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Sensitivity analysis of water at higher risk subjected to soil contaminations

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Abstract

Existence of heavy minerals in water in some regions causes serious environmental pollution and affects the soil and water resources quality. Soil and water sensitive to pollutants were investigated in this research, based on the degree of sensitivity of their parameters. The samples obtained from industrial and agricultural areas for identifying water tables at higher risk and display regions that are most sensitive to pollutants. The vulnerability to pollution was investigated on the basis of environmental contaminants, hazards and hydro-geologic parameters. A sensitive DRASTIC software based model constructed with seven most sensitive parameters: depth of water (D); recharging water table (R); aquifer media (A); environment topography (T); impact of zone (I); and conductivity (C); accompanied by Arc-View software was employed. Weighting factors, stacking the parameters and sensitivity index for selected regions were analyzed based on higher risk vulnerable water. Investigation made based on index numbers for; no risk, low to medium and higher sensitive locations. The reliability of aquifer was tested against potential risk of contamination and nitrate ions which has been used to calibrate the model. Higher nitrate concentrations falling on susceptible areas were highlighted. Result of this study may provide environmental protection measures considered for similar regions to prevent groundwater from potential risk of pollution.

Keywords: Numerical model; Risk analysis; Polluted water; Sensitive parameters.

1. Introduction

Millions of people around the world are at risk and their living environments are vulnerable and pollutions have drastic effects on their health [1]. Food industries, agriculture, environment and society suffer the most. Water contamination happens through a variety of mechanisms. Nature has been damaged as a result of processing the serious cases of water pollution, the most concerned due to human activities.

A number of research studies have been performed on modeling contaminations and management of water resources. The mostly used 1-D and 2-D models are HEC- series, MIKE-series, GODS and DRASTIC soft-wares which have been reported in literatures by several researchers [2- 7]. A three dimensional ground water model for aquifers has also been

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developed by authors using water movement module of MIKE SHE modeling software [5]. This model is physically based on a modeling system that covers the entire hydrological cycle encompassing surface and ground water flow including the unsaturated zone and evaporation-transpiration. Applying such a model requires a huge amount of data; like water and land use, aquifer, soil and vegetation characteristics, topography, ground water level, river water level, discharge and cross-sectional area of flows both in surface and porous media. The author have used this model for analyzing the transportation of heavy metals conveyed into a reservoir behind a dam through river flooding upstream of a river reservoir system [5]. The GODS (Geological Over-layers Depth Storage) model software has widely been used for transporting contaminants in porous media of saturated soils used by many researchers [5]. This model also has been used by the authors for comparing with DRASTIC model [5]. Drastic model has the ability to predict the seven most sensitive parameters [8] and hydro-geologic variables highlighted in this research study, while GODS model has restriction for handling more than four variables [5].

A drought water shed area was selected with no exclusion exposed to the urban and industrial - agricultural sources of pollutions. The studied area located at 140 km to the west of Kerman with a longitude between 15˚30′ and 31˚55′ and latitude between 55˚55′ and 55˚29′ covering a surface area of 412 Km^2. The studied plain is the main source for providing inhabitants. Implication for proper means of systematic groundwater management in this plain seems to be an essential task. One of the efficient and modern means for groundwater management was employed in this research. The geographical information system which is superior to the traditional methods for its capability, precision, speed and cost savings was also utilized. Objectives of this paper provide a sensitivity analysis for the water at higher risk and highlighted relative potential contamination of ground water resources. The result of this investigation provides an efficient management for aquifers in a region.

