribute to lowering the DRASTIC vulnerability values.

Table 7. Result of sensitivity analysis of all DRASTIC parameters

Variables	Significant % at P value < 0.05	Negative or positive %	R^2
D	98.05 %	- 84.38 %	0.01
R	100 %	+ 100 %	0.12
A*	91.41 %	+ 83.59 %	0.001
S	96.09 %	- 55.08 %	0.03
T	100 %	+ 100 %	0.07
I	100 %	+ 100 %	0.18
C	100 %	+ 100 %	0.04

Based on the sensitivity analysis that was carried out, the priority of the parameters can be ordered according to their positive effect in increasing vulnerability first, followed by those that have a reducing effect on the aquifer vulnerability:

Impact of the vadose zone (I) is the dominant control on intrinsic vulnerability, being significant in 100% of the tests with a positive influence and the highest R^2 (0.18). This agrees with results from Djemai et al. (2016) in northeastern Algeria and from similar studies in Morocco, where the vadose-zone parameter showed the strongest sensitivity and was identified as the main driver of DRASTIC vulnerability patterns in alluvial and fractured aquifers. The parameters Net recharge (R), Topography (T), and Hydraulic conductivity (C) are also significant in all simulations, with a consistently positive effect and intermediate R^2 values (0.12, 0.07, and 0.04, respectively), confirming that increasing recharge, slopes that favour focused infiltration, and more permeable formations systematically increase the vulnerability index. Comparable findings were reported for the Delhi region in India, where sensitivity analysis showed that recharge and hydraulic conductivity were among the most influential factors controlling contaminant migration and the spatial distribution of high-risk zones in DRASTIC-based maps [24].

For Aquifer media (A), the parameter is significant in 91.41% of the cases with a predominantly positive impact (83.59%), yet it has a very low R^2 (0.001), indicating that aquifer lithology sets the overall vulnerability level but contributes little to explaining local variations between grid cells. Aquifer similar pattern was observed in a Pakistan basin where the aquifer consisted largely of homogeneous carbonate formations; there, Aquifer was conceptually important but exhibited low statistical sensitivity because lithological variability at the model scale was limited [16]. In contrast, Depth to water (D) and Soil media (S), despite their high significance (approximately 98% and 96%, respectively), show a predominantly negative effect on vulnerability (around −84% for D and −55% for S) and low R^2 values (0.01 and 0.03). This confirms that deeper groundwater levels and finer, less permeable soils act as protective factors that reduce vulnerability, but the relatively small spatial variability of depth and soil texture in the basin constrains their explanatory power. Comparable behaviour has been documented in several regional DRASTIC applications for example, in Tunisia where D and S were recognized as protective parameters with negative contributions to vulnerability, yet they displayed moderate to low sensitivity in areas characterized by limited variation in water-table depth and soil properties [19].

Based on the above, a revised prioritization of the DRASTIC model parameters can be proposed, together with new weights (from the highest to the lowest influence) as an initial scheme for the modified model, while keeping the total weight close to 26, similar to the original DRASTIC:

The proposed order of parameters from highest to lowest priority is: Impact of vadose zone (I), Net recharge (R), Hydraulic conductivity (C), Topography (T), Aquifer media (A), Depth to water (D), and Soil media (S) as shown in Table 8. The weights of I, R, and C were increased because their sensitivity is 100% with a completely positive influence and relatively higher R^2 values. The weight of T was raised to 3 to reflect its clear role in controlling residence time within the Wadi Shuaib basin. The weight of A was kept at 3 because it is influential but has a low R^2, indicating a nearly homogeneous aquifer medium. In addition, the weight of D was reduced from 5 to 3 and S was kept at 2, since in this study both parameters generally act to reduce vulnerability and explain a smaller portion of the spatial variability.

Table 8. Proposed weight for DRASTIC Model parameters according to its effect & Priorities

Parameter	Original weight	Proposed weight
I	5	6
R	4	5
C	3	4
T	1	3
A	3	3
D	5	3
S	2	2

To validate the proposed set of modified weights for the DRASTIC model parameters, they should be compared against the results of the GQI maps for both the overall pollution indicator and the individual indicators (E. coli, nitrate, and turbidity) shown in Figure 12. These GQI maps do not show any apparent contradiction with the modified weighting scheme; instead, they exhibit a clear spatial agreement with it. The four GQI maps (for E. coli, turbidity, nitrate, and total GQI) display relatively high index values (approximately 90–99%) over most of the basin, with only limited hotspots where the values decrease slightly. These hotspots coincide predominantly with effective recharge zones characterized by shallow groundwater levels and highly permeable alluvial soils, which are the same locations classified as high vulnerability in the final vulnerability map.

