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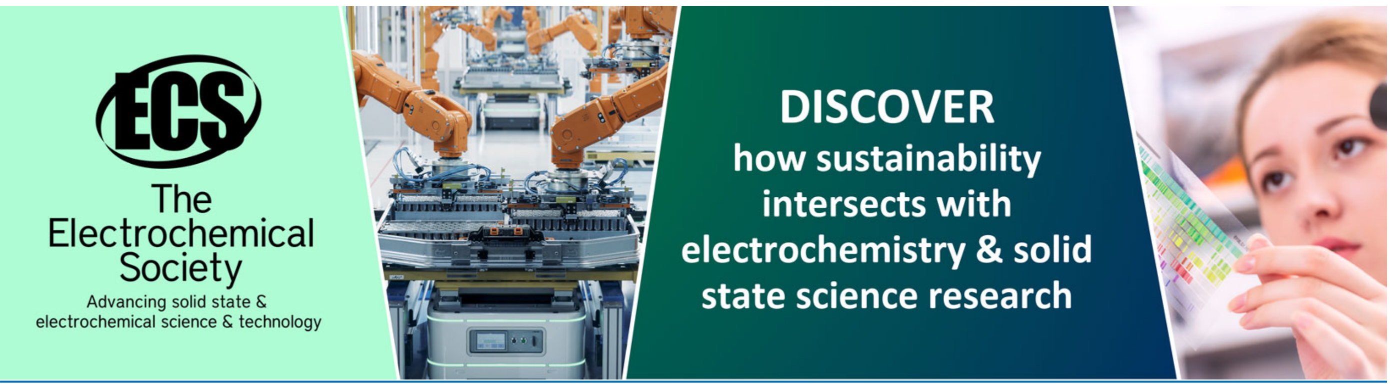

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Modeling groundwater vulnerability to pollution using Optimized DRASTIC model

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Abstract. The prediction accuracy of the conventional DRASTIC model (CDM) algorithm for groundwater vulnerability assessment is severely limited by the inherent subjectivity and uncertainty in the integration of data obtained from various sources. This study attempts to overcome these problems by exploring the potential of the analytic hierarchy process (AHP) technique as a decision support model to optimize the CDM algorithm**.** The AHP technique was utilized to compute the normalized weights for the seven parameters of the CDM to generate an optimized DRASTIC model (ODM) algorithm. The DRASTIC parameters integrated with the ODM algorithm predicted which among the study areas is more likely to become contaminated as a result of activities at or near the land surface potential. Five vulnerability zones, namely: no vulnerable(NV), very low vulnerable (VLV), low vulnerable (LV), moderate vulnerable (MV) and high vulnerable (HV) were identified based on the vulnerability index values estimated with the ODM algorithm. Results show that more than 50 % of the area belongs to both moderate and high vulnerable zones on the account of the spatial analysis of the produced ODM-based groundwater vulnerability prediction map (GVPM).The prediction accuracy of the ODM-based - GVPM with the groundwater pH and manganese (Mn) concentrations established correlation factors (CRs) result of 90 % and 86 % compared to the CRs result of 62 % and 50 % obtained for the validation accuracy of the CDM - based GVPM. The comparative results, indicated that the ODM-based produced GVPM is more reliable than the CDM - based produced GVPM in the study area. The study established the efficacy of AHP as a spatial decision support technique in enhancing environmental decision making with particular reference to future groundwater vulnerability assessment.

1. Introduction

Vulnerability is the degree to which human or environmental systems are likely to experience harm because of perturbation or stress. According to Pospecu *et al* [1] vulnerability can be identified for a specific system, hazard, or group of hazards. Vulnerability mapping entails quantifying the sensitivity of resources to the environment and is a practical visualization tool for decision making Rahman [2], Norlan [3]. In hydrogeology, vulnerability assessment is typically utilized to assess the susceptibility of a water table, an aquifer, or water well to contaminants that can reduce groundwater quality. Groundwater pollution is the artificially induced degradation of natural groundwater quality. It is primarily caused by anthropogenic and agricultural activities [4], Nobre *et al* [5], AtqurRahman [6]. These potential sources of pollution are responsible for the deterioration of groundwater quality, consequently increasing vulnerability. According to Thirumalaivasan *et al* [7], groundwater contamination has become one of the most serious global environmental problems because once an aquifer is polluted; its remediation is prohibitively costly and often impractical. The development of sustainable plans geared toward groundwater protection against contamination is therefore critical in water resources planning and management Chen, *et a*l [8], Said Ettazarini [9]. The existing methods of assessing groundwater vulnerability are classified into three categories: i) overlay and index method; ii) process-based methods that apply deterministic models based on physical processes; and iii) statistical models (National Research Council, 1993). However, this article focuses on overlay and index methods for groundwater vulnerability assessment. The overlay and index methods which emphasized on the combination of different regional maps by allocating a numerical index includes GOD, AVI and DRATIC. The most widely used among is the DRASTIC method Aller *et al* [10], Durnford *et al* [11], [12-13], Rundquist *et al* [14], Fritch *et al* [15]. However, the DRASTIC modeling technique disregards the effect of regional characteristic; hence uniform weights and rating are mostly used. The inappropriate handling of parameters rating and weighting assignment in this model often result into series of subjectivity and uncertainty in prediction. Thus several researchers have continued to enhance the model with different methods. However, fewer attempts have been made to enhance this model performance through a modification that is based upon simple statistical procedure involving the revision of the rating scale of each parameter and revision of the factor weights as proposed by Panagopoulos *et al* [16]. For reliability and precision of the assessment of pollution potential in this study, the conventional DRASTIC model (CDM) is optimized by incorporating a multi-criteria decision analysis technique.

An optimized DRASTIC model (ODM) is proposed in this study to establish a groundwater vulnerability model with high reliability and precision. Optimization is performed by normalizing the rating scale of each parameter and revising factor weights via a hybrid approach of the DRASTIC model and Analytical hierarchy process (AHP). The AHP technique is employed as a decision support model. This technique is utilized for the elicitation of attributes weights of the model parameters for the purpose of resolving the limitations of the convectional DRASTIC modeling approach in terms of the inherent subjectivity and uncertainty in the integration of data obtained from various sources.
Though, there is no record of groundwater pollution in the area investigated in this study, however, assessing groundwater quality and developing strategies to protect aquifers from future contamination are necessary in planning and designing water resources in the area. Therefore, the objectives of the study are: (1) to produce a groundwater vulnerability prediction map with high reliability and precision through application of the proposed optimized DRASTIC model (CDM) algorithm to the DRASTIC model parameters; and (2) to compare the results of the proposed CDM algorithm with the CDM algorithm via validation of the predictive models with the analyzed results of groundwater quality obtained from the study area.

2. Materials and methods

2.1. *Geography, hydrology, and hydrogeology of the study area*
The proposed methodology was applied in a site situated between the boundary of Perak and Selango in Peninsular Malaysia. Figure 1 presents the 2863 km^2 study area and shows the borehole wells and other important features. The site lies between longitudes 101º 0' E and 101º 40'E and between latitudes 3º37' N and 4º18'N in the southern part of Perak. The area is having four major underlying rock types defined by geological age, namely, Quaternary (mainly recent alluvium), Devonian (sedimentary rocks), Silurian (sedimentary rocks with lava and tuff), and acidic and undifferentiated granitoids as depicted in figure 2. The region is characterized by equatorial maritime climate with nearly uniform air temperatures throughout the year. The average daily temperature is approximately 27 ºC, and the relative humidity has a monthly mean value of 62% and 78% for the dry period and peak of the rainy season, respectively. The

general annual precipitation in Perak state ranges from 830 mm to 3,000 mm. However, 10years daily records of precipitation between 2000 and 2010 for the study area were acquired at quarter-degree resolution (0.25°) from the Tropical Rainfall Measuring Station (*TRMM*) database.

2.2. *Analytic Hierarchy Process (AHP)*

AHP is one of the most commonly utilized multi-criteria decision methods reported in literature [17]. Multi-criteria decision methods involve the assessment of a given alternatives by a group of decision makers based on a selected set of criteria. AHP is a decision support model that requires the summation of certain weights on a given level of the decision Beynon *et al* [18]. AHP involves the construction of a series of pair-wise comparison matrices, which compare the criteria to one another. Comparison is performed to estimate a rating or weight for each criteria; this rating describes the extent of the contribution of each criteria to the overall objective. Saaty's scale of 1 to 9 [19] plays a key role in the implementation of AHP. The scale is coupled with the experience and knowledge of experts or users to determine the factors or criteria affecting the decision process HO [20], [21]. AHP is capable of capturing both subjective and objective evaluation measures and providing a useful mechanism to check the consistency of the evaluation measures and alternatives suggested by experts or decision makers, thereby reducing bias in decision making Ariff *et al* [22].

2.3 *DRASTIC model*

The DRASTIC model was developed for the US Environmental Protection Agency by Aller *et a*l [10] from the National Water Well Association. The model was designed as an easy-to-use model that would allow a user with basic knowledge of hydrogeology to assess the relative potential for groundwater contamination. The term "DRASTIC" was derived from the seven variables in the model, namely, depth-to-water table, net recharge, aquifer media, soil media, topography, impact of vadose zone, and conductivity (hydraulic). These variables or parameters are utilized to define the hydrogeologic setting of an area. These parameters are further subdivided into ranges or zones that represent various hydrogeologic settings and are assigned different ratings on a scale of 1 to 10. The rating assigned to each range or zone indicates the relative importance of each parameter within the zone in contributing to aquifer vulnerability. The linear additive of the above mentioned variables is usually combined with ratings and weights to determine the DRASTIC index Aller *et a*l 10]. DRASTIC index (DI) is expressed as follows:

$$\mathrm{DI} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \tag{1}$$

Where *D*, *R*, *A*, *S*, *T*, *I*, and *C* represent the seven parameters, r is the rating, and w is the weight assigned to each parameter. The resulting index is a relative measure of vulnerability to contamination. Shown in figure 3 is the DRASTIC model evaluation approach and the optimization procedures

2.4 *Data preparation for the DRASTIC model*

The DRASTIC model with its seven parameters was derived from several data sets. This study utilized several data types, and the sources are presented in Table 1. The depth-to-water table (D) is one of the most important factors in evaluating pollution potential because it provides a greater chance for natural attenuation in terms of dispersion, absorption, and biodegradation to occur as the depth to water increases [23]. This study considered data determined based on water level measurements performed in several bore wells drilled in the year 2009 and uniformly spread in the entire study area to produce a depth-to-water table thematic map (Figure 4a). This map was evaluated for pollution potential mapping based on the ranges of depth-to-water table distribution in the area. The hydrological implication of the map indicated that at a shallower water table, the more susceptibility is the groundwater reservoir to pollution and vice-versa [4]. Hence, the pollution potential weights and ratings of depth to water thematic map classes are in accordance with Delphi technique Atiqur Rahman [6].

