GROUNDWATER VULNERABILITY MAP OF BASARA BASIN, SULAIMANI GOVERNORATE, IRAQI KURDISTAN REGION

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Abstract

The Basara basin which is one of the most promising hydrogeological basin in Iraqi Kurdistan Region, located in north east of Iraq, 25 km west of Sulaimani city, between the 496652 - 537752 East and 3911038 - 3951906 North in Universal Transverse Mercator (UTM) and lie in Zone 38N. The basin has a rectangular shape and covering an area of 571 km². The present hydrogeological investigations have revealed three inhomogeneous and anisotropic water bearing formations: Eocene Karstic Fissured Aquifer (EKFA), Intergranular Aquifer represented by Alluvium and Pliocene (AIA) & (PIA), as well as Miocene Complex Aquifer (MCA).

For the first time, not only in Kurdistan but also in Iraq, Groundwater Vulnerability Map has been constructed in this study, using DRASTIC method with the assistance of Geographic Information System (GIS) to show zonation area of high and low groundwater susceptibility to pollution. Accordingly, vulnerability classes of the study area were classified into four classes. Most of the basin shows the highest extension of the zones with very low and low vulnerability zones, in contrast the zones with high vulnerability are distributed mainly in the mountain areas, solely in the eastern Uloblagh and Kuwaik mountains, in addition to that small zones in the farthest northern corner and south western corner of the area have less or no human activity.

خريطة عرضة المياه الجوفية لحوض باسرة، محافظة السليمانية، إقليم كردستان العراق

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الخلاصة

يقع حوض باسرة شمال شرق العراق، ٢٥ كم غرب مدينة السليمانية، بين خطي طول (٤٩٦٦٥٢ و ٥٣٧٧٥٢ شرقا) و خطي عرض (٣٩١١٠٣٨ و ٣٩٥١٩٠٦ شمالا). هذا الحوض له شكل مستطيل و يغطي مساحة مقدارها ٥٧١ كم٢. اظهرت الدراسة الهيدروجيولوجية الحالية وجود ثلاثة وحدات طباقية حاملة للمياه والتي تمتاز بعدم التناظر والتجانس لوحداتها. الوحدة الأولى عرفت بالمكامن المائية الكارستية المتشققة الإيوسينية، الوحدة الثانية تمثلت بالمكامن المائية الفتاتية البينية والمتمثلة بالترسبات النهرية والترسبات البلايوسينية، بينما الوحدة الأخيرة والأقل شيوعا سميت بالمكامن المائية المعقدة العائدة الى زمن المايوسين.
لأول مرة على مستوى كردستان والعراق، تم عمل خريطة للمياه الجوفية تبين الأماكن الأقل والأكثر عرضة للتلوث مستخدما طريقة ال DRASTIC ومستعينا بنظام المعلومات الجغرافية GIS. تم تصنيف الخريطة المتشكلة الى اربعة اصناف رئيسة. أظهرت النتائج بان معظم مناطق الدراسة قليلة العرضة للتلوث (low vulnerable) ماعدا بعض الجيوب لأماكن صغيرة والواقعة في مناطق جبلية وتحديدا شرق جبلي أولوبلاغ و

كويك مع بعض الأنطقة الصغيرة الأخرى والواقعة في جناحي الشمال و الجنوب الغربي لمنطقة الحوض والتي
تمتاز بقلة النشاط البشري حيث تعرضها للتلوث عالية نسبيا (high vulnerable).

Introduction

Nowadays, aquifer vulnerability assessments are carried out in almost all developed countries in areas where water resources are under stresses originating from urbanization, industrial and agricultural activities. The Basara basin which is one of the most promising hydrogeological basin in Iraqi Kurdistan Region, is located in north east of Iraq, 25 km west of Sulaimani city, between the 496652 - 537752 East and 3911038 - 3951906 North in Universal Transverse Mercator (UTM) and lie in Zone 38N. The basin has a rectangular shape and covering an area of 571 km², (Fig.1). The present hydrogeological investigations performed by [1,2], have revealed three inhomogeneous and anisotropic water bearing formations: Eocene Karstic Fissured Aquifer (EKFA), Intergranular Aquifer represented by Alluvium and Pliocene (AIA) & (PIA), as well as Miocene Complex Aquifer (MCA), (Fig.2).

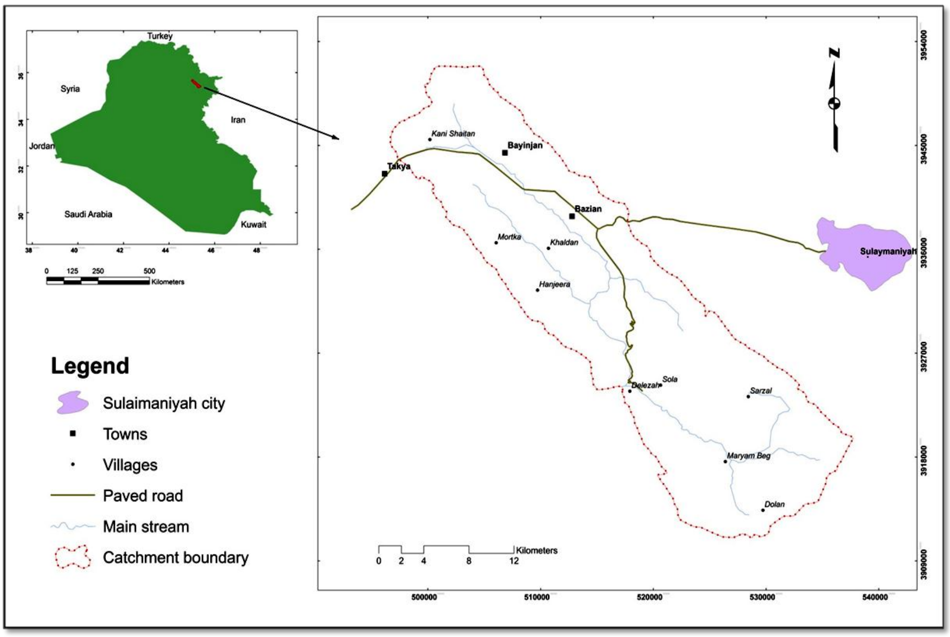

Fig 1: Location map of the Basara basin

The abstraction of groundwater from this basin, supplies water for more than 90% of populations inside the area, moreover it provides potable water for other inhabitants outside the studied basin (such as Takiya and Chamchamal towns). Within the last few years, rapid urbanization, growth in industries and agricultural activities are the main phenomena that everyone can felt. Establishing Bazian and Mass Cement factories, as well as Bazian Oil Refinery and several water bottling factories such as Ala Cola and Ice Water are examples of this growth in the area.

