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Doctoral School of Environmental Sciences

THESIS OF THE DOCTORAL PHD. DISSERTATION

COMPREHENSIVE RISK ASSESSMENT FOR SUSTAINABLE GROUNDWATER MANAGEMENT IN ARID AREAS

CASE STUDY: AGRICULTURAL EASTERN JORDAN DESERT

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by

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1. Introduction

Protecting groundwater from contamination is essential for safe, sustainable drinking water management (Sasakova et al 2018), and it is not a new activity, but since ancient times many cultures have considered the importance of protecting the quality of the groundwater and ensuring that it is not contaminated. Foster & Loucks (2006) stated the old Arabic Proverb "*Into the well from which you drink do not throw stones*". Groundwater risk assessment is composed of two components, having a linear positive relation, the contaminant load, and groundwater vulnerability (Brusseau et al 2019). The groundwater risk assessment (GRA) defined by Morris & Foster (2001) "*as the probability that groundwater in the aquifer will become contaminated to an unacceptable level by activities on the immediately-overlying land-surface, the risk will be the result of the interaction between the subsurface contaminant load and the aquifer pollution vulnerability at the location concerned*". The identification of vulnerable groundwater levels is crucial to the sustainable management and conservation of limited groundwater resources. Arid and semi-arid areas are specifically reliant on groundwater sources.

The common causes of groundwater quality deterioration can be classified by genesis were explained by Foster et al. (2002). This classification assumed a four classes of groundwater quality problems the aquifer pollution, the wellhead contamination, the saline water intrusion, and the naturally occurring contamination. The present research designed to address the first problem of "aquifer contamination" in a comprehensive groundwater contamination risk assessment (GRA) of a renewable groundwater aquifer in a dry agricultural area. The most dominant groundwater contamination sources in the world are agricultural fertilizers and pesticides, and nitrate (NO_3^{1-}) from excessive fertilizer usage in intensive agricultural areas is a widespread contaminant (Sasakova et al. 2018; Chowdhury 2016; Spalding & Exner 1993). The high nitrate concentration in the agricultural area is an indicator of the contamination from the intensive use of fertilizers (Mastrocicco et al. 2013).

Contaminants can reach groundwater via transport through the soil profile and, depending entirely on their nature, can have very serious consequences, making it a key requirement for sustainable development to protect groundwater resources from contamination that will increase the sustainability of high-quality drinking water (Sasakova et al. 2018). The definition of the sustainable development according to Brundtland (1987) is "a *development that meets the needs* *of the present without compromising the ability of future generations to meet their own needs"*. The concept of groundwater sustainability was defined by Alley et al. (1999) as "*development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences"*. Sustainable groundwater management is dictated not only by the availability of groundwater resources but also by water quality degradation (Foster et al. 2013).

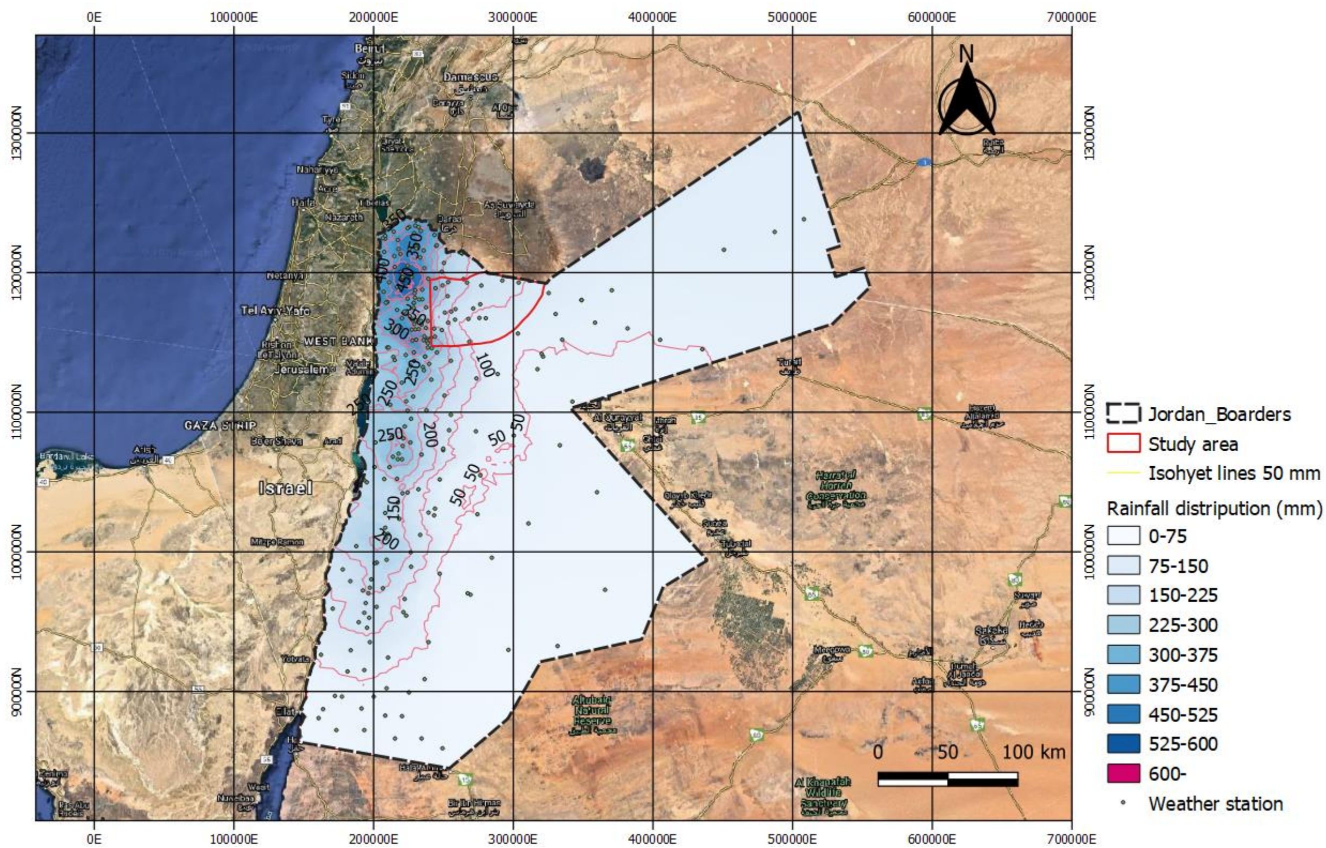

Figure 1 Jordan long Annual rainfall, own Processing, long average annual precipitation of 296 weather stations using the ordinary kriging interpolation.

The study area was chosen in Jordan, which is an example of a developing nation living in a severe water crisis. The recent studies ranked Jordan 2nd among the world's poorest countries in water resources (MOE 2014; USAID 2018). Rainfall in Jordan has an uneven distribution over the rainy season, with a long average rainy day equal to 26 rainy days per year. The average areal precipitation measured for Jordan is 82.98 mm (Figure 1**Hiba! A hivatkozási forrás nem található.**). In addition to the scarce and limited water resources in Jordan, a variety of accompanying factors have significantly aggravated the water deficit problems in recent decades according to numerous studies (USAID 2018; Arsenault 2017; MWI 2016). Currently, in Jordan groundwater resources cover 44 % of the irrigation requirements and more than 58 % of the country's water requirements. Therefore, the need is urgent to protect the groundwater resources from being contaminated. This could be done through the preparation of groundwater protection schemes to avoid groundwater resources contamination by delineation of groundwater protection zones.

2. Rationale of present study

Groundwater is naturally abundant in the Karst and Basalt regions, where intensive agricultural areas are also situated, as in the case study area of this research. Due to several reasons, these areas face a higher risk of groundwater contamination. Taking these aspects in consideration, a detailed groundwater risk assessment was planned in the Amman Zarqa Basin (AZB) located in northern part of Jordan. The comprehensive groundwater risk assessment (GRA) was carried out into two steps, the first was the investigation of the contamination load and the natural groundwater potential protectiveness. The last step was the use of the overlying modelling approaches to visualize the results of the GRA into maps.

Establishing a methodology that is widely and comprehensively applicable at the lowest cost is one of the most important priorities in enabling the water sector to manage groundwater resources sustainably in any water resource-poor country, with a view to ensuring water protection for future generations, by protecting these sources from contamination, to enhance water security and sustainability. This comprehensive groundwater risk assessment research considered the possibility of implementing, in any region like the case study area. Through an integrated study to investigate the vulnerability of groundwater and to identify the contaminants in the area using modern applications centred on statistical analyses, remote control, geographic information systems (GIS) and the available water quality, hydrogeology, and climate data.