This study adopted 10 years daily records of precipitation between 2000 and 2010 to estimate net recharge in the area using the modified version of the Chaturvedi [24] formula (Equation 2)

$$R = 6.75(P-14)^{0.5} \tag{2}$$

where R is the net recharge from precipitation during the year, and P is annual precipitation.

The obtainable net recharge values were interpolated to generate net recharge (R) map (Figure 4b) in GIS environment. The net recharge represents the annual average amount of water that infiltrates the vadose zone and reaches the water table Aller *et al* [10]. The higher the net recharge, the more vulnerable is the groundwater reservoir. This was supported in Samake *et al* [25] who reported that recharge controls the volume of water available for dispersion and dilution of the contaminant in the vadose zone. The aquifer medium (A) is a water-bearing formation that yields useable quantities of water from a well or spring Heath [25]. The nature of soil composition constituting this medium determines the attenuation capacity of pollutants. The aquifer layer delineated from 2D resistivity imaging section was interpreted and for geoelctrical parameter determination (sees Figure 5). The estimated mean resistivity values of the delineated aquifer media was evaluated for the nature, texture, porosity, permeability properties. These properties play important roles in the filtering ability of this media. The attenuation capacity of pollutants tends be lower with porous and high permeable aquifer media and vice-versa Anwar *et al* [27]. Hence, the pollution potential rating of the aquifer medium map produced (Figure 4c) was evaluated accordingly (see Table 4). Furthermore, the impact of soil media (S) on pollution potential mapping cannot be overemphasized. The amount of recharge infiltrating the ground surface, the amount of potential dispersion, and the purifying process of contaminants are strongly influenced by the underlying soil type in the area Anbazhagan *et al* [28]. The soil media (Figure 4d) in this study was prepared based on the 1962 district soil type map of Malaysia. The varying properties of the different soil types were used in the rating pollution potential of this layer (Table 4).The topography (T) for this evaluation was derived based on the sloping factor of the area which is in accordance with [25] who reported that topography is the slope variability of an area. The degree of slope, which varies from one place to another controls the likelihood that rainfall and the contained pollutants have to run off or be retained in one area long enough to infiltrate it. The slope layer (Figure 4e) is derived from the processed ASTER DEM image of 30 m resolution (downloaded from NASA’s land processes distributed active archive center (LP DAAC)). This layer was interpreted by adopting a similar approach discussed in prior studies of Adiat *et al* [29], Doumouya *et al* [30]. An area with a low slope degree (flat) tends to retain water for longer time, hence providing greater chance for the infiltration of recharge water, which may contain a considerable amount of pollutants. Meanwhile, an area with a steeper slope has little potential for recharge, thus allowing pollutants little opportunity to reach the groundwater table (see Table 4). Meanwhile, the standard descriptions of varying types of slope used in the evaluation of the slope/topography layer are presented in Table 2. The role of vadose zone in evaluating pollution potential rating has been documented in literatures Chen *et al* [8], Samake *et al* [25]. It influences the aquifer pollution potential depending on the permeability and attenuation characteristics of its soil cover media. Hence, if the vadose zone is vastly permeable, then the probability of such zones/area aquifer being vulnerable to pollution is very high [28].The vadose zone thematic layer (Fig. 4f) was generated from the estimated mean resistivity values of the delineated vadose layer (see Figure 5) and evaluated accordingly (Table 4).The hydraulic conductivity parameter (C) is an important factor that controls contaminant migration and dispersion from the injection point within the saturated zone, and consequently, within the plume concentration in the aquifer AtiqurRahman [6]. The transmission rate of water in subsurface formation is determined by this parameter, which in turn controls contaminant movement rate. Therefore, an area underlain with water bearing formation (aquifer) with high hydraulic conductivity is more vulnerable to potential contamination, relative to other formations with low hydraulic conductivity. The hydraulic conductivity layer (Figure 4g) was prepared from borehole data and evaluated for pollution potential mapping.

