Environ Earth Sci
DOI 10.1007/s12665-013-2360-9

ORIGINAL ARTICLE

Groundwater vulnerability assessment in the Melaka State of Malaysia using DRASTIC and GIS techniques

S. M. Shirazi · H. M. Imran · S. Akib · Zulkifli Yusop · Z. B. Harun

Received: 15 September 2011 / Accepted: 28 February 2013

Abstract The present work attempts to interpret the groundwater vulnerability of the Melaka State in peninsular Malaysia. The state of groundwater pollution in Melaka is a critical issue particularly in respect of the increasing population, and tourism industry as well as the agricultural, industrial and commercial development. Focusing on this issue, the study illustrates the groundwater vulnerability map for the Melaka State using the DRASTIC model together with remote sensing and geographic information system (GIS). The data which correspond to the seven parameters of the model were collected and converted into thematic maps by GIS. Seven thematic maps defining the depth to water level, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity were generated to develop the DRASTIC map. In addition, this map was integrated with a land use map for generating the risk map to assess the effect of land use activities on the groundwater vulnerability. Three types of vulnerability zones were assigned for both DRASTIC map and risk map, namely, high, moderate and low. The DRASTIC map illustrates that an area of 11.02 % is low vulnerability, 61.53 % moderate vulnerability and 23.45 % high vulnerability, whereas the risk map indicates that 14.40 % of the area is low vulnerability, 47.34 % moderate vulnerability and 38.26 % high vulnerability in the study area. The most vulnerability area exists around Melaka, Jasin and Alor Gajah cities of the Melaka State.

Keywords Groundwater vulnerability · DRASTIC · GIS · State of Melaka

Introduction

Currently, groundwater quantity and quality is a vital issue worldwide. Groundwater quantity and quality is deteriorating due to increase in urbanization and its adverse effect (Khan et al. 2011; Dimitriou and Moussoulis 2011; Shirazi et al. 2010, 2011, 2012). The Melaka State is subject to limited water resources because of the small land area and low annual rainfall compared to the other parts of Malaysia. The rainfall distribution is slightly seasonal, with the minimum occurring from December to February while the rest of the year is wet. Due to limited water availability and potential issues of water quality in Melaka, there is clearly an urgent need for rapid reconnaissance techniques that allow an assessment of groundwater vulnerability over large areas. Groundwater vulnerability mapping is based on the idea that some lands are more vulnerable to groundwater contamination than others (Piscopo 2001), which is defined as the possibility of percolation and diffusion of contaminants from the ground surface into the groundwater system. Groundwater vulnerability only deals with the hydrogeological settings, and does not include pollutant attenuation. Groundwater vulnerability to contamination has been defined by the National Research Council (1993) as the tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer.

Electronic supplementary material The online version of this article (doi:10.1007/s12665-013-2360-9) contains supplementary material, which is available to authorized users.

S. M. Shirazi (✉) · H. M. Imran · S. Akib · Z. B. Harun
Department of Civil Engineering, Faculty of Engineering,
University of Malaya, 50603 Kuala Lumpur, Malaysia
e-mail: smshirazi@gmail.com

Z. Yusop
Institute of Environmental and Water Resource Management,
Universiti Technologi Malaysia, 81310 Skudai, Johor, Malaysia

Many approaches such as process-based methods, statistical methods, and overlay and index methods were developed to evaluate aquifer vulnerability (Tesoriero et al. 1998). Although the process-based methods use simulation models to estimate the contaminant migration, they are constrained by data shortage and computational difficulties (Barbash and Resek 1996). The most widely used groundwater vulnerability mapping method to assess the groundwater vulnerability for a wide range of contamination is an empirical model called DRASTIC (Evans and Mayers 1990; Knox et al. 1993; Kim and Hamm 1999; Fritch et al. 2000; Piscopo 2001; Al-Adamat et al. 2003; Thirumalaivasan et al. 2003; Murat et al. 2004; Vias et al. 2005; Stigter et al. 2006; Herlinger and Viero 2006; Rahman 2008). Measured nitrate concentration has significant importance in improving the DRASTIC method's accuracy for groundwater vulnerability assessment (Akhavan et al. 2011). The DRASTIC model was developed by Aller et al. (1987) combined with the US Environmental Protection Agency and the National Water Well Association to be a standardized system for evaluating groundwater vulnerability to pollution. Hong and Chon (1999) conducted an investigation on groundwater contamination and interpreted spatial relationship among the quality of groundwater, geology, topography, land cover and pollution sources in the Asan and Gurogu area of Seoul city, Korea. Anbazhagan and Nair (2004) delineated groundwater quality mapping through GIS in Panvel Basin of Raigarh District, India. The GIS was a very effective tool to handle large amounts of hydrological, hydrogeological and geological data (Anbazhagan and Nair 2004; Jha and Se 2006; Jha et al. 2007; Marchant et al. 2011). The purpose of this study is to provide a vulnerability map and information on the groundwater resources in the Melaka State, which in turn could be incorporated into groundwater protection plans. The DRASTIC model has been used to compute the relative vulnerability of groundwater to contamination from surface sources of pollution. The model results can be used to provide assistance in planning groundwater-related activities. The combined data layers and maps are developed by using the computer mapping hardware and software of the GIS to combine data layers. Groundwater vulnerability is assessed by assigning point ratings to the individual data layers and then adding the point ratings together, when these layers are combined into vulnerability map.

The study area

Melaka State is the third smallest state and situated on the west coast of peninsular Malaysia. It is located between latitudes 1°06′ and 2°30′N and longitudes 101°58′ and 102°35′E. Melaka has three districts, namely, Alor Gajah, Melaka Tengah and Jasin. These are further divided into 81 mukims (parishes). The area of the state is approximately 1,650 km^2. Its population is 0.605 million and density of 385 persons per km^2 (Statistics Department of Malaysia 2000). Some dams and water plants govern the water resources of Melaka. The average annual runoff depth of Melaka is about 500–600 mm compared to approximately 1,000 mm for other parts of peninsular Malaysia. About 80–90 % of the water demand of Melaka is supplied by the Melaka and Kesang River and the remaining is imported from the Muar River of Johor (Malaysian Water Association 2008). Only 3 % of the state is covered by forest (Land and Mines Department of Melaka 2003). The naming of a lithology is based on the rock type. The three major underlying lithological formations of the study area are metamorphic, sedimentary and igneous rock (Geological Survey 1985) as shown in Fig. 1 (ESM). The study area can be divided into three groups, namely, (1) metamorphic rock (phyllite, schist and slate), mainly found in the western and central parts as well as coastal areas of the state; (2) sedimentary rocks (alluvium, sand and limestone), found in the eastern and coastal areas of the study area; (3) igneous rock (granite and acid intrusive rock), mainly found in the northern parts, but also extend into the southern parts. Some sedimentary and metamorphic rock formations also found in the eastern parts of the state.

