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Possibility of Groundwater Pollution in Halabja Saidsadiq Hydrogeological Basin, Iraq Using Modified DRASTIC Model Based on AHP and Tritium Isotopes

Twana O. Abdullah [1,2], Salahalddin S. Ali [1,3], Nadhir A. Al-Ansari [2,*] and Sven Knutsson [2]

[1] Department of Geology, University of Sulaimani, 46024 Sulaymaniyah, Kurdistan Region, NE Iraq
[2] Department of Civil, Environmental and Natural Resources and Engineering, Division of Mining and Geotechnical Engineering, Lulea University of Technology, 97187 Lulea, Sweden; twana.abdullah@ltu.se (T.O.A.); Sven.Knutsson@ltu.se (S.K.)
[3] Department of Geology, Komar University of Science and Technology, 46024 Sulaimani, Kurdistan Region, Iraq; alah.saeed@komar.edu.iq
* Correspondence: nadhir.alansari@ltu.se

Received: 15 June 2018; Accepted: 26 June 2018; Published: 28 June 2018

Abstract: An anthropogenic activity is one of the most severe environmental causes for groundwater contamination in the urban area. Groundwater thought to be one of the principal sources of water supply in Halabja Saidsadiq Basin, and therefore its vulnerability evaluation to define areas that are more vulnerable to pollution is incredibly vital. The objectives of this paper are to reveal weight modified of DRASTIC model based on the Analytical Hierarchical Process to estimate the proportional likelihood of groundwater resources pollution. Tritium isotopes analysis was chosen and applied as a pollution marker to confirm the result of this adjustment. Based on this modification, vulnerability classes that were achieved for the studied basin were alienated into five classes, including very low, low, medium, high, and very high, with vulnerability index value of (<100, >100–125, >125–150, >150–200, and >200), respectively.

Keywords: vulnerability; DRASTIC; AHP; Tritium; Halabja Saidsadiq Basin (HSB)

1. Introduction

In the case of shortage of human water requirement from surface water projects, groundwater as an alternative concept to be one of the most imperative water resources of a variety of regions on the earth. The studied basin that is located within the northeast part of Iraq (Figure 1) is an ordinary example in which groundwater is the principal resource for all human water requirements. In the perception of progression of this region in terms of population growth, developing rate of agriculture, and industrial activities leads to increasing from water requirements and increasing a huge quantity of contaminant. In addition, referring to the data collected from Groundwater Directorate in the Sulaimani city, groundwater in this region extracted from productive aquifers through many thousands of deep and shallow wells. Therefore, the research into the groundwater wherewithal and its assessment in terms of vulnerability potential to contamination within the studied basin becomes obligatory.

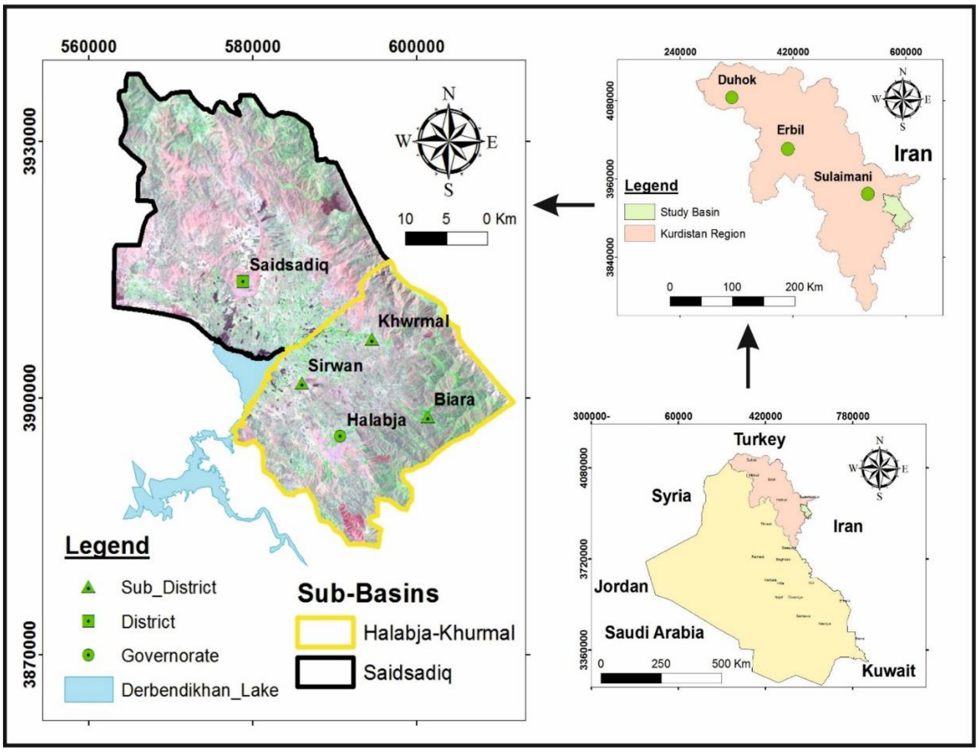

Figure 1. Location map of the Halabja Saidsadiq Basin (HSB).

