ASSESMENT OF GROUNDWATER VULNERABILITY TO POLLUTION IN WASTERN NILE DELTA AQUIFER, EGYPT

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ABSTRACT

Groundwater (GW) is an important source of water in many countries around the world. Among them, Egypt which depends mainly on ground water as a major source of water through its desert regions, specifically in the Western region of Nile Delta. However, increasingly deterioration of GW quality threatens its uses strategies. DRASTIC approach was used to determine vulnerability zones in the Western Nile Delta region. First, maps of five DRASTIC models were compared and analyzed using GIS-ArcView, including DRASTIC, Pesticide DRASTIC, modified DRASTIC, Pesticide DRASTIC-LU and Susceptibility Index (SI). Second, validation for the vulnerability models were performed by comparing Nitrate measurements. Finally, a sensitivity analysis was performed to assess DRASTICS's performance and to identify most critical hydrological parameters for vulnerability assessment. The DRASTIC, Pesticide DRASTIC-LU and SI maps ranked 25% of the Western Nile Delta region as very highly vulnerable. While the modified DRASTIC model classified 31% of the study area as very highly vulnerable. Furthermore, the sensitivity analysis showed that the vadose zone is the most important parameter for all DRASTIC models. Additionally, the validation results showed that the SI model experienced the highest correlation with Nitrate (0.66). The vulnerability maps proved its reliability as an important tool for planning of land use and effective management of GW resource Western Nile Delta region and any similar regions.

Keywords: Groundwater, DRASTIC, Susceptibility Index, sensitivity analysis, Nile Delta aquifer

1 INTRODUCTION

Water scarcity is a widespread problem in many countries around the world (Allam et al., 2015). Among them, Egypt, which face a great challenges due to its limited water resources (Fliefle and Allam 2016; Allam et al. 2016a, 2016b). Groundwater (GW) represents one of the most promising, and economically attractive options to make more water available for different uses, specifically in Western Nile Delta region (El Hassan and Allam 2017). Currently, the total abstraction of GW in the Western Nile Delta is estimated at about 3.5 billion cubic meters/year (BCM/year) (Mohie El Din et al. 2016). However, spreading pollution in GW threatens the application and the expansion of these activities in the future.

Obviously, GW pollution is a serious environmental problem not only in Egypt but also around the world (Armanuos et al. 2016). It is mainly based on increasing of the human interaction with GW environment (Mendizabal and Stuyfzand 2011). Thus, there is a significant need for an approach to accurately interpret GW monitoring data and to facilitate the rapid transfer of information to water resources managers and decision makers. In such situations, vulnerability assessment represents one of the most common tools for the management, planning, and protection of GW resources (Huan et al. 2012).

Recently, several vulnerability index methods were reported for assessment of GW vulnerability, such as DRASTIC index (Aller et al. 1987), GOD index (Foster 1987), AVI index (Van Stempvoort et al. 1993), SINTACS index (Civita 1994), SEEPAGE index (Navulur 1996), ISIS index (Navlur and Engel 1997), EPIK index (Doerfliger et al. 1999), MINNESOTA index (Murat 2000), RISK index (Petelet-Giraud et al. 2000), EPPNA index (Artuso et al. 2002) and SI index (Ribeiro 2000 in van Beynena et al. 2012). Furthermore, the remote sensing techniques and geographical information system (GIS) could serve as a useful tool in all vulnerability methods to detect the vulnerable zones of GW pollution (Brindha and Elango 2015).

The DRASTIC vulnerability method was developed by Aller et al. (1987) for assessment of GW vulnerability to pollution. It is the most commonly tool used for GW vulnerability assessment for pollution (Anane et al. 2013; Alam et al. 2014; Ahmed et al. 2015; Ahirwar and Shukla 2018; Brindha and Elango 2015; Chandoul et al. 2014; Ghazavi and Ebrahimi 2015; Gemail et al. 2017;;Rahman 2008; Saha and Alam 2014; Saatsaz and Sulaiman 2011; Trent 1993; Thirumalaivasan et al. 2003).

Seven hydrological parameters mainly affect the calculation of the DRASTIC index to assess the GW vulnerability. DRASTIC method; (D) is the depth to water, (R) is the net recharge, (A) is the aquifer media, (S) is the soil media, (T) is the topography, (I) is the impact of the vadose zone, and (C) is the hydraulic Conductivity (Aller et al. 1987). Many vulnerability index methods are available, the widely used are modified DRASTIC, Pesticide DRASTIC, Pesticide DRASTIC-LU and Susceptibility Index (SI), all of them are generated from the DRASTIC model. Obviously, landuse is an important parameter for vulnerability assessment while it adopts the impact of pollutants that may reach the GW particularly in agricultural areas (Naqa 2004). Accordingly, the DRASTIC vulnerability model was modified (modified DRASTIC) to consider the landuse impact by Umar et al. (2009). Further, the SI and Pesticide DRASTIC indices were suggested to evaluate GW vulnerability in agricultural areas (Anane et al. 2013). Specifically, the SI involves the land use impacts and excludes the type of soil media, the impact of vadose zone and the aquifer hydraulic conductivity (Ribeiro 2000). Whereas, the Pesticide DRASTIC method was proposed using the same hydrological parameters of DRASTIC method with different assigned weights. The objectives of this study were to: (1) assessing GW vulnerability of Western Nile Delta, Egypt to pollution using five vulnerability models (i.e., DRASTIC, Pesticide DRASTIC, modified DRASTIC, Pesticide DRASTIC-LU and SI), and (2) to evaluate the sensitivity of these models to the input hydrological parameters.

2 MATERIALS AND METHODS

2.1 Study Area

The study area is the Western region of the Nile delta, Egypt which extends between 29^{o} $30^{\backslash\backslash}$ to 31^{o} $00^{\backslash\backslash}$ East and 30^{o} $00^{\backslash\backslash}$ to 31^{o} $00^{\backslash\backslash}$ North. It is about 15170.6 km^{2}bounded by Rosetta branch in the east and the Mediterranean Sea in the north. It extends to the desert area in the west from Wadi El-Natrun up to the eastern edge of the Qattara Depression, as shown in Fig.1. The ground surface increases from 0.0 m in the northern area (near to the Mediterranean Sea) to reach 115 m above mean sea level in the south boundary. In winter season of 2010, the rainfall ranged from 20 mm in Cairo to 225 mm in Alexandria. Correspondingly, the evapotranspiration increased from 97.8 mm at Alexandria in the north towards the south to reach 113.5 mm at Cairo. The GW recharge in the Western Nile Delta area since 2000 to 2010, ranged from 0.0 mm in the south to 134 mm in the north, Armanuos et al. (2016).

2.2 Descriptive Statistics of the Ratings for DRASTIC, Modified DRASTIC, Pesticide DRASTIC, Pesticide DRASTIC-LU and SI Factors Layers

Descriptive statistical analysis (min, max, mean and standard deviation) of the layers rating were extracted from the generated spatial layer of each hydrological parameter. The mean value informs about the contribution of the factor to the overall vulnerability index, while the value of standard deviation (SD) represents the impact of each factor in the vulnerability index variation.

2.2.1 Mapping vulnerability zones

Groundwater vulnerability to pollution has been commonly implemented using GIS tools by overlay and index method. Vulnerability models are based on three important factors specified to each hydrological parameter: range, rating and weight, Brindha and Elango (2015). DRASTIC model (Aller et al. 1985) found vulnerability zones based on seven unique hydrological parameters of an area (Table 1). Pesticide DRASTIC vulnerability model also uses the same seven hydrological parameters of the DRASTIC model. Pesticide DRASTIC vulnerability model assigned different relative weights ranges from 1 to 5 vary from DRASTIC index (Table 1). A weight of 5 are assigned to most significant factors; depth to water, impact of vadose zone and land use, on the other hand a weight of 1 is assigned to the least significant parameter such as topography. According to the potential to cause GW pollution, similarly rating is assigned to each hydrological parameter ranging from 1 to 10 (Table 2). The vulnerability DRASTIC index (VDI) is computed from the following equation: (Aller et al. 1985)

Vulnerability DRASTIC index (VDI) = $(D_r \text{ x } D_w) + (R_r \text{ x } R_w) + (A_r \text{ x } A_w) + (S_r \text{ x } S_w) + (T_r \text{ x } T_w) + (I_r \text{ x} I_w) + (C_r \text{ x } C_w)$ (1)

Where: D is the depth to GW, R is the recharge, A is the aquifer media, S is the soil media, T is the topography, I is the impact of vadose zone, C is the hydraulic conductivity, and the subscripts r and w indicate the rating and weight, for each DRASTIC parameter.

Adopted Modified DRASTIC for vulnerability assessment was proposed by Umar et al. (2009) and Secunda et al. (1998) by including the land use parameter with the other vulnerability parameters. (Umar et al. 2009; Secunda et al. 1998).

