Groundwater Vulnerability Using DRASTIC model Applied to Halabja Saidasadiq Basin, IRAQ

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Soil Mechanics
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Licentiate Thesis

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Abstract:

The enlargement of human population regularly corresponds with change in the land cover, including expansion of urban areas, which imposes increasing the available amount of domestic and drinking water. As the surface water sources are not enough in the study area, it has become necessary to use groundwater at an increasing rate. Usually, groundwater is plentiful in the alluvial deposits or rock outcrops where the urban areas are frequently situated. Such areas face a greater risk of pollution of groundwater due to several factors. Keeping these aspects in view, groundwater vulnerability studies have been carried out in Halabja Saidsadiq Basin. The study area is situated in the Northeast of Iraq and is considered to be one of the major groundwater sources of the region. The objective of this study is to recognize the groundwater vulnerability in the area so that the groundwater can be protected from contaminations. In the current study, it was visualized to review DRASIC model, which is considered to be one of the most proper and useful methods available for assessment of the groundwater vulnerability and to modify this method for the study area. In addition, the applied model was validated by comparing its findings against the observed water quality characteristics within the region in two different seasons.

Field and official data were collected and used to map standard DRASIC model as a first attempt to map vulnerability model for the study area. Based on this model, the study area was classified into four zones of vulnerability indexes, comprises a very low, low, moderate and high vulnerability index of the coverage area of (34%, 13%, 48% and 5%) respectively. In addition, the achieved results by this model were validated; nitrate concentration analysis has been selected. Nitrate as a pollution indicator can be helpful to recognize the evolution and changes of groundwater quality. In the particular study case, the nitrate differences between two following seasons (dry and wet) were analyzed from (39) watering wells. The results of this validation confirmed that the standard DRASIC model should be modified for this specific area in order to demonstrate the most accurate vulnerability system. For this reason, three different methods were applied to modify the DRASIC Model.

The first modification is based on rate and weight adjustment based on two methods, nitrate concentration from 39 groundwater samples for modifying the recommended rating value and sensitivity analysis to modifying recommended weighting value. The new rates were calculated using the relations between each parameter of DRASIC model, and the nitrate concentration on the groundwater based on the Wilcoxon rank-sum nonparametric statistical test to compute the modified rate of each parameter. To calibrate the rate modification, the Pearson's Correlation Coefficient was applied to calculate the relation between DRASIC values and nitrate concentration. For the modified model, the correlation coefficient was 72% that was significantly higher than 43% achieved for the standard model. The results also illustrated that most of the wells with the highest nitrate levels were situated in moderate and high vulnerable areas and were attributed to use of fertilizers and pesticides for the purpose of agriculture and are considered as a main source that infiltrated into the groundwater. The modified model classified the area into five classes (very low, low, moderate, high and very high) with (7%, 35%, 19%, 35% and 4%) respectively. The results designated that the modified rate and weight of DRASIC were dramatically superior to the standard model.

The second modification of DRASIC model was based on land use and land cover for the study area. Two different scenes of landsat Thematic Mapper (TM) were used with the aid of ERDAS IMAGINE software and the GIS technique to prepare digital image classification of the study basin. Supervised classification for level I of USGS (United States Geological Survey) was
conducted with a band combination RGB/742 to prepare The Land Use and Land Cover (LULC) map. The LULC map illustrates that only five classes of land use can be identified these are: barren land, agricultural land, vegetation land, urban area and wet land or water body. The LULC map converted to LULC index map by multiplying LULC rating map with its weighted value. This index map has an additional parameter added to the standard DRASTIC model to map the modified DRASTIC vulnerability in the study basin. Once more, nitrate concentration analysis was selected and added as a pollution indicator to validate this modification. The modified DRASTIC based on LULC map classified the area into five classes: very low (1.17%), low (36.82%), moderate (17.57%), high (43.42%) and very high (1.02%). The results demonstrate that the modified DRASTIC model was dramatically superior to the standard model; and it considered being one of the most appropriate methods to apply to map vulnerability system in the study area. This conclusion is based upon the results of nitrate content, as its concentration in the dry season is much lower than in the wet season.

The third modified method of the current study is the modification of DRASTIC model based on Lineament feature of the study area. The lineament can be defined as linear features of a landscape identified with satellite images and aerial photographs, most likely have a geological origin. Due to the close relation between lineament density and groundwater flow and yield, the lineament density map was applied to the standard DRASTIC model in order to ensure accuracy towards the consideration of the effects of potential vulnerability to contamination. A lineament map is extracted from Enhanced Thematic Mapper plus (ETM+) satellite imagery using different techniques in remote sensing and GIS. The lineament density map illustrates that only six classes of lineament density can be identified ranged from (0-2.4). The lineament density map was rated and weighted and then converted to lineament index map. This index map is an additional parameter which was added to the standard DRASTIC model so as to map the modified DRASTIC vulnerability in the study area. The modified model classified the area into four categories: very low (28.75%), low (14.31%), moderate (46.91%) and high (10.04%). The results demonstrate that there is no significant variation in the rate of vulnerability. Therefore, the nitrate concentration values recorded from two different seasons of (39) watering wells showed considerable variations in nitrate concentration from dry to wet seasons. Consequently, it confirmed that the study area is capable of receiving the contaminant because of suitability in terms of geological and hydrogeological conditions. Based on this verification, it could be claimed that the effect of lineament density is weak on the vulnerability system for the area, because of its low density value.
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The Thesis
CHAPTER 1

Introduction

1. Introduction

Groundwater is a valuable source of drinking water in several regions around the world. If this important source is polluted, it may pose a serious health hazard. Groundwater can be contaminated through a wide variety of human and other activities, which may include on land disposal of waste materials and sewage, and the leaching of fertilizers and pesticides. Since late 1970s, occurrences of nitrate, bacteria and pesticides in groundwater have exhibited a significant increase in concentration and have stimulated research on the subsurface fate of contaminants. Prevention of groundwater contamination is the key to efficient and effective environmental management, as the groundwater remediation is expensive and slow. In order to protect groundwater resources, areas prone to contamination by human activity need to be delineated, which can be best accomplished through groundwater vulnerability assessment (National Research Council, 1993).

Several regions around the world are explicitly dependent on groundwater as one of the main water sources, specifically for the arid and semi arid region. In Halabja and Saidsadiq area, groundwater plays an important role in providing water for drinking, industrials and agricultural activities. Particularly, some part within the area which is characterized by luck of a water project. In addition, after considerable economic development and enhanced security in the studied basin and after many years of destruction, chemical attack in the area with many wars and now finally after changing the administrative structure of Halabja from District to Governorate in March 2014, the City of Halabja will mark the beginning of greater economic development and advancement. A point worth highlighting, is the increase of the number of people heading to this basin and its surrounding region, this means water consumption is on the rise. According to data obtained from the Directorate of Groundwater in Sulaimani City, the area holds several thousand deep wells. Thus the study and research into the groundwater resources and its potential pollution in the area has become a necessity. Moreover, it is worth noting no previous other studies have been conducted on this vital area of study in terms of contamination, especially so as it evolves into a governorate making this study of particular importance.

1.1 Previous Studies

Since this study concern groundwater vulnerability mapping, hence the light will shed fundamentally on two primary different subjects; the main endeavor is going to survey unsaturated zone with groundwater condition and then to make vulnerability mapping. Concerning making of vulnerability mapping, this study is considered as the first attempt on the study basin, which tries to construct such a sort of zonation map, particularly with the guide of utilizing most recently used tools in such a field of the study, that is called geographic information system (GIS). Some regional studies are indirectly related to hydrogeological and hydrological conditions were done on and around this area. These studies can be summarized as follows:

- Parsons Company in (1957) studied hydrogeology, climate, water quality, availability of water for drinking and irrigation in Tanjero, Halabja and Penjween basins.
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- The Hydrological condition of Sharazoor plain was studied by Polservice Hydrological Co. in (1980).
- Barzinji (2003) studied the hydrology, climate, and morphometric measurements of some watersheds in Sulaimani region.
- Raouf in (2004) studied the most feasible economically and technically proposed system to satisfy present and future water supply demand of Halabjay Shaheed, Sirwan and Said Sadiq.
- Stevanovic and Markovic M. (2004) studied the regional geology and hydrogeology of the governorates of Sulaimani, Erbil, and Dohuk, through the FAO United Nation program.
- Parsons (2006) offered a report of public water supplies, the demand and growth parameters also predicated on the expansion of the distribution systems in the urban areas to serve the full population.
- Stratigraphy and lithology of the Avroman Limestone Formation (Triassic) were studied in Iraq and Iran by Karim (2006).
- Ali (2007) studied in details the investigation of the Sharazoor-Piramagroon basin in terms of Hydrogeological and morphometrical point of view, the aquifers properties, recharge estimation, chemical and Bacteriological tests, sustainability of the groundwater resources, as well as the main risks and problems which currently have an impact on the basin are exposed.
- The water balance method is used by Al-Tamimi in (2007) for conjunctive use of surface and subsurface water in Diyala basin. He divided the basin into three sub basins, top Diyala, middle Diyala and south Diyala. The top Diyala sub-basin represent Darbandikhan basin.
- Baziany and Karim (2007) Re-studied the Qulqula conglomerate Formation in Halabja - Avroman area. They proposed a new concept for the origin of accumulated conglomerate, those studies considered the Qulqula conglomerate Formation as a part of Qulqula group, which overlies Qulqula radiolarian formation.
- Al- Jaf (2008) presented a research that made a comparative between the Digital Elevation Models (DEM) taken from the Shuttle Radar Topography Mission (SRTM) and the data taken by Global Positional System device (GPS) of Garmin Etrex type.
- Sharbazheri (2008) studied the Cretaceous / Tertiary (K/T) boundary section, which crop out within the High Folded Zone, Imbricated Zone and extended in northwest- southeast direction as narrow trend near and parallel to the Iraqi/ Iranian border.
- Saprof (2008) arranged the implementation plan for a Sirwan river project in Halabja. The feasibility study analyzes the economic and technical aspects as well as financial viability of the project.
- Al-Mashhadani, et al. (2009) studied dominant Landcover/Landuse type in Sharazur Plain by using remote sensing techniques, the results indicated that there are 12 classes of landuse/landcover.
- Karim, et al. (2009) studied historical development of the lineaments of the Western Zagros Fold-Thrust Belt, Halabja city was included; they studied sedimentology and geochemistry of the limestone successions of the lower member of the Qulqula Formation.
- Raza (2009) studied the lower member of Qulqula Formation in the Thrust Zone, (Kurdistan Region) near the Iraqi-Iranian border.
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- Al- Jaf and Al- Azawy (2010) studied integration of remote sensing images and GIS techniques to locate the mineral showings in Halabja area, using satellite data received from ETM sensor that borne on Landsat 7 satellites depending on band rationing mean bands, band ratio color composite and threshold techniques.
- AL-Taweel, et al. (2011) investigated the environment, history, and archaeology of the shahrizor survey project.

In conclusion, there is no previous study on the vulnerability assessment in the study area. In addition, there is no systematic study of the hydrogeology of the basin which is considered as the main parameter to assess the vulnerability system. This study attempts to supply more relevant detailed analysis in hydrogeology and groundwater vulnerability mapping, considering the importance of groundwater uses for water supply, industrial, agriculture and irrigation.

1.2 DRASTIC model

DRASTIC is the best and probably is the most widely applied scheme for vulnerability assessment which was developed by the US Environmental Protection Agency (USEPA) by Aller et al (1987). Generally, the DRASTIC system is composed of two major parts: (1) the designation of mapable units, termed hydrogeological settings; and (2) the application of a numerical scheme for relative ranking of hydrogeological factors (Lee, 2003). Hydrogeological setting is a composite description of all the geological and hydrological factors controlling groundwater flow into, through and out of an area (Kim and Hamm, 1999). Recently, geographic information system (GIS) techniques have been widely used in aquifer vulnerability mapping. The major advantage of GIS-based mapping are the combination of data layers and rapid change in the data parameters used in vulnerability classification (Wang et al, 2007). A DRASTIC method was derived from rating and weights associated with the seven parameters, these are: Depth to groundwater (D), Net recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of the vadose zone (I) and Hydraulic conductivity (C) (figure 1). Each parameter is subdivided into ranges and is assigned different ratings in a scale of 1 least contaminant potential for 10 highest contaminations potentials. The advantageous of DRASTIC model are:

- Provide an approach to evaluate an area based on known conditions without the need for extensive, site specific pollution data.
- Provide a basis of evaluating the vulnerability to pollution of groundwater resources based on hydrogeological parameters.
- Provide an inexpensive method to identify areas that need more investigation.
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1.3 Study Area

Halabja Saidsadiq Basin, located in the north-east of Iraq, (figure 2). This basin was divided into two sub-basins by (Ali,2007) including Halabja- Khurmal and Said Sadiq sub-basins. The whole coverage area of both sub-basin is about (1278) square kilometers with population of about (190,727) persons in (2015) according to the data achieved from Statistical Directorate in Sulaimaniyah. Geographically, it located between the latitude 35° 00' 00" and 35° 36' 00" to the north and the longitude 45° 36' 00" and 46° 12' 00" to the east. The studied basin characterizes by distinct continental interior climate of hot summers and cold winters of the Mediterranean type with the average annual precipitation ranging from (500-700) mm. The percent of about (57%) of whole studied sites are characterized by arable area due to its suitability as agricultural lands and use of fertilizers and pesticides are common practices, so it affects the groundwater quality (Huang et al, 2012). In addition, all of the municipal wastewater from the cities of Halabja and Saidsadiq and all other sub-district sites within this basin infiltrate into the groundwater every year. These two factors play an important role to select this site as a case study to reveal the applicability of the proposed modification.
1.3.1 Geology of study basin

The studied basin is located within Western Zagros Fold-Thrust Belt. Structurally, it is located within the High Folded zone, Imbricated, and Thrust Zones (Buday and Jassim, 1987, Jassim and Goff, 2006). The age of the geological formations range from Jurassic to recent, as explained in figures (3&4).

Early Jurassic includes Sarki formation (thin bedded fine grained cherty and dolomitic limestone) and Sehkanian formation (comprises dark saccharide dolomites and dolomitic limestone with some solution breccias), (Bellen et al, 1959). Lower and middle Jurassic rocks including Barsarin (limestone and dolomitic limestone), Naokelekan (bituminous limestone) and Sargalu formations, the last one consist of well-bedded and well-crystallized, black bituminous limestone and dolomitic limestone and occasionally contains shells of posidoni, (Ali, 2007).
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Figure 3: Geological map of HSB.

Figure 4: cross section through A-B line.
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The Qulqula Group consists of two formations, the Qulqula Radiolarian Formation and the Qulqula Conglomerate Formation. It occupies the lower part of the southwestern limb of the Avroman and Suren anticlines. As cited in (Ali, 2007), it had been proved by Baziany (2006) and Baziany and Karim (2007), the Qulqula Conglomerate Formation does not exist and this has been proved again during the field work of this study from the log of drilled wells. In addition to these, Bolton (1958) and Buday (1980) mentioned that the later formation is equivalent to the Quaternary sediments which exist in the foothills of Suren Mountains.

The Upper Cretaceous Kometan (Turonian) and Lower Cretaceous Balambo (Valanginian-Cenomanian) Formations are widespread and are exposed in both sub-basins. Both are, lithologically, very similar, composed of wellbedded, white or grey pelagic limestone. The only difference is that the limestone of the latter formation is occasionally marly and containing interbedded marl. Shiranish Formation (Campanian) is composed of a succession of bluish white marl and marly limestone. Lithologically, Tanjero Formation is composed mainly of an alternation of thin beds of sandstone or siltstone with interbeds of shale, marl or rarely--marly limestone (Ali, 2007).

Quaternary (Alluvial) deposits are the most important unit in the area in terms of hydrogeological characteristic and water supply. These sediments are deposited as debris flows on the gently sloping plains or as channel deposits or as channel margin deposits and over bank deposits, (Ali, 2007). As recorded from drilled well logs in this deposit, usually it consists of angular and poorly sorted clasts of boulder, gravel and sand with more or fewer amounts of clay as separate deposits and some amount of limestone and chert fragments. The thickness of these deposits was recorded from previous studies up to (150) m thick while this study for the first time has recorded for about (300) m or more in thickness.

1.3.2 Hydrogeology and hydrology of study basin

Geological condition and tectonic process usually control the hydrogeology of the study basin that affects groundwater occurrence, water level and movement. In addition permeability and porosity is the main principal factors in determining the potential of the area to be considered as a water bearing aquifer. The area where characterized by different geological units so it is characterized by different hydrogeological aquifer, all aquifer types and thickness explained in (table 1). It is clear by the data recorded from field work and from groundwater level archives by Ground Water Directorate, the mountain series which surround the basin of the northeast and southeast are characterized by high water table level, while toward center and the southeastern part have lower water table level. The groundwater movement is usually from north and northeastern towards southeast and from south and southeast towards southeast moves eastwards. Generally, groundwater movement is away from the mountains surrounding the studied basin to the nearly flat area or toward the Derbandikhan Lake (figure 5). All The aquifers represented by their geological formation were described in the geological part (refer section 1.3.1).
Table 1: Type of aquifers in HSB.

<table>
<thead>
<tr>
<th>Aquifer type</th>
<th>Geological formation</th>
<th>Thickness (m)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intergranular Aquifer</td>
<td>Quaternary deposits</td>
<td>more than 300</td>
<td>Author</td>
</tr>
<tr>
<td>Fissured Aquifer</td>
<td>Balambo Kometan</td>
<td>250</td>
<td>Ali, 2007</td>
</tr>
<tr>
<td>Fissured-Karstic Aquifer</td>
<td>Avroman Jurassic</td>
<td>200 from 80 - 200</td>
<td>Jassim and Goff, 2006</td>
</tr>
<tr>
<td>Non-Aquifer (Aquitard)</td>
<td>Qulqula Shiranish Tanjero</td>
<td>more than 500 225 2000</td>
<td>Jassim and Goff, 2006</td>
</tr>
</tbody>
</table>

Additionally, the study basin comprises several rivers and streams such as Sirwan rivers, Zalm stream, Chaqan stream, Biara, Reshen stream and Zmkan stream. All these rivers and streams are considered as a main recharge source of Derbandikhan Lake which is located to the southeast of the basin. Also there are several springs inside the basin (see figure 5). These springs are classified into three classes, less than (10 L/Sec) such as (Anab, Basak, Bawakochak and 30 other springs) springs, (10-100 L/Sec) such as (Sheramar, Qwmash, Khwrmal and Kani Saraw) and more than (100 L/Sec) such as (Garaw, Ganjan, Reshen, Sarawy Swbhan Agha and 3 other springs).
1.4 Scope of the work

Presently, there is no vulnerability assessment in Halabja Saidsadiq and the area will mark the beginning of greater economic development and advancement. This leads to increase contaminant materials from human population and constructing several factories. In addition, groundwater aquifers in the study area are considered to be the main source of water supply to various human requirements, this means that groundwater is can be easily contaminated.

In the current work, it is proposed to review the methods currently available for assessment of the groundwater vulnerability namely DRASTIC method, and to modify it to construct a suitable model for the Halabja-Saidsadiq Basin. It is further proposed to validate this method by comparing the findings with the observed water quality characteristics of the region.

1.5 Objectives of research

The approach from this study comprises of the following:

- Characterization of the geological and hydro-geological setting necessary for applying the vulnerability analysis.
- Field investigation of soil, ground water quality and land use for the study area.
- Modifying DRASTIC models to prepare the most accurate aquifer vulnerability map for the study area.
- Comparison between constructed groundwater vulnerability maps.
- Validation of the result using the existing groundwater quality scenario.
2. Groundwater vulnerability

As water travels through the ground, usual processes are in charge of attenuation of convergence of numerous contaminants including harmful microorganisms. How much attenuation happens is reliant on the sort and type of soil and aquifer attributes, the kind of contaminant and the associated activity.

In general, the term groundwater vulnerability is used to represent the intrinsic characteristics of the aquifer which determine whether it is likely to be affected by an imposed contaminant load (National Research Council, 1993).

There are two classes of vulnerability, intrinsic vulnerability, which depends exclusively on the properties of the groundwater system, and specific vulnerability, where these intrinsic properties are referenced to a particular contaminant or human activity.

Vulnerability assessment is based on the expected travel time for water to move from the ground surface to the water table. The greater the travel time, the greater are the opportunity for contaminant concentration. Aquifer vulnerability can also be measured by employing appropriate mathematical framework and further subdivided into broad classes like very high, high, low and very low, depending upon the governing criteria.

2.1 Groundwater vulnerability in the study basin

Water plays an important role in every society. Not only is it vital for life, it also sustains the environment, contributes to the development of economic, health, social, recreational and cultural activities. As surface water quantity and quality continue to diminish over the years as a result of rapid population growth, urbanization and pollution in developing countries such as Halabja Saidsadiq Basin, the most available source of potable water supply is groundwater. In addition, significant unsystematic economic progresses of the studied basin were noted. Such as, construction of many oil refineries, petrol stations with unsafe design in terms of oil leakage (photo 1). Halabja and Saidsadiq cities dispose its municipals wastewater to the environment through many sewage effluent boxes around the city (photo 2). This sewage is a complex mixture of water born wastes of human, domestic and industrial origin.

The method of waste disposal in the study basin is land filling (photo 3). This process of waste disposal focuses on burying the waste in the land. This method of disposing solid waste on land is creating nuisances or hazards to public health or safety by neglecting the principles of engineering design in the land filling processes.

Moreover, it is worth noting that no previous studies have been conducted on this vital area of study in terms of contamination assessment, especially so as it evolves into a governorate making this study of particular importance. This emphasizes the growing vulnerability and susceptibility to groundwater to potential pollution challenges.
CHAPTER 2

Groundwater Vulnerability

a) Oil storage station.

b) Oil refinery station factory1.

c) Oil refinery station factory 2.

**Photo1:** Oil leakage to the ground from different oil station at HSB.
a) Sewage effluent boxes at NE of Halabja City

b) Sewage effluent boxes at NW of Halabja City

Photo 2: Sewage effluent boxes at HSB.

