Modeling the Risk of Groundwater Contamination using Modified DRASTIC and GIS in Amman-Zerqa Basin, Jordan

Research Article

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Abstract: Amman-Zerqa Basin (AZB) is the second largest groundwater basin in Jordan with the highest abstraction rate, where more than 28% of total abstractions in Jordan come from this basin. In view of the extensive reliance on this basin, contamination of AZB groundwater became an alarming issue. This paper develops a Modified DRASTIC model by combining the generic DRASTIC model with land use activities and lineament density for the study area with a new model map that evaluates pollution potential of groundwater resources in AZB to various types of pollution. It involves the comparison of modified DRASTIC model that integrates nitrate loading along with other DRASTIC parameters. In addition, parameters to account for differences in land use and lineaments density were added to the DRASTIC model to reflect their influences on groundwater pollution potential. The DRASTIC model showed only 0.08% (3 km²) of the AZB is situated in the high vulnerability area and about 30% of the basin is located in the moderately vulnerable zone (mainly in central basin). After modifying the DRASTIC to account for lineament density, about 87% of the area was classified as having low pollution potential and no vulnerability class accounts for about 5.01% of the AZB area. The moderately susceptible zone covers 7.83% of the basin's total area and the high vulnerability area constitutes 0.13%. The vulnerability map based on land use revealed that about 71% of the study area has low pollution potential and no vulnerability area accounts for about 0.55%, whereas moderate pollution potential zone covers an area of 28.35% and the high vulnerability class constitutes 0.11% of AZB. The final DRASTIC model which combined all DRASTIC models shows that slightly more than 89% of the study area falls under low pollution risk and about 6% is considered areas with no vulnerability. The moderate pollution risk potential covers an area of about 4% of AZB and the high vulnerability class constitutes 0.21% of the basin. The results also showed that an area of about 1761 km² of bare soils is of low vulnerability, whereas about 28 km² is moderately vulnerable. For agriculture and the urban sector, approximately 1472 km² are located within the low vulnerability zone and about 144 km² are moderately vulnerable, which together account for about 8% of the total agriculture and urban area. These areas are contaminated with human activities, particularly from the agriculture. Management of land use must be considered when changing human or agricultural activity patterns in the study area, to reduce groundwater vulnerability in the basin. The results also showed that the wells with the highest nitrate levels (81-107 mg/l) were located in high vulnerable areas and are attributed to leakage from old sewage water.

Keywords: Groundwater • Nitrate • DRASTIC • Amman Zerqa Basin • Jordan

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1. Introduction

Groundwater constitutes the largest single source of freshwater in many parts of the world and provides a risk buffer to sustain critical water demands during drought cycles, especially in semi-arid and arid regions [1]. In many parts of Jordan, groundwater provides nearly all of the water supply for drinking and agricultural activities. However, the growing demand for water has placed substantial pressures on water resources. These demands for water continue to rise due rapid population growth and climate change. The increasing gap between the demand for water use and the supply of water has resulted in considerable competition between sectors. In view of the extensive reliance on groundwater resources in Jordan, contamination of groundwater became a widespread issue and poses imminent threats to these resources. Remediation of polluted aquifer resources is always expensive and protracted, and is often abandoned, leading to loss of valuable resources at a considerable economic cost. As the conservation of water resources is critically important for Jordan, groundwater vulnerability studies are increasingly becoming a subject of research [2–8]. Among others, aquifer vulnerability to pollution by the DRASTIC method has been frequently used.

Shirazi et al., [9] compared and assessed literature related to GIS-based DRASTIC method for groundwater vulnerability assessment. The paper compared various groundwater vulnerability assessments methods in order to identify research gaps. It concluded that a modified GIS-based DRASTIC method, compared to a generic DRASTIC model, was able to assess an extensive amount of complex databases and proved to be a good model for groundwater vulnerability assessment in agricultural, arid, semi-arid and basaltic regions. Al-Hallaq and Elaish [10], used the DRASTIC model to assess aquifer layers in order to determine vulnerability assessment of the groundwater contamination in the Khanyounis governorate, Egypt. Al Hallaq used ArcGIS 9.3 software to create a GIS model of the vulnerability assessment and determined that contamination rates increased when low water table levels, vadose zone, were found. Soil media and vadose zones therefore had the greatest impact on assessing groundwater vulnerability. Shamrukh et al., [11], examined the effects of nitrogen and phosphorus chemical fertilizers on groundwater contamination in the Nile valley, Egypt, and used that data to predict trends resulting from future fertilizer uses. The authors determined that phosphorus levels were not yet of concern but that simulation revealed that within 20 years it will exceed guidelines. Low elevation water supplies already exceed drinking water guideline concentrations

