1.0 INTRODUCTION

1.1 Background

Droughts, floods, water pollution, and regional conflicts over water resources occur in different corners of the world. Water-related problems take different shapes, mirroring the looming water crisis, which will undoubtedly increase during the 21stcentury. The water crisis overshadows the development efforts in most of the developing countries in the world, hindering economic growth and well- being of the population (Prinz, 2005).

One of the issues in water pollution is groundwater vulnerability. Since the development of DRASTIC model (Aller, Bennett *et al*. 1987) for groundwater vulnerability assessment by USEPA in late 1980s, this type of index method has become very popular and numerous applications have been done in US and worldwide(Levent Tezcan *et al*., 2004; Al-Zabet, 2002; Bukowski *et al*., 2006; Jamrah *et al*., 2007; Wen *et al*., 2008).

The DRASTIC model considers several factors such as Depth to water table(D), Net Recharge (R), Aquifer media (A), Soil media (S), Topography (T), including Impact effect of Vadose Zone (I) and Hydraulic Conductivity(C). Usually different ratings are assigned to each factor and then summed together with respective weights to a numerical value as the vulnerability index.

Atiqur Rahman (2008) stated that the DRASTIC model, which is used for preparing the pollution potential map, can be used as a screening tool to see whether a particular area is more or less vulnerable to groundwater pollution. This delineation has allowed city planners and administrators to direct their resources to those vulnerable areas, which are critical to groundwater pollution, thereby make most of the limited resources available to them**.** Apart from groundwater vulnerability assessment, the DRASTIC model can also be used for a wide range of applications likely in prioritization of areas for monitoring purposes (National Research Council, 1993). Consequently, it can help the planners and policy makers to select the areas for waste disposal and industrial sites.

Similar applications of DRASTIC have been performed in groundwater aquifers in United Arab of Emirates, Morocco, Tunisia, Algeria, Portugal and South Korea (Al-Zabet 2002; Kim and Hamm 1999; Kachi *et al*., 2007; Ettazarini, 2006; Stigter *et al*., 2006; Hamza, *et al*., 2007). Some groundwater basins in China, Japan and Iran were classified according their vulnerability using the DRASTIC index (Wen *et al*., 2008; Babiker *et al*., 2005; Chitsazam and Akhtari, 2008).

Groundwater quality in the Upper Litany Basin in Lebanon was also assessed based on geostatistical analysis of nitrate; the results showed a non-strong correlation to the DRASTIC vulnerability map for the same groundwater basin (Assaf and Saadeh, 2008). DRASTIC was also applied to assess groundwater vulnerability in different parts in Jordan as well as in South Korea. The parameter of the hydraulic conductivity was excluded from the DRASTIC index because of the lack of data and the DRASTI was only applied in the Azraq Basin in Jordan (Al-Adamat *et al*., 2003).

The DRASTIC index was also used in a part of the South Korea to assess groundwater vulnerability to different landfills (Lee, 2003). The effectiveness of DRASTIC vulnerability map was improved by calibrating the rating system on the basis of a statistical correlation between the standard DRASTIC vulnerability map and an actual data set of nitrate or other pollutants concentration in groundwater (USGS 1999; Rupert, 2001). Correlation of DRASTIC parameters with the actual nitrate concentration in Kherran Plain in Iran showed that the impact of the vadose zone is the most significant hydrogeological parameters in controlling nitrate concentrations in groundwater (Chitsazam & Akhtari, 2008).

The standard weights of the DRASTIC index were modified in many areas after carrying out sensitivity analysis for the DRASTIC parameters (Pathak *et al*., 2008; Almasir, 2007; Al-Kuisi *et al*., 2009). In a comprehensive vulnerability assessment of groundwater in the Northern Italy with intensive correlation approaches, it was concluded that the GOD vulnerability index is not able to analyze physical and biochemical processes controlling nitrate in the subsurface system (Debernardi *et al*., 2007). As discussed above, in spite of DRASTIC simplicity, there were several studies that attempted to modify and adjust the standard DRASTIC index to be used in groundwater vulnerability assessment for a specific pollutant or in a special hydrogeological setting. The standard DRASTIC index was incorporated with the land use index for a part of the coast aquifer to the north of Gaza Strip. The study integrated the impact of extensive land use to the DRASTIC index to assess the potential of groundwater pollution. The final assessment proved that the composite DRASTIC index exhibited indicated a close relationship to the actual groundwater pollution existing in the area. The vulnerability was specifically highly correlated to nitrate concentration in the upper aquifer (Secunda *et al*., 1998).

Similar models too can be found in the literature and applied to mapping of groundwater vulnerability such as GOD method (Foster, 1987), SINTACS (Civita, 1994), GLA (Hölting *et al*., 1995), EPIK technique (Doerfliger *et al*., 1999), COP (Vias *et al*., 2005) and PI (Goldscheider *et al*.,2000).

The GOD index related to the vertical pathways of pollutants to the saturated layer. It considers three parameters; groundwater occurrence, overall aquifer class, and depth to groundwater table (Foster, 1987). The method was also used in different regions to assess the intrinsic groundwater vulnerability (Ferreira *et al*., 2004; Mendoza and Barmen, 2006).

The SINTACS represents the same parameters of DRASTIC and was also applied in different regions in the world (Napolitano, 1995; Al-Kuisi *et al*., 2006; Cusimano *et al*., 2004; Cucchi *et al*., 2004; Corneillo *et al*., 2004; Uhan *et al*., 2008; Mahlknecht *et al*., 2006).

The GLA index or Hölting-method has been established by the Geological Surveys of the individual states of the Federal Republic of Germany to assess the capacity of the covering layers including soil and the unsaturated zone to protect the underlying aquifer. The considered parameters are the field capacity of the top soil, groundwater recharge, and rock related parameters (Hölting *et al*., 1995). The method has been applied and tested in several countries in the world and has proven its effectiveness and usefulness (Margane *et al*., 1999). The basic concept of the GLA index is that the overlaying layers have a certain capacity to reduce contaminant concentrations leaching to the groundwater table. This reduction capacity is a function of the travel time. Consequently, the protection capacity is a function of all parameters that control travel time of pollutants from the land surface to the groundwater table.

The EPIK index has the same conceptual ranking and rating system of DRASTIC. However, EPIK is a multi-attribute method which addresses the specific hydrogeological behaviour of karst aquifers. EPIK considers four parameter; epikarst, protective cover, infiltration conditions, and karst network conditions (Doerfliger *et al*., 1999).

The COP index was developed to assess intrinsic groundwater vulnerability in different karst areas (Vias *et al*., 2005). Afterward, the index has been modified by adding a new factor (K) which considers the saturated karst groundwater through gathering information on water flow paths, travel times and recovery rates (Andreo *at al*., 2009). The SINTACS is another point ranking system for the groundwater vulnerability assessment (Civita *et al*., 1990; Civita, 1993; Civita *et. al*., 2004).

The PI index was developed for the European karst aquifers and has been modified to suit the semiarid regions. It considers two major factors; the P-factor considers the groundwater table overlaying layers, and the I-factor which considers the infiltration conditions (Goldscheider *et al.,* 2000). The PI has been used in different regions in the world including some semi-arid zones (Goldscheider, 2005).

Many studies compared two or more indices in assessing groundwater vulnerability in the same basin. Six different vulnerability indices (AVI, GOD, DRASTIC, SI, EPPNA, and SINTACS) were applied in an aquifer system near Evora (Alentejo, Portugal). The results showed significant variation in the vulnerability maps of the applied indices, which emphasize the high subjectivity involved in applying the ranking system (Ferreira and Oliveira, 2004). The results obtained from another comparison between DRASTIC, GOD and AVI proved more reliability of DRASTIC index as it based on more hydrogeological parameters. There are many other studies which compared different indices in different types of groundwater aquifers. The studies agree that there is a significant difference between the final maps; this was attributed to that these indices are relatively not accurate and have a high degree of subjectivity. A more accurate and representative application of such methods requires considering more parameters that specifically reflect the behaviour, fate, and transformation of different pollutants (Margane, 1999; Gogu and Dassargues, 2000; Magiera, 2000; Magiera, 2002; Gogu *et al*., 2003; Vias *et al*., 2005; Ibe *et al*., 2001; Mendoza and Barmen, 2006).

In this present study, the modification on the DRASTIC model is in the form of modifying ranges of seven hydrogeologic parameters. Prior to this, the model parameter ranges have been modified, and it has been decided that the Analytic Hierarchy Process (AHP) will be used. The Analytic Hierarchy Process (AHP) is similar to Saaty (1980) and often referred as the Saaty method. It is popular and widely used especially in the military analysis, though it is not by any stretch of imagination restricted to military problem.

Furthermore, this study also compared the Modification DRASTIC Index by original DRASTIC model (Rosen (1994) and Widyastuti (2004) with Modification DRASTIC Index by Piscopo (2001). As an addition, study for groundwater vulnerability is very important to gauge proper understanding about the aquifer system and hydrogeological setting of the area for further development and safe exploitation of groundwater (Prasad*et.al*, 2010).

1.2 Problem Statement

The West Aceh District was one of the districts in Aceh Provinces severely affected by tsunami event. The tsunami event occurred in the West Aceh caused not only a lot of victims but also a lot of damage infrastructure especially in dug wells contamination. Most of the dug wells turned brackish and / or became polluted or even were completely destroyed as a consequence of the flood triggered by the 26 December 2004 tsunami. Therefore, in early 2005 the local people affected by the tsunami along with national and international relief organizations manage to clean up many dug wells. Unfortunately, many dug wells remained producing brackish water in 2005 (BGR, 2005).Accordingly, his research will do the mapping of groundwater vulnerability in the West Aceh district in order to estimate groundwater contaminations using DRASTIC method. This study will also modify DRASTIC parameters using AHP in order to achieve better result of estimating groundwater vulnerability.

1.3 Research Objectives

1. To produce groundwater vulnerability map using two different DRASTIC modifications, (i) Modification DRASTIC Index by original DRASTIC model (Rosen (1994) and Widyastuti (2004)) and (ii) Modification DRASTIC Index by Piscopo (2001).

2. Optimization of DRASTIC model using AHP for groundwater vulnerability assessment in West Aceh.
3. To assess the groundwater vulnerability using DRASTIC-AHP in West Aceh.

1.4 Thesis Outline

Thesis outline is guidance for thesis writing which consists of 5 chapters in this study. Chapter 1(Introduction) discusses general study area including introduction, objective, and problem statement. Chapter 2 (Geology and Hydrogeology) discusses about geology and hydrogeology of the study area. Chapter 3 (Methodology) discusses brief outline of methodology, DRASTIC, AHP, and GIS in Groundwater. Chapter 4 (DRASTIC modification and Software DRASTIC-AHP) discusses about DRASTIC modification using AHP method and developing of software DRASTIC-AHP. Meanwhile, Chapter 5 (Conclusion and Recommendation) will conclude the whole research and advocate for further research improvement in the future.

1.5 Scope of Study

The main scope of this research is assessment of groundwater vulnerability, making of software DRASTIC-AHP program for optimization of DRASTIC parameters using Delphi 7.0 and assessment of groundwater vulnerability to nitrate, phosphate, magnesium and sulphate in the West Aceh district. This study will provide a help in protecting public water supply, industries sector and agricultural purpose through developing an objective vulnerability model.

2.0 OVERVIEW OF STUDY AREA

2.1 Description of Study Area

West Aceh Regency covers a total area of 2927.95 km^2, between 04^o 06' – 04 ^{o} 47' North Latitude and 95^o 52' – 96^o 30' East Longitude which has demarcated as follows:

North	: District of Aceh Jaya and Pidie Jaya District
South	: Indonesian ocean and Nagan Raya District
West	: Indonesian ocean
East	: Central Aceh Regency and Nagan Raya District

Based on the position and location, the west district is flanked by Bukit Barisan Mountains and the Indonesian Ocean, which is a strategic position and an opportunity towards economic, industry, trade and services development (Figure 2.1).

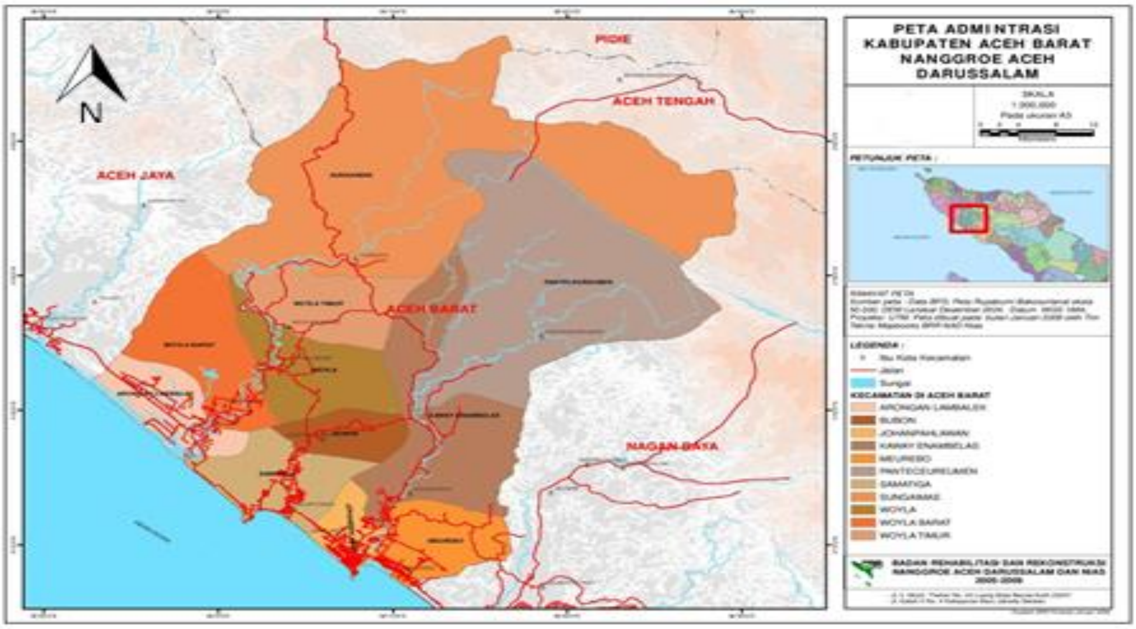


Figure 2.1 Map of West Aceh (The Agency of Rehabilitation and Reconstruction Aceh, 2009)

2.2 Geology

West Aceh is in tropical climate with high relative humidity (80–90 %) and little variation in mean for daily air temperature (25–27 °C) throughout the year. Rainfall is generally high but subject to sharp regional variations due to the prevailing monsoons and the central Barisan Mountains. West coast is the wettest with a mean of annual rainfall to 3500 mm, and this climate can rise to 3500–4500 mm in the nearby mountains (USAID, 2005). It shows in Figure 2.2.