The term of groundwater vulnerability refers to an approach that clarifies the difficulty of contaminants to pass through the unsaturated zone from the earth surfaces and then to reach to the groundwater aquifers. Vulnerability assessment has been performed as a crucial part of protection policy on land uses planning and groundwater protection zoning [1]. Various methods have been recommended for mapping groundwater vulnerability, namely; DRASTIC, COP, VLDA, GOD, AVI, and SINTACS [2]. These models have been recommended for different groundwater aquifers assessment, including inter-granular, leaky, and fissure aquifers, while, the EPIK [3,4] and PI models [5], which were typically recommended for the assessment of vulnerability in karstic aquifers. There is quick extension of groundwater vulnerability appraisal of the past decade, and in addition, the advancement and improvement in several new systems and techniques that are connected to the evaluation of groundwater vulnerability. GIS technique is a viable approach from the zone mapping and hazard evaluation on natural environmental issues [6]. This technique can be useful for taking quick decisions, as graphical depiction would be easy to take a policy decision by the makers [7]. In addition, GIS systems have been revolving around the most regularly utilized stage for assessment of groundwater vulnerability [6,8–11].

Groundwater vulnerability assessment previously mapped in the Halabja Saidsadiq Basin (HSB) based on the principle of the original DRASTIC model by [12], while, after verification, the result of this model is not reflecting the actual vulnerability situation. For this reason, DRASTIC model required to be modified, in order to connect the weight rate of all parameters in this method with the hydrogeological condition of the studied basin. In this study, AHP process was applied to modify the weight value of each parameter in the DRASTIC model. In addition, each map of vulnerability should be proved so as to appraise the validity of the applied modified model. The approach from groundwater ages that is applied to validate the reality of the results achieved from the weight-modified of the DRASTIC model. Determination of ground-water ages using tritium unstable isotope can be used to assess the vulnerability of groundwater to contamination, higher vulnerability zone should have a younger groundwater age. Areas of recent recharge are susceptible to contamination from surface waters.

Numerous methods were recommended for age dating groundwater estimation. The simplest, most frequently used, and currently, the most popular method, is the tritium (unstable isotopes) method [13].

1.1. Study Area

The studied basin (HSB) is located in the northeast part of Iraq with UTM coordinates ranged between 3,880,000 and 3,940,000 to the north and 560,000 and 610,000 to the east (Figure 1). The whole areas of the studied basin are about 1278 km^2 with the population of about 190,727 in 2015 [12]. The climate of this area has a distinct continental interior climate of hot in the summers and cold in the winters of the Mediterranean type, with the annual precipitation amount ranging from 500 to 700 mm.

1.2. Geology and Hydrogeological Setting

Tectonically, the studied basin located inside the High Folded Zone, Imbricated, and Thrust Zones [14]. Stratigraphically, several geological formations were outcropped in the studied basin of different geological time scale ranging from Jurassic to recent (Figure 2 and Table 1).

A hydraulic parameter characteristic of the groundwater aquifer is the principal criteria to decide whether the aquifer in the region is considered as a water-bearing aquifer. HSB is represented by several idiosyncratic hydrogeological aquifers. The types of water-bearing aquifers are presented in (Table 1). From the data recorded in the field by researchers and also from the data collected from the archives of Groundwater Directorate in Sulaimani, the mountain areas surrounding the studied basin of the upper east and southeast, are described by deep groundwater level. While, toward the middle and the southeastern part, the groundwater level defined as a shallower level. In addition, movement towards groundwater starts from the high elevation area in the north, upper east, south, and southeastern part towards the southwestern part, which is closed to the Derbandikhan Dam (Figure 3).

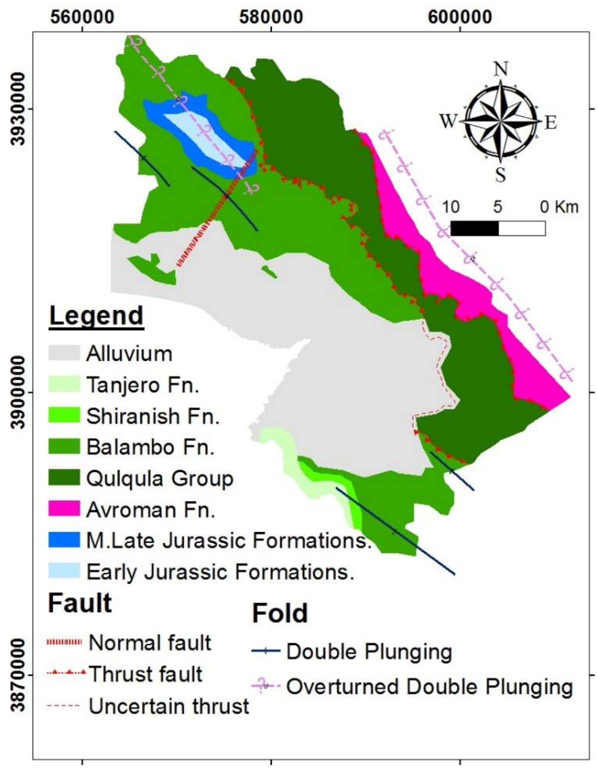

Figure 2. Geological map of the HSB, modified from [2–15].