3. Objectives

1. The main objectives of this study were to assess the contamination load and groundwater natural potential protectiveness which is called a comprehensive groundwater risk assessment. And selecting the appropriate groundwater risk assessment approaches is at the core of the

current research. To begin with, the following objectives were primarily to appropriately conduct a comprehensive groundwater risk assessment research.

a. Review the available methods of groundwater contamination risk assessment to develop appropriate methods for karstic and basaltic aquifers in dry areas.
b. Development of a multipurpose hydrogeological database for effective storage and processing of information in the GIS environment.
c. Improving and updating the quality of input datasets through the reduction of errors and thus provided data for future groundwater management research. The data updated in this research includes the hazards, land use, soil texture, groundwater quality and the hydrological information.
d. Characterization of the geological and hydro-geological setting necessary for applying all the required groundwater contamination risk assessment analysis.
e. Assess the groundwater quality in the Study area by analysing the long-term groundwater quality measurements of approximately 498 wells (WIS 2020) from 1970 to 2018.
f. Evaluate Jordan's and the study area's climatological parameters and generate the groundwater recharge map, by analysing daily climatological data from 346 weather stations.
g. Investigate the state of groundwater levels and draw the water depth and groundwater flow using historical measurements from around 80 observation wells.

2. Assess the contamination load.
3. Investigate the natural protectiveness of groundwater.
4. Creating an overlying modelling approaches to visualize the results of the groundwater risk assessment into maps, to be used in land use management and creating protection zones in further studies.
   a. Therefore, the first main objective of the overlying modelling part of this study was to evaluate the aquifer vulnerability in arid areas.
   b. The second main objective was to evaluate the potential risk of nitrate contamination.
   c. The third main objective in the overlaying modelling part was to integrate the intrinsic vulnerability and the potential risk of nitrate contamination.

d. The last main objective was to validate the vulnerability and contamination risk maps by comparing the results to the observed water quality variables in the region. Aside from comparing the results to a previous vulnerability map.
e. An additional objective was to demonstrate the combined use of DRASTIC and geographical information system (GIS) as an effective method for groundwater pollution risk assessment and water resource management.
f. The second additional objective was to evaluate the relative importance of the DRASTIC model parameters for assessing aquifer vulnerability in arid agricultural areas through sensitivity analysis.

4. Materials and methods

The comprehensive assessment of groundwater risk in this research is defined in the following scheme (Figure 2).

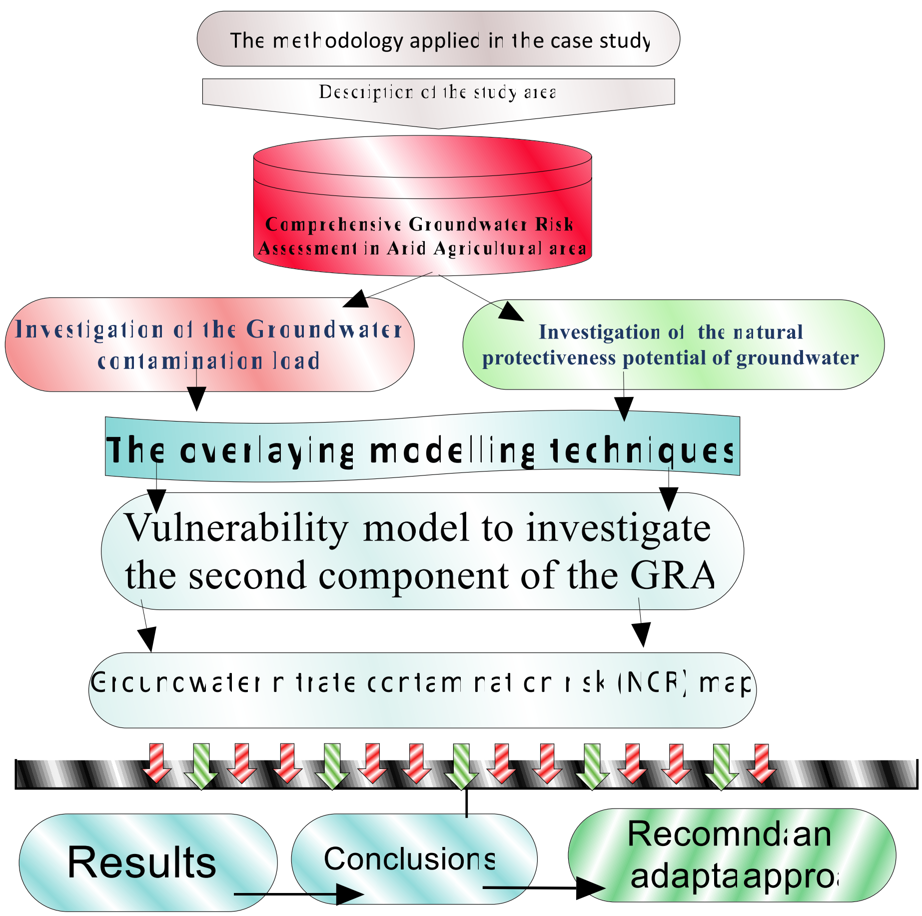

Figure 2 The general methodological scheme of the study

4.1 Selection of the study area

Several factors were considered in the selection of the study area. The data availability, the importance of the study area, the extend and outcropping of the phreatic aquifers throughout the area and to be a good representative example of an arid agricultural area. For this purpose, a review of the hydrogeological situation of all the groundwater basins in Jordan was carried out to find the most important basin to be the study area. The study area covers a surface area of 3329.9 km^2 (more than 81 % of the (AZB) area, and 3.7 % of Jordan land area).

4.2 Groundwater risk assessment in the case study area:

The groundwater risk assessment (GRA) approach in this study consists of three steps, the contamination load investigations, then the comprehensive hydrogeological review. The last step is to visualize the groundwater vulnerability, and the nitrate contamination risk in maps utilizing the overlying modelling techniques.

4.2.1 Investigation the contamination load in the study area

The major human activities on the surface of the study area are farming activities according to several official and scientific studies, but in this study, a review of the study area contamination sources has been carried out for more precise findings. In this study, the following analyses were done to investigate the water quality in the study area

1. A summary table was drawn up and discussed for the analysis of the main water parameters.
2. Correlation analyses of the main water parameters.
3. Piper diagram of the major cations and anions was used to sketch the main cation and anion concentration of the studied wells using the Plots Piper diagram model.
4. Three parameters were selected nitrate, sulfate, and the total dissolved solids to prepare spatial continuous concentration maps, to evaluate the water quality in the study area and compare it with the created vulnerability maps.

4.2.2 Investigate the natural protectiveness potential of groundwater in the study area.

In this part, the aim is to provide an overview of all available hydrogeological and climatic parameters that contribute to the GRA. This to construct a better understanding in the investigation of the natural potential protectiveness of the groundwater. In this study, the following analyses were done to investigate the natural protectiveness in the study area:

1. Climate, Geological, and Hydrogeological Systems Description of the case study area.
2. Structural geology and the Hydrogeology of the study area:
3. Groundwater Recharge in the study area:
4. Related physical features of the landscape obtained from remote sensing (RS) Technique for Groundwater Condition Assessment
    a. Geological Lineaments and Structural setting:
    b. Surface water drainage density:
5. Hydraulic conductivity of the Aquifer system in the study area:

4.2.3 The overlaying modelling techniques:

To simulate the previous investigations of both GRA components (the intrinsic vulnerability and the contamination load) an overly modelling techniques were used as explained by Figure 3. For the present study: Modified a simple overlaying approach to create a land use layer attempts of integrating it with the modified reliable DRASTIC framework to be the parameter number eight. The DRASTIC is an overlying method to detect the intrinsic vulnerability so the DRASTIC itself modified in this research to assess this vulnerability then the result intrinsic vulnerability map was combined with the land use for the Groundwater Risk Assessment of specific vulnerability. While the particular contaminant in this approach is the nitrate so the land use layer was created to reflect the potintial nitrate contamination (PNC) in the study area. Based on the literature review the method developed here is simple, reliable, and can be widely implemented. Beside this the DRASTIC model was modified by the statistical approach introduced by Napolitano & Fabbri (1996) through tow practical ways the first by applying the analyses directly using the raster calculator and the second by extracted two points files and the statistical approach was implemented in excel sheets to calculate the real DRASTIC-parameters weight.

Besides that, two scenarios were used in implementation both the ordinary and the agricultural DRASTIC approaches, the first scenario without changing the DRASTIC-parameters rating while in the second scenario a modified suggested range of recharge (R') by using a scale100 times the original rating because the recharge in the study area varied from 0 to 42 mm/year. Which is a very low amount as the area is in the dry climatic zone, with low precipitation Therefore the area was entirely rated by 1 using the original recharge parameter rating. While suggested rating was to simulate the potential increase in recharge by irrigation return flow (IRF) in intensive agricultural areas.