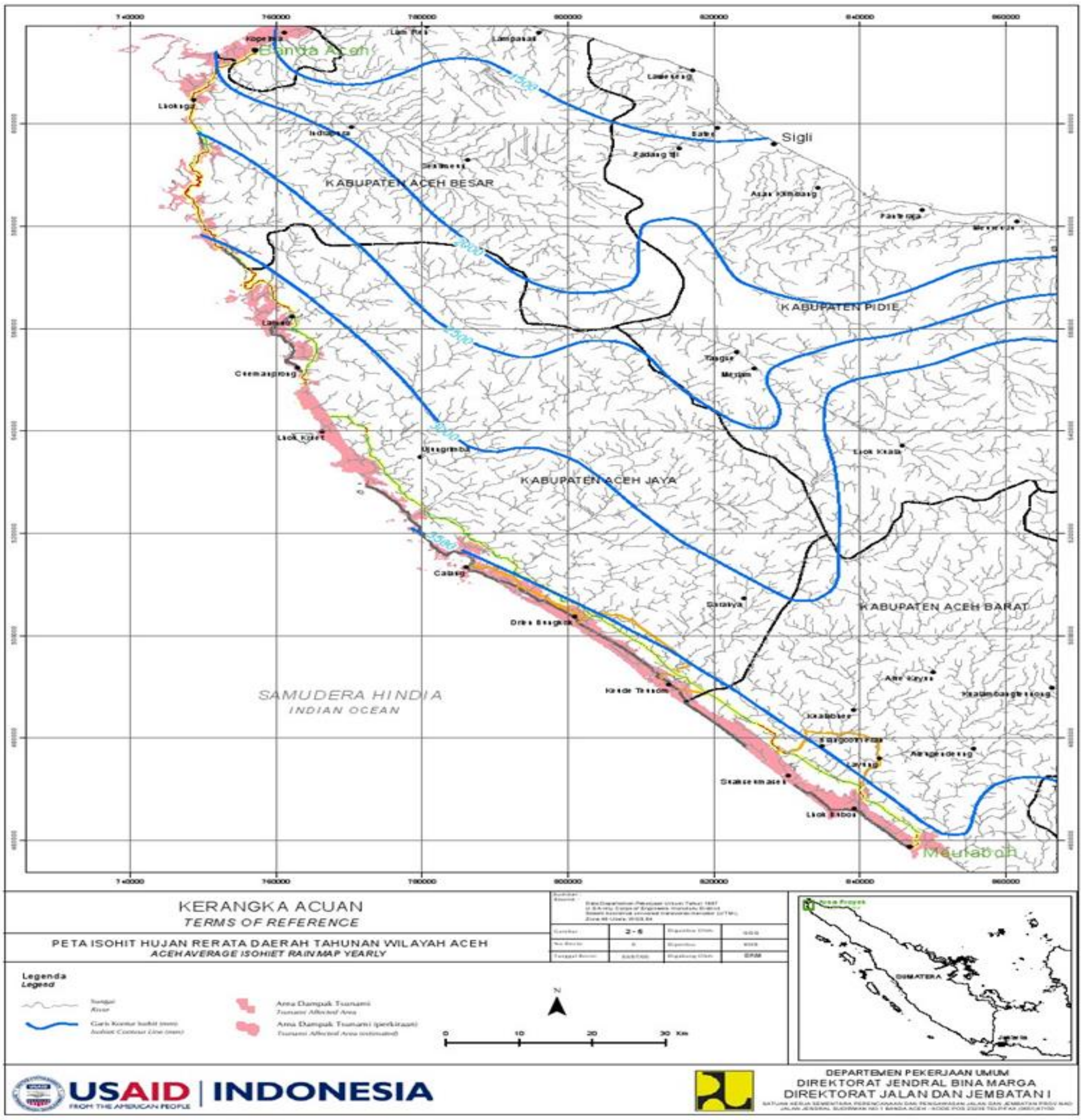


Figure 2.2 The Isohyet Map of Aceh Province (USAID, 2005)

The following section is based on the explanatory notes accompanying the Geologic Maps of the Takengon and Calang quadrangles (Bennett et al. 1981 and Cameron et al. 1983). Most of the survey area belongs to the Meulaboh Embayment which is an extensive coastal plain of low relief, occupied by unconsolidated Plio-Pleistocene sediments It has a maximum width of 50 km at Meulaboh and rarely exceeds 100 m. a.s.l. North of Teunom River which is also the coastal belt that gradually becomes narrower up to Calang Here and further north-wards Tertiary is volcanic hard rocks that occupy the coast. Towards the east of Meulaboh Embayment is terminated by the major west-wards throwing Anu-Batee Fault whose scarp defines the western edge of the embayment (Figure 2.3). To the east of the fault is the forested and rugged terrain which also forms the axial zone of the Barisan Mountain chain as the central spine of Sumatra. In this area, altitudes commonly rise up to 2,000–3,000 m. a.s.l. The south-eastern part of Barisan Mountain is composed of resistant pre-Tertiary rocks, however, large parts are underlain by block-faulted older-Tertiary formations which are more gentle relief. The hinterland of the Calang area is dominated by the Sikuleh batholith which is also surrounded by a pre-Tertiary limestone ridge and Calang altitudes can rise up nearly to 400 m. a.s.l.

The Calang area is drained by rivers flowing south-westwards into the Indian Ocean. The drainage systems are mainly dendritic, but are sometimes structurally controlled. The larger rivers crossing the Meulaboh Embayment meander slightly but are rejuvenated following recent regional uplift. Uplift continues at present, marked by a prograding coastline that has been raised by coral reefs at Meulaboh. Prominent terraces occur along the main rivers inland and near the coast that are up to 5–10 m above present river levels.

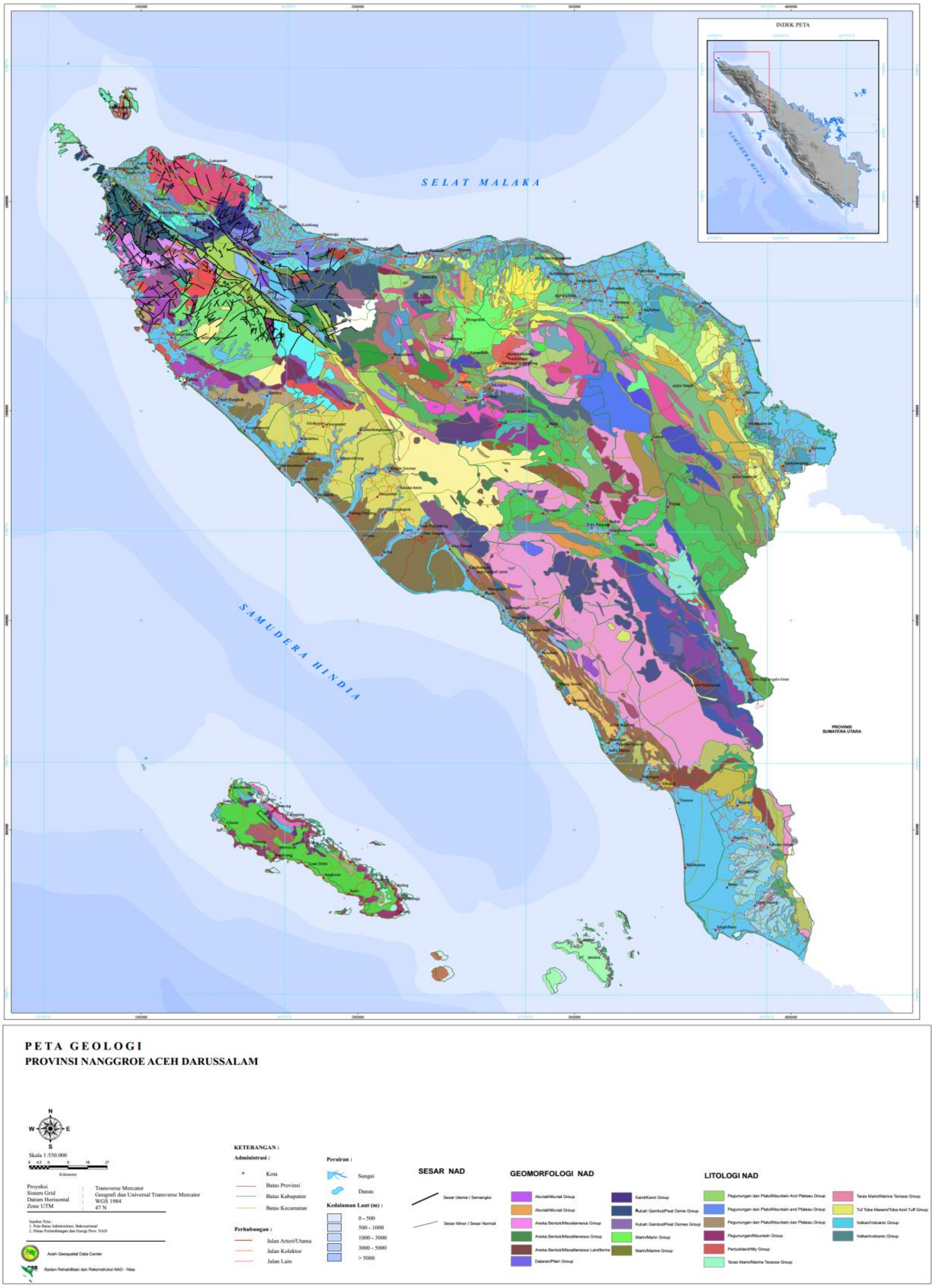


Figure 2.3 Geological Map of Aceh (Department of Mining and Energy, 2013)

The coastal belt covered by present survey is cut by a number of rivers; from SE to NW they are Tadu River, Seunagan River, Meureubo River, Bubon River, Woyla River, River Teunom, Sabe River, Rigaili River, and Langgeuen River. The distances between the mouth of the rivers average at 12 km (2–21 km).

The rivers are continuously transporting a substantial volume of suspension load which were deposited in the lower reaches of the river valley. Through this process of sedimentation, the river valleys have become an elevated ground compared to the deep lying interfluvial areas presumably swampy areas with dark brown coloured water. This geomorphological feature is the major reason why the river valleys have become the main development axes for vast settlements likely to Meulaboh and Teunom as well as other numerous villages located aside from the main coastal road.

2.3 Hydrogeology

Water supply to the entire Meulaboh Embayment depended either on shallow or medium-deep groundwater which was tapped from unconsolidated to semi-consolidated porous aquifers either on surface or river water. In the area of Calang, the capturing of springs and the development of low-yield fissured aquifers are to be considered as another option in addition to the usage of alluvial aquifers within river valleys and along coastal belt. Apart from the uppermost aquifer tapped by dug wells, the Meulaboh embayment consists of confined multi-layer porous aquifer system which often sustains artesian flow and has a moderate groundwater potential (Figure 2.4). The pressure head is built either in the higher located parts of the embayment where, for instance, some coal seams pinched out even in the mountainous area further to east. Information on the hydrogeological significance of geological formations outcropping in the survey area or in its vicinity has been compiled in Table 2.1.

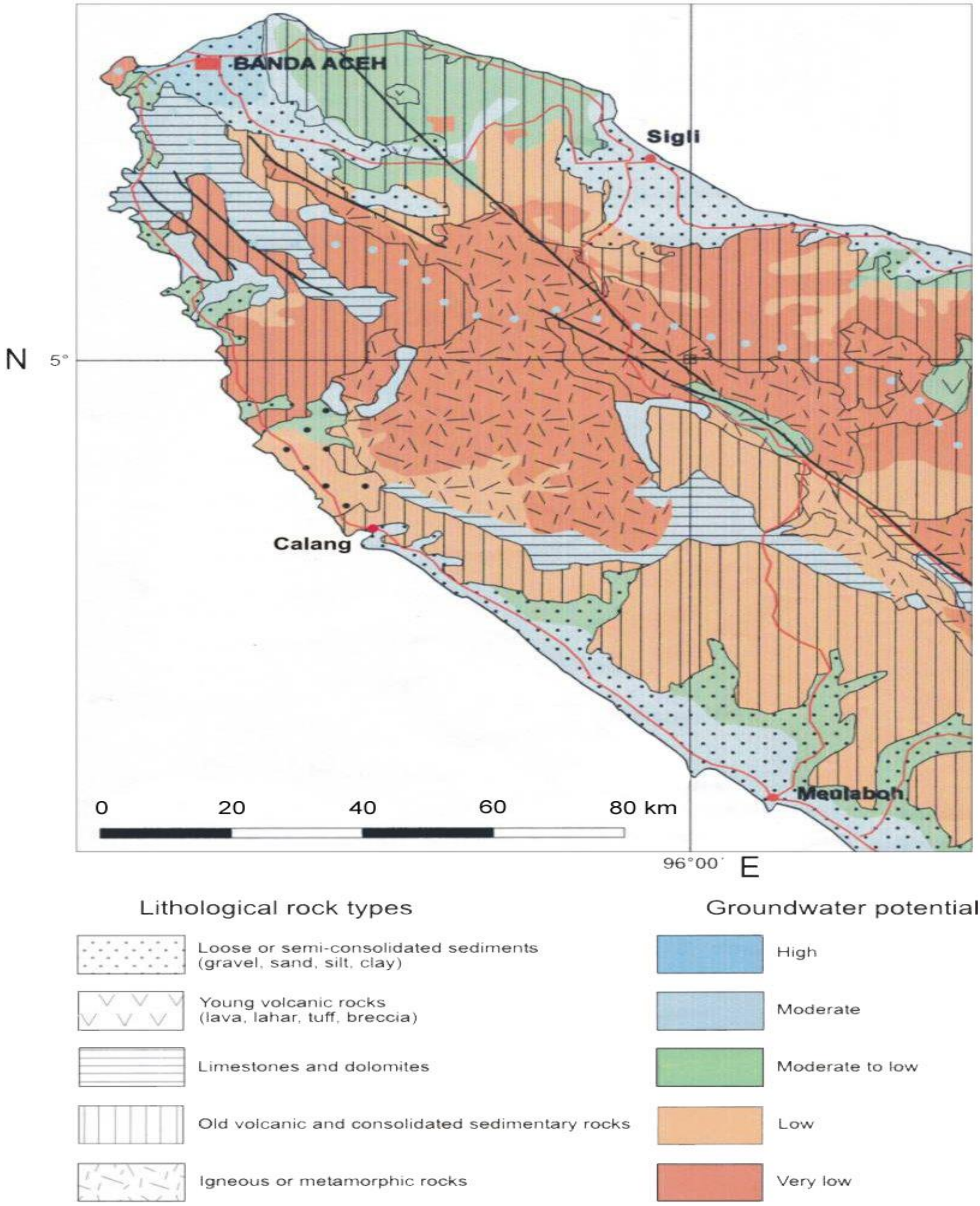


Figure 2.4 Hydrogeological Map of West Aceh Coastal Area, scale 1:1,000,000, Sheet I Medan compiled by Setiadi (2004).