The modified DRASTIC vulnerability index is computed by the equation:

Modified DRASTIC index = $(D_r \text{ x } D_w) + (R_r \text{ x } R_w) + (A_r \text{ x } A_w) + (S_r \text{ x } S_w) + (T_r \text{ x } T_w) + (I_r \text{ x } I_w) + (C_r \text{ x } C_w) + (LU_r \text{ x } LU_w)$ (2)

Where: LU is land use.

Pesticide DRASTIC index is computed by the same equation for DRASTIC index with changes in weightings (Table 1) in equation 1. Pesticide DRASTIC index does not take in account the land use map and the Pesticide DRASTIC-LU index includes the land use hydrological parameter, as shown in Table 2 and 3. Aller et al. (1987) assigned rating varies from 1 up to 10 for each DRASTIC parameters and Ribeiro (2000) ratings for landuse varies from 0.0 to 100. The landuse ratings of Ribeiro (2000) was divided by 10 and used for the model to apply similar ratings.

Susceptibility index adapted from the DRASTIC index identifies the vulnerable zones depending on five hydrological parameters: (D) depth to GW, (R) net recharge, (A) aquifer media, (T) topography (Table 2) and (LU) land use (Table 3) given by the following equation 3 (Riberio 2000)
Susceptibility index (SI):

$$(SI) = (D_r \text{ x } D_w) + (R_r \text{ x } R_w) + (A_r \text{ x } A_w) + (T_r \text{ x } T_w) + (L_r \text{ x } L_w) \qquad (3)$$

The rating in Susceptibility index was multiplied by 10. The final vulnerability index of the all five methods will produce a relative measure of GW vulnerability to contamination. Higher vulnerability index values indicate areas which are more vulnerable to pollution compared with low vulnerability index areas.

The results were five grids where each one represents the vulnerability index of one of the five models used (DRASTIC, Pesticide DRASTIC, modified DRASTIC, Pesticide DRASTIC-LU and SI). The pollution potential of DRASTIC, Pesticide DRASTIC, modified DRASTIC, Pesticide DRASTIC-LU and SI indexes are dimensionless entities.

In the current study a uniform classification using quantile classification was adopted for all five methods. Quantile method was used to classify each vulnerability index map to four vulnerable zones are low, moderate, high and very highly vulnerable to pollution. The same method was used to classify DRASTIC scores by Rahman (2008) and (Brindha and Elango, 2015).

2.3 Sensitivity Analysis

Final index of these methods is based on either, five, seven or eight hydrogeological parameters which maps the intrinsic vulnerability and specific vulnerability of GW contamination in any region, Brindha and Elango (2015). The five adopted vulnerability methods analyzed in the current study were tested by the map removal sensitivity analysis (Lodwick et al. 1990) in addition to single parameter sensitivity analysis Napolitano and Fabbri (1996).

2.3.1 Single parameter sensitivity analysis

The single parameter sensitivity analysis was proposed by (Napolitano and Fabbri, 1996) to evaluate the impact of each parameter on the vulnerability index. The assigned theoretical weight of each hydrological parameter in the model by Aller et al. (1987) to the effective weight computed in the model. (Napolitano and Fabbri, 1996) derived the equation (4) to determine the effective weight of each parameter (Napolitano and Fabbri, 1996) r:

$$W = \frac{100(P_r P_w)}{V} \tag{4}$$

Where:
W is the effective weight of each hydrological parameter, P_r and P_w are the rating value and weight of each hydrological parameter, and V is the overall vulnerability index.

2.3.2 Map removal sensitivity analysis

The map removal sensitivity analysis test allows the identification of sensitivity of GW vulnerability by removing one of the hydrological parameters from the vulnerability map, Lodwick et al. (1990). The map removal sensitivity analysis computed from the formula:

$$S = |(V/N) - (v/n)| \times (100/V) \text{ (Lodwick et al., 1990)} \tag{5}$$

Where:

S is the sensitivity measure expressed in terms of variation index; V and v are the unperturbed and the perturbed vulnerability indices, respectively; and N and n are the number of data layers used for V and v computing.

2.3.3 Comparison between model results

The following five vulnerability maps: DRASTIC, modified DRASTIC, Pesticide DRASTIC and Pesticide DRASTIC -LU and SI indices were compared to each other’s. The quantity and the location of difference between each two maps were determined by using spatial analysis capabilities; each two correspondent index maps were crossed. For each comparison the area of divergence and agreement were obtained based on the vulnerability categories. In addition, the percentage of areas where the first index value exceed the second one was calculated and the vice versa.

2.3.4 Comparison between vulnerability index and Nitrate concentration

For validation of the vulnerability models, the Nitrate concentrations in 108 wells of GW were used. The correlation matrix between the measured Nitrate in 108 locations of GW wells and the value of vulnerability index for each map was determined.

3 RESULTS AND DISCUSSION

3.1 Preparation of Various Maps

3.1.1 Depth to groundwater

Depth to GW determines the material depth through which a pollutant must travel before reaching the GW table in the aquifer (Aller et al. 1987). Depth to GW determines the contacting time with the surrounding soil media and shows the maximum chance for contaminant attenuation (Aller et al. 1987). Attenuation results from physico–chemical retention or reaction of contaminants and it also include the processes of degradation, sorption, percolation and precipitation (Robins et al. 2007). Generally, there is a larger opportunity for the attenuation process to take place as the GW depth increases because the deeper GW water levels indicate longer travel times (Aller et al. 1987). Records of the GW levels in the Western Nile Delta region are obtained from observation wells by Research Institute of groundwater of Egypt (RIGW), the observation wells have well screens at depth varies between 20 and 75 m below the GW surface, Morsy (2009). An average of the GW levels was used to produce the GW table map by interpolating the GW head from the monitoring wells that spread in the study area (Fig. 2a). Shallow water table areas were assigned as higher rating values which are more vulnerable to GW pollution and (Table 2) and deeply water level areas are assigned as lower ratings values. About 26 % of the study area has GW depth that exceeds 30.5m. Around 6.0 % of the Western Nile Delta area has GW depth ranges between 22.8-30.5m. Less than 17 % of the study area has GW depth between 0.0m and 1.53 m.

3.1.2 Recharge due to rainfall

Net recharge represents the water which penetrates from the ground surface through the unsaturated zone and reach the groundwater table. Available recharge water is able to transport a pollutant vertically to reach the water table and also horizontally through the aquifer (Aller et al. 1987). Groundwater recharge rates in any region depend on numerous factors, includes precipitation, rock permeability, water table depth, type of soil and moisture conditions, slope, wind speed and temperature (Belden, 1996).

Armanuos et al. (2016) used WetSpass model to estimate the GW recharge from rainfall in the Nile Delta area from 1970 to 2010. GW recharge in the Western Nile Delta area in 2010, ranged from 0.0 mm in the south increased towards the north to reach its maximum values about 134mm in winter season (Fig. 2b). Areas with higher recharge values in north and northWestern area assigned high ratings while middle and southern areas assigned lowing ratings values due to minimal recharge rates (Fig. 2b) and Table 2. More than 50% of the Western Nile Delta area has net recharge value bellow 50.8 mm/year. About 34% of the study area is assigned by 3 where recharge ranges from 50.8 to 101.6 mm/year. The highest rating 6 is assigned to 11.52 % of Western Nile Delta area that has a recharge value more varies between 101.6 to 134 mm/year.

3.1.3 Aquifer media

Aquifer media represents the rock type which forms the aquifer (for example; sand and gravel or limestone). The aquifer medium affects the GW flow system through the aquifer. The Nile Delta region is totally covered by the Quaternary deposits which mainly consist of Nile silt, clay, sandy clay, sands and gravels, Elewa and Nahry (2009). The geologic map of Egypt with scale 1:500000 produced by CONOCO, Co. (1987) was used, Fig. 2c. Majority of Western Nile Delta aquifer (around 35%) has Nile silt and clay where assigned by 5. Shale and sandstone cover 11.27% of the study area and is assigned with 6. About quarter of the Western Nile Delta is sand and has a weight of 7. High ratings 8, 9 and 10 are assigned to sand and gravel (9.69%), coarse sand and gravel (17%), graded sand and gravel (14.65%) respectively.

3.1.4 Soil media

Soil media has a significant effect on the volume of recharge which can penetrate the ground surface and hence on the ability of vertical contaminant movement into the vadose zone. The existence of fine-textured soil particles such as clays and silts can minimize the relative coefficient of permeability and constrain the contaminant migration (Aller et al. 1987). The National soil map of Egypt produced by European Soil Data Centre (acquired from ESDAC website) was used, Fig. 2d. Various types of soil like silt and clay, clayey sand, loamy sand, stony and loam, sand soil, gravel and sand soil cover 29.05%, 1.7%, 9.37%, 2.17%, 34.14% and 23.57% respectively. High ratings value 10 is assigned for gravel and gravely sand soil. About 35% of the area is covered by sand and assigned with 9.