Materials and methods

The DRASTIC method

DRASTIC is an empirical method developed for evaluating the pollution potential of groundwater systems on a regional scale. The method is being used increasingly in Europe and in Latin America (Lobo-Ferreira and Oliveira 2003; Ramos-Leal and Rodríguez-Castillo 2003). The goal of the model is to identify areas where special attention or protection efforts are warranted. The set of variables are grouped into three categories: land surface factors, unsaturated zone factors and aquifer or saturated zone factors which are the important considerations for the DRASTIC model (Hasiniaina et al. 2010). Four assumptions have been considered for the model: (1) the contaminant is introduced at the ground surface; (2) the contaminant is flushed into the groundwater by precipitation; (3) the contaminant has the mobility of water and (4) the area being evaluated by DRASTIC is 0.4 km^2 or larger. The acronym of DRASTIC stands for the parameters that are included in the method: Depth of water table, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone and hydraulic Conductivity of the aquifer. The weight of the parameters is shown in Table 1. The DRASTIC index is calculated roughly analogous to the likelihood that contaminants released in a region will reach the groundwater, with higher scores implying a higher likelihood of contamination. GIS is considered an adequate tool to use in the application of the DRASTIC method.

The model yields a numerical index derived from ratings and weights assigned to the seven parameters. The significant media types or classes of each parameter represent the ranges, which are rated from 1–10 based on their relative effect on the aquifer vulnerability. Then the weight ranging from 1–5 reflecting their relative importance is assigned to the parameters. The DRASTIC index is then computed applying a linear combination of all factors according to the following Eq. (1):

$$\text{DRASTIC Index} = D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W \quad (1)$$

where D, R, A, S, T, I, and C are the seven parameters of the model and the subscripts R and W are the corresponding ratings and weights, respectively. The DRASTIC index is calculated by multiplying each parameter rating with its weight, and then added together the resulting values. Each parameter is rated on a scale from one (1) to ten (10), where the rating 1 and 10 indicates the lowest and highest potential to contamination, respectively. In the next step, the parameters are weighted to express their relative importance with respect to each other. The groundwater vulnerability mapping procedures are carried out in this study incorporated with the ArcGIS software, which provide computerized mapping, and spatial data analysis that enables the manipulation and analysis of spatially referenced information to describe the relationship between landscape features. Though not originally designed as a GIS-based tool, the DRASTIC model lends itself to such an implementation (Merchant 1994). GIS applications of the DRASTIC model (Trent 1993) and its variations (Lusch et al. 1992) have been widely documented in the literature. In this study, GIS is used in a number of procedures, including: (1) converting hardcopy maps information into a digital format; (2) creating map of groundwater depth from well log, water depth records and well location information; (3) creating map of the saturated hydraulic conductivity from well log pumping data and well location information; and (4) overlaying individual characteristic maps to create the final vulnerability maps. The study flow chart is shown in Fig. 2 (ESM).

Results and discussion

To carry out the aquifer vulnerability assessment using the DRASTIC method, seven thematic maps are prepared. The successive steps are as follows.

Depth to water table

The depth of water table is defined as the distance in which the pollutants move through the soil media before reaching the groundwater table. Hence, the pollutant elapsed time and attenuation depends on the soil media and the depth of the water table, which has a significant effect on assigning the rating values of the parameters. Depth of groundwater data are collected from boreholes log information, direct measurement of water level of existing shallow boreholes and drilling wells from ground surface. The inverse distance moving average interpolation technique is performed on the measured depth to groundwater point data using a simple inverse power including a high number of input

Table 1 The DRASTIC model parameters (Aller et al. 1987)

Factor	Description	Relative weight
Depth of water table	Represents the depth from the ground surface to the water table, deeper water table levels imply less chance for contamination to occur	5
Net recharge	Represents the amount of water that penetrates the ground surface and reaches the water table, recharge water represents the vehicle for transporting pollutants	4
Aquifer media	Refers to the saturated zone material properties, it controls the pollutant attenuation processes	3
Soil media	Represents the uppermost weathered portion of the unsaturated zone and controls the amount of recharge that can infiltrate downward	2
Topography	Refers to the slope of the land surface, it dictates whether the runoff will remain on the surface to allow contaminant percolation to the saturated zone	1
Impact of vadose zone	Is defined as the unsaturated zone material, it controls the passage and attenuation of the contaminated material to the saturated zone	5
Hydraulic conductivity	Indicates the ability of the aquifer to transmit water, and hence determines the rate of flow of contaminant material within the groundwater system	3

points to generate a smooth surface. Assigning sensitivity rating values such as 10 for depth (<1.5 m), 9 for depth (1.5–4.5 m) and 7 for depth (4.6–9.0 m) and so on, is shown in Table 2 and resulted map in Fig. 1.

The net recharge

The net recharge is the amount of water from precipitation and artificial sources available to migrate down to the groundwater. The recharge is controlled by land cover, slope, permeability of soil, rainfall and amount of water that infiltrates into groundwater table. High recharge indicates the high pollution potential to contamination. Therefore, it is a significant vehicle for percolating and transporting contaminants to the saturated zone and also increases the water table. The shallow aquifer of the basin is characterized by a high recharge rate, but limited groundwater recharge into the deep aquifer due to an impermeable clay layer. The shallow aquifer is mainly recharged by direct infiltration from precipitation; therefore, the recharge map is constructed from the rainfall data according to the following Eq. (2):

$$\text{Net recharge} = (\text{Rainfall} - \text{Evaporation}) \times \text{Coefficient of Thiessen} \qquad (2)$$

The rainfall map is obtained by interpolating the 22-year mean of annual precipitation (mm/year) from four representative rainfall stations (Melaka, Devon, Felda and Mardi). The net recharge map is presented in Fig. 2 and the respective information is shown in Table 2.

The aquifer media

An aquifer is defined as “a subsurface rock unit which will yield sufficient quantities of water for use”. Aquifer media describes the consolidated and unconsolidated rock where

Table 2 DRASTIC quantitative parameters

Rating	Depth of water (m) $D \times (5)$	Net recharge (mm/year) $R \times (4)$	Aquifer media $A \times (3)$	Soil media $S \times (2)$	Topography (%) $T \times (1)$	Impact of the vadose zone $I \times (5)$	Hydraulic conductivity (m/s) $C \times (3)$
10	0–1.5		Karst limestone	Thin or absent, gravel	0–2	Karst limestone	$>9.5 \times 10^{-4}$
9	1.5–4.5	>250	Basalt	Sand stone and volcanic	2–3	Basalt	7×10^{-4}–9.5×10^{-4}
8		180–250	Sand and gravel	Peat	3–4	Sand and gravel	5×10^{-4}–7×10^{-4}
7	4.5–9.0		Massive sandstone and limestone	Shrinking and/or aggregate clay/alluvium	4–5	Gravel, sand	20×10^{-4}–5×10^{-4}
6		100–180	Bedded sandstone, limestone	Sandy loam, schist, sand, karst, volcanic	5–6	Limestone, gravel, sand, clay	30×10^{-5}–20×10^{-4}
5	9–15		Glacial	Loam	6–10	Sandy silt	20×10^{-5}–30×10^{-5}
4			Weathered metamorphic/igneous	Silty loam	10–12	Metamorphic gravel and sand	15×1^{-5}–20×10^{-5}
3	15–23	50–100	Metamorphic/igneous	Clay loam	12–16	Shale, silt and clay	10×1^{-5}–15×10^{-5}
2	23–31		Massive shale	Muck, acid, granitoid	16-18	Silty clay	5×10^{-5}–10×10^{-5}
1	>31	0–50		Non shrink and non-aggregated clay	>18	Confining layer, granite	1.5×10^{-7}–5×10^{-5}