Table 2.1 Details of the rocks occurring within the coastal area extending from south of Meulaboh to north of Calang and their hydrogeological significance (source: Bennett et al. 1981, Cameron et al. 1983, and Soetrisno& Sudadi 1986)

Name of Formation	**Symbol**	**Age**	**Lithological composition, thickness**	**Permeability of rocks**	**Type of aquifer, productivity of aquifer**
Alluvium	Qh	Holocene	Coastal and fluvial sediments composed of gravels, sands, silts and clays	Moderate to high	Extensive, moderately productive porous aquifers, well yield generally less than 5 L/s
			On Calang Quadrangle: rapid coastal progradation, strand-line deposits prominent		
			Sabe River: fluviatile granitic sands and gravels		
			2–3 m raised coral reef at Meulaboh		
MeulabohFm	Qpm	Pleistocene	Reworked gravels, sands, silts, clays; poorly exposed terraces, up to 20 m thick		
			Teunom River mouth area: 5–10 m terraces composed of sands and gravels		
TututFm	QTt	Plio-Pleistocene	Poorly lithified conglomerates, sandstones, lignitic mudstones, thin lignites and seat earths, thickness of several hundred metres (in coal exploration holes: >240 m)	Generally low; locally moderate in unconsolidated rocks	Locally, moderately productive porous to fissured aquifers, well yield generally less than 5 L/s
Dykes and sills	Qpd	Probably Pleistocene	Mainly mafic micrograbboids		
TanglaFm	Tlt	Probably Late Oligocene to Early Miocene	Coastal zone on Calang Quadrangle: In part volcanic and conglomeratic sandstones, siltstones, mudstones.		
TanglaFm Volcanic Facies	Tltv		Localised intermediate volcanics, especially SE of Calang, where basalts (Tltv) also occur	Low to moderate	Poorly productive fissured aquifer
Calang Volcanic Fm	Tmvc	Probably Middle to Late Miocene	Calang: Extrusive and subvolcanic intrusive porphyritic hornblendic andesites; subordinate basalts, microgabbroids, breccias and agglomerates		
			NW of Teunom River : Andesites, vesicular basalts, crystal tuffs; thin sediment interbeds including coals		
Teunom Limestone Fm, reef member	Mutlr	Late Jurassic to Early Cretaceous	NE, E to SE of Calang: massive, commonly recrystallised reef-like limestone; faulted against or marmorised by Sikuleh batholith	Moderate, depending on fissures, fractures and solution channels	Fissured to karstic moderately productive aquifer, well yields and spring discharges vary in wide range

Fifteen spring locations are marked on the Hydrogeological Map of Quadrangle Lhokruet (Soetrisno and Sudadi,1986). There is one major karstic spring which emerges from the reef-like limestones of Teunom Formation (Mutlr) at the southern slope of Gunung Sawah Geunie (296 m), around 12 km NE of Calang. Its discharge is supposed to be in the range of 80 L/s.

A more detailed description of the unconsolidated to semi-consolidated porous aquifer system which comprises from top to bottom of the Alluvium, Meulaboh and Tutut formations is only feasible for the surroundings of Meulaboh area and the lower reaches of the Bubon River valley (Samatiga District).

The upper 10–20 m of fine to coarse sands might represent Alluvium and Meulaboh Formation; this is rather shallow unconfined aquifer that has been traditionally tapped by dug wells. The underlying silts, sandy clays and lignite or peat (up to 60–66 m.b.g.l) act as a low-yielding aquifer (quasi-aquitard; Q: 0.5–1 L/s). Correspondingly, the specific capacity is as low as 0.05–0.7 L/s.m roughly equals to transmissivity about 5 to 65 m^2/d (Rio Tinto and IAGI 2005). Below 60–66 m.b.g.l is the succession of fine to coarse sandy horizons alternating with sandy clays which constitute a multi-layer aquifer system that has been tapped by the SDC wells and also from the abandoned Perusahaan Daerah Air Minum (PDAM) West Aceh wells up to 100 and 175 m.b.g.l (meters below ground level) respectively. The transmissivity (T) ranges from 20 to70 m^2/d while the corresponding hydraulic conductivity (K) is around 1–3·10 5 m/s which shows some typical fine sand to silty sand. The wells yielded 7.5–9 L/s and the specific capacity was between 0.4 and 0.9 L/s·m (Ploethner, 1983). This aquifer system was confined; as some of the wells had been artesian in flowing.

Most of the emergency supply wells which recently sunk along the coastal road and passing through Kuala District (Suak Puntong Village to Camp Cot Mee) have been found between 40–70 m deep, sustained artesian flow (0.1–0.5 L/s) with a pressure head of 0.3–0.5 m above ground level. A detailed interpretation of helicopter-borne electromagnetic data has revealed that this artesian aquifer, for instance at Langkak Village, data represented by a 20 to 40 m thick horizon which is confined by an approximately 10 m thick with low resistivity layer which in turn is overlaid by a near-surface aquifer .

In May - June 1993 the depth of shallow groundwater averaged at 1.4–1.6 m.b.g.l, due to a steeper surface morphology was at 2.3 m.b.g.l in Teunom area Moreover, the EC averaged at 220–330 µS/cm disregarding a few extreme values, by comparison river water averaged at 110 µS/cm (IWACO 1993). In October 2005, a few dug wells were monitored and the EC of the shallow groundwater was found between 350 and 1400 µS/cm near to the coast, whereas EC was at 140–200 µS/cm further inland.

In Meulaboh and surroundings as well as in the Bubon River valley emergency supply wells (IAGI & Rio Tinto, SDC) that sunk in 2005 encountered groundwater with an EC varying over a wide range of 260 to 5700 µS/cm at a depth ranging from 6 to 36 m.b.g.l, and greater depth (70–100 m.b.g.l) EC ranged from 430 to 3200 µS/cm. The hot spots are Suak Timah Village near the mouth of Bubon River and Ujung Tanjong Village and Penaga Paya SE of Meulaboh. In contrast, some of the 40 emergency wells drilled in 2005 by Solidarités predominantly in the Kuala District and Meureubo tapped groundwater (10–120 m.b.g.l) with low salinity (EC: 150–850 µS/cm apart from one exception of 1300 µS/cm). A rehabilitated Dutch well (120 m) located near the harbour and an abandoned PDAM well (175 m) produced groundwater with EC of 440 and 620 µS/cm, respectively.

The nine deep water supply wells of PDAM Meulaboh were drilled in early 1980s and which had been reportedly abandoned since mid-1990s due to the fact that algae and elevated iron concentrations in the raw water. These conditions could not be sufficiently eliminated possibly due to the presence of elevated ammonia concentrations. Since then, PDAM Meulaboh has been running a river intake and a surface water treatment plant. Since December 2004 earthquake, the river intake has been endangered by saltwater encroachment, whereas quality of treatment is poor due to lack of funds. A water quality monitoring conducted by Spanish Red Cross & CRS have revealed that Meureubo River showed elevated EC values of >3000 µS/cm at surface and >15,000 µS/cm at 3 m depth up to 2 km inland in September 2005. This saltwater encroachment is probably caused by a substantial land subsidence as a consequence of the December 2004 earthquake.

3.0 METHODOLOGY

3.1 Task and Work Plan

The basis of this work plan is referred to the objectivity of the study mentioned before. The tasks identified for the implementation of this research are:

1. Data Collection,
2. DRASTIC Model,
3. Mapping of Groundwater Vulnerability and GIS (Geographic Information System),
4. AHP (Analytical Hierarchy Process).

3.2 Data Collection

In the early part of this research, few selected data related to the DRASTIC model were reviewed and analysed, to include the followings:

1. Borehole data (water table level) from Ministry of Energy and Mineral Resources Aceh Province.
2. Average annual rainfall from Indonesian Agency for Meteorology, Climatology and Geophysics.
3. Geology map from the Ministry of Energy and Mineral Resources Aceh Province.
4. Soil map from the Office Region of the National Land Agency Aceh Province.
5. Topographical sheets from the Office Region of the National Land Agency Aceh Province.
6. Geological profile from Ministry of Energy and Mineral Resources Aceh Province.
7. Hydraulic conductivity from field work.

3.3 Drastic Model

One of the most popular in overlay method index for estimating groundwater vulnerability is DRASTIC (Aller, et al. 1987). The DARSTIC model uses a scoring system based on seven hydrogeologic characteristics of a region. The acronym DRASTIC stands for the parameters included in the method: Depth to water table, Recharge rate, Aquifer media, Soil media, Impact of vadose zone media, and hydraulic Conductivity of the aquifer.

DRASTIC is applied by identifying map able units, called hydrogeologic settings, in which all seven parameters have nearly constant values. Each parameter in a hydrogeologic setting is assigned using a numerical rating from 0–10 (0 meaning low risk; 10 meaning high risk) which is multiplied by a weighting factor varying from 1–5. Two sets of weights, one for general vulnerability and the other for vulnerability to pesticides can be used.

$$\text{DRASTIC Index (DI)} = D_w.D_r + R_w.R_r + A_w.A_r + S_w.S_r + T_w.T_r + I_w.I_r + C_w.C_r \qquad (1)$$

Where D, R, A, S, T, I, and C are the seven parameters and the subscripts w and r are the corresponding rating and weights respectively. Table 3.1 and Table 3.2 show weight and rating value.

Table 3.1 DRASTIC model parameter weight for Aller*et al*. (1987)

No	Parameter		Weight
1	D	Depth to Water Table	5
2	R	Net Recharge	4
3	A	Aquifer Media	3
4	S	Soil Media	2
5	T	Topography	1
6	I	Impact of Vadose Zone	5
7	C	Conductivity	3

Table 3.2 DRASTIC model parameter rating for Alleret al. (1987)

No	**Depth to Water Table Interval (feet)**	Rating
1	0 – 5	10
2	5 – 10	9
3	15 – 30	7
4	30 – 50	5
5	50 – 75	3
6	75 -100	2
7	>100	1
No	**Rainfall Interval (Inches/years)**	Rating
1	0 – 2	1
2	2 – 4	3
3	4 – 7	6
4	7 – 10	8
5	>10	9
No	**Aquifer Media**	Rating
1	Massive Shale	2
2	Metamorfic /Igneous	3
3	Weathered metamorphic	4
4	Glacial Till	5
5	Bedded Sandstone, limestone and Shale Sequence	6
6	Massive Stone	6
7	Massive Limestone	6
8	Sandy Loam	7
9	Loamy Sandy	8
10	Sand and Gravel	8
11	Basalt	9
12	Karst Limestone	10
No	**Soil Media**	Rating
1	Thin or Absent	10
2	Gravel	10
3	Sand	9
4	Peat	8
5	Loamy Sand	8
6	Shrinking and or Aggregated Clay	7
7	Sandy Loam	6
8	Loam	5
9	Silty Loam	4
10	Clay Loam	3
11	Muck	2
12	Non Shrinking and or Non Aggregated Clay	1
No	Topography (%)	Rating
1	0-2	10
2	2-6	9
3	6-12	5
4	12-18	3
5	>18	1

Table 3.2 Continued		
No	**Vadose Zone Material**	Rating
1	Confining Layer	1
2	Silt/Clay	1
3	Sandy Loam	2
4	Loamy Sand	3
5	Shale	3
6	Limestone	3
7	Sand	4
8	Sand Stone	6
9	Bedded Limestone, Sand Stone, Shale	6
10	Sand and Gravel with Significant Clay and Silt	6
11	Basalt	9
12	Karst Limestone	10
No	**Hydraulic Conductivity (GPD/FT^2)**	Rating
1	1-100	1
2	100-300	2
3	300-700	4
4	700-1000	6
5	1000-2000	8
6	>2000	10

3. 4 Drastic Modification by Rosen and Widyastuti

Lars Rosen is one scientist from Chalmers University of Technology at Sweden. He did a study of DRASTIC classification methodology with special emphasis on Swedish conditions. In his study, it concluded that the concept of hydrological setting in DRASTIC is excellent. The user is able to trace parameter values backwards for each mapped hydrogeologic setting. Lars Rosen also said weighting and integrating values of indices of key parameters represent a logical procedure but it can be misleading if the final simplistic index without qualifying explanation is displayed for mapping the vulnerability for contamination (Rosen, 1994).