This pattern supports the conceptual assumption that I (impact of the vadose zone), R (net recharge), C (hydraulic conductivity), and T (topography) are the dominant parameters controlling contaminant transport. Consequently, increasing their weights in the modified DRASTIC model reflects the role that is independently confirmed by the GQI maps in the field. Moreover, the fact that the overall GQI still falls within the "good" quality class, while exhibiting localized declines after storm events, is consistent with a vulnerability model that assigns higher weights to rapid-transport parameters (I, R, C, T), because these parameters better explain the quick response of indicators such as E. coli and turbidity than more slowly varying parameters such as D (depth to water) and S (soil media).

Finally, the absence of extensive areas with poor water quality, despite the presence of some high-vulnerability hotspots, supports the view that the proposed re-weighting does not overestimate risk but rather focuses on potential-risk zones that show a measurable quality response under increased loading (rainfall events, leakage of wastewater). Therefore, from both a hydrogeological standpoint and a spatial-correspondence perspective, the proposed weights can be recommended as a preliminary modified DRASTIC configuration, with the proviso that the procedure be completed by recalculating a new vulnerability map using the adjusted weights and statistically comparing it with GQI and nitrate data to quantitatively verify the improvement in correlation in future work.

4. Conclusions and recommendations

The findings of this study demonstrate that the classical DRASTIC framework can reliably delineate the intrinsic vulnerability of the Wadi Shuaib sub-basin, but that its performance is significantly enhanced when calibrated to local hydrogeological conditions. The modified vulnerability map indicates that roughly three quarters of the basin fall within low to very low vulnerability classes, whereas only about 11% of the area is classified as high to very high vulnerability, mainly in the south-western sector where shallow groundwater levels, highly permeable alluvial Entisols and intensive agricultural activities coincide. These settings favour rapid percolation and limited sorption, confirming that groundwater depth, vadose-zone properties and hydraulic conductivity are the principal controls on vulnerability in the study area.

Sensitivity analysis, together with the spatial patterns of the Groundwater Quality Index (GQI) for E. coli, nitrate, turbidity and the combined indicator, showed a strong spatial agreement between high-vulnerability zones and locations that exhibit short-term deterioration in water quality following storm events, while total GQI values (approximately 90–99%) generally remain within the "good" class. This concordance supports the proposed re-weighting of the DRASTIC parameters, which assigns greater importance to the impact of the vadose zone, net recharge, hydraulic conductivity and topography, and relatively lower weights to aquifer media, depth to water and soil media. The modified DRASTIC configuration therefore provides a more realistic representation of pollution risk and constitutes a robust decision-support tool for delineating wellhead protection areas, prioritizing land-use controls and targeting mitigation measures in Wadi Shuaib and comparable semi-arid basins. Future work should focus on recalculating vulnerability with updated monitoring data and quantitatively validating the model against additional hydrochemical indicators to further refine its predictive capability.

References

[1] Abbassi B.E., Khrisat H. and Alnewashi, Q.: Municipal solid waste management at Salt City in Jordan: Community perspective. Journal of Food, Agriculture & Environment, 2009, 7(2), pp.740–745. Available at: https://www.wflpublisher.com/Abstract/2351

[2] Al-Kharabsheh N. and Al-Kharabsheh A.: Influence of urbanization on water quality deterioration of Northern Wadi Shu'eib catchment area springs, Jordan. Jordan Journal of Earth and Environmental Sciences, 2014, 6(1), pp.29–35.

[3] Aller L., Bennett T., Lehr J.H., Petty R.J.: DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings. 1987, EPA Report 600/2-87-035.

[4] Department of Statistics, Jordan statistical yearbook, 2016, Issue No. 67, Amman.

[5] Gonçalves V., Albuquerque A., Carvalho P., Almeida P. and Cavaleiro V.: Groundwater vulnerability assessment to cemeteries pollution through GIS-based DRASTIC index. Water, 2023, 15(4), 812. https://doi.org/10.3390/w15040812 .

[6] Hammour N. and El-Naqa A.: GIS based hydrogeological vulnerability mapping of groundwater resources in Jerash area–Jordan. Geofísica Internacional, 2008, 47(2), pp.85–97. https://doi.org/10.22201/igeof.00167169p.2008.47.2.70

[7] Jiries A., Ta'any R., Abbassi B. and Oroud I.: Agriculture water use efficiency in Wadi Shu'eib area, Jordan. Polish Journal of Environmental Studies, 2010, 19(2), pp.317–324 .

[8] Khrisat, H.T.: Optimization of integrated solid waste management improvement scenarios for Salt City in Jordan using computer based decision support tool. Open Access Library Journal, 2022, 9, e8900. https://doi.org/10.4236/oalib.1108900 .

[9] Khrisat H. T.: Risk assessment of drinking water using WSP for Azraq Spring-Jordan. Open Access Library Journal, 2022, 9, e8899. https://doi.org/10.4236/oalib.1108899 .