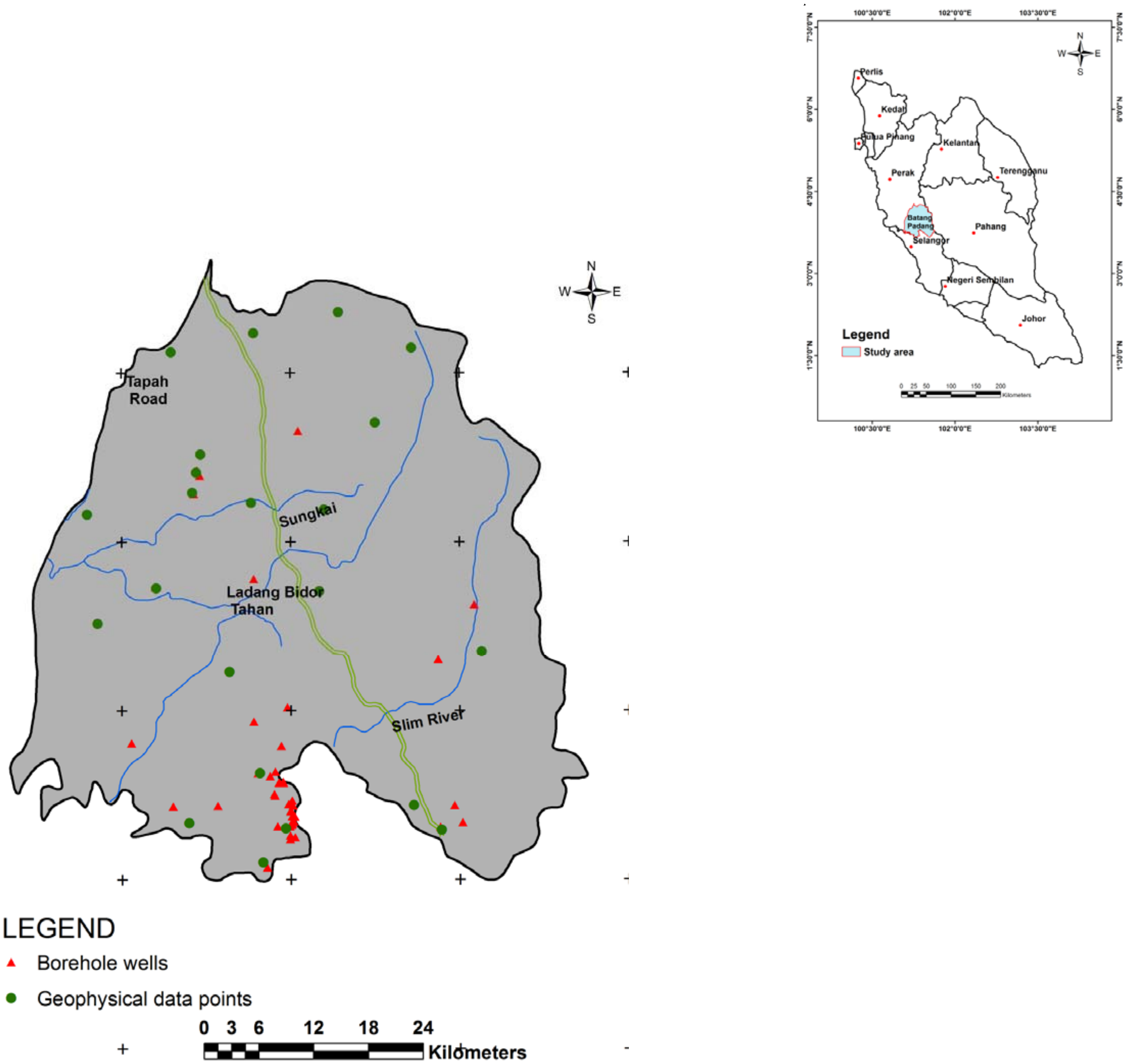

Figure 1. Study area location

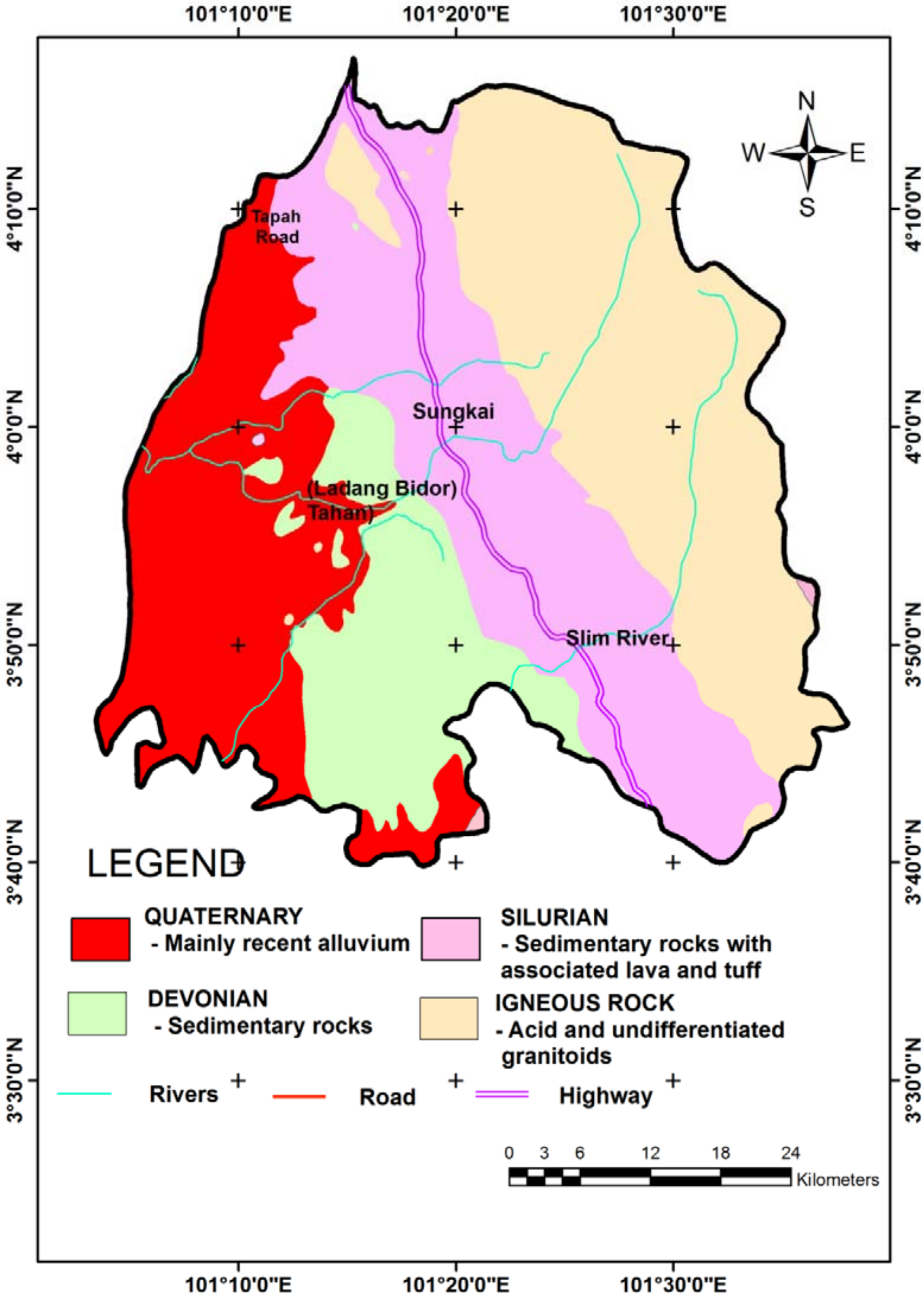

Figure 2. Geological map of the area

Table 1. Information and sources of data used in this study

Data type	Detail of data	Format	Output layer
Borehole data	Malaysian Department of Mineral and Geosciences Date acquired: 12 Feb, 2009	Table and lithology log	Depth to water table(D)
Average annual rainfall	Climatic Research Unit database CRU 2.1 Resolution: 0.5^0	Table	Recharge (R)
Geophysical data	Batang Padang, Perak	Point	Aquifer (A)
Soil map	Ministry of agriculture Kuala Lumpur, Malaysia(1962) Scale: 24 mile : 1 inch	Map	Soil type (S)
Remote sensing imagery	ASTER DEM data NASA((LP DAAC) Resolution: 30 m	Satellite image	Topography/Slope (T)
Geophysical data	Batang Padang, Perak	Point	Impact of vadoze zone(I)
Borehole data	Malaysian Department of Mineral and Geosciences Date acquired: 12 Feb, 2009	Table and lithology log	Hydraulic conductivity(C)

Table 2. Regional slope classification based on Soil Terrain (SOTER) Model

Slope (%)	Classification	Groundwater storage potentiality
0 - 2	Flat	Very high
2 - 8	Undulating	High
8 - 15	Rolling	Moderate
15 - 30	Moderately steep	Low
30 - 60	Steep	Very low

Table 3. Saaty scale for pair-wise comparisons

Score	Judgment	Explanation
1	Equally	Two factors contribute equally to the objective
3	Slightly favour	Slightly favour one attribute over another
5	Strongly favour	Strongly favour one attribute over another
7	Very strongly	Strongly favour one attribute with demonstrated importance over another
9	Extremely	Evidence favouring one attribute over another is one of the highest possible order of affirmation
2,4,6,8	Intermediate	The intermediate values are used when compromise is needed

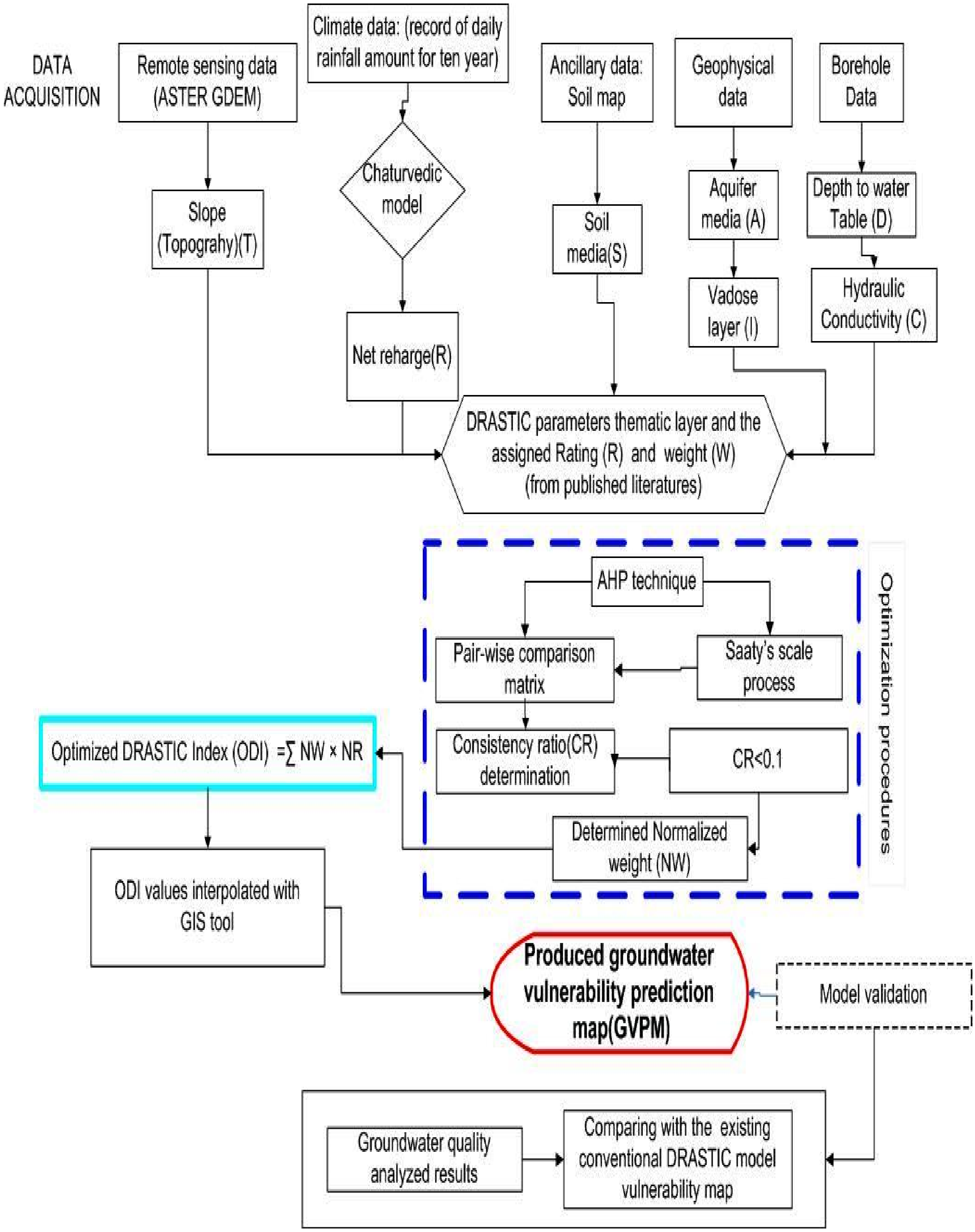

Figure 3. The DRASTIC model evaluation approach and the optimization procedures methodology

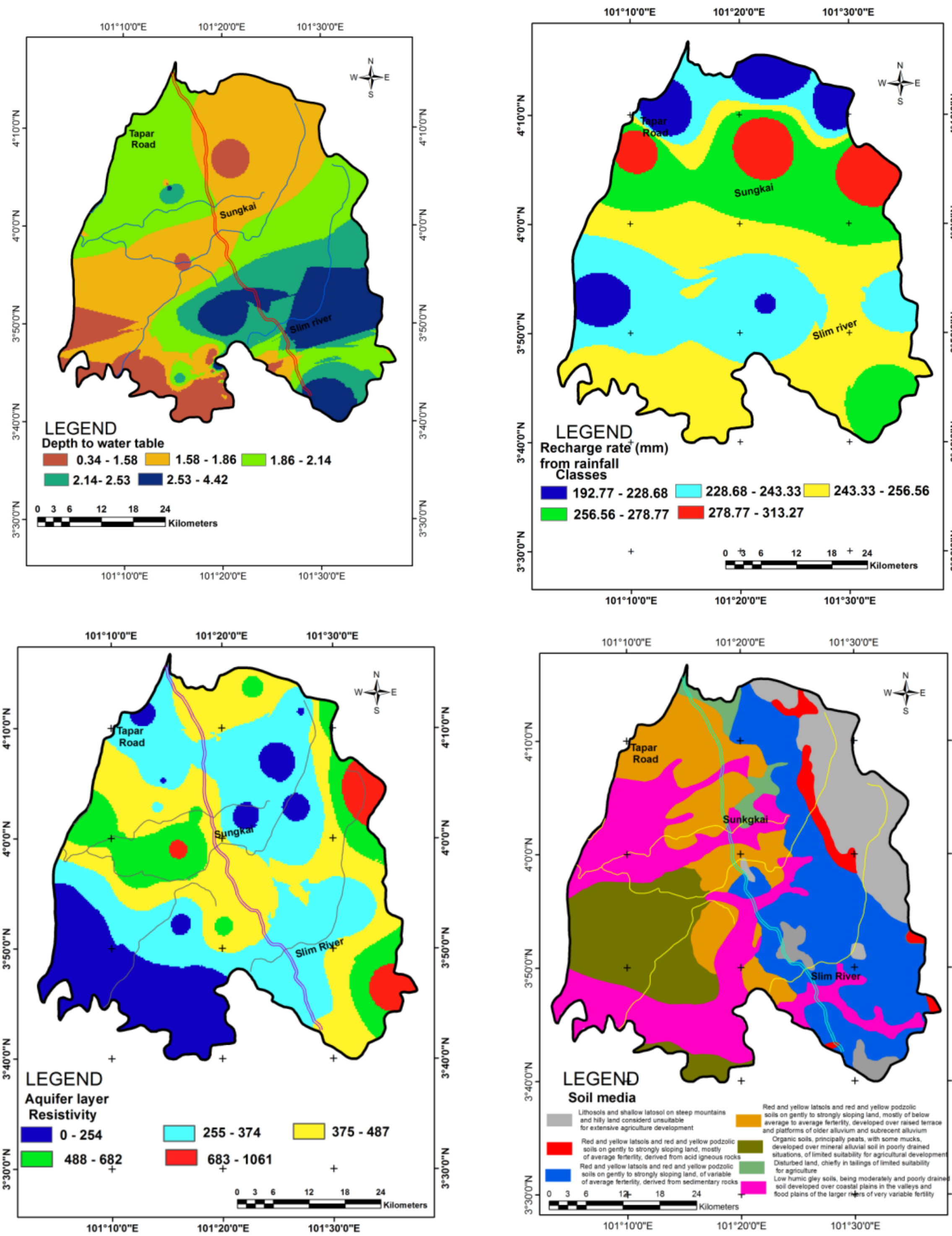

Figure 4. Groundwater pollution potential influencing factors used for DRASTIC model: (a) Depth to water table layer; (b) Rainfall data layer; (c) Aquifer media; (d) Soil media; (e) Topography/slope ; (f) Vadose zone layer and (g) Hydraulic conductivity