3.1.5 Topography

Topography represents the variation of ground surface slope. Topography is an important parameter which affects the probability that a pollutant on water will run off based on slope values above the ground surface or remain longer time on the ground surface to be able to infiltrate. Slopes which hence a greater opportunity for pollutants to penetrate are connected with a higher potential of pollution (Anane et al. 2013). Slope map was derived from the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) 90-m resolution (downloaded from USGS website). The 90-m resolution of the SRTM was adjusted for all the grid model maps. The slope layer was categorized and rated regarding to Table 2. Small slopes areas are assigned higher ratings value, on the other hand, steeply slope areas are assigned with low ratings as given in Table 2. Slope range of 0 to 2 % occupies more than 45 % of Western Nile Delta area and its rating value is 10. A rank of 9 is assigned for 26.8% of the study area which has 2 to 10% slope. Areas with steep slopes (18%-61%) are assigned with rating value of 1 which indicates its minimal effect on the GW vulnerability.

3.1.6 Impact of vadose zone

The unsaturated zone (vadose zone) is well-defined as that soil zone above the water table which is unsaturated soil or discontinuously saturated soil (Aller et al. 1987). The soil type of vadose zone controls the attenuation characteristics through sorption, biodegradation, mechanical infiltration and dispersion and volatilization (Aller et al. 1987). Many researchers have stated the significant impact of the vadose zone permeability on the aquifer’s contamination (Timmons and Dylla 1981; Richards et al. 1996; McLay et al. 2001). Large area of Nile Delta region is covered with clay cap, the thickness of the clay cap layer ranges from 5–20 m in the South and the Middle areas of the delta, and reaches 50 m in the Northern area (Diab et al., 1997), Fig. 2e. The clay cap thickness map was produced by RIGW (Morsy, 2009). As all the study area are covered by clay, areas with shallow clay cap thickness are more vulnerable to pollution and assigned higher ratings value where areas with deeply clay cap are less vulnerable to pollution and assigned lower ratings value, the same technique used by Gemail et al. (2017). More than half of the study area has clay cap thickness ranges between 0.0 to 10m and assigned with rating 10. About quarter of the area has clay thickness varies from 10 to 20m and has ranking rate of 8. Less than 4 % of the Western Nile Delta area has clay thickness more than 40m and assigned with low rating value of 2.

3.1.7 Hydraulic conductivity

Hydraulic conductivity represents the capacity of the aquifer materials to transmit the water and to control the GW flow and the contaminant transport in the aquifer (Aller et al. 1987). Generally, for unconsolidated porous medium, in the case of Nile Delta aquifer, hydraulic conductivity varies with the particle size; sand and gravel exhibit high values (Todd and Mays 2005). Areas with higher hydraulic conductivities are more vulnerable to GW pollution and are assigned higher rating values while areas with lower hydraulic conductivity are assigned lower ratings, Fig. 2f. and Table 2. The hydraulic conductivity of Western Nile Delta aquifer ranges from 30 to 100 m/day. About 31% of the study area has hydraulic conductivity in the range of 30 to 41 m/day and is assigned with 6. Around 32 % of Western Nile Delta area has 41 to 82 m/day with rating of 8. The value ranges between 82-100 m/day are found in 37.32 % of the study area and assigned with higher rating value of 10.

3.1.8 Landuse

Land use is a crucial factor on the GW contamination through the pollution produced by the different anthropogenic activities (Ribeiro 2000 in Van Beynena et al. 2012). It has negatively impact on GW system due to the use of pesticides and fertilizers in agricultural areas, and through the chemical compounds disposal into the surface water bodies and the landfills linked with industrial areas. Armanuos et al. (2016) used ENVI software to generate the land use and land cover map for the Nile Delta region for the year 2009. The data set of image from Global Land Survey (GLS) for the year 2009 was used, acquired from the USGS website. The main land uses present in the study area are: agriculture land, barren soil, urban areas and water areas, Fig. 2g. Landuse map is one of the parameters for GW vulnerability mapping in modified DRASTIC and Pesticide DRASTIC-LU models. Landuse was given a weightage of 5 in modified DRASTIC and Pesticide DRASTIC-LU methods whereas in SI, the proposed weightage by Riberio (2000) was used (Table 3). About more than 55% of the study area is classified as agricultural land and assigned with rating value of 8. Around 30% and 15% of the study area are classified as desert and urban area and assigned with rating value of 2 and 9 consequently.

3.1.9 Aquifer vulnerability map

Table 4 shows the statistical variation analysis in rating of parameters derived from each hydrogeological layer. The contribution to aquifer vulnerability map by the slope is much higher which is followed by impact of vadose zone, hydraulic conductivity, recharge and then soil type whereas the contribution of depth to GW level in arriving at the aquifer vulnerability map was low followed by aquifer media and landuse.

Ranges of final indices derived by using the five models were 102 to 187 (DRASTIC), 112 to 232 (modified DRASTIC), 97 to 212 (Pesticide DRASTIC), 107 to 257 (Pesticide DRASTIC-LU) and 20 to 89 (SI). The obtained indices range varies in the five models, a uniform classification method i.e. quantile classification technique was adopted to categorize the areas to low, moderate, high and very high vulnerable to GW pollution. Fig. 3 presents the vulnerability index maps obtained from the five vulnerability models.

Percentage of vulnerable areas in DRASTIC, Pesticide DRASTIC-LU and SI are relatively similar (Table 5). The Pesticide DRASTIC-LU and SI models include landuse impact which is not considered in DRASTIC. Vulnerability index map derived from modified DRASTIC and Pesticide DRASTIC methods have different areas compared with the other methods. In the vulnerability index map attained from modified DRASTIC and pesticide DRASTIC methods, the area of moderate and high vulnerable zone has comparatively similar. In the vulnerability map derived from modified DRASTIC, the percentage area of very highly vulnerable zone has increased compared to Pesticide DRASTIC this due to the inclusion of land use map. On the other hand, in the vulnerability map derived from Pesticide DRASTIC, the area of low vulnerable zone has increased compared to modified DRASTIC. With the accounting of landuse hydrological parameter, some regions classified as highly vulnerable zone in DRASTIC are changed to be very highly vulnerable to pollution in both modified DRASTIC and Pesticide DRASTIC-LU models which is similar to Pesticide DRASTIC model. Area classified as low vulnerable in case of pesticide DRASTIC was about 27% whereas in other models it was below 24%. Area classified as very highly vulnerable in the case of modified DRASTIC was about 31% whereas in other models it was below 25%.

Eastern parts of the Western Nile Delta are classified as highly vulnerability based on DRASTIC, modified DRASTIC, Pesticide DRASTIC and pesticide DRASTIC-LU while in SI model all the zones are widely distributed (Fig. 3). Southern parts of the Western Nile Delta area classified as low vulnerability based on all vulnerability index models whereas Pesticide DRASTIC has the higher area compared with other models. Topography influence the final index of DRASTIC, modified DRASTIC, Pesticide DRASTIC and Pesticide DRASTIC-LU models. Agricultural areas are classified to moderate to very high vulnerable to pollution in DRASTIC, modified DRASTIC, Pesticide DRASTIC and Pesticide DRASTIC-LU models.

3.2 Validation with Nitrate Measurements

Fig. 4 shows the comparison between nitrate measurements and the vulnerability models. The correlation coefficients between Nitrate measurements and vulnerability models (DRASTIC, modified DRASTIC, pesticide DRASTIC, pesticide DRASTIC-LU and SI) are found 0.59, 0.63, 0.47, 0.57 and 0.66 respectively. The modified DRASTIC, pesticide DRASTIC-LU and SI vulnerability models shows high correlation with Nitrate measurements which consider the landuse impact in the computation process. SI vulnerability model presents high correlation with nitrate measurements compared with other models whereas soil type, impact of vadose zone and hydraulic conductivity were not considered in calculation.

3.3 Variation in Model Results

Table 6 shows some discrepancy by comparing the results of the five vulnerability index maps. The vulnerability index maps was reclassified by assigning a number 1 for low, 2 for moderate, 3 for high and 4 for very highly vulnerable zones. This reclassification allows subtracting the reclassified index map of one model with another. The resulted maps after subtracting the models have ranges from -3 to 3 for ten model comparisons. Comparison between the two models, DRASTIC and modified DRASTIC, having a value of -1 indicates that DRASTIC model is one Vulnerability category lower than modified DRASTIC where in case of -2 and -3 indicated increased discrepancy. Positive values +1 and +2 indicates that DRASTIC index have two vulnerability categories higher than modified DRASTIC. A zero value indicates that the mapping vulnerability zones by the both models are accurate. In general, negative number indicates the underestimation where positive numbers imply overestimation with a degree range between +1 to +3.

Closely comparable results were between Modified DRASTIC versus Pesticide DRASTIC-LU (66%) followed by Modified DRASTIC versus SI (60%) then Pesticide DRASTIC versus DRASTIC (49%) and DRASTIC versus modified DRASTIC (48%) was observed. Least comparability results were between Pesticide DRASTIC versus Modified DRASTIC (24%) followed by Pesticide DRASTIC versus SI (31%) and then DRASTIC versus Pesticide DRASTIC-LU (37%) was observed. Underestimation of DRASTIC versus SI, Pesticide DRASTIC versus SI, Pesticide DRASTIC-LU versus SI, Pesticide DRASTIC versus DRASTIC and DRASTIC versus Pesticide DRASTIC-LU is primarily due to including landuse with a highest weightage. Overestimation of DRASTIC versus Pesticide DRASTIC-LU, Pesticide DRASTIC versus Modified DRASTIC, DRASTIC versus modified DRASTIC and Pesticide DRASTIC versus Pesticide DRASTIC-LU. Generally, Pesticide DRASTIC-LU seems to calculate well in relation to other models with relatively lower overestimation and higher underestimation.

