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Evaluation of Groundwater Sensitivity to Pollution Using GIS-Based Modified DRASTIC-LU Model for Sustainable Development in the Nile Delta Region

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Abstract: The groundwater resources in the Nile Delta region are an important resource for freshwater because of rising water demand due to anthropogenic activities. The goal of this study is to quantify groundwater sensitivity to pollution in the Nile Delta by a modified GIS-based DRASTIC-LU model. In this study, we utilized two types of modified DRASTIC-LU models, generic and pesticide, to determine the groundwater vulnerability rates to contamination. The results of the generic DRASTIC-LU model showed that the research region, except for the northwestern part with moderate vulnerability of 3.38%, is highly and very highly vulnerable to pollution with 42.69 and 53.91%, respectively. Results from the pesticide DRASTIC-LU model, on the other hand, also confirmed that, except for the northwestern and southern parts with a moderate vulnerability of 9.78%, most the Nile Delta is highly and very highly vulnerable with 50.68 and 39.53%, respectively. A validation of the model generated was conducted based on nitrate concentrations in the groundwater and a sensitivity analysis. Based on the nitrate analysis, the final output map showed a strong association with the pesticide vulnerability model. Examining the model sensitivity revealed that the influence of depth to water and net recharge were the most important factors to consider.

Keywords: GIS; Nile Delta region; modified DRASTIC-LU; groundwater vulnerability; geospatial technique

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1. Introduction

Groundwater is the lifeblood for plenty of rural people around the world, as well as a critical component of worldwide food production. Approximately half of the world's drinking water and a large portion of the world's irrigation water supply is derived from groundwater. In Egypt, the depletion of groundwater for farming, industry, and residential purposes has increased. Thus, reliance on groundwater and its quality are progressively increasing day after day and became a huge issue of considerable environmental and social concern. Particularly, there are numerous reasons that can seriously disturb the groundwater quality, for example, rapid population growth, random planning, different land-use–land-class patterns, and invalid drainage systems, including dumping waste from industrial, agricultural, and rural regions. All these factors have made groundwater pollution a hugely challenging problem [1,2]. Consequently, several techniques have been established to assess the groundwater pollution potential, with the groundwater vulnerability techniques being the most popular. Principally, groundwater vulnerability describes the sensitivity of an aquifer system to deterioration because of an outside action.

In the last few decades, a variety of models based on diverse techniques and procedures have been utilized around the world. The modified DRASTIC-LU model based on a geographic information system (GIS) is one of the most popular techniques applied to monitor groundwater susceptibility to pollution depending on the aquifer's hydrogeological conditions. The DRASTIC evaluation was developed by [3], and it is an abbreviation for seven hydrological elements: depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and aquifer hydraulic conductivity. This model was later modified to improve the evaluation of groundwater vulnerability for a specific aquifer system by adding new model elements that is the land-use layer [4–6]. The modified DRASTIC-LU model consists of eight factors; each is given a relative weight between one and five, and then separated into subclasses based on a grading scale of one to ten. Based on its impact on the aquifer's susceptibility to pollution, the most critical factor is given a weight of five and the least significant is given a weight of one. Similarly, subclasses are given ratings based on the kind of data, the range of data, and the rate of contamination risk. Static ratings and weights are allocated to the parameters as a result. GIS has been found useful when utilized in studies applying the DRASTIC model [7–17].

The modified DRASTIC model is distinguished by its ability to use a simple and flexible criteria structure. The biggest disadvantage of this model is that the weights and rates are originally assumed or based on the experiences of evaluation specialists. Some researchers have offered various strategies to address this problem, including modifying the structure's weights and/or rates, deleting or adding other components, employing sensitivity analyses and calibration procedures, and combination with the analytic hierarchy process [4,18]. Shirazi and his coworkers used DRASTIC and GIS methodologies to assess groundwater susceptibility in the Malaysian state of Melaka, and generated a risk map to quantify the impact of land use on groundwater susceptibility [19]. Some other researchers utilized the land-use factor in a modified DRASTIC model, including [4,8]. Many researchers have suggested using nitrate as a sign of groundwater contamination to estimate the accuracy of the susceptibility method and its relevance to the study region [18,20].

The major goals of this research are to (1) compute the modified DRASTIC vulnerability value to acquire a groundwater susceptibility map for the research region, (2) use the single parameter sensitivity analysis to detect the influence of each modified DRASTIC input layer on the model, and (3) use map removal sensitivity analysis to detect the most sensitive model factors. It is hoped that the yield of this work can be utilized as a helpful guide for groundwater management and protection decision-making at both planning and operational levels. It can also be applied to other portions of the world with similar hydrogeologic and socio-economic settings.

The Study Area

The Nile Delta lies between longitudes 29°30′ and 32°00′ East and latitudes 30°00′ and 31°30′ North. It is surrounded by the Mediterranean Sea from the north, its apex is Cairo from the south, the Suez Canal from the east, and Nubariya Canal from the west (see Figure 1). It is situated in an arid climatic zone along the Mediterranean coast, with an average annual precipitation of 150 mm/y. Although the Nile Delta only accounts for roughly 2% of Egypt's total area, it is home to almost 41% of the country's people and over 63% of its agricultural land [21]. It is characterized by low relief.

The Nile Delta is comprised of Quaternary and Tertiary deposits. The Quaternary is represented by Holocene and Pleistocene sediments. The Holocene consists of sand dunes, coastal deposits, sabkha deposits and silty clay sediments capping the flood plain (Bilqas Formation). The Pleistocene comprises desert crusts and graded sand and gravel that contain the main water-bearing formation (Mit Ghamr Formation) (see Figure 2) [22,23]. The Tertiary, on the other hand, comprises sediments of Pliocene, Miocene, Oligocene, Eocene, and Paleocene ages. The Pliocene sediments represent the lower limit of the major water-bearing formation on top of the Miocene sediments [22,24,25]. In the study area, the most significant regional aquifer is the Quaternary aquifer that is made up of Pleistocene sand and gravel interbedded with clay. It extends over the entire Nile Delta flood plain. The Nile aquifer's clay cap is a semi-confining layer that ranges in thickness from 5 to 20 m in the south and the central parts of the Delta and reaches 60 m in the north [22,26]. The Nile Delta has long been exposed to many geological, hydrogeological and geophysical studies [21,23,27–32].