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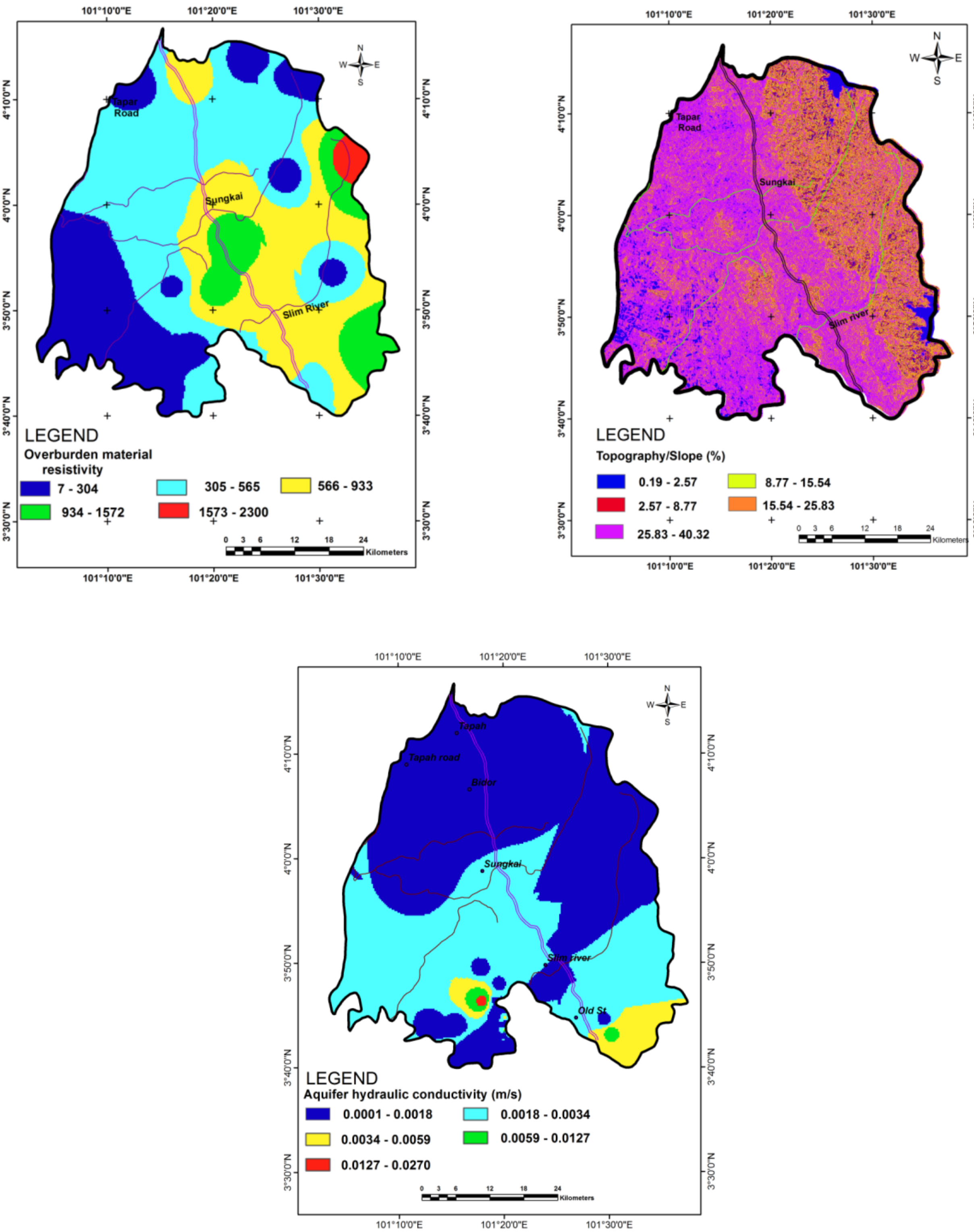

Figure 4. Continued

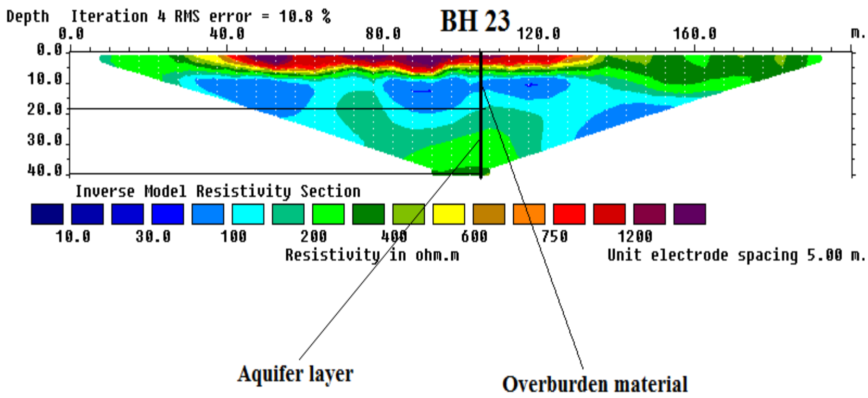

Figure 5. Example of 2D section showing how aquifer media and vadose layer were delineated

2.5. DRASTIC model and decision model optimization procedures

2. 5. 1. Pairwise construction and comparison

The major limitation of the DRASTIC method is its inherent subjectivity in determining rating scales and weighting coefficients [4]. The method is optimized in the present study with a decision model technique. AHP helps in reducing the complexity of the decision problem by considering two parameters/factors at a time, with each parameter being scored according to its relative influence/importance on the pollution potential evaluation. The comparison ratings are based on a scale of 1 to 9 (see Table 3). Construction of the AHP matrix with Saaty's scale in this study was however guided by the use of published expert weights previously assigned to the DRASTIC parameters where parameters are weighted from "1" to "5" according to their relative contribution to potential contamination as reported in the works of (Chen *et al* [8]; AtiqurRahman[6]; Pradhan *et al* [31]; Aller *et al*[10]) coupled with the several field observation in the area. The process adopted for the used Saaty's scale in this study is presented in Table 5, where A, B and C are used for indicating a more preference, less preference and equality in between two factors at a time, respectively. Thereafter, the pair-wise comparison matrix shown in Table 6 was developed. The pair-wise comparison was normalized, where each cell of the matrix was divided by its column total. The normalized weight (NW) was obtained by computing the average value of the normalized pair-wise comparisons. The consistency ratio (CR) obtained for the pair-wise comparison matrix was 0.039 (see Table 6). According to [32] CR=0.039 indicates that the comparisons of the parameters characteristics are perfectly consistent and that the determined normalized weights can be utilized (see Table 4).

2. 5. 2. Estimation of DRASTIC vulnerability index

Using the given equation (1), the conventional DRASTIC vulnerability index based on the rating (R) and the assigned relative weigh (see Table 4) was estimated. Thereafter, the R and W of each factors in equation 1 were substituted with the normalized rating (NR) and the normalized weight (NW) in Table 4. Hence, the conventional DRASTIC model algorithm in equation (1) becomes an optimized DRASTIC model algorithm for estimating optimized DRASTIC index (ODI) in equation (3):

$$ODI = D_{NW}D_{NR} + R_{NW}R_{NR} + A_{NW}A_{NR} + S_{NW}S_{NR} + T_{NW}T_{NR} + I_{NW}I_{NR} + C_{NW}C_{NR} \quad (3)$$

The DI and ODI vulnerability indices were estimated using equations (1) and (3), respectively. The, DI and ODI values obtained for all the grids are presented in Table 7 and Table 8, respectively.

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Table 4. Probability ratings (R) and weight (W) assignment for classes of the DRASTIC parameters (Modified after (Atiqur Rahman [6] and Nobre et al [5])

DRASTIC parameters	**Ranges(classes)**	**Pollution Potentiality for groundwater vulnerability**	**Rating (R)**	**Normalized Rating(NR)**	**Relative Weight**	**Normalized Weight (NW)**
Depth to water (D)	0.34 -1.58	High	5	0.33		
	1.58 -1.86	Medium high	4	0.26		
	1.86 – 2.14	Medium	3	0.2	5	0.31
	2.14 -2.53	Low	2	0.13		
	2.53 – 4.42	Very low	1	0.07		
Recharge(R)	1,082 – 1,292	Very low	1	0.07	4	0.16
	1,292 – 1,476	Low	2	0.13		
	1,476 – 1,681	Medium	3	0.2		
	1,681 - 1,887	Medium high	4	0.26		
	1,887 – 2,161	High	5	0.33		
Aquifer media (A)	0 –254(silty-clay with fine sand)	Very low	1	0.07		
	255-374(silty-clay with gravel/siltstone)	Low	2	0.13		
	375-487(claysand with gravel)	Medium	3	0.2	3	0.08
	488–682(weathered sandstone/coarse gravel)	Medium high	4	0.26		
	683–1061(coarse sand/gravel/Fractured/ jointed sandstone)	High	5	0.33		
Soil media(S)	Lithosol&Shallow latosol(Steep mountail)	Very low	1	0.07		
	Red &Yellow podozolic soil from acid igneous rock	Low	2	0.13		
	Red &Yellow latsols podozolic soil from sedimentary rocks	Medium	3	0.2		
	Red &Yellow latsols podozolic soil from older and sub recent alluvium	Medium high	4	0.26	2	0.04
	Organic soil- peat and poorly drained	Very low	1	0.07		
	Low humic gley soil developed in the valley and flood plain	High	5	0.33		

	Agricultural land	Medium high	4	0.26		
Topography (T)	0 - 2.57	(Flat)High	5	0.33		
	2.57 – 8.77	(Undulating) Medium high	4	0.26		
	8.77 – 15.54	(Rolling)Medium	3	0.2		
	15.54 – 25.83	(Moderately steep)Low	2	0.13	1	0.02
	25.83 – 40.32	(Steep)Very low	1	0.07		
Impact of vadose zone (I)	7 –304 clay/silty sand/consolidated shale)	Very Low	1	0.07		
	305 -565 (silty sand with gravel)	medium	3	0.2		
	566-933 (fracture /weathered sandstone With coarse grave	High	5	0.33	5	0.31
	934 –572(Sandstone with gravel)	Medium high	4	0.26		
	1573 -300(consolidated sandstone/fresh)	Low	2	0.13		
Hydraulic Conductivity(C)	0.0001 – 0.0018	Very low	1	0.07		
	0.0018 – 0.0034	Low	2	0.13		
	0.0034 – 0.0059	Medium	3	0.2	3	0.08
	0.0059 – 0.0127	Medium high	4	0.26		
	0.0127 – 0.0270	High	5	0.33		