for nitrogen levels. The paper emphasizes that continuous monitoring and early detection of contamination levels is essential and deep wells can be used as an alternative water supply. Al-Hanbali and Kondoh [12], examined groundwater contamination vulnerability within the Dead Sea groundwater basin, Jordan, using the DRASTIC model and HAI index. The authors determined that groundwater quality is related to the amount of human activity, proximity to fault and drainage systems, and the impact of the vadose zone, aquifer medium present in the area. The study determined that water table depth and hydraulic conductivity parameters had very little impact on contamination results which were verified using nitrate concentrations provided by the Jordanian ministry of water and irrigation. Jasem and Alraggad [13], emphasized that land use map and detailed environmental impact assessment study of groundwater should be carried out before beginning any project. Examining the land use of an area, based on the contamination risk assessment, is the proposed method used to lower contamination of precious groundwater resources. Contamination assessment for the Azraq basin, Jordan, was examined as the study area and authors used the DRASTIC vulnerability index, examined rainfall, topographic detail, soil permeability, human activities and classified the area into four vulnerability zones. Awawdeh and Jaradat [7], assessed the aquifers vulnerability to contamination in the Yarmouk River basin based on modified DRASTIC method. The general DRASTIC index for groundwater pollution was low in the whole basin, and the pesticide DRASTIC vulnerability map indicated that about 31% of the basin is classified as having moderate vulnerability, which may be attributed to agricultural activities in the area.

Amman Zerqa Basin (AZB) is a transboundary basin shared between Jordan and Syria, of which about 90% lies in Jordan. It is home for about 60% of Jordan's population [14] and hosts about 70% of Jordan's industrial activities. AZB is subject to extreme and increasing water scarcity, where more than 28% of total groundwater abstractions in Jordan come from this basin. The geographic location and altitudinal variations of AZB, in a transitional area between the highlands in the west and the desert in the east (Figure 1), makes it of diverse biological communities, land use patterns as well as climatic conditions. The average annual precipitation in the western part of the basin is about 400 mm and is relatively densely populated, whereas the average annual rainfall in the eastern basin (fully desertic) is about 150 mm with small communities of Bedouins.

Irrigated cultivation is common in the vicinity of groundwater wells and along the Zerqa River banks, whereas rain-fed agriculture is found in highlands where

Figure 1. Map showing the location of the AZB.

high rainfall occurs. The basin is also covered by sporadic vegetation (normally used for grazing), bare soil, rocky areas and forests. In addition to the intensive agriculture with frequent use of fertilizers and pesticides, the basin has also suffered from unplanned industrial development which have resulted in land degradation and desertification, mining and salinization of groundwater, reduced river base flow, and deforestation processes. In addition, Zerqa River received wastewater discharged from Khirbet As-Samra wastewater treatment plant. Nitrate concentrations in excess of Jordan standards for drinking water are widespread, particularly in the intensively cultivated areas [11, 15, 16]. In Jordan, groundwater contamination is of particular concern as groundwater resources are the principal source of water for irrigation, drinking and industrial activities.

Protection of groundwater resources is always cheaper than remediation and restoration of the aquifer, and in most cases it is very difficult to remediate an aquifer to its original state. One of the tools supporting decision-making in aquifer protection is the evaluation of shallow aquifer vulnerability. Groundwater vulnerability maps have become a widely accepted tool in the land use planning process.

In this paper, The main objective is to produce vulnerability maps of groundwater resources in the AZB using the DRASTIC method, and develops a Modified DRASTIC model by combining the generic DRASTIC model with landuse activities and lineament density for the study area with a new model map that evaluates pollution potential of groundwater resources in AZB to various types of pollution. In addition, parameters to account for differences in land use and lineaments density were added to the DRASTIC model to reflect their

influences on groundwater pollution potential. Therefore, Two additional parameters were added to DRASTIC model in order to map the groundwater vulnerability in the study area more accurately: lineaments density and land use/land cover. The depth to water alone does not provide a protection for groundwater against the contaminants infiltration as it is possible that the pollutant may penetrate the aquifer through fractures even if the aquifer is deep [17]. Following this logic, the modified DRASTIC system is the sum of the original DRASTIC system and the fractures density which is obtained by using aerial photographs and geological maps. Also, the AZB contains many agricultural activities, industrial, and urban centers that depend on septic tanks that are the most hazardous potentials that may affect the groundwater. It is important to make clear the distinction between vulnerability and risk because risk of pollution is determined not only by the intrinsic characteristics of the aquifer (which are relatively static) but also by the existence of potentially polluting activities (which are dynamic factors that can in principle be both changed and controlled [18]. To evaluate potential risk, an additional parameter can be integrated into the analysis, which is the landuse map.