Photo 3: Municipal waste disposal method at HSB.
2.2 Validity of DRASTIC model and factors affecting it

Inherent in each hydrogeological setting are the physical characteristic which affect the groundwater pollution potential. Many different biological, physical and chemical mechanisms may actively affect the attenuation of a contaminant and, thus, the pollution potential of that system. Because it is neither practical nor feasible to obtain quantitative evaluation of intrinsic mechanism from a regional perspective. DRASTIC model has been used to map groundwater vulnerability to pollution in many areas in the world. Since this method is used in different places without any changes, it cannot consider the effects of pollution type and characteristics. Therefore, the method needs to be calibrated and corrected for a specific aquifer and pollution. DRASTIC model has been designed for a regional scale and might be effect by some local factors of a specific aquifer system; these factors have not been mentioned in this model. Some of these factors are:

- As illustrated by Babiker et al. (2005) the weights used to calculate the vulnerability index might change based on the different geological and hydrogeological condition of the specific area.
- The rate value of each parameter in DRASTIC model might change from one place to another based on the relationships between each parameter and the popular chemical component such as nitrate concentration on the groundwater.
- Land uses in developing cities can be complicated by the presence of urban agricultural activities. The agricultural sector increases its activity and land coverage in the surroundings of the urban centers. The urbanization processes exceeds the capacity of the territorial planning set by the local government. The easiest parameter to evaluate the human impact over the area is land-use that represents directly the human activities and the impact on the natural resources exploitation around the urban area. For this reason it is important to conclude that the land-use is affecting the vulnerability system and this parameter has not been included in the DRASTIC model.
- The land cover of the earth surface that naturally occur such as barin land, forest, grassland, vegetation, snow and water bodies. Different land covers might have different vulnerability behavior. The ability of contaminant to transport from earth surface through the unsaturated zone in agricultural area is differed that of antiquated land. Therefore, it can be mentioned that, the land cover is one of the most important parameter that affect the vulnerability system.
- Some natural features of the earth surface which has a geological origin such as lineament feature, joint and fractures, also play an important role to control the vulnerability system depending on it is density percentage. These features increase the permeability of the ground which helps the contaminant to transport easily through the unsaturated zone to reach the groundwater bodies.
CHAPTER 3

Methodology

3. Methodology

The required data to use in mapping groundwater vulnerability are presented in table (2). The shape files were created with the aid of ESRI-GIS software (Arc Map 10) from features such as (geological, hydrogeological, Soil map and hydrochemical data) in the study area. Topographic map was digitized and converted from slope map into shape files. Depth to water levels was measured from several wells in the field using electrical sounder and achieved as well as from previous well records. While thickness of saturation zone was determined from drilled wells directly supervised by researchers for this study during field work, and collected from archives of the Groundwater Directorate in Sulaimani and other private company which drilled those wells inside the study basin. Hydraulic conductivity was computed from well pumping test analysis of the wells using (AQTESOLV) software. Water samples of 39 watering wells from different groundwater aquifers in Halabja Saidasadig area were collected and sampled in one-liter polyethylene bottles and analyzed for nitrate concentration determination to be used for modification and validation. Water samples were stored in the refrigerator until analyzed to prevent deterioration and changes of their quality. The samples were analysed by Laboratory department of Environmental Directorate of Sulaimani. In addition, three methods were applied to modify DRASTIC model namely, rate and weight modification, modification based on land use and land cover and modification based on lineament feature in the study area (Figure 6).

Table (2): Source of data for DRASTIC model.

<table>
<thead>
<tr>
<th>Data type</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to water Table</td>
<td>Achieves of Groundwater Directorate in Sulaimani with data from field</td>
</tr>
<tr>
<td>Net Recharge</td>
<td>Halabja Meteorological Station and Water Balance Method</td>
</tr>
<tr>
<td>Aquifer Media</td>
<td>Achieves of Groundwater Directorate in Sulaimani and Geological Map</td>
</tr>
<tr>
<td>Topographic Map</td>
<td>DEM with 30 m pixel size</td>
</tr>
<tr>
<td>Impact of vadose zone</td>
<td>Achieves of Groundwater Directorate in Sulaimani</td>
</tr>
<tr>
<td>Hydraulic Conductivity</td>
<td>Achieves of Groundwater Directorate in Sulaimani with data from field</td>
</tr>
<tr>
<td>LULC and Lineament maps</td>
<td>Landsat Thematic Mapper (TM)</td>
</tr>
</tbody>
</table>
3.1 Preparing Layers Maps of standard DRASTIC model

To achieve the intrinsic groundwater vulnerability, the scope of groundwater pollution was analyzed by developing the seven map layers and generating the DRASTIC model which is recommended by The United State Committee of Environmental Protection Agency (Aller et al., 1987). Each parameter has a specific rate and weight value in order to evaluate the intrinsic vulnerability index as explained in table (3). Geological and hydrogeological character as mentioned by (Aller et al., 1987) is the fundamental criteria which were used to assign the label unit of the map. In addition, Aller et al. (1987) defines the seven parameters by the short form “DRASTIC” which is used to map groundwater vulnerability. Rating from 1 to 10 and weighting from 1 to 5 was recommended to assigning each parameter. The standard DRASTIC index (DI_{w,r}) calculated based on the linear combination of all factors as demonstrated by the following equation:

$$\text{DI} = D_w D + R_w R + A_w A + S_w S + T_w T + I_w I + C_w C \quad \ldots \ldots \ldots (1)$$

Where:

- DI is the DRASTIC Index, \((D,R,A,S,T,I\) and \(C)\) are the seven parameters,
- \(w\) is the weight of the parameter and \(r\) is the rate of the parameter.
- \(D\) is the depth of groundwater.
- \(R\) is the net recharge.
- \(A\) is the aquifer media.
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S is the soil media
T maps to refer to topographic map that describes the slope of the surface area
I map is the impact on vadose zone
C is the hydraulic conductivity

All the recommended rate and weight are scheduled in table (3).

In addition, as recommended by several researchers such as (Rupert, 1999, Javadi et al, 2011 and Neshat et al, 2013) cited in (Neshat , 2014) to applying modification to this model, the geological and hydrogeological condition of a region can be particularly considered to include or exclude parameters.

Table 3: Standard DRASTIC weight and rate after (Aller et al, 1987).

<table>
<thead>
<tr>
<th>Depth to water (m)</th>
<th>Net Recharge Range (mm/year)</th>
<th>Aquifer Media</th>
<th>Soil Media</th>
<th>Topography</th>
<th>Impact of vadose Zone</th>
<th>Hydraulic Conductivity Range (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45-10</td>
<td>&lt;50</td>
<td>Massive shale</td>
<td>Thin or Absent Gravel</td>
<td>10</td>
<td>0.2</td>
<td>Confining layer</td>
</tr>
<tr>
<td>1.5-4.5</td>
<td>50-100</td>
<td>Metamorphic/ Igneous</td>
<td>Sand</td>
<td>9</td>
<td>2-6</td>
<td>Silty/ clay</td>
</tr>
<tr>
<td>4.5-7.5</td>
<td>100-175</td>
<td>Weathered metamorphic/ Igneous</td>
<td>Peat</td>
<td>8</td>
<td>6-12</td>
<td>Shale</td>
</tr>
<tr>
<td>7.5-10</td>
<td>175-250</td>
<td>Glacial Till</td>
<td>Shrinking and/or aggregated clay</td>
<td>7</td>
<td>12-18</td>
<td>Limestone</td>
</tr>
<tr>
<td>10-12.5</td>
<td>&gt;250</td>
<td>Bedded sandstone, limestone, shale</td>
<td>Sandy loam</td>
<td>6</td>
<td>&gt;18</td>
<td>Sandstone, Bedded Limestone</td>
</tr>
<tr>
<td>12.5-15</td>
<td>5</td>
<td>Massive sandstone ,massive limestone</td>
<td>Loam</td>
<td>5</td>
<td>sandstone, shale, sand and gravel</td>
<td>6</td>
</tr>
<tr>
<td>15-19</td>
<td>4</td>
<td>Sand and gravel</td>
<td>Silty loam</td>
<td>4</td>
<td>Metamorphic/ Igneous</td>
<td>4</td>
</tr>
<tr>
<td>19-23</td>
<td>3</td>
<td>Basalt</td>
<td>Clay loam</td>
<td>3</td>
<td>Sand and gravel</td>
<td>8</td>
</tr>
<tr>
<td>23-30</td>
<td>2</td>
<td>Karst limestone</td>
<td>Muck</td>
<td>2</td>
<td>Basalt</td>
<td>9</td>
</tr>
<tr>
<td>&gt;30</td>
<td>1</td>
<td>Non shrinking and non-aggregated clay</td>
<td>Karst limestone</td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

DRASTIC weight: 5

3.1.1 Depth to groundwater (D-Map)

D is the depth of groundwater or depth to Static Water Level (SWL) which describes the distance of unsaturated zone that pollutant desires to travel through to reach the water table. For this study, groundwater level measured in nearly about 1200 wells. These data were used in the GIS
environment by interpolating them to construct depth to water table map as a raster format. The Inverse Distance Weighted (IDW) used to interpolate the data and then reclassified based on the ranging and rating recommended by (Aller et al, 1987). Part of the data was collected on August and September 2014 by the researcher during the field work and the other part was from the archives of GWDS. In Halabja-Saidsadiq basin the depth of groundwater varies from zero to more than (100) m. Therefore, ten classes were illustrated with the studied basins including (0-1.5, 1.5-4.5, 4.5-7.5, 7.5-10, 10-12.5, 12.5-15, 15-23, 23-30 and more than 30)m (Figure 7).

3.1.2 Net Recharge (R-Map)

R is the net recharges which define the amount of water that penetrates into ground and move through unsaturated zone to reaches the water table. The net recharge was estimated at the meteorological data for the period (2001-2002) to (2013-2014), based on the following equation recommended by (Mehta et al, 2006):

\[ NR = P - ET - R_0 \] ………………. (2)

Where, NR: is the net recharges in mm/year, P: is the annual precipitation in mm; ET is the calculated evapotranspiration in mm/year, R_0 is the total runoff in mm. P is calculated from the average total annual precipitation for the mentioned period which is about (691.16) mm/year. While ET was calculated based on Crop Water Balance method and as claimed by Allen et al (2006), the principle of this method is based on FAO Penman Monteith method using ( CROPWat 8.0) software. R_0 was calculated based on Soil Conservation Service method (SCS) to estimate the total runoff for the basin. The basin was divided into several curve numbers (CN) that was recommended by ( Ali, 2007) and then using the following equation :

\[ Q = \frac{(P-0.2S)^2}{(P+0.8S)} \quad \text{for } P > 0.2S \] ……….(3)

\[ S = \frac{25400}{CN} - 254 \] …………………………(4)

Where: Q = accumulated runoff excess in (mm). P = accumulated average monthly rainfall (mm). So the annual runoff of this basins are about (169) mm and the annual net recharge for whole basin is equal to (172.54 ) mm. Finally, the net recharges map of the basin was constructed based on the net recharge percent distribution of the basin based on the curve number map proposed by (Ali, 2007) and then the resulted map were converted from polygon to raster format in GIS environment, figure (7).

3.1.3 Aquifer (A-Map)

A is the aquifer media which is describing the media that has ability to store a prospective amount of water. The organization of this parameter was based on the geological map of the basin and drilling well logs to produce the polygon distribution of the area. Four sections of the aquifer media was classified in the studied basin which are: fissured limestone in the northeast, northwest and south of the basin; mixture of gravel, sand, clay and rock fragment in the central and southern part; bedded sandstone and clayston in the northeast and southeast and, media rock contain marl and marly limestone in the south. The rated value of each media based on Aller et al (1987) is illustrated as (9, 6, 5 and 3) respectively. Finally, the constructed map was also converted to the raster formats from polygon to raster tool as demonstrated in figure (7).
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3.1.4 Soil (S-Map)

S is the soil media (texture and type) which has a considerable impact on controlling the movement towards sufficient amount of water into the ground and this also defines the ability of a pollutant to move vertically into the vadose zone (Lee, 2003). Three different soil media was founded in the area based on soil map proposed by FAO (2001) and Berding (2003). Soil media (Figure 7) was classified into (Silty loam, Shrinking and/or aggregated clay and thin or absent) with rating of (4, 7 and 10) respectively that was proposed by Aller et al (1987).

3.1.5 Topographic (T-Map)

T maps to refer to topographic map that describes the slope of the surface area. The pollutants are remaining for a long period over an area with low percent of slopes value and vice versa (Hernandez et al, 2004). This map was constructed from the digital elevation model (DEM) with pixel size of (30 m) and the slope aspect was then calculated from it in Arc GIS 10. It was sliced into ranges and assigned a rating ranging from 1 to 10 based on table (3). The topography of the area was then allocated to five classes ranging from (0-2, 2-6, 6-12, 12-18 and more than 18) percents as explained in figure (7).

3.1.6 Impact of vadose zone (I-Map)

I-map is the impact on vadose zone which is describing the unsaturated zone above the water table. The classification principle is quite similar to the aquifer media which is based on the geological condition and the data recorded from drilled well logs with slightly different from the lateral distribution. Three segments of vadose zone was comprised (sand and gravel, sandston and cherty limestone, fissured or karst limestone) occupying area of (35%, 24% and 41%) respectively. The map with organized different rate of vadose zone (4, 5 and 8) respectively was constructed and then converted to raster format as shown in figure (7).

3.1.7 Hydraulic conductivity (C-Map)

C is the hydraulic conductivity which is describing the ability of the aquifer material to transmit water through it. Therefore, contaminant migration is limited depending on the permeability of the medium (Hamamin, 2011). The hydraulic conductivity map was constructed by employing the pumping test result of about (100) wells. The pumping test data analysed using (AQTESOL 4.0) software to determine the transmissivity of the aquifer using equation (5) to calculate hydraulic conductivity:

\[ C = \frac{T}{b} \]  \hspace{1cm} (5)

Where: C is the hydraulic conductivity in (m/day), T is the transmissivity in (m²/day) and b is the aquifer saturated thickness in (m). The area with high hydraulic conductivity revealed higher chance of distribution of pollution. Two classes of conductivity rating were achieved (1 and 4) as shown in figure (7).
After generating all the required layers, each pixel was classified and rated, then, multiplied by their respective weighting factor and the DRASTIC index was determined. The resulted index was divided into several groups proposed by Aller et al. (1987). Small values designated low vulnerability potential and large one is communicated to those areas that have high Vulnerability potential.

3.2 Rate and weight modification of DRASTIC model

![Figure 7: Rate map of all parameters of standard DRASTIC.](image)
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3.2.1 Rate modification using nitrate concentration

As mentioned previously, due to the fact that the study area is characterized by an active agricultural exertion, nitrate concentration had been used to modify the standard DRASTIC method for the studied basin. Sampling and analysis for nitrate concentration was carried out for 39 well samples on May 2014. Figure (8) illustrates the location of the sampled wells and the GPS techniques was used for precise location of each well.

![Nitrate sampling sites and class concentration at study basin.](image)

Fig 8: Nitrate sampling sites and class concentration at study basin.

Normally, nitrate moves toward the groundwater from the surface, so it was used as the primary control parameter for contamination. The genuine condition of the area can be established for the vulnerability index by using nitrate as an indicator. As proposed by Panagopoulos et.al (2006), the rates and weights can be optimized but the following conditions should be satisfied; the agricultural activities should be the only source of nitrate concentration on the surface, reaching nitrate to the groundwater should be due to recharges from the surface over a long period.

In this method, the rates of five maps of DRASTIC methods were modified according to the mean nitrate concentration including depth to water table, net recharge, soil media, impact on vadose zone and hydraulic conductivity. While both aquifer media and topography remain the same. The Wilcoxon rank-sum nonparametric statistical test was used to compute the modified rate of each parameter in the DRASTIC method. The highest and lowest rates were allocated to the highest and lowest mean nitrate concentration respectively and the residual rates were modified linearly (Wilcoxon, 1945). In addition, if there is no data onto mean of nitrate concentration on each class, the standard rate of DRASTIC method have been used. The new DRASTIC map was designed using the new modified rating system (Figure 9).
3.2.2 Weight modification using sensitivity analysis

As illustrated by Babiker et al. (2005) the weights used to calculate the vulnerability index might change based on the different geological and hydrogeological conditions of the study area. Sensitivity analysis evaluates the effective weights of each parameter and compares it with their original weights. The effective weight is referring to the function of the value of a single parameter as well as the weight assigned to it by the DRASTIC model (Babiker et al. 2005). The impact on each parameter in the index computation was assessed by achieving the sensitivity analysis. Equation (6) was used to calculate the effective weight of each polygon (Javadi et al., 2011).

\[ W = \left( \frac{PrPw}{V} \right) \times 100 \]  

Where: \( W \) is the effective weight of each parameter, \( Pr \) and \( Pw \) are the rating value and weight of each parameter, and \( V \) is the overall vulnerability index.
3.3 Effect of Land use and land cover on DRASTIC model

The effect of human and natural process as a fundamental environmental erratic can be identified from land use/ land cover map (Meyer and Turner, 1992). Land use / land cover is normally marked by a short term of (LULC). Land cover (LC) defines the cover of the earth surface that naturally occur such as bare land, forest, grassland, vegetation, snow and water. Land uses (LU) illustrate the modification of land cover due to human processes or man-made modification (Cihlar et al, 2001). Remote sensing technique and field survey can be used to supervise LULC. As mentioned by Mas (1999) and cited in Jwan et.al (2013), remotely sensed satellite images are the most widespread source of data onto mapping LULC, because of its availability and repetitive data acquisition, improved quality of multi-spatial and multi-temporal remote sensing data at different (spatial, spectral, and digital) format suitable for computer processing and new analytical techniques.

Two different scenes of landsat Thematic Mapper (TM) had been used to prepare LULC map because the study basin is located in between them. Images consist of seven spectral bands of cell size (30x30 m) for Bands 1 to 5 and 7. While, spatial resolution to Band 6 (thermal infrared) is 120 meters, however this band re-sampled to 30-meter pixels. Nearly, scene size is 170 km north-south by 183 km east-west and the date back to (03-05-2010). Figure (10) illustrates the TM landsat image of the study basin.

Figure 10: TM landsat map (2010) of study basin
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The most important steps in LULC preparation are classification processes because it gives you the degree of accuracy. There are several proposed methods of LULC classification in the world, but the USGS (United States Geological Survey) system that developed by Anderson et.al (1976) was applied in this study. The factors that support the selection of this method is the availability of remote sensing data and it’s suitability for application to the study basin. The USGS system of classification consists of four levels, from I to IV; the difference between them depends on the resolution of remote sensing data used for classification (Bety, 2013).

ERDAS IMAGINE software was used to prepare the digital image classification of the study basin. Supervise classification for level I of USGS was done with band combination RGB / 742 for image that covered the basins. The study area was extracted from the resultants map of classification according to the catchment area of HSB using ArcGIS software. The analyses were also supported by field work. Many points were taken with GPS and several photos were taken as well to check the accuracy and validity of the final map of classification.

In addition, to modify the likely risk of groundwater vulnerability an additional parameter can be inserted into the analysis to show the realistic of vulnerability assessment. In this study, LULC map was used because it muscularly affects the quality of groundwater where agriculture as the main land use type is the main factor in changing from soil nature and hydraulic conductivity (Merchant, 1994).

Therefore, LULC map was rated and weighted as additional parameter and added to standard DRASTIC model. The LULC rating map was rated based on the values given in table 4. Furthermore, it was converted to a raster grid and multiplied by the weight of the parameters (Lw = 5) to construct LULC index map. Then, to modify the original DRASTIC indexes map, it was combined with LULC index map based on equation (7) (Secunda et al, 1998). The results demonstrate the effect of specific land uses type on the vulnerability system.

\[ MD(i) = DI + (LULC\ Index) \] \……………….. (7)

where: MD(i) is the modified DRASTIC model; DI is the standard DRASTIC index and the LULC index (ratings·weights).

Table 4: Rate and weight for LULC classes (Secunda et al, 1998).

<table>
<thead>
<tr>
<th>Level I Classes</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation and Barren Land</td>
<td>5</td>
</tr>
<tr>
<td>Water and wet area</td>
<td>7</td>
</tr>
<tr>
<td>Urban area and agriculture land</td>
<td>8</td>
</tr>
</tbody>
</table>

Weight=5

3.4 Effect of Lineament density map on DRASTIC model

The lineament can be defined as linear features of a landscape identified with satellite images and aerial photographs; most likely it has a geological origin. Generally, lineaments are underlined by structural zone, fractured zone, a series of faults or fold-aligned hills zone of localized weathering and zone of increased permeability and porosity.
Lineament distribution of HSB prepared from image of landsat 8 Thematic Mapper (TM). Images consist of nine spectral bands of cell size (30x30 m). The Operational Land Imager (OLI) spectral band of gray scale was used. Nearly, scene size is 170 km north-south by 183 km east-west and the date back to (11-02-2013). Figure (11) illustrates the TM landsat image of the study basin of extracted lineament distribution.

A lineament distribution of the site was extracted using PCI Geomatica technique. The lineament extraction algorithm of PCI Geomatica software consists of edge detection, thresholding and curve extraction steps (PCI Geomatica, 2001). Figure (12) illustrates the final lineament distribution of HSB extracted from the above mentioned satellite image.

Furthermore, the lineament density map was constructed using line density of the spatial analysis tool of Arc Map 10. This tool calculates the magnitude per unit area from polyline features that fall within a radius around each cell. Higher intensity of lineament feature may increase the probability of contaminant movement toward groundwater.

**Figure 11:** TM landsat 8 image (2013) of HSB. **Figure 12:** Extracted lineament map of HSB with extracted lineament

In HSB area most of the aquifers that are surrounding the basin were developed in fractured rock, so groundwater mostly moves through the fracture of these rocks. In addition, there are many linear features that appear in the alluvial deposits as a result of effective against zone of increasing porosity and permeability. So, lineament density measured as a main parameter with DRASTIC model to assess groundwater vulnerability more precisely. The lineament density map as shown in figure 28 had been rated and weighted. The calculated lineament density was assigned ranges and rating based on table 5. The weight of lineament density was assigned a value based on its valuable significance and it is measured as (5), (Al-Rawabdeh et al, 2013 and Al-Rawabdeh et
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Therefore, lineament index map constructed by multiplying the mentioned weight to the rated lineament map using map algebra tool of Arc map 10 software.

To modify likely risk of groundwater vulnerability an additional parameter that can be added into the original DRASTIC model to show the realistic of vulnerability assessment. In this study, Lineament map was used because of its close relationship of groundwater. In addition, previous studies revealed that there is a close relation between lineament and groundwater yield and flow, (Lattman and Parizek ,1964). Therefore, Lineament indexes map as additional parameter was added to the standard DRASTIC model based on equation (8) (Al-Rawabdeh et al, 2014). The result demonstrates the effect of lineament concentration on the vulnerability system.

\[ DL(i) = DI + (\text{Lineament density Index}) \ldots \ldots (8) \]

Where: \( DL \) is the modified DRASTIC model based on density of lineament; \( DI \) is the standard DRASTIC index and the Lineament density index (ratings•weights).

Table 5:

<table>
<thead>
<tr>
<th>Range of lineament density</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2-1.1</td>
<td>1</td>
</tr>
<tr>
<td>1.2-1.3</td>
<td>2</td>
</tr>
<tr>
<td>1.4-1.5</td>
<td>3</td>
</tr>
<tr>
<td>1.5-1.8</td>
<td>4</td>
</tr>
<tr>
<td>1.9-2.0</td>
<td>5</td>
</tr>
<tr>
<td>2.1-2.2</td>
<td>6</td>
</tr>
<tr>
<td>2.3-2.4</td>
<td>7</td>
</tr>
<tr>
<td>2.5-2.6</td>
<td>8</td>
</tr>
<tr>
<td>2.7-2.8</td>
<td>9</td>
</tr>
<tr>
<td>2.9-4.0</td>
<td>10</td>
</tr>
</tbody>
</table>

\[ \text{Weight}=5 \]

3.5 Comparison and validation of the work

The achieved vulnerability models after standard DRASTIC model and modified DRASTIC models were compared. This comparison is required to confirm the validity of the theoretical sympathetic of current hydrogeological conditions of the study area. In addition, each vulnerability map should be validated after its construction in order to estimate the validity of the theoretical sympathetic of current hydrogeological conditions (Bruyere et al, 2001, Perrin et al, 2004 and Zwahlen, 2004). Several methods can be applied for the validation of vulnerability assessments (Zwahlen, 2004). These include hydrographs, chemographs and tracers (natural or artificial). In order to validate both applied models at HSB, nitrate concentration analysis was selected. Nitrate as a pollution indicator can be used to recognize the groundwater quality evolution in terms of quality changing. In this particular study, the nitrate differences between two following seasons (dry and wet) were analyzed from (39) watering wells, (Figures 13a and 13b). The samples were collected and analyzed at the end of September 2014 for dry season and end of May 2015 for
wet season. The selected wells for nitrate concentration measurement were located nearly in all vulnerability zones at each model.