Table 5. The expert process adopted for the used Saaty's scale based on published literatures expert Assigned weights (After: Chen *et al* [8]; AtiqurRahman[6]; Pradhan *et al* [31])

Factor 1/(weight)	Extremely favors (9)	Very strong Favors (7)	Strongly favor (5)	Slightly favor (3)	Equal (1)	Slightly favor (3)	Strongly favor (5)	Very strong Favors (7)	Extreme favors (9)	Factor 2/(weight)
Depth to water table/(5)				A						Recharge/ (4)
Depth to water table/(5)			A							Aquifer media/ (3)
Depth to water table/(5)		A								Soil media/ (2)
Depth to water table/(5)	A									Topography/ Slope/ (1)
Depth to water table/(5)					C					Impact of Vadose zone/(5)
Depth to water table/(5)			A							Hydraulic conductivity /(3)
Recharge/ (4				A						Aquifer media/(3)
Recharge/ (4)			A							Soil media/(2)
Recharge/ (4)	A									Topography/ Slope/(1)
Recharge/ (4)						B				Impact of Vadose zone/(5)
Recharge/ (4)				A						Hydraulic conductivity /(3)
Aquifer media/(3)				A						Soil media/(2)
Aquifer media/(3)			A							Topography/ Slope/(1)
Aquifer media/(3)							B			Impact of Vadose zone/(5
Aquifer media/(3)					C					Hydraulic conductivity /(3)
Soil media/(2)				A						Topography/ Slope/(1)
Soil								B		Impact of

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media/(2)										Vadose zone/(5)
Soil media/(2)						B				Hydraulic conductivity /(3)
Topograph y/Slope/(1)									B	Impact of Vadose zone/(5)
Topograph y/Slope/(1)							B			Hydraulic conductivity /(3)
Impact of Vadose zone/(5)			A							Hydraulic conductivity /(3
										Hydraulic conductivity /(3

Table 6. A pairwise comparison matrix for calculation criteria weights for pollution potential mapping using DRASTIC parameters

	D	**R**	**A**	**S**	**T**	**I**	**C**	**Weights**	**CR**
D	1	3	5	7	9	1	5	0.31	0.039
R	1/3	1	3	5	9	1/3	3	0.16	
A	1/5	1/3	1	3	5	1/5	1	0.08	
S	1/7	1/5	1/3	1	3	1/7	1/3	0.04	
T	1/9	1/9	1/5	1/3	1	1/9	1/5	0.02	
I	1	3	5	7	9	1	5	0.31	
C	1/5	1/3	1	3	5	1/5	1	0.08	

Table 7. Conventional DRASTIC index (DI) calculations

Grid Nos	Grid Center's coordinates		D(W=5)		R(W=4)		A(W=3)		S(W=2)		T(W=1)		I(W=5)		C(W=3)		DI
	LONG	LAT	R	R*W	R	R*W	R	R*W	R	R*W	R	R*W	R	R*W	R	R*W	$\sum W*R$
1	754386.3	468233.4	3	15	3	12	2	6	3	6	2	2	3	15	1	3	59
2	765042.5	468233.4	4	20	3	12	5	15	1	2	2	2	1	5	1	3	59
3	743977.9	456833.7	3	15	4	16	3	9	4	8	1	1	4	20	1	3	71
4	754386.3	456833.7	4	20	4	16	4	12	4	8	2	2	5	25	1	3	84
5	765042.5	456833.7	4	20	5	20	1	3	3	6	4	4	5	25	1	3	80
6	775450.8	456833.7	4	20	4	16	3	9	1	2	2	2	5	25	2	6	79
7	733321.8	445434.1	3	15	3	12	5	15	5	10	1	1	4	20	1	3	75
8	743977.9	445434.1	3	15	3	12	4	12	5	10	1	1	4	20	1	3	72
9	754386.3	445434.1	3	15	3	12	5	15	5	10	1	1	5	25	1	3	81
10	765042.5	445434.1	4	20	4	16	5	15	4	8	2	2	3	15	1	3	78
11	775450.8	445434.1	3	15	3	12	3	9	1	2	3	3	5	25	2	6	72
12	733321.8	434034.5	4	20	1	4	1	3	1	2	1	1	1	5	2	6	41
13	743977.9	434034.5	4	20	1	4	1	3	1	2	4	4	4	20	1	3	56
14	754386.3	434034.5	4	20	2	8	4	12	4	8	2	2	5	25	2	6	79
15	765042.5	434034.5	2	10	1	4	3	9	3	6	4	4	3	15	2	6	54
16	775450.8	434034.5	1	5	2	8	4	12	3	6	2	2	1	5	3	9	47
17	786107	434034.5	1	5	2	8	4	12	1	2	4	4	1	5	4	12	48
18	733321.8	422882.7	5	25	1	4	3	9	3	6	4	4	4	20	3	9	76
19	743977.9	422882.7	4	20	1	4	3	9	3	6	5	5	5	25	2	6	74
20	754386.3	422882.7	2	10	2	8	3	9	3	6	2	2	5	25	1	3	62
21	765042.5	422882.7	2	10	1	4	4	12	4	8	1	1	5	25	2	6	65
22	775450.8	422882.7	1	5	2	8	2	6	4	8	2	2	4	20	4	12	60
23	786107	422882.7	2	10	2	8	4	12	3	6	4	4	1	5	4	12	56
24	743977.9	411235.2	5	25	2	8	3	9	3	6	5	5	3	15	2	6	73
25	754386.3	411235.2	5	25	2	8	3	9	4	8	3	3	3	15	4	12	79
26	775450.8	411235.2	1	5	2	8	1	3	3	6	1	1	1	5	5	15	43
27	786107	411235.2	2	10	2	8	4	12	3	6	2	2	4	20	4	12	68

Table 8. Optimized DRASTIC index (ODI) calculations.

Grid No	Grid Center's coordinates		D(NW = 0.31)		R(NW = 0.16)		A(NW = 0.08)		S(NW = 0.04)		T(NW=0.02)		I(NW=0.31)		C(NW=0.08)		ODI
	LONG	LAT	NR	NR*NW	NR	NR*NW	NR	NR*NW	NR	NR*NW	NR	NR*NW	NR	NR*NW	NR	NR*NW	
1	754386.3	468233.4	0.2	0.062	0.2	0.032	0.1	0.0104	0.2	0.008	0.1	0.0026	0.2	0.062	0.1	0.0056	0.183
2	765042.5	468233.4	0.3	0.0806	0.2	0.032	0.3	0.0264	0.07	0.0028	0.1	0.0026	0.1	0.0217	0.1	0.0056	0.172
3	743977.9	456833.7	0.2	0.062	0.3	0.0416	0.2	0.016	0.26	0.0104	0.1	0.0014	0.3	0.0806	0.1	0.0056	0.218
4	754386.3	456833.7	0.3	0.0806	0.3	0.0416	0.3	0.0208	0.26	0.0104	0.1	0.0026	0.3	0.1023	0.1	0.0056	0.264
5	765042.5	456833.7	0.3	0.0806	0.3	0.0528	0.1	0.0056	0.2	0.008	0.3	0.0052	0.3	0.1023	0.1	0.0056	0.260
6	775450.8	456833.7	0.3	0.0806	0.3	0.0416	0.2	0.016	0.07	0.0028	0.1	0.0026	0.3	0.1023	0.1	0.0104	0.256
7	733321.8	445434.1	0.2	0.062	0.2	0.032	0.3	0.0264	0.33	0.0132	0.1	0.0014	0.3	0.0806	0.1	0.0056	0.221
8	743977.9	445434.1	0.2	0.062	0.2	0.032	0.3	0.0208	0.33	0.0132	0.1	0.0014	0.3	0.0806	0.1	0.0056	0.216
9	754386.3	445434.1	0.2	0.062	0.2	0.032	0.3	0.0264	0.33	0.0132	0.1	0.0014	0.3	0.1023	0.1	0.0056	0.243
10	765042.5	445434.1	0.3	0.0806	0.3	0.0416	0.3	0.0264	0.26	0.0104	0.1	0.0026	0.2	0.062	0.1	0.0056	0.229
11	775450.8	445434.1	0.2	0.062	0.2	0.032	0.2	0.016	0.07	0.0028	0.2	0.004	0.3	0.1023	0.1	0.0104	0.230
12	733321.8	434034.5	0.3	0.0806	0.1	0.0112	0.1	0.0056	0.07	0.0028	0.1	0.0014	0.1	0.0217	0.1	0.0104	0.134
13	743977.9	434034.5	0.3	0.0806	0.1	0.0112	0.1	0.0056	0.07	0.0028	0.3	0.0052	0.3	0.0806	0.1	0.0056	0.192
14	754386.3	434034.5	0.3	0.0806	0.1	0.0208	0.3	0.0208	0.26	0.0104	0.1	0.0026	0.3	0.1023	0.1	0.0104	0.248
15	765042.5	434034.5	0.1	0.0403	0.1	0.0112	0.2	0.016	0.2	0.008	0.3	0.0052	0.2	0.062	0.1	0.0104	0.153
16	775450.8	434034.5	0.1	0.0217	0.1	0.0208	0.3	0.0208	0.2	0.008	0.1	0.0026	0.1	0.0217	0.2	0.016	0.112
17	786107.0	434034.5	0.1	0.0217	0.1	0.0208	0.3	0.0208	0.07	0.0028	0.3	0.0052	0.1	0.0217	0.3	0.0208	0.114
18	733321.8	422882.7	0.3	0.1023	0.1	0.0112	0.2	0.016	0.2	0.008	0.3	0.0052	0.3	0.0806	0.2	0.016	0.239
19	743977.9	422882.7	0.3	0.0806	0.1	0.0112	0.2	0.016	0.2	0.008	0.3	0.0066	0.3	0.1023	0.1	0.0104	0.235
20	754386.3	422882.7	0.1	0.0403	0.1	0.0208	0.2	0.016	0.2	0.008	0.1	0.0026	0.3	0.1023	0.1	0.0056	0.196
21	765042.5	422882.7	0.1	0.0403	0.1	0.0112	0.3	0.0208	0.26	0.0104	0.1	0.0014	0.3	0.1023	0.1	0.0104	0.197
22	775450.8	422882.7	0.1	0.0217	0.1	0.0208	0.1	0.0104	0.26	0.0104	0.1	0.0026	0.3	0.0806	0.3	0.0208	0.167
23	786107.0	422882.7	0.1	0.0403	0.1	0.0208	0.3	0.0208	0.2	0.008	0.3	0.0052	0.1	0.0217	0.3	0.0208	0.138
24	743977.9	411235.2	0.3	0.1023	0.1	0.0208	0.2	0.016	0.2	0.008	0.3	0.0066	0.2	0.062	0.1	0.0104	0.226
25	754386.3	411235.2	0.3	0.1023	0.1	0.0208	0.2	0.016	0.26	0.0104	0.2	0.004	0.2	0.062	0.3	0.0208	0.236
26	775450.8	411235.2	0.1	0.0217	0.1	0.0208	0.1	0.0056	0.2	0.008	0.1	0.0014	0.1	0.0217	0.3	0.0264	0.106
27	786107.0	411235.2	0.1	0.0403	0.1	0.0208	0.3	0.0208	0.2	0.008	0.1	0.0026	0.3	0.0806	0.3	0.0208	0.194