2. Description of the problem and modeling

A map of the vulnerability (Figure 1), the GIS medium and the DRASTIC model was employed. Arc-GIS software was applied to implicate the geographical information. DRASTIC model was created for the protection of ground water resources. The model already was used by many research centers: environmental protection agency (EPA) and reserved world water agency (RWWA) [2-3]. The seven most sensitive hydrological parameters affecting the conveyance of the pollutants were combined together and indexed to evaluate the potential contamination. Analytical procedure was carried out, encapsulated and summarized. The raw data was transformed into a layer and given to software. The water depth layer, the data of water level from 28 gauges, during forty years were used. Average measurements, during this period, for the equal water depth were sorted and given to the surfer software from which an isometric map was drown to determine the recharging layer , Figure 2. The Piscopo technique [9] was employed and adjusted to cope with the Aler grading [8]. The gradient technique was used for finding the amount of rainfall and soil permeability and the recharging potential of the area. Using 40 years rainfall data at twenty stations, the isometric map of equal rainfall areas was drawn. Total infiltration (TIN) was extracted from the Arc-GIS software. Based on TIN, the isometric map of equal rainfall locations, the region was classified into different classes. The same procedure was adopted to provide the topography of the area which was classified into four classes. Soil permeability and soil gradation map (Figure 3) were considered and soil classification was performed with respect to soil sorted in 5 different classes. To extract the soil layer, the soil map of the area was employed. To extract the topographic layer, the map of the topography with a scale of 1 / 25000 was used. To determine the layer type of the aquifer, the information obtained from the 20 wells columns in the vicinity of the plain were used. The information was obtained from the district water management organization, a numerical value of aquifer media was obtained from each log, based on average weighting factor. The topographic map (Figure 4) was transformed by numerical values in the Arc-GIS software. The semi-saturation layer was determined based on the information from the water wells. To determine the hydraulic gradient layer, the results of the pumping tests were performed at the site of gauges in the region. In these gauges the transmissibility (T) and storage coefficient (S) were computed.

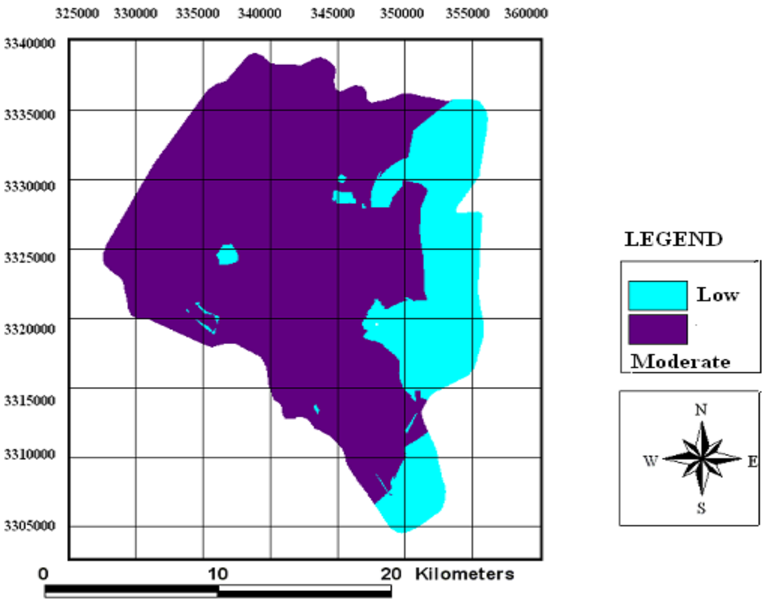

Figure 1. Sensitivity of the studied area.