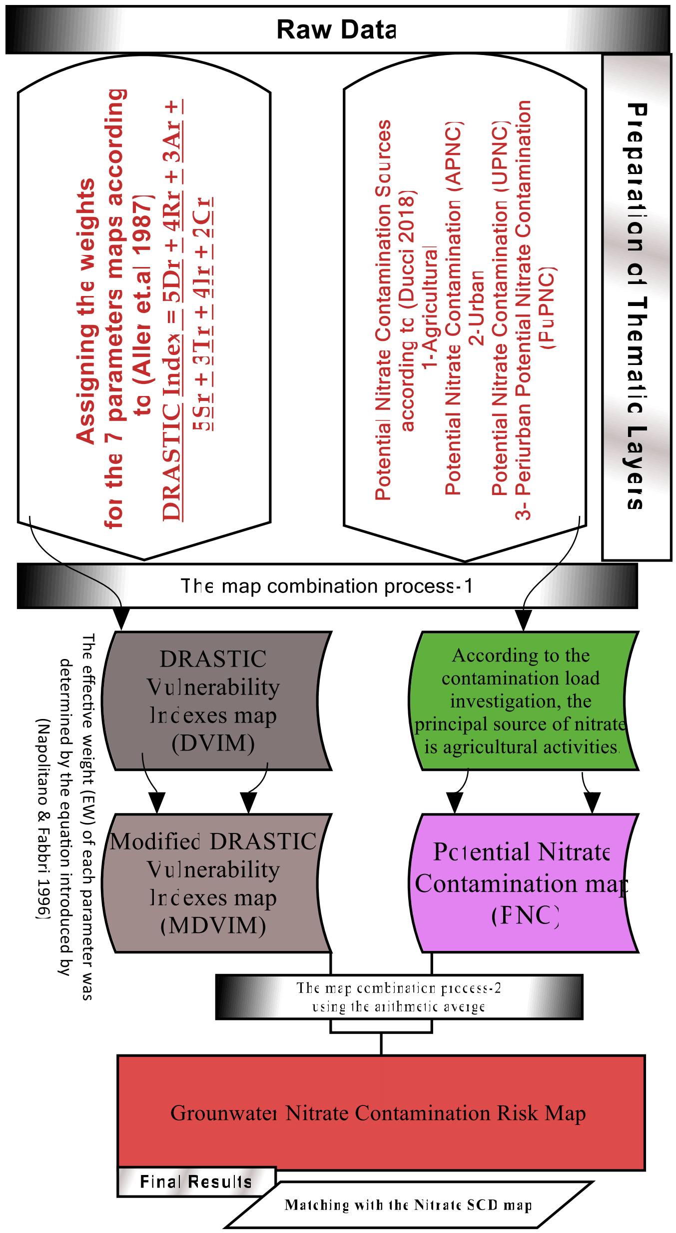

Figure 3 Flow chart simplifies the overlaying modelling techniques used in the case study.

Finally, long-term groundwater nitrate, sulfate and total dissolved solid concentration analyses were used to produce six spatial continuous data (SCD) maps and match the resulting vulnerability and risk map for nitrate contamination. And a comparison with the COP Intrinsic Vulnerability Indexes has been made and the analysis shows that the DRASTIC preferability is particularly versatile by simple modification by measuring the effective weight of the parameters so that the DRASTIC can be appropriate for dry and wet areas, but the COP model is only applicable in wet areas.

Three overlay modelling steps were performed to create the groundwater intrinsic vulnerability map, potential nitrate contamination (PNC) map and the groundwater nitrate contamination risk (NCR) map.

4.2.3.1 Investigate the second component of the GRA by modified intrinsic vulnerability model:

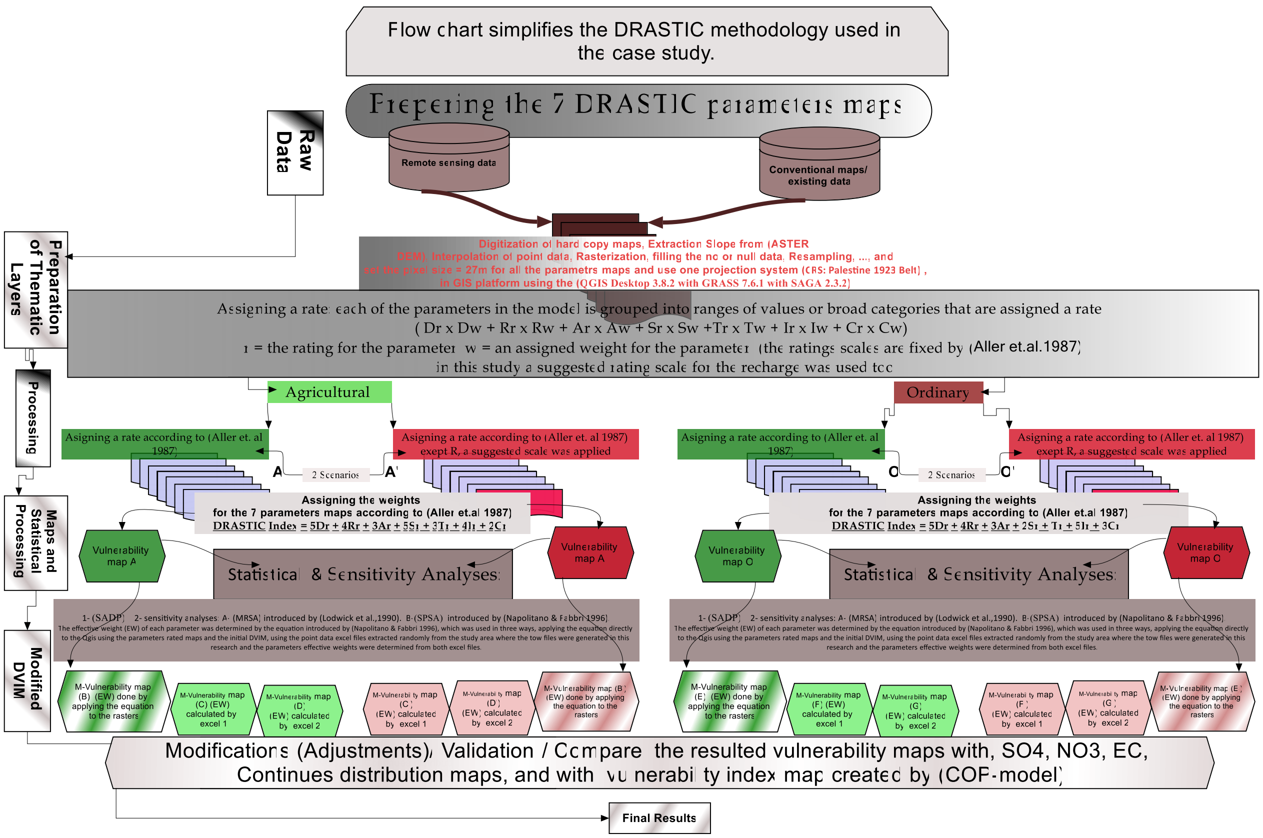

Figure 4 The Schematic flow chart describes the DRASTIC-model approaches used for this study to create appropriate intrinsic vulnerability map.

The tow DRASTIC approaches applied in this research are summarized in Figure 4. The agricultural and Ordinary (generic) DRASTIC approaches were used in this study to develop the groundwater intrinsic vulnerability map in addition to the former intrinsic vulnerability map created by COP-model as set out in Vías et al. (2006). Aller et al (1987) created the DRASTIC model for the United States Environmental Protection Agency (EPA). The main steps here are:

1. Development of the DRASTIC seven thematic Layers.
2. DRASTIC Statistical and Sensitivity analyses:
    a. Statistical analyses of DRASTIC rated parameters (SADP).
    b. Sensitivity analyses:
        i. Map removal sensitivity analyses (MRSA).
        ii. Single-parameter sensitivity analysis (SPSA).
3. DRASTIC validation.

4.2.3.2 Groundwater nitrate contamination risk (NCR) map

The last step in the overlying modeling application in this study is creating the groundwater nitrate contamination risk (NCR) map as discriped in Figure 3. Groundwater risk map generally, is a combination of existing hazardous substances and the aquifer vulnerability. But due to the difficulties of recognizing all possible sources of contaminants and the presence of a real contamination problem, the susceptibility is more directed towards a particular contaminant. While, due to the results of the contamination loads investigation, Nitrate was selected as a particular contaminant in the study area.