Land use classification	Rating
Animal husbandry, horticulture, urban and agricultural area	8
Palm tree and other permanent crops land	5
Water body	3
Swamps and marsh land, grass and wetland and others	2
Forest land	1

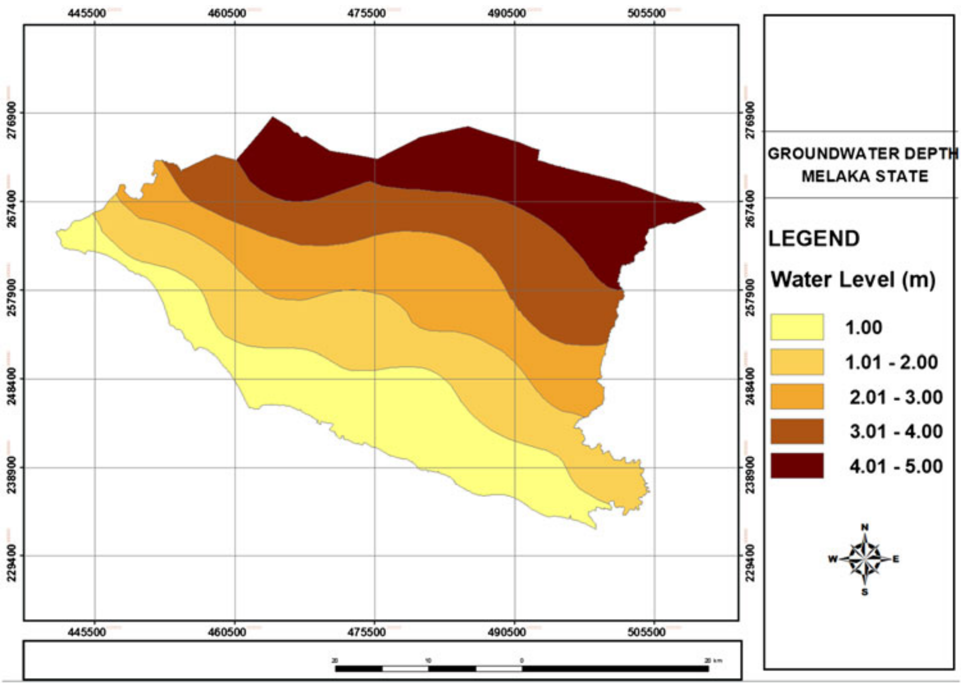


Fig. 1 Depth of ground water level map of Melaka

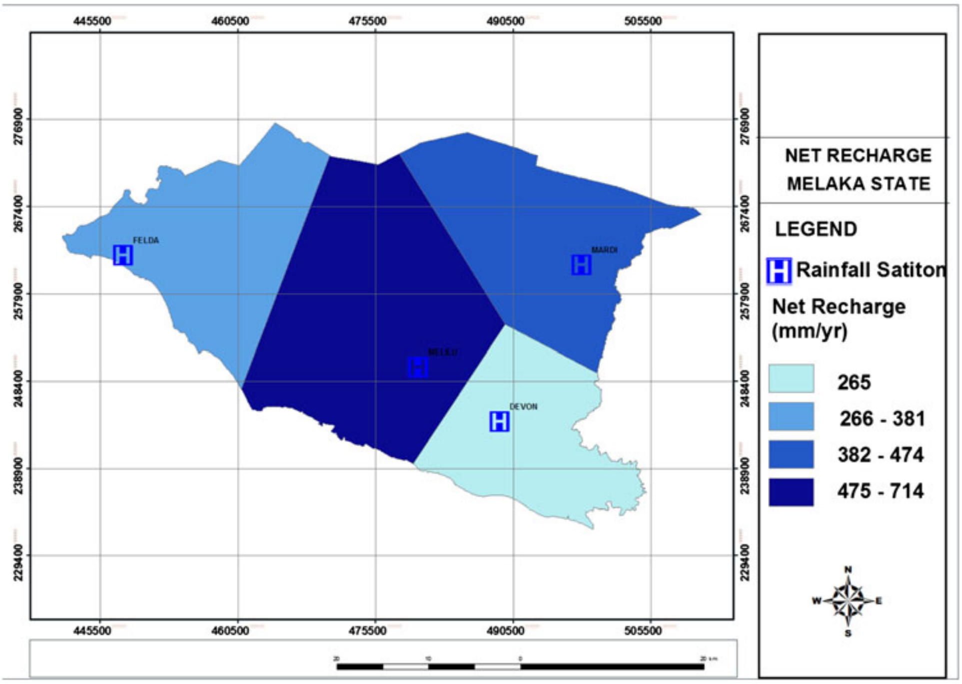


Fig. 2 Net recharge map of Melaka

water is contained. This includes the pore spaces and fractures in the media where water is held. Therefore, the aquifer media affects the flow within the aquifer. This flow path controls the rate of contaminant contact within the aquifer (Aller et al. 1987). Based on 238 shallow and 20 deep boreholes available aquifer media data in the study area (Table 2), the aquifer media map is generated as shown in Fig. 3.

The soil media

Soil media has significant impact on the amount of recharge and attenuation of contaminants that can infiltrate into the groundwater table. The presence of fine-textured materials such as silt and clay can decrease relative soil permeability and restrict contaminant migration. Soil