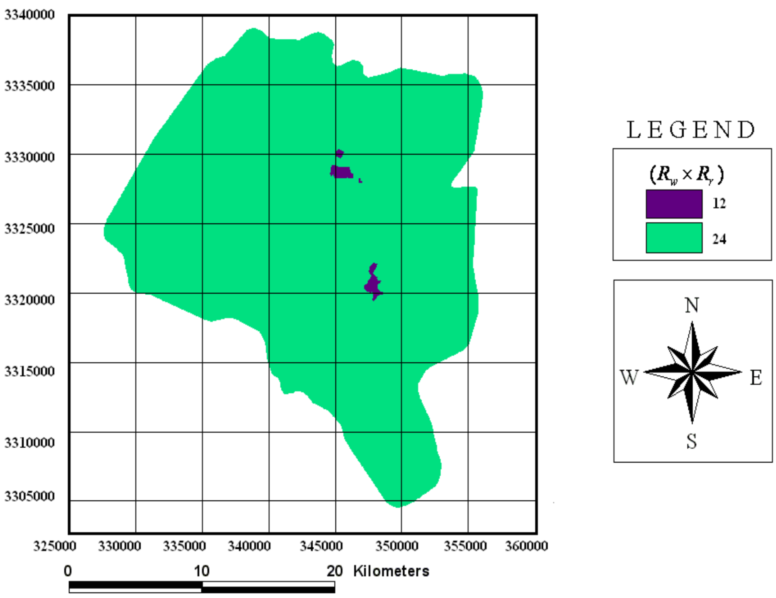

Figure 2. Sensitivity due to recharging.

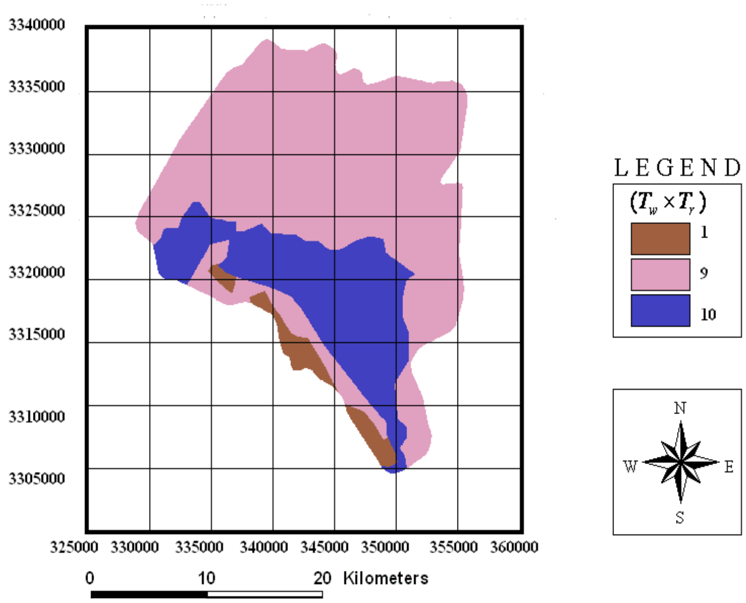

Figure 3. Sensitive soil permeability, soil gradation.

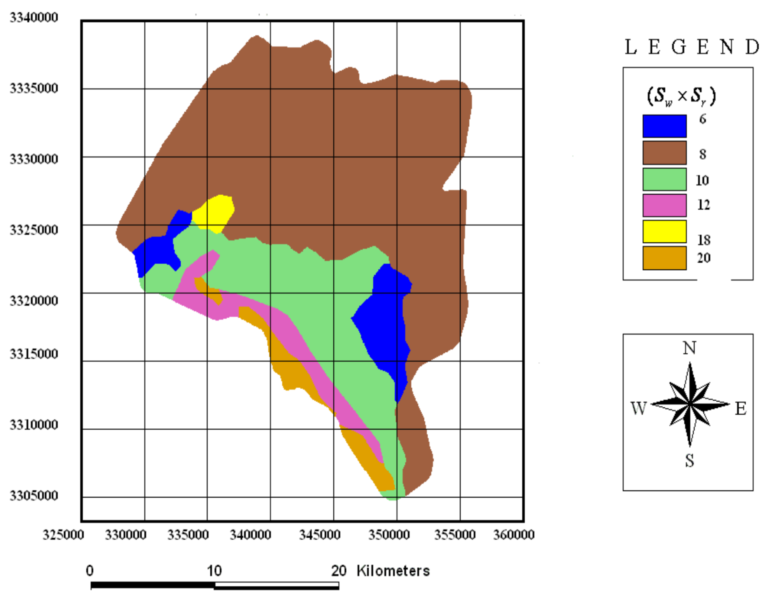

Figure 4. Sensitive topographic layer.