3.4 Sensitivity of the Parameters

3.4.1 Single parameter sensitivity analysis

The soil type is observed to be the most effective inputs of the DRASTIC model beside and impact of the vadose zone parameter, with the highest weight of five equivalents to 20.31 %, followed by topography (16.31), depth to water level (16.05) and aquifer media (12.05 %). Recharge and conductivity parameters have the lowest weight below (10.00%), Table 7. In modified DRASTIC, the parameter impact of vadose zone was the most prominent, as reflected by its effective weight (mean, 24.34 %), which exceeded the theoretical weight by (mean, 6.48 %). Similarly, the landuse has also shown higher effective weight (mean, 17.21 %). The recharge, soil type and aquifer media on the other hand, have shown significantly lower effective weight below (10.0%).

The parameters impact of vadose zone and soil type, were observed to be the most significant in the calculation of Pesticide DRASTIC model. In Pesticide DRASTIC-LU model, soil media, impact of vadose zone and landuse were found the highest important parameters whereas recharge and conductivity parameters were the lowest important ones in DRASTIC, Modified DRASTIC and Pesticide DRASTIC-LU models.in SI model, aquifer type and landuse were the two parameters with highest impact.

3.4.2 Map removal method

In DRASTIC model, the highest sensitivity index is observed upon removal of the impact of vadose zone data layer (2.70 %), followed by the depth to water level (1.90 %) and conductivity (0.69%), Table 8. The variation of the Pesticide DRASTIC vulnerability index also seems to be high sensitive to the removal of the data layers of soil media (1.87%), depth to water (1.64%) and impact of vadose zone (1.29%) from the computation, Table 8. In modified DRASTIC model, the highest sensitivity index is shown upon the removal of the impact of vadose zone data layer (1.92 %), followed by depth to water level (1.33%) and landuse (1.29 %), Table 8. The variation of the Pesticide DRASTIC-LU vulnerability index also seems to be high sensitive to the removal of the data layers of soil media (1.48%), depth to water (1.16%), conductivity (1.12%) and impact of vadose zone (1.10%) from the computation. In SI vulnerability index model, the highest sensitivity index is observed upon removal of the aquifer media (4.19 %) and followed by the landuse (3.20 %) and topography (2.1%). The least average variation index is found by removing the recharge layer in the DRASTIC model (0.35%), as shown in Table 9. Similarly, in Pesticide DRASTIC model, the least average variation index is found by removing the recharge layer 0.45 %). The least average variation index is found by removing the recharge layer and conductivity in the pesticide DRASTIC-LU model (0.70%). In SI model removing recharge layer and depth to water level achieved also the least average variation index (0.97%) and (1.31%) respectively.

4 CONCLUSIONS

The current study assessed the GW vulnerability zones based on combination of the hydrogeological parameters. Five vulnerability models: DRASTIC, modified DRASTIC, Pesticide DRASTIC, Pesticide DRASTIC-LU and IS were applied to assess the GW vulnerability to pollution in Western Nile Delta region. The Modified-DRASTIC model ranked 31% of the study area as very highly vulnerable to pollution. Furthermore, DRASTIC, Pesticide-DRASTIC -LU and SI classified 25% of the study area as very highly vulnerable to pollution. Results derived from Pesticide DRASTIC model were not comparable with that of SI, modified DRASTIC or Pesticide DRASTIC-LU. On the other hand there was close comparison between Modified DRASTIC model versus Pesticide DRASTIC-LU, SI and also between Pesticide DRASTIC versus DRASTIC. The model was validated using Nitrate concentrations. The results confirmed that a highly correlation was found with both Pesticide DRASTIC-LU and SI models. The results proved the importance of including land use parameter in the vulnerability computations. The vulnerability models proved its reliability as an effective tool for investigating the GW vulnerability zones in the Western Nile Delta, Egypt.

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Table 1. Hydrological parameters and weightage used for the five vulnerability models

Parameter	Generic DRASTIC weights (Aller et al. 1987)	Pesticide DRASTIC weights (Aller et al. 1987)	Modified DRASTIC (Brindha and Elango 2015)	Pesticide DRASTIC-LU weights (Brindha and Elango 2015)	SI Susceptibility Index (Ribeiro 2000)
Depth to water (D)	5	٥	٥	٥	0.186
Net recharge (R)	4	4	4	4	0.212
Aquifer media (A)	3	3	3	3	0.259
Soil media (S)	2	5	2	5	----
Topography (T)	1	3	1	3	0.121
Impact of vadose zone (I)	5	4	5	4	----
Hydraulic conductivity (C)	3	2	3	2	----
Land use (LU)	----	----	5	5	0.222

Table 2. Ratings of hydrological layers (Aller et al. 1987)

Parameter	Value	Rating	DRASTIC	Modified DRASTIC	Pesticide DRASTIC	Pesticide DRASTIC-LU
Depth to water	(0.0-1.53)	10	50	50	50	50
	(1.53-4.58)	9	45	45	45	45
	(4.58-9.15)	7	35	35	35	35
	(9.15-15.25)	5	25	25	25	25
	(15.25-22.8)	3	15	15	15	15
	(22.8-30.5)	2	10	10	10	10
	≥30.5	1	5	5	5	5
Net Recharge	(0.0-50.8)	1	4	4	4	4
	(50.8-101.6)	3	12	12	12	12
	(101.6-134)	6	24	24	24	24
Aquifer Media	Coarse sand and gravel	10	30	30	30	30
	Graded sand and gravel	9	27	27	27	27
	Sand and gravel	8	24	24	24	24
	Sand	7	21	21	21	21
	Shale and sandstone	6	18	18	18	18
	Silt and clay	5	15	15	15	15
Soil Media	Gravel and gravely sand soil	10	20	20	50	50
	Sandy soil	9	18	18	45	45
	Stony and loamy sand soil	6	12	12	30	30
	Loamy soil	5	10	10	25	25
	Clayey sand soil	4	8	8	20	20
	Sabkha, silt and clay	3	6	6	15	15
Topography (slope %)	(0-2)	10	10	10	30	30
	(2-6)	9	9	9	27	27
	(6-12)	5	5	5	15	15
	(12-18)	3	3	3	9	9
	≥18	1	1	1	3	3
Impact of vadose Zone	Very low permeability (GW depth 0-10m)	10	50	50		
	Very low permeability (GW depth 10-20m)	8	40	40		
	Very low permeability (GW depth 20-30m)	6	30	30		
	Very low permeability (GW depth 30-40m)	4	20	20		
	Very low permeability (GW depth 40-50m)	2	10	10		
Hydraulic conductivity	(28.7-41) m/day	6	18	18	12	12
	(41- 82) m/day	8	24	24	16	16
	≥ 82 m/day	10	30	30	20	20
Land use	Urban area	9	---	45	----	45
	Agriculture area	8		40		40
	Barren soil	2		10		10
	Water body	1		5		5

Table 3. SI ratings for landuse (0.0 is lowest, 100 is highest) (Ribeiro 2000)

Landuse	Rating
Agriculture areas	
Irrigation perimeters (annual crops, paddy fields)	90
Permanent crops (orchards, vine yards)	70
Heterogeneous agriculture areas	50
Pastures and agro-forested areas	50
Artificial areas	
Industrial waste discharge, landfills	100
Quarries, shipyards, open air mines	80
Continuous urban areas, airports, harbors, rail roads, areas with industrial or commercial activity, layout green spaces	75
discontinuous urban areas	70
Natural areas	
Aquatic environments (salt marshes, Salinas, intertidal zones)	50
Forests and semi-natural zones	0
Water Bodies	0

Table 4. Statistical summary of the DRASTIC parameters map

Parameter	Min	Max	Mean	SD
D	1	10	5.54	3.42
R	1	9	7.41	3.14
A	5	10	6.74	1.58
S	3	10	6.97	2.95
T	1	10	9.11	1.32
I	2	10	8.42	2.09
C	6	10	8.13	1.65
LU	1	9	6.37	2.86

Table 5. Percentage of vulnerability zone for each index model

Index	Low (%)	Moderate (%)	High (%)	Very High (%)
DRASTIC	22.7	27.7	25.9	23.7
Modified-DRASTIC	15.2	20.7	33.2	31.0
Pesticide-DRASTIC	27.8	22.1	31.2	18.9
Pesticide-DRASTIC - LU	24.4	25.3	25.4	24.9
SI	24.9	24.6	25.4	25.2