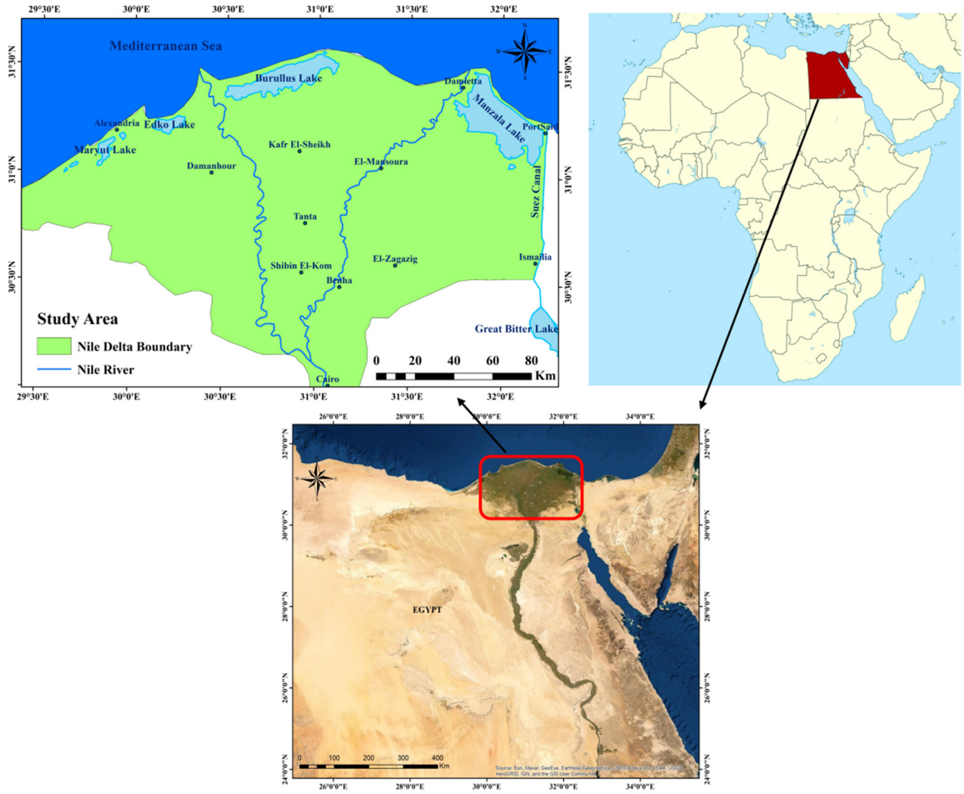

Figure 1. Location map of the study area.

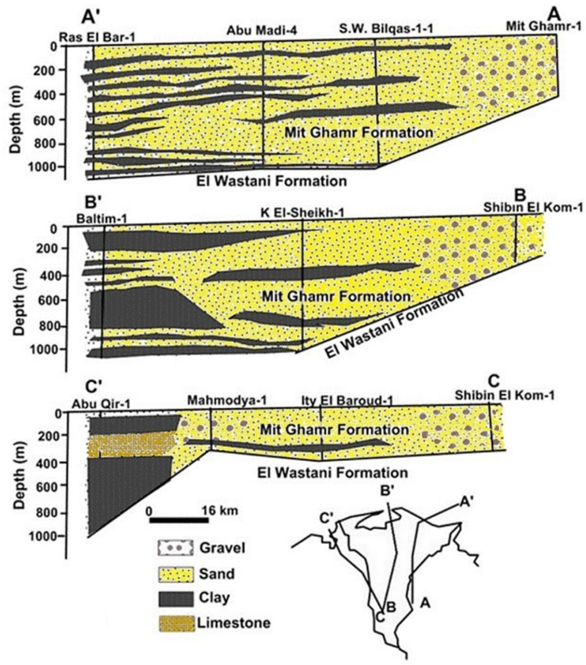

Figure 2. Three north (A′, B′ and C′)–south (A, B and C) lithological cross-sections in the Nile Delta region [22,23].

2. Materials and Methods

The DRASTIC model is a numerical rating system created by Aller et al. (1987) [3] for assessing the tendency of groundwater to contaminate. It depends on seven hydrogeologic factors, namely, depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity. Based on a range of values and interpretation of obtainable data, each of these parameters is evaluated from 1 to 10. The ratings are then multiplied by a relative weight ranging from one to five (Table 1). The most important factor will have a weight of five, while the least important will have a weight of one. The DRASTIC index (DI) is computed by multiplying and summing the rates and weights of each factor as shown in Equation (1). Groundwater becomes more vulnerable as the DI value increases [3].

$$DI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (1)$$

where D, R, A, S, T, I, and C are the seven factors of the DRASTIC method and subscripts *R* and *W* represent the rating and weight of the factors.

Table 1. Weights of modified DRASTIC-LU factors.

	Modified Generic DRASTIC	Modified Pesticide DRASTIC
Depth to water (D)	5	5
Net recharge (R)	4	4
Aquifer media (A)	3	3
Soil media (S)	2	5
Topography (T)	1	3
Impact of vadose zone (I)	5	4
Hydraulic conductivity (C)	3	2
Land use (LU)	5	5

Modified DRASTIC-LU model: by adding a new parameter to the generic and pesticide DRASTIC model, a new DRASTIC-LU model was developed by Secunda et al. (1998), Brindha and Elango (2015), and Allouche et al. (2017) [4–6]. The LU factor has been assigned a weight of five ($LU_w = 5$) as shown in Table 1. By adding the LU factor to Equation (2), the DRASTIC-LU index model is calculated as follows:

$$\text{The DRASTIC-LU index (Vulnerability Index)} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w + LU_r LU_w \quad (2)$$

where D = depth to water table, R = aquifer recharge, A = aquifer media, S = soil media, T = topography, I = impact of vadose zone, C = hydraulic conductivity, LU = land use and subscripts r and w represent, respectively, the rating and weight of these factors.

There are two types of modified DRASTIC-LU model, generic and pesticide to evaluate the groundwater vulnerability to contamination. Each of these two types includes eight parameters.

We used the nitrate concentrations in groundwater to validate the model, where it is considered as an effective indicator of pollutant migration from the surface to the groundwater, predominantly in farming areas. We collected 121 representative groundwater samples from the eastern side of Nile Delta where the sensitivity analysis method was also applied to validate the model's final output map.

3. Application of Modified DRASTIC-LU Model Using GIS

The GIS technique was used in this research to execute the modified DRASTIC-LU model as shown in the flowchart of Figure 3 and described in the following steps:

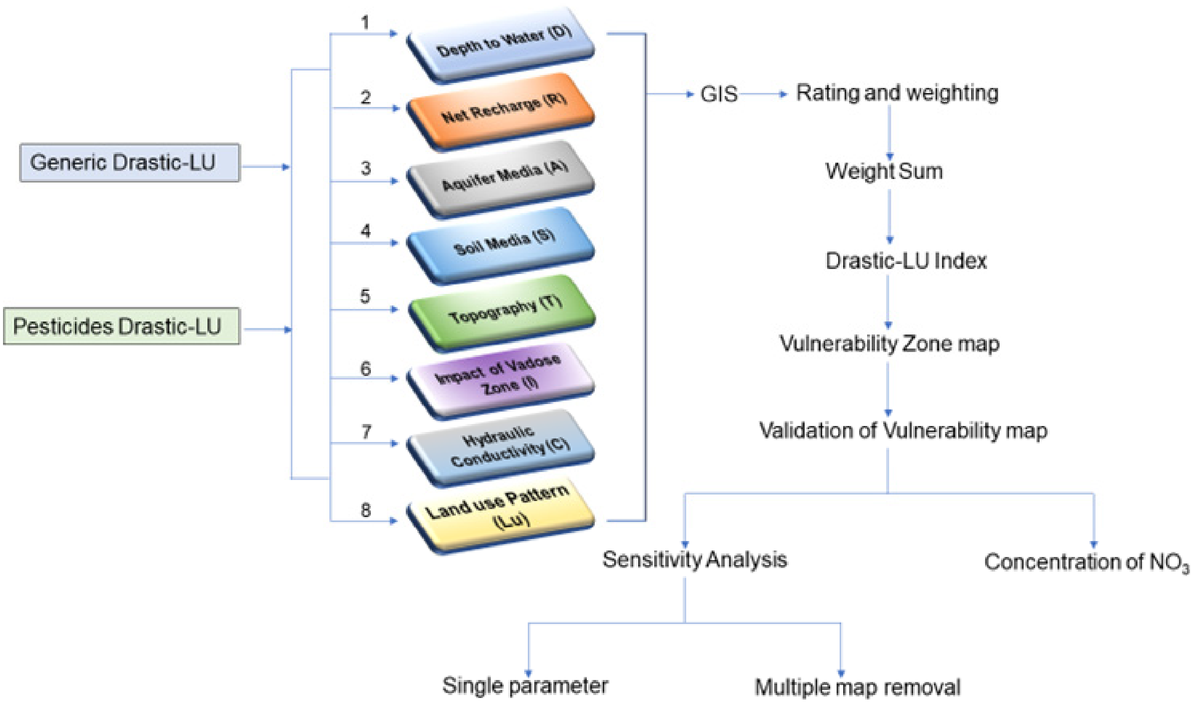

Figure 3. Flow diagram of the methodology implemented for groundwater vulnerability analysis.