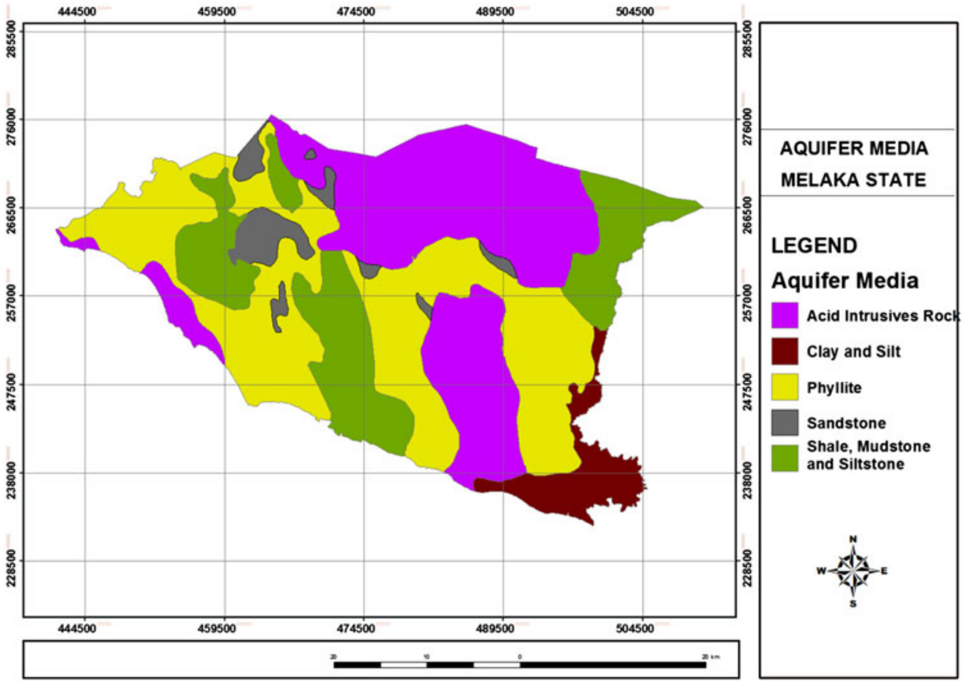


Fig. 3 Aquifer media map of the study area

media can be described in terms of its textural classifications and ranked in order of pollution potential. The soil media map (Fig. 4) of the study area is prepared from the collected data of the soil surveys, borehole data and the annual report of the Department of Agriculture, Malaysia. The rating ranges of the different soil texture media are represented in Table 2.

The topography

Topography refers to the slope variability of the land surface. The degree of slope determines the extent of runoff of the pollutant and degree of settling (long enough to infiltrate). The slope of the land surface dictates whether water will run off on the surface, or whether it will infiltrate into

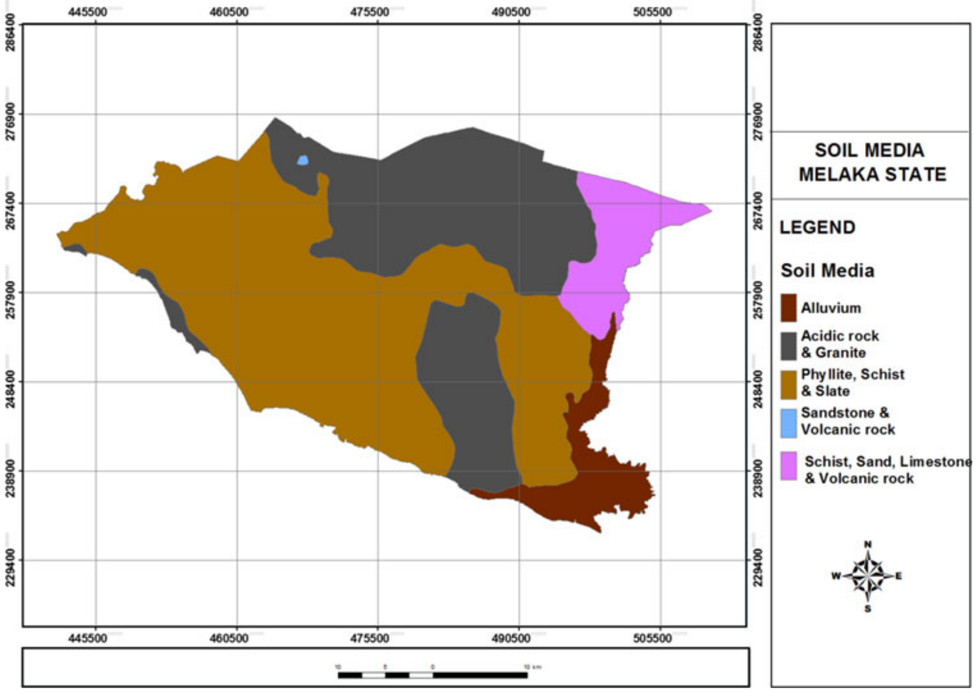


Fig. 4 Soil media map of the study area

the soil. Contaminants will similarly leave the area as runoff, or settle into the ground, eventually reaching the groundwater table (Brady and Weil 2002). Topography also gives some indication, where pollutants will concentrate. Runoff from agricultural crops is channeled from a higher elevation to a lower elevation, making lower slopes more vulnerable to contamination. The topography of the study area is obtained from the digital elevation model covering the study area as shown in Fig. 5. Slope values are calculated from the topographic elevations using the Spatial Analyst Tools of ArcGIS. The slope values are rated based on the standardized 1–10 scale, with 1 and 10 being the lowest and highest slope, respectively, as shown in Table 2.

The impact of vadose zone

The parameter represents the influence of the unsaturated zone above the water table. It controls the passageway and attenuation of the contaminants into the aquifer. The vadose zone had significant contribution for diminishing groundwater pollution, because some pollutant attenuation processes such as biodegradation, filtration, mechanical straining, chemical reaction and dispersion occurred in this layer (Piscopo 2001). The impact of vadose zone map is presented in Fig. 6, and the rating ranges of the parameter are shown in Table 2.