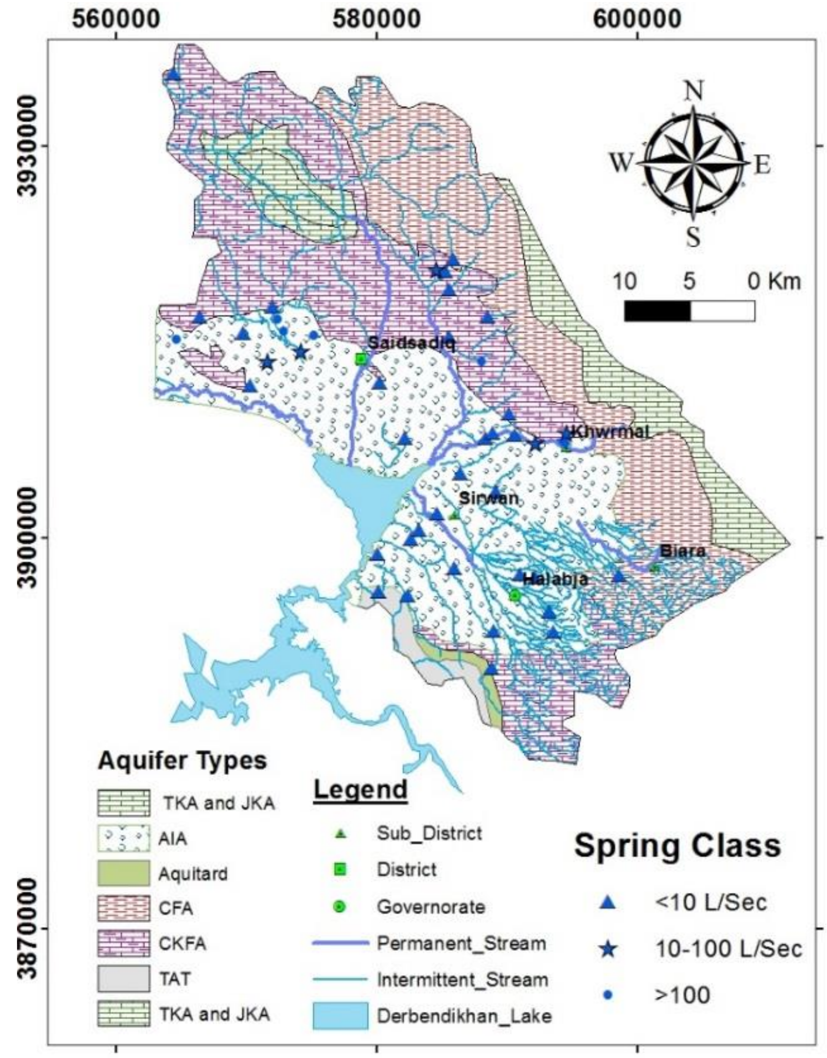

Figure 3. Hydrogeological map of the HSB, modified from [2–15].

Furthermore, several streams exist on the studied basin, including Sirwan, Zalm, Chaqan, Biara, Reshen, and Zmkan [2]. Also, many springs located inside of the studied basin (Figure 4). These springs are classified into three divisions based on the capacity of water discharges. The first spring group that it is discharging under 10 L/S, (for example, Anab, Basak, Bawakochak, and other 30 different springs). The second group having discharges ranged between 10 to100 L/S, (for example, Sheramar, Qwmash, Khwrmal, and Kani Saraw), The final group was those that have water discharge of more than 100 L/S (for example, Garaw, Ganjan, Reshen, Sarawy Swbhan, and Agha) [2–12].

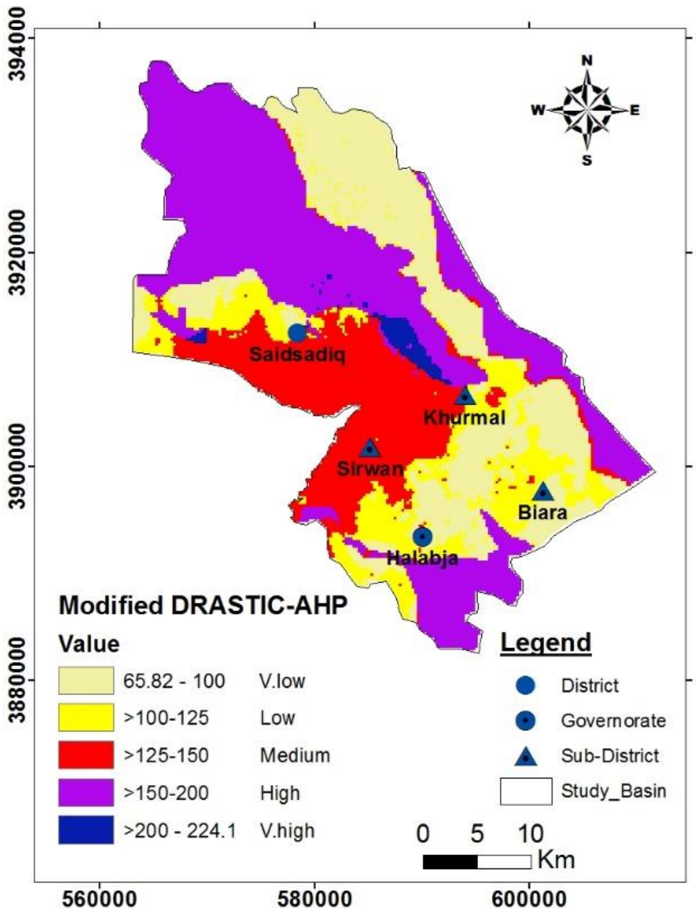

Figure 4. Modified DRASTIC index map using Analytic Hierarchy Process (AHP) method.

Table 1. Types of aquifer in the HSB.

Aquifer	Formation	Thickness (m)	References
Intergranular Aquifer (AIA)	Quaternary deposits	more than 300	[2]
Fissured Aquifer (CFA)	Balambo Kometan	250	[15]
Fissured-Karstic Aquifer (CKFA)	Avroman Jurassic formation	200 From 80 to 200	[16]
Karstic-Aquifer (TKA) and (JKA)	Avroman Jurassic	200 80–200	[16]
Non-Aquifer (Aquiclude, Aquitard and TAT)	Qulqula Shiranish Tanjero	more than 500 225 2000	[17]

2. Methodology

2.1. Material and Source of Data

The required data into this evaluation was accumulated from the field, and a while later from the records of the related organization, for instance, groundwater directorate in Sulaimaniyah City. Arc Map 10 in GIS technique was used to produce the shape file of each layer. Tritium Unstable Isotope was utilized for groundwater age estimation to use it to affirm the legitimacy of the proposed applied model to map groundwater vulnerability system for the studied basin.