2. Methodology

2.1. Materials and Data Sources

All relevant data attributes were used to create the shape files with ESRI-GIS software, including the geological, hydrogeological, hydrological, hydrochemical, and environmental aspects in the study area, sources of data are presented in Table 1. Structural contour maps, drainage boundaries, groundwater flow systems, and the topographic map were digitized and converted into shape files (layers) (Table 1). Formation thickness, saturation thickness, and depth to water levels were also calculated. In addition, water samples were selected to cover most of the aquifers in the study area. Water samples in 54 wells (Figure 2) from different groundwater aquifers in the AZB were collected and sampled in one-liter polyethylene bottles and analyzed for NO_3^- (by Spectrophotometer).

Water samples were stored in the refrigerator until analyzed to prevent deterioration and changes in water quality. The pH of each water sample was estimated by a pH meter. A spectrophotometer (Thermo, Evolution100) was used to determine the concentration of NO_3^- . Nitrate concentration was determined by adding 25 mL from each sample into an Erlenmeyer flask. 0.5 mL 1N HCl was added to the sample and to the blank (distilled water) and the absorbance was measured by the use of a spectrophotometer at 220 nm [19]. A calibration curve

Figure 2. Locations of water samples in the study area.

was used to determine the expected ion concentration of a measured sample. The curve contained at least three concentrations of each standard ion solution. When plotting the absorbance of the desired standard with its concentration, the curve must have a linear relationship with regressions (R^2) and cover more than 99% of the calibrated range; taking into consideration that all of the reference standards were certified.

2.2. Groundwater Aquifers

The hydrogeology of the study area is controlled by the dominant geological structures that affect water level, movement, and occurrence of groundwater. The principal factors in determining the potential of the area to be water-bearing is the permeability and secondary porosity, both of which are directly related to the structure [23]. Groundwater occurs mostly in fractured and cavernous limestone, fractured chert; sandstone voids, and wadi fill deposits, which includes four aquifer systems. The Aquifer Complex for the AZB is split up into three sections. The upper aquifer complex consists of limestone and marl of the Upper Cretaceous with a thickness ranging between of 600 and 700 m. Groundwater generally moves eastwards and is made up of the alluvial deposits aquifer, restricted to major wadis and plateau gravel deposits (silts, clays, and gravel); basalt aquifer. It covers most of Wadi Dhuleil and north-east desert areas, and Amman-Wadi Sir (B2/A7) aquifer, overlying the Hummer Aquifer (comprised of Al-Hisa, B2, and Wadi Es Sir, A7), which composed of chert and limestone.

The middle aquifer system (the late Cretaceous aquifers) consists of Hummar (A4) and Na'ur (A1/2) formations. The

Figure 3. Hydrogeological map of the study area (modified after [20]).

Upper Cretaceous aquifers, within the Ajlun and Belqa groups, represent the main aquifers in the study area. The Ajlun group yields water generally from limestone and dolomitic limestone, whereas the Belqa group drains its water from the limestone and chert horizons. The A1/2 is a confined aquifer, separated from A4 by a thick bed of Fuheis marl aquifer (A3). Two subunits are recognized within this aquifer: the lower part (A1) consists of marls and ranges in thickness between 60 and 120m, forming the confining layer that separates the A1/2 from the underlying Kurnub Sandstone Aquifer. The upper part (A2) consists of a thick limestone layer of 100 and 150 m thickness (Figure 3) [23]. The lower aquifer complex, with a thickness increasing northward, consists of sandstone interrupted by thin layers of marl and limestone from the lower Cretaceous. According to Salameh and Udult [24], the thickness is about 600 m with a general groundwater movement towards the west. The lower aquifer system consists of the Kurnub group with a maximum thickness of about 300 m [25]. It crops out in the north of the upper AZB and encounters at a depth of about 480 m south of Amman and 530 m near Zerqa. It is a semi-confined aquifer that underlies the carbonate aquifers and is separated by the marls and shales of Na'ur formation by a thickness of about 100 m. More details of the geology is shown in Figure 4.

2.3. Generic DRASTIC Model

DRASTIC method to estimate vulnerability of an aquifer is a popular tool because of the minimum data requirement. The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against natural impacts, especially with regard to contaminants entering the subsurface environment [27]. Vulnerability maps show

Table 1. Data sources for the DRASTIC model.