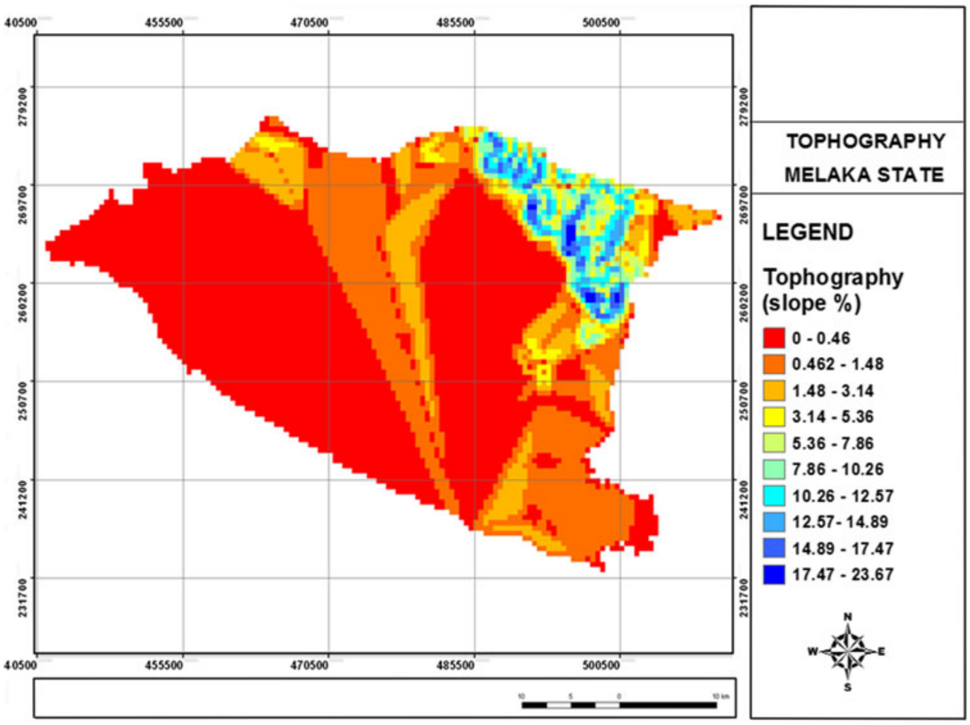
Hydraulic conductivity

The hydraulic conductivity controls the rate of groundwater movement into the saturated zone, thereby controlling the degree and fate of the contaminants. This parameter shows the transmitting rate of infiltrate water into the groundwater system. The vertical hydraulic conductivity is used in this context. The value of hydraulic conductivity indicates the intensity of groundwater pollution potential, in which higher conductivity shows the higher susceptibility to pollution. Hydraulic conductivity is calculated from the pumping test data of the boreholes, and improved after calibration of the mathematical model in a steady state. The vertical hydraulic conductivity values of the aquifer materials in the study area are commonly less than 1 m/day, and assigned the constant rating value one (1) through the whole study area as shown in Fig. 3 (ESM).

Land use

Land use and anthropogenic activities have a significant impact on the groundwater vulnerability of most of the area. Due to land use pattern such as agricultural, industrial, commercial and urban, the pollution potential intensity also varies. Hydrogeological parameters can be greatly hampered by land use pattern. Agricultural pesticide, drilling well, septic system, mining operation, dumping

Fig. 5 Topography map of the study area



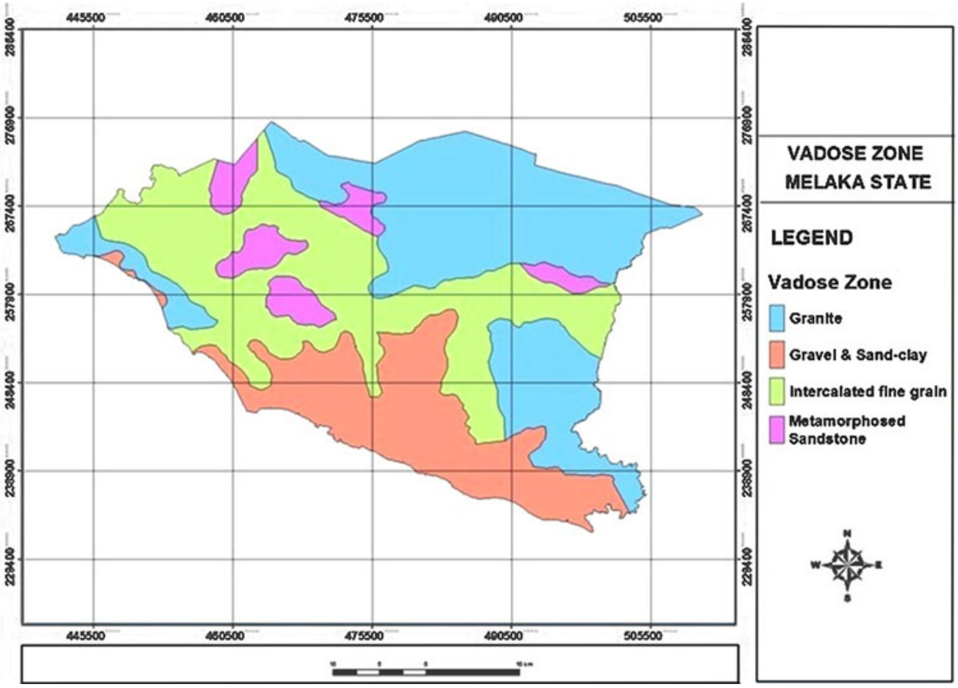


Fig. 6 Impact of vadose zone map

station, industrial and commercial waste can change the properties of hydrogeological parameters. Land use classifications of Melaka (Table 3) show that a major part of the area is used for agricultural activities. The second major area is designated as urban settlements and associated non-agricultural land. In addition, the remaining parts of the area are categorized as horticultural land, forestland, swamps and marshland, and wetland forest. Groundwater is more vulnerable to nitrate concentration in agricultural areas (Akhavan et al. 2011; Mishima et al. 2011). Nitrate distribution in groundwater system mainly depends on the soil dynamics; recharge rate, groundwater movement and on-ground nitrogen loading (Uhan et al. 2011). The presence of nitrate in groundwater system easily indicates the pollution potentiality by agricultural and anthropogenic activities. Land use classification of Melaka easily indicates that groundwater quality of the study area is greatly affected by the agricultural, industrial and urban activities.

Development of DRASTIC map

Features such as depth to water table, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity (Table 2) are deemed important in the development of the DRASTIC map as well as risk map. The GIS coverage is all in raster format and values for each overlay are assigned according to the pixel value of each area that resulted from multiplying the ratings with its appropriate DRASTIC weight. Since the minimum possible DRASTIC index for using these parameters is 23 and the maximum is 230, this range is divided into four classes

Table 3 Types and areas of land use in Melaka

Classification of land use	2007		2008		2009	
	Area (Ha)	Percentage	Area (Ha)	Percentage	Area (Ha)	Percentage
Forest	5,079.66	3.06	5,079.66	3.05	5,079.66	3.05
Agriculture	99,754.00	60.25	99,754.00	59.98	99,754.00	59.98
Urban and Industrial	7,033.08	4.25	7,033.08	4.23	7,033.08	4.23
Aborigines Reserve	667.07	0.40	667.07	0.40	667.07	0.40
Federal land	8,159.63	4.93	2,413.76	1.45	2,413.76	1.45
State land	716.83	0.43	706.38	0.42	706.38	0.42
Others	48,157.57	26.68	50,646.05	30.45	50,646.05	30.45
Total	165,567.88	100.0	166,300.00	100.00	166,300.00	100.00

Source: Department of Land and Mines, Melaka

Table 4 DRASTIC index for the study area

Vulnerability classification	DRASTIC index range		Percent of area (%)	
	Conventional DRASTIC	Modified DRASTIC	Conventional method	Modified method
High	>159	>175	27.45	38.26
Moderate	120–159	140–175	61.53	47.34
Low	80–119	100–139	11.02	14.40