The first component of the NCR is the potintial nitrate contamination (PNC) was created by overlapping three land use weighted thematic layers responding to the nitrate contamination factors. According to Ducci (2018) each layer was classified into five :

1. The agricultural potential nitrate contamination (APNC):
2. The urban potential nitrate contamination (UPNC):
3. The Peri-urban Potential Nitrate Contamination (PuPNC):

The index overlay combination, considering all the above three classified land use maps of equal weight the resulting values are the arithmetic average of the input values, starting from 1 (very low) to 5 (very high) PNC classes. The final step to create the NCR map was by overlapping the PNC map and the modified DVIM map according to the equation $NCR = \frac{PNC+DVIM}{2}$. The NCR map was matched with the nitrate SCD map to evaluate the above adopted methodology.

5. Results and discussion

5.1 Investigation of the Groundwater contamination load.

In the selected study area through the field visits, the hazard files, water quality analyses, classification of the production wells into purposes of uses, shows the highest portion of contamination is related to the agricultural uses so it turns out that the most important potential source of pollution drives from agricultural activities

5.1.1 The study area agricultural activity

The study area agricultural activity intensity map indicated that there is an intensive irrigated agricultural activity in the northeastern part of the study area (Table 1). While the study area original natural vegetation is scattered with short plants and it is within the range proposed for rain-fed cereals crops, not intensive crops according to land suitability maps prepared by MOE & UNDP (2015). The total number of productive groundwater wells in Jordan in 2019 reached 3321 wells, 1009 of which are in the AZB and 900 of these wells in the study area, and thus more than 28 % of Jordan's wells are in the study area. Most of these wells for agricultural purposes with a percentage reach 69 % of the total number of the production wells in the study area and 23 % for drinking water purposes. It demonstrates the agricultural nature of human activities in the study area rather than industrial activities. To conclude in the study area, agricultural activities are the key sources of contamination by both non-point sources or by point sources such as FMB and other sources of contamination as hazard locations exist in the study area, for example, fertilizer factories and poultry farms.

Table 1 The agriculture intensity in the study area, the original map source (MOA 2020).

Agricultural activities	% Of the study area
Agric. > 75 %*	8.354084
Agric. 50-75 %	5.923244
Agric. 25-50 %	27.84274
Agric. 10-25 %	3.878595
Agric. < 10 %	23.63339
No agric., dom. pasture	28.59867
No agric., other land uses	1.769272

*The intensive agricultural activities cover 75 % of the agricultural areas in these areas.

5.1.2 Analyses of groundwater quality data in the study area:

By analyses the two water quality files it was found that in the first file for the period from 1970 to 2005 there were about 6459 nitrate measurements and about 2607 of which were above 50 mg/l, and about 7427 TDS measurements 1901 of which were above 1000 mg/l (1850 μS/cm), and 6364 sulfate measurements, 213 of which were above 500 mg/l. While the second data file from 2006-2018 there were 976 nitrate measurement 268 of which were above 50 mg/l, and about 35 TDS measurements 6 of which were above 1000 mg/l, and there were 873 sulfate measurements 76 of which were above 500 mg/l. In the studied wells the long-term Sulfate concentration less than 500 mg/l is possibly derived naturally from gypsum dissolution while the high concentration may be derived from the use of the fertilizer.

Potassium ions may have come from irrigation return flow (IRF) as the concentration varied from 0.1 to 257 mg/l with an average concentration equal 8.5 while the commercial chemical fertilizers used in AZB have a high concentration of potassium. The nitrate concentration varied from 0.2 to 376 mg/l with an average of 46 mg/l and the phosphate ranges from 0.01 to 0.27 mg/l, the high nitrate and phosphate concentration in the groundwater of the study area is mainly related to the use of fertilizers in agricultural areas.

5.1.3 Temporal changes in water quality:

The reviewing of several studies shows an increasing pattern of the concentration of nitrate and salinity.

5.1.4 Piper diagram:

According to the Piper-trilinear model, the dominant hydro-chemical facies in the studied wells are the Ca–Mg–Cl and Na–Cl, according to the order of their dominance, with an average sodium/potassium around 40 %, 35 % carbonate, 70 % chloride, 40 % sulfate, 60 % calcium/magnesium, while calcium reach more than 80 % but the wells plotted ranges from less than 20 % up to more than 80 % because part of the wells pumping from the basalt aquifer and some wells from the highly karstic A7/B2 aquifer and some wells from both aquifers as both aquifers hydrogeological connected in the eastern part of the study area see the cross-section. The range of carbonate concentration among the wells is high again due to the different types of aquifers, the basaltic wells show very low concentration, but the karstic A7B2 wells show higher concentration. The low solubility of minerals through the limestone in the A7/B2 aquifer indicates the major ions (+/-) concentration must be with a natural origin. However, it was observed from the plots that calcium does not exceed sodium and potassium, and that chloride-sulfate exceeds other ions, suggesting an anthropogenic source (Sarikhani et al. 2014) which is mainly in this study area due to the agricultural activities. Moreover, as the plot shows, the high sulfate concentration indicates an anthropogenic source for the wells classified in the piper diagram above the average sulfated plotted line of the study area wells 40 % (more than 65 % of the wells plotted above the 40 % sulfate average concentration line). The combination of Na–HCO_3 and Ca–Mg–HCO_3 is mainly the result of precipitation water infiltration, IRF, and anthropogenic activity.

5.1.5 Correlation coefficient matrix of major water parameters in the study area:

The correlation between the water parameters measured, such as nitrate and TDS and sulfate, indicates a strong correlation which can be due to the use of commercial chemical fertilizers used in AZB, which consist mainly of ammonium sulfate compositions. TDS was found to correlate strongly with major cations, magnesium, calcium, sodium (r=0.895, r=0.86, r=0.896, respectively) and moderately acceptable correlation with potassium (r=0.4). TDS correlate strongly with the anions, chloride, sulfate, nitrate, and phosphate (r=0.9496, r=0.863, r=0.6, r=0.6 respectively). Sodium concentrations showed a very good correlation with chloride (r=0.89679) indicating that these ions have been derived from the same sources. calcium and magnesium concentrations showed a very good correlation (r=0.85) indicating the presence of the same source of Ca and Mg, from the dissolution of calcite and dolomite the main minerals in the karstic aquifer's geological formations in the study area A7/B2.

5.2 Investigation of the natural protectiveness potential of groundwater.

5.2.1 The study area hydrogeological units' investigations results

1. Based on the hydrogeology, geological studies, fault density, thickness, and texture of the soil layer, the area is considered almost naturally unprotected from the intensive agricultural activity on the surface.
2. Besides of studying the geological formations and the soil properties, the climatic data analyses show the fragility of this area in the view of low precipitation and the general

characteristic as arid areas, which conclude the natural replenishment of the deterioration groundwater aquifer can be very difficult

3. The geological and drainage lineament density were studied and the GWR was calculated which indicated a good rate of precipitation is percolating through the vadose zone (infiltrating) to reach the groundwater but the amount very low as the precipitation rate is low in the study area.
4. The investigations of the hydraulic conductivity (HC) values of the studied area hydrogeological formations show a high HC of these formations.
5. The main climate class in the study area is arid, as well as the very small area in the western part of the case study area is warm-temperate according to Köppen-Geiger climate classification map modified after Kottek et al. (2006).
6. The mean GWR in the study area is 14 mm/ year, the maximum 42.6 mm/year, the minimum is zero in the south part as the outcropping formation there is the B3 which is aquitard.
7. The calculated geological lineament density in the study area is considered to be high density based on Muthumaniraja et al. (2019) classification. The mean density of geological lineaments is 0.5214 km/km^2 with a standard deviation of 0.4015 and the coefficient of variation is 0.77.

5.3 The overlaying modelling techniques

The results of the three overlying modelling steps are described and discussed as follows:

1. Investigate the second component of the GRA (the intrinsic vulnerability model results), which is the longest step in this section and mostly aims to present the capability of different techniques in groundwater intrinsic vulnerability mapping for groundwater management against contamination in arid agricultural area. The two DRASTIC approaches were implemented in this study and the results of the agricultural DRASTIC approaches were presented and discussed while the same steps were also applied to implement the Ordinary DRASTIC approach and the results of this approach also presented in the tables and figures. While a former COP model results were utilized for a comparison with the DRASTIC approaches.

2. Create a land use thematic layer to simulate the possible Nitrate contamination load. While the suggested simple approach in this part aiming to
3. Creating the Nitrate contamination risk map by combining the land use thematic layer created in the second step with the most representative intrinsic vulnerability map created in the first step. While according to intrinsic vulnerability scheme in this study the number of the instinct vulnerability maps is 16 plus the COP intrinsic map.