Figure 13: Sample site for nitrate concentration analysis: a) Dry season, b) Wet season.
4. Result and Discussion

This chapter presents the assessment of aquifer vulnerability and generation of vulnerability maps by integrating multiple data sets. A modification of the DRASTIC method has also been incorporated into this chapter and the results from validation of all methods of the computed groundwater quality have been presented.

4.1. Result of standard DRASTIC model

The DRASTIC parameters were entered into ArcView software in GIS environment as vector map layers. The ratings and weights were assigned to the DRASTIC parameters, as given by Aller et al. (1987). The ratings for all DRASTIC parameters were subsequently added to obtain the total cell rating. For all parameters, the maps illustrate a rating variation on 1-10.

The depth of groundwater maps for the study area for spring seasons was prepared because this season to be more critical with respect to the groundwater vulnerability (as the water table is shallowest), the waters table map for this period was considered. The depth of groundwater was classified according to DRASTIC rating (Table 3) and the final maps for the study area was generated (Figure 14). This map shows ten rating classes (1 to 10) based on depth to water table. The shallowest water table has been observed in the southwestern and central parts of the study area, resulting in maximum potential for groundwater pollution with high scores (10). The deeper water table, which has a rating of 1, has been observed in a very large portion of the study area especially in the mountain ranges from the northern, northeastern part of the study area. In addition, the depth to water table from 1.5 to 30 m having rating of 9 to 2, are only present in the central part of the study area.

The principal source of groundwater is precipitation, which infiltrates into the strata of the ground and percolates to the water table. Return flow from irrigation also adds up to the groundwater recharge. “Net recharges” are to represent the total quantity of water, which is applied to the ground surface and infiltrates to reach the aquifer. It includes the average annual amount of infiltration and does not take into consideration distribution, intensity or duration of recharge events. The recharge is important because it is a principal vehicle for leaching and transporting solid or liquid contaminants to the water table. Therefore, greater the recharge, higher is the potential for pollution. The net recharges were assigned a weight “4” in the DRASTIC method (Table 3). The reclassification of the net recharges map, prepared earlier (refer section 3.1.2), (Figure 7), was done according to the DRASTIC rating (Table 3).
Figure 14: Rating map of depth to groundwater (D-map).

Figure 15: Rating map of Net recharge (R-map).
The map for net recharges (Figure 15) shows five rating classes (1, 3, 6, 8 and 9). The highest score (9) corresponds to the northeastern and northwestern part, which related to the type of geological strata (Karstic Aquifer). This type of aquifer is characterized by presence of karst and fractures which leads to transport a high amount of precipitation toward groundwater. Middle net recharges have also been observed in the central part of the study area, rating as 6. The lowest score of 1 has been observed in few parts scattered over the entire study area, including center of cities and districts, due to most of these area are covered by asphalt and concrete and prevent the movement of precipitation water downwards.

Aquifer media refers to the consolidated or unconsolidated medium which serves as an aquifer, such as sand and gravel or limestone (Aller et al., 1987). This parameter was assigned a weight “3” in the DRASTIC method (Table 3). The geological description of the study area (refer section 1.2.1) indicates that there are four types of aquifer namely (sandy or silty deposits, compacted cherty limestone, alluvial deposits and Karstic or fissured limestone), having a rating of 3, 5, 6 and 9 respectively (Figure 16). The most part of study area is karstic or fissured limestone with rating of “9”, situated in the northeastern and northwestern part, which have significant potential for groundwater contamination. Alluvial deposits with rating value of 6 come in the second order and covered most of the central part of the study area.

![Figure 16: Rating map of Aquifer media (A-map).](image)

The soil has a noteworthy impact on the quantity of groundwater recharge; and then influences the ability of pollutants to move vertically into the vadose zone. Furthermore, where the soil zone is quite thick, the attenuation processes of filtration, biodegradation, sorption and volatilization may be quite significant. This parameter was assigned a weight “2” in the DRASTIC method (Table 3). The reclassification of soil map prepared earlier (refer section 3.1.4) was done
according to the DRASTIC rating (Table 3). The Soil map (Figure 17) shows three rating classes (4, 7 and 10). The high score “10” is seen to correspond to the area of thin or absence of soil, this type of soil generally located in the mountain ranges. The Lower score “4” represents the other parts of the study area, where the soil is silty loam and is situated in the central part. While the rating value of 7 represents the area with shrinking and/or aggregated clay, which cover a small area in the southwestern part of the study area.

Figure 17: Rating map of Soil media (S-map).

Topography refers to the slope and slope variability of the land surface. Topography facilitates controlling the probability that a pollutant will run off or remain on the surface in an area long enough to infiltrate. In the DRASTIC outline, the topography parameter was assigned a weight “1”. The reclassification of the slope map prepared earlier (refer section 3.1.5), was done according to the DRASTIC ratings (Table 3), and the layer for this parameter was generated. The area having rating value of 1,3,59 and 10. The topography map (Figure 18) indicates that the slope distribution of the study area is steeper along the mountain ranges and gentler in the area closed to the Derbendikhan Lake.
The type of vadose zone media determines the reduction characteristics of the material below the typical soil horizon and above the water table. This parameter was assigned a weight “5” in the DRASTIC method. Based on the geological description of the study area (refer section 1.2.1), vadose zone has been observed to consist of three segments comprised (sand and gravel, sandstone and cherty limestone, fissured or karst limestone) occupying areas of 35%, 24% and 41% respectively. The constructed map with organized different rates of vadose zone 4, 5 and 8 respectively, was then converted to raster format as shown in figure (19).

Hydraulic conductivity refers to the ability of the aquifer material to transmit water, which controls the rate at which groundwater would flow under a given hydraulic gradient. In the DRASTIC method this parameter was assigned a weight “3”. On the basis of the hydraulic conductivity map prepared earlier (refer section 3.1.7), two classes of conductivity rating were achieved (1 and 4) as shown in figure (20). Its values within the study area exceed less than 4 m/day and 12-30 m/day respectively.
The process of combination of all the above mentioned layers and computation of DRASTIC index has been graphically presented in figure 21. The standard DRASTIC vulnerability model of HSB consists of four vulnerability classes including: very low, low, moderate and high vulnerability index. The map illustrates the supremacy over moderate and very low vulnerability zones which covers an area of 614 and 435 Km² or (48% and 34%) of the whole studied area respectively. Geological and hydrogeological conditions control the vulnerability system, moderate vulnerability zone occupies two different areas in terms of these conditions. The first one is the mountains surrounding the studied basin that includes the fissured and karstic aquifer. While the second area comprise the Quaternary deposits surrounding the area of Derbandikhan reservoir southwest of the basin, this might be related to the high water tables level and high percent of coarse grain material such as gravel, sand and rock fragment. Additionally, the zone with low vulnerability is considered as the third class in terms of spreading and occupy 166 km² or 13% of the overall surface area of the basin. The zone with high vulnerability indexes cover only 64 km² or 5% of the total area and is located in the center of the basin. This area is characterized by high water table level and presence of several springs with fractured limestone which help to transport contaminant more easily.
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Figure 20: Rating map of Hydraulic conductivity (C-map).

Figure 21: Standard DRASTIC Map for HSB.
4.2. Result of Rate and weight modification of DRASTIC model

The Pearson’s Correlation Coefficient was applied to standard DRASTIC model (McCallister, 2015) to calculate the relation between standard DRASTIC indexes value and nitrate concentration. This correlation factor refers to linear correlation between two variables. The outcome was 43% that is fairly low (Table 9). This means that the intrinsic vulnerability indexes require to be modified to illustrate a realistic evaluation of the contamination potential for the studied basin. Therefore, nitrate concentration on 39 sampled points was used on the five maps of standard DRASTIC method separately including DRATSIC maps. The nitrate concentration values and DRASTIC rate at each map were measured and then the mean of nitrate values calculated at each range of rate. Based on the Wilcoxon rank-sum nonparametric statistical test, the modified rate of (DRASTIC) parameters was defined. Table 6 shows the modified rate of DRASTIC layers based on the nitrate concentration.

Figure 22 demonstrates the new modified DRASTIC map depending on the new rating (refer section 3.2.1). It shows that 15% and 29% of the area fall in the moderate and very low vulnerability zone respectively. These percentages were 48% and 34% respectively before the modification. The calculated area was 15% for low and 38% for high vulnerability class while before the modification it was 13% and 5% respectively. In addition, very high vulnerability zone was recognized that covers 3% of the study basin. To show the spatial distribution of the index before and after the modification, the two maps were compared. The result showed that 15% had similar classes, while 85% showed a difference in one class or more, indicating the effectiveness of the proposed method. The result of Pearson’s Correlation Coefficient confirms this effectiveness, because for rate modified DRASTIC map is (69%), (table 9) which is significantly higher than the standard one (43%).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range</th>
<th>Standard rating</th>
<th>Mean nitrate concentration (mg/L)</th>
<th>Modified Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to water table</td>
<td>0-1.5</td>
<td>10</td>
<td>31</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>1.5-4.5</td>
<td>9</td>
<td>27.6</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>4.5-7.5</td>
<td>8</td>
<td>11.2</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>7.5-10</td>
<td>7</td>
<td>10</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>10-12.5</td>
<td>6</td>
<td>No Data</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>12.5-15</td>
<td>5</td>
<td>No Data</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>15-19</td>
<td>4</td>
<td>7.5</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>19-23</td>
<td>3</td>
<td>5.83</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>23-30</td>
<td>2</td>
<td>No Data</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>&gt;30</td>
<td>1</td>
<td>1.45</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>&lt; 50</td>
<td>1</td>
<td>No Data</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>50-100</td>
<td>3</td>
<td>1.6</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>100-175</td>
<td>6</td>
<td>1.8</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>175-250</td>
<td>8</td>
<td>18.5</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>&gt;250</td>
<td>9</td>
<td>No Data</td>
<td>10.0</td>
</tr>
<tr>
<td>Net Recharge</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil Media</td>
<td>Clay loam with rock fragment</td>
<td>4</td>
<td>1.6</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Silty loam Sandy loam</td>
<td>7</td>
<td>No Data</td>
<td>7.0</td>
</tr>
</tbody>
</table>
New effective weighting factors were obtained using the standard DRASTIC map and then sensitivity analysis was applied. The mean of effective weight was calculated based on the previously explained formula (refer section 3.2.2). Obviously, it can be noticed that there are some significant differences in the theoretical values proposed by Aller et al (1987) as all parameters changed from its weighting value. Because the new weighting values calculated based on the vulnerability index achieved from the specific properties of the ground in the study area, while the recommended theoretical values assumed everywhere in the world. Hydraulic conductivity designates the maximum deviation between the original and new effective weights with 53% decrease while soil media shows the highest increasing percent which is 31%. The net recharges also decreased from its weight value of only 6%. Moreover, several parameters illustrated an increase in the effective weight value including: depth to water, aquifer media, topography and impact of the vadose zone with increasing percentage of 3%, 12%, 3% and 12% respectively. Figure
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23 shows the weight modified DRASTIC map using the computed effective weights. The results are slightly different compared to the standard DARASTIC vulnerability map with four classes of vulnerability. These classes are: very low, low, moderate and high with 32%, 16%, 38% and 14% of the total area respectively. Because of the computed modified vulnerability index was based on the specific ground conditions of studied basins, so it makes these differences and the modified one is considered more reliable.

Table 7: Modified weight for standard DRASTIC based on sensitivity analysis.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Standard weight</th>
<th>Standard weight (%)</th>
<th>Effective weight (%)</th>
<th>Mean Modified weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>1</td>
<td>10.0</td>
<td>22.4</td>
<td>25.6</td>
</tr>
<tr>
<td>R</td>
<td>4</td>
<td>17.4</td>
<td>8.0</td>
<td>16.3</td>
</tr>
<tr>
<td>A</td>
<td>3</td>
<td>13.0</td>
<td>18.0</td>
<td>14.7</td>
</tr>
<tr>
<td>S</td>
<td>2</td>
<td>8.7</td>
<td>16.0</td>
<td>11.4</td>
</tr>
<tr>
<td>T</td>
<td>1</td>
<td>4.3</td>
<td>2.0</td>
<td>4.5</td>
</tr>
<tr>
<td>I</td>
<td>5</td>
<td>21.7</td>
<td>40.0</td>
<td>24.5</td>
</tr>
<tr>
<td>C</td>
<td>3</td>
<td>13.0</td>
<td>6.0</td>
<td>6.1</td>
</tr>
</tbody>
</table>

Figure 23: Effective weight (weight modified) DRASTIC map based on sensitivity analysis.

The modified rate and weight applied to the DRASTIC model to see the intrinsic vulnerability situation in the area. Both modified rate-weight results have been applied together as well to the same proposed formula (refer section 3.2). Figure 24 illustrates the modified rate-weight applied to DRASTIC model. The outcome map has great dissimilarity with the standard DRASTIC
map and fairly similar to the rate modified using nitrate concentration, with some differences in the rate of the low and very low vulnerability zone (Table 8).

![Modified DRASTIC vulnerability map](image)

**Figure 24:** Combination of rate-weight modified of DRASTIC vulnerability map.

**Table 8:** Result of DRASTIC index ratio for standard and modified maps.

<table>
<thead>
<tr>
<th>Vulnerability class</th>
<th>Standard %</th>
<th>Modified rate %</th>
<th>Modified weight %</th>
<th>Combined modification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>34</td>
<td>29</td>
<td>32</td>
<td>7</td>
</tr>
<tr>
<td>Low</td>
<td>13</td>
<td>15</td>
<td>16</td>
<td>35</td>
</tr>
<tr>
<td>Medium</td>
<td>48</td>
<td>15</td>
<td>38</td>
<td>19</td>
</tr>
<tr>
<td>High</td>
<td>5</td>
<td>38</td>
<td>14</td>
<td>35</td>
</tr>
<tr>
<td>Very high</td>
<td>---</td>
<td>3</td>
<td>---</td>
<td>4</td>
</tr>
</tbody>
</table>

Pearson’s correlation factor was calculated statistically between the Modified DRASTIC index value of all rates, weight and combined rate and weight modified methods with mean of nitrate concentration. The result tabulated in table 9 shows an increase in the correlation factor of to 72 %. According to these results, the combination of modified rate and weight method has a higher correlation factor and is recommended as the most appropriate method to be applied for the study basin.
Table 9: Pearson's Correlation factors between the standard and modified vulnerability index and nitrate concentration.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Number of data</th>
<th>Pearson’s Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard DRASTIC Index</td>
<td>39</td>
<td>43%</td>
</tr>
<tr>
<td>Modified weight DRASTIC Index</td>
<td></td>
<td>57%</td>
</tr>
<tr>
<td>Modified rate DRASTIC Index</td>
<td></td>
<td>69%</td>
</tr>
<tr>
<td>Combined modify rate and weight DRASTIC Index</td>
<td></td>
<td>72%</td>
</tr>
</tbody>
</table>

4.3. Result of Effect of Land use and land cover on DRASTIC model

The LULC map of the study basin is exposed in figure 25. This map is produced based on USGS method of classification (Bety, 2013), using remote sensing and GIS techniques from satellite landsat images (ETM+, 2010) (refer section 3.3). The map demonstrates that only five classes can be recognized as explained on table (10) with percent and the area of land covering in each.

Table 10: LULC classes type in the study basin.

<table>
<thead>
<tr>
<th>Level I Classes</th>
<th>Area _Km²</th>
<th>Area _%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>16.79</td>
<td>1.31</td>
</tr>
<tr>
<td>Agriculture</td>
<td>449.77</td>
<td>35.19</td>
</tr>
<tr>
<td>Barren Land</td>
<td>766.36</td>
<td>59.97</td>
</tr>
<tr>
<td>Vegetation</td>
<td>39.75</td>
<td>3.11</td>
</tr>
<tr>
<td>Water and wet land</td>
<td>5.33</td>
<td>0.42</td>
</tr>
</tbody>
</table>

The map illustrates that barren land covered most of the studied basin land with an area of (766.36) km² or (59.97%) of total studied area. In addition, agriculture lands cover an area of (449.77) km² or (35.19%) occupy mostly the central and northwestern parts of studied basin. The remaining classes of (vegetation, urban area and water and wet land) were covering an area of 39.75, 16.79 and 5.33 Km² or (3.11%, 1.31% and 0.42%) of the whole studied area respectively. To check the accuracy of the final LULC map several points in the field were taken with GPS in each class and matched on the map. In addition, several photos of each point were taken as well, to verify the accuracy of this classification and the result of field surveys did coincide with the theoretical classification using remote sensing. Photo (4 and 5) illustrates urban area and agriculture land as an example for checking accuracy with coordinate value of (579195,3912525 and 589644,3909281) respectively.
Figure 25: LULC map for the study basin.

The map of ratings of LULC in (Figure 26) illustrates rating of values ranging from 5 to 8 (Table 11). Urban areas and agricultural land were assigned a probability rating of 8, because chemical contaminant concentrations such as nitrogen in groundwater from human activities in urban and agriculture areas were higher than in all other land use areas (Secunda et al, 1998). Vegetation and barren land areas were combined and assigned to probability rating of 5, as they
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contain low nitrogen of nearly similar concentrations. Water body and wet land area was rated 7 (Secunda et al, 1998) as water act as a good transporter for contaminant.

Table 11: Rating value for each LULC classes type, after (Secunda et al, 1998)

<table>
<thead>
<tr>
<th>Level I Classes</th>
<th>Rating value</th>
<th>Area%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation and Barren Land</td>
<td>5</td>
<td>63.1</td>
</tr>
<tr>
<td>Water and wet area</td>
<td>7</td>
<td>0.4</td>
</tr>
<tr>
<td>Urban area and agriculture land</td>
<td>8</td>
<td>36.5</td>
</tr>
</tbody>
</table>

Additionally, it can be noted from figure (26), that the rating value of class (5) occupies most of the studied basin with 63.1% of the entire studied area. This class is located in most of the surrounding mountains and areas of high percent of pasture. Rationally, in terms of land use, these areas have the lowest effect environmentally on vulnerability aspects. Moreover, urban area and agricultural land were rated probability of 8 and occupies 36.5% of the intact studied area. This is referred to human activities in these areas compared to other land use class. Water body and wet land occupy only 0.4% of the whole area with rating value of (7).

Figure 26: LULC rating map for the study basin.

Furthermore, the LULC rating map as a raster grid was multiplied using map algebra in GIS environment by the weight of the parameters (Lw = 5) to construct LULC index map as
shown in Figure 27. The index values were classified into three classes (25, 35, and 40), which occupied (63.1%, 0.4%, and 36.5%) of the total area of studied basins respectively.

Figure 27: LULC index map for the study basin.

Figure (28) demonstrates the modified DRASTIC index map based on LULC index map with ranging of (88-221). The range of index values was divided into five classes including very low to very high vulnerability classes (Table 12).

Table 12: Modified DRASTIC index value of each class at study basin.

<table>
<thead>
<tr>
<th>Vulnerability class</th>
<th>Drastic Index</th>
<th>Area (Km²)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>88-100</td>
<td>14.95</td>
<td>1.17</td>
</tr>
<tr>
<td>Low</td>
<td>&gt;100-125</td>
<td>470.7</td>
<td>36.82</td>
</tr>
<tr>
<td>Moderate</td>
<td>&gt;125-150</td>
<td>224.51</td>
<td>17.57</td>
</tr>
<tr>
<td>High</td>
<td>&gt;150-200</td>
<td>554.85</td>
<td>43.42</td>
</tr>
<tr>
<td>Very high</td>
<td>&gt;200-221</td>
<td>12.99</td>
<td>1.02</td>
</tr>
</tbody>
</table>

The modified vulnerability map shows that about 43.42% of the study basin has high vulnerability to contamination with index values ranging between 150 to 200. Low vulnerability measured as a second effective class of the studied area with (36.82%). While, very low, moderate and very high areas comprise 1.17%, 17.57% and 1.02% respectively. In terms of land use class, agriculture and barren lands occupies most of studied basin with total area of (1216.3) Km² or 95.16% of the whole studied area. The effect of agriculture activity can be clearly noticed on the modified DRASTIC models compared to standard one, as the agriculture land plays a significant role to convert the moderate vulnerability zone in the central and north western parts to high.
vulnerability zone. In addition, both barren with agriculture lands are the main factors to rise up very low vulnerability zone to low vulnerability in the north east and south east of the study basin.

Figure 28: Modified DRASTIC Map based on LULC for the study basin.

4.4. Result of Effect of Lineament feature on DRASTIC model

The lineament density map of the study basin is exposed in figure 29. This map is produced by applying GIS techniques from lineament map extracted from satellite landsat 8 images (ETM+, 2013), (refer section 3.4). The map reveals that HSB divided in between six classes of lineament density distribution as explained on table (13) with percent and the area of land covering with each.

<table>
<thead>
<tr>
<th>Class</th>
<th>Range of lineament density distribution</th>
<th>Rating</th>
<th>Area _ Km²</th>
<th>Area _ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class-I</td>
<td>&gt;2.1-2.4</td>
<td>7</td>
<td>1.5</td>
<td>0.12</td>
</tr>
<tr>
<td>Class-II</td>
<td>&gt;1.83-2.1</td>
<td>5</td>
<td>5.4</td>
<td>0.42</td>
</tr>
<tr>
<td>Class-III</td>
<td>&gt;1.57-1.83</td>
<td>4</td>
<td>9.2</td>
<td>0.72</td>
</tr>
<tr>
<td>Class-V</td>
<td>&gt;1.3-1.57</td>
<td>3</td>
<td>23.9</td>
<td>1.87</td>
</tr>
<tr>
<td>Class-VI</td>
<td>&gt;1.05-1.3</td>
<td>2</td>
<td>72.3</td>
<td>5.66</td>
</tr>
<tr>
<td>Class-VII</td>
<td>0-1.05</td>
<td>1</td>
<td>1165.7</td>
<td>91.2</td>
</tr>
</tbody>
</table>
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Figure 29 illustrates the Lineament density map of HSB, it can be noticed that Class-VII which is characterized by low density of lineament distribution covered most of the studied basin lands with an area of (1165.7) km² or (91.2%) of total studied area. In addition, the higher lineament density range is Class-I which is occupying only 1.5 Km² or (0.12%) of the whole HSB, which is located along the mountain ranges of the northwestern portion of studied basins, coincident with major subsurface structural development along Swren Mountain namely developed thrust fault and overturned double plunging anticline as explained in the geological map (Figure 3).

The remaining classes of (Class-II, Class-III, Class-V and Class-VI) are covering an area of 5.4, 9.2, 23.9, and 72.3 Km² or (0.42%, 0.72%, 1.87% and 5.66%) of the whole studied area respectively. Furthermore, from the result mentioned above, it can be concluded that HSB is considered as relatively low lineament density.

The map of ratings lineament in (Figure 30) illustrates rating to value ranging from 1 to 7 (Table 14). Class-I was assigned a probability rating of 7 and occupies only 0.12% of HSB area, because the density range of the lineament considered as high intensity. While Class-VII assigned a probability rating of 1, as they contain low density range which is only (0-1.05).

Additionally, density ranges of classes (Class-II, Class-III, Class-V, Class-VI) were rated as (5, 4, 3 and 2) respectively and occupied (0.42, 0.72, 1.87 and 5.66) of the whole HSB area respectively.

Furthermore, the lineament density rating map as a raster grid was multiplied using map algebra in GIS environment by the weight of the parameters (Lw = 5) to construct Lineament
The index value classified into six classes as well (5,10,15,20,25 and 35).

![Figure 30: Lineament rating map for HSB.](image)

![Figure 31: Lineament index map for HSB.](image)

Figure (32) demonstrates modified DRASTIC index map based on lineament index map with ranging of (68-196). The range of index values was divided into four classes including very low to high vulnerability classes (Table 14).