2.2. DRASTIC Vulnerability Model

To accomplish the inherent groundwater vulnerability, the extent of groundwater contamination was examined by applying the model, which is called the DRASTIC model; this model was suggested by The United States Committee of Environmental Protection Agency [18]. The DRASTIC models to define the seven parameters by the abbreviation for "DRASTIC", which is utilized to outline groundwater vulnerability system. Weighting from 1 to 5, and rating from 1 to 10, was suggested to assign every parameter. The required data were collected and used in the GIS environment to map the groundwater vulnerability system in the studied basin. The Inverse Distance Weighted (IDW) used to interpolate the data and then reclassified based on the ranging and rating, as recommended by [18]. The rate values of the DRASTIC model were modified by [12], and this modified rate was applied for the current study, while the weight value was modified based on AHP method in the following section. The original vulnerability index value based on the DRASTIC model ($DI\ (w - r)$) is calculated from the linear relationship of all parameters, as established by the following equation, [18]:

$$DI = D_W D_r + R_W R_r + A_W A_r + S_W S_r + T_W T_r + I_W I_r + C_W C_r \quad (1)$$

where: DI is the vulnerability index value, (D, R, A, S, T, I, and C) refer to all of the parameters in the DRASTIC model (D = depth to groundwater level, R = the net recharge, A = the Aquifer media, S = the soil media, T = topography, I = impact of vadose zone, and C = the hydraulic conductivity), w refers to the weight value, and r is the rate value of each parameter.

2.3. Analytic Hierarchy Process (AHP) Applied to DRASTIC Model

Analytical Hierarchical Process (AHP) is a way to deal with basic leadership that includes organizing different decision criteria onto a hierarchy, evaluating the virtual impact on these criteria, evaluating alternative to each criterion, and confirming the validity of these alternatives. The crucial of the Analytic Hierarchy Process (AHP) are an arrangement of axioms that precisely delimit the degree of the environmental issue [19]. It depends on the very much characterized numerical structure of reliable networks and their related right eigenvector's capacity to produce genuine or estimated weights [19,20]. The AHP technique compares criteria or parameters with reference to a criterion, in an ordinary, pair wise mode. To do as such, the AHP utilizes an essential absolute numbers scale that has been confirmed practically and by physical and decision problem trial. The basic scale has been appeared to be a scale that catches singular inclinations, as for quantitative and subjective traits similarly too or superior to different scales [21,22].

In this model, grouping criterion can be perceived and weighted, and the gathered information can likewise be analyzed, quickening the procedure of decision making. The hierarchy is deconstructed into a pair comparison matrix. This pair wise comparison is utilized to decide the comparative impact on each parameter in terms of each criterion. In the original analytic hierarchy approaches, the (9) point scale is utilized, where each point is compared to a declaration of the relative significance of two variables. These modify to utilize a scale of values ranging from (1 to 9), as shown in Table 2. This will permit the decision maker to assess the role of each factor to reach the purpose independently throughout pair wise appraisal.

The standard structures of the decision issue are comprised of numbers, which were symbolized by m; whilst alternatives were given numbers symbolize by n. The estimations of a_{ij} ($i = 1, 2, 3, \ldots, m$) and ($j = 1, 2, 3, \ldots, n$) utilized to imply the execution esteems as far as the ith and jth in a matrix [23]. The model correlation grid for any issue and the relative centrality of the criteria can be represented in a decision matrix, as follows:

$$A = \begin{matrix} a_{11} & a_{12} & a_{13} & a_{1n} \\ a_{21} & a_{22} & a_{23} & a_{2n} \\ a_{31} & a_{32} & a_{33} & a_{3n} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ a_{m1} & a_{m2} & a_{m3} & a_{mm} \end{matrix} \tag{2}$$

Table 2. Scale of relative significance for pair wise comparison [21].

Intensity of Importance	Definition
1	Equal importance
2	Equal to moderately importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extreme importance

The priority vector is dictated by normalizing the eigen value to (1) (divided by their total) as takes after [21]:

$$Pri = \frac{Egi}{\sum_{i=1}^{n} Egi} \tag{3}$$

where Egi is the eigen value for the row i ($Egi = \sqrt[n]{a_{11} \times a_{12} \times a_{13} \ldots\ldots a_{1n}}$) and n is the value of elements in row i. The lambda max (λ_{max}) was achieved from [21]:

$$\lambda_{max} = \sum_{j=1}^{n} \left[W_j \sum_{i=1}^{m} a_{ij} \right] \tag{4}$$

where a_{ij} is the summation of criteria in each column in the matrix and W_j is the value of weight for each criterion, which is equivalent to the priority vector in the matrix of decision. Thus, in this revise λ_{max} = 7.03. The consistency index (CI) is calculated by [21]:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5}$$

where n is the size of the matrix. In this revise, n = 7 and λ_{max} = 7.03; consequently, CI = 0.005. The consistency ratio (CR) was calculated according to [21], as follows:

$$CR = \frac{CI}{RI} \tag{6}$$

where RI_7 is random index (RI = 1.32) for n = 7 (Table 3), wherever this table shows the mean random index value for matrixes with different size. If the CR is less than 0.1, the ratio designates a sensible consistency level in the pair wise comparison. In this revise, $CR = 0.004 < 0.1$, the pair wise comparison matrices were equipped for (7) parameters (Table 4).