5.3.1 Vulnerability model to investigate the second component of the GRA (intrinsic vulnerability) results and discussion:

1. The seven rated DRASTIC parameter maps to calculate the DIVM Displayed in Figure 5).
2. All the created DIVMs of the study created in this research were classified into four groups according to DRASTIC Indexes scorings (DIS) as low, moderate, high, and very high ((DIS<100), (DIS 100-140), (DIS 140-200) and (DIS>200) respectively), (Figure 6), and (Figure 7).
3. In the Agricultural DRASTIC approach, the range of DIS for both initial vulnerability maps in the first scenario (A) ranges from 39 to 171, and ranges from 139-192 in the second scenario (A´). While in the Ordinary DRASTIC approach, the range of the DIS for both initial vulnerability maps in the first scenario (O) ranges from 30 to170, and ranges from 30 to 183 in the second scenario (O´).
4. The uppermost risk of contamination of groundwater in the study area originates from the hydraulic conductivity parameter (C) (mean value is 9.1). Then the high risk in the study area caused by the aquifer media parameter map (A) (mean value is 8.64) and the topography parameter map (T) (mean value is 8.22). (According to the statistical analyses of DRASTIC rated parameters (SADP)).
5. The impact of vadose zone parameter map (I) (mean value is 6.74) the soil media parameter map (S) (mean value is 3.14) imply moderate risks of contamination, while depth to groundwater parameter map (D) and the net recharge parameter map (R) impose a very low risk of contamination of groundwater (mean value is 1).
6. While the recharge parameter map (R´) used to compute the DVIM in the second scenario which used a modified recharge scale, not the original recharge rating scale provided by Aller

et al. (1987), the net recharge parameter map (R´) on the second approach have a moderate influence, not a very low as in the first approach (mean value is 5.5).

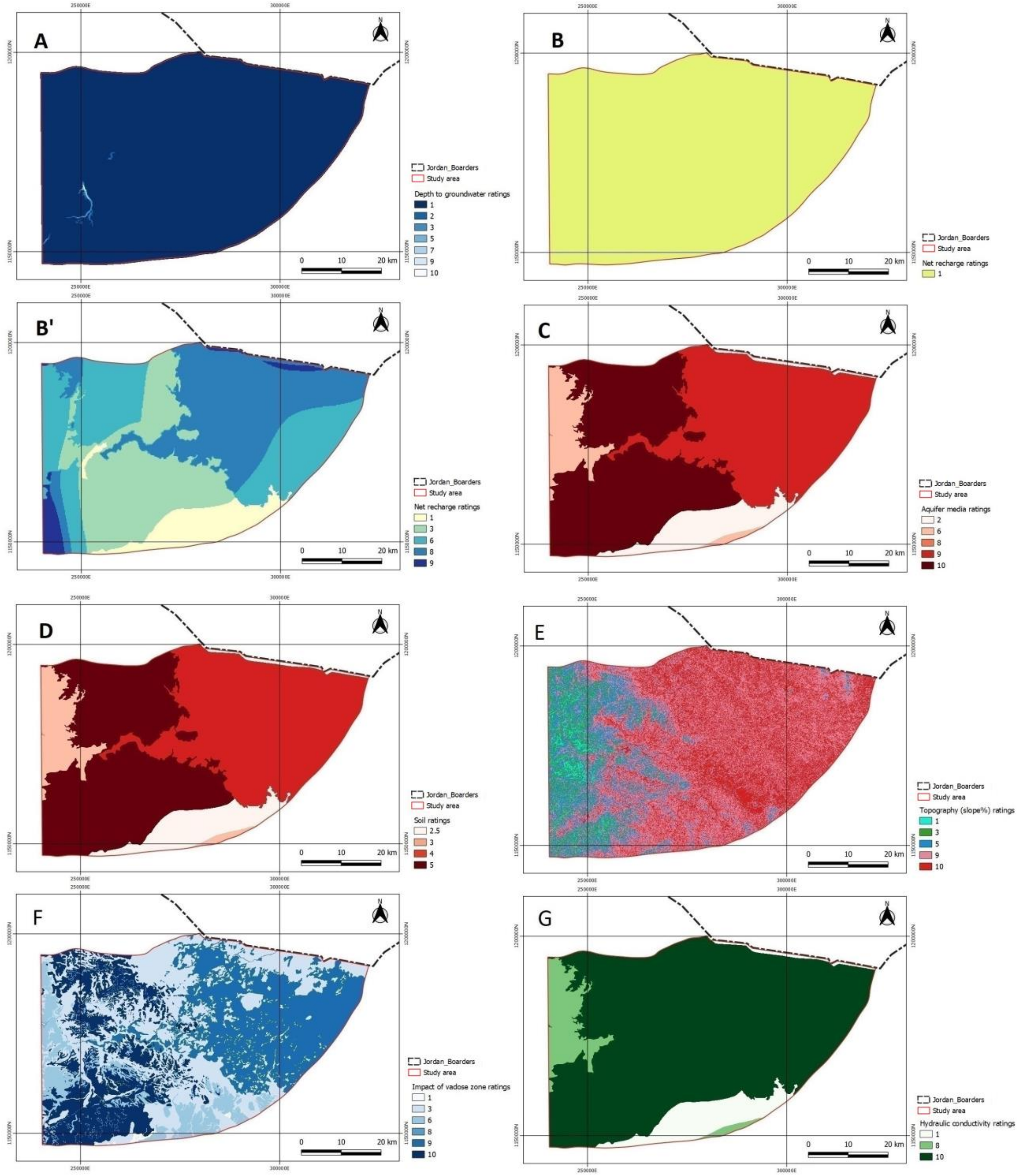

Figure 5 The rated DRASTIC parameter maps used to calculate the DIVM: (A) Depth to water, (B) Net recharge, (C) Aquifer media, (D) Soil, (E) Topography (slope%), (F) Impact of vadose zone, (G) Hydraulic conductivity. (B') Net recharge with a suggested rating.