![Table 14: Standard and modified DRASTIC index value based on lineament feature at HSB.](image)

<table>
<thead>
<tr>
<th>Vulnerability class</th>
<th>Standard DRASTIC</th>
<th>Modified DRASTIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Index value</td>
<td>Area (%)</td>
</tr>
<tr>
<td>Very low</td>
<td>63-100</td>
<td>34</td>
</tr>
<tr>
<td>Low</td>
<td>&gt;100-125</td>
<td>13</td>
</tr>
<tr>
<td>Moderate</td>
<td>&gt;125-150</td>
<td>48</td>
</tr>
<tr>
<td>High</td>
<td>&gt;150-191</td>
<td>5</td>
</tr>
</tbody>
</table>

The modified vulnerability map delineates that around (47%) of HSB has moderate vulnerability to pollution with index values ranging between 125 to 150. While, low vulnerability measured as a second effective class of the examined region with (29%). Furthermore, (low and high) classes to involve (14%, and %10) respectively. By comparison with Standard DRASTIC and its modification in light of lineament density factor, table 14, there is no significant variation on the index value and the occupied areas as well for classes of low and moderate, while the region of high and very low classes were slightly different. Generally, this modification can be reasoned by the
fact that lineament density has very little impact on the vulnerability demonstrated for HSB on the grounds that larger part of the examined region (about 91.2% of entire HSB area) is characterized by low lineament density distribution.

Figure 32: Modified DRASTIC lineament index Map for HSB.

4.5. Result of comparison and validation of the work

The comparison of results from the original DRASTIC and modified DRASTIC methods are given in table 15, and figure 33. The index values of standard DRASTIC and modified DRASTIC based on lineament feature are distributed among four classes, while modified DRASTIC based on rate and weight modification and LULC are distributed in five classes. The index value of standard DRASTIC and modified DRASTIC model based on lineament features to attain their peak of moderate class and then in very low class as second the highest vulnerability index range values, while modified DRASTIC based on rate and weight modification and LULC attain their peak in high class and second highest vulnerability range is in low vulnerability class. This difference is apparently because of the sensitivity in the original DRASTIC framework displayed by rate and weight modification, and the effect of land uses which is not mentioned in standard DRASTIC model as considered to be an effective parameter on DRASTIC model.
Table 15: Vulnerability classes at each model.

<table>
<thead>
<tr>
<th>Vulnerability Class</th>
<th>Index range</th>
<th>DRASTIC (%)</th>
<th>DRASTIC-rate and weight modified (%)</th>
<th>Modified DRASTIC with LULC (%)</th>
<th>Modified DRASTIC with lineament feature (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V.low</td>
<td>&lt;100</td>
<td>34</td>
<td>7</td>
<td>1.17</td>
<td>29</td>
</tr>
<tr>
<td>Low</td>
<td>&gt;100-125</td>
<td>13</td>
<td>35</td>
<td>36.82</td>
<td>14</td>
</tr>
<tr>
<td>Moderate</td>
<td>&gt;125-150</td>
<td>48</td>
<td>19</td>
<td>17.57</td>
<td>47</td>
</tr>
<tr>
<td>High</td>
<td>&gt;150-200</td>
<td>5</td>
<td>35</td>
<td>43.42</td>
<td>10</td>
</tr>
<tr>
<td>V.high</td>
<td>&gt;200</td>
<td>----</td>
<td>4</td>
<td>1.02</td>
<td>----</td>
</tr>
</tbody>
</table>

Figure 33: Comparison between vulnerability classes at each model.

Every vulnerability map should be validated after developing in order to confirm the validity of the theoretical sympathetic of current hydrogeological conditions (Bruy’ere et al, 2001; Perrin et al, 2004 and Zwahlen, 2004). For this purpose, validation between maps of standard and all type of modified DRASTIC maps was attempted in two ways. In the first approach, Pearson’s correlation factor (refer section 3.5) was calculated statistically between the standard and modified DRASTIC indexes value and mean of nitrate concentration. The result are tabulated in table 16, shows an increase in the correlation factor of 72 % and 71% for the modified DRASTIC model based on rate-weight modification and LULC respectively. While for standard and modified DRASTIC based on lineament feature, the factor was 43% and 40% respectively. According to these results, the modified rate and weight and LULC methods have a higher correlation factor and are recommended as the most appropriate methods to be applied in the study basin.
The second approach was to examine nitrate concentration analysis. Nitrate as a contamination marker can be helpful to recognize the evolution and changes of groundwater quality. In this study, the nitrate differences between two following seasons (dry and wet) were analyzed from (39) watering wells. The samples were collected and analyzed at the end of September 2014 for the dry season and at the end of May 2015 for the wet season. The selected wells for nitrate concentration measurement located approximately in all vulnerability zones at each model (Figures 35a and 35b, 36a and 36b, 37a and 37b, 38a and 38b).

The results of the analyses of the seasonal distribution of nitrate showed that during the rains (wet season), nitrate level is higher relative to the dry season (Table 17). The average of nitrate concentration on the wet season is above 30 mg/l. However, in the dry season, the value is just above 10 mg/l. This condition can be attributed to several main factors. One of these factors is rising up the water table in the wet season and vice versa for the dry season. Secondly, the impact on land uses activity is significant in the wet season, specifically using chemical contaminants (nitrate) for agriculture purpose. Finally rainfall plays an important role to transport nitrate based on specific condition of aquifer characteristics. Consequently, these considerable variations in nitrate concentration of the dry to wet seasons verify the suitability of applying vulnerability system in HSB. Figure (34) illustrates the comparison between each model with nitrate concentration in both seasons. The results show a better match of the rate and weight modification of DRASTIC model and the modified DRASTIC based on LULC with increasing from nitrate concentration of dry to wet season. With increasing nitrate concentration the vulnerability rates increased as well. Therefore, these considerable variations in the nitrate concentration on dry to wet seasons, verify the sensibility of the gradation and distribution of vulnerability levels acquired using both mentioned models. While, vulnerability levels achieved using standard DRASTIC and modified DRASTIC based on lineament methods can not be considered as a real vulnerability condition in HSB. This results confirm that land use pattern and human activity are considered being the most effective factors to express the real vulnerability system and these parameters are not included in the standard DRASTIC model. In addition, lineament feature has no effect on the vulnerability system in HSB as a result of its low density percentages.

### Table 16: Pearson’s Correlation factors.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Number of data</th>
<th>Pearson’s Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard DRASTIC Index</td>
<td>39</td>
<td>43%</td>
</tr>
<tr>
<td>Modified rate and weight DRASTIC Index</td>
<td></td>
<td>72%</td>
</tr>
<tr>
<td>Modified DRASTIC Index-LULC</td>
<td></td>
<td>71%</td>
</tr>
<tr>
<td>Modified DRASTIC Index-Lineament</td>
<td></td>
<td>40%</td>
</tr>
</tbody>
</table>

Table (17) Seasonal distribution of nitrate concentration at each Vulnerability class.

<table>
<thead>
<tr>
<th>Vulnerability Model</th>
<th>Nitrate concentration-Dry season (mg/l)</th>
<th>Nitrate concentration-Wet season (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V.low</td>
<td>Low</td>
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<tr>
<td>Standard DRASTIC</td>
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<td>2-4</td>
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<tr>
<td>Rate-Weight modified</td>
<td>0-2</td>
<td>&gt;10</td>
</tr>
<tr>
<td>LULC modified</td>
<td>N.A</td>
<td>&lt; 7</td>
</tr>
</tbody>
</table>
### Result and Discussion

<table>
<thead>
<tr>
<th>Lineament Modified</th>
<th>0-2</th>
<th>&gt;10</th>
<th>&gt;10</th>
<th>&gt;10</th>
<th>----</th>
<th>20-30</th>
<th>&gt;20</th>
<th>&gt;30</th>
<th>&gt;30</th>
<th>----</th>
</tr>
</thead>
</table>

**Figure 34:** Comparison of all models with nitrate concentration for HSB.

**Figure 35:** Standard DRASTIC model with nitrate concentration  
(a) dry season  
(b) Wet season

---

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CHAPTER 4                                  Result and Discussion

Figure 36: Rate-Weight Modified DRASTIC model with nitrate concentration
a) dry season  b) Wet season

Figure 37: Modified DRASTIC -LULC model with nitrate concentration
a) dry season  b) Wet season
Figure 38: Modified DRASTIC-Lineament model with nitrate concentration: 
a) Dry season and b) Wet season.
5. Conclusions

Potential contaminants can be found in every country, rural area and on every city block. Due to such reason, groundwater protection is significantly importance. Systematic studies have been conducted in the present work to develop an appropriate method suitable for assessment of the groundwater vulnerability of the HSB area by developing a multipurpose database in GIS environment, and by validating the developed vulnerability methods by comparing the findings with the observed water quality characteristics of the region.

To evaluate the potential vulnerability of groundwater contamination in the HSB, the standard DRASTIC index models was applied to a GIS environment. Although the DRASTIC method usually gives satisfactory results of the evaluation of groundwater intrinsic vulnerability to contamination, but it is difficult to consider these results as an accurate groundwater vulnerability evaluation. Therefore, it is necessary to calibrate and modify the original DRASTIC model in order to obtain more accurate results. Seven parameter maps were developed in a GIS environment to generate generic models and three different methods were applied separately on standard DRASTIC model to modify the generic model. The DRASTIC vulnerability index values ranged between 63 and 199.4. Based on the proposed method were recommended by Aller et al (1987) and hydrogeological field investigation, these values were reclassified into four vulnerability classes comprises (very low to high).

In the first attempt on the modified standard DRASTIC model, nitrate concentration was applied to modify the original rate proposed by Aller et al (1987) and secondly the sensitivity analysis was applied to establish the effective weight of each parameter in DRASTIC model. So both modified rate and weight were applied separately to compute a new DRASTIC model. And then, both modifications were applied together to construct the combined rate-weight modified DRASTIC map. Additionally, the sensitivity weights analysis showed that the D, A, S and I parameters had a considerable impact in the study basin. The proposed modifications might improve the DRASTIC indexes vulnerability map and groundwater quality management, specifically for the agricultural areas with the use of nitrates. The modified DRASTIC vulnerability index values ranged between (73.64 - 222.8) with five vulnerability classes comprises (very low to very high).

The second endeavor to modify standard DRASTIC model are based on the impact of human activity on the vulnerability system in HSB. For this reason LULC map was constructed and was rated and weighted as additional parameter and added to the standard DRASTIC model. The LULC map demonstrates that only five classes can be recognized including barren land, agricultural land, vegetation, urban area and wet land or water body. The modified DRASTIC vulnerability index values ranged between 88 and 221 with five vulnerability classes comprises (very low to very high) . The highly vulnerable areas constitute 43.42% of the basin and mostly are located in the central and north western of Halabja Saidsadiq basin with land use type of agriculture and barren land. This percent was only 5% before modification. The effect of agricultural activities were clearly noticed on the modified DRASTIC models relative to the standard one, as the agriculture land plays a significant role to convert the moderate vulnerability zone in the central and north west parts to high vulnerability zone. In addition both barren with agriculture lands are the main factors
to rise up very low vulnerability zone to low vulnerability in the north east and south east of the Halabja Saidsadiq basin.

The third enterprise to modify the standard DRASTIC model was based on the density of lineament feature. Lineament as linear features of a landscape may have an effective role in the vulnerability system in HSB, because of its close relationship with groundwater and act as an assistant factor to transport contaminant toward groundwater easily. Landsat Thematic Mapper (TM) was used to prepare the Lineament map. The lineament density map constructed from spatial distribution of lineament feature with the aid of GIS technique. The map demonstrates that six classes can be recognized from low to high density. Each class has specific rate and weight values based on its impact environmentally. The modified DRASTIC vulnerability index values based on the effect of lineament feature ranged between (68 and 196) with four vulnerability classes comprise (very low to high). The result of the modified DRASTIC model gives the same result as achieved by the standard one. The moderate vulnerable areas constitute (46.91%) of the basin of modified results and mostly are located in the central and north west of the HSB. This percent was 48% before modification which is considered as weak variation. High vulnerability class varied from (5%) to (10%) after modification and located in the area of mountain with high lineament density. In addition, a huge variation in the rate of vulnerability has not been seen for the remaining classes. Therefore, it could be argued that the effect of lineament density is weak on the vulnerability processes in HSB. Therefore, the standard and modified models provided nearly the same outcome as a result of low lineament density values.

The comparisons of results from the original DRASTIC and modified DRASTIC methods are given in Table 15, and Figure 33. The index values of standard DRASTIC and modified DRASTIC based on lineament feature are distributed among four classes, while modified DRASTIC based on the rate and weight modification and LULC are distributed in five classes. The index value of standard DRASTIC and modified DRASTIC model based on lineament features attains their peak in moderate class and then in very low class as seconds the highest vulnerability index range values. The modified DRASTIC based on rate and weight modification and LULC attain their peak in high class and second highest vulnerability range is in low vulnerability class. This difference is apparently because of introducing greater sensitivity in the original DRASTIC framework displayed by rate and weight modification, and the effect of land uses which is not mentioned in the standard DRASTIC models as considered being an effective parameter on DRASTIC model.

Each vulnerability map should be validated after its construction in order to estimate the validity of the theoretical sympathetic of current hydrogeological conditions and to show the accuracy of the modeled vulnerability system. Two methods were applied for the validation of the result, in the first approach, Pearson’s correlation factor was calculated statistically between the standard and the modified DRASTIC indexes value and mean of nitrate concentration. The results show that there is a good relation between modified DRASTIC index based on rate -weight modification and LULC and nitrate concentration. This relation was 72% and 71% for modified DRASTIC model based on rate -weight modification and LULC respectively. While for standard and modified DRASTIC based on lineament feature, the factor was 43% and 40% respectively. According to these results, the modified rate and weight and LULC methods have a higher correlation factor and are recommended as the most appropriate methods to be applied in the study basin.
CHAPTER 5

Conclusions

The second approach examine was the use of the nitrate concentration analysis. Nitrate as a contamination marker can be helpful to recognize the evolution and changes of groundwater quality. In this study, the nitrate differences between two following seasons (dry and wet) were analyzed from (39) watering wells. The results of the analyses of the seasonal distribution of nitrate showed that during the rains (wet season), nitrate level is higher than in the dry season. Consequently, these considerable variations in nitrate concentration of dry to wet seasons verify the suitability of applying vulnerability system in HSB. The results of the comparison between each model with nitrate concentration on both season, show better match of rate and weight modification of DRASTIC model and the modified DRASTIC based on LULC with increasing from nitrate concentration of dry to wet season, with increasing nitrate concentration the vulnerability rates increased as well. Therefore, these considerable variations in nitrate concentration on dry to wet seasons, verify the sensibility of the gradation and distribution of vulnerability levels acquired using both mentioned models. While, vulnerability levels achieved using the standard DRASTIC and modified DRASTIC based on lineament methods can not be considered as a real vulnerability condition in HSB. These results confirms that land use pattern and human activity are considered being the most effective factors to express the real vulnerability system and these parameters are not included in standard DRASTIC model. In addition, lineament feature has no effects on vulnerability system in HSB as a result of its low percentages of density.
6. Future Work

1. Applying different proposed models for vulnerability assessment in the HSB such as (COP, VLDA).
2. Correlation between DRASTIC models on one of isotopes component such Tritium (³H), to know the relationship between the age of groundwater and vulnerability performance of the aquifer.
3. Using comparison methods of the final vulnerability models which will result from various models of vulnerability assessments.
4. Selecting a suitable model for the vulnerability assessment in HSB to prevent the groundwater pollution.
7. References

References

References

References

Paper I
Groundwater assessment of Halabja Saidsadiq Basin, Kurdistan region, NE of Iraq using vulnerability mapping

Twana O. Abdullah1,2 · Salahalddin S. Ali3 · Nadhir A. Al-Ansari4

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Abstract Halabja Saidsadiq Basin is located in the northeastern part of Iraq covering an area of about 1278 km² with a population of about 190,727. Groundwater is the principal source of water in this area. Agricultural practices within the basin are widespread and located close to groundwater wells. This poses imminent threat to these resources. DRASTIC model integrated with GIS tool has been used to evaluate the groundwater vulnerability of this area. In addition, the DRASTIC model was modified using nitrate concentrations and sensitivity analysis to modify the recommended weighting value to get accurate results. The modified rates were calculated using the relations between each parameter and the nitrate concentration in the groundwater based on the Wilcoxon rank-sum non-parametric statistical test. While, to calibrate all types of modifications, the Pearson’s correlation coefficient was applied. The standard vulnerability map of the studied basin classified the basin into four zones of vulnerability index including very low (34 %), low (13 %), moderate (48 %), and high (5 %) vulnerability index, while the combined modification classified the area into five classes: very low (7 %), low (35 %), moderate (19 %), high (35 %), and very high (4 %). The results demonstrate that both modified DRASTIC rate and weight were dramatically superior to the standard model; therefore, the most appropriate method to apply is the combination of modified rate-weight.

Keywords Vulnerability · Nitrate concentration · Sensitivity analysis · Modified DRASTIC · Halabja Saidsadiq Basin

Introduction

Many regions in the world are explicitly dependent on groundwater as one of the main water resources, specifically in arid and semi-arid regions. In Halabja and Saidsadiq area which is located in the northeastern part of Iraq (see Fig. 1), groundwater plays an important role in providing water for drinking and industrial and agricultural activities (GWDS 2014). This area in the past was destroyed by army attacks by chemical weapons. In addition, some parts of the area are characterized by the lack of water projects. After 2003, the area is experiencing considerable economic development and enhanced security. Furthermore, the administrative structure of Halabja has been changed from district to governorate in March 2014; this will definitely enhance the beginning of greater economic development and advancement. In view of these changes, there is an increase in the numbers of people heading to live in this basin and its surrounding regions. This is imposing a growing demand for water which has placed substantial pressures on water resources. It should be mentioned, however, that the area has a large number of surface
water projects which are also heavily dependent on groundwater for drinking, irrigation, and industry.

According to data obtained from the Directorate of Groundwater in Sulaimani City, several thousand deep wells exist in the studied area. As a consequence, the study of the groundwater resources and its potential pollution in the area becomes a necessity. Moreover, it is worth noting that no previous studies have been conducted on this vital area in terms of contamination.

The most suitable, effective, and widely used model to assess groundwater vulnerability to a wide range of potential contaminants is DRASTIC which has been developed by the Environmental Protection Agency (EPA) of the USA to recognize the pollution potential of aquifers (Aller et al., 1987, Fritch et al., 2000; Piscopo, 2001; Neshat et al., 2013; Abdullah et al., 2015b).

In any specified area, vulnerability to contamination identifies a dimensionless index function of hydrogeological factors, anthropogenic influences, and sources of contamination (Plymale and Angle, 2002). The DRASTIC index comprises seven parameters with different rating and weighting value and is calculated based on the following equation (Aller et al., 1987):

\[ V = \sum_{i=1}^{7} (W_i \times R_i) \]  

where 
- \( V \) = index value, 
- \( W_i \) = weighting coefficient for parameter \( i \), and 
- \( R_i \) = related rating value.

DRASTIC method as designed by Aller et al. (1987) consists of seven physical parameters. The most important mappable factor that controls groundwater pollution comprises to be the depth to water (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone media (I), and hydraulic conductivity (C). These parameters are weighted from one to five based on their relative significance in contributing to the contamination potential. All rating and weighting value are explained in Table 1 based on Aller et al. (1987). The achieving index is a qualified measure of vulnerability to contamination; areas with a higher index value are more vulnerable than those with a lower index (Table 1), standard DRASTIC weight and rate after Aller et al. (1987).

Javadi et al. (2011) mentioned that in spite of its attractiveness, the DRASTIC method does have some inconvenience including the effect of regional characteristics which are not accounted and the same rating and weight values have been used everywhere. In addition, there is no regular algorithm to examine and confirm the method for an aquifer. Therefore, as recommended by Kalinski et al. (1994) and some other researchers, it is important to correlate the vulnerability index with chemical or contaminant parameters based on the specific situation in terms of man-made chemical activities.

In order to modify and correlate the precision of the vulnerability method and its applicability to the current study area, two methods counting nitrate as a chemical contaminant indicator and effective sensitivity weight have been selected. Normally, nitrate is not present in groundwater under natural conditions, so if it is present, it may indicate the movement of...
a contaminant from the surface to the ground until reaching the groundwater (Javadi et al. 2011), especially in the land dedicated to agricultural use. Consequently, this paper distinguished a first attempt for groundwater vulnerability mapping in this basin and the first attempt for modifying DRASTIC method in Kurdistan region. Therefore, modifying the DRASTIC method as a means of vulnerability assessment using nitrate concentration and sensitivity method is the main objective of this paper. Definitely, the DRASTIC computation is controlled by both associated rates and weights value so calibration of these parameters becomes a necessity. This study will, therefore, focus on calibrating both parameters to achieve a higher degree of accuracy.

Study area

Geographically, Halabja Saidsadiq Basin is located in the northeastern part of Iraq between the latitude 35° 00′ 00″ and 35° 36′ 00″ N and the longitude 45° 36′ 00″ and 46° 12′ 00″ E (Fig. 1). Ali (2007) divided this basin into two sub-basins by including Halabja-Khurmal and Saidsadiq sub-basins. The whole area of both sub-basins is about 1278 km² with population of about 190,727 in early 2015 according to the data achieved from Statistical Directorate in Sulaimaniyah. It is characterized by a distinct continental interior climate with hot summers and cold winters of the Mediterranean type with the average annual precipitation ranging from 500 to 700 mm. About 57% of the studied area is an arable area due to its suitability for agriculture. Consequently, the uses of fertilizers and pesticides are common practices, so it affects the groundwater quality (Huang et al. 2012). Normally, different types of inorganic chemical fertilizer were used in the studied area, namely sodium nitrates and chemical compounds that contain nitrogen in amide form (Statistical Directorate in Sulaimaniyah 2014). In addition, all of the municipal wastewater from the cities of Halabja and Saidsadiq and all other sub-district sites within this basin infiltrate into the groundwater every year.

Geology of the study basin

Geologically, the studied area is located within western Zagros fold-thrust belt, structurally located within the High Folded, Imbricated, and Thrust Zones (Buday and Jassim 1987; and Jassim and Guff 2006). The age of the exposed rocks in the area is from Jurassic to recent (Figs. 2 and 3). The oldest exposed rocks in the basin are Sarki and Sehkanian Formations of Jurassic age (Bellen et al. 1959). These are followed by lower and middle Jurassic rocks including Barsarin (limestone and dolomitic limestone), Naokalekan (bituminous limestone), and Sargalu (Ali 2007) Formations. The Qulqula Group
consists of two formations, the Qulqula Radiolarian Formation and the Qulqula Conglomerate Formation. The exposures of the Upper Cretaceous Kometan (Turonian) and Lower Cretaceous Balambo (Valanginian-Cenomanian) Formations are widespread in the area where they are exposed in both sub-basins. Shiranish Formation (Campanian) and Tanjero Formation are also exposed in the basin but with restricted outcrops.

Quaternary (Alluvial) deposits are the most important unit in the area in terms of hydrogeological characteristic and water supply. These sediments are deposited as debris flow on the gently sloping plains, as channel deposits, as channel margin deposits, and as overbank deposits (Ali 2007). Previous studies (e.g., Ali 2007; Baziany 2006; Baziany and Karim 2007) stated that the thickness of recent deposits is up to 150 m thick while field observations in this study had recorded thicknesses of these deposits up to nearly 300 m.