Rosen (1994) stated that DRASTIC has some advantageous statistical properties from the use of a fairly large number of correlated parameters. The variability between difference evaluators tends to be kept at low level since the objective functions for DRASTIC index is based on fairly large number of parameters. Because of the correlation between the parameters, the probability of misjudgement of single parameters is also low, provided that the parameters are treated separately in the classification procedure.

Other side, Widayastuti is an expert at Gajah Mada University and has same concept with Rosen. She did a study about groundwater vulnerability at Sleman and Ngemplak District in Yogyakarta Province (Widyastuti, 2004). She used DRASTIC by US Environmental Protection Agency (Aller et.al, 1987). In modification by Widyastuti (2004), it have seven variables, from which the name of the model is derived, include Depth to water, Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, and Conductivity (hydraulic).

The numerical ranking system, another DRASTIC component, is used to assess the groundwater-pollution potential for each hydrogeologic variable. The system contains three parts: 1) weights; 2) ranges; and 3) ratings (Widyastuti, 2004). Each DRASTIC parameter has been assigned a relative weight, range and rating. Table 3.3 and 3.4 illustrates the weights, ranges and ratings for both modifications. Finally, the ratings are used to quantify the ranges/media with regard to likelihood of groundwater pollution.

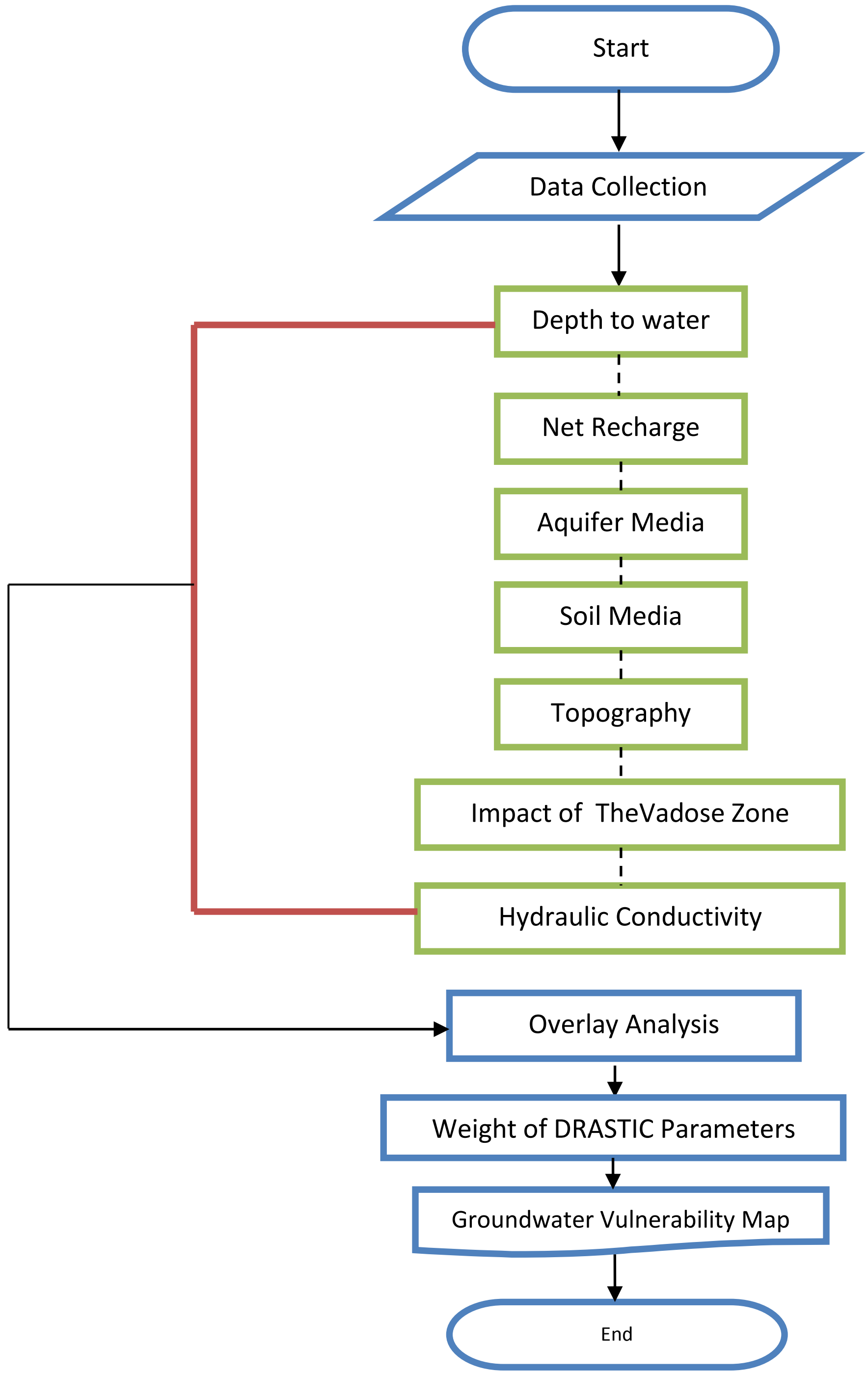


Figure 3.1 Flow Chart of Drastic Model

Table 3.3 Weight of Vulnerability Parameters in Rosen (1994) and Widyastuti (2004)

No	Parameter		Weight
1	D	Depth to Water Table	5
2	R	Recharge	4
3	A	Aquifer Media	3
4	S	Soil Media	2
5	T	Topography	1
6	I	Impact of Vadose Zone	5
7	C	Conductivity	3

Table 3.4 Rating of Parameters in Rosen (1994) and Widyastuti (2004)

No	**Depth to Water Table Interval (m)**	Rating
1	0 – 1.5	10
2	1.5 – 3	9
3	3-9	7
4	9-15	5
5	15-22	3
6	22-30	2
7	>30	1
No	**Rainfall Interval (mm/years)**	Rating
1	0 – 1500	2
2	1500-2000	4
3	2000 - 2500	6
4	2500 - 3000	8
5	>3000	10
No	**Aquifer Media**	Rating
1	Massive Shale	2
2	Metamorfic /Igneous	3
3	Weathered metamorphic	4
4	Glacial Till	5
5	Bedded Sandstone, limestone and Shale Sequence	6
6	Massive Stone	6
7	Massive Limestone	6
8	Sandy Loam	7
9	Loamy Sandy	8
10	Sand and Gravel	8
11	Basalt	9
12	Karst Limestone	10
No	**Soil Media**	Rating
1	Thin or Absent	10
2	Gravel	10
3	Sand	9
4	Peat	8
5	Loamy Sand	8
6	Shrinking and or Aggregated Clay	7
7	Sandy Loam	6

Table 3.4 Continued		
8	Loam	5
9	Silty Loam	4
10	Clay Loam	3
11	Muck	2
12	Non Shrinking and or Non Aggregated Clay	1
No	**Topography (%)**	Rating
1	0-2	10
2	2-6	9
3	6-12	5
4	12-18	3
5	>18	1
No	**Vadose Zone Material**	Rating
1	Confining Layer	1
2	Silt/Clay	1
3	Sandy Loam	2
4	Loamy Sand	3
5	Shale	3
6	Limestone	3
7	Sand	4
8	Sand Stone	6
9	Bedded Limestone, Sand Stone, Shale	6
10	Sand and Gravel with Significant Clay and Silt	6
11	Basalt	9
12	Karst Limestone	10
No	**Hydraulic Conductivity (m/day)**	Rating
1	0 – 0.86	1
2	0.86 – 2.59	2
3	2.59 – 6.05	4
4	6.05 -8.64	6
5	8.64 -17.18	8
6	>17.18	10

3.5 Drastic Modification by Piscopo

Gennaro Piscopo is one of expert from New South Wales (NSW) Australia and he graduated from University of Technology Sydney focuses on environmental modelling. He did the research about modification DRASTIC parameters. One of study area is Macquarie Catchment in state of NSW. The Macquarie Catchment Groundwater Vulnerability Map has been produced as a part of the implementation of the Water Management Act 2000 in Australia, introduced in an effort to achieve more sustainable water use. The ultimate aim, as part of this implementation, is to complete vulnerability and availability mapping for the whole State of NSW.

This will provide the Department of Urban Affairs and Planning (DUAP), the Catchment Management Board, the Councils of the Macquarie Catchment, and other regulating agencies with a regional tool using a Geographical Information System (GIS) for determining the suitability of various developments in the region within a spatial context. In order to achieve this, a number of spatial attributes need to be mapped, such as geology, depth to water table, soil properties, slope and any other attributive considered relevant. These are then weighted, ranked, and combined to produce a final ranking value using the appropriate algorithm, which defines the groundwater vulnerability. The method used for creating the Macquarie Catchment groundwater vulnerability map is a modification of the DRASTIC approach, first devised by the USEPA. Modification DRASTIC Parameters by Piscopo are shown in Table 3.5 and Table 3.6.

Table 3.5 Weight of Vulnerability Parameters in Piscopo (2001)

No	Parameter		Weight
1	D	Depth to Water Table	4
2	R	Recharge	2
3	A	Aquifer Media	5
4	S	Soil Media	2
5	T	Topography	1
6	I	Impact of Vadose Zone	5
7	C	Conductivity	Not Used

Table 3.6 Rating of Depth to Water Table in Piscopo (2001)

No	Depth to Water Table Interval (m)	Rating
1	< 5	10
2	5 – 10	8
3	10 – 15	6
4	15 – 20	4
5	> 20	1

Table 3.7 Rating of Topography in Piscopo (2001)

No	Topography (%)	Rating
1	<2	10
2	2 – 10	8
3	10 – 20	5
4	20 – 33	2
5	>33	1

Table 3.8 Rating of Depth to Water Table in Piscopo (2001)

No	Aquifer Media	Rating
1	Alluvium 1	10
2	Alluvium 2	6
3	Porous Sidementary	6
4	Limestone	9
5	Volcanic	7
6	Igneous 1 (Carboniferous)	5
7	Igneous 2 (Palezoic)	3
8	Metasediment	1

The following equation is used to generate a recharge value. This recharge value is then grouped into a range of values that are given a rating for use in the final DRASTIC calculation.

$$\text{Recharge Value} = \text{Slope \%} + \text{Rainfall} + \text{Soil Permeability} \qquad (2)$$

Table 3.9 Slope % for Recharge Value in Piscopo (2001)

No	Slope (%)	Factor
1	< 2	4
2	2 – 10	3
3	10 – 33	2
4	> 33	1

Table 3.10 Rainfall for Recharge Value in Piscopo (2001)

No	Rainfal (mm/years)	Factor
1	<850	4
2	700 – 850	3
3	500 – 700	2
4	> 500	1

Table 3.11 Soil Permeability for Recharge Value in Piscopo (2001)

No	Soil Permeability (%)	Factor
1	High	4
2	Mod-High	3
3	Moderate	2
4	Slow	1

Table 3.12 Rating of Recharge Table in Piscopo (2001)

No	Recharge	Rating
1	11 – 13	10
2	9 – 11	8
3	7 – 9	5
4	5-7	3
5	3-5	1

Table 3.13 Rating of Vadose Zone Impact Table in Piscopo (2001)

No	Range	Rating
1	8 – 10	10
2	6 – 8	8
3	4 – 6	5
4	3 – 4	3
5	2 – 3	1

For calculating Impact of Vadose Zone use the formula below.

$$\text{Vadose Zone} = \text{Soil Permeability} + \text{DTWT} \tag{3}$$

Table 3.14 Rating of Soil Media Table in Piscopo (2001)

No	Range	Rating
1	High	10
2	Mod – High	8
3	Moderate	5
4	Slow	3
5	Very Slow	1

3.6 GIS in Groundwater Management

GIS is a powerful tool and has great promise to be used in environmental problem solving. Most environmental problems have an obvious spatial dimension and spatially distributed models can interact with GIS. GIS has been found to be very effective to assess the groundwater quality (Kistemann, *et.al*, 2008). GIS are designed to manage, analyse and display all types of spatial data. It provides a visualization platform in which layered, spatially distributed databases can be manipulated with ease. This capability makes GIS a powerful tool in conducting groundwater modelling. The application of traditional data processing methods for groundwater modelling is very difficult and time consuming because the data is massive and usually needs to be integrated. GIS is capable of developing within a short period of time (Nas and Berktay, 2006).

Geographic information systems (GIS) have become a useful and an important tool in hydrology and also to hydrologists in the scientific study and management of water resources. Climate changes and greater demands on water resources require a more knowledgeable disposition of arguably one of our most vital resources. As every hydrologist knows, water is constant in motion. Henceforth, water in its occurrence varies spatially and temporally throughout the hydrologic cycle, whereby its study using GIS is especially practical. Previously, GIS systems were mostly static in their geospatial representation of hydrologic features. Today, GIS platforms have become increasingly dynamic, narrowing the gap between historical data and current hydrologic reality (Maruo, Y, 2009).

The most common application of GIS found during the literature review is creating groundwater contamination vulnerability maps. The map can reveal the areas of extreme and high groundwater vulnerability. Modelling groundwater contamination vulnerability can be divided into handful of steps. The first step is to construct a spatial database of the area of interest containing information that will affect the vulnerability to groundwater contamination. Information layers such as land use, soil characteristic, bedrock geology, topography, recharge, hydraulic conductivity, groundwater levels, well locations and climate were common data layers which have been used. The combination of these layers enables the vulnerability of an area to be assessed for specific pollutants. Once the groundwater contamination vulnerability map reveals a classification model then the vulnerability classes can be created. This is done by ranking the input layers according to their impact on groundwater vulnerability.

Some cases are found to be using low numbers to represent high vulnerability and high numbers represent low vulnerability. Finally, the vulnerability score of each layers are combined to create a vulnerability index. Vulnerability index can be represented in either a numerical value or a comparison value such as very high, high, low, etc. The second is to create a number of models of an area. In each of the models one of the variables is weighted more than the other depending on the degree of impact on the system. The different models are then compared to find common trends and patterns. A graphical representation of vulnerable aquifers, combined with graphical representations of potential sources of contamination and public water supplies, would allow decision makers to evaluate current land use practices and make recommendations for changes in land use regulations which would better prevent the groundwater from contamination. For example, it may not be considered responsible to build a new chemical plant in the contributing area of a particularly vulnerable aquifer or area of an aquifer. Additionally, such a representation would provide a quick tool for determining possible and responsible parties if contamination is found, thereby expediting the remediation process.