In the procedure of weight evaluating, the significance and weight of each parameter were compared with each parameter in this study. It was done throughout the execution of the views of the expert that have worked in this field. Each parameter has specified a value of weight that it merits by assuming the method of straightforward additive weighting. Then, these weights have been applied for organizing the comparison matrix of the AHP to get the right weight for each parameter (Tables 3 and 4). A sum of (7) map layers was entered on the Map Algebra tool of the GIS throughout the summation of the products of multiplying the weight of each criterion (W) (which was calculated by the AHP method) by the rating value of the parameter that was calculated using rate-weight modification method. This assisted to generate the map of weight modified DRASTIC vulnerability index based on AHP method (Table 4).

Table 3. Random inconsistency indices for different values of (*n*) [24,25].

n	1	2	3	4	5	6	7
RI	0	0	0.58	0.9	1.12	1.24	1.32

To validate the result of the modified weight of the DRASTIC model, the concept of regression analysis was applied. Statistically, a value is regularly necessary to decide how intimately a convinced function (vulnerability index value in this study) hysterics an exacting experimental data set (groundwater tritium value and groundwater age). In this study, we have focused on the value of R^2, as calculated in Excel software, to find out the linear relationship of our data (vulnerability index value and groundwater tritium value). The ranges of R^2 value starting from 0 to 1, with 1 or close to 1 confirming an excellent fit between the data and the line drawn through them, and 0 confirming no statistical relationship between them.

Table 4. Pair wise comparisons matrix for selecting suitable landfill site, Eigenvector, and significance weights.

	D	*I*	*R*	*A*	*C*	*S*	*T*	Eigenvector	Priority Vector (Weight)	DRASTIC Weight	Modified Weight
D	1.0	1.0	2.0	3.0	3.0	5.0	7.0	2.5	0.28	5.00	6.42
I	1.0	1.0	2.0	3.0	3.0	5.0	7.0	2.51	0.28	5.0	6.42
R	0.5	0.5	1.0	2.0	2.0	3.0	5.0	1.47	0.16	4.0	3.76
A	0.33	0.33	0.5	1.0	1.0	2.0	3.0	0.85	0.10	3.0	2.19
C	0.33	0.33	0.5	1.0	1.0	2.0	3.0	0.85	0.10	3.0	2.19
S	0.20	0.20	0.33	0.50	0.50	1.0	2.0	0.49	0.05	2.0	1.25
T	0.14	0.14	0.20	0.33	0.33	0.5	1.0	0.30	0.03	1.0	0.77
SUM	3.5	3.5	6.5	10.8	10.8	18.5	28.0	8.99	1.00	23.0	23.0

3. Result and Discussion

3.1. Modified DRASTIC Model

After set up, the weight for each parameter using the AHP method, the ultimate vulnerability map was attained by running the model in the (ArcGIS 10.3) environment by using the seven parameters data layers. Accordingly, vulnerability classes of the studied area were reclassified into five classes that were based on the proposed table recommended by [18], which depict the qualified likelihood of pollution of the groundwater resources. The map thus obtained is shown in the Figure 4. These five classes are v. low, low, medium, high, and v. high. v. low groundwater vulnerability risks zone (index: <100) with covered area of (30%); low vulnerability risk zone (index: >100–125) that covering 7% of the whole area within the studied basin, moderate vulnerability zone (index: >125–150) covered (25%), high vulnerability zone (index: >150–200) covered only (35%) of the whole area v. high vulnerability zones with index value of more than (200) covered (3%) of the whole studied basin.

3.2. Validation against Groundwater Age Using Unstable Isotopes

Determination of ground-water ages can be applied to appraise the vulnerability of groundwater to pollution. Areas of recent recharge are susceptible to contamination from surface waters. Various methods survive for estimation dating from groundwater age. The easiest, widely used, and presently mainly accepted, method is the tritium (unstable isotopes) method.

Tritium or ^{3}H is a radioactive isotope of hydrogen (through one proton and two neutrons) with a half-life of (12.4) year [26]. Concentrations of Tritium are deliberate in tritium units (TU) where 1 TU is described as the occurrence of one tritium in 1018 atoms of hydrogen (H). Testing of atmospheric nuclear weapons in the (1950s) and near the beginning (1960s) discharged tritium to the atmosphere at levels numerous orders of magnitude over the previous concentration. During groundwater recharge from precipitation, this tritium mixed with the groundwater in the form of High-Temperature Oxidation (HTO) with tritium as part of the water molecule [27].

In the current study, and for unstable isotope analysis for (Tritium), one rain sample and twenty samples from groundwater wells which were penetrating different aquifer were used to find the groundwater age. Rain sample had a tritium value of (4.8) TU and a mean value of groundwater samples were (4.28) TU for (CKFA, TKA, and JKA) aquifers and (2.28 and 3.03) TU for (CFA and AIA) aquifers, respectively, Table 5. For the purpose of comparison of changing tritium value with time, there is no previous study concerning tritium value range in the studied basin, while [28], studied tritium value in several samples of groundwater in the Basara basin, which is located in the north-east of Iraq, 25 km west of Sulaimani city, and revealed that the tritium concentration in the spring and well samples is within 5.5 to 7.0 TU. It is concluded that the value closely resembles the present time. In addition, several studies in the world confirmed that tritium levels in meteoric and groundwater waters were decreased with time [29].

Table 5. Results of Trituim analysis of groundwater samples in the HSB.