3.1. Data Layers Collection

Here, the modified DRASTIC-LU model was used to create a map of the groundwater's susceptibility to contamination in the Nile Delta area. The weights and ratings of the modified generic DRASTIC model and modified pesticide DRASTIC model, were used. This model consisted of eight factors and each factor was derived from different maps as follows: depth to water (D) was produced from [33–35], the topography (T) was generated using a digital elevation model (DEM) derived from SRTM global elevation data (1 Arc second resolution, SRTM plus v3), and the aquifer media (A) were derived from [36]. Recharge (R) of the Pleistocene aquifer was created from [37], the hydraulic conductivity (C) was from [38], the soil (S) was derived from [39], the vadose zone (I) was derived from [40,41] and land use (LU) was from Sentinel-2 imagery at 10 m resolution by ESRI.

3.2. Management of Data Layers

Each of the data layers exploited to determine groundwater vulnerability was adjusted using the following procedures:

1. The first phase entails that every data layer that has an impact on groundwater vulnerability was digitized through turning of visible features on a map image into editable features that can be given extra spatial and non-spatial properties. The digitizing process began with the creation of new layers in ArcCatalog, followed by the addition of features such as points, lines, or polygons to them in ArcMap.
2. The data was converted from vector features such as points, lines, or polygons to raster data.
3. Interpolation by inverse distance weighting (IDW) was applied to convert the data layers in the point feature to a raster surface [42,43], while rasterization was used to convert the data layers in the polygon feature to a raster structure.
4. Reclassification of layers was defined as the replacing of input cell values with new output cell values [42,44]. Every data layer was classed in this research according to a general scale that illustrates its impact on groundwater contamination. For each data layer, there were ten classes varying from ten to one, with ten representing the largest pollution risk and one representing the least contamination risk. All data layers were

reclassified using the spatial analyzer provided in ArcGIS program, as illustrated in Table 2.

5. As a result of these steps, a relative weight ranging from 1 to 5 was given to the reclassified layers, and all cell values in each layer were multiplied by their weight. The most critical component was assigned a weight of 5, while the least important was assigned a weight of 1, based on their influence on the aquifer's susceptibility to pollution [3].
6. The final step was analyzing data by overlapping all layers. The overlap method is defined as "the spatial process of placing a thematic layer above another to form a new layer". All data layers were overlaid during this process to create a modified DRASTIC-LU model for groundwater susceptibility to contamination as shown in Equation (2).

Table 2. Ranges and ratings for modified DRASTIC-LU factors be according [3].

Parameter	Range	Rating
Depth to water	0.27–3.5	10
	3.6–6.7	9
	6.8–9.8	7
	9.9–13	5
	14–16	3
	17–19	3
	20–23	3
	24–26	2
	27–29	2
	30–32	1
Net recharge (mm/day)	0.03–0.35	6
	0.36–0.66	8
	0.67–0.98	9
	0.99–1.3	9
	1.4–1.6	9
	1.7–1.9	9
	2–2.2	9
	2.3–2.6	9
	2.7–2.9	9
	3–3.2	9
Aquifer media	Gravel and Gravelly sand	9
	Sand dunes	7
	Sand and Clay loams	5
	Sabkha deposits	3
	Nile alluvium	1
Soil	Dissected Limestone	10
	Gravelly sand and Sand dunes	10
	Sand and sand loam	9
	Mixed sandy and Carbonate	9
	Sand and clay loam	8
	Urban	5
	Clay loam	3
	Silty Clay	1
Topography (slope) (%)	0–0.17	10
	0.18–0.55	10
	0.56–1.5	10
	1.6–4.9	9

Table 2. *Cont.*

Parameter	Range	Rating
Impact of vadose zone	Sand dunes	7
	Sandy clay	5
	Clayed sand	5
	Sabkha Deposits	3
	Silty clay	1
Hydraulic conductivity (m/day)	15–32	1
	33–50	2
	51–67	3
	68–85	4
	86–100	5
	110–120	6
	130–140	7
	150–150	8
	160–170	9
	180–190	10
Land use	Water	7
	Agriculture	6
	Urban	5
	Desert	3
	Limestone	1

4. Results and Discussion

4.1. Depth to Water Table (D)

The depth to groundwater parameter has a major influence on determining groundwater contamination risk. Groundwater tables that are deep have adequate residence time to detoxify water as it flows within soil layers, making them less sensitive to contaminants [45]. The raster layer was divided into 10 classes by the spatial analyst (reclassify tool) in the GIS environment, and ratings were assigned to the classes depending on their risk of contamination as shown in Table 2. The depth to water map shows that the majority of the Nile Delta region, especially eastern parts, are within a range from 0.27 to 9.8 m, where this area has rates of 7, 9 and 10, indicating strong contamination capability as shown in Figure 4a,b. The northwestern parts of the Nile Delta reflected high sensitivity to pollution with rates from five to nine, while the southwestern parts of the area are distinguished by low susceptibility to contamination with rates one to three due to the very high depth to water. The central parts of the region around Tanta and Kafr El-shiekh Cities have rates of five, seven, and nine, indicating strong contamination. These results are in agreement with other published work reported from the northwestern and central portions of the Nile Delta by Salem et al. (2019) and Metwally et al. (2022) [16,46], respectively.

4.2. Net Recharge (R)

The recharge rate varied between 0.03 and 3.2 mm per day (Figure 5a). As indicated in Figure 5b, the research area's net recharge was classified into three classes, with ratings of six, eight, and nine, compatible with the DRASTIC rating regulation. The more recharge, the more pollution is likely to be directed to the groundwater table. Most parts of the study region show very high susceptibility to contamination with a rate of nine, probably due to the presence of a large percentage of drainage and irrigation canals which leads to an increase in the amount of recharge, while the northeastern and southwestern parts showed rates varying from six to eight [35].