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2.6. Preparation of the groundwater vulnerability model maps

The DI and ODI vulnerability indices values for each grid in Table 7 and Table 8, respectively were plotted at the center of the grids. Using the coordinates of the grids' center, the obtained DI and ODI values estimated were utilized for modeling the groundwater vulnerability prediction maps (GVPM) shown in Figures 6 and 7 using the kriging interpolation technique in GIS environment. Thereafter, it was observed from the model maps that the DI and ODI values for the study area are in the range 5.67 to 84.45 and 0.0178 to 0.2639. Employing the natural break classification method according to [33] in GIS platform, the DI and ODI values in Tables 7 and 8 were classified into possible five levels of groundwater vulnerability zones namely; No vulnerable (NV), Very low vulnerable (VLV), Low vulnerable (LV), Moderate vulnerable (MV) and High vulnerable (HV) as presented in Table 9

.

Table 9. The possible groundwater vulnerable zone classification

DI Values	ODI Values	Classifications
5.67 – 36.88	0.0178 – 0.1047	No vulnerable (NV)
36.88 – 51.70	0.1047 – 0.1491	Very low vulnerable (VLV)
51.70 – 61.28	0.1491 – 0.1857	Low vulnerable (LV)
61.28 – 70.55	0.1857 – 0.2176	Moderate vulnerable (MV)
70.55 -84.45	0.2176 – 0.2639	High vulnerable (HV)

3. Results and Discussion

3.1. Distribution of vulnerable zones in the area

The GVPM models (Figures 6 and 7) were evaluated for the distribution of the different groundwater vulnerable zones in GIS environment. Figure 8 shows the area percentages distribution covering the predicted vulnerable zones namely NV, VLV, LV, MV and HV estimated from the produced groundwater vulnerability prediction maps (Figures 6 and 7). It was deduced from figure 8 that more than 50 % of the area are under the moderate to high vulnerable zones which are areas that are highly susceptible to contamination AtiqurRahman [6].

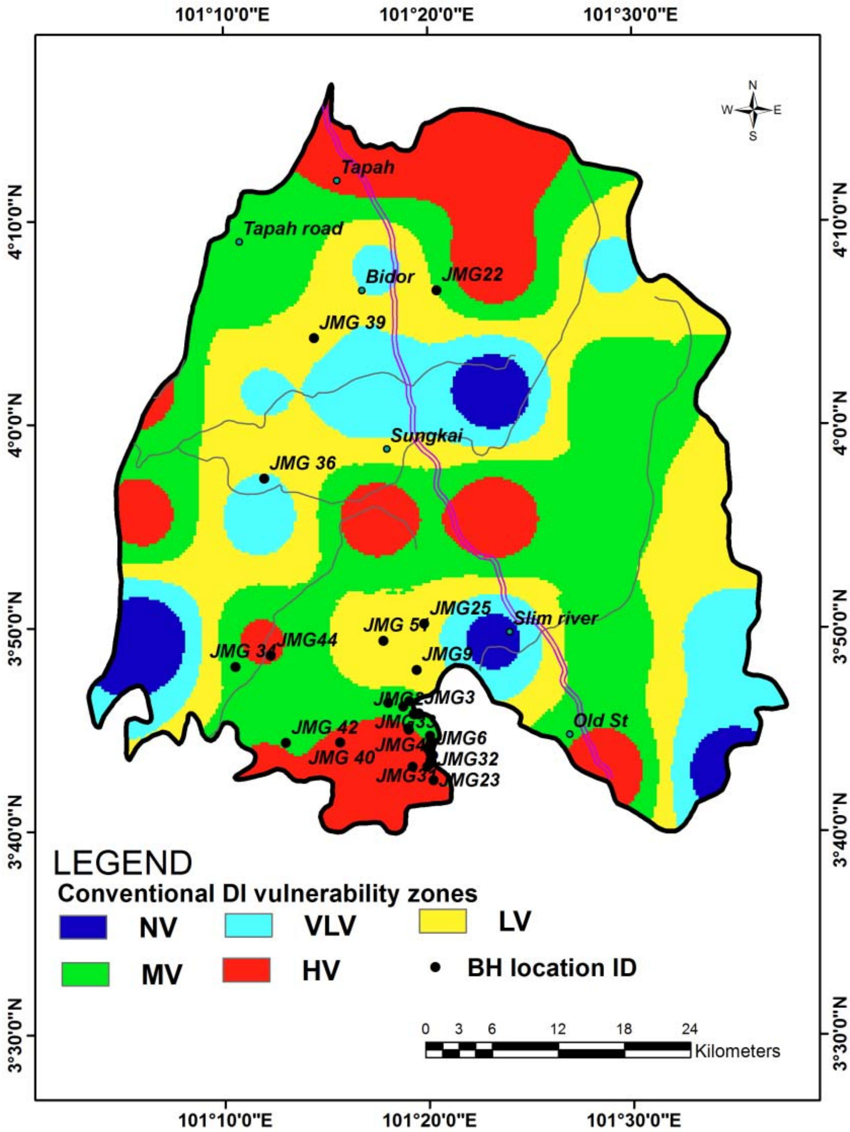

Figure 6. GVPM produced by conventional DRASTIC model

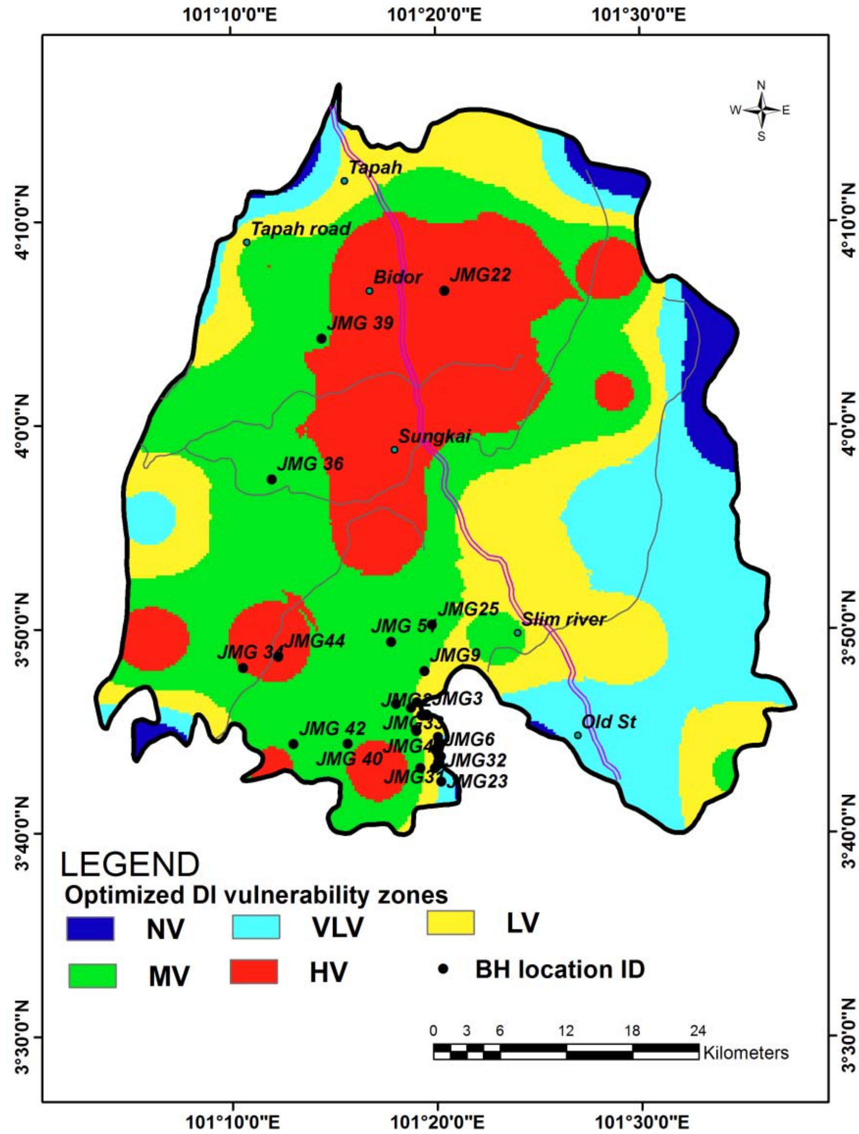

Figure 7. GVPM produced by Optimized DRASTIC model

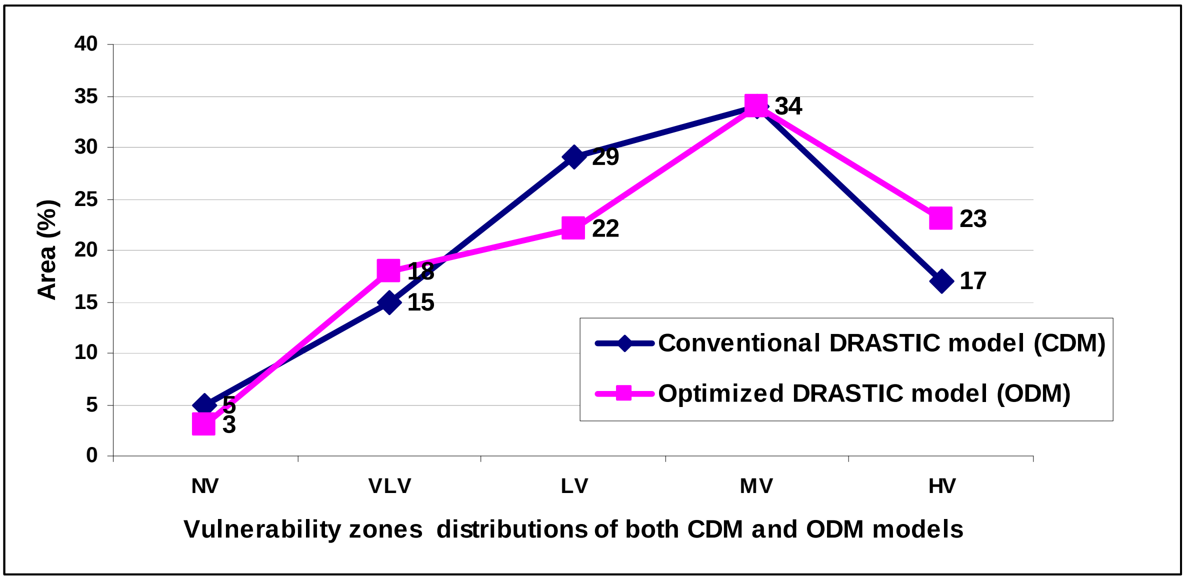

Figure 8. Percentage of vulnerable zones distribution between CDM and ODM approach