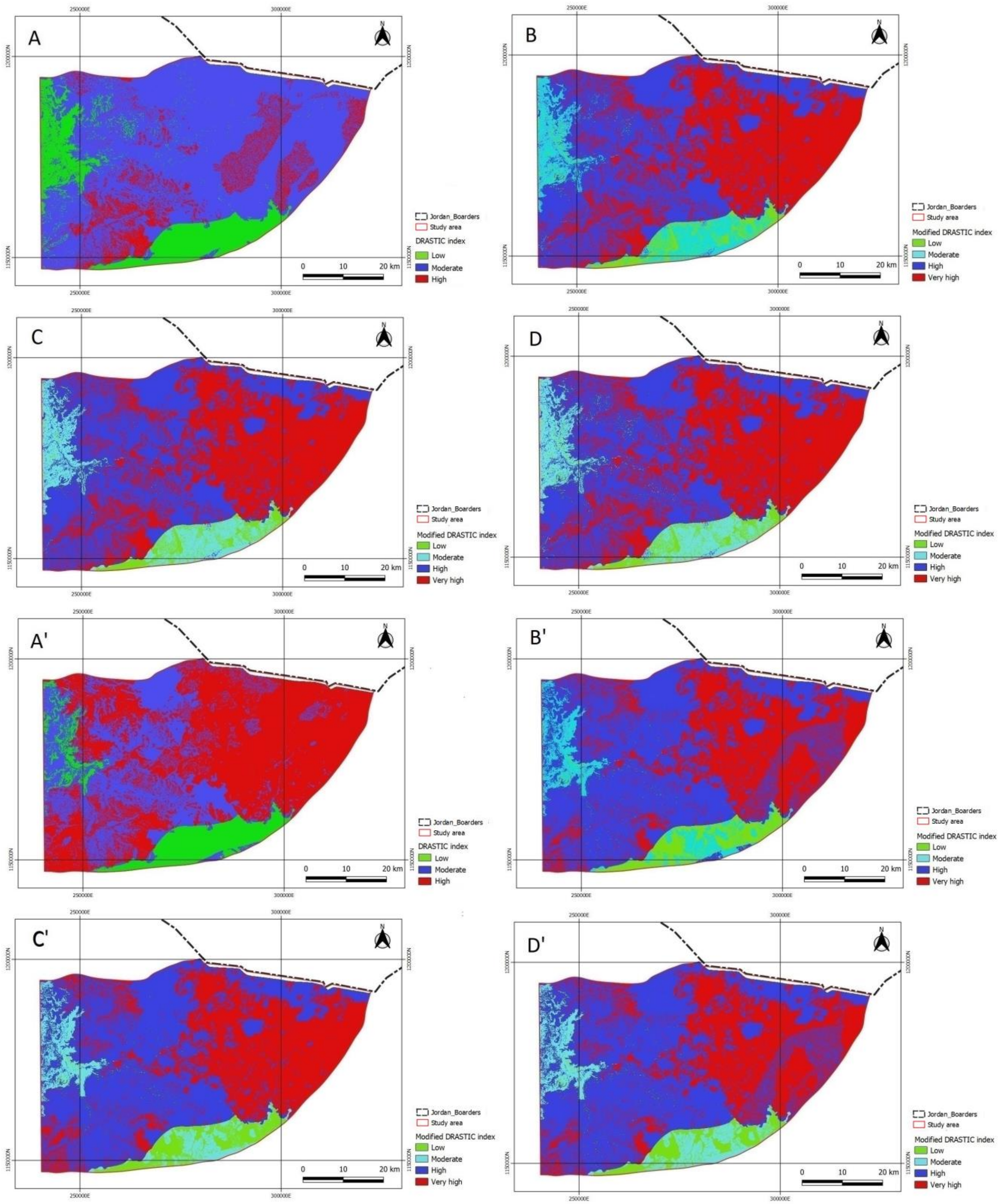

Figure 6 Agricultural DRASTIC indexes vulnerability maps: (A) DRASTIC Vulnerability map A (first scenario), (B) Modified DRASTIC vulnerability map, (C)Modified DRASTIC using extracted 6000 random points, (D) Modified DRASTIC using the extracted 9000points, (the Second scenario with suggested R ratings): (A') DRASTIC Vulnerability map, (B') Modified

DRASTIC,(C')Modified DRASTIC using the extracted 60000 points, (D') Modified DRASTIC using the extracted 900000 points.

7. (R´) and (I) are highly variable among the DRASTIC rated parameters with the coefficient of variation (CV=0.44), while T, C, A, and S are moderately variable (CV are 0.283 and 0.268, 0.257, 0.227 respectively).
8. D and R are the least variable parameter (CV are 0.1 and 0 respectively) those tow parameters maps are created according to Aller et al. (1987) ranges and ratings as the other parameters but D and R in the study area mainly got a scoring rate of one because the depth to water in the study area is mostly plotted in the lowest risk range of the depth ranges while the recharge despite the good percentage to recharge to the precipitation (10 %) but the amount of recharge very low which indicated to be plotted in the lowest risk range of the recharge DRASTIC ranges and ratings scale.
9. The correlation analysis between the DRASTIC parameters indicated a strong relationship exists between (A) aquifer media and Hydraulic conductivity (C) (r > 0.9) this result can be explained by the same origin of those parameters where they were created from the simplified hydrogeological map.
10. Due to low correlations between the DRASTIC-rated parameters at (95 % confidence-level), these DRASTIC-rated parameters in the study region were generally considered to be independent.
11. For both scenarios of DRASTIC implementation in this study it can be noticed from the table of MRSA that with increasing the number of the removed parameters, the variation index does increase, which illustrated the significance of using all seven parameters, otherwise the computed DVIM would be sensitively influenced.
12. According to the Single-parameter sensitivity analysis (SPSA), the agricultural DVIM seems to be most sensitive to the hydraulic conductivity parameter (C) in the first scenario, as it showed a clear high variation of the vulnerability index, with mean variation index=2.362 %. While in the second scenario the removal of the depth parameter (D) showed the highest variation, in general, the agricultural DVIM showed a noted sensitivity of removing any of its seven components in the study area in both scenarios.

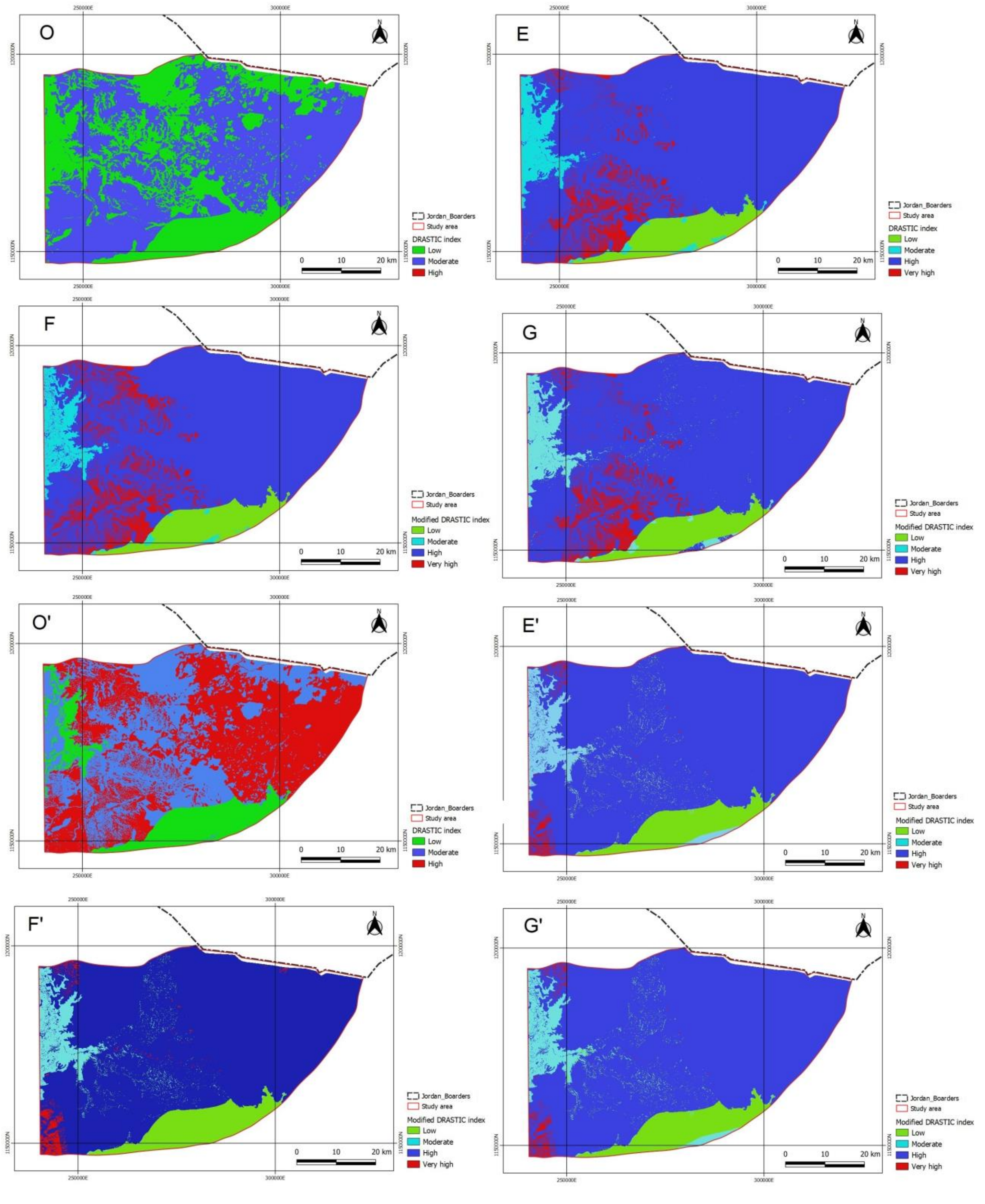

Figure 7 Ordinary DRASTIC indexes vulnerability maps: (O) DRASTIC Vulnerability map (first scenario), (E) Modified DRASTIC vulnerability map, (F)Modified DRASTIC using extracted 6000 random points, (G) Modified DRASTIC using the extracted 9000points, (the Second scenario with suggested R ratings): (O') DRASTIC Vulnerability map, (E') Modified DRASTIC, (F') Modified

DRASTIC using the extracted 60000 points, (G') Modified DRASTIC using the extracted 900000 points.

13. The Ordinary DVIM most sensitive to the impact to the vadose zone (I) in the first scenario, as it showed the highest variation of the vulnerability index, with mean variation index =2.149 %. While in the second scenario the removal of the Topography parameter (S) showed the highest variation, and from the rest results the ordinary DVIM showed a noted sensitivity of removing any of its seven parameters in both scenarios.
14. Upon both sensitivity analyses results (MRSA) and (SPSA), a significant variation in the DVIM assessment is expected if a lower number of DRASTIC seven parameters have been used.
15. The effective weights of the depth to water parameter (D) is less than the original assigned weight this due to the low variability of this parameter and low a risk contribution to contamination as almost all the study area belongs to the lowest risk DRASTIC (D) range.
16. The real weight for the aquifer media, impact to vadose zone, and hydraulic conductivity increased as these elements reflect the geological formation in the study area which are dominated by karstic and fractured basaltic formations thus have a high influence on the DVIM assessment.
17. As a result, the effective weight results indicate that the three geological parameters, which have an effective weight higher than the theoretical weight, generally regulate the vulnerability in the region.
18. The explanation for the existence of a new vulnerability class (a very high vulnerability class) in all modified DVIMs can be explained by reference to the effective weight tables. which indicates an increase in (I, C, and A) weight as these DRASTIC-parameters have a greater effect on the vulnerability index assessment process in the study area while the weight of the less influencing parameters (D and R) decreased
19. The agricultural modified DRASTIC map (B) was selected to represent the study area intrinsic groundwater vulnerability as the ordinary DRASTIC less estimated the vulnerability of the study area and the Agricultural DRASTIC designed by Aller et al. (1987) to assess the vulnerability when the agricultural activities are the main source of the possible contamination.
20. The agricultural modified DRASTIC map (B) was validated by studying the matching and correlation between the groundwater vulnerability map (B) and the water quality SCD maps.