The third step of GIS in groundwater quality modelling is running groundwater modelling like DRASTIC and MODFLOW in a GIS environment. In these models, groundwater models play a role of analysis whereas GIS play the role of displaying the map and find out the areas that are mostly concerned. The DRASTIC model was used for vulnerability assessment in studying area using hydro-geological parameters, aquifer recharge, and the final map of DRASTIC aquifer vulnerability for the area that was developed in ARCGIS software (Figure 3.2).

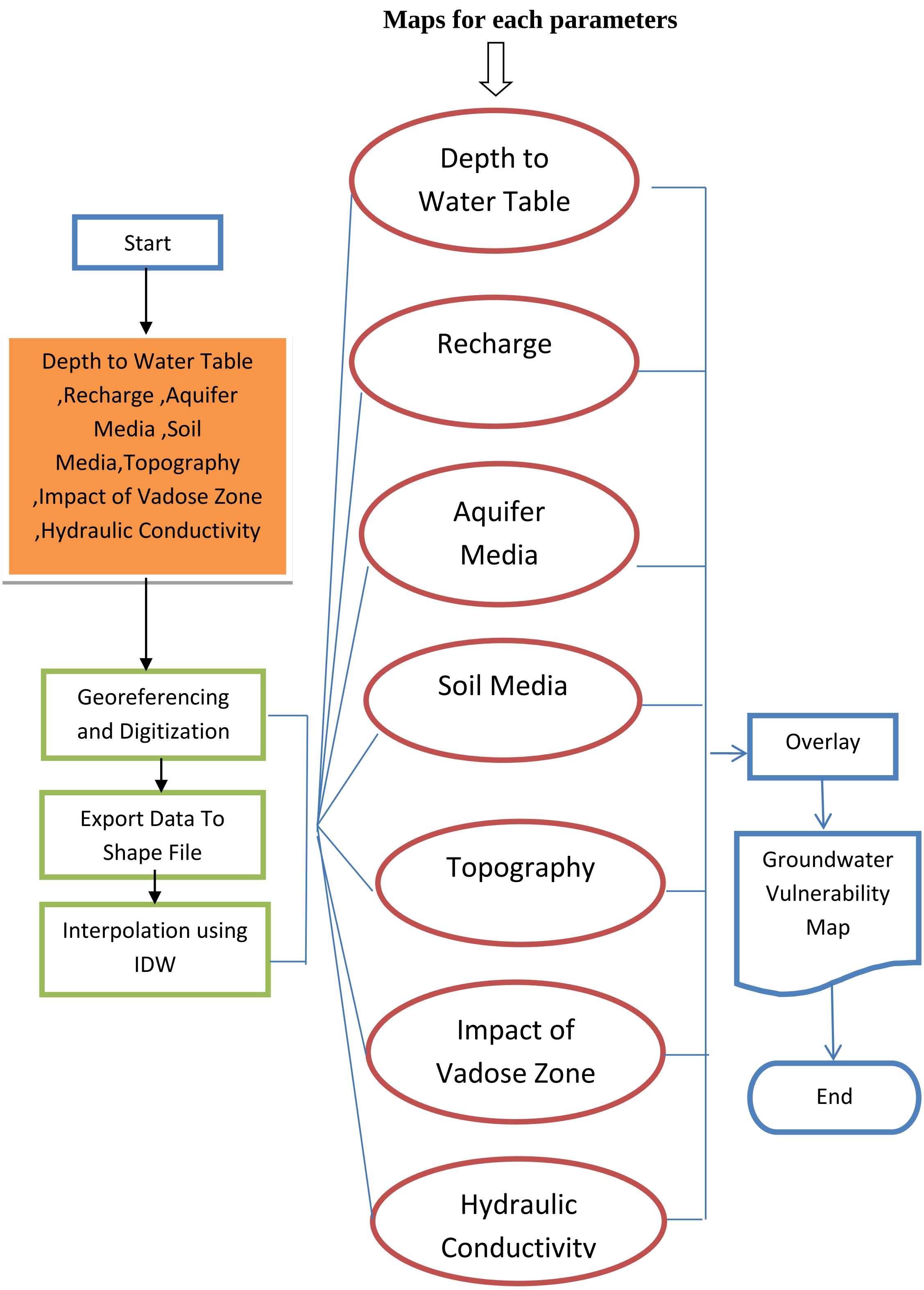


Figure 3.2 Mapping for DRASTIC Model and GIS

3.7 AHP (Analytic Hierarchy Process)

The foundation of the Analytic Hierarchy Process (AHP) is a set of axioms that carefully delimits the scope of the environmental problem (Saaty 1986). It is based on the well-defined mathematical structure of consistent matrices and their associated right-eigenvector's ability to generate true or approximate weights, Merkin (1979), Saaty (1980, 1994). The AHP methodology compares criteria or alternatives with respect to a criterion, in a natural, pairwise mode. To do so, the AHP uses a fundamental scale of absolute numbers that has been proven in practice and validated by physical and decision problem experiments.

The fundamental scale that has been shown to be a scale that captures individual preferences with respect to quantitative and qualitative attributes just as well or better than other scales (Saaty 1980, 1994). It converts individual preferences into ratio scale weights that can be combined into a linear additive weight w (a) for each alternative a. The resultant w (a) can be used to compare and rank the alternatives and, hence, assist the decision maker in making a choice. Given that the three basic steps are reasonable descriptors of how an individual comes naturally to resolving a multi criteria decision problem, then the AHP can be considered to be both a descriptive and prescriptive model of decision making. Therefore, the AHP perhaps, the most widely used decision making approach in the world today. Its validity is based on many hundreds (now thousands) of actual applications in which the AHP results were accepted and used by the cognizant decision makers (DMs), Saaty (1994).

The analytic hierarchy process (AHP) is a structured technique for organizing and analysing complex decisions. The AHP, as a compensatory method, assumes complete aggregation among criteria and develops a linear additive model. The weights and scores are achieved basically by pairwise comparisons between all options with each other (ODPM, 2004).The basic procedure to carry out the AHP consists of the following steps:

1. Structuring a decision problem and selection of criteria is the first step to decompose a decision problem into its constituent parts. In its simplest form, this structure comprises a goal or focus at the topmost level, criteria (and sub criteria) at the intermediate levels, while the lowest level contains the options. Arranging all the components in a hierarchy provides an overall view of the complex relationships and helps the decision maker to assess whether the elements in each level are of the same magnitude so that they can be compared accurately. An element in a given level does not have to function as a criterion for all the other elements in the level below. Each level may represent a different cut at the problem so the hierarchy does not need to be complete (Saaty, 1990). When constructing hierarchies, it is essential to consider the environment surrounding the problem and to identify the issues or attributes that contribute to the solution as well as to identify all participants associated with the problem.
2. Priority setting of the criteria by pairwise comparison (weighing) for each pair of criteria, the decision maker is required to respond to a question such as “How important is criterion A relative to criterion B?”. Rating the relative “priority”of the criteria is done by assigning a weight between 1 (equal importance) and 9 (extreme importance) to the more important criterion, whereas the reciprocal of this value is assigned to the other criterion in the pair. The weightings are then normalized and averaged in order to obtain an average weight for each criterion.

3. Making pairwise comparison of options on each criterion (scoring). For each pairing within each criterion, the better option is awarded a score, again, on a scale between 1(equally good) and 9 (absolutely better)as noted in Table 3.15, whilst the other option in the pairing is assigned a rating equal to the reciprocal of this value. Each score records how well option “X” meets criterion “Y”. Afterwards, the ratings are normalized and averaged. Comparison of elements in pairs require that they are homogeneous or close with respect to the common attribute; otherwise significant errors may be introduced into the process of measurement (Saaty, 1990).
4. Obtaining an overall relative score for each option in the final step is the option scores which are combined with the criterion weights to produce an overall score for each option. The extent to which the options satisfy the criteria is weighed according to the relative importance of the criteria. Finally, after judgements have been made on the impact of all the elements and priorities have been computed for the hierarchy as a whole, sometimes and with care, the less important elements can be dropped from further consideration because of their relatively small impact on the overall objective. The priorities can then be recomputed throughout, either with or without changing the judgements (Saaty, 1990).

In this study, AHP is used to modify DRASTIC parameters in order to obtain optimal results.It was decided to use the AHP method as it is one of the best known and widely used Multi Criteria Evaluation (MCA) approaches. It also allows users to assess the relative weight of multiple criteria or multiple options against the actual given criteria in an intuitive manner (Saaty, 1980). Figure 3.3 shows methodology for combination AHP ,Delphi and GIS.

Table 3.15 The Saaty Rating Scale

No	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective (1)
2	Somewhat more important	Experience and judgement slightly favour one over the other (3)
3	Much more important	Experience and judgement strongly favour one over the other (5)
4	Very Much More Important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated inpractice (7)
5	Absolutely More Important	The evidence favouring one over the other is of thehighest possible validity (9)
6	Intermediate Value	When compromise is needed (2,4,6,8)

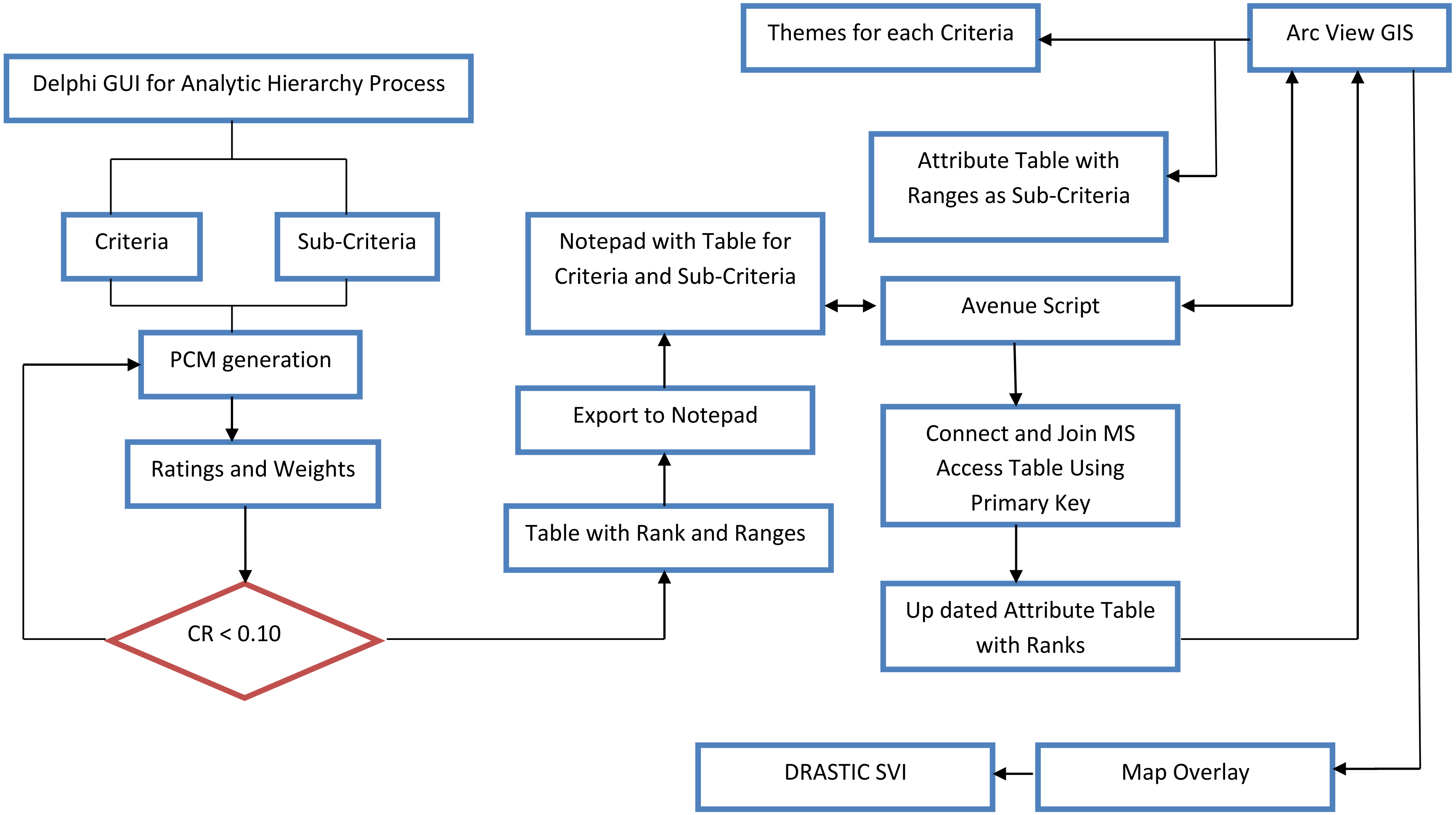


Figure 3.3 Methodology for Delphi-AHP-GIS

4.0 RESULT AND DISCUSSION

4.1 Drastic

4.1.1 Depth to Water Table

The water table is the surface as to water pressure head becomes equal to the atmospheric pressure (where gauge pressure = 0). It may conveniently be visualized as the "surface" of subsurface materials which had been saturated with groundwater in given vicinity. However, saturated conditions may extend above the water table as surface tension holds water in some pores below atmospheric pressure. Individual points on the water table are typically measured as the elevation which means water that had risen in a well screened for shallow groundwater (Freeze and Cherry, 1979).

In this research, the depth to water table data that obtained from the Department of Mines and Energy Aceh (2012), provided information about ranges of depth to water table (the maximum value of depth to water is 2.56 m while the minimum value of depth to water is 0.33 m). The first model Drastic used in this research was the DRASTIC model with modification by Rosen (1994) and Widyastuti (2004), where the presented model indicated majority of wells area depth of less than 1.5 meters (92.59%) or 384.14km^2 of the total area and the well with a depth of more than 1.5 meters spread as many as 7.41 % of the total area (30.73 km^2) which are noted in Table 4.1.Thereafter it was converted into grid to make it raster data for GIS operation. The depth-to-water table is distributed using IDW method (Inverse Distance Weight) in ArcGIS 10. The depth-to-water table map is shown in Figure 4.1.