Sample Code	Site	3H (TU) ± σ	Average 3H	Aquifer
ITB	Banishar Mosques Well	4.7 ± 0.3		
ITB2	Basak Well	3.8 ± 0.3		
ITJ	Jalela Village Well	4 ± 0.3		
ITS1	Saraw Swbhan Agha	4.5 ± 0.3	4.28	CKFA. TKA and JKA
ITM	Mzgawta	4 ± 0.3		
ITSb	SheraBara	4.3 ± 0.3		
ITT2	Tawanawal	4.6 ± 0.3		
ITD	Darbarulla	4.3 ± 0.3		
ITTh	Halabaj Taymwr Hassan	3.3 ± 0.3		
ITS	Sirwan	2.3 ± 0.3		
ITSs	Shekhan Shanadactry Road Project	3.1 ± 0.3		
ITSm	Soila Mesh	3 ± 0.3	3.03	
ITGs	Gulajoy Saroo	3.2 ± 0.3		AIA
ITMh	Mstakani Haji Ahmad	3 ± 0.3		
ITT	Taza De	3 ± 0.3		
ITB3	Bezhawa	3.3 ± 0.3		
ITX	Kharpane Well	2.4 ± 0.3		
ITBk	Balkhay Khwaroo	2.3 ± 0.3	2.28	
ITS2	Sargat	2.1 ± 0.3		CFA
ITBb	Bani Bnok	2.3 ± 0.3		

Groundwater age estimation using tritium only provides semi-quantitative, "ball park" values. There is no specific classification for age estimation based on tritium results. [30], classified the age of samples by classifying water as being modern and pre-bomb. Tritium values greater than (0.3) TU are used to represent modern water (i.e., recharge after 1965) and values that are less than or equal to (0.3) TU to represent pre-bomb spikes to recharge (i.e., recharge before 1965). While [31] classified groundwater age, as follows:

- <0.8 TU designates sub-modern water (prior to 1950s).
- 0.8 to 5 TU designates a mix of sub-modern and modern water.

- >5 to 15 TU designates modern water (<5 to 10 years).
- >15 to 30 TU designates s some bomb tritium.
- >30 TU designates recharge generate in the 1960s to 1970s.

Based on both of the classifications, the tritium value, Table 5 indicates that the groundwater is modern or a mix of sub-modern and modern water. The tritium data provide insight as to the mean residence time of "old" versus "new" groundwater in the study. The basic premise for using groundwater age to establish vulnerability is that groundwater with a relatively rapid vertical transport rates have a younger age. Since most contaminants are present near the earth's surface, younger groundwater is, therefore, more vulnerable.

Old groundwater is more likely to be isolated from the contaminating activities that are ubiquitous in the urban and suburban environments. Additionally, results of the tritium analysis revealed that groundwater in the (CKFA, TKA, and JKA) aquifers are younger than in both (AIA and CFA); moreover, groundwater in the (AIA) aquifer is younger than (CFA) as tritium value of AIA is higher than in CFA, Figure 5. In view of this classification, groundwater vulnerability was assessed based on tritium (^{3}H) and groundwater age. This approach examines the similarity with a spatial pattern of variability of these maps, along with a common cross-section, A-B (Figure 5), to see the linear relationship between vulnerability index value and groundwater tritium value. The results show a better match between the patterns of the tritium value of groundwater and vulnerability index value achieved from modified DRASTIC based on the AHP method, (Figure 6). This relation is designed based on R square, which is also called the coefficient of determination. Calculate by multiply R times R to get the R square value. R square or coefficient of determination shows percentage variation in the y-axis (Tritium value), which is explained by all of the x variables together (Vulnerability Index Value). Therefore, based on this verification, it can be concluded that the modified DRASTIC vulnerability model reflecting the real vulnerability situation in the studied basin.

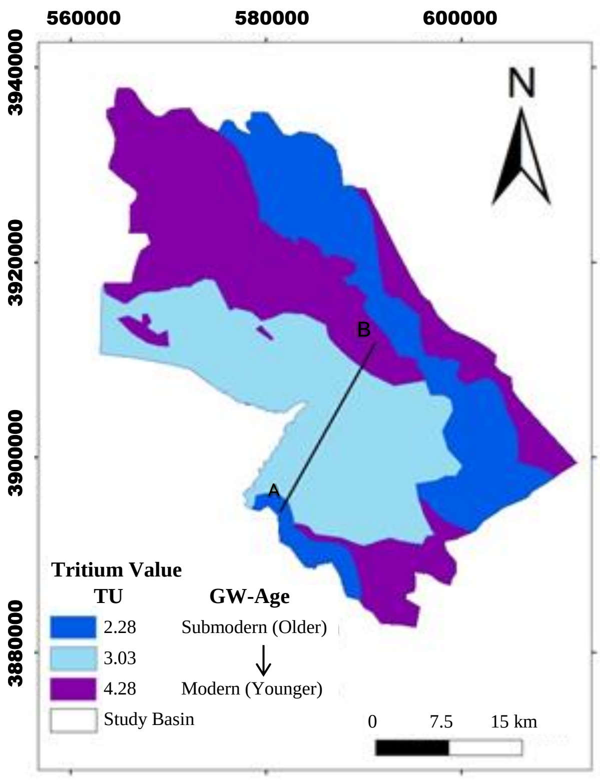

Figure 5. Groundwater age and Tritium value of aquifers at the HSB.