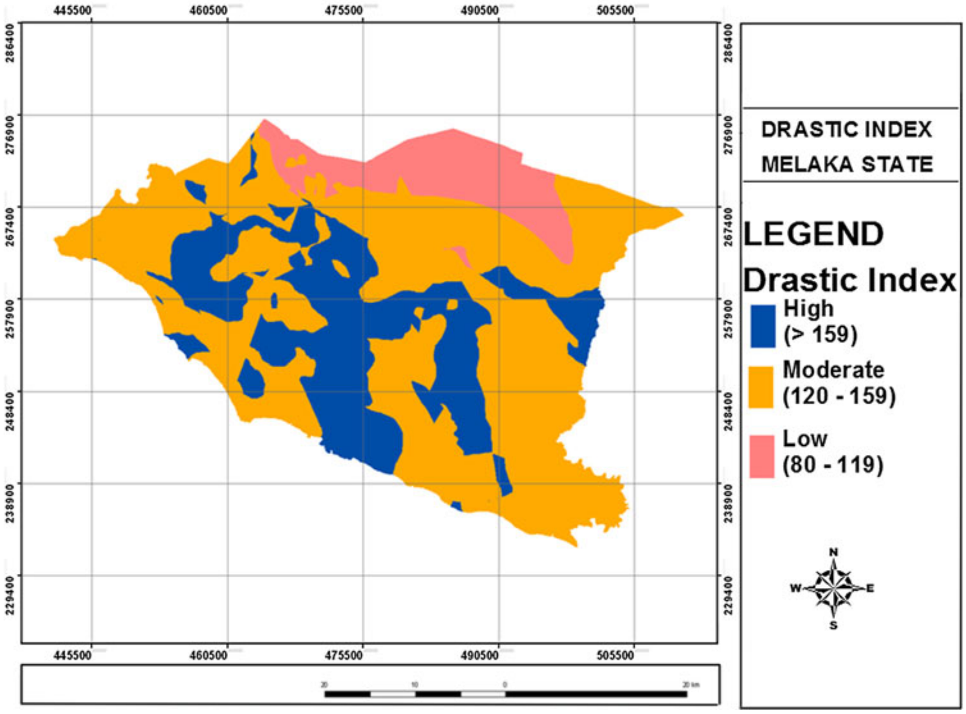


Fig. 7 The DRASTIC aquifer vulnerability map

(Aller et al. 1987). The resulted DRASTIC index values are between 80 and 173 in this study. The DRASTIC indices are classified into three categories, namely, high vulnerability (>159), moderate vulnerability (120–159) and low vulnerability (80–119). The range of classifications and the affected area categorization are presented in Table 4. Resulted DRASTIC map shows that 27.45 % of the area is laid under high vulnerability, 61.53 % moderate vulnerability and 11.02 % low vulnerability.

The DRASTIC map clearly illustrates that only a very small part of the study area (North) has low vulnerability to pollution, and the most parts of the study area have recorded moderate vulnerability to pollution as shown in Fig. 7. The area marked as high vulnerability falls in and around Melaka, Jasin and Alor Gajah cities. These areas are generally located over the unconfined shallow highly permeable locally recharged aquifers. Topsoil of these areas is mostly sand, which is potential aquifer for groundwater production. The recharge from the surface is very high due to the high permeability and agricultural practices, which might have caused groundwater contamination. The high vulnerability classification comprises the second largest area of vulnerability.

Development of risk map

The study evaluates the potential risk of groundwater based on the land use activities combining with the DRASTIC map. The risk map is generated using the additional parameter (land use), incorporating into the conventional DRASTIC method. This combination has been called the modified DRASTIC method. Agricultural, industrial and urbanization impacts on the groundwater vulnerability are greatly focused in the risk map. To develop the risk map, the land use map is rated and weighted (Table 2) based on the assumptions (Secunda et al. 1998; Al-Adamat et al. 2003; Saidi et al. 2010). The land use map is converted into raster grid and multiplied by the weight of the parameter ($L_w = 5$). In order to establish a spatial relationship between land use and DRASTIC map, the land use map is overlaid on the conventional DRASTIC map. Final resultant grid coverage is added with conventional DRASTIC

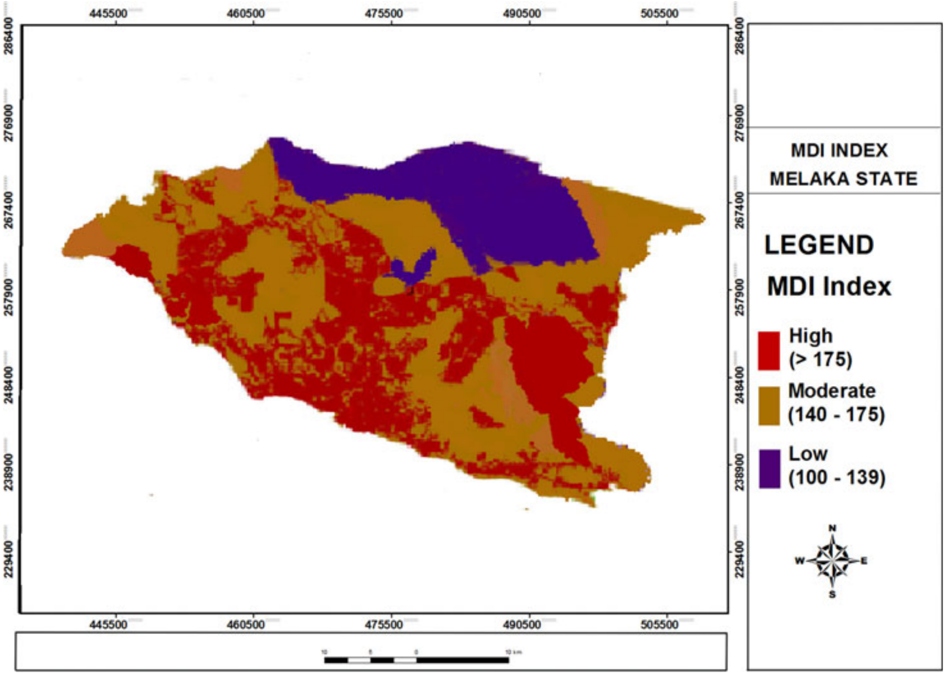


Fig. 8 Modified DRASTIC aquifer vulnerability map

Table 5 Correlation coefficient and significance

Parts of the formula	General formula of Pearson	Correlation coefficient, *r*	Correlation between	Pearson's critical value of '*r*' at 1 % probability level	Significance
$\Sigma(\mathrm{DI}-\overline{\mathrm{DI}})\,(\mathrm{NO_3}-\overline{\mathrm{NO_3}})$ $\sqrt{\left[\Sigma(\mathrm{DI}-\overline{\mathrm{DI}})^2\Sigma(\mathrm{NO_3}-\overline{\mathrm{NO_3}})^2\right]}$	$r_{xy}=\frac{\Sigma(X-\overline{X})(Y-\overline{Y})}{\sqrt{\Sigma(X-\overline{X})^2\,\Sigma(Y-\overline{Y})^2}}$	0.77	Nitrate and DI	0.3843	Calculated coefficient values are always highly greater than Pearson's critical value. Therefore, correlations are highly significant at the 1 % probability level
$\Sigma(\mathrm{MDI}-\overline{\mathrm{MDI}})\,(\mathrm{NO_3}-\overline{\mathrm{NO_3}})$ $\sqrt{[\Sigma(\mathrm{MDI}-\overline{\mathrm{MDI}})^2\,\Sigma(\mathrm{NO_3}-\overline{\mathrm{NO_3}})^2]}$		0.82	Nitrate and MDI		
$\Sigma(\mathrm{DI}-\overline{\mathrm{DI}})\,(\mathrm{Cl}-\overline{\mathrm{Cl}})$ $\sqrt{[\Sigma(\mathrm{DI}-\overline{\mathrm{DI}})^2\,\Sigma(\mathrm{Cl}-\overline{\mathrm{Cl}})^2]}$		0.62	Chloride and DI		
$\Sigma(\mathrm{MDI}-\overline{\mathrm{MDI}})\,(\mathrm{Cl}-\overline{\mathrm{Cl}})$ $\sqrt{[\Sigma(\mathrm{MDI}-\overline{\mathrm{MDI}})^2\,\Sigma(\mathrm{Cl}-\overline{\mathrm{Cl}})^2]}$		0.70	Chloride and MDI		