21. It is evident that the modified agricultural DVIM corresponds to the continuous distribution maps of the average and maximum concentrations of nitrate, sulfate, and EC elements.
22. According to COP-model, the study area is assigned as the very low to moderate vulnerable areas. Which is against the study area geological nature which characterized by highly karstification aquifers and fractured high permeable basalt in addition to the failure of this model to coop with the several studies discussed the groundwater quality deterioration and the increasing trend of the groundwater contamination and the recommendations to regulator the agricultural activities in this highly vulnerable area.

5.3.2 Groundwater nitrate contamination risk (NCR) map.

This part was created to simplify the use of an enormous amount of spatial data, using overlying modelling techniques, to produce the visualization results of groundwater nitrate contamination risk (NCR) in the study area. The results of the three overlying models used in this research are shown in (Figure 8). These simulations represent as far as possible:

1. The natural groundwater protectiveness by intrinsic vulnerability model, via the agricultural modified (DVIM) DRASTIC vulnerability indexes map (B), which was selected after creating several modified DVIMs by the tow DRASTIC approaches the Ordinary and the Agricultural, and by adopted tow implementation scenarios for each DRASTIC approaches and modified all the resulted DVIMs by the statistical approach introduced by Napolitano & Fabbri (1996). DVIM (B) indicate that 40 % of the study area fall under the very high vulnerability condition (value of the DRASTIC Indexes scorings (DIS) > 200) and about 45% of the study area fall under the high vulnerability condition (value of the DIS is between 140-200), which reflect the fragility of the groundwater natural protectiveness in the study area. While the findings of the previous GRA investigations suggest that agricultural practices are the key cause of contamination, and the natural potential protectiveness of the groundwater by studying the geological and hydrogeological parameters revealed a fragility of this protectiveness.
2. The nitrate potential contamination by a land use thematic map created via simple overlying model to simulate the possible nitrate contamination loads. The overly of the three-land use nitrate contamination potential maps indicated parallel to the contamination load investigation that the main source of the nitrate contamination in the study area is related to

agricultural activities, where the study area classified into very high, high, moderate, low, and very high APNC classes in 8.35 %, 5.92 %, 27.84 %, 27.51 % and 30.36 % of the studied area, respectively.

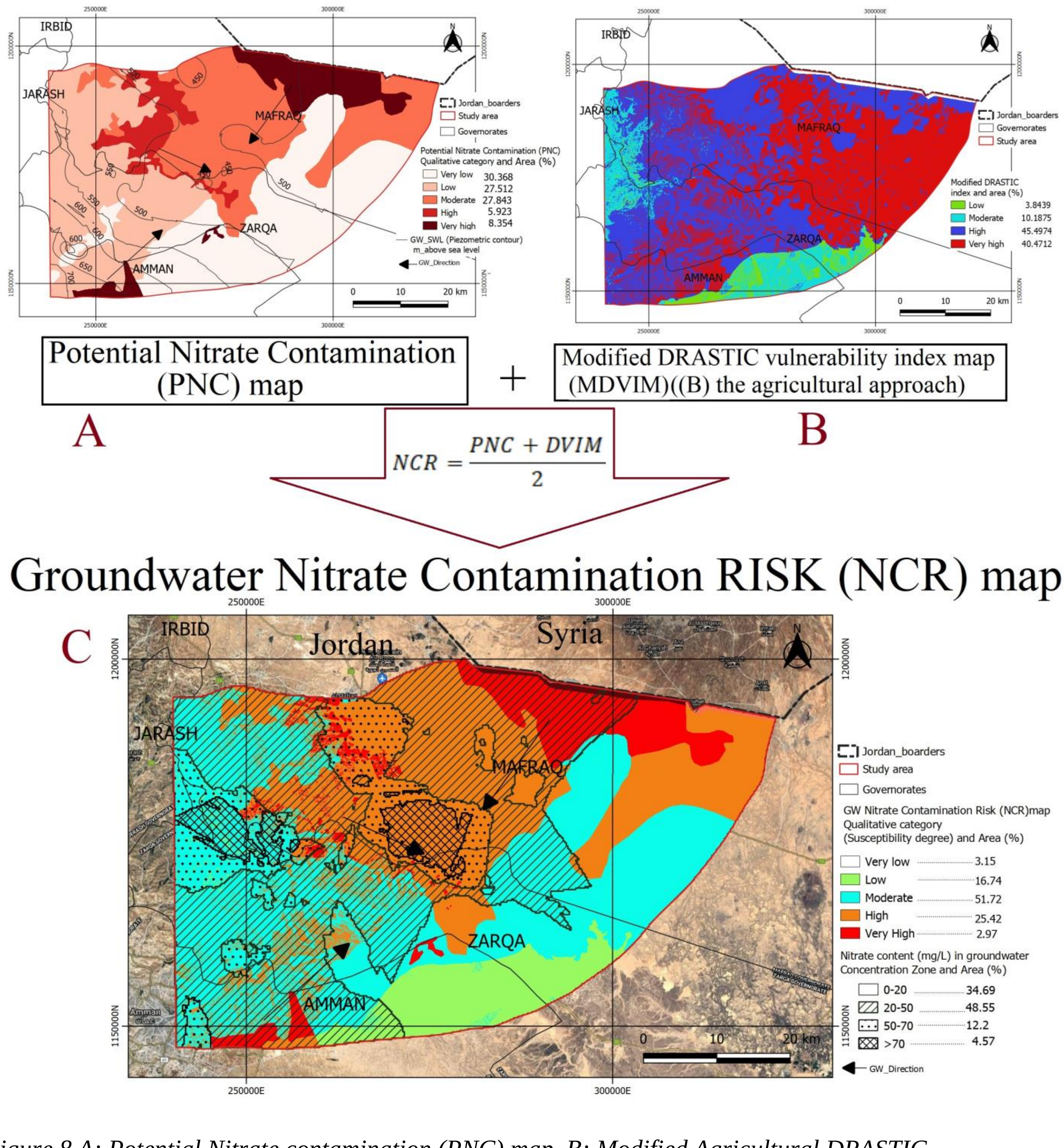

Figure 8 A: Potential Nitrate contamination (PNC) map, B: Modified Agricultural DRASTIC vulnerability index map (MDVIM) (B). the agricultural approach, and C: Groundwater Nitrate contamination RISK (NCR) map.

While a very low, low, moderate, and high UPNC classes were classified in 95.9 %, 3.5 %, 0.9 %, and 0.01 % of the studied area, respectively. Then very low and low PuPNC classes were classified in 95 % and 5 % of the studied area, respectively. The PNC map resulted by overlapping the previouse three classified land use thematic layers responding to the nitrate contamination factors indicated that the study area classified into five PNC clasess from very low to very high.

3. The nitrate contaminaton risk (NCR) map created by overlapping the PNC map and the modified agricultural DVIM (B) of equal weight (using the arithmetic average of the input values) indicated the study area assigned a very high, high, moderate, low, very low NCR classes in 2.96 %, 25.42 %, 51.72 %, 16.73 %, 3.15 % of the studied area, respectively.

6. CONCLUSION

Thus, the study revealed the following main conclusions:

1. The SCD of the nitrate, sulfate, and EC concentration distributions in the groundwater aquifer demonstrates a very strong correlation, and a relatively very close probability of distribution for each parameter long average concentration spatial distribution maps and following a related parallel anisotropic distribution pattern. This ensures that these three parameters come from the same source.
2. The positive good correlation between these three parameters approved in the correlation matrix table which implemented directly by the measured concentrations values. This strong correlation indicated a possibility of the same resources causing the increase of these parameters' concentrations in the study area.
3. The primary factors influencing groundwater chemistry are derived from the natural dissolution of the aquifer rocks, especially the carbonates. While the chemical fertilizers and the irrigation return flows (IRF) are the main anthropogenic sources of disturbing the natural groundwater composition.
4. The dominant groundwater hydro-chemical facies in the study area are the Ca–Mg–Cl and Na–Cl, according to the order of their dominance, with an average sodium/potassium around 40 %, 35 % carbonate, 70 % chloride, 40 % sulfate, 60 % calcium/magnesium, while calcium reach more than 80% but the wells plotted ranges from less than 20 % up to more than 80 % because part of the wells pumping from the basalt aquifer and some wells from the highly

karstic A7/B2 aquifer and some wells from both aquifers as both aquifers hydrogeological connected in the eastern part of the study area.