3.2. Model validation

The produced groundwater vulnerability prediction maps (Figures 6 and 7) were subjected to validation assessment to establish their reliability and validity for efficient groundwater resources quality preservation in the area. The approach according to Kalinski *et al* [33] and McLay *et al* [34] where chemical and contaminant parameters concentrations in groundwater samples were used to correlate vulnerability index were adopted for validation technique in this study. The groundwater quality analysis obtained in the area enabled determination of physio-chemical parameters and heavy metals element concentration records in the groundwater samples obtained from the drilled boreholes in the area. However, it should note that, a rare reference on groundwater contamination problem was present in the area despite being an area covered with agricultural lands. Hence, this study aimed to assess impending contamination to be model from estimated vulnerability index in the area. The determined physio-chemical parameters and heavy metals that were assumed to be completely soluble in water include pH, TDS, nitrate (NO_3), sulfate (SO_4), calcium (Ca), iron (Fe), zinc (Zn) and manganese (Mn). The records of the concentrations of these chemical parameters and elements were compared with the WHO (World Health Organization) and Food and Agriculture Organization (FAO) standard levels to assess the water quality status of the boreholes sampled. Hence, the water quality in the area has been classified into good or bad depending on the permissible limit of these standards. Y and X are used for indicating good and bad water qualities, respectively depending on the measured concentrations of each chemical elements/parameters relatively to the permissible limit based on WHO and FAO standards. Therefore, for each determined parameters where the concentration (mg/l) is within the permissible limit of these standards, “Y” is indicated (see Table 10). On the other hand, where we have the measured concentration of the chemical elements exceeded the permissible limit, “X” is indicated. The results of this water quality assessment from each boreholes drilled across the entire study area were used to assess the accuracy of the vulnerable maps produced. The locations of these boreholes and their respective names are displayed on the prediction maps shown in figures 6 and 7. The comparison results based on Table 11 general showed that water quality in the area is relatively of good status. However, the level of concentration of pH and Manganese chemical elements which exceeded the permissible limit of FAO and WHO standards have shown traceable groundwater contamination or pollution in the area. Hence, these two chemical parameters were used as groundwater contamination indices for evaluating prediction accuracy of the GVPM models. The DRASTIC vulnerability index of the most vulnerable zones i.e the moderate and the high (MV and HV) of the vulnerability maps were spatially correlated with concentration records of pH and Mn in each of the boreholes located in those zones. The considered MV and HV are in accordance with Artiqur Rahman [6] and Thirumalaivasan *et al* [7] where the moderate to high vulnerable zones in a predicted vulnerability map are typified areas that are highly susceptible to pollution compare to the NV, VLV and LV zones that are areas that are characterized with attributes of high resistance to pollution.

The results of the spatial relationship of the conventional DRASTIC vulnerability index model (CDM) and the optimized DRASTIC index model (ODM) to groundwater pH and Manganese (Mn) concentration in the area are shown in figure 9.

Table 10 Groundwater quality evaluation criteria based on FAO and WHO standards (After FAO [35] and WHO [36])

Standards	Physio-chemical Parameters					Heavy Metals			Water quality remark	
	pH	TDS	NO_3	Ca	SO_4	Fe	Zn	Mn	Good	Bad
WHO	6.5 – 8.5	500	50	75	20	0.5 - 50	3	0.1	Y	
FAO	6.5 – 8.5	2000	10	20	20	-	0.01	-		X

The results in Figure 9 present the comparative analysis of the prediction accuracy of GVPM models both for the conventional DRASTIC model and the optimized DRASTIC model(Figures 6 and 7), respectively. The results clarified the prediction accuracy of the produced GVPM based on optimized DRASTIC model (ODM) compare to GVPM based on conventional DRASTIC model (CDM) in the study area. The computed correlation factor results obtained from the spatial relationship between the vulnerability index of MV and HV zones of ODM - based model map to pH and Mn concentrations yielded 90 % and 86 %, respectively while the CDM - based model map have correlation factor of 62 % and 50 %, respectively. These results established the reliability and validity of the ODM based groundwater vulnerability prediction map as decision support tool that can provide a satisfactory assessment of intrinsic vulnerability of groundwater to pollution in the study area.

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4. Conclusions

This study developed an optimized DRASTIC model (ODM) algorithm through application of AHP as a decision support model to conventional DRASTIC model (CDM) algorithm. With the sound mathematical basis of AHP application to the weights of the CDM parameters, namely, depth-to-water table, recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity, obtainable in the vicinity of oil palm plantation and other agricultural activities in southern Perak, Malaysia, the optimized DRASTIC index for groundwater vulnerability modeling in the area was obtained.. Five vulnerable zones, namely, NV, VLV, LV, MV, and HV where more than 50 % of the area belong to MV and HV zones were identified based on application of the ODM algorithm. The prediction accuracy of the ODM - based groundwater vulnerability prediction map with the groundwater pH and Mn concentrations yielded correlation factor of 90 % and 86 %, respectively compared to 62 % and 50 % correlation factors computed for CDM - based prediction map. These results indicated that the optimized DRASTIC model (ODM) could provide better results as compared with the conventional DRASTIC model (CDM). An advantage of optimized DRASTIC model (ODM) algorithm is that it can provide an excellent insight into the reduction of bias in decision making in vulnerability mapping through appropriate management of the uncertainty and subjectivity of the CDM parameters. The ODM-based vulnerability prediction model map produced in this study is recommended for evaluating groundwater vulnerability to pollution in the study area. Therefore, the ODM–based groundwater vulnerability prediction map (GVPM) can be utilized as an economical tool to identify the zones of concern and as a tool to overcome problems regarding the haphazard and uncontrolled development of land and undesirable activities that can affect groundwater quality in the study area. However, the produced GVPM can only be utilized as a screening tool and not as a replacement for detailed site-specific analysis.

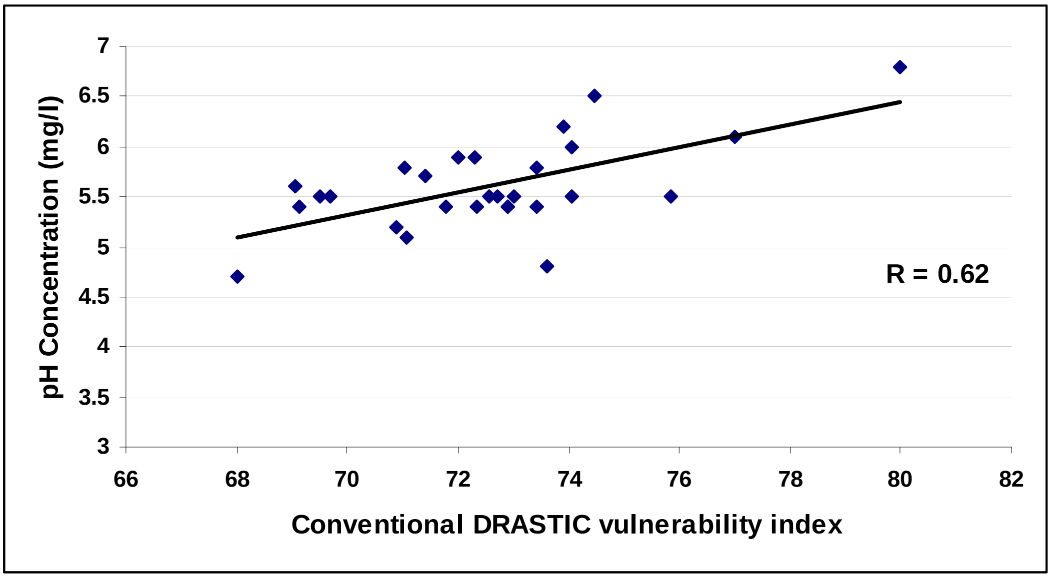
5. Acknowledgments

This project was carried out with financial support from RUI, Investigation Of The Impacts Of Summertime Monsoon Circulation To The Aerosols Transportation And Distribution In Southeast Asia Which Can Lead To Global Climate Change, 1001/PFIZIK/811228 and Science Fund, Environmental Effects And Its Influence of Increased Green House Gasses In Peninsular Malaysia, 305/PFIZIK/613615.