3. Analysis

Data was analyzed and proper weighting factors were given to each concerned layer. Based on Aler's classification [8], the water depth was classified in six groups (Table 1). The final depth was obtained using Arc-GIS software. The layer has the greatest value since it has the lowest ground water depth in the center of the plain and the value decreases towards the margins. The recharging layer was sorted according to Piscopo [9] in four groups of 1 to 8. Multiplying this by the weighting factor, the related layer, considered as 4, the map of recharging layer (Figure 2) was obtained (Table 2). The map of the aquifer medium (Figure 5) was extracted by multiplication of the standard value of the aquifer layer (Table 3) by the weighting factor 3. A numerical value of 27 was recorded for the northern part of the plain, because of the coarse grain soil in the deeper parts, in the central areas of the plain because of the existence of fine grain soil in the deeper parts this value is reduced to 15.

Table 1. Sensitivity due to depth.

Range	Rank
0-2	10
2-3	9
3-9	7
9-15	5
15-23	3
23-30	2
>30	1

Table 2. Sensitivity due to recharging.

Range	Rank
0-50	1
50-100	3
100-175	6
175-250	8
>250	9

Table 3. Sensitivity due to aquifer medium.

medium	Range	Rank
Shale	1-3	1
Shale rocks	2-5	3
Weathered rocks	3-5	4
Sedimentary rocks	4-6	5
Mixed loosed soils	5-9	6
Sand stones	4-9	6
Lime stones	4-9	6
Sandy gravels	4-9	8
Basalts	5-10	9

Aler's soil classification table was used. A numerical value was allocated for each type of deposits presented in the plain (Table 4). In the case of soil layer, to obtain the map of the soil (Figure 3), the boundaries of different deposits were determined based on the assortment of the regional soil, a weighting factor 2 was allocated and the value of the layer was multiplied by the weighting factor. As it was expected the degree of sensitivity in the centre of the plain was found lower than in the periphery. The slope map of region was extracted from the topography map (Figure 4) based on the Aler's table [8]. The slope of the area was classified, for every slope interval a different grade was allocated (Table 5). It is clear that in the northern and southern parts of the plain, because of the steeper slope, a lower numerical value is allocated, the infiltration of the pollutant and its opportunity to diffuse in this part of the plain is little, on the other hand, in the centre of the plain with moderate slope, more opportunity is available for the water to infiltrate, the transformation of the pollutants is also high. In the case of the semi-saturated layer, based on the Aler's classification and the type of each log, every log has given a different value (Table 5). After grading and given weighting factor, it was observed that the lowest value attributed to the centre of the plain was 25 and the highest value attributed to the periphery was 45. Based on the Aler's table of hydraulic gradient of flow, a numerical value is allocated to each hydraulic gradient boundary and the hydraulic gradient map (Figure 6) was obtained (Table 6). This map was multiplied by the weighting factor of 3 to provide the final map. It was observed that the value of the hydraulic gradient of the flow decreased from 18 in the North-East to 3 in the South-West. This indicated that susceptibility to contamination is higher in the North-East than the South-West of the plain.

Table 4. Sensitivity due to soil layers.

Range	Rank
Thin saturated layer	10
Gravels	10
Sands	9
Silts	8
Dense clays	7
Coarse loam	6
Medium loam	5
Silt loam	4
Clay loam	3
Loose soils	2
Loose clay	1

Table 5. Sensitivity due to topography.

Range	Rank
0-2	10
2-6	9
6-12	5
12-18	3
>18	1

By corporation of the 7 layers, an objective map (Figure 6) was provided in a variety of forms including results in the tables. One of the main objectives of employing GIS was geology, incorporation of different information layers, analysis of space patterns and presentation of a sensitive model to pollutants, based on the existing realities. The seven sensitive parameters called layers provided a common cover and the susceptibility to contamination for the regional plain. Using the Arc-GIS, the seven layers were affecting each other. DRASTIC sensitivity index was computed based on the following formula.

$$DRASTIC\ index = (D_r \times D_w)+(R_r \times R_w)+(A_r \times A_w)+(S_r \times S_w)+(T_r \times T_w)+(I_r \times I_w)+(C_r \times C_w) \qquad (1)$$

where, letters indicate the name of the layer, the sub-letter *w* indicates the weight of the layer, sub-letter *r* indicates the ranking number as weighting factor based on sensitivity of parameters. DRASTIC indices were evaluated at numbers between; 23–230, for low to highest sensitive regions.