**Hydrogeology and hydrology of the study basin**

Permeability and porosity are the main principal factors in determining the potential of the area to be considered as a water-bearing aquifer. The area is characterized by at least four different hydrogeological aquifers due to the presence of different geological units. The characteristic features of the aquifers are tabulated in Table 2. The collected in the field and those listed in the archives of the groundwater department at Sulaimani show that the mountain series, which surround the basin in the northeast and southeast, are characterized by high depth of groundwater. Toward the center and the southeastern part, the groundwater level has a relatively lower depth. The movement of groundwater is usually from high elevated areas at the north and northeast and south and southeast toward southwest or generally toward the reservoir of Derbandikhan Dam (Fig. 4).
Furthermore, several rivers exist in the area, such as Sirwan, Zalm, Chaqan, Biara, Reshen, and Zmkan. All these rivers impound their water in Derbandikhan reservoir. There are several springs within the basin (see Fig. 4). These springs can be classified into three classes according to their water discharge. The first group has a discharge that is less than 10 L/S (such as Anab, Basak, Bawakochak, and 30 other springs). The second group has a discharge of 10 to 100 L/S (such as Sheramar, Qwmash, Khwrmal, and Kani Saraw), and finally, those having a water discharge more than 100 L/S (such as Garaw, Ganjan, Reshen, Sarawy Swbhan Agha, and three other springs) (Fig. 4).

**Methodology**

**Material and source of data**

The data used and their source for groundwater vulnerability mapping are presented in Table 3 and the processes explained in Fig. 5. Features were used to create the shape files with ArcMap 10 software, including the geological, hydrogeological, soil map, and hydrochemical data for the study area. The topographic map of the area was digitized and converted from a slope map into shape files. Depth to water levels was measured from several wells in the field using an electrical sounder in addition to previous records of drilled and tested wells. The thickness of the saturated zone was determined from drilled wells directly supervised by researchers for this study during field work. In addition, relevant data were added which were obtained from the Groundwater Directorate in Sulaimani and other private companies. Pumping test results of the wells within the area were used to calculate the hydraulic conductivity. “AQTESOLV” software was used in these calculations. Water samples from 39 wells from different groundwater aquifers in Halabja Saidsadiq Basin were collected in 1-L polyethylene bottles and analyzed for nitrate concentration. These samples were stored in the refrigerator until analysis to prevent deterioration and changes in water quality. The samples were analyzed by the Laboratory of the Department of Environmental Directorate of Sulaimani.

**Table 2** Type of aquifers in the study basin

<table>
<thead>
<tr>
<th>Aquifer type</th>
<th>Geological formation</th>
<th>Thickness (m)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intergranular aquifer</td>
<td>Quaternary deposits</td>
<td>More than 300</td>
<td>Authors</td>
</tr>
<tr>
<td>Fissured aquifer</td>
<td>Balambo</td>
<td>250</td>
<td>Ali 2007</td>
</tr>
<tr>
<td>Fissured-karstic Aquifer</td>
<td>Jurassic</td>
<td>200</td>
<td>Jassim and Goff 2006</td>
</tr>
<tr>
<td>Non-aquifer (Aquitard)</td>
<td>Qulpala</td>
<td>From 80 to 200</td>
<td>Goff 2006</td>
</tr>
<tr>
<td></td>
<td>Shiranish</td>
<td>More than 500</td>
<td>Jassim and Goff 2006</td>
</tr>
<tr>
<td></td>
<td>Tanjero</td>
<td>225</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2000</td>
<td></td>
</tr>
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</table>
Standard DRASTIC model

DRASTIC model applied in a GIS environment has been used to evaluate the vulnerability of the study area. This model is recommended by the US committee of Environmental Protection Agency (Aller et al. 1987). Seven parameters are used in the model (see Table 2) to represent the concept of the hydrogeological setting that includes the major geologic and hydrologic factors affecting and controlling the groundwater movement into, through, and out of an area (Aller et al. 1987). Each parameter has a specific rate and weight value in order to evaluate the intrinsic vulnerability index. In addition, Aller et al. (1987) defined the seven parameters by the short form “DRASTIC” which is used to mapping groundwater vulnerability (Tables 1 and 2). Each parameter has a rating on a scale of 1 to 10, based on functional curves. This rating is then

<table>
<thead>
<tr>
<th>Data type</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to water table</td>
<td>Archives of Groundwater Directorate in Sulaimani with data from field</td>
</tr>
<tr>
<td>Net recharge</td>
<td>Halabja Meteorological Station and water balance method</td>
</tr>
<tr>
<td>Aquifer media</td>
<td>Archives of Groundwater Directorate in Sulaimani and geological map</td>
</tr>
<tr>
<td>Soil media</td>
<td>Soil map by FAO 2001 and Berding 2003.</td>
</tr>
<tr>
<td>Topographic map</td>
<td>DEM with 30 m pixel size</td>
</tr>
<tr>
<td>Impact of vadose zone</td>
<td>Archives of Groundwater Directorate in Sulaimani</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>Archives of Groundwater Directorate in Sulaimani with data from field</td>
</tr>
</tbody>
</table>
scaled by a weighting factor from 1 to 5, according to their relative susceptibility to pollutants. The standard DRASTIC index ($DI_{w-r}$) calculated is based on the linear combination of all parameters as demonstrated by the following equation:

$$DI = DWD_r + RWR_r + AWA_r + SWS_r + TWT_r + JWI_r + CWC_r$$  \( (2) \)

where $DI$ is the DRASTIC index; $D, R, A, S, T, I,$ and $C$ are the seven parameters; $w$ is the weight parameter, and $r$ is the rate of the parameter. All the recommended rates and weight are scheduled in Table 1.

$D$ is the depth to groundwater which is described as the distance of the unsaturated zone that pollutant desires to travel through to reach the water table. For this paper, groundwater levels were measured and documented in about 1200 wells. Water table measurements were taken in May and in early June because these months are considered as the potential worst-case scenario due to the low depth of groundwater. The inverse distance weighted (IDW) were used to interpolate the data to construct the depth to water table layer as a raster format and then reclassified based on the ranges and rating recommended by Aller et al. (1987). In Halabja Saidsadiq basin, the depth to groundwater varies from zero to more than 100 m. Therefore, nine classes were used for the studied basin. These are $0–1.5, 1.5–4.5, 4.5–7.5, 7.5–10, 10–12.5, 12.5–15, 15–23, 23–30,$ and more than $30$ m.

$R$ is the net recharge which defines the amount of water that penetrates into the ground and move through the unsaturated zone to reach the water table. The net recharge was estimated from the meteorological data for the period starting from 2001 to 2002 to 2013–2014 based on the following equation which was recommended by Mehta et al. (2006):

$$NR = P - ET - R_0$$  \( (3) \)

where $NR$ is the net recharge in millimeters per year, $P$ is the annual precipitation in millimeter, $ET$ is the calculated evapotranspiration in millimeters per year, $R_0$ is the total runoff in millimeters. $P$ was calculated from the average total yearly precipitation which is about 691.16 mm/year. While $ET$ were calculated based on crop water balance method by FAO Penman Monteith method using CROPWat8.0 software (Allen et al. 2006). $R_0$ was calculated based on the Soil Conservation Service (SCS) method to estimate the total runoff for the basin. The basin was divided into several curve numbers (CN) that were recommended by Ali (2007) and then using the following equation:

$$Q = (P - 0.2S)^2 / (P + 0.8S) \text{ for } P > 0.2S$$  \( (4) \)

$$S = (25400/CN) - 254$$  \( (5) \)
where \( Q \) = accumulated runoff excess (mm), \( P \) = accumulated average monthly rainfall (mm), \( S_0 \) the annual runoff of this basin is about 169 mm and the annual net recharge for the whole basin is equal to 172.54 mm. Finally, the net recharge percent distribution over the basin and then the resulting map was converted from polygon to raster format in GIS environment.

Aquifer media (A) and the impact of the vadose zone were constructed based on the geological map of the basin and from the drilling well logs. Four sections of the aquifer media were classified in the studied basin. The rated values for each media based on Aller et al. (1987 and 1985) were illustrated as 9, 6, 5, and 3. While, three segments of the vadose zone were comprised with organized rating values of 4, 5, and 8. \( S \) is the soil media (texture and type) which defines the ability of a pollutant to move vertically into the vadose zone (Lee 2003). Three different soil media were found in the area based on the soil map proposed by FAO (2001) and Beardin (2003) including silty loam, shrinking, and/or aggregated clay and thin or absent with ratings of 4, 7, and 10, respectively.

\( T \) map refers to the topographic map that describes the slope of the surface area. The pollutants are remaining for a long period over an area with a low percent of slope value and vice versa (Hernandez et al. 2004). This map was constructed from the digital elevation model (DEM) with a pixel size of 30 m, and the slope aspect was then calculated from it in ArcGIS 10. The topography of the area was classified into five classes ranging as 0–2, 2–6, 6–12, 12–18, and more than 18 %. Hydraulic conductivity \( (C) \) describes the ability of the aquifer material to transmit water through it, and contaminant migration is controlled by the permeability of the media (Harnamn 2011). The hydraulic conductivity map was constructed by employing the pumping test result of about 10 wells. The pumping test data were analyzed using AQTESOL 4.0 software to determine the transmissivity of the aquifer, and then, Eq. (6) was used to calculate the hydraulic conductivity:

\[
C = \frac{T}{b}
\]

where \( C \) is the hydraulic conductivity (m/day), \( T \) is the transmissivity (m²/day), and \( b \) is the aquifer saturated thickness (m). The area with high hydraulic conductivity revealed a higher chance of distributing pollutants. Two classes of conductivity rating were achieved. After generating all the required layers, each pixel was classified and rated then multiplied by their respective weighting factor and the DRASTIC index was determined. The final index obtained was divided into several groups as proposed by Aller et al. (1987). A small value designated low vulnerability potential while a large value represents areas that have high vulnerability potential.

Modification of the DRASTIC model

Using nitrate concentration

Due to fact that the study area is characterized by an active agricultural exertion, nitrate concentration was used to modify the standard DRASTIC method for the studied basin. Sampling and analysis for nitrate concentration were carried out for 39 groundwater samples in two different seasons, the samples were collected and analyzed at the end of September 2014 for dry season and end of May 2015 for wet season. The May 2015 samples were used to modify the model, while the variation in nitrate concentration from dry to wet season was used to validate the model. Figure 6 illustrates the location of the sampled wells where GPS technique was used to get the precise location of each well.

Normally, nitrate infiltrates from the surface toward the groundwater, so it was used as the primary control parameter for contamination. The genuine condition of the area can be established for the vulnerability index by using nitrate as an indicator. Panagopoulos et al. (2006) and Neshat et al. (2014) proposed that the rates and weights can be optimized but the following conditions should be satisfied: the agricultural activities should be the only source of nitrate concentration on the surface, and nitrate reaching to the groundwater should be due to recharges from the surface over a long period.

In this method, the rates of five maps of DRASTIC method were modified according to the mean nitrate concentration including depth to water table, net recharge, soil media, impact of vadose zone, and hydraulic conductivity, while both aquifer media and topography were kept the same. The Wilcoxon rank-sum non-parametric statistical test (Neshat et al. 2013) was used to compute the modified rate of each parameter in the DRASTIC method. The highest and lowest rates were allocated to the highest and lowest mean nitrate concentrations, respectively, and the residual rates were modified linearly (Wilcoxon 1945 cited in Neshat et al. 2013). In addition, if there is no data for mean concentration of nitrate in each class, the standard rate of the DRASTIC method was used. The new maps were designed using the new modified rating system for each parameter in the DRASTIC model.

Using sensitivity analysis

As illustrated by Babiker et al. (2005), the weights used to calculate the vulnerability index might be changed based on the different geological and hydrogeological conditions of the study area. Sensitivity analysis evaluates the effective weights of each parameter and compares it with their original weights. The effective weight is the function of the value of a single parameter as well as the weight assigned to it by the DRASTIC model (Babiker et al. 2005). The impact of each parameter in the index computation was assessed by achieving
a sensitivity analysis. Equation (7) was used to calculate the effective weight of each parameter (Javadi et al. 2011).

\[
W = \left( \frac{PrPw}{V} \right) \times 100
\]  

(7)

where \( W \) is the effective weight of each parameter, \( Pr \) is the rating value and \( Pw \) is the weight value of each parameter, and \( V \) is the overall vulnerability index.

**Result and discussion**

**Assessment of standard and modified vulnerability mapping**

Figure 7 shows the original vulnerability map of the studied basin with four zones of vulnerability index. These are very low, low, moderate, and high vulnerability index. The map obviously illustrates the dominance of moderate and very low vulnerability zones which covers an area of 614 and 435 km\(^2\) or 48 and 34 % of the whole studied area, respectively. The moderate vulnerability zone occupies two different areas in terms of geological and hydrogeological conditions. The first is the area of mountains surrounding the studied basin which comprises the fissured and karstic aquifer. While the second area comprises the Quaternary deposits surrounding the area of Derbandikhan reservoir in the southwest of the basin, this might be related to the high water table level and high percentage of coarse grain material such as gravel, sand, and rock fragment. Furthermore, the zone with low vulnerability comes in the third sequence and occupies 166 km\(^2\) or 13 % of the overall surface area of the basin. The zone with a high vulnerability index covers only 64 km\(^2\) or 5 % of the total area and is located in the center of basin. This area is characterized by a high water table level and the presence of several springs with fractured limestone.
The Pearson’s correlation coefficient applied (McCallister 2015) to calculate the relation between standard DRASTIC index value and nitrate concentration, this correlation factor refers to linear correlation between two variables. The outcome was 43% that is fairly low (Table 4). This means that the intrinsic vulnerability index requires to be modified to illustrate a realistic evaluation of the contamination potential in the studied basin. Therefore, nitrate concentration from 39 sampled points was used on the five maps of standard DRASTIC method separately including DRASTIC maps. The nitrate concentration value and DRSIC rate at each map were measured and then the mean of nitrate value calculated at each range of rate. Based on the Wilcoxon rank-sum non-parametric statistical test, the modified rate of DRSIC parameters were defined. Table 4 shows the modified rate of DRSIC layers based on the nitrate concentration.

Figure 8 exemplifies the new modified DRASTIC map depending on the new rating. It shows that 15 and 29% of the area fall in the moderate and very low vulnerability zone, respectively. These percentages were 48 and 34%, respectively, before the modification. The calculated area was 15% for low and 38% for high vulnerability class while before the modification, it was 13 and 5%, respectively. In addition, a very high vulnerability zone was recognized that covers 3% of the study basin. To show the spatial distribution of the index before and after the modification, the two maps were compared. The result showed that 15% had similar classes, while 85% showed a difference of one class or more, indicating the effectiveness of the proposed method. The result of Pearson’s correlation coefficient confirms this effectiveness because rate modified DRASTIC map is 69% which is significantly higher than the standard one which is equal to 43%.
Assessment of vulnerability based on sensitivity analysis

New effective weighting factors were obtained using the standard DRASTIC map and then sensitivity analysis was applied. The mean of effective weight calculated based on the previously explained formula number (Eq. (7)) and are presented in Table 5. Obviously, it can be noticed that there are some significant differences from the theoretical values proposed by Aller et al. (1987) as all parameters changed in its weighting value because the new weighting values calculated are based on the vulnerability index achieved from the specific properties of the ground in the study area while the recommended theoretical values are assumed everywhere in the world. Hydraulic conductivity designates the maximum deviation between the original and new effective weights with 53% decrease while soil media shows the highest increasing percent which is 31%. The net recharge also decreased in its weight value with only 6%. Moreover, several parameters illustrated an increase in the effective weight value including depth to water, aquifer media, topography, and impact of the vadose zone with increasing percentage of 3, 12, 3, and 12%, respectively. Figure 9 shows the weight-modified DRASTIC map using the computed effective weights. The results are slightly different compared to the standard DRASTIC vulnerability map with four classes of vulnerability. These classes are very low, low, moderate, and high with 32, 16, 38, and 14% of the total area, respectively. Because of computed modified vulnerability index based on the specific ground conditions of studied basin, it makes these differences and the modified one more reliable.

**Combination of rate and weight modification**

The rates and weights of the variables used were modified as explained in sub-sections “Using nitrate concentration” and “Using sensitivity analysis” using both nitrate concentration and sensitivity analysis methods. The modified rate and weight applied to the DRASTIC model to see the intrinsic vulnerability situation in the area. Both modified rate-weight results have been applied together as well in the same proposed formula in Eq. (2). Figure 10 illustrates the modified rate-weight applied to the DRASTIC model. The outcome

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range</th>
<th>Standard rating</th>
<th>Mean nitrate concentration (mg/L)</th>
<th>Modified rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to water table</td>
<td>0–1.5</td>
<td>10</td>
<td>31</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>1.5–4.5</td>
<td>9</td>
<td>27.6</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>4.5–7.5</td>
<td>8</td>
<td>11.2</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>7.5–10</td>
<td>7</td>
<td>10</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>10–12.5</td>
<td>6</td>
<td>No data</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>12.5–15</td>
<td>5</td>
<td>No data</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>15–19</td>
<td>4</td>
<td>7.5</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>19–23</td>
<td>3</td>
<td>5.83</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>23–30</td>
<td>2</td>
<td>No data</td>
<td>2.0</td>
</tr>
<tr>
<td>Net recharge</td>
<td>&lt; 50</td>
<td>1</td>
<td>No data</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>50–100</td>
<td>3</td>
<td>1.6</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>100–175</td>
<td>6</td>
<td>1.8</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>175–250</td>
<td>8</td>
<td>18.5</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>&gt;250</td>
<td>9</td>
<td>No data</td>
<td>10.0</td>
</tr>
<tr>
<td>Soil media</td>
<td>Clay loam with rock fragment</td>
<td>4</td>
<td>1.6</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Silty loam</td>
<td>7</td>
<td>No data</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>Sandy loam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thin or absent</td>
<td>10</td>
<td>17.7</td>
<td>10.0</td>
</tr>
<tr>
<td>Impact of vadose zone</td>
<td>Sand and gravel with clay</td>
<td>4</td>
<td>1.3</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>Limestone with bedded claystone</td>
<td>5</td>
<td>2</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>Limestone</td>
<td>8</td>
<td>18.5</td>
<td>10.0</td>
</tr>
<tr>
<td>Hydraulic Conductivity</td>
<td>0–4</td>
<td>1</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>12–30</td>
<td>4</td>
<td>16.55</td>
<td>10.0</td>
</tr>
</tbody>
</table>
map has great dissimilarity with the standard DRASTIC map and fairly similar to the rate modified using nitrate concentration with some differences in the rate of the low and very low vulnerability zone.

Comparison of modified methods

Pearson’s correlation factor

Pearson’s correlation factor was calculated statistically between the modified DRASTIC index value for all suggested types of modified methods and mean of nitrate concentration. The result tabulated in Table 6 shows an increase in the correlation factor up to 72 %. According to these results, the combination of modified rate and weight method has a higher correlation factor and is recommended as the most appropriate method to be applied in the study basin.

Dry-wet seasons variation in nitrate

Every vulnerability map should be validated after construction in order to estimate the validity of the theoretical sympathetic of current hydrogeological conditions (Perrin et al. 2004 cited in Abdullah et al. 2015a). Several methods can be applied for the validation of vulnerability assessments (Zwahlen 2004); these include hydrographs, chemographs, and tracers (natural or artificial). In order to validate both applied models at Halabja Saidsadiq Basin (HSB), nitrate concentration analysis has been selected. Nitrate as a pollution indicator can be helpful to recognize the evolution and changes of groundwater quality. In the particular studied case, the nitrate differences between two following seasons (dry and wet) were analyzed from (39) groundwater samples. The samples were collected and analyzed at the end of September 2014 for dry season and end of May 2015 for wet season. The selected wells for nitrate
concentration measurement are located nearly in all vulnerability zones at each model.

In relation to nitrate values for dry season (absence of rainfall for a long period) (Table 7), low nitrate levels were identified with concentration values ranging between 0 and just above 10 mg/L. While for wet season which is characterized by a period of high rainfall, the nitrate concentration extremely rose up in all samples. For achieved standard

![Fig. 9](image)

**Table 5** Modified weight for standard DRASTIC based on sensitivity analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Standard weight</th>
<th>Standard weight (%)</th>
<th>Effective weight (%)</th>
<th>Mean modified weight</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>D</strong></td>
<td>5</td>
<td>21.7</td>
<td>10.0</td>
<td>22.4</td>
</tr>
<tr>
<td><strong>R</strong></td>
<td>4</td>
<td>17.4</td>
<td>8.0</td>
<td>16.3</td>
</tr>
<tr>
<td><strong>A</strong></td>
<td>3</td>
<td>13.0</td>
<td>18.0</td>
<td>14.7</td>
</tr>
<tr>
<td><strong>S</strong></td>
<td>2</td>
<td>8.7</td>
<td>16.0</td>
<td>11.4</td>
</tr>
<tr>
<td><strong>T</strong></td>
<td>1</td>
<td>4.3</td>
<td>2.0</td>
<td>4.5</td>
</tr>
<tr>
<td><strong>I</strong></td>
<td>5</td>
<td>21.7</td>
<td>40.0</td>
<td>24.5</td>
</tr>
<tr>
<td><strong>C</strong></td>
<td>3</td>
<td>13.0</td>
<td>6.0</td>
<td>6.1</td>
</tr>
</tbody>
</table>

**Fig. 9** Effective weight (weight modified) DRASTIC map based on sensitivity analysis
DRASTIC vulnerability classes, namely very low, low, moderate, and high, the averages of nitrate concentration in dry season were <2, 2–4, >10, and >10 mg/L, respectively, while in wet season, the concentration significantly rose up (0–20, 20–30, >30, and >30 mg/L), respectively. This condition refers to several main factors such as rising up the water table in the wet season and vice versa for the dry season. Secondly, the impact of land use activity is significant in wet season specifically using chemical contaminants (nitrate) for agriculture purpose. Finally, rainfall plays an important role to transport nitrate based on specific condition of aquifer characteristics. Consequently, these considerable variations in nitrate concentration from dry to wet seasons verify the suitability of applying this model in HSB.

Furthermore, nitrate concentration again applied in verification for modified DRASTIC model. Vulnerability classes realized by this model in HSB were very low, low, moderate, high, and very high. The low and high classes covered a significant portion of the area of HSB. The average of nitrate concentration in dry season was >10 mg/L for both classes. Whereas, for wet season, the concentrations considerably rose up (>30 mg/L) for each class. Therefore, these considerable variations in nitrate concentration from dry to wet seasons verify the sensibility of the gradation and distribution of vulnerability levels acquired using the modified DRASTIC model (Fig. 11).

Table 6  Pearson’s correlation factors between the standard and modified vulnerability index and nitrate concentration

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Number of data</th>
<th>Pearson’s correlation coefficient (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard DRASTIC index</td>
<td>39</td>
<td>43</td>
</tr>
<tr>
<td>Modified weight DRASTIC index</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>Modified rate DRASTIC index</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>Combined modify rate and weight</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>DRASTIC index</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Conclusion

Both standard and modified DRASTIC index models were applied in GIS environment to assess the potential vulnerability of groundwater contamination in the Halabja Saidaq Basin. Seven parameter maps were developed in a GIS environment to generate standard models, and the modification was applied in several phases. Standard DRASTIC method gave acceptable results in the assessment of intrinsic vulnerability of groundwater to pollution, but it is difficult to consider these results as an accurate groundwater vulnerability evaluation. In addition, the results of low Pearson’s correlation factor with the nitrate concentration (43 %) proved that standard DRASTIC model needs to be calibrated. Firstly, nitrate concentration applied to modify the original rate proposed by Aller et al. (1987), and secondly, the sensitivity analysis was applied to establish the effective weight of each parameter in DRASTIC model. So both modified rate and weight were applied separately to compute a new DRASTIC model. And then, both modifications applied together to construct the combined rate-weight modified the DRASTIC map. The proposed modifications might improve the DRASTIC index vulnerability map and groundwater quality management, specifically for the agricultural areas with the use of nitrates. The DRASTIC vulnerability index values ranged between 63–191, 67.5–223, 68–199.4, and 73.64–222.8 for the standard, modified rate, modified weight, and combined modification, respectively, and the percentage rate of each class is explained in the Table 8.