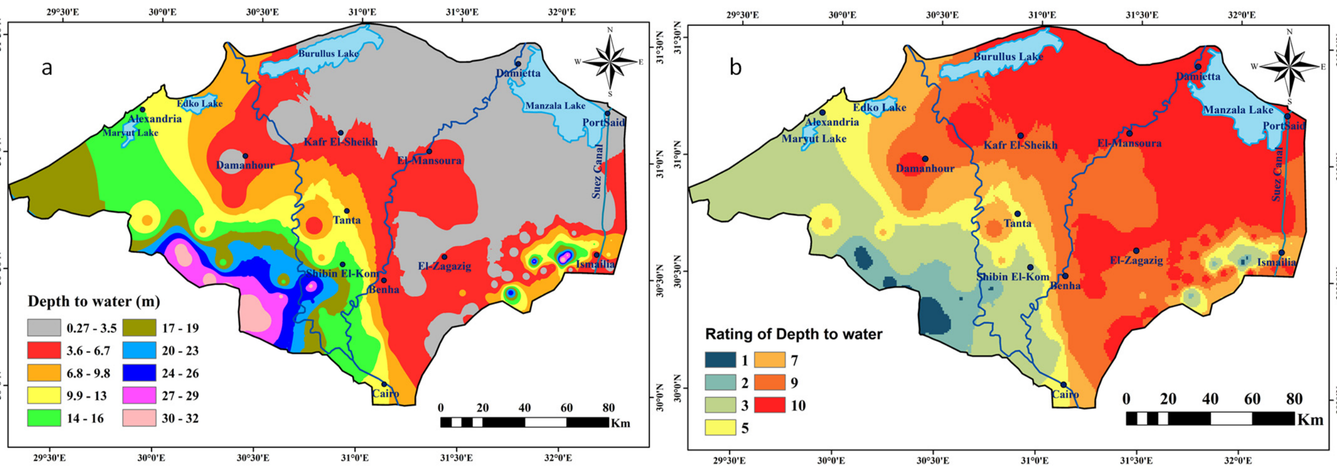

Figure 4. The map indicates to the spatial distribution of (**a**) depth to water and (**b**) depth to groundwater rating map.

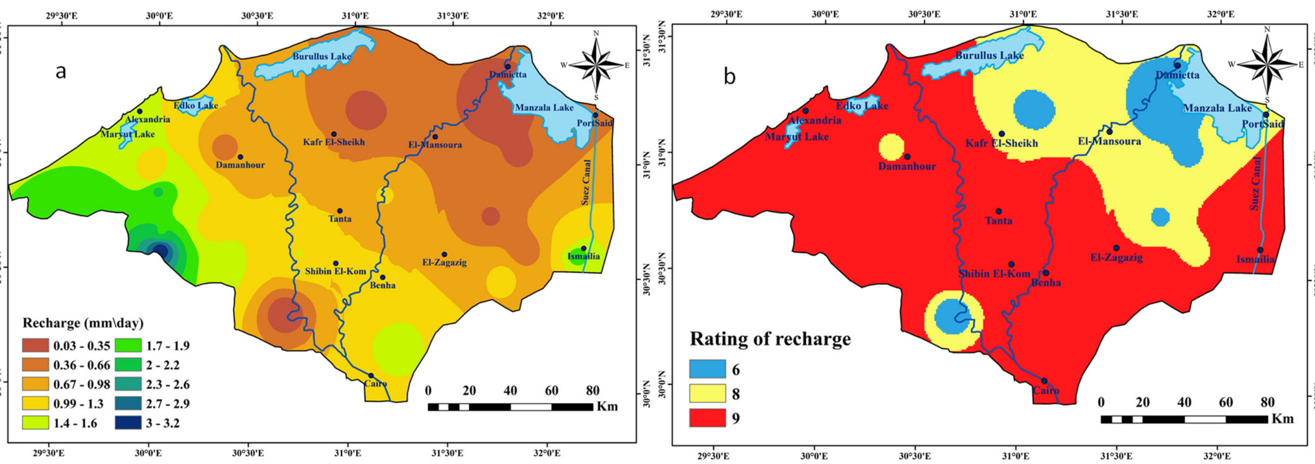

Figure 5. (**a**) Groundwater recharge map of the study area and (**b**) recharge rating map.

4.3. Aquifer Media (A)

The state of the rock, whether consolidated or unconsolidated, acts as an aquifer. The contaminant's mobility through the aquifer is determined by the aquifer's material [47]. The coarser media receive a higher rating than the finer media (Table 2). Overall, the larger the grain and the more fractures, the greater the permeability of the rock medium and the greater the risk of contamination to the aquifer [48]. The generated aquifer media map in the research region shows that the region of the Nile Delta has a rate of one to nine as shown in Figure 6a,b. A huge part of the study region has silty clay and sand with clay loam as the Nile Delta region is completely covered by Quaternary deposits [49].

4.4. Soil (S)

USDA (2010) divided the Nile Delta soil into taxonomic groupings and the soil texture of these units that cover the Nile Delta region is divided into silty clay, clay loam, mixed sandy and carbonates, gravelly sand, gravel sand and sand dunes, and dissected limestone as indicated in Figure 7a [50]. The type of clay present in a soil, in addition to the grain size of the soil, have a significant influence on its contamination risk [3]. The soil medium has six classes, as shown in Figure 7b. The silty clay type dominates the soil texture in the eastern and middle regions. The northern section of the affected area is distinguished by clay loamy soil. Sandy soil dominates the southwestern portion and the northeastern part of the research region.

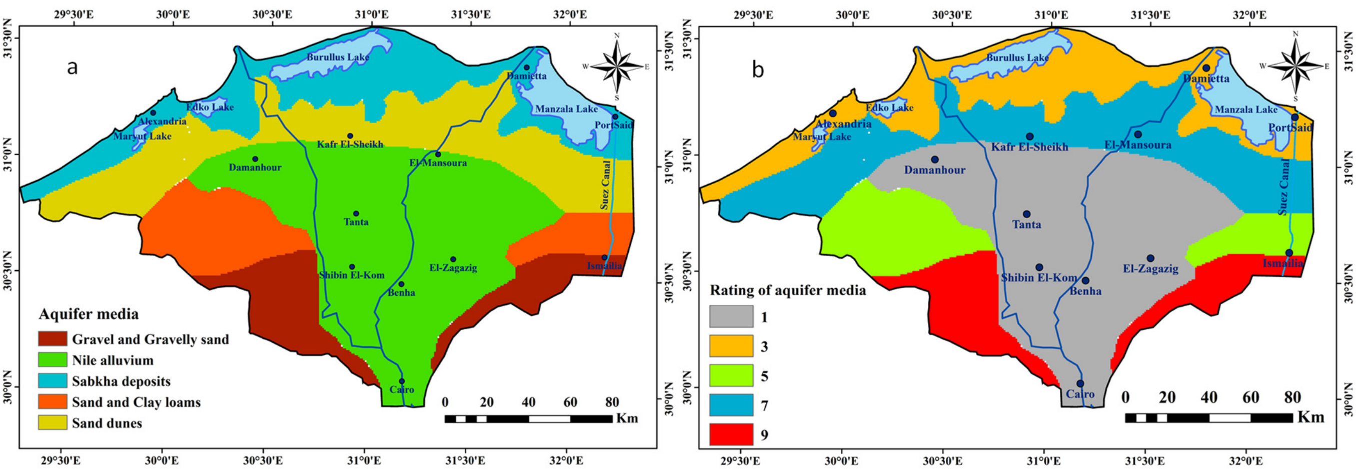

Figure 6. (**a**) Aquifer media layer and (**b**) rating map of aquifer media.