In contrast, providing water with high quality and sufficient quantity for those sectors have been increased dramatically, while the over-exploitation of the aquifers and the occasional depletion of annual precipitation have also been increased the decline of the groundwater supply. Its wealth to mention also, although this region has 700 mm of annual rainfall in average which precipitated during winter and spring seasons, but a problem of water shortage rises during dry season represented by Summer and Autumn where no or very limited rainfall occur. Moreover, lack of knowledge of groundwater management and little or no regulated protection of aquifer will be affected negatively in the future. Accordingly, this study is considered as the first attempt not only in Kurdistan, but also overall the Iraq, which tries to construct a vulnerability zonation map especially with the aid of using most recently tool in such field of study, that is called geographic information system (GIS).

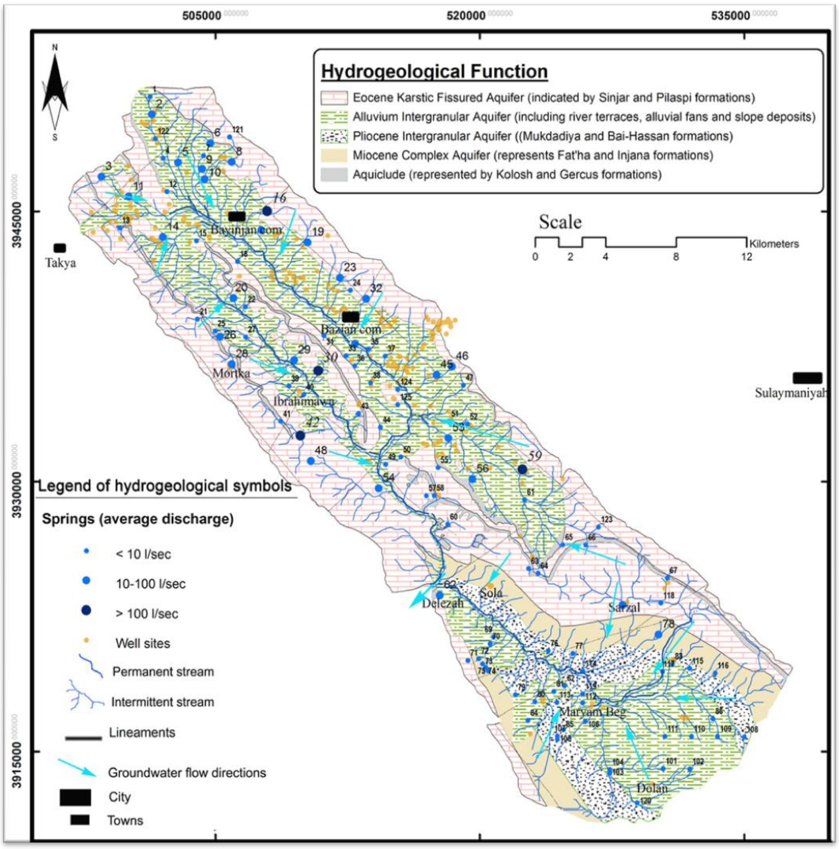

Fig.2: Hydrogeological map of Basara Basin

Previous studies

The vulnerability studies can provide valuable information for stakeholder working on preventing further deterioration of the environment [3]. Aquifer vulnerability studies are useful in the evaluation of the economic impacts of the waste disposal in highly vulnerable areas. Moreover, they are providing preliminary information and criteria for decision making in such areas as designation of land use controls, delineation of monitoring networks, and management of water resources in the context of regional planning as related to protection of groundwater quality. Yet internationally, vulnerability maps were becoming an essential part of groundwater protection schemes and a valuable tool in environmental management [4]. The first attempt to the concept of groundwater vulnerability to contamination was applied by Margat (1968) in France [5]. Then there were several approaches for developing aquifer vulnerability assessment maps, such as DRASTIC [6], GOD [7], AVI [8], SINTACS [9], A thorough overview of existing methods is given in [10] and in [11]. These methods have been mainly applied to groundwater protection in porous aquifers, except the EPIK [12,13], PI [14] and COP [15] methods which were specifically developed for the assessment of vulnerability in karstic area [16]. Recently, the concept VURAAS (Vulnerability and Risk assessment for Alpine Aquifer System) was developed in Alpine karst area in Austria, by [17,18], in which the final result of this system is the risk map which shows areas at varying degree of potential groundwater contamination risks. The map of vulnerability and the map of Hazards are the basis for the risk map. While there is no study performed for vulnerability mapping in the area, some regional studies are indirectly related to hydrogeological and hydrological conditions were done on and around this area. Among these studies are [19, 20, 21, 22, 2, 23] and finally [1]

DRASTIC method

The best known and probably the most widely applied scheme of vulnerability assessment was developed by the US Environmental Protection Agency (USEPA) and is known as the DRASTIC methodology [6], applied later in several regions by different researchers where they modified this system to meet a wide range of application such as land use index, lineaments, aquifer thickness and impact of contaminant. [24] developed a software package AHP-DRASTIC to derive rating and weights for modified DRASTIC model parameters [25]

In general, the DRASTIC system is composed of two major parts: (1) the designation of mappable units, termed hydrogeological settings; and (2) the application of a numerical scheme of relative ranking of hydrogeological factors [26]. Hydrogeological factors help to evaluate the relative groundwater pollution potential of any hydrogeological setting. Recently, geographic information system (GIS) techniques have been widely used in aquifer vulnerability mapping. The major advantage of GIS-based mapping is the combination of data layers and rapid change in the data parameters used in vulnerability classification [27]

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) (Fig 3). Each parameter is subdivided into ranges and is assigned different ratings in a scale of **1** least contaminant potential to **10** highest contaminations potential.