Table 6. Percentage of study area by difference in vulnerability classes

Index compared	-3	-2	-1	0	1	2	3
DRASTIC versus modified DRASTIC	0	0	15	48	10	27	0
Pesticide DRASTIC versus Pesticide DRASTIC-LU	0	0	24	42	12	21	0
DRASTIC versus SI	2	6	17	45	23	6	0
Pesticide DRASTIC versus SI	5	13	16	31	25	9	0
Modified DRASTIC versus SI	0	5	13	60	17	3	0
Pesticide DRASTIC-LU versus SI	1	7	19	41	28	4	0
Pesticide DRASTIC versus DRASTIC	0	17	19	49	15	0	0
Pesticide DRASTIC versus Modified DRASTIC	0	23	13	24	7	32	0
DRASTIC versus Pesticide DRASTIC-LU	0	5	17	37	12	27	2
Modified DRASTIC versus Pesticide DRASTIC-LU	0	0	17	66	16	1	0

Table7. Theoretical and effective weight of vulnerability model parameters

Parameter	Weight	Theoretical Weight (%)	Effective Weight			
			Min	Max	Mean	SD
DRASTIC						
D	5	21.74	3.40	4.38	18.41	11.26
R	4	17.39	2.27	20.16	6.04	4.31
A	3	13.04	8.11	24.43	13.92	3.47
S	2	8.70	3.21	17.24	9.54	4.09
T	1	4.35	0.58	9.01	6.28	1.08
I	5	21.74	6.25	49.02	29.06	8.26
C	3	13.04	10.34	27.27	16.68	3.20
Modified DRASTIC						
D	5	17.86	2.62	40	14.83	8.74
R	4	14.29	1.81	19.35	4.96	3.52
A	3	10.71	6.52	21.74	11.63	3.49
S	2	7.14	2.62	15.87	7.96	3.62
T	1	3.57	0.47	8.26	5.19	1.02
I	5	17.86	4.87	44.64	24.34	8.03
C	3	10.71	8.25	23.81	13.82	2.89
LU	5	17.86	2.64	30.61	17.21	6.97
Pesticide DRASTIC						
D	5	19.23	2.28	41.32	16.05	10.08
R	4	15.38	1.94	19.67	5.34	3.96

A	3	11.54	7.08	22.50	12.05	9.25
S	5	19.23	7.56	37.88	20.31	8.06
T	3	11.54	1.69	24.19	16.30	2.81
I	4	15.38	4.52	41.24	20.12	5.72
C	2	7.69	5.88	18.52	9.65	1.91
Pesticide DRASTIC-LU						
D	5	16.13	2.26	35.46	13.33	8.03
R	4	12.90	1.61	18.89	4.47	3.29
A	3	9.68	5.91	20.83	10.27	2.95
S	5	16.13	6.30	35.21	17.35	7.33
T	3	9.68	1.38	22.39	13.79	2.63
I	4	12.90	3.60	37.38	15.20	5.45
C	2	6.45	4.92	16.95	8.16	1.70
LU	5	16.13	2.30	31.69	15.36	6.37
SI						
D	0.186	18.6	2.92	41.74	16.61	8.72
R	0.212	21.2	2.98	31.88	8.08	5.16
A	0.259	25.9	16.96	83.3	33.42	14.33
T	0.121	12.1	1.49	58.36	20.68	6.87
LU	0.222	22.2	0.0	78.13	21.96	15.12

Table8. Statistical summary of one map removal sensitivity analysis for vulnerability models

	Mean	Max	Min	SD
DRASTIC				
D	١,٩١	5.39	٠,٠٣	1.١٠
R	٠,١٨	1.82	٠,١٨	0.١٩
A	0.53	2.09	0.01	0.37
S	0.18	1.38	0.01	0.19
T	0.54	5.79	0.03	0.59
I	2.70	6.40	0.03	1.20
C	0.69	2.79	0.01	0.35
Modified-DRASTIC				
D	1.33	6.00	0.05	0.73
R	0.78	3.75	0.01	0.71
A	0.70	4.02	0.0	0.78
S	0.70	3.20	0.0	0.78
T	0.72	3.20	0.03	0.85
I	1.92	6.28	0.01	1.18
C	0.62	4.28	0.01	0.64
LU	1.29	٢,٥٨	0.73	0.27
Pesticide DRASTIC				
D	١,٦٤	5.78	٠,٠0	٠,٩٢
R	٠,٤٥	3.10	٠,٠٢	0.٥٣
A	٠,٤٥	3.40	٠,٠١	0.٥٠

S	١,٨٧	5.52	٠,٠	٠,٧٧
T	0.٤٣	1.65	٠,٠	0.٣٢
I	١,٢٩	6.43	٠,٠	٠,٧٩
C	٠,٥٩	3.71	٠,٠١	0.5٣
Pesticide DRASTIC-LU				
D	١,١٦	5.74	٠,٠	٠,٦٧
R	٠,٧٣	4.28	٠,٠٢	0.٦٦
A	٠,٧١	4.32	٠,٠٣	0.٧٦
S	١,٤٨	5.39	٠,٠٤	٠,٨١
T	0.٣١	1.41	٠,٠	0.٢٨
I	١,١	6.03	٠,٠٣	٠,٨٦
C	١,١٢	4.20	٠,٠٣	0.٧٠
LU	0.٩٨	2.74	٠,٤٧	0.٢٧
SI				
D	١,٢٧	5.43	٠,٠٣	٠,٦٩
R	٠,٩٧	2.97	٠,٠٢	٠,٥٠
A	٤,١٩	15.83	٠,٠٢١	3.٤٥
T	٢,١٠	4.57	٠,٠١	١,٣٨
LU	٣,٢٠	8.06	٠,٠	١,١٩

Table 9. Statistical summary of map removal sensitivity analysis-DRASTIC

Parameters used	Mean	Max	Min	SD
DRASTIC				
DASTIC	0.35	1.81	0.01	0.28
DASIC	0.78	3.59	0.03	0.77
DAIC	0.73	1.94	0.01	0.58
DIC	0.91	2.71	0.12	0.71
DI	1.24	4.57	0.05	1.25
I	4.٧٠	٨,٠٤	٠,١٥	٢,٧٠
Modified DRASTIC				
DASTIC-LU	0.78	3.75	0.01	0.71
DASIC-LU	0.62	2.96	0.03	0.57
DAIC-LU	0.42	1.75	0.05	0.35
DIC-LU	0.38	2.07	0.0	0.32
DI-LU	0.54	1.93	0.05	0.37
I-LU	3.42	8.8	0.11	2.47
I	4.45	7.61	0.14	2.50
Pesticide DRASTIC				
DASTIC	0.45	3.10	0.02	0.53
DASTI	0.66	2.50	0.02	0.51
DSTI	0.77	2.83	0.01	0.64
STI	1.89	8.97	0.05	1.33
SI	3.20	7.79	0.11	2.28

S	3.98	6.71	0.06	1.75
Pesticide DRASTIC-LU				
DASTIC-LU	0.73	4.28	0.02	0.66
DASTI-LU	0.70	3.92	0.02	0.63
DSTI-LU	0.76	4.54	0.02	0.66
STI-LU	1.08	8.01	0.01	1.22
SI-LU	1.29	8.29	0.02	1.45
S-LU	3.00	8.09	0.05	1.89
S	4.06	29.06	0.09	2.56
SI				
DAT-LU	0.97	2.96	0.02	0.50
AT-LU	1.31	9.18	0.07	0.36
A-LU	2.78	8.51	0.12	2.59
A	1.32	3.04	0.18	0.68

Figure 1. Study area description
Figure 2. DRASTIC input hydrological parameters
Figure 3. Vulnerability index maps
Figure 4. Correlation coefficient between Nitrate and vulnerability index