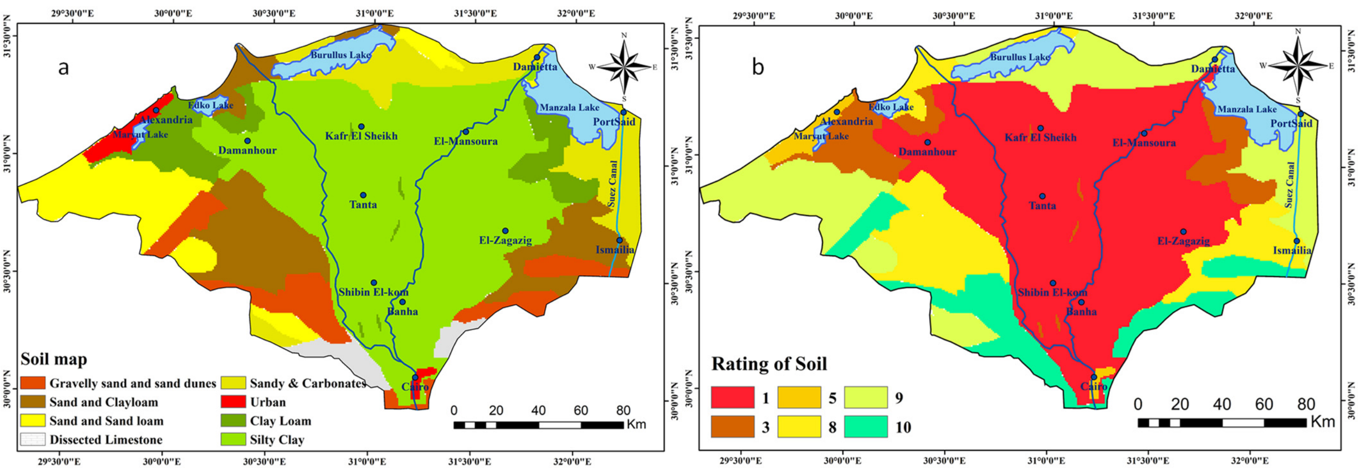

Figure 7. (**a**) Soil media map of the study area and (**b**) rating of soil media.

4.5. Topography (T)

The slope map of the study region was calculated as a percentage from a digital elevation model (DEM) (see Figure 8a). The research region was divided into four classes, which reflected a relatively flat slope in keeping with the DRASTIC rating. The area was given a 9 and 10 rating (see Figure 8b). The majority of the area is highly susceptible to pollution, probably as a result of its low relief [16].

4.6. Impact of Vadose Zone (I)

The unsaturated zone (vadose zone) is defined as the soil zone above the water table that is unsaturated or discontinuously saturated. Sorption, biodegradation, mechanical infiltration and dispersion are all controlled by the soil type in the vadose zone [3]. The vadose zone is assigned to the study area by the Bilqas Formation. As shown in Figure 9a, the lithology of the formation varies from clayey sand in the south to sandy clay in the centre to sandy facies in the north [40]. Figure 9b describes the effect of vadose zone rating in the research region. The northern parts were given a rate of seven because they demonstrated a high susceptibility to contamination due to their sandy facies. Because the middle and southern regions have clayey vadose zones, they were assigned ratings of one and five, respectively.

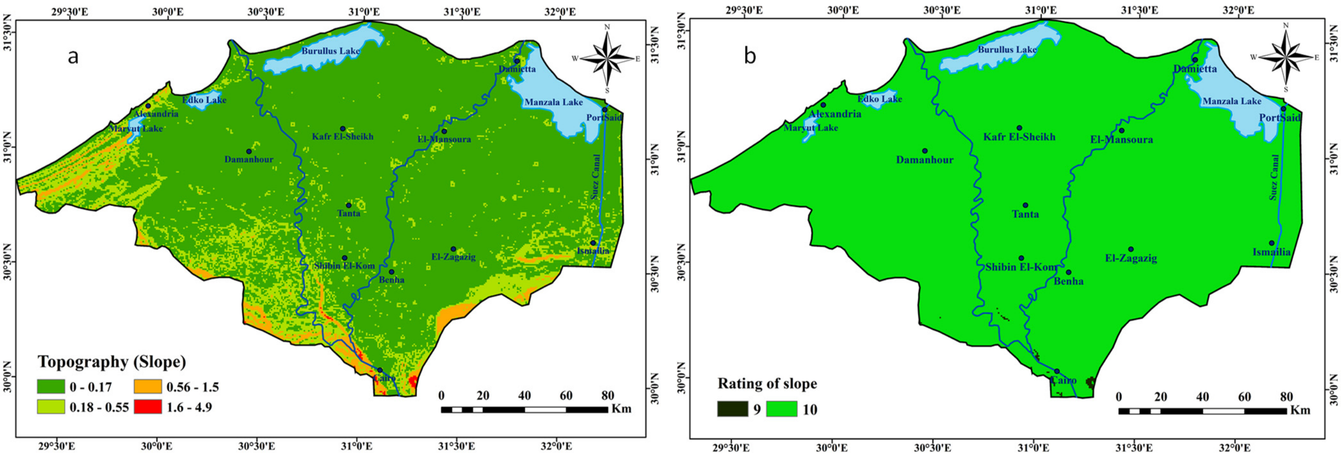

Figure 8. (**a**) Slope map ranges of the study area and (**b**) rating of slope layer.

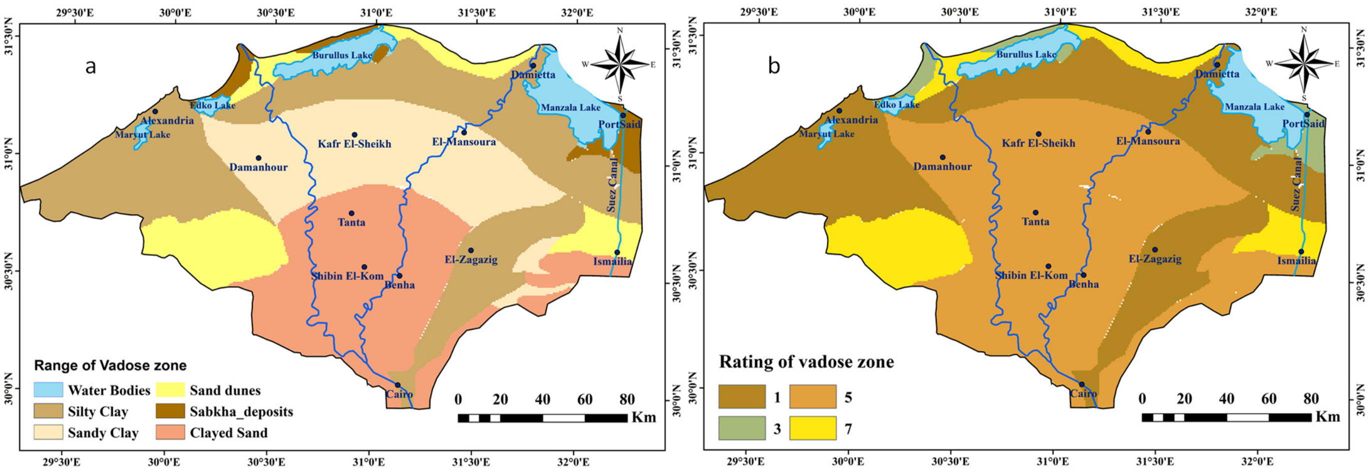

Figure 9. (**a**) Impact of the vadose zone layer and (**b**) vadose zone rating map.