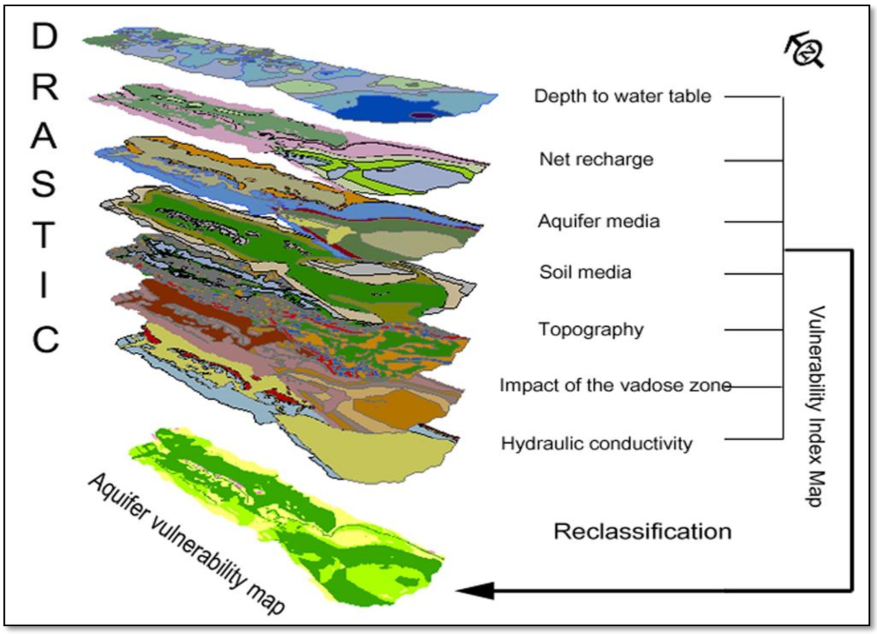

Fig 3: Methodology flowchart for DRASTIC method

1- Depth to water table map (D_MAP)

This factor deals with the duration of contaminant in liquid phase to travel through the unsaturated zone to reach the water table in the aquifer. In general the deeper the water table, the longer the pollutant material in liquid phase takes to reach the groundwater which gives a chance for attenuation of contaminant material by degradation or natural retention. Generally, Depth of water is computed from water table surface topography, then water table contours are digitized, geo-referenced and rasterized. For this study, groundwater headmeasurements were made in 283 wells These data were recorded in the GIS environment to construct depth to water table map (Fig 4). The layer was converted to raster format with 80 m cell size. Most of the data were collected on August and September, 2009 by the team from Directorate of Groundwater of Sulaimaniyah (DGWS) and partly by the researcher during field works. The rating for this parameter presents a wide range of variation from the occurrence at ground level at the zones of natural discharge represented by springs to greater depths exceeding 110 m close to the Bazian Oil Refinery site.

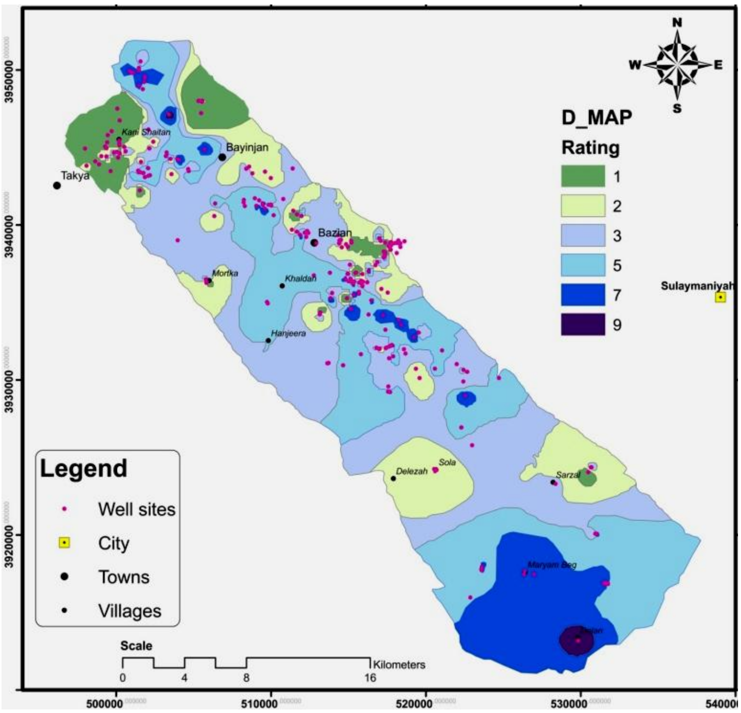

Fig 4: Rating map of (depth to water table) (D_map) of the Basara basin

The rating for depth to water table varies from 9 (for 1.5 - 4.5 m water table depth) to 1 (for more than 30 m depth), based on the ranges and rating for depth to groundwater table proposed by [6] (Table 1).

Table 1:Ranges and rating for depth to groundwater table (6).

Rating	Depth to water (m)
10	Between 0 and 1.5
9	1.5 - 4.5
7	4.5 - 9
5	9 - 15
3	15 - 23
2	23 - 30
1	More than 30

As can be depicted from the depth to water table map (Fig.4), the southern part and some sites in the central area are the shallowest location in the basin; therefore the highest rating value belongs to these areas. In contrast, northern and northwestern part have water table more than 30 m, this probably related to overexploited withdrawal groundwater at these locations, especially nowadays some of the densely settlement towns (like Takya and Chamchamal cities where they are located several kilometers to the west of the area) provide all or most of their consumption of potable water on the groundwater through drilling wells percolating both Sinjar and Pilaspi formations close to Kani Shaitan area) in addition to that several big factories of water bottling (such as Ala Cola and Ice Water were built inside these areas), as well as the two big cement factories (Bazian and Mass Cement) have their own drilling wells where they are draying water for their production. All these activities make groundwater to be depleting more in comparison to the surrounding area. It is necessary to mention that, the sharp topography in the area may cause great values of groundwater depth; at the end, all these factors depleted the groundwater table make the area less vulnerable and have rating of 1 and 2.

2- Net recharges (R_MAP)

According to [28], net recharge; is the total depth of water which infiltrates into the aquifer on an annual basis. Contaminant can move with groundwater easily depending on water quantity. Therefore, net recharge is a very important factor for assessment of aquifer vulnerability. Net recharge includes the average annual amount of infiltration and does not take into consideration the distribution, intensity or duration of recharge events [29]. Thus, the more the recharge, the greater the contamination of groundwater will occur. In order to evaluate the net recharge percolated to the basin, the simple groundwater balance has been used, eq (1).

$NR = P - ET - R_0$ ……………….eq (1)

Where;
NR: is the net recharge in mm/year,
P: is the annual precipitation in mm;
ET: is the evapotranspiration in mm/year calculated by FAO Penman Monteith method and R_0 is the total runoff in mm. Total runoff for each month is calculated using SCS method, accordingly the annual runoff was 149 mm/year (approximately 21.5 % of the annual precipitation), while the expected evapotranspiration for the wet season (October to May) was 387 mm, [1]. Accordingly, the total expected average net recharge is estimated in 96 million cubic meters per year or 168 mm/year on average or 24 % of the total annual rainfall (when recharges from surface runoff are not considered in this calculation) with sharp variations, ranging from hardly 15mm/year to 238 mm/year, the results is given in (Table 2).