[10] Khrisat H.T. and Al-Bakri J.: Assessment of groundwater vulnerability in Azraq catchment in Fuhais-Jordan using DRASTIC model. Open Journal of Geology, 2019, 9, pp.364–377. https://doi.org/10.4236/ojg.2019.97024 .

[11] Khrisat H. T.: Impact of using different mulches on clay soil temperature, moisture, and saved water at AsSalt City-Jordan. Journal of Research and Applications in Agricultural Engineering, 2025, pp.1–7. https://doi.org/10.53502/jraae-214875

[12] Lakhdar Seraiche L., Dougha M., Ghodbane M., Selmane T., Ferhati A. and Djemiat D.E.: Groundwater vulnerability assessment in semi-arid regions using GIS-based DRASTIC models and FUZZY AHP: South Chott Hodna. Desalination and Water Treatment, 2025, 323, 101380. https://doi.org/10.1016/j.dwt.2025.101380 .

[13] Ministry of Water and Irrigation (MWI), National water master plan for Jordan, 2004. Amman: MWI .

[14] Ministry of Water and Irrigation (MWI), National water master plan for Jordan, 2004. Amman: MWI .

[15] Awawdeh M., Al-Kharabsheh N., Obeidat M., & Awawdeh M.: Groundwater vulnerability assessment using modified SINTACS model in Wadi Shueib, Jordan. Annals of GIS, 2020, 26(4), 377–394 https://doi.org/10.1080/19475683.2020.1773535 .

[16] Muhammad A.M., Zhonghua T., Dawood A.S. and Earl B.: Evaluation of local groundwater vulnerability based on DRASTIC index method in Lahore, Pakistan. Geofísica Internacional, 2015, 54(1), pp.67–81. https://doi.org/10.1016/j.gi.2015.04.003

[17] Rahmani Gh. R., Chitsazan M., Zaresefat M., Kalantari N. Evaluation of groundwater quality for drinking with GQI in Ize – Piyon plain. Fourth International Conference on Water Resources Management of Iran, 2011.

[18] Riepl D.: Knowledge-based decision support for integrated water resources management with an application for Wadi Shueib, Jordan. PhD thesis, 2012, Universität Karlsruhe .

[19] Saidi S., Bouri S. and Ben Dhia H.: Sensitivity analysis in groundwater vulnerability assessment based on GIS in the Mahdia–Ksour Essaf aquifer, Tunisia: A validation study. Hydrological Sciences Journal, 2011, 56(2), pp.288–304. https://doi.org/10.1080/02626667.2011.552886 .

[20] Singhal B.B.S. and Gupta R.P.: Applied hydrogeology of fractured rocks, 2nd ed. Dordrecht: Springer, 2010, ISBN-13:978-9048187980.

[21] Ta'any A.: Assessment of groundwater vulnerability to pollution sources at Salt urban area. MSc thesis, 2009, Al-Balqa Applied University, Jordan.

[22] Ta'any R.: Hydrological and hydrochemical study of the major springs in Wadi Shu'eib catchment area. MSc thesis, 1992, Yarmouk University, Jordan .

[23] Tesoriero A.J., Inkpen E.L. and Voss F.D.: Assessing ground-water vulnerability using logistic regression. In: Proceedings of the Source Water Assessment and Protection Conference, Dallas, TX, 1998, pp.157–165 .

[24] Singhal B.B.S. and Gupta R.P.: Applied hydrogeology of fractured rocks, 2nd ed. Dordrecht: Springer, 2010, ISBN-13:978-9048187980,

[24] Tomer T., Katyal D. and Joshi V.: Sensitivity analysis of groundwater vulnerability using DRASTIC method: A case study of National Capital Territory, Delhi, India. Groundwater for Sustainable Development, 2019, 9, 100271. https://doi.org/10.1016/j.gsd.2019.100271

[25] Zagana E., Obeidat M., Kuells C. and Udluft P.: Chloride, hydrochemical and isotope methods of groundwater recharge estimation in eastern Mediterranean areas: A case study in Jordan. Hydrological Processes, 2007, 21(16), pp.2112–2123. https://doi.org/10.1002/hyp.6390
[26] Babiker I.S., Mohamed M.A.A., Hiyama T.: Assessing groundwater quality using GIS. Water Resour. Manage, 2007, 21(4): 699 –715. https://doi.org/10.1007/s11269-006-9059-6
[27] Singh A., Srivastav S. K., Kumar S., & Chakrapani G. J.: A modified-DRASTIC model (DRASTICA) for assessment of groundwater vulnerability to pollution in an urbanized environment in Lucknow, India. Environmental Earth Sciences, 2015, *74,* 5475-5490. https://doi.org/10.1007/s12665-015-4558-5