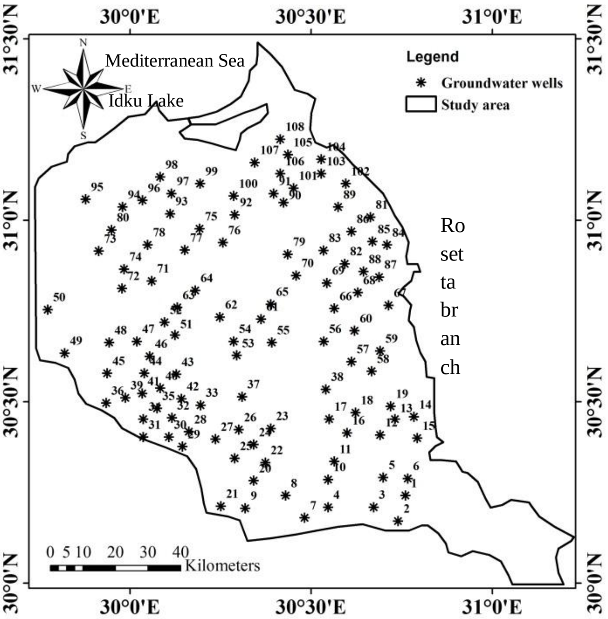
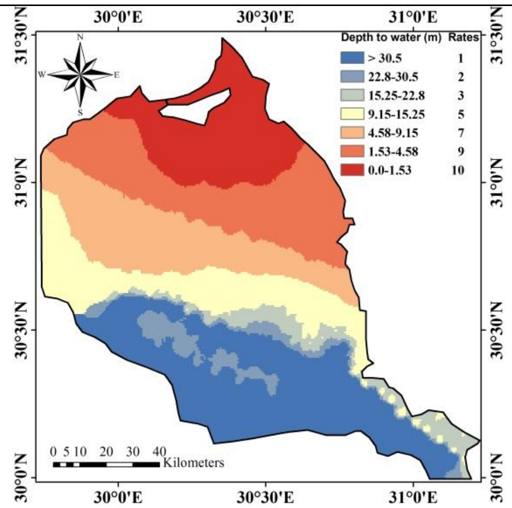
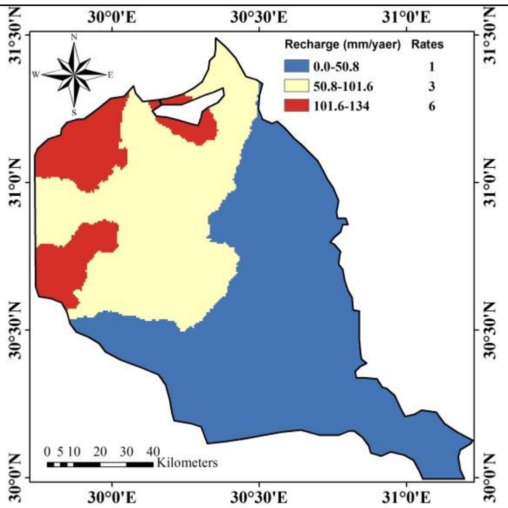
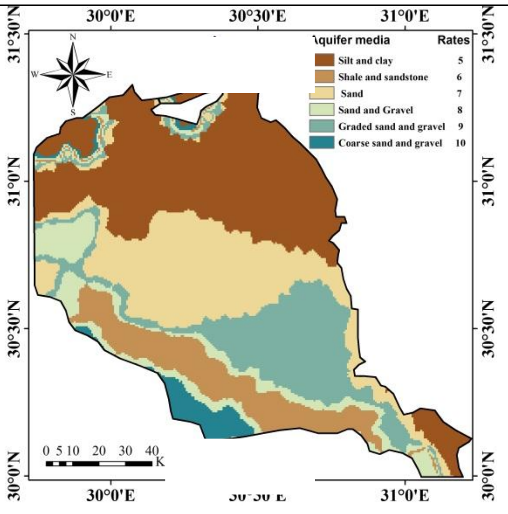
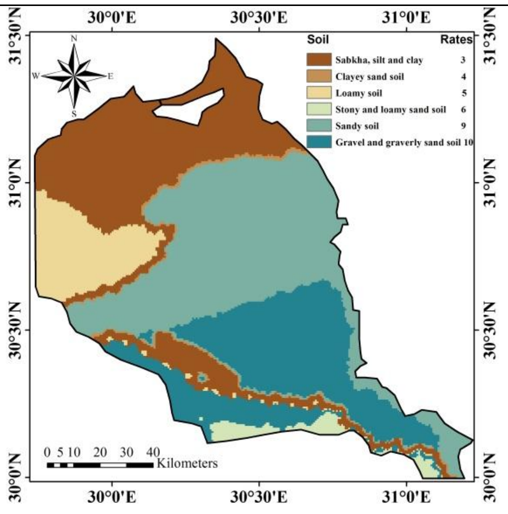


Figure 1. Study area description


Depth to water (m) Rates
> 30.5 1
22.8-30.5 2
15.25-22.8 3
9.15-15.25 5
4.58-9.15 7
1.53-4.58 9
0.0-1.53 10
0 5 10 20 30 40 Kilometers
30°0'E
30°30'E
31°0'E
30°0'N
30°30'N
31°0'N
31°30'N
N
S
E
W


Recharge (mm/yaer) Rates
0.0-50.8 1
50.8-101.6 3
101.6-134 6
0 5 10 20 30 40 Kilometers
30°0'E
30°30'E
31°0'E
30°0'N
30°30'N
31°0'N
31°30'N
N
S
E
W


Aquifer media Rates
Silt and clay 5
Shale and sandstone 6
Sand 7
Sand and Gravel 8
Graded sand and gravel 9
Coarse sand and gravel 10
0 5 10 20 30 40 K
30°0'E
30°30'E
31°0'E
30°0'N
30°30'N
31°0'N
31°30'N
N
S
E
W


Soil Rates
Sabkha, silt and clay 3
Clayey sand soil 4
Loamy soil 5
Stony and loamy sand soil 6
Sandy soil 9
Gravel and graverly sand soil 10
0 5 10 20 30 40 Kilometers
30°0'E
30°30'E
31°0'E
30°0'N
30°30'N
31°0'N
31°30'N
N
S
E
W