5. The range of carbonate concentration among the wells is high due to the different types of aquifers, the basaltic wells show very low concentration, but the karstic A7B2 wells show higher concentration. The low solubility of minerals through the limestone in the A7/B2 aquifer indicates the major ions (+/-) concentration must be with a natural origin. However, it was observed from the plots that calcium does not exceed sodium and potassium, and that chloride-sulfate exceeds other ions, suggesting an anthropogenic source which is mainly in the study area the agricultural activities.
6. The high sulfate concentration indicates an anthropogenic source for the wells classified in the piper diagram above the average sulfated plotted line of the study area wells 40 % (more than 65 % of the wells plotted above the 40 % sulfate average concentration line).
7. The natural groundwater potential protectiveness can be recognized as weak in the study area according to the hydrogeological overview, the outcropping of the high permeable geological formations, and the thin weak protectiveness texture of the soil cover and high density of geological lineaments. Combined with a good percentage of groundwater recharge from the precipitation which is indicator that the irrigation in the study area will cause an increase in the recharge and increase the passages of the agricultural contamination.
8. The overlying modelling techniques used in this study to simulate the intrinsic vulnerability and the specific vulnerability, concludes the following:

   a. The DRASTIC-model, even though it gives relatively satisfactory results in the evaluation of groundwater intrinsic vulnerability to pollution, cannot be used for the truthful assessment of the groundwater pollution risk in the arid highly permeable areas without modifications. Besides, the hydrogeological conditions provided in the original DRASTIC-model by Aller et al. (1987) do not make special provisions for hazardously sensitive, karstic, and fractured basaltic rocks domains. However, the flexibility of the application DRASTIC model and its ability to be applied in areas belong to different environmental characteristics was clear by the ease, efficiency, and simplicity of finding the parameters real weight in the modification approach.

   b. Using the statistical sensitivity analysis approach to avoid subjectivity associated with the selection of ratings and weights of the seven model parameters conclude that the seven

DRASTIC components were essential and significant in the calculations of DVIM. Furthermore, optimizing the weights of the DRASTIC parameters using the aforementioned optimization procedure by Napolitano & Fabbri (1996) which can be easily achieved using simple statistical approaches was more effective and reliable than changing the ratings of the DRASTIC parameters as suggested in the second scenario.

c. The statistical analyses show that aquifer media (A) and hydraulic conductivity (C) are the most significant parameters which dictate the high vulnerability in the study area.

d. The correlation between the modified DIVM (both DRASTIC approaches the ordinary and Agricultural) and the concentration of the contaminants indicates a better representation than the COP-model. Besides DRASTIC model shows great correspondence between the sensitivity of the area to pollution and the distribution of geological outcropping. One of the key findings is the importance of using a suitable vulnerability model that is appropriate for the hydrogeological, climatic, and contamination risk load in the study area. While, referring to the comparison results between COP-model and DRASTIC-model its recommended not to use, COP-model for dry areas and to use DRASTIC model.

e. The application of DRASTIC model needs to be adjusted by finding the actual weight of the parameters to improve the consistency of the implementation of the model.

f. Using the contamination-prone maps models showed the ease of simulating the area's susceptibility to pollution in a visualization map. And the overlying modeling techniques used in this study are very simple to use and require for the appropriate management of agricultural areas.

g. The modified agricultural DIVM demonstrated that (40 %, 45 %, 10 %, 3 %) of the case study area is under very high, high, moderate, and low groundwater vulnerability to contamination respectively. This calls for an urgent plan to control the spread of agricultural activities, especially in the mid-and north-eastern areas, while the southern part of which about 3 % of the study area is somehow naturally protected as the outcropping layer is aquitard.

h. The groundwater NCR indicated the study area, assigned a very high, high, moderate, low, very low NCR classes in 2.96 %, 25.42 %, 51.72 %, 16.73 %, 3.15 % of the studied area, respectively.

i. The groundwater NCR map represents a particular current groundwater contamination risk, whereas the current land use might have been changed so that the created groundwater NCR may not be reliable and may require to be modified to represent changes in land use or changes in the selected contamination parameters. Therefore, the modified DVIM is more reliable to be used for future strategic land use planning.

Ultimately, the main benefits of the approaches proposed in this study are the potential of being implemented on a broad scale, simple availability, and versatility of starting data, even from various sources. Besides, the reliability of the overlying modeling techniques used to create the NCR map (in terms of accordance with the nitrate concentration zones) and the intellectual methodology of the NCR map generated, seems to be useful and have a significant potential for being employed worldwide.

7. Key scientific findings and important output of this research

The efforts to incorporate the methodological approaches proposed here would result in a cost-effective solution to maintaining the source of community drinking water and achieving the desired protection of groundwater for future generations. The research can also be used as a method to raise public awareness of groundwater problems in developed countries. The research is intended to establish a holistic pattern for the use of several scientific methods in a systematic and monotonous manner to investigate groundwater risk in support of sustainable ground water management.

The study has shown that the overlay models used to create contamination vulnerability maps are better suited for dry areas through Jordan as an example. The developed integrated overlaying approach is mostly aimed at assessing groundwater vulnerability and evaluating the estimation problem of nitrate contamination in arid agricultural areas. This included the use of the updated version of the DRASTIC vulnerability mapping methodology, the fuzzy hierarchy methodology for contamination source mapping, and the computational simulation of the nitrate contamination risk map.

The modification implemented in this study with the application of the widespread intrinsic vulnerability model (DRASTIC) is based on a series of innovations that have taken place on this model since the beginning of its use in groundwater vulnerability studies. In my doctoral research I have applied a Modified simple overlaying approach to create a land use layer attempts of integrating it with the modified reliable DRASTIC framework to be the parameter number eight in the overlaying approach of this study. The updated composite DRASTIC-land use model was then able to determine specific groundwater vulnerabilities by including the introduced land use parameter. But in this study due to the difficulties of recognizing all possible sources of contaminants, the susceptibility is more directed towards a particular contaminant which is in this dessertation the nitrate. Therefore, the land use layer has been created to represent possible nitrate contamination (PNC) in the study area. Lastly, the thesis presents the following key findings on the level of groundwater studies in Jordan:

1. Improved the quality of input datasets through the reduction of errors and thus provided data for future research.
2. Showed that spatially explicit methods can improve the analysis of pollution sources and risks in the study area and Jordan. As well as the SCD representation and the statistical methods for assessment and representation and analyzing groundwater quality data can determine the extent of pollution in a cost-effective manner.
3. Provided a comprehensive analysis on the potential application of the DRASTIC model in arid areas.

8. SUMMARY

The study demonstrates that intensive land use in arid areas imposes tremendous pressure on groundwater. The comprehensive investigations of the contamination loads, the potential protectiveness of the aquifers and the anthropogenic activities indicate that the contamination load is primarily attributable to agricultural activities and accompanied with a high susceptibility to contamination. This study, shows that remote sensing and GIS techniques are powerful tools in groundwater studies, providing possibilities for the use of vast spatial data, especially in the overlaying modelling techniques. And concluded that a significant proportion of the case study area is hazardous to contaminants, demonstrated by the vulnerability and nitrate contamination RISK Maps.

Groundwater vulnerability models are the most useful tools to simulate the various control factors that govern the surface contamination leaching process towards the aquifers. A study illustrating the significance of vulnerability models in dry areas, in the case of Jordan, and its contribution to groundwater sustainability. Two DRASTIC approaches (ordinary and agricultural DRASTIC) were performed with two scenarios. Sensitivity tests were applied to modify and examine the original theoretical weights and avoid the subjectivity in ratings and ranges of the parameters. Real parameters weights were calculated for the two scenarios in each DRASTIC approach by different methodologies rely on the (GIS) and using the extracted random points with the values of the seven rated DRASTIC parameters-maps. Long average and maximum concentrations of nitrate, sulfate, and salinity were used to assess the DRASTIC results since agriculture is the main source of pollution in the area. A comparison between the COP-model and the DRASTIC-model indicates the appropriate use of DRASTIC in arid areas. The procedure, successfully applied in this study with a reasonably good match between the RISK map and the nitrate distribution in groundwater, appears to be accurate and has with the contamination load investigations a large potential to be applied worldwide.

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