4.7. Hydraulic Conductivity (C)

The pollutant movement is greatly influenced by hydraulic conductivity: the greater the hydraulic conductivity, the higher the potential for contamination [3]. As demonstrated in Figure 10a,b, hydraulic conductivity in the study region was classed into ten classes that range from 15 to 190 m/day, with ratings of 1 to 10. The eastern parts of the Nile Delta reflected high sensitivity to pollution with rates from 6 to 10 due to their high values of hydraulic conductivity, while the western parts of the region revealed low sensitivity with rates from 1 to 3 and the central parts showed moderate sensitivity with rates of 5 and 6.

4.8. Landuse (LU)

The land-use (LU) pattern has a substantial effect on the quality of the groundwater [4]. When the research region is primarily covered by farming fields, using LU as an input may be a suitable way to analyze the susceptibility of aquifers. Contaminants infiltrate groundwater in different ways depending on land usage. Most parts of the study region are used for agricultural, according to the land-use classification. The second significant section of the area is made up of urban areas. The remainder of the region is divided into three categories: desert, water body, and limestone as shown in Figure 11a. Land-use classification revealed that agricultural and urban activities had a huge influence on groundwater contamination in the research region, where they represent 69.26 and 16.45% with rates of six and five, respectively. Limestone and desert have less effect on groundwater pollution with 3.04 and 2.92% with rates of one and three, respectively (Figure 11b). All these results are compatible with published outcomes of [35,51].

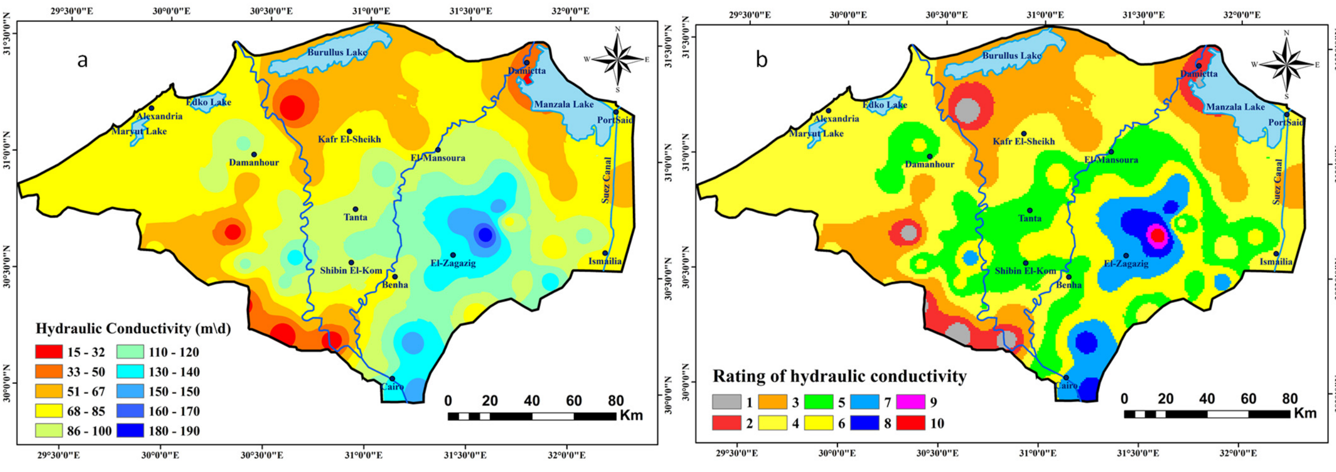

Figure 10. (**a**) Spatial distribution of hydraulic conductivity and (**b**) rating of hydraulic conductivity.

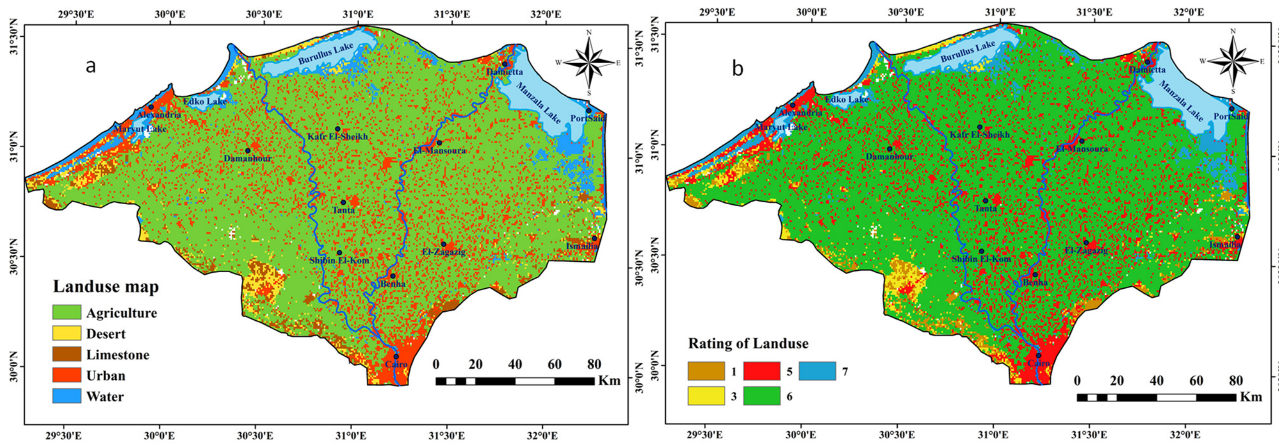

Figure 11. (**a**) Land-use map of study area and (**b**) rating of land use.

5. Creation of Vulnerability Map

The adjusted DRASTIC-LU Index [DI] was computed to build a vulnerability map by adding the products of each factor's ratings and weights using Equation (2) and the results are shown in Figure 12a,b. When the value of DI increases, the relative pollution risk or aquifer vulnerability rises with it [3]. The weights and ratings from the generic DRASTIC model and the pesticide DRASTIC model were used to create two susceptibility maps.

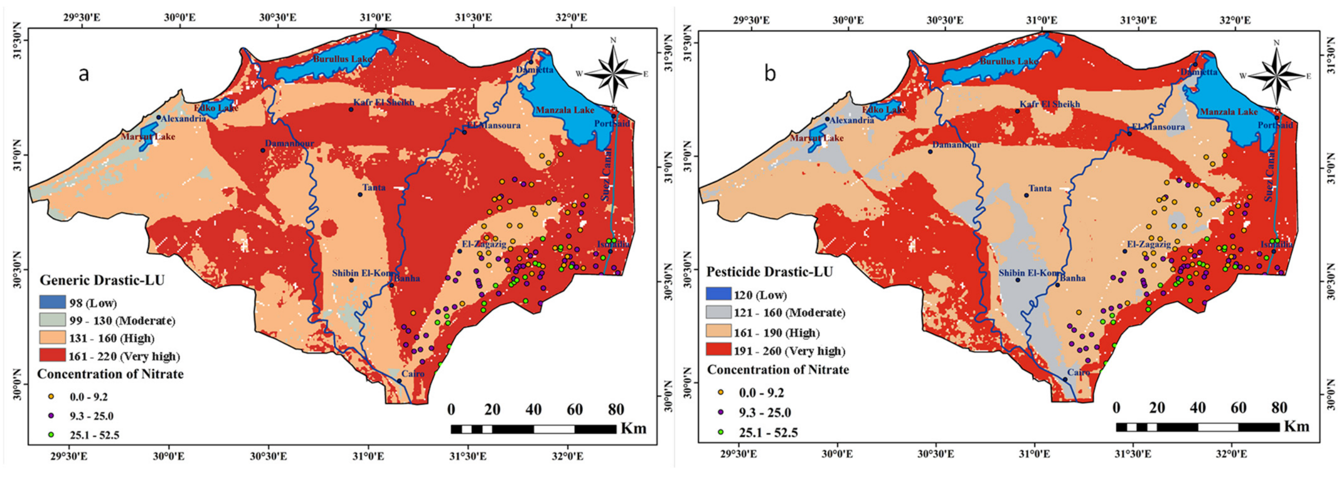

Figure 12. Vulnerability map generated by (**a**) generic DRASTIC-LU and (**b**) pesticide DRASTIC-LU model.