Using the above formula, the DRASTIC index for the Khatun Abad plain was computed to be between 69 to171. Finally by sorting the above index, based on Table 7, the susceptibility map (Figure 7) for the case under consideration was provided. It has shown that areas with low to high susceptibility to contamination can be found in this region. Also it was found that a 13.96 percent of the whole area located in low stage vulnerability, 84.05 percent in medium stage vulnerability and 1.98 percent in high stage vulnerability. In terms of regional area, from a total area of 126.45 Km^2, 17.65 Km^2 were located in low stage vulnerability, 106.25 Km^2 in medium stage vulnerability, and 2.50 Km^2 in high stage vulnerability. The medium stage vulnerability boundaries are located in the central part of the plain where the level of the underground water is high and most of the agricultural and urban lands are located in this part. The low stage vulnerability boundaries are located in the periphery of the plain where the level of underground water is low and agricultural land and urban areas respect to central parts of it exists. In the high stage vulnerability area the infiltration of the pollutants is higher due to the low gradient and coarse grain soils.

Table 6. Impact of the Vadose Zone Media.

Zone Medium	Rating	Rank
Compacted	1	1
Loosed soils	2-6	3
Shale	2-5	3
Lime stones	2-7	6
Sand stones	4-8	6
Mixed soils	4-8	6
Sand- Silt- Clay	4-8	6
Metamorphic	2-8	4
Gravels	6-9	8
Basalts	2-10	9

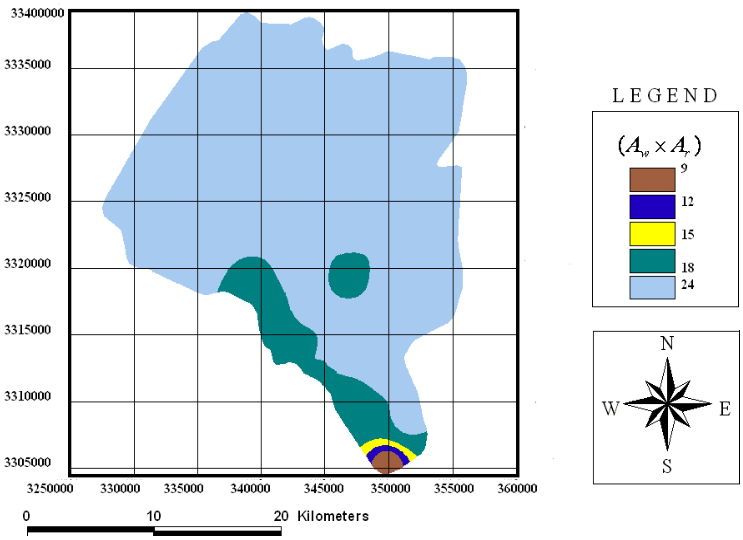

Figure 5. Sensitive aquifer media.