Pearson’s correlation factor showed that there is a good relation between the modified DRASTIC index and nitrate concentration which were 69, 57, and 72 % for modified (rate using nitrate), weight (sensitivity analysis), and combined rate-weight methods, respectively. The factor value of all types of modifications was higher than the standard one which is (43 %). On the other hand, the considerable variations in nitrate concentration from dry to wet seasons verify the sensitivity of the gradation and distribution of vulnerability levels acquired using the modified DRASTIC model (Fig. 11). So these two factors confirmed that the combined rate-weight modification is the most appropriate method to apply in the studied basin.

Nitrate concentration classified the area into five classes (0–2, 2.01–4, 4.01–7, 7.01–10, and more than 10 mg/L). The very high, high, and moderate vulnerable zones were characterized by a high percentage of nitrate concentration as they are situated in more than 10 mg/L class, this is definitely related to extensive agriculture activity and closeness to the wastewater discharges as well, while zones of very low and low situated in classes of 0–2 and 2–4, respectively. Apart from the mountain area which utility of nitrate is impossible so the nitrate analysis samples had not been collected and the same standard rate value was used. Finally, the results confirmed that the modified DRASTIC was significantly more sensible than the standard method.

Table 7 Mean nitrate concentration in both dry and wet seasons at each vulnerability class

<table>
<thead>
<tr>
<th>Standard DRASTIC vulnerability category</th>
<th>Mean nitrate concentration (mg/L)</th>
<th>Rate-weight modified DRASTIC vulnerability category</th>
<th>Mean nitrate concentration (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry season</td>
<td>Wet Season</td>
<td>Dry season</td>
</tr>
<tr>
<td></td>
<td>Very low</td>
<td>0–20</td>
<td>Very low</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>2–4</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>&gt;10</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>&gt;10</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Very high</td>
</tr>
</tbody>
</table>

Table 8 Result of DRASTIC index ratio for standard and modified maps

<table>
<thead>
<tr>
<th>Vulnerability class</th>
<th>Standard (%)</th>
<th>Modified rate (%)</th>
<th>Modified weight (%)</th>
<th>Combined modification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>34</td>
<td>29</td>
<td>32</td>
<td>7</td>
</tr>
<tr>
<td>Low</td>
<td>13</td>
<td>15</td>
<td>16</td>
<td>35</td>
</tr>
<tr>
<td>Medium</td>
<td>48</td>
<td>15</td>
<td>38</td>
<td>19</td>
</tr>
<tr>
<td>High</td>
<td>5</td>
<td>38</td>
<td>14</td>
<td>35</td>
</tr>
<tr>
<td>Very high</td>
<td>—</td>
<td>3</td>
<td>—</td>
<td>4</td>
</tr>
</tbody>
</table>

Fig. 11 Comparison of both models with mean nitrate concentration
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Paper II
EFFECT OF AGRICULTURAL ACTIVITIES ON GROUNDWATER VULNERABILITY: CASE STUDY OF HALABJA SAIDSADIQ BASIN, IRAQ

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Groundwater is one of the main sources of water in Halabja-Saidsadiq Basin of northeast Iraq. It covers an area of 1278 square kilometers with population of about 190,727. In this study, the standard DRASTIC method has been applied to generate a map of groundwater pollution vulnerability of the basin. In addition, two different scenes of landsat Themetic Mapper (TM) were used with the aid of ERDAS IMAGINE software and the GIS technique to prepare digital image classification of the study basin. Supervised classification for level I of USGS was conducted with band combination RGB/742 to prepare The Land Use and Land Cover (LULC) map. The LULC map illustrates that only five classes of land use can be identified these are: barren, agricultural, vegetation, urban and wet land or water body. The LULC map converted to LULC index map. This index map has an additional parameter added to the standard DRASTIC model to map the modified DRASTIC vulnerability in the study basin. Nitrate concentration analysis was selected and added as a pollution indicator to validate this modification. In this study, the nitrate concentration between two different seasons (dry and wet) was analyzed from (30) water wells. The standard vulnerability map of the studied basin classified the basin into four vulnerability index zones: very low (34%), low (13%), moderate (48%) and high (5%). While the combined modification classified the area into five classes: very low (1.17%), low (36.82%), moderate (17.57%), high (43.42%) and very high (1.02%). The results s that the modified DRASTIC model was dramatically superior to the standard model; therefore, the most appropriate method to apply is the combination of standard DRASTIC model with LULC index map. This conclusion is based on the results of nitrate content, as its concentration in the dry season is much lower than in the wet season.
INTRODUCTION

Many regions in the world are explicitly dependent on groundwater as one of the main water resource, specifically in arid and semi-arid regions. In Halabja and Sairadsie area which is located northeastern part of Iraq (Figure 1), groundwater plays an important role in providing water for drinking, industrial and agricultural activities. Prior 2003, this area was destructed by army attacks by chemical weapons. In addition, some parts of the area are characterized by the lack of water projects. After 2003, the area is experiencing considerable economic development and enhanced security. Furthermore, the administrative structure of Halabja has been changed from District to Governorate in March 2014; this will definitely enhance the beginning of greater economic development and advancement. In view of these changes, there is an increase in the number of people heading to live in this basin and its surrounding regions. This is imposing a growing demand for water. It should be mentioned however, that the area has large number of surface water projects which are also heavily dependent on ground water for drinking, irrigation and industry.

According to the data obtained from the Directorate of Groundwater in Sulaimani City, several thousand deep wells exits in the studied area. As a consequence, the study of the groundwater resources and its potential pollution in the area become a necessity. Moreover, it is worth noting that no previous studies have been conducted on this vital area in terms of contamination.

The most suitable, effective and widely used models to assess groundwater vulnerability to a wide range of potential contaminants is DRASITC which has been developed by Environmental Protection Agency (EPA) of the United States to organize the potential pollution of aquifers (Aller et al. 1987, Evans et al., 1990; Fritch, et al., 2000; Knox et al., 1993; Piscopo, 2001; Rundquist et al., 1991; Secunda et al., 1998).

In any specified area, vulnerability to contamination identifies a dimensionless index function of hydrogeological factors, anthropogenic influences and sources of contamination (Pymale and Angle, 2002). The DRASTIC index comprises seven parameters with different rating and weighting value and is calculated based on the following equation (Aller, et al.,1987):

\[ V = \sum_{i=1}^{7} (W_i \times R_i) \]  

where \( V \) = index value, \( W_i \) = weighting coefficient for parameter \( i \), and \( R_i \) = related rating value.

DRASTIC method as designed by Aller et al. (1987) consist of seven physical parameters. The most important map able factor that control groundwater pollution comprise to be the depth to water (D), Net recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone media (I), and Hydraulic conductivity (C). These parameters are weighted from one to five based on their relative significance in contributing to the contamination potential. All rating and weighting value are explained in table (1) based on Aller et al. (1987). The achieving index is a qualified measure of vulnerability to contamination; areas with a higher index value are more vulnerable than those with a lower index.

The effect of human and natural process as an fundamental environmental erratic can be identified from land use/ land cover map (Meyer and Turner, 1992). Land use / land cover normally marked by a short term of (LULC). Land cover (LC) defines the cover of the earth surface that naturally occur such as barren land, forest, grassland, vegetation, snow and water. Land use (LU) illustrates the modification of land cover due to human processes or man-made modification (Chilar et al., 2001). Remote sensing technique and field survey can be used to supervise LULC. As mentioned by (Mas, 1999) and cited in
Table 1. Data for the DRASTIC index (Aller et al., 1987).

<table>
<thead>
<tr>
<th>Depth to water</th>
<th>Net Recharge</th>
<th>Aquifer Media</th>
<th>Soil Media</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (m)</td>
<td>Range (mm/year)</td>
<td>Rating</td>
<td>Range</td>
</tr>
<tr>
<td>0-4.5</td>
<td>10</td>
<td>&lt;50</td>
<td>1</td>
</tr>
<tr>
<td>1.5-4.5</td>
<td>9</td>
<td>50-100</td>
<td>3</td>
</tr>
<tr>
<td>4.5-7.5</td>
<td>8</td>
<td>100-175</td>
<td>6</td>
</tr>
<tr>
<td>7.5-10</td>
<td>7</td>
<td>175-250</td>
<td>8</td>
</tr>
<tr>
<td>10-12.5</td>
<td>6</td>
<td>&gt;250</td>
<td>9</td>
</tr>
<tr>
<td>12.5-15</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-19</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19-23</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23-30</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;30</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DRASTIC weight: 5</td>
<td>DRASTIC weight: 4</td>
<td>DRASTIC weight: 3</td>
<td>DRASTIC weight: 2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Topography</th>
<th>Impact of Vadose Zone</th>
<th>Hydraulic Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range %</td>
<td>Rating</td>
<td>Range</td>
</tr>
<tr>
<td>0-2</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>2-6</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>6-12</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>12-18</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>&gt;18</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>DRASTIC weight: 1</td>
<td>DRASTIC weight: 5</td>
<td>DRASTIC weight: 3</td>
</tr>
</tbody>
</table>
(Jwan et al., 2013), remotely sensed satellite images is the most widespread source of data for mapping LULC, because of its availability and repetitive data acquisition, improved quality of multi-spatial and multi-temporal remote sensing data at different (spatial, spectral, and digital) format suitable for computer processing and new analytical techniques.

The objective of this study is to prepare the land use/land cover map of study basin and employ it as an additional parameter to the DRASTIC model to exemplify the realistic potential of groundwater vulnerability to pollution.

**STUDY AREA**

Geographically, Halabja Saidişi Basin is located in the northeastern part of Iraq between the latitude 35° 00’ 00” and 35° 36’ 00” N and the longitude 45° 36’ 00” and 46° 12’ 00” E (Figure 1). Ali (2007) divided this basin into two sub-basins by including Halabja- Narmal and Saidişi sub-basins. The whole area of both sub-basins is about 1278 square kilometers with population of about 190,727 in early 2015 according to the data achieved from Statistical Directorate in Sulaimaniyah. It is characterized by a distinct continental interior climate with hot summers and cold winters of the Mediterranean type with the average annual precipitation ranging from 500 to 700 mm. About 57% of the studied area is an arable area due to its suitability for agriculture. Consequently, the use of fertilizers and pesticides are common practices, so it affects the groundwater quality (Huang et al., 2012, Al-Rawabdeh et al., 2013, 2014). In addition, all of the municipal wastewater from the cities of Halabja and Saidişi and all other sub-district sites within this basin infiltrate into the groundwater every year.

![Figure 1. Location map of study basin.](image-url)
Geology of the study basin

Geologically, the studied area is located within Western Zagros Fold-Thrust Belt. Structurally, located within the High Folded zone, Imbricated, and Thrust Zones (Buday, 1980, Buday and Jassim, 1987, and Jassim and Goff, 2006). The age of the exposed rocks in the area is from Jurassic to recent (Figures 2 and 3). The oldest exposed rocks in the basin are of Sarki and Sehkanian (Bellen et al., 1959) of Jurassic age. These are followed by lower and middle Jurassic rocks including Barsarin (limestone and dolomitic limestone), Naokelkan (bituminous limestone) and Sargalu Formations, (Ali, 2007). The Qulqula Group consists of two formations, the Qulqula Radiolarian Formation and the Qulqula Conglomerate Formation. In addition, the exposures of the Upper Cretaceous Komentan (Turonian) and Lower Cretaceous Balambo (Valanginian-Cenomanian) Formations are widespread in the area where they are exposed in both sub-basins. Shiranish Formation (Campanian) and Tanjero Formation (Campanian-Maastrichtian) are also exposed in the basin but with restricted outcrops.

Quaternary (Alluvial) deposits are the most important unit in the area in terms of hydrogeological characteristic and water supply. These sediments are deposited as debris flow on the gently sloping plains or as channel deposits or as channel margin deposits and over bank deposits (Ali, 2007). Previous studies (e.g. Ali, 2007, Baziany, 2006, Baziany and Karim, 2007) stated that the thickness of these deposits are recorded up to 150 m thick while field observations in this study has recorded thicknesses of these deposits up to nearly 300 m.

Figure 2. Geological map of study basin.

Hydrogeology and hydrology of the study basin

Permeability and porosity are the main principal factors in determining the potential of the area to be considered as a water bearing aquifer. The area is characterized by at least four different hydrogeological aquifers due to presence of different geological units. The characteristic features of the aquifers are tabulated in Table 2. From the collected data in the field and those listed in the archives of the Groundwater Directorate at Sulaimaniyah, show that the mountain series which surround the basin in the northeast and southeast, are characterized by high depth of groundwater. Toward the center and the southeastern part of the study area, the groundwater level has a relatively lower depth. The
movement of groundwater is usually from high elevated areas at the north and northeast and south and southeast towards southwest or generally toward the reservoir of Derbandikhah Dam (Figure 4).

Figure 3. Cross section through line A-B (FAO, 2001 and Ali, 2007)

Table 2. Type of aquifers in the study basin.

<table>
<thead>
<tr>
<th>Aquifer type</th>
<th>Geological formation</th>
<th>Thickness (m)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intergranular Aquifer</td>
<td>Quaternary deposits</td>
<td>more than 300</td>
<td>Authors</td>
</tr>
<tr>
<td>Fissured Aquifer</td>
<td>Balambo</td>
<td>250</td>
<td>Ali, 2007</td>
</tr>
<tr>
<td>Fissured-Karstic Aquifer</td>
<td>Avroman Jurassic formation</td>
<td>200 From 80 to 200</td>
<td>Jassim and Goff, 2006</td>
</tr>
<tr>
<td>Non-Aquifer (Aquitard)</td>
<td>Qulqula Shiranish Tanjero</td>
<td>more than 500 225 2000</td>
<td>Jassim and Goff, 2006</td>
</tr>
</tbody>
</table>

Furthermore, several rivers exist in the area, such as Sirwan, Zalm, Chaqan, Biara, Reshen and Zmkan. All these rivers impound their water in Derbandikhah reservoir. There are several springs within the basin (see Figure 4). These springs can be classified into three classes according to their water discharge. The first group having discharge that is less than 10 L/S (such as Anab, Basak, Bawkochak and 30 other springs springs). The second group having discharge of 10 to 100 L/S (such as Sheramar, Qwmash, Khwrmal and Kani Saraw) and finally those having water discharge more than 100 L/S (such as Garaw, Ganjan, Reshen, Sarawy Swbhan Agha and 3 other springs) (Figure 4).
METHODOLOGY

Materials and source of data

The data used for groundwater vulnerability mapping and their source are presented in Table 3. Features were used to create the shape files with (Arc Map 10) software, including the geological, hydrogeological, soil map and hydro chemical data for the study area. The topographic map of the area was digitized and converted from slope map into shape files. Depth to water levels was measured from several wells in the field using electrical sounder in addition to previous records of drilled and tested wells. The thickness of saturated zone was determined from drilled wells directly supervised by researchers for this study during field work. In addition, relevant data were added which were obtained from the Groundwater Directorate in Sulaimani and other private companies. Pumping test results of the wells within the area were used to calculate the hydraulic conductivity. “AQTESOLV” software was used in these calculations. LULC had been prepared using satellite image remote sensing technique with the aid of (ERDAS IMAGING software) and GIS. Nitrate concentration analysis used to validate the proposed modification.

Standard DRASTIC Model

DRASTIC model applied in a GIS environment was used to evaluate the vulnerability of the study area. This model is recommended by the United State Committee of Environmental Protection Agency (Aller et al., 1987). Seven parameters are used in the model (see Table 2) to represent the concept of
Table 3: Source of data for DRASTIC model.

<table>
<thead>
<tr>
<th>Data type</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to water table</td>
<td>Archives of Groundwater Directorate in Sulaimani with data from field.</td>
</tr>
<tr>
<td>Net recharge</td>
<td>Halabja Meteorological Station and Water Balance Method.</td>
</tr>
<tr>
<td>Aquifer media</td>
<td>Archives of Groundwater Directorate in Sulaimani and Geological Map.</td>
</tr>
<tr>
<td>Soil media</td>
<td>Soil Map by FAO 2001 and Berding 2003.</td>
</tr>
<tr>
<td>Topographic map</td>
<td>DEM with 30 m pixel size.</td>
</tr>
<tr>
<td>Impact of vadose zone</td>
<td>Archives of Groundwater Directorate in Sulaimani.</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>Archives of Groundwater Directorate in Sulaimani with data from field.</td>
</tr>
</tbody>
</table>

the hydrogeological setting that includes the major geologic and hydrologic factors affecting and controlling the groundwater movement into, through and out of an area (Aller et al., 1987). Each parameter has a specific rate and weight value in order to evaluate the intrinsic vulnerability index. In addition, Aller et al. (1987) defined the seven parameters by the short form “DRASTIC” which is used to mapping groundwater Vulnerability (Tables 1 and 2). Each parameter has a rating on a scale of 1 to 10, based on functional curves. This rating is then scaled by a weighting factor from 1 to 5; according to their relative susceptibility to pollutants. The standard DRASTIC index (DI_weight) calculated is based on the linear combination of all parameters as demonstrated by the following equation:

\[ DI = D_w D_r + R_w R_r + A_w A_r + S_w S_r + T_w T_r + L_w L_r + C_w C_r \]

(2)

where DI is the DRASTIC Index, \( D, R, A, S, T, L \) and \( C \) are the seven parameters, \( w \) is the weight parameter and \( r \) is the rate of the parameter. All the recommended rates and weights are shown in Table 1.

D is the depth to groundwater which is described as the distance of unsaturated zone that pollutant desires to travel through to reach the water table. For this paper, groundwater level were measured and documented in about 1200 wells. Water table measurements were taken in May and early June because these months are considered as the potential worst-case scenario due to the low depth of groundwater. The Inverse Distance Weighted (IDW) were used to interpolate the data to construct the depth to water table layer as a raster format and then reclassified based on the ranges and rating recommended by Alter et al. (1987). In Halabja-Saidsadq basin the depth to groundwater vary from zero to more than 100 m. Therefore, ten classes were used for the studied basin. These are 0-1.5, 1.5-4.5, 4.5-7.5, 7.5-10, 10-12.5, 12.5-15, 15-23, 23-30 and more than 30m.

R is the net recharge which defines the amount of water that penetrates into ground and move through the unsaturated zone to reach the water table. The net recharge was estimated from the meteorological data for the period starting from 2001-2002 to 2013-2014 based on the following equation which was recommended by Mehta et al. (2006):

\[ NR = P - ET - R_0 \]

(3)

where NR is the net recharge in mm/year, P is the annual precipitation in mm, ET is the calculated
evapotranspiration in mm/year, and $R_0$ is the total runoff in mm.

$P$ was calculated from the average total yearly precipitation which is about (691.16) mm/year.

ET was calculated based on Crop Water Balance method by FAO Penman Monteith method using (CROPWat8.0) software, (Allen et al., 2006).

$R_0$ was calculated based on Soil Conservation Service method (SCS) to estimate the total runoff for the basin.

The basin was divided into several curve number (CN) that was recommended by (Ali, 2007) and then using the following equation:

\[ Q = (P-0.2S)^2/(P+0.8S) \] for $P=0.2S$ \hspace{1cm} (4)

\[ S = (25400/CN)-254 \] \hspace{1cm} (5)

where $Q$ = accumulated runoff excess in (mm), and $P$ = accumulated average monthly rainfall (mm).

$S$, the annual runoff of this basin is about 169 mm and the annual net recharge for whole basin is equal to 172.54 mm.

The net recharge map of the basin constructed was based on the net recharge percent distribution over the basin the map was converted from polygon to raster format in GIS environment.

Aquifer media (A) and the impact of vadose zone were constructed based on the geological map of the basin and from the drilling well logs. Four sections of the aquifer media were classified in the studied basin. The rated value for each media based on Aller et al. (1987) was illustrated as (9, 6, 5 and 3). While three segment of vadose zone were comprised with organized rating value of 4, 5 and 8. $S$ is the soil media (texture and type) which defines the ability of a pollutant to move vertically into the vadose zone (Lee, 2003). Three different soil media were found in the area based on soil map proposed by (FAO, 2001 and Berding, 2003) including, Silty loam, Shrinkling and/or aggregated clay and thin or absent with rating of 4, 7 and 10 respectively.

$T$ map refers to the topographic map that describes the slope of the surface area. The pollutants are remaining for a long period over an area with low percent of slope value and vice versa (Hernandez et al., 2004). This map was constructed from the digital elevation model (DEM) with pixel size of (30 m) and the slope aspect was then calculated from it in Arc GIS 10. The topography of the area was classified into five classes ranging as 0-2%, 2-6%, 6-12%, 12-18% and >18%. Hydraulic conductivity (C) describes the ability of the aquifer material to transmit water through it and contaminant migration is control by the permeability of the media (Hamamin, 2011). The hydraulic conductivity map was constructed by employing the pumping test result of about 10 wells. The pumping test data were analyzed using (AQTESOL 4.0) software to determine the transmissivity of the aquifer and then equation (6) was used to calculate the hydraulic conductivity:

$$ C = \frac{T}{b} $$ \hspace{1cm} (6)

where $C$ is the hydraulic conductivity in (m/day), $T$ is the transmissivity in (m²/day), and $b$ is the aquifer saturated thickness in (m).

The area with high hydraulic conductivity revealed higher chance of distributing pollutants. Two classes of conductivity rating were achieved, 1 and 4. After generating all the required layers, each pixel was classified and rated, then, multiplied by their respective weighting factor and the DRASTIC index was determined. The final index obtained was divided into several groups as proposed by (Aller et al., 1987). Small value designated low vulnerability potential while large value represents areas that have high vulnerability potential.
Land use/ land cover (LULC) map

Two different scene of landsat Thematic Mapper (TM) had been used to prepare LULC map because the study basin is located in between them. Images consist of seven spectral bands with cell size (30x30 m) for Bands 1 to 5 and 7. While, spatial resolution for Band 6 (thermal infrared) is 120 meters, however this band re-sampled to 30-meter pixels. Nearly, scene size is 170 km north-south by 183 km east-west and the date back to (03-05-2010). Figure 5 illustrates the TM landsat image for the study basin.

![Figure 5. TM landsat map (2010) of study basin](image)

The most important steps in LULC preparation is classification processes because it gives you the degree of accuracy. There are several proposed methods for LULC classification in the world, but the USGS system that developed by Anderson et al., 1976 is applied in this study. The factors that support us to select this method is depends on remote sensing data which are available and it is suitable for application in the study basin as well. The USGS system of classification consists of four levels, from I to IV; the difference between them depends on the resolution of remote sensing data used for classification, (Bety, 2013)

ERDAS IMAGINE software was used to prepare digital image classification of the study basin. Supervised classification for level I of USGS done with band combination RGB / 742 for image covered basin. The study area is extract from the results map of classification according to the catchment area of HSB using ArcGIS software. The analyses are supported by field works. Many
points taken with GPS and several photos were taken as well to check the accuracy and validity of the final map of classification.

**Modified standard DRASTIC model using LULC Index Map**

As mentioned previously, to modify the likely risk of groundwater vulnerability an additional parameter can be inserted into the analysis to show the realistic of vulnerability assessment. In this study, LULC map was used because it musically affects the quality of groundwater where agriculture as the main land use type is the main factor in changing of soil nature and hydraulic conductivity (Merchant, 1994).