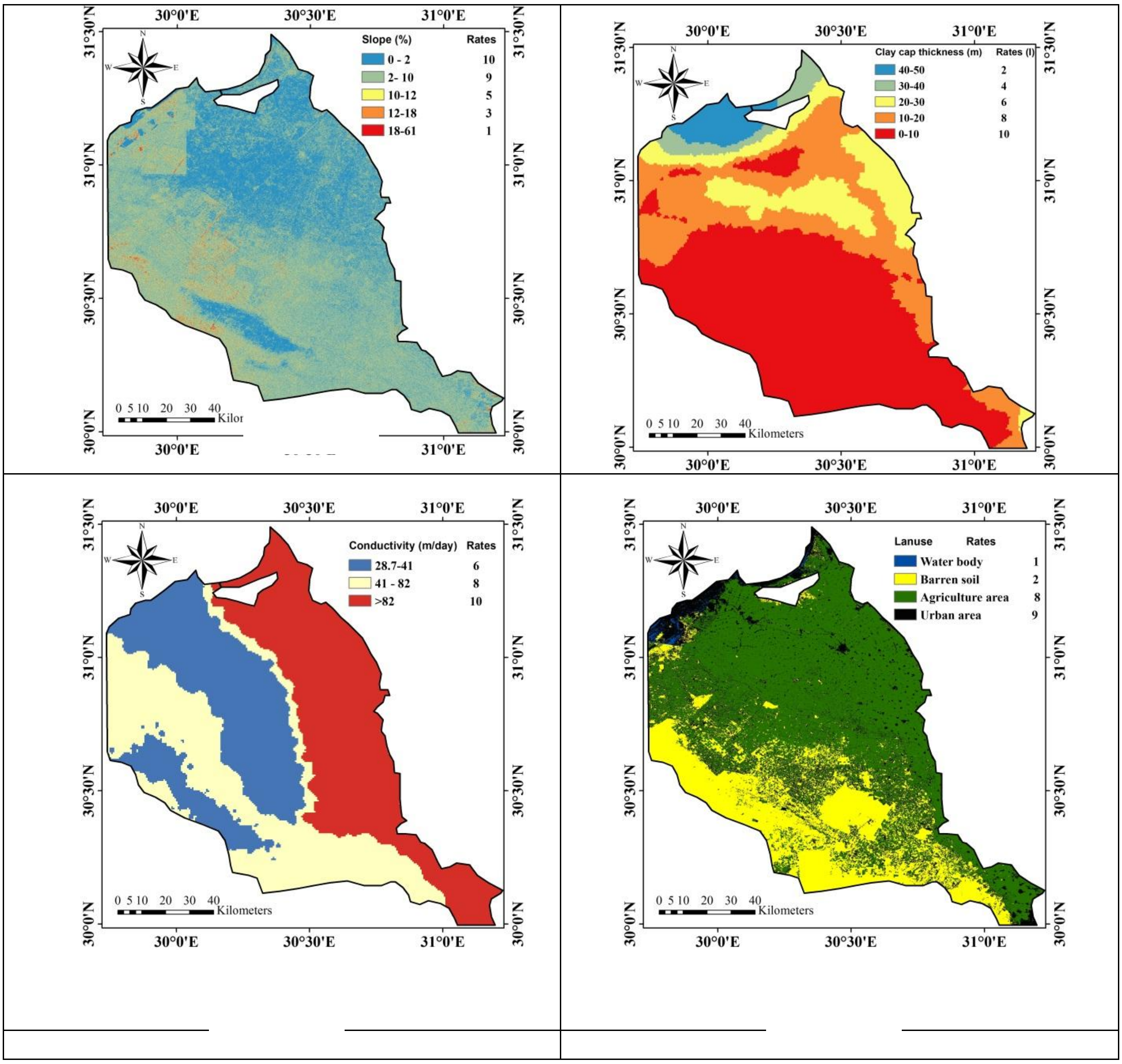
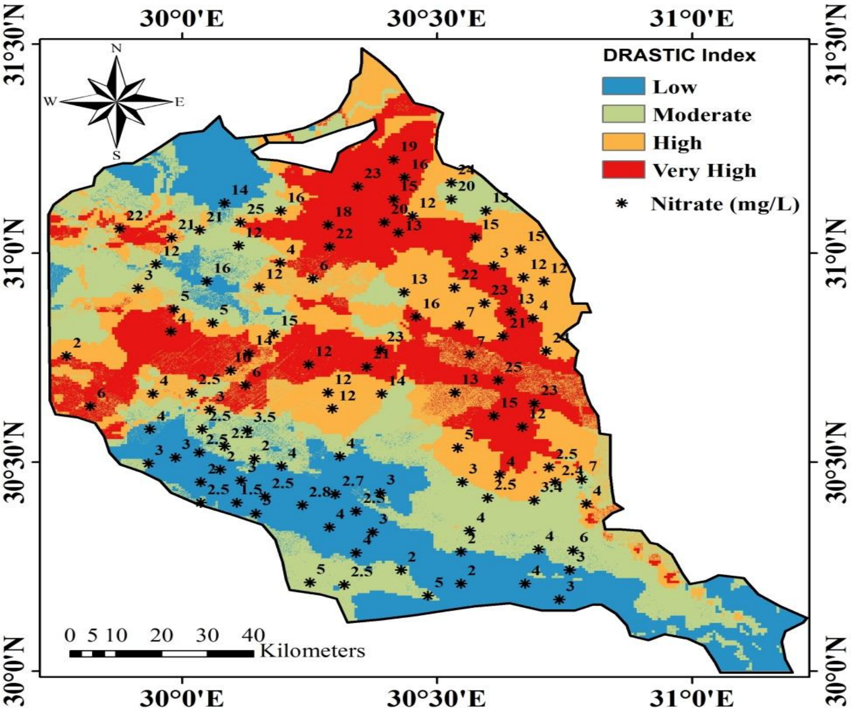
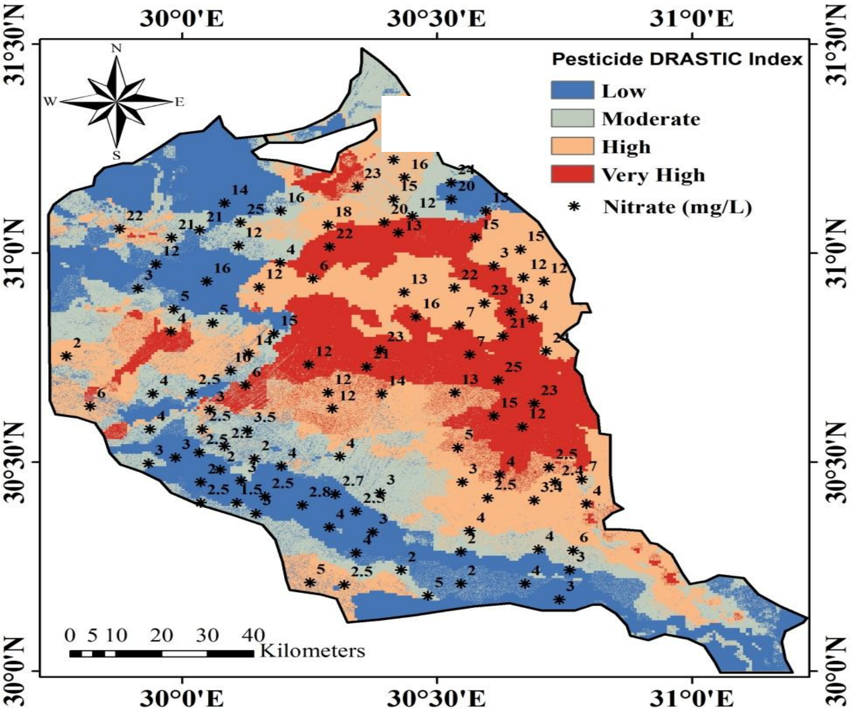
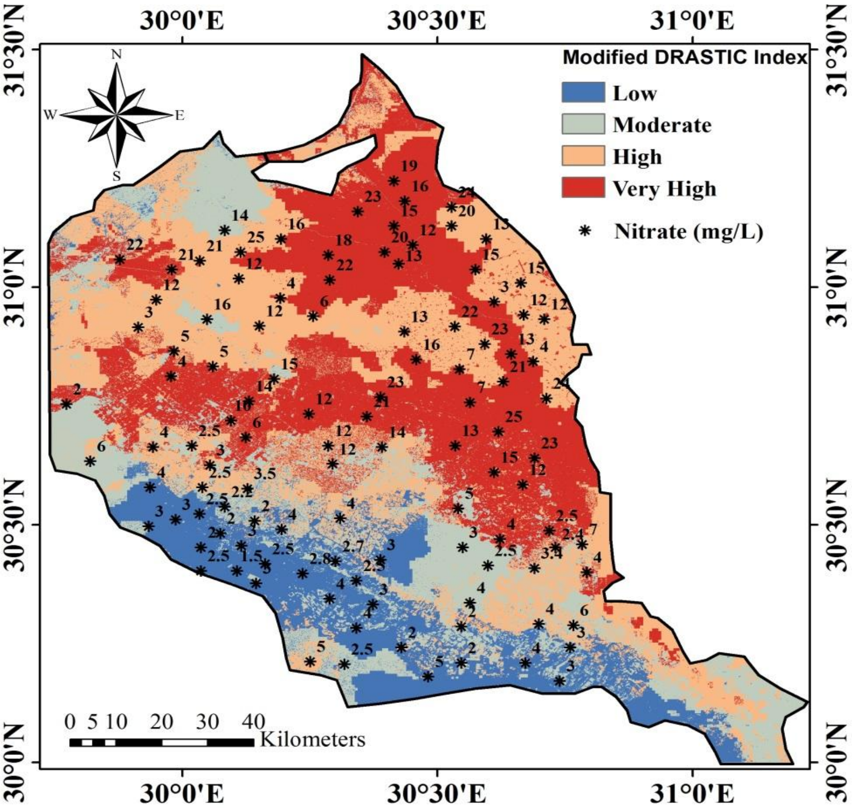
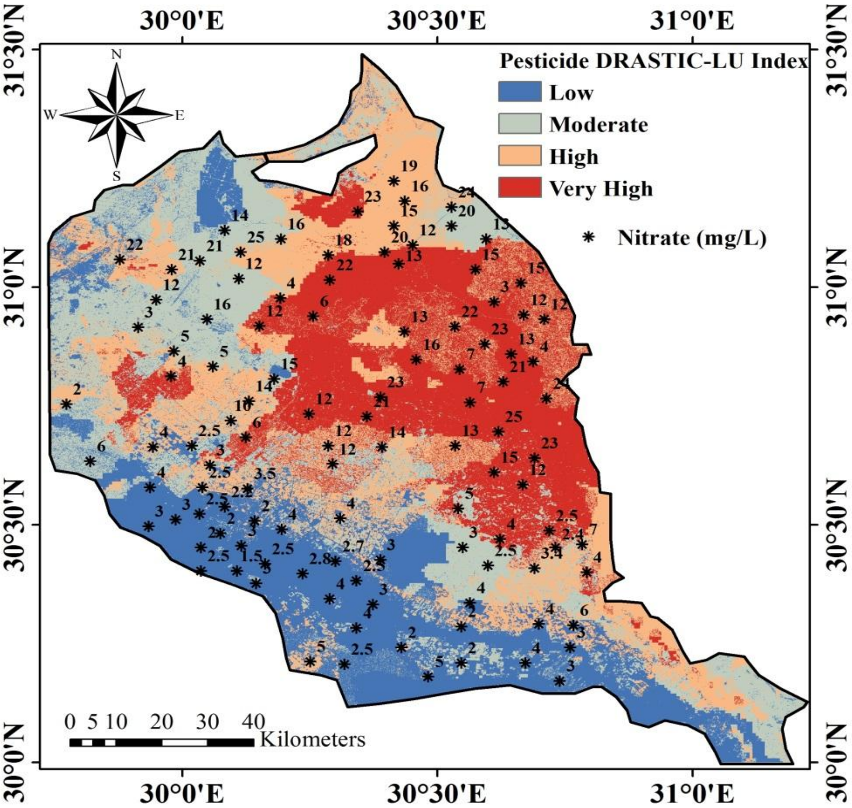


Figure 2. DRASTIC input hydrological parameters: (a) depth to water, (b) recharge, (c) aquifer media, (d) soil media, (e) topography, (f) impact of vadose zone, (g) conductivity and (LU) landuse


30°0'E
30°30'E
31°0'E
31°30'N
31°0'N
30°30'N
30°0'N
N
S
W
E
DRASTIC Index
Low
Moderate
High
Very High
* Nitrate (mg/L)
0 5 10 20 30 40
Kilometers


30°0'E
30°30'E
31°0'E
31°30'N
31°0'N
30°30'N
30°0'N
N
S
W
E
Pesticide DRASTIC Index
Low
Moderate
High
Very High
* Nitrate (mg/L)
0 5 10 20 30 40
Kilometers


30°0'E
30°30'E
31°0'E
31°30'N
31°0'N
30°30'N
30°0'N
N
S
W
E
Modified DRASTIC Index
Low
Moderate
High
Very High
Nitrate (mg/L)
0 5 10 20 30 40
Kilometers