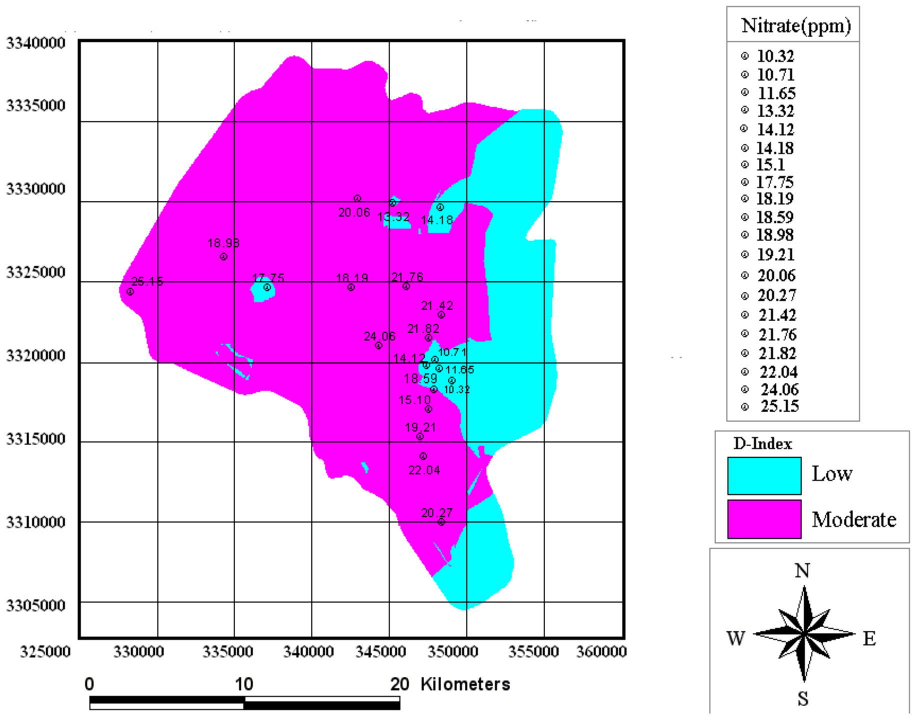

Figure 6. Impact of the Vadose Zone Media.

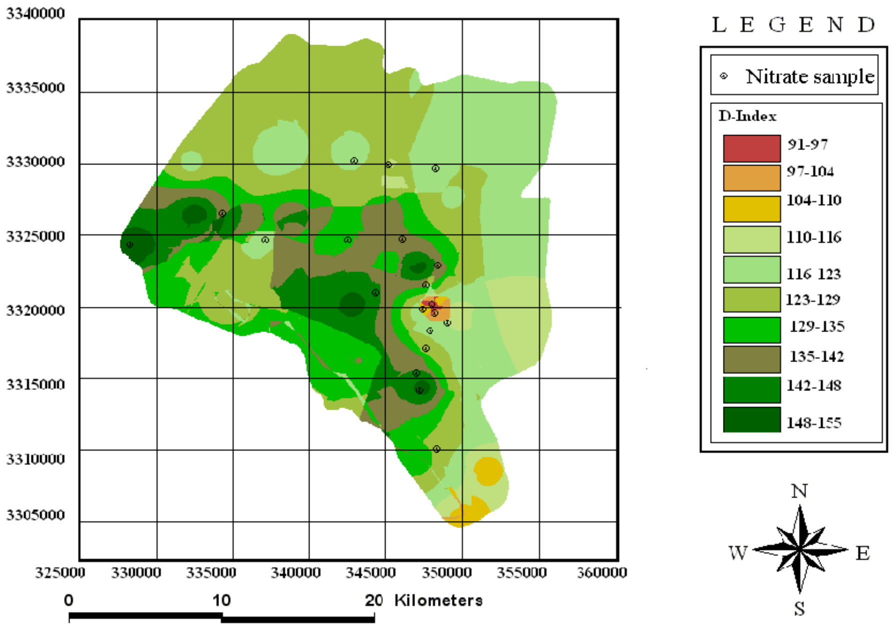

Figure 7. Sensitivity of superimposed parameters.

Table 7. Sensitivity of the region.