Another model used in this research was Piscopo (2001) from NSW Department of Land and Water Conservation, Australia. These models have 5 classifications for depth to water table with range<5 meters with values of 10 and the maximum range are> 20 meters with value of 1. In Piscopo model (2001), the depth to water table feature was created by combining actual depth to water table data with topography as the principal surface aquifers are located in unconsolidated sediments and fractured aquifers, and therefore considered to be unconfined. The groundwater is predominantly contained in the fractured and unconsolidated sediment aquifer system, which were generally recharged locally. This model indicated that all areas have a range less than 5 meters which means that all areas displayed rating value of 10 as shown in Figure 4.2.

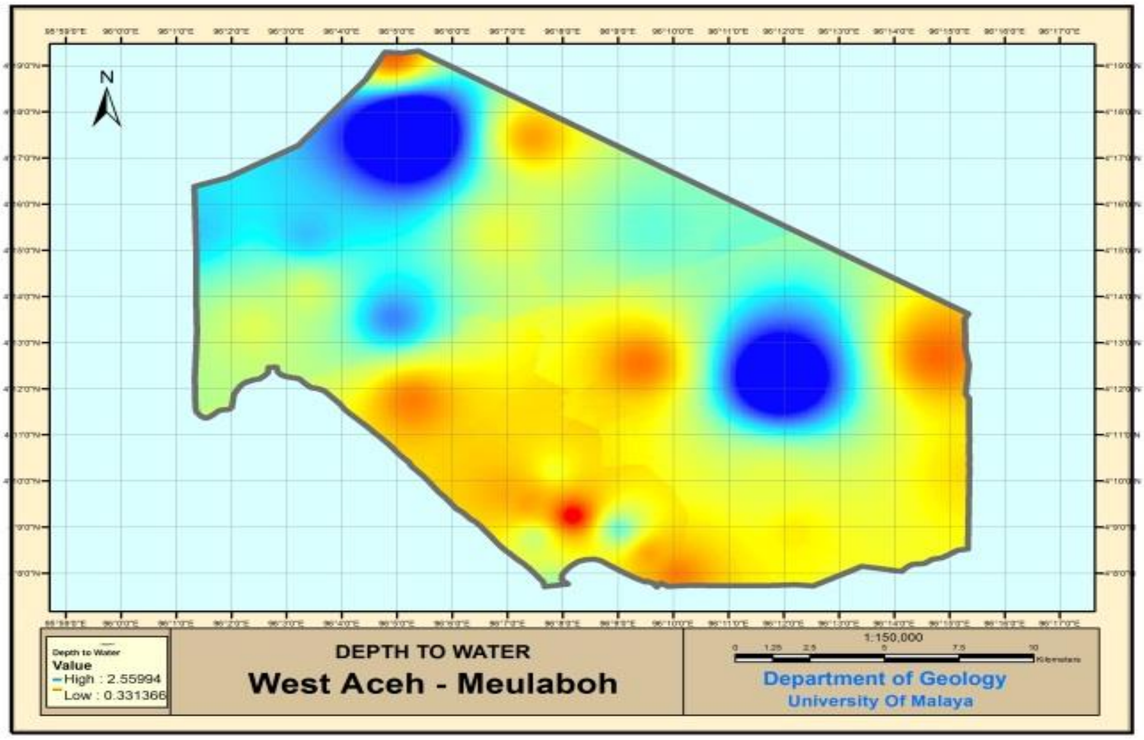


Figure 4.1 Depth to Water Table Using Modification Rosen (1994) and Widyastuti (2004)

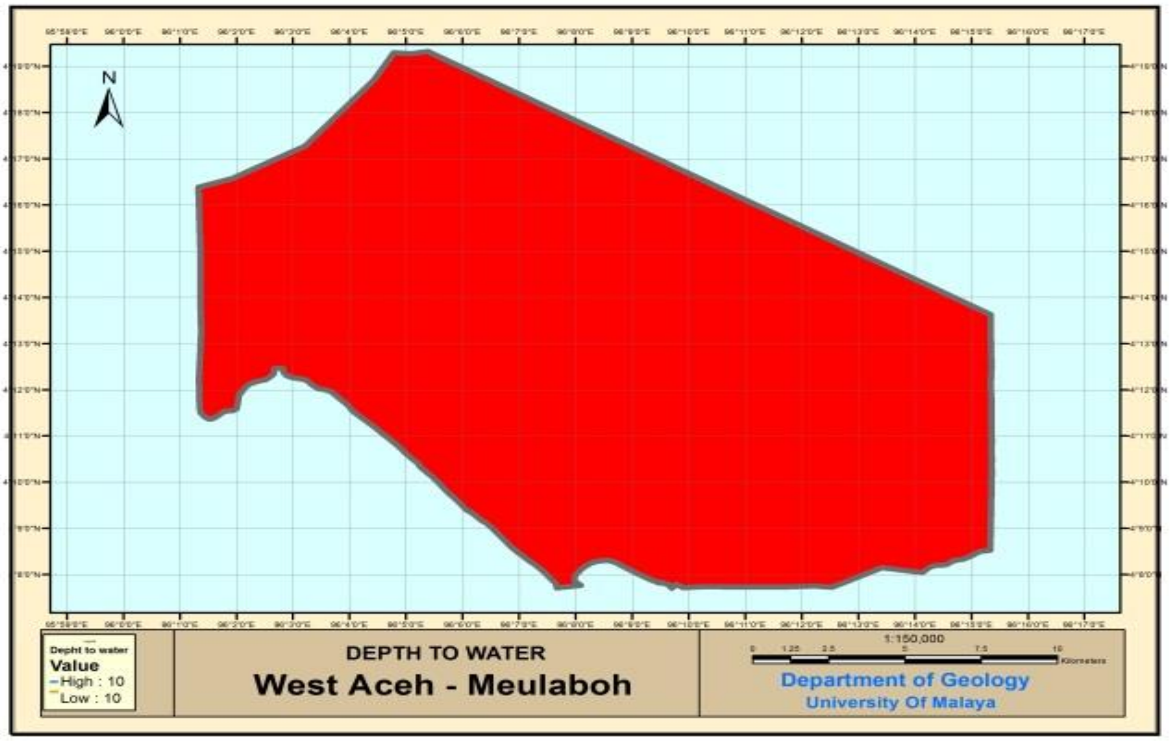


Figure 4.2 Depth to Water Table Using Modification Piscopo (2001)

Table 4.1 Index Depth to Water Table Using Modification Rosen (1994) and Widyastuti (2004)

No	Depth (m)	W x R	Percent of Distribution (%)	Area (Km^2)
1	0 - 1.5	5 x 10	92.59	384.14
2	1.5 – 3	5 x 9	7.41	30.73

4.1.2 Recharge

The R parameter represents recharge to the aquifer. Recharge is the principal means for leaching and transporting contaminants to the water table; therefore greater recharge increases the likelihood that contaminants will reach the groundwater. In DRASTIC model, Recharge is the total sum of water that falls on the soil surface and infiltration to reach the aquifer (Aller*et.al*, 1987).

Recharge data of the research area had been prepared by Indonesian Meteorological, Climatological and Geophysical Agency. The amount of rainfall that contributes to the Net Recharge to the work location is from 3500 mm/years to 4000 mm/years, thereafter this means having a maximum rating of vulnerability for model modification by Rosen (1994) and Widyastuti (2004) in all study areas as noted inTable4.2.The recharge parameter was distributed by using IDW method (Inverse Distance Weight) in ArcGIS 10 which is shown in Figure 4.3.

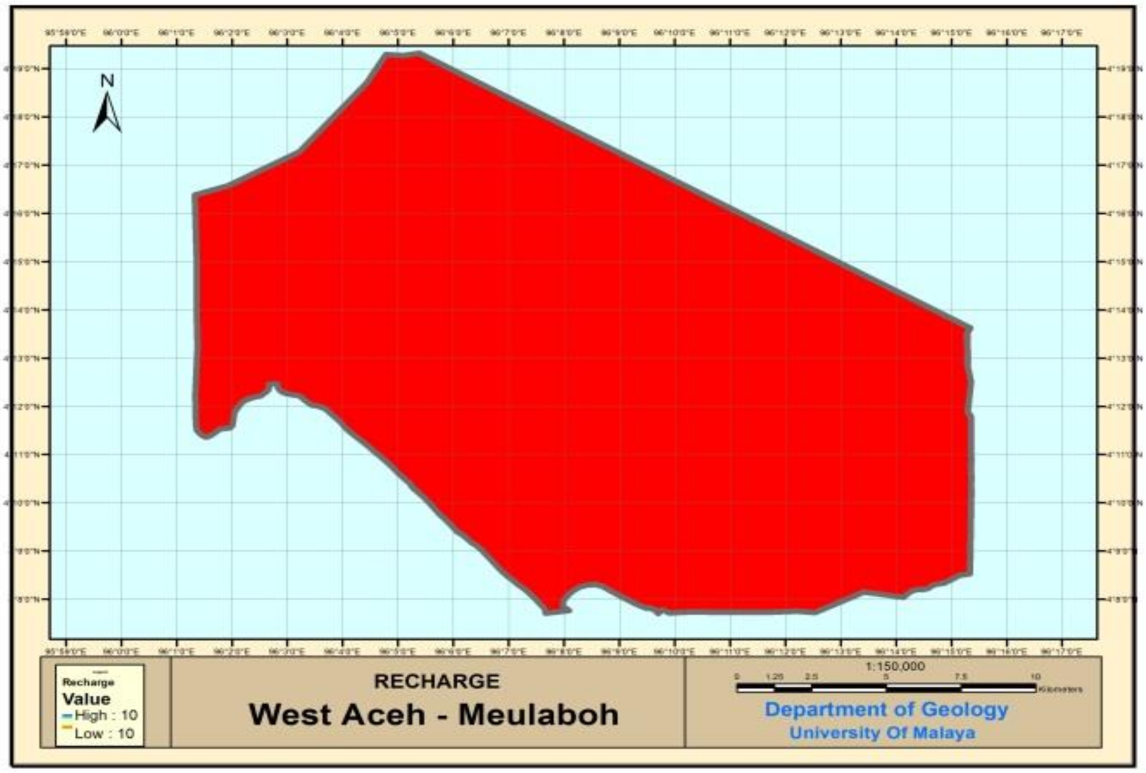


Figure 4 .3 Recharge Using Modification Rosen (1994) and Widyastuti (2004)

For modification of Piscopo (2001), the factors used to generate the recharge map for this study included slope, soil permeability and rainfall (Figure 4.4). Soil permeability is the measure of the soil’s ability to permit water to flow through its pores or voids. In Piscopo (2001), calculation recharge parameter is strongly influenced by slope, soil permeability and rainfall. Other side, Depth to water table and aquifer media are considered to be minor contributors of calculating recharge parameter because as they are used as other component maps, they will not be used in the recharge map. Assigning relative permeability factors to the basic soil classification groups within the study area has created the soil permeability map.

The model presented indicated that 51.85% of the study area (215.12 km^2) has a rating value of 10 because this area study have high precipitation value and high permeability where the potential for groundwater contamination in this area is greater than another one (48.15% = 199.76 km^2) as noted in Table 4.3.

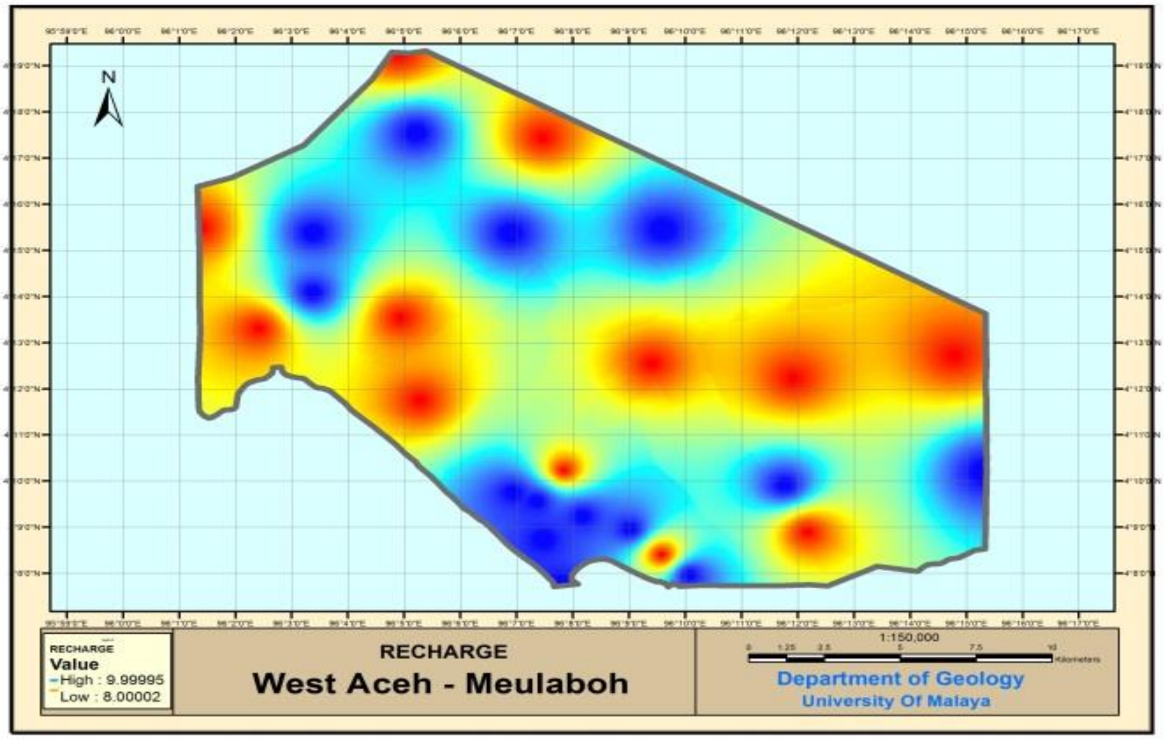


Figure 4.4 Recharge Using Modification Piscopo (2001)

Table 4.2 Index Recharge Using Modification Rosen (1994) and Widyastuti (2004)

No	**Recharge**	**W x R**	**Percent of Distribution (%)**	**Area (Km^2)**
1	> 3000	4 x 10	100	414.88

Table 4.3 Index Recharge Using Modification Piscopo (2001)

No	**Recharge**	**W x R**	**Percent of Distribution (%)**	**Area (Km^2)**
1	11.0 -13.0	2 x10	51.85	215.12
2	9.0 - 11.0	2 x 8	48.15	199.76

4.1.3 Aquifer

The aquifer media controls the groundwater flow system within the aquifer and in turn the contaminants in the aquifer. The path length and the porosity in the aquifer media have a large impact on the flow of the contaminant. The path length that the ground waters take determines the time available for several processes such as sorption, reactivity, and dispersion. In addition, the porosity of different aquifer media influences the amount of contact between contaminant and aquifer media (Freeze and Cherry, 1979).