Therefore, LULC map was rated and weighted as additional parameter and added to standard DRASTIC model. The LULC rating map was rated based on the values given in Table 3. Furthermore, it was converted to a raster grid and multiplied by the weight of the parameters ($L_w = 5$) to construct LULC index map (Abdullah et al., 2014). Then, to modify the original DRASTIC index map, it was combined with LULC index map based on equation (7) (Secunda et al., 1998). The results demonstrate the effect of specific land use type on the vulnerability system.

$$MD(i) = DI + (\text{LULC Index})$$  \hspace{1cm} (7)

where $MD(i)$ is the modified DRASTIC model, $DI$ is the standard DRASTIC index, and the LULC index (ratings-weights).

**Table 3: Rate and weight for LULC classes (Secunda et al., 1998).**

<table>
<thead>
<tr>
<th>Rate</th>
<th>Level I Classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Vegetation and Barren Land</td>
</tr>
<tr>
<td>7</td>
<td>Water and wet area</td>
</tr>
<tr>
<td>8</td>
<td>Urban area and agriculture land</td>
</tr>
</tbody>
</table>

Weight=5

**RESULT AND DISCUSSION**

**Assessment of standard vulnerability mapping**

Figure 6 shows the original DRASTIC vulnerability model of HSB with four zones of vulnerability index. These are: very low, low, moderate and high vulnerability index. The map obviously illustrates the dominance of moderate and very low vulnerability zones which covers an area of 614 and 435 Km² or (48% and 34%) of the whole studied area respectively. The moderate vulnerability zone occupies two different areas in terms of geological and hydrogeological conditions. The first is the area of mountains surrounding the studied basin which comprises the fissured and karstic aquifer. While the second area comprises the Quaternary deposits surrounding the area of Derbandikhan reservoir in the southwest of the basin, this might be related to the high water table level and high percent of coarse grain material such as gravel, sand and rock fragment. Furthermore, the zone with low vulnerability comes in the third sequence and occupy 166 km² or 13% of the overall surface area of the basin. The zone with high vulnerability index cover only 64 km² or 5% of the total area and is located in the center of basin. This area is characterized by high water table level and presence of several springs with fractured limestone.

**Assessment of LULC map**

The LULC map of the study basin is shown in Figure 7. This map is produced based on USGS
method of classification (Bety, 2013), using remote sensing and GIS techniques from satellite landsat images (ETM+, 2010). The map demonstrates that only five classes can be recognized as explained on Table 4 with percent and the area of land covering of each.

![Standard DRASTIC Index Map](image)

Figure 6. Standard DRASTIC Map for study basin.

Table 4: LULC classes type in the study basin.

<table>
<thead>
<tr>
<th>Area_ %</th>
<th>Area_ Km²</th>
<th>Level I Classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.31</td>
<td>16.79</td>
<td>Urban</td>
</tr>
<tr>
<td>35.19</td>
<td>449.77</td>
<td>Agriculture</td>
</tr>
<tr>
<td>59.97</td>
<td>766.36</td>
<td>Barren Land</td>
</tr>
<tr>
<td>3.11</td>
<td>39.75</td>
<td>Vegetation</td>
</tr>
<tr>
<td>0.42</td>
<td>5.33</td>
<td>Water and wet land</td>
</tr>
</tbody>
</table>

The map illustrates that barren land covered most of the studied basin land with an area of (766.36) km² or (59.97%) of total studied area. In addition, agriculture land cover with an area of (449.77) km² or (35.19%) occupy mostly the central and northwestern parts of the studied basin. The remaining classes of
(vegetation, urban area and water and wet land) covering an area of 39.75, 16.79 and 5.33 Km² or (3.11%, 1.31% and 0.42%) of the whole studied area respectively. To check the accuracy of the final LULC map several points in the field were taken with GPS in each class and matched on the map. In addition, several photos of each point were taken as well, all results verify the accuracy of this classification and the result of field survey coincide the theoretical classification using remote sensing.

Photos 1 and 2 illustrate urban area and agriculture land as an example for checking accuracy with coordinate value of (579195,3912525 and 589644,3909281) respectively and both point placed on LULC map (Figure 7).

Photo 1. Urban area at Saidsadiq District  
Photo 2. Agriculture land close to Banishar Village

Assessment of LULC rating and index maps

The map of ratings of LULC in (Figure 8) illustrate rating value ranging from 5–8 (Table 5). Urban areas and agricultural land were assigned a probability rating of 8, because chemical contaminant concentrations such as nitrogen in groundwater from human activities in urban and agriculture areas were higher than in all other land use areas (Secunda et al., 1998). Vegetation and barren land areas were combined and assigned a probability rating of 5, as they contain low nitrogen of nearly similar concentrations. Water body and wet land area were rated allocated of 7 (Secunda et al., 1998) as water acts as a good transporter for contaminant.

Additionally, it can be noted from Figure 8, rating value of class (5) occupies most of studied basin with 63.1% of the entire studied area. This class located in most of surrounding mountains and areas of high percent of pasture. Rationally, in terms of land use, these areas have the lowest effect environmentally on vulnerability aspects. Moreover, urban area and agricultural land were rated of probability of 8 and occupies 36.5% of the intact studied area. This is refer to human activities in these area compared to other land use class. Water body and wet land occupies only 0.4% of the whole area with rating value of (7).

Furthermore, the LULC rating map as a raster grid was multiplied using map algebra in GIS environment by the weight of the parameters (Lw = 5) to construct LULC index map as shown in Figure 9. The index value classified into three classes (25, 35 and 40) , which occupies (63.1%, 0.4% and 36.5%) of the total area of studied basin respectively.
Figure 7. LULC map for the study basin.

Table 5: Rating value for each LULC classes type, after (Secunda et al., 1998)

<table>
<thead>
<tr>
<th>Area%</th>
<th>Rating value</th>
<th>Level I Classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>63.1</td>
<td>5</td>
<td>Vegetation and Barren Land</td>
</tr>
<tr>
<td>0.4</td>
<td>7</td>
<td>Water and wet area</td>
</tr>
<tr>
<td>36.5</td>
<td>8</td>
<td>Urban area and agriculture land</td>
</tr>
</tbody>
</table>

Weight=5

Assessment of modified DRASTIC vulnerability model

Figure (10) shows the modified DRASTIC index map based on LULC index map with ranging of (88-221). The range of index values was divided into five classes including very low to very high vulnerability classes (Table 6).

The modified vulnerability map shows that about 43.42% of the study basin has high vulnerability to contamination with index values ranging between 150 to 200. Low vulnerability measured as a second effective class in the studied area with (36.82%). While, very low, moderate and very high areas comprise 1.17%, 17.57 and 1.02 respectively. In terms of land use class, agriculture and barren lands occupies most of studied basin with total area of (1216.3) Km² or 95.16% of the whole studied area. The effect of agriculture activity clearly seen on the modified DRASTIC model compared to
Figure 8. LULC rating map for the study basin.

Figure 9. LULC index map for the study basin.

Figure 10: Modified DRASTIC Map for the study basin.
Table 6: Modified DRASTIC index value of each class at study basin.

<table>
<thead>
<tr>
<th>Area (%)</th>
<th>Area(Km²)</th>
<th>Drastic Index</th>
<th>Vulnerability class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.17</td>
<td>14.95</td>
<td>88-100</td>
<td>Very low</td>
</tr>
<tr>
<td>36.82</td>
<td>470.7</td>
<td>&gt;100-125</td>
<td>Low</td>
</tr>
<tr>
<td>17.57</td>
<td>224.51</td>
<td>&gt;125-150</td>
<td>Moderate</td>
</tr>
<tr>
<td>43.42</td>
<td>554.85</td>
<td>&gt;150-200</td>
<td>High</td>
</tr>
<tr>
<td>1.02</td>
<td>12.99</td>
<td>&gt;200-221</td>
<td>Very high</td>
</tr>
</tbody>
</table>

standard one, as the agriculture land plays a significant role to convert the moderate vulnerability zone in the central and north western parts to high vulnerability zone. In addition, both barren with agriculture lands are the main factors to rise up very low vulnerability zone to low vulnerability in the north east and south east of the study basin.

Validation of proposed modified DRASTIC model

In order to validate the proposed modified DRASTIC Vulnerability model using LULC map, nitrate concentration analysis has been selected. Nitrate as a pollution indicator can be helpful to recognize the evolution and changes of groundwater quality. In the particular study case, the nitrate differences between two following seasons (dry and wet) were analyzed from (30) water wells. The samples were collected and analyzed on end of September 2014 for dry season and end of May 2015 for wet season. The selected wells for nitrate concentration measurement located in all vulnerability zones and land use classes. The final nitrate classes from the chemical analysis of groundwater samples for both seasons are used to know the impact of human activities on groundwater quality (Figures 11 and 12).

In relation to nitrate values for dry season (absence of rainfall for a long period), low nitrate levels were identified with concentration value ranging between zero to just above 10 mg/l. While for wet season which is characterized by a period of high rainfall, the nitrate concentration extremely rose up in all wells as recorded from the result. Figures 11 and 12 verify this fluctuation in nitrate concentration between both seasons, specifically in the central portion of the studied basin with high agriculture activity (Table 7). This condition refers to several main factors such as rising up the water table in the wet season and vise versa for dry season and secondly, the impact of human activity is significant in wet season specifically using chemical contaminants (nitrate) for agriculture purpose. Finally rainfall plays an important role to transport nitrate based on specific condition of vulnerability properties of ground strata and land use type. Consequently, these considerable variations in nitrate concentration from dry to wet seasons verify the susceptibility of this modification. Therefore, the combination of standard DRASTIC and LULC index maps is the most appropriate method to apply in this basin.

CONCLUSION

Both standard and modified DRASTIC index model applied in GIS environment to assess the potential vulnerability of groundwater contamination in the Halabja Sai'hsadiq basin. Even though the DRASTIC method regularly affords acceptable results in the assessment of intrinsic vulnerability of groundwater to pollution but it might be difficult to consider the result as an accurate risk assessment of the groundwater. Two different scene of landsat Thematic Mapper (TM) had been used to prepare LULC map. Images consist of seven spectral bands with cell size (30x30 m) for Bands 1 to 5 and 7. ERDASIMAGINE software was used to prepare digital image classification of the study basin.
Table 7. Nitrate concentration in both dry and wet seasons at each Vulnerability class.

<table>
<thead>
<tr>
<th>Nitrate Concentration (mg/l)</th>
<th>Land use Class</th>
<th>Vulnerability category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Season</td>
<td>Dry season</td>
<td></td>
</tr>
<tr>
<td>N.A</td>
<td>N.A</td>
<td>Mostly barren land</td>
</tr>
<tr>
<td>Mostly &lt; 20</td>
<td>&lt; 7</td>
<td>Mostly barren with low barren land</td>
</tr>
<tr>
<td>&gt;30</td>
<td>&gt;10</td>
<td>Mostly agricultural land</td>
</tr>
<tr>
<td>&gt;30</td>
<td>&gt;10</td>
<td>Mostly agriculture with low barren land</td>
</tr>
<tr>
<td>&gt;30</td>
<td>&gt;10</td>
<td>Mostly agricultural land</td>
</tr>
</tbody>
</table>

Supervised classification for level I of USGS done with band combination RGB / 742 for image covered basin. The LULC map demonstrates that only five classes can be recognized including barren land, agricultural land, vegetation, urban area and wet land or water body. Each class has specific rate and weight value based on its impact environmentally as explained in table (5). Seven parameter maps were developed in a GIS environment to generate standard models and one parameter (LULC) is added to modify it. The DRASTIC vulnerability index values ranged between 63 and 191, 88 and 221 for standard and modified respectively.
The vulnerability zones are given in Table 8. It can be noted that, standard DRASTIC model clarify only four vulnerability classes comprises (very low to high) while the modified one comprises five classes from very low to very high vulnerability zones. The highly vulnerable areas constitute 43.42% of the basin and mostly are located in the central and north western of Halabja Saidasdiq basin with land use type of agriculture and barren land. This percent was only 5% before modification. The effect of agriculture activity clearly seen on the modified DRASTIC model compared to standard one, as the agriculture land plays a significant role to convert the moderate vulnerability zone in the central and north west parts to high vulnerability zone. In addition both barren with agriculture lands are the main factors to rise up very low vulnerability zone to low vulnerability in the north east and south east of the Halabja Saidasdiq basin.

Nitrate concentration of groundwater was evaluated for validation of the modified DRASTIC results where 30 groundwater samples have been analyzed for nitrate in two different seasons. The result of nitrate concentration in dry season (just above 10 mg/l) considerably lower than in wet season (more than 30 mg/l). This result confirms that nitrate as a chemical pollutant how rapidly rises up from October 2014 to June 2015. This variation is referring to the impact of human activity such as agriculture and hydrogeological with vulnerability properties of ground strata. Therefore, the combination of standard DRASTIC and LULC index maps is the most appropriate method to be applied in this basin based on the nitrate transmission.

Table 8. Result of DRASTIC index ratio for standard and modified maps.

<table>
<thead>
<tr>
<th>Modified rate %</th>
<th>Standard rate %</th>
<th>Vulnerability class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.17</td>
<td>34</td>
<td>Very low</td>
</tr>
<tr>
<td>36.82</td>
<td>13</td>
<td>Low</td>
</tr>
<tr>
<td>17.57</td>
<td>48</td>
<td>Medium</td>
</tr>
<tr>
<td>43.42</td>
<td>5</td>
<td>High</td>
</tr>
<tr>
<td>1.02</td>
<td>---</td>
<td>Very high</td>
</tr>
</tbody>
</table>

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Paper III
Groundwater Vulnerability Mapping Using Lineament Density on Standard DRASTIC Model: Case Study in Halabja Saidsadiq Basin, Kurdistan Region, Iraq

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Abstract

Groundwater is the most important source of water in the Halabja-Saidsadiq Basin. In this study, to generate a map of groundwater pollution vulnerability of the basin, the standard DRASTIC method has been applied. Due to the close relation between lineament density and groundwater flow and yield, the lineament density map was applied to the standard DRASTIC model in order to ensure accuracy towards the consideration of the effects of potential vulnerability to contamination. A lineament map is extracted from Enhanced Thematic Mapper plus (ETM+) satellite imagery using different techniques in remote sensing and GIS. The lineament density map illustrates that only six classes of lineament density can be identified ranged from (0 - 2.4). The lineament density map was rated and weighted and then converted to lineament index map. This index map is an additional parameter which was added to the standard DRASTIC model so as to map the modified DRASTIC vulnerability in HSB. The standard vulnerability map, classified the basin into four vulnerability index zones: very low (34%), low (13%), moderate (48%) and high (5%). While the modified model classified the area into four categories as well: very low (28.75%), low (14.31%), moderate (46.91%) and high (10.04%). The results demonstrate that there is no significant variation in the rate of vulnerability. Therefore, the nitrate concentration between two different seasons (dry and wet) was analyzed from (30) water wells, considerable variations in nitrate concentration from dry to wet seasons had been noted. Consequently, it confirmed that the HSB are capable to receive the contaminant because of suitability in terms of geological and hydrogeological conditions. Based on this verification, it could be claimed that the effect of lineament density is...
weak on the vulnerability system in HSB, because of its low density value.

Keywords

Vulnerability, Lineament, Landsat TM 8, DRASTIC, Halabja Saidsadiq Basin (HSB)

1. Introduction

Many regions in the world are explicitly dependent on groundwater as one of the main water resources, specifically in the arid and semi-arid regions. In Halabja and Saidasadiq area which is located in the northeastern part of Iraq (Figure 1), groundwater plays an important role in providing water for drinking, industrial and agricultural activities. This area in the past was destructed by army attacks by chemical weapons. In addition, some parts of the area are characterized by the lack of water projects. After 2003, the area is experiencing considerable economic development and enhanced security. Furthermore, the administrative structure of Halabja has been changed from District to Governorate in March 2014; this will definitely enhance the beginning of greater economic development and advancement. In view of these changes, there is an increase in the numbers of people heading to live in this basin and its surrounding regions. This is imposing a growing demand for water which has placed substantial pressures on water resources. It should be mentioned however, that the area has large number of surface water projects which are also highly dependent on ground water for drinking, irrigation and industry.

According to data obtained from the Directorate of Groundwater in Sulaimani City, several thousand deep wells exits in the studied area. As a consequence, the study of the groundwater resources and its potential pollution in the area become a necessity. Moreover, it is worth noting that no previous studies have been conducted on this vital area in terms of contamination.

The most suitable, effective and widely used models to assess groundwater vulnerability to a wide range of potential contaminants is DRASTIC which has been developed by Environmental Protection Agency (EPA) of the United States to organize the pollution potential of aquifers [1]-[7].

In any specified area, vulnerability to contamination identifies a dimensionless index function of hydrogeological factors, anthropogenic influences and sources of contamination [8]. The DRASTIC index comprises seven parameters with different rating and weighting value and is calculated based on the following equation [1]:

\[ V = \sum_{i=1}^{7} (W_i \times R_i) \]  

where: \( V \) = index value, \( W_i \) = weighting coefficient for parameter \( i \) and \( R_i \) = related rating value.

DRASTIC method as designed by [1] consist of seven physical parameters. The most important mapable factor that control groundwater pollution is the Depth to groundwater (D), Net recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone media (I), and Hydraulic conductivity (C). These parameters are weighted from one to five based on their relative significance in contributing to the contamination potential. All rating and weighting value are explained in Table 1 based on [1]. The achieving index is a qualified measure of vulnerability to contamination; areas with a higher index value are more vulnerable than those with a lower index.

The objective of this study is to prepare the lineament density map of HSB and employ it as an additional parameter to the DRASTIC model to exemplify the realistic potential of groundwater vulnerability to pollution. The lineaments refer to as linear features perceived on satellite images, aerial photographs and Digital elevation model (DEM) after processing and enhancing, which most probably related or originated from a geological feature. In addition, based on the previous studies, a close relationship has been recognized between lineaments or lineaments density and groundwater flow and yield [9]-[11]. Consequently, mapping of lineaments is crucial to groundwater survey, management and development [12]. Higher values of lineament density might designate more potential groundwater contamination. A lineaments map is extracted from Enhanced Thematic Mapper plus (ETM+) satellite imagery using different techniques in remote sensing and GIS environment.
Table 1. Data for the DRASTIC index [1].

<table>
<thead>
<tr>
<th>Depth to Water (m)</th>
<th>Net Recharge (mm/year)</th>
<th>Aquifer Media</th>
<th>Soil Media</th>
<th>Topography</th>
<th>Impact of Vadose Zone</th>
<th>Hydraulic Conductivity (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 4.5</td>
<td>&lt;50</td>
<td>Massive Shale</td>
<td>Thin or Absent, Gravel</td>
<td>Confining Layer</td>
<td>1</td>
<td>&lt;4</td>
</tr>
<tr>
<td>1.5 - 4.5</td>
<td>50 - 100</td>
<td>Metamorphic/Igneous</td>
<td>Sand</td>
<td>3</td>
<td>Silty/Clay</td>
<td>4 - 12</td>
</tr>
<tr>
<td>4.5 - 7.5</td>
<td>100 - 175</td>
<td>Weathered Metamorphic/Igneous</td>
<td>Peat</td>
<td>8</td>
<td>Shale</td>
<td>12 - 30</td>
</tr>
<tr>
<td>7.5 - 10</td>
<td>175 - 250</td>
<td>Glacial Till</td>
<td>Shrinking and/or Aggregated Clay</td>
<td>Limestone</td>
<td>6</td>
<td>30 - 40</td>
</tr>
<tr>
<td>10 - 12.5</td>
<td>&gt;250</td>
<td>Bedded Sandstone, Limestone, Shale</td>
<td>Sandy Loam</td>
<td>6</td>
<td>Sandston, Beded Limestone</td>
<td>40 - 80</td>
</tr>
<tr>
<td>12.5 - 15</td>
<td>5</td>
<td>Massive Sandstone, Massive Limestone</td>
<td>Loam</td>
<td>5</td>
<td>Sandstone, Sand, sand and Gravel</td>
<td>&gt;80</td>
</tr>
<tr>
<td>15 - 19</td>
<td>8</td>
<td>Sand and Gravel</td>
<td>Silty Loam</td>
<td>4</td>
<td>Metamorphic/Igneous</td>
<td>4</td>
</tr>
<tr>
<td>19 - 23</td>
<td>3</td>
<td>Basalt</td>
<td>Clay Loam</td>
<td>3</td>
<td>Sand and Gravel</td>
<td>8</td>
</tr>
<tr>
<td>23 - 30</td>
<td>2</td>
<td>Karst Limestone</td>
<td>Muck</td>
<td>2</td>
<td>Basalt</td>
<td>9</td>
</tr>
<tr>
<td>&gt;30</td>
<td>1</td>
<td>Non Shrinking and Non-Aggregated Clay</td>
<td></td>
<td>1</td>
<td>Karst Limestone</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DRASTIC Weight:</th>
<th>DRASTIC Weight:</th>
<th>DRASTIC Weight:</th>
<th>DRASTIC Weight:</th>
<th>DRASTIC Weight:</th>
<th>DRASTIC Weight:</th>
<th>DRASTIC Weight:</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

2. Study Area

Geographically, Halabja Saidaq Basin is located in the northeastern part of Iraq between the latitude 3860000 and 3930000 N and the longitude 560000 and 610000 E (Figure 1). Ali [13] had divided this basin into two sub-basins including Halabja-Khurmal and Said Sadiq sub-basins. The whole area of both sub-basins is about 1278 square kilometers with population of about 190,727 in early 2015 according to the data achieved from Statistical Directorate in Sulaimanyah. It is characterized by a distinct continental interior climate with hot summers and cold winters of the Mediterranean type with the average annual precipitation ranging from 500 to 700 mm. About 57% of the studied area is an arable area due to its suitability for agriculture. Consequently, the use of fertilizers and pesticides are common practices, so it affects the groundwater quality [14]. In addition, all of the municipal wastewater from the cities of Halabja and Saidaq and all other sub-district sites within this basin infiltrate into the groundwater every year.
2.1. Geology of Study Area

Geologically, the studied area is located within Western Zagros Fold-Thrust Belt. Structurally, located within the High Folded zone, Imbricated, and Thrust Zones [15]-[17]. The age of the exposed rocks in the area is from Jurassic to recent (Figure 2, Figure 3). The oldest exposed rocks in the basin are of Sarki and Sehkanian of Jurassic age [18]. These are followed by lower and middle Jurassic rocks including Barsarin (limestone and dolomitic limestone), Naokelekan (bituminous limestone) and Sargalu Formations, [13]. The Qulqula Group consists of two formations, the Qulqula Radiolarian Formation and the Qulqula Conglomerate Formation. Furthermore, the exposures of the Upper Cretaceous Kometan (Turonian) and Lower Cretaceous Balambo (Valanginian-Cenomanian) Formations are widespread in the area where they are exposed in both sub-basins. Shiranish Formation (Campanian) and Tanjero Formation (Campanian-Maastrichtian) are also exposed in the basin but with restricted outcrops.

Quaternary (Alluvial) deposits are the most important unit in the area in terms of hydrogeological characteristic and water supply. These sediments are deposited as debris flow on the gently sloping plains or as channel deposits or as channel margin deposits and over bank deposits [13]. Previous studies such as [13] [19] [20] stated that the thickness of these deposits are recorded up to 150 m thick while field observations in this study has recorded thicknesses of these deposits up to nearly 300 m.