The rating of net recharge varies from low vulnerability **1** (for 15 to 45 mm/year), such as that of urban area, aquiclude or aquifers with very low to low permeable rocks, (Kolosh, Gercus, Fat'ha and Injana formations fall within this rate) to high vulnerability **8** (for 220 to 238 mm/year) in the karstic fissured aquifer represented by both Sinjar and Pilaspi formations, based on the proposed table given by [6] (Table 3).

Table 2: Expected amount of net recharge for each month and for each geological zones based on SCS and soil water balance methods. (1)

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total		
P	36.5	88.3	110	118	112	103	85	38.7	0.0	691.6		
Surplus	0	0	*87.8*	*97.9*	*84.5*	*46.5*	0	0	0	316.8		
Runoff	0	0	*37.5*	*43.0*	*39.2*	*29.3*	0	0	0	149		
Proposed CN	Net recharge in (mm)								Enclosed area (km^2)	Volume (x 10^6 m^3)	Net recharge in (mm)	Net recharge %
90	0	0	6.1	8.3	0.3	0.0	0	0	12.39	0.18	14.7	**2**
86	0	0	15.9	18.4	10.2	0.0	0	0	64.77	2.88	44.5	**6**
83	0	0	22.8	25.5	17.2	0.0	0	0	45.76	3.0	65.5	**9**
69	0	0	50.3	54.7	45.3	13.7	0	0	156.5	25.68	164.1	**24**
65	0	0	56.9	61.9	52.1	19.8	0	0	50.9	9.71	190.7	**28**
62	0	0	61.5	66.9	56.8	24.1	0	0	14.33	3.0	209.3	**30**
60	0	0	64.4	70.1	59.8	26.7	0	0	144.6	31.96	220.9	**32**
57	0	0	68.5	74.6	64.0	30.4	0	0	81.97	19.46	237.5	**34**
									571.3	***95.87***		
T. NR x10^6 m^3	0	0	21.4	24.6	22.4	16.7	0	0				***95.87***
T. NR in mm	0	0	*50.3*	*54.9*	*45.3*	*17.3*	0	0				***167.8***

Table 3: Ranges and rating for the net recharge in (mm/year) (6)

Factors	Range (mm/year)	Rating
Net Recharge	Less than 50	1
	50 - 100	3
	100 - 175	6
	175 - 250	8
	More than 250	9

The net recharge map was prepared using the inverse distance weight (IDW) interpolation method of ArcGIS spatial analyst (Fig 6).

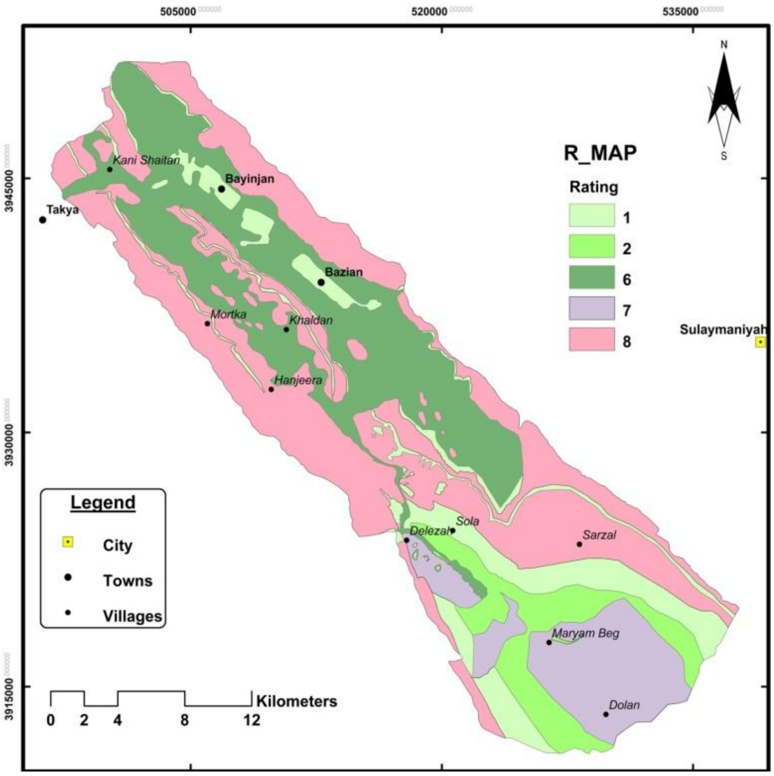

Fig.6: Rating map of net recharge (R_map) of the Basara basin

3- Aquifer media (A_MAP)

This factor refers to the consolidated or unconsolidated rocks through which water circulate in the aquifer. In those rocks with inter-granular porosity, or secondary (inter-granular dissolution and dolomitization in carbonate rocks), the dispersive component is controlled by the size and lithology of the walls. In fractured or karstified rocks, the advective component of transport is prevailing, thus aquifer media is responsible for the system flow control, which defines the path and length the contaminant has the cross (30). This parameter is highly related to the geological setting of the area. Accordingly, geological map of the basin was prepared from the field studies, benefiting from previous investigation done by [2,30]and Directorate of Geological Survey of Baghdad (2007). The main aquifer which is being exploited in the central part of the basin is the Quaternary alluvial aquifer, in which the hydrologic condition changes according to the overlying layers, in most cases it is unconfined and it changes to semi-confined and even to the confined aquifer. The thickness was mapped using a previous geo-electrical survey done in the area by (2), in addition to the archives of the drilling well; it ranges between 50 m in most central part to 100 m at Dargazen village. This aquifer is mostly sand, silt and gravel with inter-beds of sliding part of Sinjar Formation. The two other most important aquifers are Pilaspi and Sinjar aquifers; they are classified as karstic fissured aquifer. However, fracture and fissured network system of Sinjar aquifer believed to be slightly more developed than the Pilaspi as the pumping test showed the transmissivity of this aquifer is more than the previous one. The DRASTIC ratings were assigned according to the permeability of each aquifer medium (Table 4). The fracture and fissured aquifer are most vulnerable medium with respect to contamination and it was assigned with rating of 7 and 8 respectively. Furthermore, most of the clastic formations identified as semi permeable to impermeable and assigned a rating of 2 and 3 at the southern part, where clay is more predominant, which implies low values of vulnerability for this area, while most of the central part is particularly difficult to classify, because it is composed of multi-layer set in which the changes in depth and facies changes are abundant, this clearly felt from the geo-electrical survey carried out in the area by (2) (Fig 7). Finally the aquifer media of the basin was obtained and the rating was between 2 and 8, based on (6) (Fig 8).