Rate of recharging		Soil permeability		Rainfall		Slope	
Range	score	Range	factor	Rain(mm)	factor	Slope (%)	factor
11-13	10	High	5	>850	4	<2	4
9-11	8	Medium	4	700-850	3	2-10	3
7-9	5	Low	3	500-700	2	10-33	2
5-7	3	Very low	2	<500	1	>33	1

4. Sensitivity tests

Sensitivity analysis was performed using the following two methods:

- Map removal method
- Single parameter method

4.1. The analysis of map removal

The map removal method was employed by Lodwick and his team [10]. This method shows the sensitivity of the vulnerability map by removal of one or more of the layers. The formulation for computing the sensitivity of map removal is as follows:

$$S = (|V/N - V'/n|/N) \times 100 \quad (2)$$

where S is the amount of sensitivity index; V' and V are indication of non turbulent and turbulent respectively. N and n are the number of layers used in computing V and V'.

The real vulnerability indices were obtained by contribution of all seven parameters considered as the non turbulent vulnerability indices. The computed vulnerability and employed fewer layers were considered as the turbulent vulnerability. In this method, each of the employed parameters were eliminated and a new vulnerability index was obtained at each time for the remaining layers overlapping each other. By this procedure, the effect of the eliminated layer in the model to some extent was identified. In fact, in this way the most effective pollution parameter was identified. Analysis of Khatun Abad plain was carried out by DRASTIC model and the results are given in Tables 7 and 8. The most sensitive parameter affecting the vulnerability was the hydrostatic depth. The value of this index is displayed in table as 29.62. This was due to its heavy weighting factor, characteristic of the aquifer medium and lack of proper and detailed information. As can be seen, after the parameter of water depth, the most effective and sensitive parameters were; aquifer medium, hydraulic gradient, topography, recharging, unsaturated medium and soil media respectively.

Table 8. The sensitivity, the map removal analysis.

Standard Deviation (%)	Min (%)	Max (%)	Average (%)	Removed parameter
18.70	0	82.61	29.62	D
9.32	0	40.21	16.22	R
8.87	0	30.83	15	A
8.20	0	31.52	14.31	S
10.52	0	40.50	18.70	T
12.30	0	47.81	21.72	I
7.42	4.9	36.40	20.70	C

4.2. Single parameter analysis

This method was developed by Napolitano and Fabri [6] to evaluate the effect of the parameters on the vulnerability indices. This method was used to compare the effective or real weighting factor for each of the sensitive parameters, with the theoretical weighting factor, allocated to the same parameter in the DRASTIC analytical model. Effective weighting factor was computed using the following formula;

$$W = (P_r P_w / V) \quad (3)$$

where W is the effective weight of each parameter; P_r and P_w are the score and weighting factors for each of parameters, respectively. V is the final indices for vulnerability. The sensitivity analysis of map removal indicated the importance of employed parameters in the model. The evaluation of vulnerability indices in the considered region was used to compare the effective values and the theoretical weighting factor of the sensitive parameters. In Table 9 the effective and theoretical weighting factors of the DRASTIC parameters did not completely coincide with others. In some cases there are considerable differences between them. The depth to hydrostatic parameter was the most effective parameter in the vulnerability evaluation (on average effective weight = 29.21). This was expected and confirmed the results obtained by sensitivity analysis of map removal. The average effective weight of this parameter was a little more than the theoretical weight, which was allocated by DRASTIC model [10]. The topography in the unsaturated region and hydraulic gradient parameters indicated higher sensitivity with heavier effective weights to the theoretical weights. The soil media, aquifer medium, recharging parameters, displayed less sensitivity with lighter effective weights. These results indicate that the depth of groundwater, topography, unsaturated region and hydraulic gradient parameters have greater effects on the ground water pollution. The application of the DRASTIC model premises within the boundaries of the region has shown that the soil, aquifer medium and recharging have less effects on the underground water vulnerability compared with the theoretical recommendation of the model [6-7,10].

Table 9. The sensitivity, the single parameter analysis.