Figure 12a shows the susceptibility map formed by the generic DRASTIC-LU model, while Table 3 shows the brief of susceptibility levels and percentage of each class. It is shown that 53.91% of the study region has an extreme vulnerability to pollution, 42.69% has high susceptibility to pollution, 3.38% has a moderate vulnerability and about 0.01% has a low vulnerability.

Table 3. Generic DRASTIC-LU vulnerability classes.

Generic DRASTIC-LU	Vulnerability Level	Area %
Legend		
98	Low	0.01
99–130	Moderate	3.38
131–160	High	42.69
161–220	Very High	53.91

The vulnerability map of the pesticide DRASTIC-LU model illustrated in Figure 12b and Table 4 shows that 39.53% of the research region has a very high susceptibility to pollution around the eastern and western parts of the region, 50.68% has a high vulnerability, 9.78% covering the northeast and south parts of the study region has a moderate susceptibility and 0.01% has a low susceptibility.

Table 4. Pesticide DRASTIC-LU vulnerability classes.

Pesticide DRASTIC-LU	Vulnerability Level	Area %
Legend		
120	Low	0.01
121–160	Moderate	9.78
161–190	High	50.68
191–260	Very High	39.53

5.1. Validation of the Vulnerability Map

5.1.1. Assessment the Status of Nitrate Pollution

Nitrate values were evaluated for 121 groundwater samples obtained from the eastern parts of the research region to validate the vulnerability evaluation. NO_3 values ranged from 0.08 to 52.5 mg/L. Fertilizers, animal waste, and sewage all contribute to nitrate levels in the water [52]. The nitrate data show a strong association with the pesticide vulnerability DRASTIC-LU model (Figure 12b). This result shows that models that use the land-use parameter are better at assessing an aquifer's contamination vulnerability. All recorded nitrate polluted wells were located in moderate to very high-hazard areas, according to the confirmation test, and the dispersion of wells in moderate, high, and very high-risk areas is revealed in Figure 12a,b. This is probably because most parts of the study region are covered by farm areas, and thus the "agricultural runoff flow" significantly added to the higher NO_3 levels reported in the groundwater of the region. This is accompanied by the effect of urban expansion, industrial discharges, and other sources.

5.1.2. Sensitivity Analysis of Modified DRASTIC-LU Model

A sensitivity analysis evaluates the level of doubt or variety in the final outcomes of a model [53]. It may be useful to determine the most effective vulnerability indicators, and then investigate how to deal with pollution and aquifer crisis management correctly. Single component sensitivity analysis and map removal sensitivity analysis were performed in this analysis.

Single-Parameter Sensitivity Analysis Method (SPSA)

The theoretical and effective weights of the elements utilized to create the modified DRASTIC-LU index were compared. The effective weight was calculated using Equation (3) below [54]:

$$W = ((Pr \times Pw) \div V) \times 100 \quad (3)$$

where W refers to the effective weight of every factor, Pr and Pw represent the rating value and weight of each factor, and V indicates the total vulnerability index.

Results from the single component sensitivity method for the modified DRASTIC-LU model are summarized in Table 5a,b. As shown in the table, the effective and theoretical weights of the modified DRASTIC-LU elements did not match completely, and in some cases were notably different.

Table 5. Statistics of sensitivity analysis according to a single parameter for:

(a) Generic DRASTIC-LU.

Index	The Single Parameter Sensitivity Analysis								
Generic DRASTIC-LU		Theoretical Weight	Theoretical Weight %	Effective Weight				Effective wt	Effective wt %
	Parameter			Min.	Max.	Mean	Standard Deviation		
	D	5	17.8	2.94	35.9	21.9	8.93	6.15	21.9
	R	4	14.2	14.04	30.0	21.5	3.10	6.02	21.5
	A	3	10.7	1.69	20.1	7.51	5.34	2.10	7.51
	S	2	7.14	1.05	15.0	5.26	4.58	1.47	5.26
	T	1	3.57	4.74	8.33	6.22	0.71	1.74	6.22
	I	5	17.8	2.65	22.1	11.2	6.54	3.16	11.2
	C	3	10.7	1.88	18.7	8.62	2.97	2.41	8.62
	LU	5	17.8	2.62	23.08	17.6	3.15	4.94	17.6

(b) Pesticide DRASTIC-LU.

Index	The single Parameter Sensitivity Analysis								
Pesticide DRASTIC-LU		Theoretical Weight	Theoretical Weight %	Effective Weight				Effective wt	Effective wt %
	Parameter			Min.	Max.	Mean	Standard Deviation		
	D	5	16.1	2.42	31.8	19.3	8.24	6.01	19.3
	R	4	12.9	12.6	25.5	18.7	2.82	5.80	18.7
	A	3	9.68	1.38	15.3	6.38	4.42	1.98	6.38
	S	5	16.1	2.48	28.2	10.8	9.00	3.37	10.8
	T	3	9.68	11.9	21.1	16.2	2.02	5.04	16.2
	I	4	12.9	1.72	15.3	7.93	4.63	2.46	7.93
	C	2	6.45	1.02	11.6	5.05	1.92	1.57	5.05
	LU	5	16.1	2.17	20.6	15.4	2.91	4.77	15.4

The most impactful factors in vulnerability evaluation by the generic DRASTIC-LU model were depth to water and net recharge, with average effective weights of 21.96 and 21.51%, respectively. The depth to water and net recharge further exposed a high impact on susceptibility evaluation in the pesticide DRASTIC-LU model, with average effective weights of 19.39 and 18.72%, respectively. To optimize the DRASTIC-LU index's factor selection, the obtained modified DRASTIC-LU index values needed to be revised by applying the SPSA and weights evaluation. The new effective weight of the eight parameters had to be applied to obtain SPSA DRASTIC-LU index as shown in Figure 13a,b. A contrast of the SPSA DRASTIC-LU map with the nitrate concentration values reveals that the SPSA-DRASTIC-LU model is more valid than the DRASTIC-LU model.