Table 11 Groundwater quality analysis and the comparison results with the FAO and WHO standards

BH NAMES	**BH location coordinates**		**Physio-chemical Parameters**										**Heavy Metals**						**General BH Water quality Remark**
	LAT	LONG	pH	B	TDS	B	NO_3	B	Ca	B	SO_4	B	Fe	B	Zn	B	Mn	B	
JMG2	416182	758308	6.5	X	338	Y	3.90	Y	3.6	Y	3.8	Y	53.8	Y	0.02	Y	0.50	X	Y
JMG3	416304	758263	5.6	X	102	Y	0.09	Y	4.7	Y	0.6	Y	53.7	Y	0.12	Y	0.54	X	Y
JMG 4	416214	757808	5.5	X	100	Y	0.05	Y	3.2	Y	0.2	Y	59.9	Y	0.10	Y	0.26	X	Y
JMG6	412612	759329	5.5	X	41	Y	0.10	Y	5.3	Y	0.3	Y	39.0	Y	0.10	Y	0.51	X	Y
JMG9	420230	758064	5.9	X	29	Y	0.00	Y	1.6	Y	7.1	Y	28.2	Y	0.10	Y	0.38	X	Y
JMG16	411468	757687	5.4	X	33	Y	0.25	Y	1.4	Y	2.4	Y	23.2	Y	0.10	Y	0.45	X	Y
JMG17	411450	759032	5.5	X	73	Y	0.10	Y	3.8	Y	18.4	Y	16.9	Y	0.03	Y	0.71	X	Y
JMG1 8	411716	759298	5.8	X	39	Y	0.05	Y	4.5	Y	1.9	Y	44.8	Y	0.35	Y	1.16	X	Y
JMG 19	411616	759198	6.8	X	59	Y	0.01	Y	5.0	Y	1.9	Y	37.1	Y	0.00	Y	1.21	X	Y
JMG21	416181	757886	6	X	38	Y	0.68	Y	2.7	Y	0.2	Y	51.3	Y	0.10	Y	0.24	X	Y
JMG22	454638	759856	5.8	X	46	Y	0.05	Y	2.7	Y	0.2	Y	52.0	Y	0.09	Y	0.54	X	Y
JMG23	410246	759591	5	X	68	Y	0.20	Y	4.2	Y	62.7	Y	36.3	Y	0.04	Y	1.20	X	Y
JMG25	424414	758753	5.1	X	38	Y	0.00	Y	1.8	Y	1.5	Y	20.2	Y	0.10	Y	0.43	X	Y
JMG27	414271	759280	5.1	X	27	Y	0.00	Y	1.2	Y	0.6	Y	20.9	Y	0.10	Y	0.19	X	Y
JMG28	413718	759359	5.7	X	58	Y	0.10	Y	2.8	Y	1.5	Y	42.5	Y	0.03	Y	0.52	X	Y
JMG29	412513	759574	5.5	X	82	Y	6.90	Y	3.8	Y	3.8	Y	38.5	Y	0.10	Y	0.59	X	Y
JMG31	412037	759330	5.4	X	10	Y	0.10	Y	0.5	Y	1.9	Y	4.1	Y	0.10	Y	0.13	X	Y
JMG32	411971	759431	5.4	X	19	Y	0.30	Y	2.2	Y	0.3	Y	14.9	Y	0.10	Y	0.39	X	Y
JMG33	416909	756862	5.4	X	21	Y	0.00	Y	1.6	Y	1.0	Y	17.9	Y	0.10	Y	0.28	X	Y
JMG 34	420497	741653	5.5	X	30	Y	0.20	Y	1.8	Y	0.7	Y	24.5	Y	0.10	Y	0.48	X	Y
JMG 35	414952	757311	6.1	X	50	Y	0.10	Y	3.8	Y	3.4	Y	17.1	Y	0.03	Y	0.91	X	Y
JMG 36	437560	744242	5.3	X	31	Y	0.10	Y	2.5	Y	0.2	Y	46.3	Y	0.10	Y	0.37	X	Y
JMG 38	413076	759094	5.4	X	29	Y	0.10	Y	2.8	Y	0.3	Y	25.1	Y	0.01	Y	0.51	X	Y
JMG 39	450292	748761	5.5	X	90	Y	0.05	Y	3.2	Y	0.5	Y	30.7	Y	0.07	Y	0.48	X	Y
JMG 40	413664	751115	6.2	X	58	Y	0.05	Y	5.2	Y	3.1	Y	7.3	Y	0.06	Y	0.20	X	Y
JMG 41	413109	759150	5.5	X	43	Y	0.03	Y	2.5	Y	0.2	Y	30.7	Y	0.10	Y	0.35	X	Y
JMG 42	413618	746226	5.4	X	5	Y	0.20	Y	2.4	Y	0.2	Y	32.8	Y	0.10	Y	0.29	X	Y
JMG 43	413220	759138	5.9	X	56	Y	0.00	Y	2.4	Y	0.4	Y	31.5	Y	0.10	Y	0.32	X	Y
JMG45	414808	757378	5.4	X	57	Y	0.20	Y	3.1	Y	1.9	Y	26.2	Y	0.01	Y	0.67	X	Y
JMG 47	417237	755516	5.2	X	63	Y	0.00	Y	3.2	Y	0.5	Y	34.7	Y	0.01	Y	0.76	X	Y
JMG 50	417408	757405	5.9	X	3	Y	0.10	Y	1.7	Y	2.9	Y	25.0	Y	0.10	Y	0.36	X	Y
JMG 51	422877	755057	4.9	X	28	Y	0.10	Y	3.1	Y	1.0	Y	34.0	Y	0.07	Y	0.52	X	Y
JMG44	421523	744839	4.7	X	43	Y	0.10	Y	1.2	Y	3.3	Y	19.2	Y	0.01	Y	0.25	X	Y

B:Water quality measurement level; Y: Good water quality and X: Bad water quality



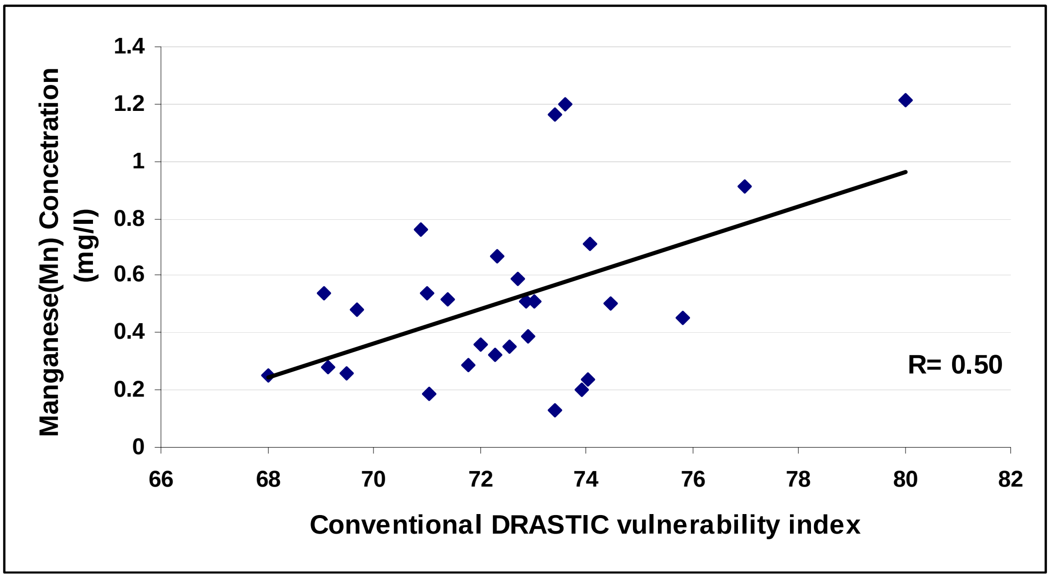
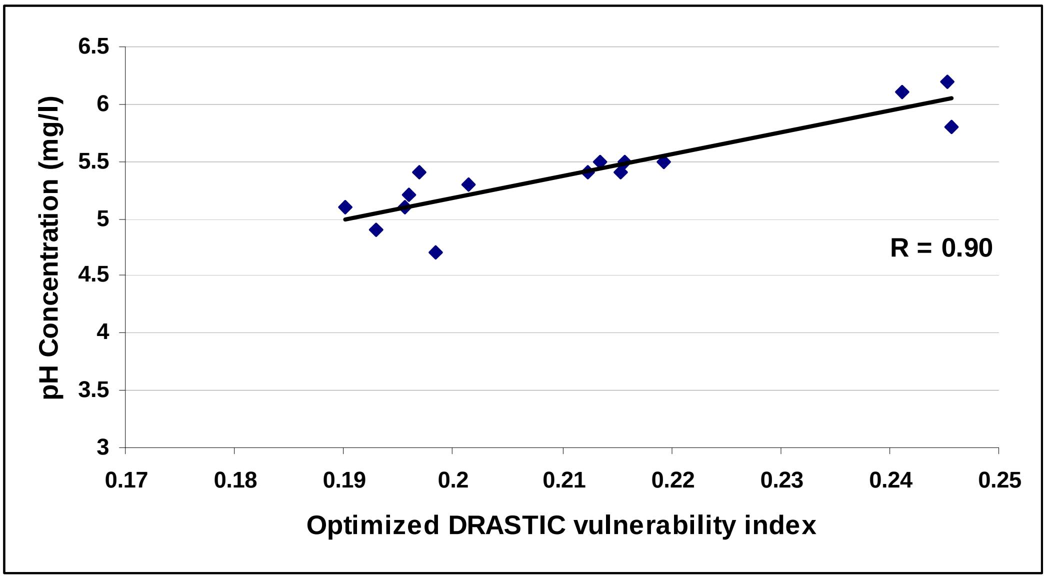


Figure 9. Spatial relationship of conventional DRASTIC vulnerability index and optimized DRASTIC vulnerability index to groundwater pH and Mn concentrations in the study area.



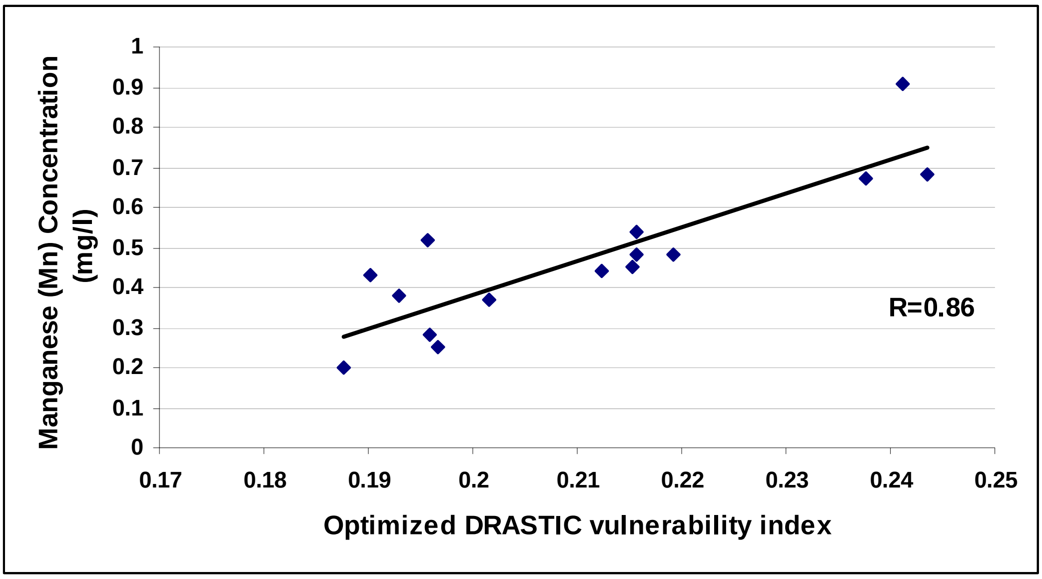


Figure 9. Continued

6. References

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