Table 4: Ranges and rating for the Aquifer media, (6)

Factors	Range	Rating	Typical rating
Aquifer media	Massive shale	1 - 3	2
	Metamorphic/ Igneous	2 - 5	3
	Weathered metamorphic / Igneous	3 - 5	4
	Glacial Till	4 - 6	5
	Bedded sandstone, limestone, shale	5 - 9	6
	Massive sandstone, massive limestone	4 - 9	6
	Sand and gravel	4 - 9	8
	Basalt	2 - 10	9
	Karst limestone	9 - 10	10

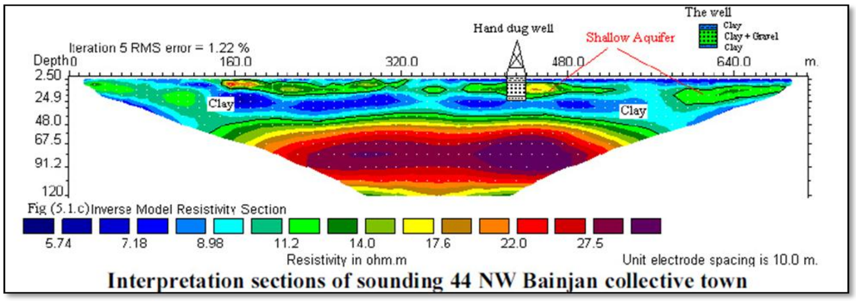

Fig 7: 2D electrical tomography inside the studied area (2)

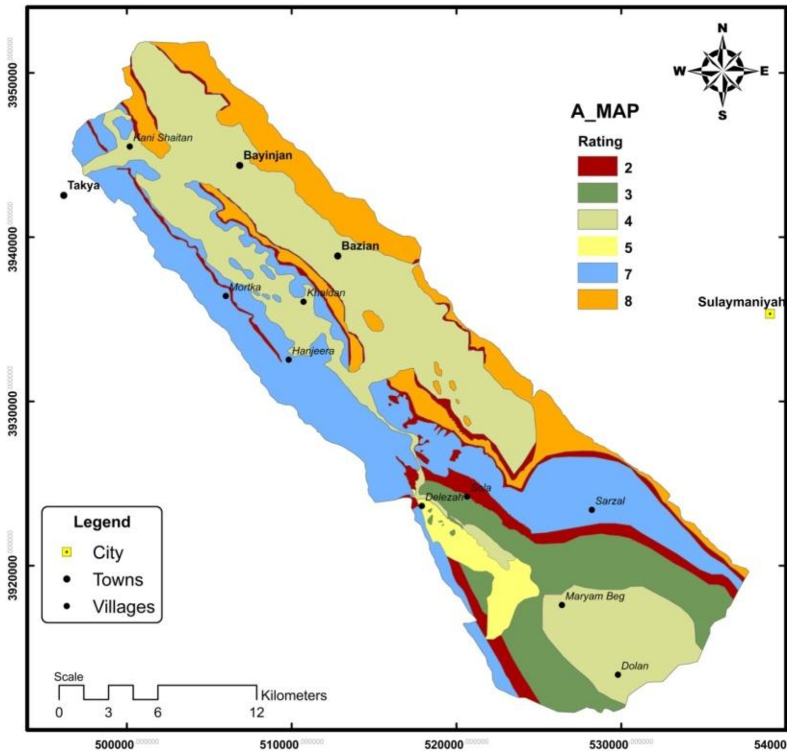

Fig 8: Rating map of aquifer media (A_map) of the Basara basin

4- Soil media (S_MAP)

Soil has a significant impact on the amount of recharge that can infiltrate into the ground, and hence on the ability of a contaminant to move vertically into the vadose zone [26].

For this study, the soil media of the basin was taken from soil map prepared by [1], and reclassified in order to meet the new classification of the DRASTIC system. Each class was assigned with rating from **10** (Thin or absent soil cover) to **2** (for Muck and clay loam), according to table proposed by [6] (Table 5). According to the present map, 4 main classes were identified. The predominant soils are clay loam, silty loam and sandy loam. Extension and types of each soil in the studied area is presented in soil media (Fig.9) and tabulated in (Table 5).

Table 5: Ranges and rating for soil media, (6)

Factors	*Range*	*Rating*
Soil media	Thin or Absent ,Gravel Sand Peat Shrinking and/or aggregated clay Sandy loam Loam Silty loam Clay loam Muck Non shrinking and non- aggregated clay	10 9 8 7 6 5 4 3 2 1

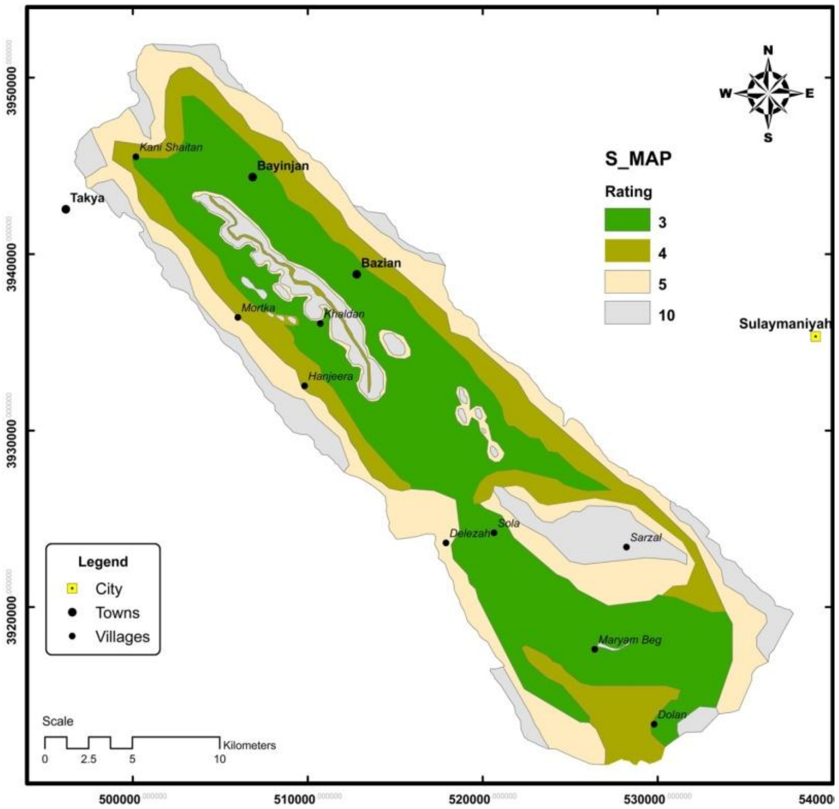

Fig 9: Rating map of soil media (S-map) of the Basara basin

The highest vulnerability values for this factor [10] are located within the mountains area, where no soil or thin layer of weathered soil covers is predominant. On the contrary, the lower values (3 and 4) are related to the Quaternary and clastic formations where clay and silty loam are more frequently found.