Media aquifer in West Aceh was obtained from hand drill method. It is generally in the form of sand and gravel, massive sandstone, thin sandstone, and massive shale. The results of field measurement, after media analysed the existing aquifer, can be divided into 4 types of aquifer media, namely: sand and gravel (permeability 5–9 x 10^{-2} cm/sec), Sandstone massif (1–4 x 10^{-2}cm/sec), Thin Sandstone, shale (permeability 5–9 x 10^{-3} cm/sec), and Shale massif (permeability 1– 4 x 10^{-3}cm/sec).

The model using modification by Rosen (1994) and Widyastuti (2004), contains massive shale with rating value of 2 (77.78% = 322.68 km^2) and massive sandstone with rating value of 6 (22.22% = 92.19 km^2) as noted in Table4.4. On the other hand, the modification of Piscopo (2001) reveals alluvium 1 with rating of 10 (51.85% = 215.12 km^2) and Alluvium 2 with rating value of 6 (48.15% = 199.76 km^2) as noted in Table 4.5.

Figure 4.5 and Figure 4.6 show the aquifer media map using IDW method (Inverse Distance Weight) in ArcGIS 10.Rosen (1994) and Widyastuti (2004), gave 3 for weight of vulnerability model, instead Piscopo (2001) gave 5 for weight of vulnerability model. That means Piscopo focuses on aquifer because aquifer medium also influences the amount of effective surface area of materials with which the contaminant may come in contact within the aquifer. The route which a contaminant flows can be strongly influenced by fracturing, porosity, or by an interconnected series of openings which provide preferential pathways for groundwater flow.

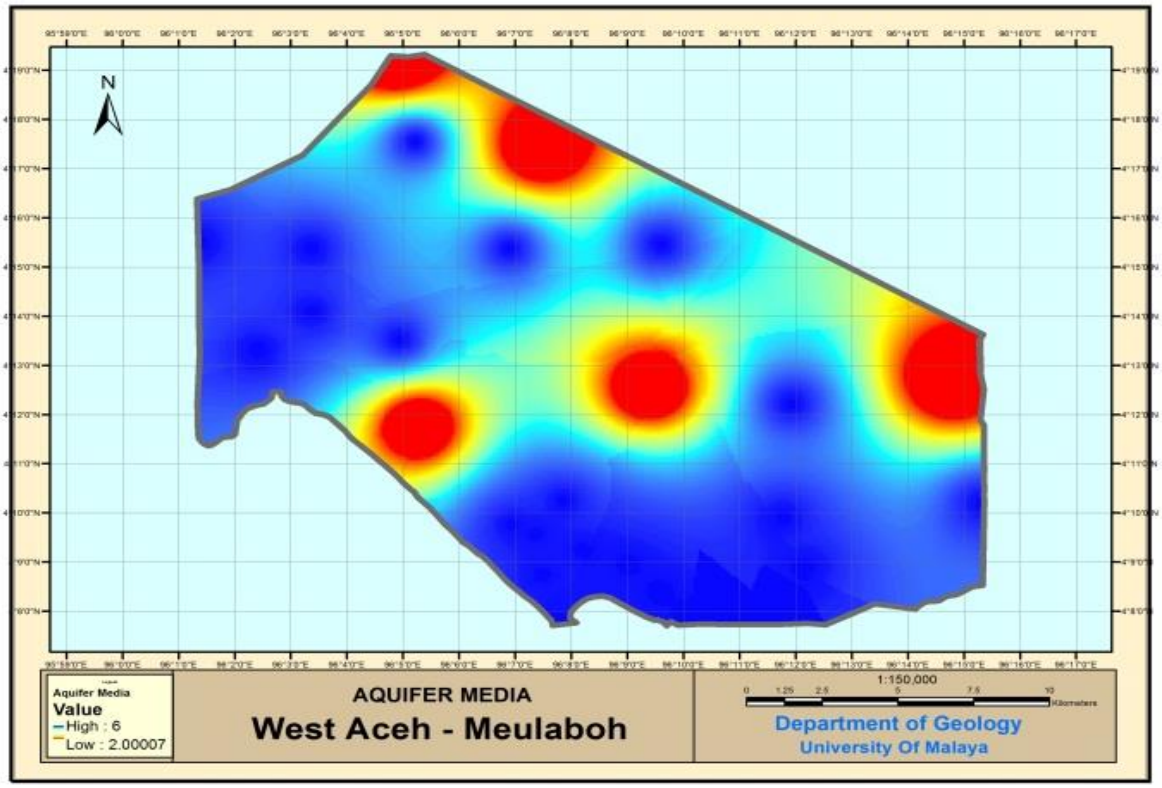


Figure 4.5 Aquifer Media Using Modification Rosen (1994) and Widyastuti (2004)

Table 4.4 Index Aquifer Using Modification Rosen (1994) and Widyastuti (2004)

No	Aquifer	W x R	Percent of Distribution (%)	Area (km^2)
1	Massive Shale	3 x 2	77.78	322.68
2	Massive Sandstone	3 x 6	22.22	92.19

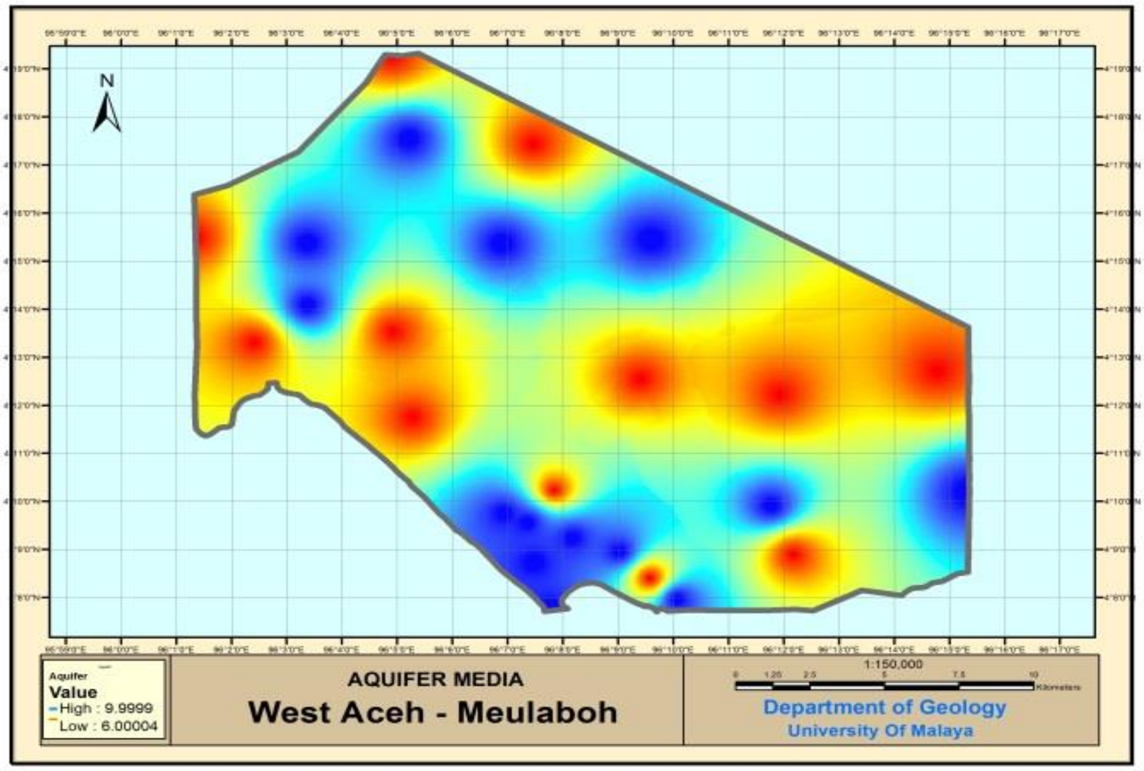


Figure 4.6 Aquifer Using Modification Piscopo (2001)

Table 4.5 Index Aquifer Using Modification Piscopo (2001)

No	Aquifer Media	W x R	Percent of Distribution (%)	Area (km^2)
1	Alluvium 1	5 x 10	51.85	215.12
2	Alluvium 2	5 x 6	48.15	199.76

4.1.4 Soil Media

This parameter represents the textural class of soil, the upper portion of vadose zone, that characterized by significant biological activity, significant impact on recharge, the site of filtration, sorption, and biodegradation. The composition of the soil media directly affected the amount of groundwater recharge and the ability of contaminants to infiltrate into the vadose zone (Prasad, 2010). A soil map that was prepared from the district soil map of National Land Agency Aceh and weightages and ratings were assigned for further research (Table 4.6 and Table 4.7).

In the model with modification by Rosen (1994) and Widyastuti (2004), it contains sandy loam 66.67% (276.58 km^2) and silty loam 33.33% (138.29 km^2).Figure 4.7 shows the map of modification soil media parameter. In model Piscopo (2001), 3 classifications for soil media parameter such as Mod-High 51.85% (215.12 km^2), Moderate 25.93% (107.56 km^2) and Slow 22.22% (92.20 km^2) had been displayed. Figure 4.8 shows the map of modification by Piscopo (2001).

Table 4.6 Index Soil Media Using Modification Rosen (1994) and Widyastuti (2004)

No	Soil Media	W x R	Percent of Distribution (%)	Area (km^2)
1	Sandy Loam	2 x 6	66.67	276.58
2	Silty Loam	2 x 4	33.33	138.29

Table 4.7 Index Soil Media Using Modification Piscopo (2001)

No	Soil Media	W x R	Percent of Distribution (%)	Area (km^2)
1	Mod-High	2 x 8	51.85	215.12
2	Moderate	2 x 6	25.93	107.56
3	Slow	2 x 4	22.22	92.20

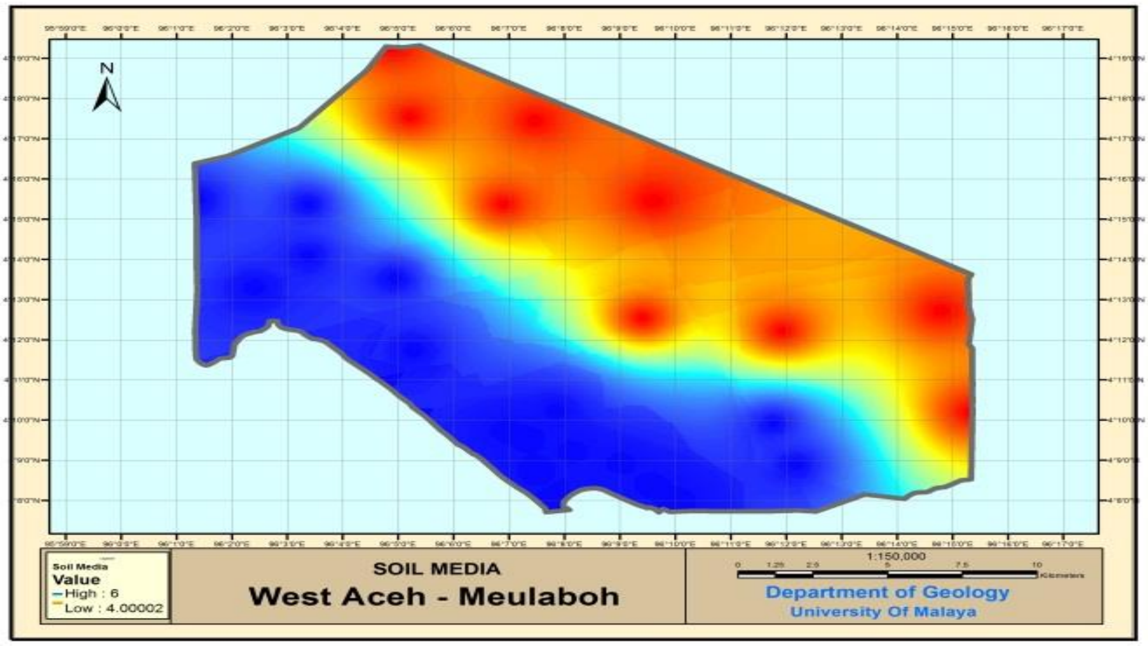


Figure 4.7 Soil Media Using Modification Rosen (1994) and Widyastuti (2004)

4.1.5 Topography

Topography is considered as the slope, and slope variability of the land surface. When the slope is steep, there is a tendency to be more potential for pollutant runoff and therefore little pollutant retention and in turn little infiltration of contaminants. On the other hand, shallow slopes have more potential for pollutant retention and in turn infiltration of contaminants (Freeze and Cherry, 1979). Topography map has been generated from DEM (Digital Elevation Model) which was obtained from National Land Agency Aceh.