Standard Deviation (%)	Min (%)	Max (%)	Average (%)	Theoretical weight (%)	Theoretical weight	Parameter
9.82	7.90	51.82	29.21	21.70	5	D
7.25	3.29	30.82	13.14	17.40	4	R
7.82	0.12	21.12	10.72	13	3	A
3.21	0.50	18.10	6.28	8.70	2	S
4.51	0.82	19.34	7.21	4.30	1	T
9.80	7.83	52.80	24.60	21.70	5	I
10.50	3.72	32.90	15.80	13	3	C

5. Results and Discussion

The samples taken by the rural water and sewage system management organization were used in the analysis. The drinking and agricultural water wells of the region were employed. Investigations included ten drinking and agricultural wells in which proper dispersions were analyzed. The result extracted from the DRASTIC method undertakes the effects of Manure and fertilizer used in the region, as well as the concentrated nitrate ions (NO_3^-) considered in the analysis of the samples. Unified Testing Material (UTM) was utilized for the wells in the region. The result of ten analyzed wells based on the equivalent nitrate map was extracted as shown in Table 10. The amount of nitrates in the 20 points were sampled and analyzed. These points are located at East, North-East, West and South of the targeted area which were found vulnerable and at high risk. Result of investigations has shown that some regions of the plain were rather sensitive with an index above the average. There has been some location with high sensitivity index as shown in illustrated maps (Figures 1-7). The results on maps and in tables provide that the model has worked well with what expected based on the physical reality.

Table 10. Nitrate concentrations, and drastic index.

$Q=\frac{Nitrate}{D\text{–}Index}$	Drastic index	Concentrations (ppm)	Sampling location (UTM)
0.136	138	18/98	334350E - 3326553N
0.119	126	15.1	347414E - 3316790N
0.149	119	17.75	345730E - 3320210N
0.116	100	11.65	348370E - 3320084N
0.119	119	14.18	345287E - 3330051N
0.117	113	13.32	344305E - 3330169N
0.173	119	20.06	343047E - 3330208N
0.155	138	21.42	348484E - 3322982N
0.165	132	21.82	347659E - 3321574N
0.166	145	24.06	344401E - 3320648N
0.145	151	22.04	346613E , 3313889N
0.157	138	21.76	346772E , 3325503N
0.160	126	20.27	348462E , 3310026N
0.166	151	25.15	350000E , 3323150N
0.131	107	14.12	347376E , 3319831N
0.113	94	10.71	348130E , 3320042N
0.1	113	10.32	349125E , 3318896N
0.156	119	18.59	347979E , 3318353N
0.132	145	19.21	347104E , 3315094N

6. Conclusions

The results obtained from this research are outlined as follows:

- The surveyed case was studied and the displayed model verified the designed criteria based on the physical reality.
- This comprehensive analysis was the first applied research involving case studies, useful for regions, to recognize contaminants, predict potential risks and control a safe water environment.
- The sensitivity index associated with the hydrostatic depth layer in the Northern and Southern regions varied from the central limits of the plain. The hydrostatic depth varied from 40 meters in the North and South of the plain to 4 meters in its centre. Based on properties of soil and water, this is physically accurate and is expected.
- The map of the aquifer indicated that in the Northern parts of the plain, due to the alluvial cone, the aquifer medium consist of coarse grains, whereas in the centre, it is made of fine grains. In the Southern parts of the plain, the grains are coarser compared to the centre, so, the sensitivity and susceptibility to contamination was higher in the Northern part due to coarse grains and lower levels heights in the centre of the plain.

- The minimum sensitivity index of the plain was found as 69 and its maximum was 171, so, with respect to pollution risk, most of the plain had a low to medium potential risk and the smaller portion had a high potential risk.
- The analysis of the sensitivity and map removal indicate that the parameters associated to depth of water had the highest sensitive effects on the aquifer pollution. Aquifer medium, hydrostatic gradient, topography, recharging, unsaturated medium and soil media were the most sensitive parameters, respectively.
- parameter susceptibility analysis indicated that the depth to groundwater level topography, unsaturated region and hydraulic gradient parameters had more effects on the ground water pollution potentials, in the examined areas, compared to the DRASTIC model. The soil media, aquifer medium, recharging parameters, had less effects on the ground water vulnerability, compared to the DRASTIC method.

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