Table 6: Extension and rating of soil type in the studied area

Soil type	*Rating*	*Extension area (km^2)*	*Extension area (%)*
Clay Loam	3	230	40.3
Silty loam	4	112	19.5
Loam and sandy loam	5	145	25.4
Thin or soil absent	10	84	14.8

5-Topography (T_MAP)

Topography refers to slope and slope variability over the land surface. It controls the likelihood of a pollutant to be evacuated by runoff or to remain on the ground time enough to infiltrate. When slopes are under 2%, the velocity of direct runoff is quite small, thus favoring infiltration and evapotranspiration. Conversely, when slopes are over 18%, rainwater easily runoff and can evacuate greater amounts of substances either dissolved or suspended [30]. The digital elevation model (DEM) from NASA srtm satellite image with resolution of 80 m is used to construct the topography map layer from elevation points and the topography map by interpolation. The slope aspect was then calculated from the topography map in Arc GIS 9.3. It was sliced into ranges and assigned a rating ranging from 1 to 10 based on standard table prepared for this purpose (Table 7). Flat areas were assigned high rates because they slow down the runoff and allowing more time for the contaminants to percolate down to reach the groundwater، whereas steep areas increase the runoff washing out the contaminants hence are assigned low rates [31].

Table 7: Ranges and rating for topography (6)

Factors	*Range (percent slope)*	*Rating*
Topography (%)	0 - 2	10
	2 - 6	9
	6 - 12	5
	12 - 18	3
	More than 18	1

Topographically, the studied area is diverted and conditioned by the geology and the deformation phase that took place during the tectonic activity during Cretaceous in the area, trending structures towards NW-SE direction. The highest peaks frequently reach heights over 1600m, being the most outstanding the ranges in the south western part of the area, while the lowest elevation (680m) recorded close to Basara gorges. For the evaluation of vulnerability of this factor, slopes have been smoothed and slope ranges were assigned with a rating from 10 to 1, based on the proposed table recommended by [6] (Fig 10).

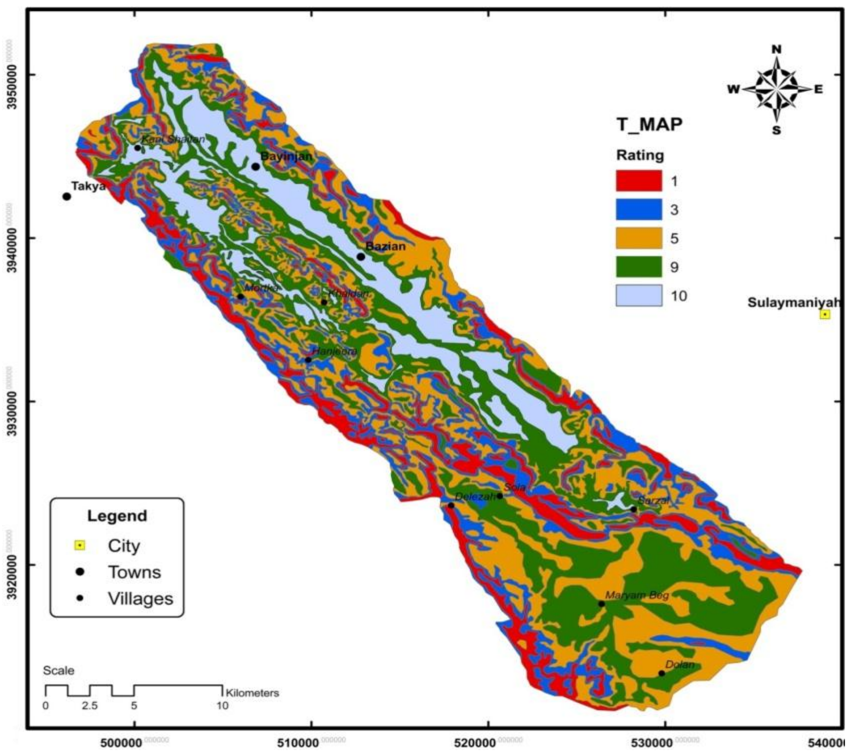

Fig 10: Rating topography map (T_map) of the Basara basin

6- Impact of the vadose zone (I_MAP)

The vadose zone is defined as the zone above the water table or unsaturated zone. Percolation of precipitation and any kind of surface water is occurred within this zone, so it has an important role in attenuating the pollutant materials. Based on [31], in a stratified sedimentary media with strong variations in the hydraulic conductivity, a pollutant can reach an aquifer even when the horizontal distance from its location at the ground surface is large, while open fractures and karstic cavities enable a strong concentration of infiltration water and decrease the attenuation potential of the vadose zone. This parameter was obtained using drilling profiles from private drilling company and from directorate of groundwater aided by geo-electrical section carried out by previous studies. These profiles were used to encode the geological units according to the DRASTIC model rating system. Coarse media was assigned a high rating value compared to the fine media types (Table 8).

Table 8: Ranges and rating for impact of the vadose zone (6)

Factors	Range	Rating	Typical rating
Impact of the vadose zone media	Confining layer	1	1
	Silt/ clay	2 – 6	3
	Shale	2 – 5	3
	Limestone	2 – 7	6
	Sandstone, Bedded limestone, sandstone, shale, sand and gravel	4 – 8	6
	Metamorphic/ Igneous	2 - 8	4
	Sand and gravel	6 – 9	8
	Basalt	2 - 10	9
	Karst limestone	8 - 10	10

The most vulnerable areas are related to the unsaturated zone of limestone lithology, with higher values (rate with 8). Generally, these zones are located at the ranges where the permeable formations that constitute the aquifers Sinjar and Pilaspi in addition to clastic and un-consolidated material from Bai Hassan and slope deposits formations among other outcrop. The recent deposits in the central part of the basin use to have vadose zones where gravel and sand levels alternate with clay and silt that considerably decreased the vulnerability values (rate with 2). Nevertheless, in other cases these lithologies present lower contents in fine materials, which can result in medium vulnerability values (3 to 5) such as the case of Kolosh, Gercus, Injana and Fatha formations (Fig 11).