Data Source	Criteria
Depth to groundwater	[20] (WAJ, 2006)
Net Recharge	[21, 22] (WAJ, 2006); (MOA, 1994)
Aquifer media	[20] (WAJ, 2006)
Soil media	[21] (MOA, 1994)
Topography	DEM from 90 meter resolution (Radar DEM)
Impact of Vaduz zone	[20] (WAJ, 2006)
Hydraulic Conductivity	[20] (WAJ, 2006)
Land use map	[22] (Salameh, 2006)

Figure 4. Geological cross-section A-A' from Amman Zerqa Basin [26].

the distribution of areas that are highly vulnerable to contamination.

The DRASTIC model uses seven parameters of the natural system, which are rated from 1 to 10. Each parameter is then weighted from 1 to 5. The rates and weights are multiplied for each parameter and added together to produce a so-called vulnerability index [8, 28–31]. The most significant parameters have weights of 5, and

the least are assigned a weight of 1 (Table 2). These parameters include the depth to groundwater (D), net recharge (R), lithology of the aquifer (A), soil texture (S), topography (T), lithology of vadose zone (I), and hydraulic conductivity (C) (Table 3). Each of the seven DRASTIC parameters is mapped and classified either into ranges or into significant media types, based on its pollution potential (Figure 5). Each factor or parameter is

also assigned a subjective rating. Weight multipliers are then used for each factor to balance and enhance their importance. The final vulnerability map is based on the DRASTIC index (DI) which is computed as the weighted sum overlay of the seven layers, using Equation (1):

$$DI = Dr \cdot Dw + Rr \cdot Rw + Ar \cdot Ar + Sr \cdot Sw + Tr \cdot Tw + Ir \cdot Iw + Cr \cdot Cw \quad (1)$$

where D , R , A , S , T , I , and C are the seven parameters; r is the rating value, and w is the weight associated with each parameter (Table 4).

Once the DRASTIC Index is computed, it is possible to identify areas that are more susceptible to groundwater contamination. The higher the DRASTIC Index, the greater the groundwater pollution potential. The seven sets of data layers are digitized and converted to raster data sets that are processed using ArcGIS 9.2. In the DRASTIC method, it is assumed that: (1) the contaminant is introduced at the ground surface; (2) the contaminant is flushed into the groundwater by precipitation; (3) the contaminant has the mobility of water; and (4) the area evaluated is 100 acres or larger [28]. Furthermore, the numerical weights and ratings, established using the Delphi technique [20], are well defined and have been used worldwide (2, 8, 27, 32, 33, 34, 35, 36, 37, 38). The Delphi technique uses the practical and research experiences of professionals in the area of interest to assess levels of risk. The sources for the seven factors are presented in (Table 1).

2.4. Modifications of DRASTIC Model

2.4.1. Modified DRASTIC Model based on Lineaments Density Map

The lineaments refer to as linear features detected on aerial photographs and satellite images, which presumably have a geological origin. Generally, lineaments are underlain by a zone of localized weathering and increased permeability and porosity. Previous studies have revealed a close relationship of lineaments (or lineaments density) and groundwater flow and yield [39–44]. Therefore, mapping of lineaments is essential to groundwater surveys, development and management [45]. Higher lineament density values may indicate more potential groundwater contamination. A lineaments map is derived from Enhanced Thematic Mapper plus (ETM+) satellite imagery.

In the study area, most of the aquifers are developed in fractured rock, so groundwater mainly moves through fault and fracture. Integrated lineament density and the DRASTIC model assess groundwater susceptibility more

accurately. The method of photolineament factor value calculation is shown in (Figure 6).

The calculated lineament density was assigned ranges and ratings according to Table 4. The weight of lineament density was assigned a value based on its relative importance. Figure 7 shows the lineament density as assigned by ranges and ratings (Table 4) and overlaid with the DRASTIC model. The modified DRASTIC system index was calculated using Equation (2):

$$DL(i) = DI + (\text{Lineament Density Index}) \quad (2)$$

where: $DL(i)$ is the modified DRASTIC model using lineament density; DI is the generic DRASTIC index and the (lineament density index (ratings· weights)).

Table 4 shows the distribution of the lineament density rate of the study area; the value of 1 covers 77.08%, the value of 5 covers 3.20%, and the value of 10 covers 0.432% of the study area.

2.4.2. Modified DRASTIC Model based on Land Use Map

It is important to make a clear distinction between vulnerability and risk. This is due to the fact that risk of pollution is determined not only by the intrinsic characteristics of the aquifer (which are relatively static) but also by the existence of potentially polluting activities (which are dynamic factors) that can in principle be both changed and controlled [18]. To evaluate potential risk, an additional parameter can be integrated into the analysis, which is the land use map. Land use map is an important factor that must be included in groundwater vulnerability maps because it strongly affects the groundwater quality as shown in Table 5.