30°0'E
30°30'E
31°0'E
31°30'N
31°0'N
30°30'N
30°0'N
N
S
W
E
Pesticide DRASTIC-LU Index
Low
Moderate
High
Very High
Nitrate (mg/L)
0 5 10 20 30 40
Kilometers

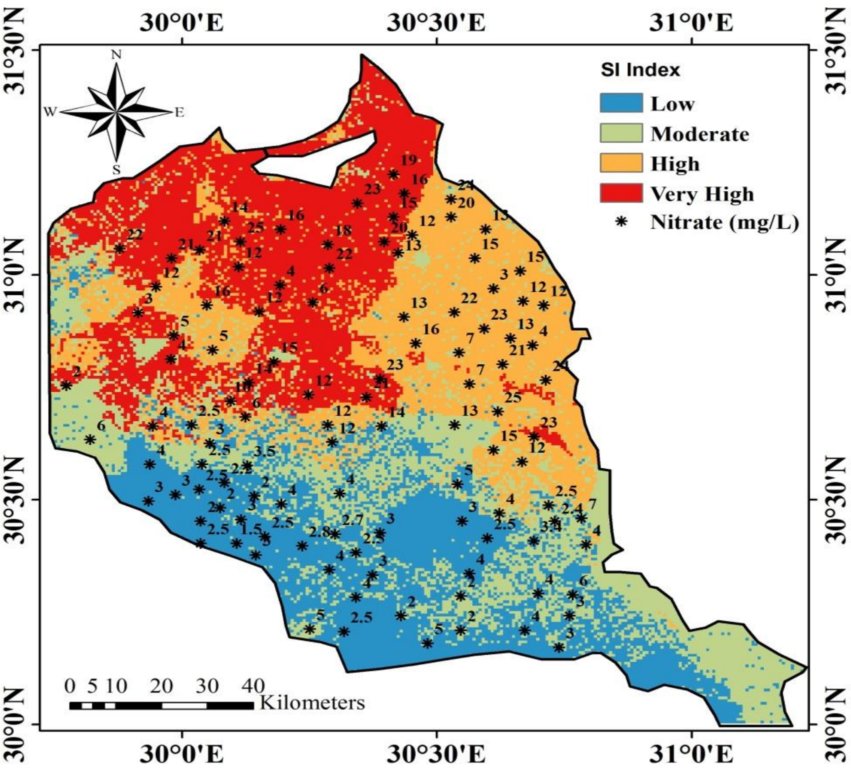
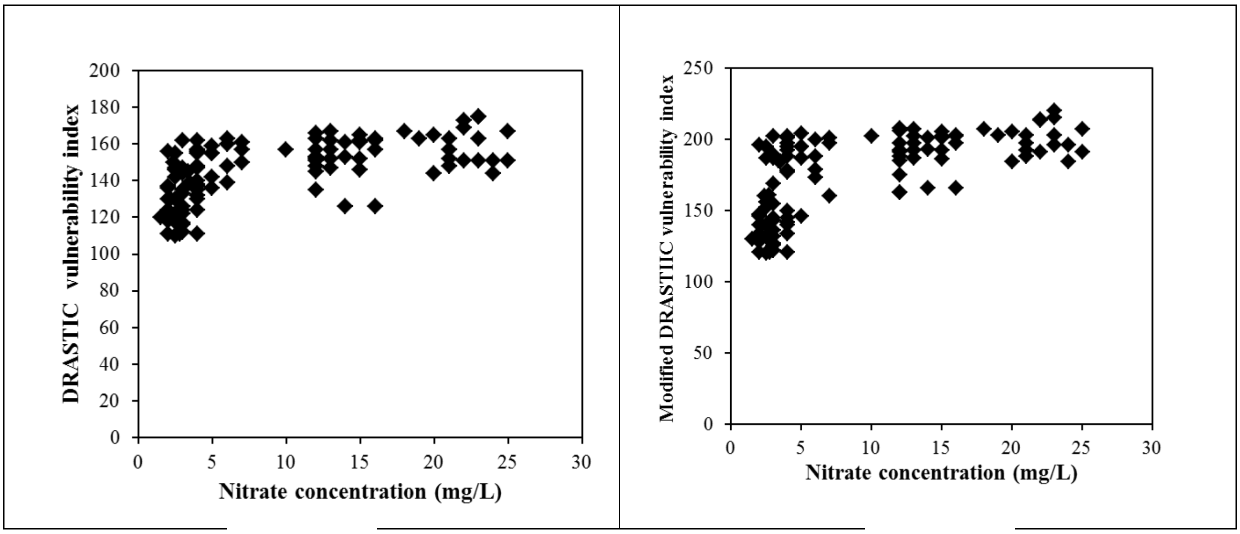


Figure 3. Vulnerability index maps: (a) DRASTIC, (b) Pesticide DRASTIC, (c) modified DRASTIC, (d) Pesticide DRASTIC-LU and (e) SI vulnerability indices



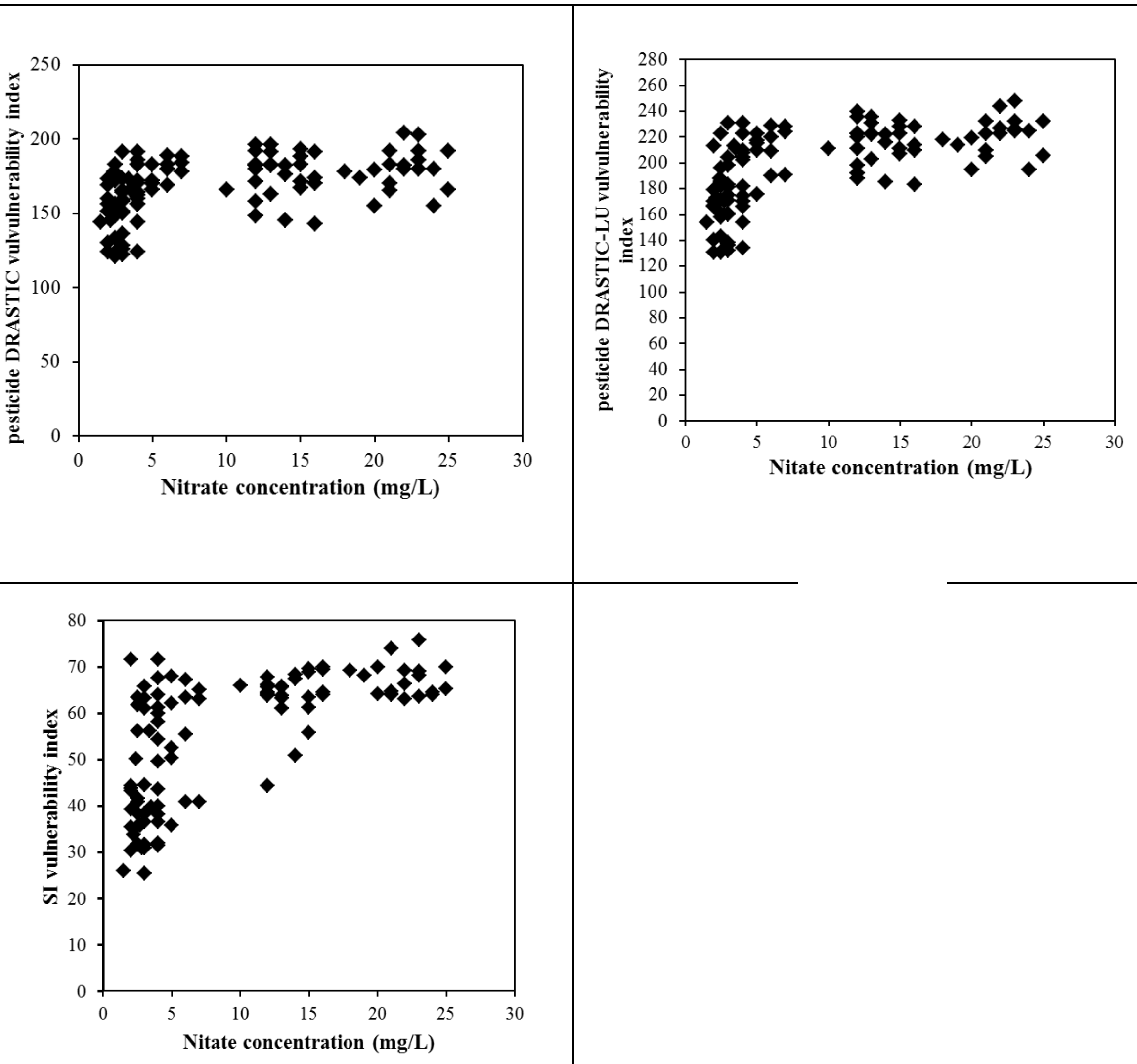


Figure 4. Correlation between Nitrate concentration and (a) DRASTIC, (b) Pesticide DRASTIC, (c) modified DRASTIC, (d) Pesticide DRASTIC-LU and (e) SI