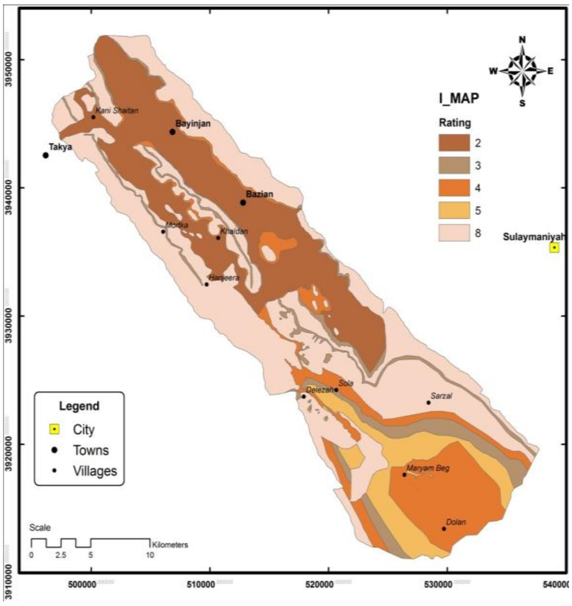

Fig.11: Rating map of the impact of the vadose zone (I_map) of the Basara basin

7- Hydraulic conductivity (C_MAP)

Hydraulic conductivity controls the rate of groundwater movement in the saturated zone, thus, contaminant migration is limited depending on the permeability of the medium [25]. For assessing the hydraulic conductivity, the scaled values based on pumping tests data, drilling wells profiles and electrical tomography sections have been used (Fig 12). Accordingly, 58 wells were selected for calculating the transmissivity by pumping test, and then hydraulic conductivity is estimated based on the following equation:

C = T / b;

where C is the hydraulic conductivity in (m/day), T is the transmissivity in (m^2/day) and b is the aquifer saturated thickness in (m). The different hydraulic conductivity zones in the area were defined and assigned ratings according to (table 9).

Table 9: ranges and rating for the hydraulic conductivity (6)

Factors	*C (m/day)*	*Rating*
Hydraulic conductivity	Less than 4.0	1
	4.0 – 12.0	2
	12.0 – 30.0	4
	30.0 – 40.0	6
	40.0 – 80.0	8
	More than 80.0	10

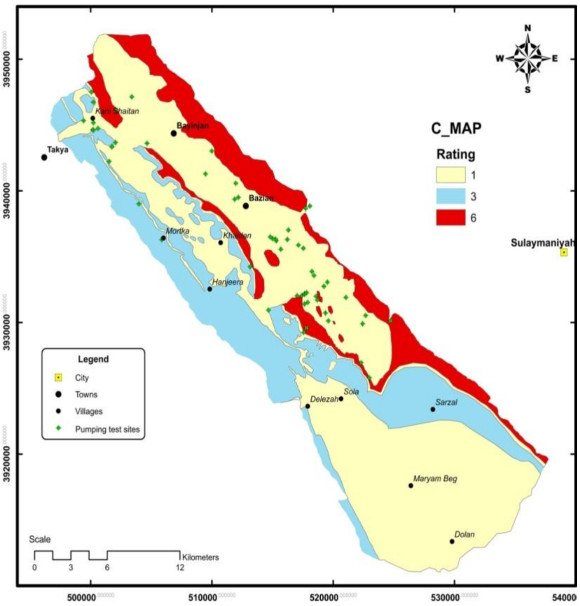

Fig 12: Rating hydraulic conductivity map (C_map) of the Basara basin

Most of the pumping tests carried out in the area were single well test. Thus results of such tests may not reflect the real case of hydraulic conductivity, accordingly 3 wells were selected for analyzing the pumping test, both constant and recovery test were applied using the principal of observation well, each tests carried out in a different aquifer in the area. Generally, results of the hydraulic conductivity calculated for the wells penetrating Alluvium Intergranular Aquifer (AIA), and even the observation well test which was applied during this study, as well as some wells which are penetrating complex and other inter-granular aquifers in the area, have showed the hydraulic conductivity less and around 1.0 m/day, this might be attributed to the repetition of the fine, medium and coarse grained textures, as well as variations in permeability from one site to another. The results of nearly 45 single well tests carried out mostly in Sinjar and partly in Pilaspi karstic-fissured aquifers, showed values between (0.1 – 35) and (0.5 – 2) m/day respectively. But, when the observation well tests applied, the results of both Sinjar and Pilaspi were (43 m/day) and (8.5 m/day) respectively. The fissures and general aquifer's anisotropy may contribute occasionally to this better permeability as cited by [21]. Thus, a result of the present study was applied to all outcrops exposed by karstic-fissured aquifers, i.e. all areas where Sinjar is exposed; a hydraulic conductivity of 43 m/day, while for the outcrop of Pilaspi an 8.5 m/day was applied. Accordingly, the central and most southern zone of the basin has the lowest hydraulic conductivity rating value (1). In contrast, high rating C value is assigned to the Sinjar aquifer where the outcrop is exposed, (rating with 6). The Pilaspi aquifer in the basin show low vulnerability [3]. The positions of the test wells and rating distribution are shown in (Fig 12)

Vulnerability map

Vulnerability maps nowadays have been produced for a number of purposes. For example, they provide a measure of the likelihood of contamination, assist in ensuring that protection schemes are not unnecessarily restrictive for human economic activity, help in the choice of engineering preventative measures, and enable major developments, which have a significant potential to contaminate, to be located in areas of relatively low vulnerability and therefore, of relatively low risk from a groundwater perspective [4]. The linear additive combination of the prepared previous seven parameter maps with ratings and weights was used to calculate the DRASTIC vulnerability index (***DVI***) as given bellow:

$$DVI = (Dr \times Dw) + (Rr \times Rw) + (Ar \times Aw) + (Sr \times Sw) + (Tr \times Tw) + (Ir \times Iw) + (Cr \times Cw)$$

Where; *D*, *R*, *A*, *S*, *T*, *I*, and *C* are the seven factors of the DRASTIC method, ***w*** the weight of the factor, and ***r*** the rating associated. The weighting represents an attempt to define the relative importance of each factor in its ability to affect pollution transport and it varies from 1 to 5 (Table 10). The higher the value for the (***DVI***) the greater the vulnerability of that location of the basin will occur. The final groundwater vulnerability map was obtained at a scale of (1:250,000) using the seven hydrogeological data layers in GIS environment (Fig 13). All parameter maps were converted into raster format and multiplied by their respective weights. The range of the DRASTIC vulnerability index in the studied basin was between **37** and **168**. Accordingly, vulnerability classes of the study area were reclassified into four classes based on the proposed table recommended by (6) (Table 11).