The extensive land use, mainly agriculture, can result in potential changes of soil nature and hydraulic conductivity [46]. Thus, land use is rated and weighted as additional DRASTIC model factor. ETM + satellite imagery was used to infer categories of land use/land cover in the study area in order to introduce a land use factor into DRASTIC index. The land use map of the AZB is shown in Figure 8.

The western and northeastern parts of the study area contain more than 31.79% of agricultural activities and vegetation. According to the National Soil Map and Land use Project of Jordan, the land use of the AZB varies from urban and non-agricultural land, to non-vegetated and sparsely vegetated land (bare rocks and basalt) to ruined agricultural land (open field crops and fallow lands). Remote sensing technique was used to produce the land use map using satellite Landsat images (ETM+, 2002). Accordingly, the total amount of irrigated land

Table 2. DRASTIC parameters used in the study [28].

1. Depth to Groundwater							
Ranges (m)	Ratings(Dr)	Index (D)	Area (%)	Area (km ²)			
0 – 1.5	10	50	0.03	1			
1.5 – 4.75	9	45	0.08	3			
4.75 – 9.14	7	35	0.18	17			
9.14 – 15.24	5	25	0.5	19			
15.24 – 22.86	3	15	1.08	41			
22.86 – 30.48	2	10	5.12	194			
> 30.48	1	5	93.01	3527			
Weight 5							
2. Net Recharge (mm/year)							
3-5	1	2	18.58	663			
5-7	3	6	45.01	1606			
7-9	5	10	36.41	1299			
Weight 2							
3. Aquifer Media							
Muwaqqar chalky marl (marl, limestone)	2	6	6.2	233.75			
Kurnub (Sandstone)	6	18	9.4	357.85			
Lower Ajlun (marl, limestone, dolomite)	8	24	20.1	762.96			
Rijam/Wadi Shallaleh (limestone, chalk, chert)	9	27	64.3	2438.46			
Basalt							
Amman/Wadi Sirlimestone (dolomitic limestone)							
Weight 3							
4. Soil Media							
Clay Loam	3	6	17.16	651			
Silty Loam	4	8	39.86	1512			
Loam	5	10	15.21	577			
Shrinking and/or	7	14	19.22	729			
Sand	8	16	8.54	324			
Weight 2							
5. Topography (%)							
0-2	1	1	12.5	447			
2—6	3	3	13.22	473			
6—12	5	5	14.23	509			
12—18	9	9	30.22	1081			
> 18	10	10	29.83	1067			
Weight 1							
6. Impact of the Vadose Zone							
Silt/clay	2	10	1.53	58			
Shale, Limestone	3	15	40.68	1543			
Sandstone, Bedded limestone, Sand and gravel with silt	6	30	35.51	1347			
Sand and gravel	8	40	19.88	754			
Basalt	9	45	2.4	91			
Weigh 5							
7. Hydraulic Conductivity (m/s)							
4.716·10 ⁻⁷ – 4.716·10 ⁻⁵	1	3	18.96	719			
4.716·10 ⁻⁵ – 1.41·10 ⁻⁴	2	6	38.1	1445			
1.41·10 ⁻⁴ – 3.3·10 ⁻⁴	4	12	15.37	583			
3.3·10 ⁻⁴ – 4.716·10 ⁻⁴	6	18	8.28	314			
4.716·10 ⁻⁴ – 9.43·10 ⁻⁴	8	24	17	647			
> 9.43·10 ⁻⁴	9	27	2.24	85			
Weigh 3

Figure 5. (a) Map index of depth-to groundwater table, (b) The spatial distribution for the ratings of the net recharge parameter, (c) Surface distribution of the hydrological units, (d) the spatial distribution for the index of the soil media parameter, (e) the spatial distribution for the ratings of the slope parameter, (f) the spatial distribution for the ratings of the unsaturated zone parameter, (g) Map index of hydraulic conductivity.

Table 3. Description and original weights of the intrinsic and specific model parameters [32].