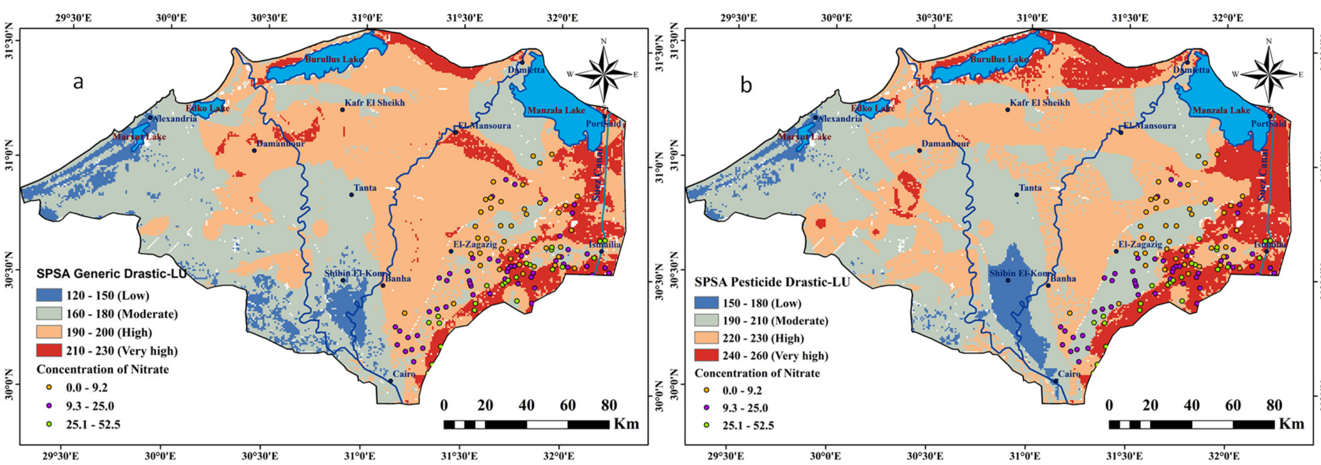

Figure 13. Validation of vulnerability map generated by (**a**) SPSA Generic DRASTIC-LU and (**b**) SPSA pesticide DRASTIC-LU model.

Map Removal Sensitivity Analysis Method (MRSA)

The map removal process, as published via Lodwick et al. (1990) [55] evaluates the susceptibility of the modified DRASTIC-LU index by eliminating one or more components at a time. This is achieved using Equation (4):

$$S = \left\{ \left(\frac{V}{N} - \frac{V'}{n}\right)/V \right\} \times 100 \quad (4)$$

where
S = sensitivity evaluation
V = disturbed susceptibility index (actual index resulting from the application of all eight factors); V' = disturbed vulnerability index (a lower number of factors were used to estimate the susceptibility index.) N and n = sum of data layers applied to compute V and V′.

Table 6a displays the outcomes of the sensitivity analysis of the MRSA method and the variation of the susceptibility index for the modified DRASTIC-LU model. The factor of depth to water showed a higher mean variation than the other factors, due to the strong sensitivity of the susceptibility index in the generic DRASTIC-LU model to the absence of these factors. Furthermore, hydraulic conductivity was the least effective factor in the generic DRASTIC-LU model (a mean variation index of 0.61 percent).

Moreover, the depth to water was the highest vulnerable factor of all eight elements applied in the pesticide DRASTIC-LU model, as the factor's removal result was 1.37%. After depth to water, the removal of soil and the influence of hydraulic conductivity factors were significantly less sensitive to the vulnerability index, because the weights and mean variation of these two factors were lower (1.26 and 1.06). Moreover, land use was the least effective factor in the pesticide DRASTIC-LU model (a mean variation index of 0.50%). Table 6b displays the conclusions of the multiple map removal sensitivity analysis method after eliminating several DRASTIC-LU factor layers at a time.

Table 6. Statistics of sensitivity analysis upon:

(a) One Map Removal.									
	Variation Index %					Variation Index %			
Generic DRASTIC-LU	Min	Max	Mean	Standard Deviation	Pesticide DRASTIC-LU	Min	Max	Mean	Standard Deviation
D	0.00	3.35	1.62	0.8992	D	0.00	2.76	1.37	0.69
R	0.22	2.50	1.29	0.4429	R	0.02	1.86	0.89	0.40

Table 6. *Cont.*

(a) One Map Removal.									
		Variation Index %					Variation Index %		
Generic DRASTIC-LU	Min	Max	Mean	Standard Deviation	Pesticide DRASTIC-LU	Min	Max	Mean	Standard Deviation
A	0.02	1.54	0.87	0.5703	A	0.01	1.59	0.90	0.59
S	0.04	1.64	1.05	0.6242	S	0.44	2.25	1.26	0.34
T	0.60	1.11	0.90	0.1008	T	0.00	1.23	0.54	0.28
I	0.00	1.41	0.82	0.4692	I	0.01	1.54	0.70	0.61
C	0.00	1.52	0.61	0.3338	C	0.12	1.64	1.06	0.27
LU	0.00	1.51	0.80	0.3212	LU	0.00	1.48	0.50	0.30
(b) Multiple map removal sensitivity analysis									
Generic DRASTIC-LU		Variation Index %			Pesticide DRASTIC-LU		Variation Index %		
Removed Maps	Min.	Max.	Mean	Standard Deviation	Removed Maps	Min.	Max.	Mean	Standard Deviation
DR	0.00	5.48	3.08	1.35	DR	0.00	4.52	2.28	1.23
DRA	0.17	5.62	2.72	1.36	DRA	0.00	4.27	1.69	1.05
DRAS	0.00	5.87	1.87	1.41	DRAS	0.00	5.26	1.76	1.29
DRAST	0.02	5.92	1.95	1.20	DRAST	0.06	8.11	3.09	1.85
DRASTI	0.00	8.40	1.77	1.44	DRASTI	0.00	9.96	2.42	1.74
DRASTIC	0.00	10.58	5.59	2.25	DRASTIC	0.00	10.33	3.53	2.09

6. Conclusions

The groundwater sensitivity to widespread pollution in the Nile Delta region was evaluated by a GIS-based modified DRASTIC-LU method. The groundwater susceptibility map was found to be the most cost-effective method for the detection zones of probable groundwater pollution, especially given the disorganized and unconstrained expansion of land and undesirable activities harming groundwater conditions. Here, two types of modified DRASTIC-LU models, generic and pesticide, were utilized to evaluate the levels of groundwater pollution vulnerability. Based on the results of the susceptibility map developed by the generic DRASTIC-LU model, we divided the study region into four susceptibility groupings for groundwater pollution: very high, high, moderate, and low susceptibility. The ratio of vulnerability to pollution was found to be very high for 53.91% of the area, high for 42.69%, moderate for 3.38%, and low for only 0.01%. The susceptibility map formed by the pesticide DRASTIC-LU model, on the other hand, showed that around 39.53% of the study region seemed to have a very high susceptibility to pollution, 50.68% had a high susceptibility, and 9.78% had a moderate susceptibility, and about 0.01% of the research region had a low susceptibility.

The concentration levels of nitrates measured from the 121 groundwater samples gathered from the eastern part of the study region varied from 0.08 to 52.5 mg/L.

The nitrate data show a strong association with the pesticide vulnerability model DRASTIC-LU. The results of SPSA using the generic DRASTIC-LU model proved that depth to water and net recharge had the greatest effect on the susceptibility evaluation, with a mean of 21.96 and 21.51, while they represented 19.39 and 18.72 using the pesticide DRASTIC-LU. Moreover, the results of the MRSA method by the generic and pesticide DRASTIC-LU models showed that depth to water and soil had the largest influence on susceptibility, with mean values of 1.62 and 1.05 (generic) and 1.37 and 1.26 (pesticide), respectively.

In light of the obtained results, it is recommended that there should be measures put in place to: (1) establish effective environmental policies to preserve groundwater from pollution; (2) improve the ecological integrity through the application of land-use planning; (3) avoid the extra use of fertilizers in agricultural activities as they can quickly penetrate groundwater.

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