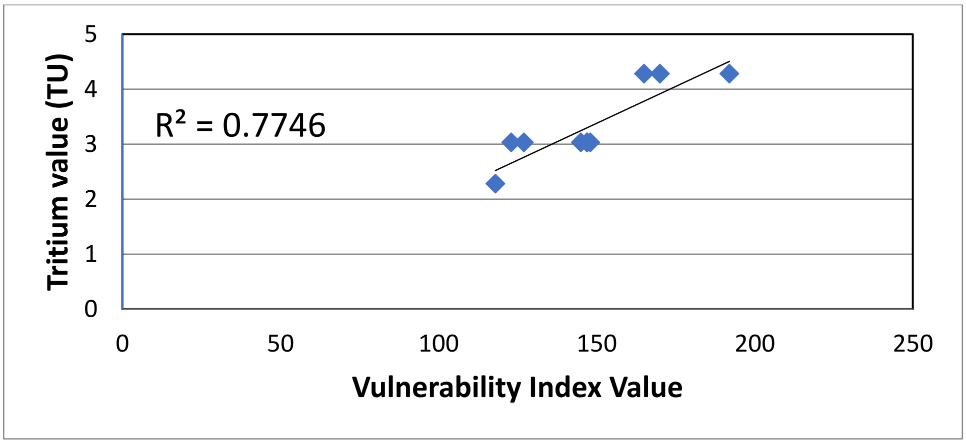

Figure 6. Modified DRASTIC model based on AHP model vs. Tritium value (TU).

4. Conclusions

This study utilized the DRASTIC model and GIS technique to assess the aquifer vulnerability in the studied area. Seven environmental parameters that comprise depth to water, net recharge, aquifer media, soil media, topography, the impact of the vadose zone, and hydraulic conductivity were used to represent the hydrogeological set of the studied basin. The result of groundwater vulnerability to pollution assessment demonstrates index values, which vary from 65 to 224. According to the results of the groundwater vulnerability assessment, the studied basin has been alienated into five zones of relative vulnerability: v. low, low moderately, high, and v. high vulnerability zone, Table 6. The maximum areas have fallen under the high vulnerable zone, accounting for 35% (447 km^2). This area is characterized by high water table level and the presence of several springs with fractured limestone lithologically. While v. low, low, medium, and v. high vulnerability zones have been covered an area of (30%, 7%, 25%, and 3%) or (383, 89, 320, and 38) km^2 of the entire study area, respectively. There should be a detailed and frequent monitoring in high and moderately vulnerable zones in order to monitor the changing level of pollutants. The above study also helps in screening the site selection of waste dumping.

Table 6. Result of Modified DRASTIC index ratio based on the AHP process.

Vulnerability Class	Modified DRASTIC—AHP	Covered Area%
Very low	65–100	30
Low	>100–125	7
Medium	>125–150	25
High	>150–200	35
Very high	>200–224	3

A ground-water age was applied to assess the vulnerability of groundwater to contamination. Areas of recent recharge are susceptible to contamination from surface waters. In the current study, one rain sample and twenty samples from groundwater wells were used to analyses unstable isotopes (Tritium) to find the groundwater age. Groundwater samples represent different aquifers that the wells were penetrating. Rain sample had a tritium value of 4.8 TU and a mean value of groundwater samples was 4.28 TU for CKFA, TKA, and JKA aquifers and 2.28 and 3.03 TU for CFA and AIA aquifers, respectively, (Table 5).

This approach examines the similarity in a spatial pattern of variability of these maps along with a common cross-section, A-B line (Figures 4 and 5). The results show a better match between the patterns of the tritium value of groundwater and the modified DRASTIC based on AHP method of R^2

of more than 0.77, the closer of the value of R-squared on the graph to 1.0, confirm the better the fit of the regression line, (Figure 6).

Author Contributions: T.O.A. did the field and lab work. S.S.A., N.A.A.-A. and S.K. did the discussion of the results with T.O.A. and supervision.