index (DI), and consequently, the modified DRASTIC index (MDI) is calculated using the Eq. (3) (Secunda et al. 1998).

$$\mathrm{MDI} = \mathrm{DI} + L_r L_w \tag{3}$$

where, r and w represent the rate and weight of the land use parameter. The risk map indicates the parts of the study area, and types of anthropogenic activities which are more liable for the groundwater vulnerability. The risk map is classified into three categories; low (100–139), moderate (140–175) and high (>175) vulnerability which is presented in Fig. 8. The results of the analysis show that 38.26 % of the area is high vulnerability, 47.34 % moderate vulnerability and 14.40 % low vulnerability. The risk map indicates that high vulnerability area is increased more than 11 % compare to conventional DRASTIC map (Table 4), which is resulted from the agricultural, industrial and urban activities. The most vulnerability of groundwater exists in the Melaka, Jasin and Alor Gajah city areas and its surroundings due to the urban and some industrial waste water infiltration as well as agricultural activities.

Validation of the methods

The two water quality parameters nitrate and chloride are used to validate both the conventional DRASTIC and modified DRASTIC methods. Generally, nitrate is not present in groundwater. Therefore, its presence in groundwater system easily indicates the groundwater contamination, in which contaminants transport by infiltration water from the ground surface into groundwater system. Nitrate and chloride concentration values are used to develop the correlations with the values of conventional DRASTIC index (DI) and modified DRASTIC index (MDI). Correlation is a technique for investigating the relationship between two quantitative, continuous variables. The linear correlation coefficient measures the strength and the direction of a linear relationship between two variables. The correlations between the parameters are developed based on Pearson's correlation method (Pearson 1900). In this study, the highest nitrate and chloride concentration values are correlated with the highest DRASTIC index values. The correlation coefficients are found 0.77 and 0.82 between DI and nitrate concentration, and MDI and nitrate concentration values, respectively, as shown in Table 5. At the same time, other correlation coefficients between the values of DI and chloride concentration as well as MDI and chloride concentration are found as 0.62 and 0.70, respectively (Table 5). The comparison between correlation coefficients and the Pearson's critical value of 'r' at 1 % probability level illustrates that the strong correlation exists between the above-mentioned parameters, which is ensured the validity of the methods.

Conclusions

1. An attempt has been made to assess the aquifer vulnerability of Melaka groundwater plain employing the empirical index called DRASTIC model. In addition, the modified DRASTIC method has been applied to assess the effect of land use activities on groundwater vulnerability. The GIS techniques have provided efficient facilities for analysis and high capabilities in handling a large quantity of spatial data. The thematic maps of the model are constructed, classified and encoded employing various maps by GIS functions.
2. The result of the DRASTIC map analysis shows 27.45 % of the area is high vulnerability, which is mainly due to the aquifer media of the Melaka River basin and its surrounding areas. About 61.53 % of the area is categorized as moderate vulnerability which is under threat by high permeable as well as locally high recharge unconfined shallow aquifers, and 11.02 % of the area is under the low vulnerability, which is high land and located in the north parts of the study area.
3. Risk map shows that the high vulnerability area increases more than 11 % compare to DRASTIC map, which is resulted from agricultural, urban and industrial activities. The most vulnerability zone exists at the Melaka, Alor Gajah and Jasin city areas, and its surrounding region.
4. The study has been conducted to assist managers, planners and regulatory agencies in the task of assessing the relative groundwater vulnerability to contamination from different sources of contaminants. The results can be used for helping direct resources and land use management in the appropriate areas to prioritize close monitoring and protection or act accordingly. Moreover, the study will also be helpful to industry personnel to understand groundwater contamination resulted from various practices associated with them, and to university personnel who are involved to teach the fundamentals of groundwater contamination and hydrogeology.
5. The conventional DRASTIC and modified DRASTIC methodology are demonstrated in this study, and are generic in nature. The typical rating range for each hydrogeologic factor is developed as guides, and is not designed to be representative of each and every area. The user can adjust corresponding rating ranges for each factor within the settings to reflect various conditions within an area to calculate the pollution potential DRASTIC index or a specialized index for land use. Thus, the method can be applied in other regions in Malaysia or elsewhere with appropriate modification of rating ranges of the hydrogeological settings and providing adequate data are available.
6. In summary, the DRASTIC can be used as a proficient tool when the assumptions of the methodology are met. However, it is necessary to practice precaution and consider the particular situations when the deviations occur from the assumptions. In this case, the user needs to understand and reconsider each DRASTIC feature, and criteria upon which DRASTIC is created.

Acknowledgments Financial support by the Institute of Research Management and Monitoring (IPPP), University of Malaya (UM), Malaysia, under UMRG research grant number RG 092/10SUS and JSPS-ACP under Ministry of Higher Education (MOHE) are gratefully acknowledged.

References

Akhavan S, Mousavi SF, Abedi-Koupai J, Abbaspour KC (2011) Conditioning DRASTIC model to simulate nitrate pollution case study: Hamadan–Bahar plain. Environ Earth Sci 63:1155–1167

Al-Adamat RAN, Foster IDL, Baban SMJ (2003) Groundwater vulnerability and risk mapping for the basaltic aquifer of the Azraq Basin of Jordan using GIS, remote sensing and DRASTIC. Appl Geogr 23:303–324

Aller L, Bennet T, Lehr HJ, Petty JR, Hackett G (1987) A standardized system for evaluating groundwater pollution potential using hydrogeologic settings. EPA-600/2-87-035: 622

Anbazhagan S, Nair AM (2004) Geographic information system and groundwater quality mapping in Panvel Basin, Maharashtra, India. Environ Geol 45(6):753–761

Barbash JE, Resek EA (1996) Pesticides in groundwater: distribution, trends, and governing factors. Ann Arbor, Chelsea

Brady NC, Weil RR (2002) The nature and properties of soils. Prentice Hall, Englewood Cliffs