The DRASTIC model parameters	Parameters description	Original weight
Depth to water	Represents the depth from the groundwater table levels, the deeper the groundwater table, the lesser chance for contamination to occur	5
Net Recharge	Represents the amount of water which penetrates the ground surface and reaches the water table, recharge water represents the vehicle for transporting pollutants	4
Aquifer media	Refers to the saturated zone material properties, which controls the pollutant attenuation processes.	3
Soil media	Represents the uppermost weathered portion of the unsaturated zone and controls the amount of recharge that can infiltrate downward	2
Topography	Refers to the slope of the land surface, it dictates whether the runoff will remain on the surface to allow contaminant percolation to the saturated zone.	1
Impact of vadose zone	Is the unsaturated zone material, it controls the passage and attenuation of the contaminated material to the saturated zone.	5
Hydraulic Conductivity	Indicates the ability of the aquifer to transmit water, hence determines the rate of flow of contaminant material within the groundwater system.	3

Figure 6. Lineament map of the AZB.**Table 4.** Ranges and ratings of lineament density.

Range of the Distribution of Density	Rating	Area (km ²)	Area (%)
0.2-1.1	1	2913	77.08
1.2-1.3	2	297	7.86
1.4-1.5	3	231	6.11
1.5-1.8	4	144	3.81
1.9-2.0	5	121	3.2
2.1-2.2	6	28	0.741
2.3-2.4	7	14	0.37
2.5-2.6	8	10	0.265
2.7-2.8	9	5	0.132
2.9-4.0	10	16	0.432

Figure 7. (a) Lineament density map of AZB; (b) Map of lineament density index.

Figure 8. The major land use classes in the AZB (modified after [22]).

Table 5. Land use categories for the study area and the weights of the parameters [47].

Land use category	Rate	Area (km ²)	Area (%)
Urban	3	366	9.75
Irrigated agriculture	2	1193	31.79
Uncultivated land	1	2102	56.09
Forest	1	76	2.03
Land use weight (L_w) 5			

(Highlands, Wadi Dhuleil, and Khaldiya areas) is about 17,000,000 m² [22]. Based on Figure 8, the land use types of the AZB are: 56.09% bare rock, 41.54% thin soils and urbanization, whereas the remaining area is water and forest (Table 5).

The land use map (Figure 8) was rated according to the values given in Table 5. The map was converted to a raster grid and multiplied by the weight of the parameters ($L_w = 5$) as shown in Figure 9. The resulting grid coverage was then added to the DRASTIC index, based on Equation (3) [47].

$$MD(i) = DI + (\text{Land Use Index}) \quad (3)$$

where: $MD(i)$ is the modified DRASTIC risk assessment model; DI is the generic DRASTIC index and the land use index (ratings-weights).

Figure 9. The result of multiplying the land use ($L_r \cdot L_w$).

Table 6. DRASTIC index categories and areas vulnerable to groundwater pollution in the AZB.

Vulnerability Class	DRASTIC Index	Area (km ²)	Area (%)
No	24-61	45	1.19
Low	62-99	2624	69.20
Moderate	100-137	1120	29.54
High	138-175	3	0.08
Total		3792 km ²	100%

3. Results and Discussion

3.1. Assessment of Aquifer Vulnerability Based on the Generic DRASTIC Model

The DRASTIC model used to produce a vulnerability map of the study area was computed by the sum of each parameter rating multiplied by the assigned weights using ArcGIS, as shown in Equation (1). The higher the calculated DRASTIC index, the greater the potential for groundwater contamination is. The final DRASTIC vulnerability map (Figure 10) was generated by overlaying all seven layers, resulting in a DRASTIC index range of 24-175, which was reclassified according to the criteria in Table 6 and Figure 10. Table 6 shows the DRASTIC index and vulnerability class.

The results indicate that only 0.08% (3 km²) of the AZB is within the high vulnerability zone with a DRASTIC index values ranging from 138 to 175, and is mainly in the central area of Amman old city. It could be noticed that the wells with relatively higher NO₃⁻ concentrations are those in the Industrial activities and high density

Figure 10. Generic DRASTIC vulnerability map classes of groundwater.

urban areas centers that depend on septic tanks which are the most hazardous potentials that might affect groundwater. Approximately 30% of the basin is located in the moderately vulnerable zone. Interestingly, the proposed location of the nuclear power plant (in central basin) is within the moderate vulnerability zone.

3.2. Assessment of Aquifer Vulnerability Based on Lineaments Density

The minimum possible modified DRASTIC index, using the lineaments density parameter, is 29 and the maximum is 225 (Figure 11). This range of values was divided into four classes as follows: (a) 29-75 (No risk), (b) 76-122 (Low), (c) 123-169 (Moderate), (d) 170-225 (High).

The vulnerability map shows that approximately 87.03% of the area is classified as having low pollution potential with values ranging between 76 and 122. The no vulnerability class for the modified DRASTIC lineament density index has values varying from 29 to 75, which is about 5.01% of the AZB area. The moderately susceptible zone accounts for 7.83% of the basin's total area with values that vary from 123 to 169. The high vulnerability class has values ranging between 170 and 225, which constitutes 0.13% of the basin's area (Table 7 and Figure 11).