Table 10: Weights of the factors in the DRASTIC method, (6)

Factor	DRASTIC method
D: ***D***epth to Water	5
R: Net ***R***echarge	4
A: ***A***quifer Media	3
S: **S**oil Media	2
T: ***T***opography	1
I: ***I***mpact of the vadose zone	5
C: Hydraulic ***C***onductivity	3

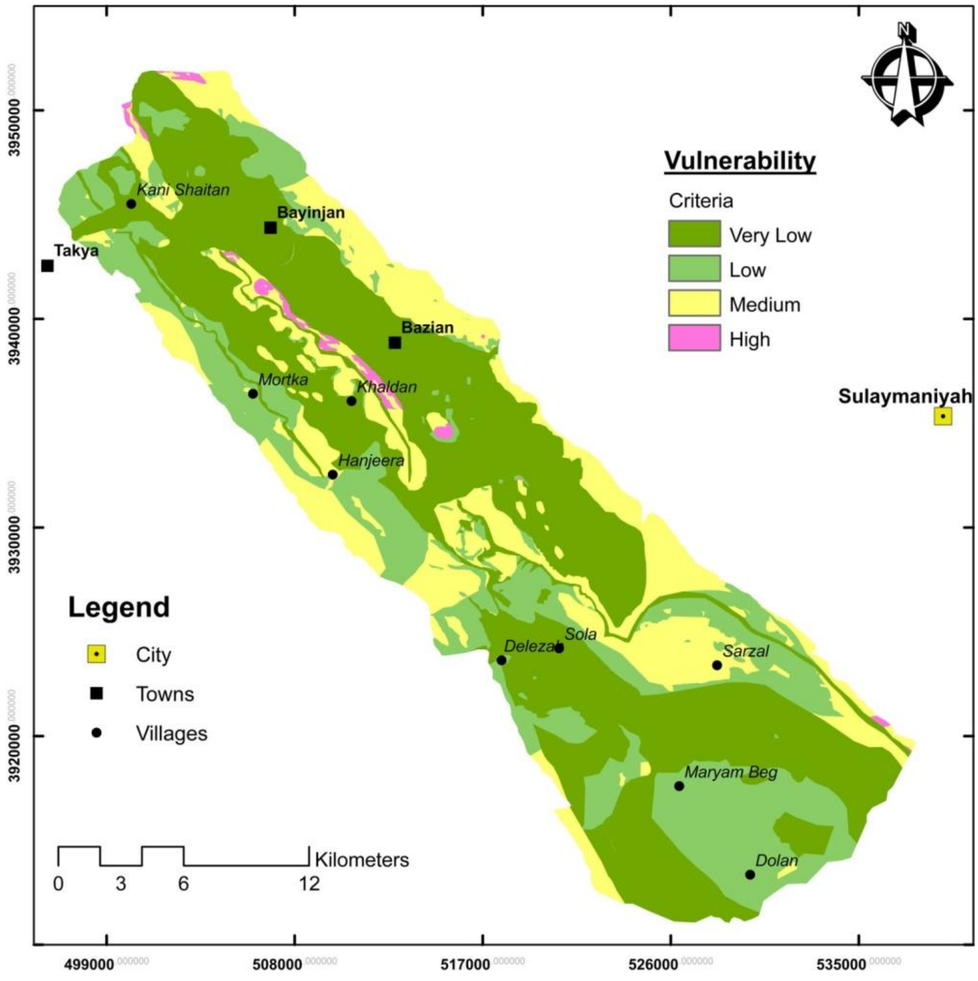

Fig 13: Groundwater vulnerability map of the Basara basin

Groundwater Hazards

Based on the prepared vulnerability map of the groundwater to pollution in the Basara basin by DRASTIC method, most of the basin show the highest extension of the zones with very low and low vulnerability zones which occupying an area of 281 Km^2 or 49 % and 151 km^2 or 26.5 % of the studied basin respectively comparing to the other zones of the catchment area.

Table 11: Ranges of vulnerability using DRASTIC method (6)

Index of vulnerability	Vulnerability degree
Less than 100	Very low
100 – 125	Low
125 – 150	Medium
150 – 200	High
More than 200	Very High

The zones with medium vulnerability occupy 131 km^2 or 23 % of the basin, while the zones with high vulnerability occupy only 8 km^2 or 1.3 % of the total surface of the basin. The zones with high vulnerability are distributed mainly in the mountain areas, solely in the eastern Uloblagh and Kuwaik Mountains, in addition to the small zones in the farthest northern corner and south eastern corner of the area with scarce of human activity. The high vulnerability in these zones are probably related to the shallowness of the water table, the high infiltration rate as well as the high permeability of the vadose zone materials, which are mainly constituted by karstic fissured outcrops of Sinjar Formation. Most of the medium vulnerability zones are located within the Sinjar and pilaspi formations. In contrast, the areas with very low and Low vulnerability zones are located in the central and southern part of the basin, frequently at plain and over clastic formations with greater occupation and activity. The reasons for such low vulnerability especially in the central and southern part is related to the confining layers and low permeability which impede movement of groundwater downward, and the greater depth of the water table in those locations. However, in future, such areas could be vulnerable to conservative pollutants in long term when continuously and widely discharged and leached materials occur. Despite this suitable disposition, any activities that implies the generation of waste disposal must be accompanied by a study about the impact on groundwater especially for the physical and chemical properties of the soil. Local studies must assess the pollution risk of the activity particularly in sites where industrial projects are active, such as Bazian Oil Refinery project where it is close to the Pilaspi aquifer and most of its waste which composed of heavy metal and other pollutant sources are disposed over the plain area, if such cases continued without treatment plant and finding suitable solution for this plume pollution source, a great risk to the quality of groundwater will happen in the future. Since both Bazian Cement and Mass Cement factories are directly located on the outcrop of Sinjar Formation, activities for such factories probably influence the quality of groundwater; especially where they are located directly on the outcrop of Sinjar aquifer, the later has a large hydraulic conductivity, in case if the pollutant material drained into the aquifer, the flow of groundwater will spread-out over most of the area within a short time, thus monitoring their actions and taking samples for sureness the quality of groundwater at such sites are highly recommended.

Conclusions and Recommendations

For the first time in Iraq, the ***groundwater vulnerability map*** using DRASTIC system was constructed using GIS techniques by this study. Based on this map, most of the basin shows the highest extension of the zones with very low and low vulnerability zones. In contrast the zones with high vulnerability is distributed mainly in the mountain areas, solely in the eastern Uloblagh and Kuwaik Mountains, in addition to that, small zones in the farthest northern corner and south western corner of the area have less or no human activity. The anthropogenic pollution may endanger water resources within the few next decades, particularly in Bazian sub basin where agriculture and industrial activities is very high. Accordingly, attention should be paid for environmental protection in this area. Preparation of a vulnerability map for the other basins in Kurdistan is highly recommended to provide information and criteria for decision making and management of water resources to protect the groundwater quality.
Application of other methods of vulnerability methodology like EPIK, GOD and VURAS is also necessary which is more frequently used in karstic medium.

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