Dimitriou E, Moussoulis E (2011) Land use change scenarios and associated groundwater impacts in a protected peri-urban area. Environ Earth Sci 64:471–482

Evans BM, Mayers WL (1990) A GIS-based approach to evaluating regional groundwater pollution potential with DRASTIC. Soil Water Conserv 45:242–245

Fritch TG, McKnight CL, Yelderman JC, Arnold JG (2000) Aquifer vulnerability assessment of the paluxy aquifer, Central Texas, USA, using GIS and a modified DRASTIC approach. Environ Manage 25:337–345

Hasiniaina F, Zhou J, Guoyi L (2010) Regional assessment of groundwater vulnerability in Tamtsag basin, Mongolia using DRASTIC model. J Am Sci 6(11):65–78

Herlinger R Jr, Viero AP (2006) Evaluation of contaminants retention in soils from Viamao District, Rio Grande do Sul State, Brazil. Environ Geol 50:47–54

Hong IA, Chon HT (1999) Assessment of groundwater contamination using geographic information systems. Environ Geochem Heal 21(3):273–289

Jha MK, Peiffer Se (2006) Applications of RS and GIS technologies in groundwater hydrology: past, present and future. Bayreuth University Press, Bayreuth

Jha M, Chowdhury A, Chowdary V, Peiffer S (2007) Groundwater management and development by integrated remote sensing and geographic information systems: prospects and constraints. Water Res Manage 21:427–467

Khan HH, Khan A, Ahmed S, Perrin J (2011) GIS-based impact assessment of land-use changes on groundwater quality: study from a rapidly urbanizing region of South India. Environ Earth Sci 63:1289–1302

Kim YJ, Hamm SY (1999) Assessment of the potential for ground water contamination using the DRASTIC/EGIS technique, Cheongju area, South Korea. Hydrogeol J 7:227–235

Knox RC, Sabatini DA, Canter LW (1993) Subsurface transport and fate processes. Lewis Publishers, USA

Land and Mines Department of Melaka (2003) Report of land use in Melaka State Melaka

Lobo-Ferreira JP, Oliveira MM (2003) On the experience of groundwater vulnerability assessment in Portugal: Aquifer vulnerability and risk international workshop AVR03, Salamanca, Gto.Mexico, p 10. Meteorological Department, Thailand (personal communication)

Lusch DP, Rader CP, Barrett LR, Rader NK (1992) Aquifer vulnerability to surface contamination in Michigan. Map and Descriptive Information, Center for Remote Sensing, Michigan State University

Malaysian Water Association (2008) 50th year achievement in water industry, Melaka. Bi-Monthly, April/May, Issue No. 15

Marchant AP, Banks VJ, Royse K, Quigley SP, Wealthall GP (2011) An initial screening tool for water resource contamination due to development in the Olympic Park 2012 site, London. Environ Earth Sci 64:483–495

Merchant JW (1994) GIS-based groundwater pollution hazard assessment a critical review of the DRASTIC model. Photogr Eng Remote Sens 60(9):1117–1127

Mishima Y, Takada M, Kitagawa R (2011) Evaluation of intrinsic vulnerability to nitrate contamination of groundwater: appropriate fertilizer application management. Environ Earth Sci 63: 571–580

Murat V, Rivera A, Pouliot J, Miranda-Salas M, Savard MM (2004) Aquifer vulnerability mapping and GIS: a proposal to monitor uncertainty associated with spatial data processing. Geofi Int 43(4):551–565

National Research Council (1993) Groundwater vulnerability assessment: predictive relative contamination potential under conditions of uncertainty. National Academy Press, Washington, DC

Pearson K (1900) On the criterion that a given system of deviations from the probable in the case of a correlated system of variables is such that it can be reasonably supposed to have arisen from random sampling. Philos Mag 5(50):157–175 (reprinted in K. Pearson (1956), pp 339–357)

Piscopo G (2001) Groundwater vulnerability map explanatory notes—Castlereagh Catchment. Australia NSW Department of Land and Water Conservation, Parramatta

Rahman A (2008) A GIS based DRASTIC model for assessing groundwater vulnerability in shallow aquifer in Aligarh, India. Appl Geogr 28:32–53

Ramos-Leal JA, Rodríguez-Castillo R (2003) Aquifer vulnerability mapping in the Turbio river valley, Mexico, a validation study. Geofí Int 42:141–156

Saidi S, Bouri S, Dhia HB (2010) Groundwater vulnerability and risk mapping of the Hajeb-jelma aquifer (Central Tunisia) using a GIS-based DRASTIC model. Environ Earth Sci 59:1579–1588

Secunda S, Collin M, Melloul AJ (1998) Groundwater vulnerability assessment using a composite model combining DRASTIC with extensive land use in Israel's Sharon region. J Environ Manage 54:39–57

Shirazi SM, Akib S, Salman FA, Alengaram UJ, Jameel M (2010) Agro-ecological aspects of groundwater utilization—a case study. Sci Res Essays 5(18):2786–2795

Shirazi SM, Ismail Z, Akib S, Sholichin M, Islam MA (2011) Climatic parameters and irrigation requirement of crops. Int J Phys Sci 6(1):15–26

Shirazi SM, Imran HM, Akib S (2012) GIS-based DRASTIC method for groundwater vulnerability assessment: a review. J Risk Res 15(8):991-1011

Statistics Department of Malaysia (2000) Population distribution by local authority areas and Mukim population and housing census. Statistics Department of Malaysia, Kuala Lumpur

Stigter TY, Ribeiro L, Dill AMMC (2006) Evaluation of an intrinsic and a specific vulnerability assessment method in comparison with groundwater salinisation and nitrate contamination levels in two agricultural regions in the south of Portugal. Hydrogeol J 14:79–99

Survey Geological (1985) Map of geological features in peninsular Malaysia. Director General of Geological Survey, Ipoh

Tesoriero AJ, Inkpen EL, Voss FD (1998) Assessing ground-water vulnerability using logistic regression. In: Proceedings of source water assessment and protection 98 conference, Dallas, pp 157–165

Thirumalaivasan D, Karmegam M, Venugopal K (2003) AHP-DRASTIC: software for specific aquifer vulnerability assessment using DRASTIC model and GIS. Environ Model Softw 18:645–656

Trent VP (1993) DRASTIC mapping to determine the vulnerability of ground water to pollution. In: Proceedings of conference on geographic information, system and water resources, pp 537–545

Uhan J, Vižintin G, Pezdic J (2011) Groundwater nitrate vulnerability assessment in alluvial aquifer using process-based models and weights-of-evidence method: lower Savinja Valley case study (Slovenia). Environ Earth Sci 64:97–105

Vias JM, Andreo B, Perles MJ, Carrasco F (2005) A comparative study of four schemes for groundwater vulnerability mapping in a diffuse flow carbonate aquifer under Mediterranean climatic conditions. Environ Geol 47(4):586–595