3.3. Assessment of Aquifer Vulnerability Based on Land use

The range of the Modified DRASTIC risk assessment index MD (i) based on land use is 29-255. The range of values was divided into four classes: (a) 29-68 (No risk), (b)

Figure 11. Generic DRASTIC vulnerability map classes of groundwater.

Table 7. Modified DRASTIC index categories using lineament density and areas vulnerable to groundwater pollution.

Vulnerability Class	DRASTIC Index	Area (km ²)	Area (%)
No	29-75	190	5.01
Low	76-122	3300	87.02
Moderate	123-169	297	7.83
High	170-225	5	0.13
Total		3792 km ²	100%

69-108 (Low), (c) 109-148 (Moderate), and (d) 149-190 (High) (Table 8 and Figure 12).

The vulnerability map shows that about 71% of the study area has low pollution potential with values ranging between 69 and 108. No vulnerability area accounts for about 0.55% whereas moderate pollution potential zone covers an area of 28.35%. The high vulnerability class based on the DRASTIC Modified risk assessment index with values ranging between 149 and 190, constitutes

Table 8. Modified risk assessment index MD (i) (using land use) for the study area.

Vulnerability Class	DRASTIC Index	Area (km ²)	Area (%)
No	29-68	21	0.55
Low	69-108	2692	70.99
Moderate	109-148	1075	28.35
High	149-190	4	0.11
Total		3792 km ²	100%

Figure 12. Final Modified DRASTIC risk assessment class's index

0.11% of AZB (Table 8 and Figure 12).

Urban areas were assigned a probability rating of 3 (Table 5), because nitrogen species concentrations in groundwater in urban areas were higher than in all other land use areas, whereas irrigated agriculture areas were assigned a probability rating of 2. Rangeland, dryland agriculture, and forest areas were combined and assigned a probability rating of 1, as they contain low nitrogen of nearly similar concentrations.

3.4. Assessment of Aquifer Vulnerability Based on the Modified DRASTIC Model

The modified DRASTIC system index was calculated using Equation (4):

$$\text{Final Modified DRASTIC} = DI + DL(i) + MD(i) \quad (4)$$

DI: DRASTIC Vulnerability Map; *DL(i)*: DRASTIC Modified Lineament density index; *MD(i)*: DRASTIC Modified risk assessment index. The final DRASTIC ($DI + DL(i) + MD(i)$) values were classified into No, Low, Moderate, and High pollution potential classes. The vulnerability map shows that slightly more than 89% of the area falls under low pollution potential with final DRASTIC values ranging between 83 and 131. The no vulnerability final DRASTIC index values ranging between 34 and 82, accounts for about 5.9%. The moderate pollution potential covers an area about 4.24% of AZB. The high vulnerability class of values 181-229, accounts for about 0.21% of the basin (Table 9 and Figure 13).

Table 9. The final modified DRASTIC index ($DI + DL(i) + MD(i)$) for the study area.

Vulnerability Class	DRASTIC Index	Area (km ²)	Area (%)
No	34-82	223	5.88
Low	83-131	3400	89.66
Moderate	132-180	161	4.24
High	181-229	8	0.21
Total		3792	100

Figure 13. The final modified DRASTIC vulnerability index map of groundwater in AZB.

3.5. The Vulnerability of Groundwater Pollution and Land Use

The relationship between groundwater and land use in the study area was assessed. Data were cross-tabulated for the sensitivity of groundwater pollution in terms of description (No, Low, Moderate, and High) and the land-use map (Agriculture, Urban, Bare soil and Forest). The final relationship is shown in Table 10 and Figure 14.

Table 10 and Figure 14 show that a total area of about 1761 km² of bare soils is of low vulnerability, whereas about 28 km² is moderately vulnerable. While these areas are largely unexploited, the moderate vulnerability class must be used with caution. The area must be carefully managed to prevent further deterioration (above moderate vulnerability) in the future.

For agriculture and the urban sector approximately 1472 km² are located within the low vulnerability zone and about 144 km² are moderately vulnerable, which together account for about 8% of the total agriculture and urban area (Table 10). Thus, these areas are contaminated with human activities, particularly from the

Table 10. Distribution of land use within the sensitive groundwater vulnerability.