Conflicts of Interest: The authors declare no conflicts of interest

References

1. Foster, S.S.D. *Groundwater Recharge and Pollution Vulnerability of British Aquifers: A Critical Overview*; Geological Society Special Publication: London, UK, 1988; Volume 130.
2. Abdullah, T.O.; Ali, S.S.; Al-Ansari, N.A. Groundwater assessment of Halabja Saidsadiq Basin, Kurdistan region, NE of Iraq using vulnerability mapping. *Arab. J. Geosci.* **2016**, *9*, 223. [CrossRef]
3. Doerfliger, N.; Zwahlen, F. *Groundwater Vulnerability Mapping in Karstic Regions (EPIK)—Application to Groundwater Protection Zones*; Swiss Agency for the Environment, Forests and Landscape (SAEFL): Bern, Switzerland, 1998.
4. Doerfliger, N.; Jeannin, P.Y.; Zwahlen, F. Water vulnerability assessment in karst environments: A new method of defining protection areas using a multi-attribute approach and GIS tools (EPIK method). *Environ. Geol.* **1999**, *39*, 165–176. [CrossRef]
5. Goldscheider, N.; Klute, M.; Sturm, S.; Hotzl, H. The PI Method a GIS—Based Approach to Mapping Groundwater Vulnerability with Special Consideration of Karst Aquifers. *Z. Angew. Geol.* **2000**, *46*, 157–166.
6. Ghosh, A.; Tiwari, A.K.; Das, S. A GIS based DRASTIC model for assessing groundwater vulnerability of Katri Watershed, Dhanbad, India. *Model. Earth Syst. Environ.* **2015**, *1*. [CrossRef]
7. Singh, P.K.; Tiwari, A.K.; De Maio, M. Evaluation of aquifer vulnerability in a coal mining of India by using GIS-based DRASTIC model. *Arab. J. Geosci.* **2016**, *9*, 1–15. [CrossRef]
8. Saha, D.; Alam, F. Groundwater vulnerability assessment using DRASTIC and Pesticide DRASTIC models in intense agriculture area of the Gangetic plains India. *Environ. Monit. Assess.* **2014**, *186*, 8741–8763. [CrossRef] [PubMed]
9. Edet, A. An aquifer vulnerability assessment of the Benin Formation aquifer, Calabar, southeastern Nigeria, using DRASTIC and GIS approach. *Environ. Earth Sci.* **2014**, *71*, 1747–1765. [CrossRef]
10. Nasri, N.; Chebil, M.; Guellouz, L.; Bouhlila, R.; Maslouhi, A.; Ibnoussina, M. Modelling nonpoint source pollution by nitrate of soil in the Mateur plain, northeast of Tunisia. *Arab. J. Geosci.* **2015**, *8*, 1057–1075. [CrossRef]
11. Shrestha, S.; Semkuyu, D.J.; Pandey, V.P. Assessment of groundwater vulnerability and risk to pollution in Kathmandu Valley, Nepal. *Sci. Total Environ.* **2016**, *556*, 23–35. [CrossRef] [PubMed]
12. Abdullah, T.O.; Ali, S.S.; Al-Ansari, N.A.; Knutsson, S. Groundwater Vulnerability Mapping using Lineament Density on Standard DRASTIC Model: Case Study in Halabja Saidsadiq Basin, Kurdistan Region, Iraq. *Engineering* **2015**, *7*, 644–667. [CrossRef]
13. Blavoux, B.; Lachassagne, P.; Henriot, A.; Ladouche, B.; Marc, V.; Beley, J.; Olive, P. A Fifty-Year Chronicle of Tritium Data for Characterising the Functioning of the Evian and Thonon (France) Glacial Aquifers. *J. Hydrol.* **2013**, *494*, 116–133. [CrossRef]
14. Buday, T. *The Regional Geology of Iraq: Stratigraphy and Paleogeography*; Kassab, I.I., Jassim, S.Z., Eds.; Publications of Geological Survey of Iraq: Baghdad, Iraq, 1980.
15. Ali, S.S. Geology and Hydrogeology of Sharazoor-Piramagroon Basin in Sulaimani Area, Northeastern Iraq. Unpublished Ph.D. Thesis, Faculty of Mining and Geology, University of Belgrade, Beograd, Serbia, 2007.
16. Jassim, S.Z.; Goff, J.C. *Geology of Iraq*; Jassim, Ed.; Geological Society of London: London, England, 2006.
17. Buday, T.; Jassim, S. *The Regional Geology of Iraq: Tectonis, Magmatism, and Metamorphism*; Kassab, I.I., Abbas, M.J., Eds.; State Establishment of Geological Survey and Minieral Investigations: Baghdad, Iraq, 1987.
18. Aller, L.; Bennett, T.; Lehr, J.H.; Petty, R.H.; Hackett, G. *DRASTIC: A Standardized System for Evaluating Groundwater Pollution Potential Using Hydrogeologic Setting*; USEPA Report 600/2-87/035; Robert S. Kerr Environmental Research Laboratory: Ada, OK, USA, 1987.
19. Saaty, T.L. Axiomatic foundation of the analytic hierarchy process. *Manag. Sci.* **1986**, *32*, 841–855. [CrossRef]
20. Merkin, B.G. *Group Choice*; John Wiley & Sons: New York, NY, USA, 1979.

21. Saaty, T.L. *The Analytic Hierarchy Process: Planning, Priority Setting, Resources Allocation*; McGraw: New York, NY, USA, 1980.
22. Saaty, T.L. How to make a decision: The analytic hierarchy process. *Interfaces* **1994**, *24*, 19–43. [CrossRef]
23. Uyan, M. MSW landfill site selection by combining AHP with GIS for Konya, Turkey. *Environ. Earth Sci.* **2014**, *71*, 1629–1639. [CrossRef]
24. Chang, C.W.; Wu, C.R.; Lin, C.T.; Lin, H.L. Evaluating digital video recorder systems using analytic hierarchy and analytic network processes. *Inf. Sci.* **2007**, *177*, 3383–3396. [CrossRef]
25. Isalou, A.A.; Zamani, V.; Shahmoradi, B.; Alizadeh, H. Landfill site selection using integrated fuzzy logic and analytic network process (F-ANP). *Environ. Earth Sci.* **2013**, *68*, 1745–1755. [CrossRef]
26. Kumar, P.R.; Somashekar, R.K. Environmental Tritium and Hydrochemical Investigations to Evaluate Groundwater in Varahi and Markandeya River Basins, Karnataka, India. *J. Environ. Radioact.* **2011**, *102*, 153–162.
27. UN (United Nations); ILO (International Labour Organisation); WHO (World Health Organization). Environmental Health Criteria for Selected Radionuclides. Environmental Health Criteria 25. Available online: http://www.inchem.org/documents/ehc/ehc/ehc25.htm (accessed on 10 June 2018).
28. Hamamin, D.F.; Ali, S.S. Hydrodynamic study of karstic and intergranular aquifers using isotope geochemistry in Basara basin, Sulaimani, North-Eastern Iraq. *Arab. J Geosci.* **2013**, *6*, 2933–2940. [CrossRef]
29. Davies, G. *Results of Ground-Water Tracing Experiments in the Nelson-WoosterHumphreyTunnel*; Cambrian Ground Water Co.: Oak Ridge, TN, USA, 2002.
30. Mckenzie, J.M.; Mark, B.G.; Thompson, L.G.; Schotterer, U.; Lin, P.-N. A hydrogeochemical survey of Kilimanjaro (Tanzania): Implications for water sources and ages. *Hydrogeol. J.* **2010**, *18*, 985–995. [CrossRef]
31. Motzer, W.E. Age Dating Groundwater. Available online: http://www.primarywaterinstitute.org/images/pdfs/Tritium_in_groundwater.pdf (accessed on 10 June 2018).