2.2. Hydrogeology of Study Area

Permeability and porosity are the main principal factors in determining the potential of the area to be considered as a water bearing aquifer. The area is characterized by at least four different hydrogeological aquifers due to presence of different geological units. The characteristic features of the aquifers are tabulated in Table 2. From the collected data in the field and those listed in the archives of the Groundwater Directorate at Sulaimaniyah show that the mountain series, which surround the basin in the northeast and southeast, are characterized by high depth of groundwater. Toward the center and the southeastern part, the groundwater level has a relatively lower depth. The movement of groundwater is usually from high elevated areas at the north and northeast and south and southeast towards southwest or generally toward the reservoir of Derbandikhan Dam (Figure 4).

Furthermore, several rivers exist in the area, such as Sirwan, Zalm, Chaqan, Biara, Reshen and Zmkan. All these rivers impound their water in Derbandikhan reservoir. There are several springs within the basin. These springs can be classified into three classes according to their water discharge. The first group having discharge that is less than 10 L/S (such as Anab, Basak, Bawakochak and 30 other springs springs). The second group having discharge of 10 to100 L/S (such as Sheramar, Qwmash, Khwrmal and Kani Saraw) and finally those
Figure 2. Geological map of HSB.
Table 2. Types of aquifers in the study basin.

<table>
<thead>
<tr>
<th>Aquifer Type</th>
<th>Geological Formation</th>
<th>Thickness (m)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intergranular Aquifer</td>
<td>Quaternary deposits</td>
<td>More than 300</td>
<td>Authors</td>
</tr>
<tr>
<td>Fissured Aquifer</td>
<td>Balambo</td>
<td>250</td>
<td>Ali, 2007</td>
</tr>
<tr>
<td>Fissured-Karstic Aquifer</td>
<td>Avroman</td>
<td>200</td>
<td>From 80 to 200</td>
</tr>
<tr>
<td>Non-Aquifer (Aquitard)</td>
<td>Qalqula</td>
<td>More than 500</td>
<td>Shiranzish and Tanjero</td>
</tr>
</tbody>
</table>

having water discharge more than 100 L/S (such as Garaw, Ganjan, Reshen, Sarawy Swbian Agha and 3 other springs) (Figure 4). The regional lineaments in HSB have been showed on Figure 4 [22].

3. Methodology
3.1. Material and Source of Data

The data used and their source for groundwater vulnerability mapping are presented in Table 3. Features were used to create the shape files with (Arc Map 10) software, including the geological, hydrogeological, soil map and hydrochemical data for the study area. The topographic map of the area was digitized and converted from slope map into shape files. Depth to water levels was measured from several wells in the field using electrical sounder in addition to previous records of drilled and tested wells. The thickness of saturated zone was determined from drilled wells directly supervised by researchers for this study during field work. In addition, relevant data were added which were obtained from the Groundwater Directorate in Sulaimani [23] and other private companies. Pumping test results of the wells within the area were used to calculate the hydraulic conductivity. “AQTESOLV” software was used in these calculations. Lineament map and lineament density map were prepared using satellite image remote sensing technique with the aid of (Envi Program and PCI Geomatica technique) and GIS. The modified DRASTIC model prepared from standard one and lineament density map applied in GIS environment.
Figure 4. Hydrogeological map of HSB.
Table 3. Source of data for DRASTIC model and Lineament map.

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to Water Table</td>
<td>Achieves of Groundwater Directorate in Sulaimani with Data from Field.</td>
</tr>
<tr>
<td>Net Recharge</td>
<td>Halabja Meteorological Station and Water Balance Method.</td>
</tr>
<tr>
<td>Aquifer Media</td>
<td>Achieves of Groundwater Directorate in Sulaimani and Geological Map.</td>
</tr>
<tr>
<td>Topographic Map</td>
<td>DEM with 30 m Pixel Size.</td>
</tr>
<tr>
<td>Impact of Vadose Zone</td>
<td>Achieves of Groundwater Directorate in Sulaimani.</td>
</tr>
<tr>
<td>Hydraulic Conductivity</td>
<td>Achieves of Groundwater Directorate in Sulaimani with Data From Field.</td>
</tr>
<tr>
<td>Lineament Map</td>
<td>From Landsat 8 Date back to (11/2/2013).</td>
</tr>
</tbody>
</table>

3.2. Standard DRASTIC Model

DRASTIC model applied in a GIS environment has been used to evaluate the vulnerability of the study area. This model is recommended by the United States committee of Environmental Protection Agency [1]. Seven parameters are used in the model (see Table 2) to represent the concept of the hydrogeological setting that includes the major geologic and hydrologic factors affecting and controlling the groundwater movement into, through and out of an area [1]. Each parameter has a specific rate and weight value in order so that the intrinsic vulnerability index can be evaluated. In addition, [1] defined the seven parameters by the short form “DRASTIC” which is used to mapping groundwater Vulnerability (Table 1). Each parameter has a rating on a scale of 1 to 10, based on functional curves. This rating is then scaled by a weighting factor from 1 to 5; according to their relative susceptibility to pollutants. The standard DRASTIC index (DI(w-r)) calculated is based on the linear combination of all parameters as demonstrated by the following equation:

\[ DI \left( w, r \right) = D \cdot w + R \cdot r + A \cdot w + S \cdot r + T \cdot w + I \cdot r + C \cdot w + T \cdot r \]

where: 
- DI is the DRASTIC Index, 
- (D, R, A, S, T, I and C) are the seven parameters, 
- w is the weight parameter and 
- r is the rate of the parameter. 
All the recommended rate and weight are scheduled in Table 1.

D is the depth to groundwater which is describes as the distance of unsaturated zone that pollutant desires to travel through to reach the water table. For this paper, groundwater level were measured and documented in about 1200 wells. Water table measurements were taken in May and early June because these months are considered as the potential worst-case scenario due to the low depth of groundwater. The Inverse Distance Weighted (IDW) were used to interpolate the data to construct the depth to water table layer as a raster format and then reclassified based on the ranges and rating recommended by [1]. In Halabja-Saidsadiq basin the depth to groundwater vary from zero to more than 100 m. Therefore, ten classes were used for the studied basin. These are

- 0 - 1.5, 1.5 - 4.5, 4.5 - 7.5, 7.5 - 10, 10 - 12.5, 12.5 - 15, 15 - 23, 23 - 30 and more than 30 m.

R is the net recharge which defines the amount of water that penetrates into ground and move through the unsaturated zone to reach the water table. The net recharge was estimated from the meteorological data for the period starting from 2001-2002 to 2013-2014 based on the following equation which was recommended by [24]:

\[ NR = P - ET - R_0 \]

where, 
- NR: is the net recharge in mm/year, 
- P: is the annual precipitation in mm; 
- ET is the calculated evapotranspiration in mm/year, 
- R_0 is the total runoff in mm. 

P was calculated from the average total yearly precipitation which is about (691.16) mm/year. While ET were calculated based on Crop Water Balance method by FAO Penman Monteith method using (CROPWat8.0) software [25]. R_0 was calculated based on Soil Conservation Service method (SCS) to estimate the total runoff for the basin. The basin was divided into several curve number (CN) that was recommended by [1] and then using the following equation:

\[ Q = \left( P - 0.2S \right) / \left( P + 0.8S \right) \] for \( P > 0.2S \)
where: $Q =$ accumulated runoff excess in (mm), $P =$ accumulated average monthly rainfall (mm). So the annual runoff of this basin is about 169 mm and the annual net recharge for whole basin is equal to 172.54 mm. Finally, the net recharge map of the basin constructed was based on the net recharge percent distribution over the basin and then the resulted map was converted from polygon to raster format in GIS environment.

Aquifer media (A) and the impact of vadose zone were constructed based on the geological map of the basin and from the drilling well logs. Four sections of the aquifer media were classified in the studied basin. The rated value for each media based on [1] was illustrated as (9, 6, 5 and 3). While three segment of vadose zone were comprised with organized rating value of 4, 5 and 8. $S =$ the soil media (texture and type) which defines the ability of a pollutant to move vertically into the vadose zone [26]. Three different soil media were found in the area based on soil map proposed by [21] [27] including, Silty loam, Shrinking and/or aggregated clay and thin or absent with rating of 4, 7 and 10 respectively.

$T$ map refers to the topographic map that describes the slope of the surface area. The pollutants are remaining for a long period over an area with low percent of slope value and vice versa [28]. This map was constructed from the digital elevation model (DEM) with pixel size of (30 m) and the slope aspect was then calculated from it in Arc GIS 10. The topography of the area was classified into five classes ranging as 0% - 2%, 2% - 6%, 6% - 12%, 12% - 18% and more than 18%. Hydraulic conductivity (C) describes the ability of the aquifer material to transmit water through it and contaminant migration is control by the permeability of the media [29]. The hydraulic conductivity map was constructed by employing the pumping test result of about 100 wells. The pumping test data were analyzed using (AQTESOL 4.0) software to determine the transmissivity of the aquifer and then Equation (6) was used to calculate the hydraulic conductivity:

$$C = \frac{T}{b}$$

where: $C =$ the hydraulic conductivity in (m/day), $T =$ the transmissivity in (m²/day) and $b =$ the aquifer saturated thickness in (m). The area with high hydraulic conductivity revealed higher chance of distributing pollutants. Two classes of conductivity rating were achieved 1 and). After generating all the required layers, each pixel was classified and rated, then, multiplied by their respective weighting factor and the DRASTIC index was determined. The final index obtained was divided into several groups as proposed by [1]. Small value designated low vulnerability potential while large value represents areas that have high vulnerability potential.

### 3.3. Lineament Map and Lineament Density Map

The lineament defines as linear features in a landscape identified on satellite images and aerial photographs, most likely have a geological origin. Generally, lineaments are underlain by structural zone, fractured zone, a series of fault or fold-aligned hills zone of localized weathering and zone of increased permeability and porosity.

Lineament distribution for HSB prepared using image of landsat 8 Thematic Mapper (TM). Images consist of nine spectral bands with cell size (30 × 30 m). The Operational Land Imager (OLI) spectral band in gray scale was used. Nearly, scene size is 170 km north-south by 183 km east-west and the date back to (11-02-2013). Figure 5 illustrate the TM landsat image for the study basin with extracted lineament distribution.

A lineament distribution over the site extracted using PCI Geomatica technique. The lineament extraction algorithm of PCI Geomatica software consists of edge detection, thresholding and curve extraction steps [30]. Figure 6 illustrates the final lineament distribution over HSB extracted from mentioned above satellite image.

Furthermore, the lineament density map was constructed using line density in the spatial analysis tool in Arc Map 10. This tool calculates a magnitude per unit area from polyline features that fall within a radius around each cell. Higher intensity of lineament feature may increases the probability of contaminant movement toward groundwater.

### 3.4. Lineament Rating and Index Map

In HSB area most of aquifers that surrounding the basin are developed in fractured rock, so groundwater mostly moves through the fracture of the rocks. In addition there are many linear features that appear in the alluvial deposits as a result of effective of zone of increasing porosity and permeability. So, lineament density measured as a main parameter with DRASTIC model to assess groundwater vulnerability more precisely. The lineament
Figure 5. TM landsat 8 image (2013) of HSB.
Figure 6. Extracted lineament map of HSB with extracted lineament.
density map as showed in Figure 8 had been rated and weighted. The calculated lineament density was assigned ranges and rating based on Table 4. The weight of lineament density was assigned a value based on its valuable significance and it measured as (5) [9] [31]. Therefore, lineament index map constructed by multiplying the mentioned weigh to the rated lineament map using map algebra tool in Arc map 10 software.

3.5. Modify Standard DRASTIC Model Using Lineament Index Map

To modify likely risk of groundwater vulnerability an additional parameter can be added into the original DRASTIC model to show the realistic of vulnerability assessment. In this study, Lineament map is used because of its close relationship with groundwater. In addition, previous studies revealed that there is a close relation between lineament and groundwater yield and flow [10]. Therefore, Lineament index map as additional parameter added to standard DRASTIC model based on the Equation (7) [9]. The result demonstrates the effect of lineament concentration on the vulnerability system.

\[
DL_i = DI + (\text{Lineament density Index})
\]

where: MD(i) is the modified DRASTIC model based on density of lineament; DI is the standard DRASTIC index and the Lineament density index (ratings-weights).

4. Result and Discussion

4.1. Assessment of Standard Vulnerability Mapping

Figure 7 show the standard DRASTIC vulnerability model of HSB with four vulnerability classes including: very low, low, moderate and high vulnerability index. The map obviously illustrates the dominance of moderate and very low vulnerability zones which covers an area of 614 and 435 km² or (48% and 34%) of the whole studied area respectively. In terms of the geological and hydrogeological conditions, moderate vulnerability zone occupies two different areas. The first one is the mountains surrounding the studied basin that includes the fissured and karstic aquifer. While the second area comprises the Quaternary deposits surrounding the area of Derbandikhan reservoir in the southwest of the basin, this might be related to the high water table level and high percent of coarse grain material such as gravel, sand and rock fragment. Furthermore, the zone with low vulnerability considers as the third class in terms of spreading and occupy 166 km² or 13% of the overall surface area of the basin. The zone with high vulnerability index cover only 64 km² or 5% of the total area and is located in the center of basin. This area is characterized by high water table level and presence of several springs with fractured limestone.

<table>
<thead>
<tr>
<th>Table 4. Rate and weight for Lineament density [9].</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range of Lineament Density</td>
</tr>
<tr>
<td>0.2 - 1.1</td>
</tr>
<tr>
<td>1.2 - 1.3</td>
</tr>
<tr>
<td>1.4 - 1.5</td>
</tr>
<tr>
<td>1.5 - 1.8</td>
</tr>
<tr>
<td>1.9 - 2.0</td>
</tr>
<tr>
<td>2.1 - 2.2</td>
</tr>
<tr>
<td>2.3 - 2.4</td>
</tr>
<tr>
<td>2.5 - 2.6</td>
</tr>
<tr>
<td>2.7 - 2.8</td>
</tr>
<tr>
<td>2.9 - 4.0</td>
</tr>
</tbody>
</table>
Figure 7. Standard DRASTIC Map for HSB.
4.2. Assessment of Lineament Density and Index Maps

The lineament density map of the study basin is exposed in Figure 8. This map is produced by applying GIS techniques from lineament map extracted from satellite landsat 8 images (ETM+, 2013). The map reveals that HSB divided in to six classes of lineament density distribution as explained on Table 5 with percent and the area of land covering of each.

Figure 8 illustrate the Lineament density map of HSB, it can be noted that Class-VII which is characterized by low density of lineament distribution covered most of studied basin land with an area of (1165.7) km² or (91.2%) of total studied area. In addition, the higher lineament density range is Class-I which is occupy only 1.5 Km² or (0.12%) of the whole HSB, which is located along the mountain ranges in the northwestern portion of studied basin, coincident with major subsurface structural development along Sirwan Mountain namely developed thrust fault and overturned double plunging anticline as explained on geological map, Figure 2.

The remaining classes of (Class-II, Class-III, Class-V and Class-VI) covering an area of 5.4, 9.2, 23.9, and 72.3 Km² or (0.42%, 0.72%, 1.87% and 5.66%) of the whole studied area respectively. Furthermore, from the result mentioned above, it can be concluded that HSB considered as relatively low lineament density.

The map of ratings lineament in (Figure 9) illustrates rating value ranging from 1 - 7 (Table 5). Class-I was assigned a probability rating of 7 and occupies only 0.12% of HSB area, because the density range of lineament considered as high intensity. While Class-VII assigned a probability rating of 1, as they contain low density range which is only (0 - 1.05). Additionally density ranges of classes (Class-II, Class-III, Class-V, Class-VI) were rated as (5, 4, 3 and 2) respectively and occupied (0.42, 0.72, 1.87 and 5.66) of the whole HSB area respectively.

Furthermore, the lineament density rating map as a raster grid was multiplied using map algebra in GIS environment by the weight of the parameters (Lw = 5) to construct Lineament index map as shown in Figure 10. The index value classified into six classes as well (5, 10, 15, 20, 25 and 35), which occupies the same area as mentioned previously in the lineament rating map explanation.

4.3. Assessment of Modified DRASTIC Vulnerability Model

Figure 11 demonstrate modified DRASTIC index map based on lineament index map with ranging of (68 - 196). The range of index values was divided into four classes including very low to high vulnerability classes (Table 6).

<table>
<thead>
<tr>
<th>Class</th>
<th>Range of Lineament Density Distribution</th>
<th>Rating</th>
<th>Area_Km²</th>
<th>Area %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class-I</td>
<td>&gt;2.1 - 2.4</td>
<td>7</td>
<td>1.5</td>
<td>0.12</td>
</tr>
<tr>
<td>Class-II</td>
<td>&gt;1.83 - 2.1</td>
<td>5</td>
<td>5.4</td>
<td>0.42</td>
</tr>
<tr>
<td>Class-III</td>
<td>&gt;1.57 - 1.83</td>
<td>4</td>
<td>9.2</td>
<td>0.72</td>
</tr>
<tr>
<td>Class-V</td>
<td>&gt;1.3 - 1.57</td>
<td>3</td>
<td>23.9</td>
<td>1.87</td>
</tr>
<tr>
<td>Class-VI</td>
<td>&gt;1.05 - 1.3</td>
<td>2</td>
<td>72.3</td>
<td>5.66</td>
</tr>
<tr>
<td>Class-VII</td>
<td>0 - 1.05</td>
<td>1</td>
<td>1165.7</td>
<td>91.2</td>
</tr>
</tbody>
</table>

Table 5. Lineament density classes rating in HSB.

<table>
<thead>
<tr>
<th>Vulnerability Class</th>
<th>Standard DRASTIC</th>
<th>Modified DRASTIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Index Value</td>
<td>Area (%)</td>
</tr>
<tr>
<td>Very Low</td>
<td>63 - 100</td>
<td>34</td>
</tr>
<tr>
<td>Low</td>
<td>&gt;100 - 125</td>
<td>13</td>
</tr>
<tr>
<td>Moderate</td>
<td>&gt;125 - 150</td>
<td>48</td>
</tr>
<tr>
<td>High</td>
<td>&gt;150 - 191</td>
<td>5</td>
</tr>
</tbody>
</table>
Figure 8. Lineament density map for HSB.
Figure 9. Lineament rating map for HSB.
Figure 10. Lineament index map for HSB.
Figure 11. Modified DRASTIC lineament index map for HSB.
The modified vulnerability map shows that about (47%) of HSB has moderate vulnerability to contamination with index values ranging between (125 - 150). Whilst, very low vulnerability measured was a second effective class in the studied area with (29%). In addition, (low and high) classes comprise (14%, and 10%) respectively. By comparing between Standard DRASTIC and its modification based on lineament density factor, Table 6, clearly it can be noted that there is no significant variation on the index value and the occupy area as well for classes of low and moderate, only the area of high and very low slightly changed. Taken as a whole from this modification, it can be concluded that lineament density is not effect on the vulnerability model at HSB because majority of the studied area characterized by low density range of lineament distribution which is about (91.2%) of whole HSB area.

4.4. Validation of Modified Model

Each vulnerability maps should be validate after constructing in order to estimate the validity of the theoretical sympathetic of current hydrogeological conditions [32]-[34]. Several methods can be apply for the validation of vulnerability assessments [34]; these include hydrographs, chemographs and tracers (natural or artificial). In order to validate both applied models at HSB, nitrate concentration analysis has been selected. Nitrate as a pollution indicator can be used to recognize the groundwater quality evolution in terms of quality changing. In the particular studied case, the nitrate differences between two following seasons (dry and wet) were analyzed from (30) water wells. The samples were collected and analyzed on end of September 2014 for dry season and end of May 2015 for wet season. The selected wells for nitrate concentration measurement located nearly in all vulnerability zones at each models.

In relation to nitrate values for dry season (absence of rainfall for a long period), (Table 7), low nitrate levels were identified with concentration value ranging between zero to just above 10 mg/l. For modified DRASTIC vulnerability classes namely (very low, low, moderate and High), the average of nitrate concentration in dry season were (<2, 0 - 2, >10 and >10) mg/l respectively (Figure 12(a)). While for wet season the concentration were significantly rose up (0 - 20, 20 - 30, >30 and >30) mg/l respectively (Figure 12(b)). This condition refers to several main factors such as rising up the water table in the wet season and vice versa for the dry season. Secondly, the impact of human activity is significant in wet season specifically using chemical contaminants (nitrate) for agriculture purpose. In addition, rainfall plays an important role to transport nitrate based on specific condition of vulnerability properties of ground strata. Consequently, these considerable variations in nitrate concentration from dry to wet seasons verify that there is no effect of lineament density on standard DRASTIC model in HSB. Therefore, the result once more confirmed that the standard model required to be modified with other different parameters such as land use pattern or rate and weight modification.

5. Conclusions

To assess the prospective vulnerability of groundwater pollution in the HSB standard DRASTIC index model applied in GIS environment. Although the DRASTIC method regularly affords acceptable results in the assessment of intrinsic vulnerability of groundwater to pollution but it might be difficult to consider the result as an accurate risk assessment of the groundwater. Therefore, lineament density distribution as an additional parameter applied to modify it. Landsat o Thematic Mapper (TM) had been used to prepare Lineament map. Images consist of nine spectral bands with cell size (30 × 30 m), the Operational Land Imager (OLI) spectral band in gray scale was used with PCI Geometrica technique. The lineament density map constructed from lineament

<table>
<thead>
<tr>
<th>Standard DRASTIC Vulnerability Category</th>
<th>Nitrate Concentration (mg/l) Dry Season</th>
<th>Modified DRASTIC Vulnerability Category</th>
<th>Nitrate Concentration (mg/l) Dry Season</th>
</tr>
</thead>
<tbody>
<tr>
<td>V. Low</td>
<td>&lt;2</td>
<td>V. Low</td>
<td>0 - 2</td>
</tr>
<tr>
<td>Low</td>
<td>0 - 2</td>
<td>Low</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Medium</td>
<td>&gt;10</td>
<td>Moderate</td>
<td>&gt;10</td>
</tr>
<tr>
<td>High</td>
<td>&gt;10</td>
<td>High</td>
<td>&gt;10</td>
</tr>
</tbody>
</table>

Table 7. Nitrate concentration in both dry and wet seasons at each vulnerability class.
Figure 12. Modified model with nitrate concentration: (a) dry season; (b) wet season.
map in GIS environment. The map demonstrates that six classes can be recognized from low to high density. Each class has specific rate and weight value based on its impact environmentally as explained in Table 4. Seven parameter maps were developed in a GIS environment to generate standard models and one parameter (Lineament density index map) is added to modify it. The DRASTIC vulnerability index values ranged between (63 and 191), (68 and 196) for standard and modified respectively.

The vulnerability classes are elucidated in the Figure 13. As can be noted, both standard and modified DRASTIC model clarify only four vulnerability classes comprises (very low to high). The moderate vulnerable areas constitute (46.91%) of the basin for modified results and mostly are located in the central and north west of the HSB. This percent was 48% before modification which is considered as weak variation. High vulnerability class varied from (5%) to (10%) after modification and located in the area of mountain with high lineament density. In addition, a huge variation in the rate of vulnerability has not been seen for the remaining classes. Nitrate as a pollution indicator can be supportive to distinguish the evolution and changes of groundwater quality. In the particular study case, the nitrate differences between two following seasons (dry and wet) were analyzed from (30) water wells to validate the results. The result illustrates considerable variations in nitrate concentration from dry to wet seasons. So it can be concluded that HSB are capable to receiving the contaminant due to its suitability in terms of geological and hydrogeological conditions. As a result, it could be argued that the effect of lineament density is weak on the vulnerability process in HSB. Because standard and modified models provided nearly the same outcome as a result of low lineament density value, on the other hand, nitrate contributed a big variation in its concentration.

References

Land and Water Conservation, Parramatta.