Vulnerability Class	Agriculture	Urban	Bare Soil	Forest	Total (km ²)
No	44.704	2.333	184.575	5.605	237.322
Low	1200.007	271.577	1761.248	69.749	3315.200
Moderate	52.674	91.465	28.067	0.559	173.348
High	0.008	0.089	0.000	0.000	0.097
Total (km ²)	1297.385	365.464	1973.897	75.913	3690

Figure 14. Histogram showing distribution of land use with sensitive groundwater vulnerability.

agriculture. Management of land use must be considered when changing human or agricultural activity patterns in the study area, to reduce groundwater vulnerability in the basin.

3.6. Groundwater Vulnerability and Nitrate Concentration

Nitrate (NO_3^-) is among the most important indicators of water resource contamination. It comes into the water supply through the nitrogen cycle, rather than from dissolved minerals [47]. Although point sources of nitrogen, such as septic systems, contribute to the nitrate pollution of groundwater [48], most of the nitrate in groundwater is from fertilizers applied to agricultural fields [50–52]. Urban development can also increase the nitrate concentration in groundwater [53, 54] through landfills, septic tanks and cesspools, domestic and industrial effluents, and leaky sewage systems and gasoline stations [54–56]. Distribution of NO_3^- concentrations are presented in Figure 15.

It was observed that samples with high NO_3^- concentrations were found in the high vulnerability zone (Figure 16). NO_3^- concentration in groundwater in the southwestern part of the study area, around the central Amman city, is ranging between 81 to 107 mg/l with an average concentration of about 98 mg/l. The

Figure 15. NO_3^- concentrations in groundwater samples from the study area.

maximum acceptable NO_3^- level in drinking water is 50 mg/l based on Jordan drinking water standards (or 45 mg/l according to the WHO). Generally, NO_3^- concentration above 10 mg/l in groundwater indicates anthropogenic contamination. NO_3^- concentration was found to increase near the central Amman city location, which is in the high vulnerable area. These high levels of NO_3^- are probably attributed to leakage from old sewage water and from the present industrial wastewater infiltrated into the aquifer. Figure 16a shows the relationship between the concentration of NO_3^- and the risk map of the study area and Figure 16b shows the location of samples with high NO_3^- concentrations combined to the vulnerability map (Table 11).

Other samples with relatively low NO_3^- concentrations can probably be related to soil characteristics and depth water table that allow insignificant NO_3^- loading to enter the aquifers. 41 wells are located in the low risk zones with the highest NO_3^- concentration of about 60 mg/l, lowest of 5.8 mg/l, and an average of about 31 mg/l.

7 wells are situated in the moderate risk area, with the highest and lowest NO_3^- levels of 61.8 mg/l and 3.5 mg/l, respectively. The average concentration of NO_3^- in the

Table 11. Maximum, minimum, and average NO_3^- concentrations of the risk map of the study area.

		Low Risk	Moderate Risk	High Risk
NO_3^- (mg/l)	Max	60.1	61.8	107.2
	Min	5.8	3.5	81.1
	Average	31	42.1	97.7
	[57] WHO (2011)	50		
	[58] Jordanian standard for drinking water (1997)	50

Figure 16. (a) Relationship map of NO_3^- concentration with the risk map in the AZB; (b) Locations of samples with high NO_3^- concentration on the vulnerability class's map.

moderately vulnerable zone is about 42.1 mg/l.

4. Conclusions

The objective of this research is to evaluate the potential vulnerability of groundwater contamination in

the AZB using the original and modified DRASTIC index applied in a GIS environment. Although the DRASTIC method usually gives satisfactory results in the evaluation of groundwater intrinsic vulnerability to contamination, it cannot be used for accurate assessment of the groundwater contamination risks. Therefore, it is necessary to calibrate and modify the original model in order to obtain more accurate results. Seven parameter maps were developed in a GIS environment to generate generic models and two parameters are added to modify the generic model (land use and lineament density maps). The DRASTIC vulnerability index values ranged between 34 and 299. Based on the hydrogeological field investigation and using a quintile classification method, these values were reclassified into four classes. The highly vulnerable areas constitute only 0.21% of the basin and are located in the central west of the AZB. Nitrate concentration of groundwater was evaluated for validation of the DRASTIC results. 54 groundwater samples have been analyzed for nitrate. In the low risk vulnerability zone, 41 groundwater wells showed an average nitrate concentration of 31 mg/l with highest values of 60 mg/l. In the moderate pollution risk zone, 7 wells showed nitrate concentration ranging between 3.5 and 61.8 mg/l. In the high risk zone, 4 wells found with nitrate concentration that varied from 81 to 107 mg/l. Higher nitrate concentrations were observed in the high vulnerable area and are located closer to wastewater discharges.

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