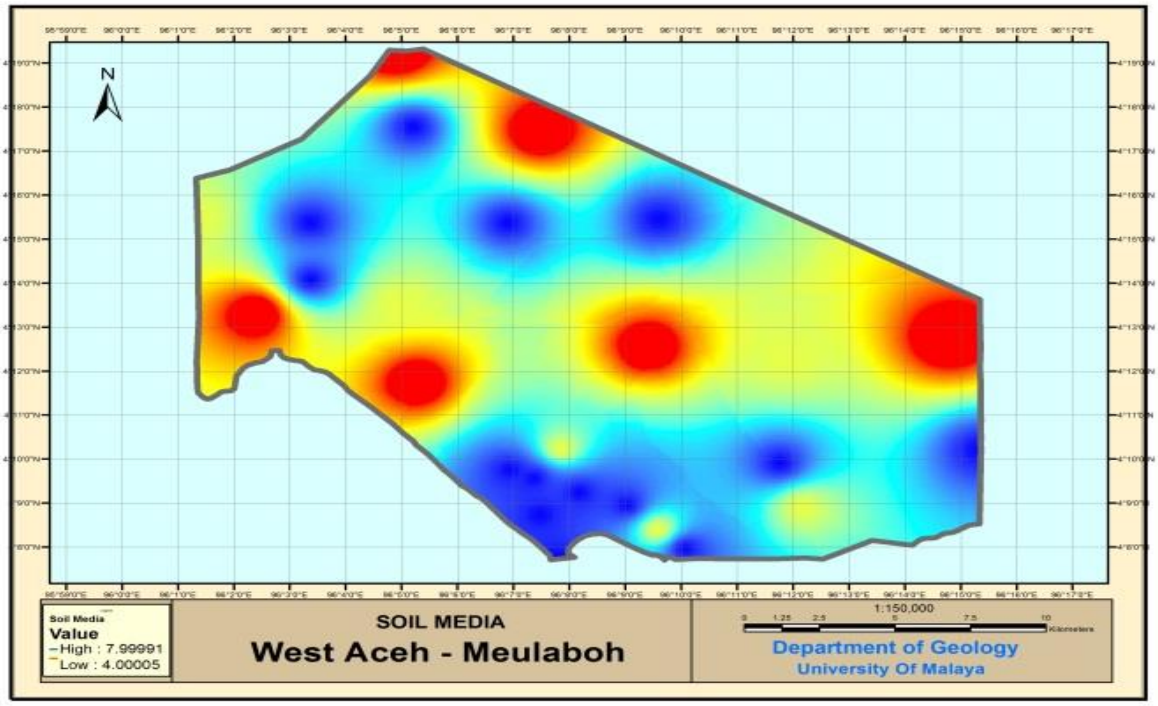


Figure 4.8 shows Soil Media Using Modification Piscopo (2001)

In the model modification by Rosen (1994), Widyastuti (2004) and model Piscopo (2001) show same values for topography parameter with slope between 0 and 2.0 % which are noted in Table 4.8 and Table 4.9. The maps were shown inFigure4.9 and Figure 4.10. Both model modification Rosen (1994) and model Piscopo (2001) applied the same standards for topography parameter.

Table 4.8 Index Topography Using Modification Rosen (1994) and Widyastuti (2004)

No	Slope (%)	W x R	Percent of Distribution (%)	Area (km^2)
1	0 - 2.0	1 x 10	100	414.88

Table 4.9 Index Topography Using Modification Piscopo (2001)

No	Slope (%)	W x R	Percent of Distribution (%)	Area (km^2)
1	0 - 2.0	1 x 10	100	414.88

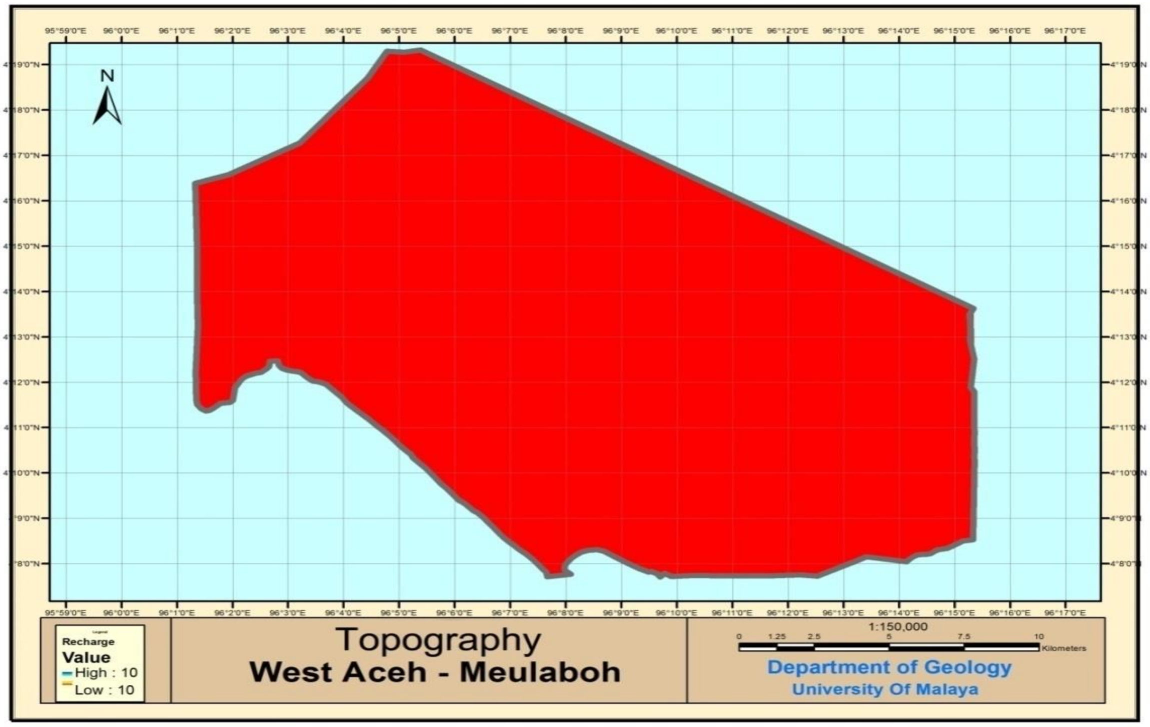


Figure 4.9 Topography Using Modification Rosen (1994) and Widyastuti (2004)

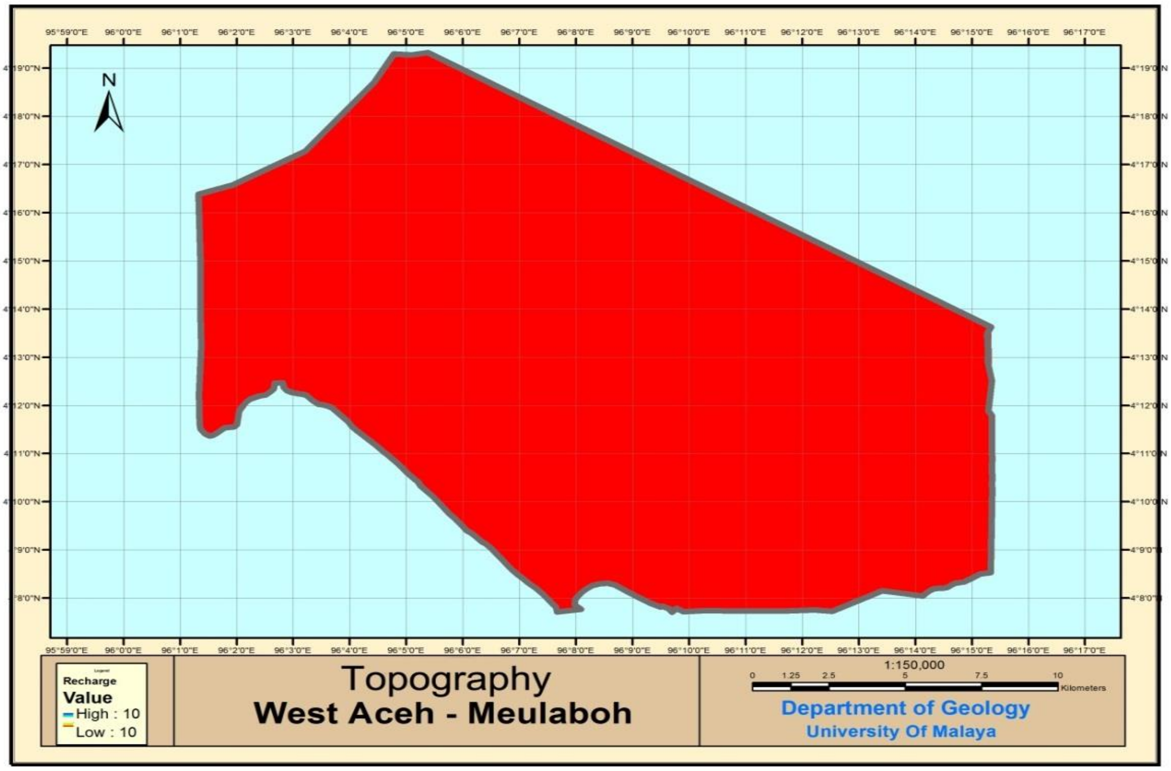


Figure 4.10 Topography Using Modification Piscopo (2001)

4.1.6 Impact of Vadose Zone

The vadose zone is the layer of soils above the water table which is unsaturated or intermittently saturated. The type of material that present in the vadose zone determines the attenuation characteristics, length, path, and time available for attenuation and quantity of material that are able to come in contact with. The impact of vadose zone incorporates two different features; the depth to water table and the soil permeability (Aller*et.al*, 1987).

Impact of vadose zone was prepared from the lithological cross-sections obtained from the geophysical data. The vadose zone has a high impact on water movement when it is composed from a permeable material. The weights and ratings for the vadose zone are shown in Table 4.10 and Table 4.11. Vadose zones have been mapped as shown in Figure 4.11 and Table 4.12. In the model modification by Rosen (1994) and Widyastuti (2004), vadose zone contains Silt/Clay 25.93 % (107.56 km^2), Shale 7.41 %

(30.73 km^2) and Sandstone, Sand and Gravel with Significant Silt and Clay 66.67% (276.58 km^2).

As discussed earlier that this feature attempts to classify zone of soil and regolith (saprolite) found above the water table, known as the vadose zone, with regard to its ability to allow any potential contaminant move to the aquifer. The vadose zone in the purposes of study area vulnerability map incorporates soil permeability and depth to water table. The used equation incorporates the factors that believed to be important to the vadose zone for the study area. This equation provides a vadose zone Value for a particular area which is defined by these factors and relative to another zone within this context of study area. This vadose zone value is then grouped into a range of values, which are given a rating for use in the final DRASTIC calculation. In modification by Piscopo (2001), it contains 8.0 – 10.0 (51.85%) and 6.0 -8.0 (48.15 %).

Table 4.10 Index Vadose Zone Using Modification Rosen (1994) and Widyastuti (2004)

No	Vadose Zone	W x R	Percent of Distribution (%)	Area (km^2)
1	Silt or Clay	5 x 1	25.93	107.56
2	Shale	5 x 3	7.41	30.73
3	Sandstone Sand , Gravel, Silt and Clay	5 x 6	66.67	276.58

Table 4.11 Index Vadose Zone Using Modification Piscopo (2001)

No	Vadose Zone	W x R	Percent of Distribution (%)	Area (km^2)
1	8.0 - 10.0	5 x 10	51.85	215.12
2	6.0 - 8.0	5 x 8	48.15	199.76

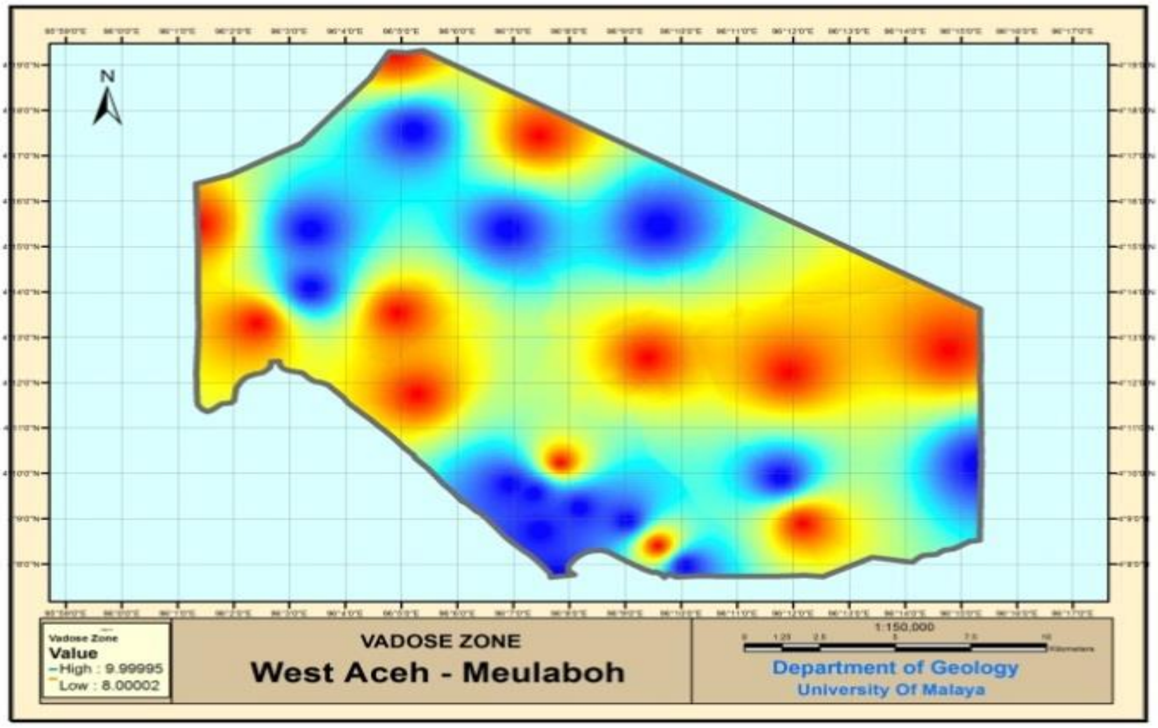


Figure 4.11 Vadose Zone Using Modification Rosen (1994) and Widyastuti (2004)

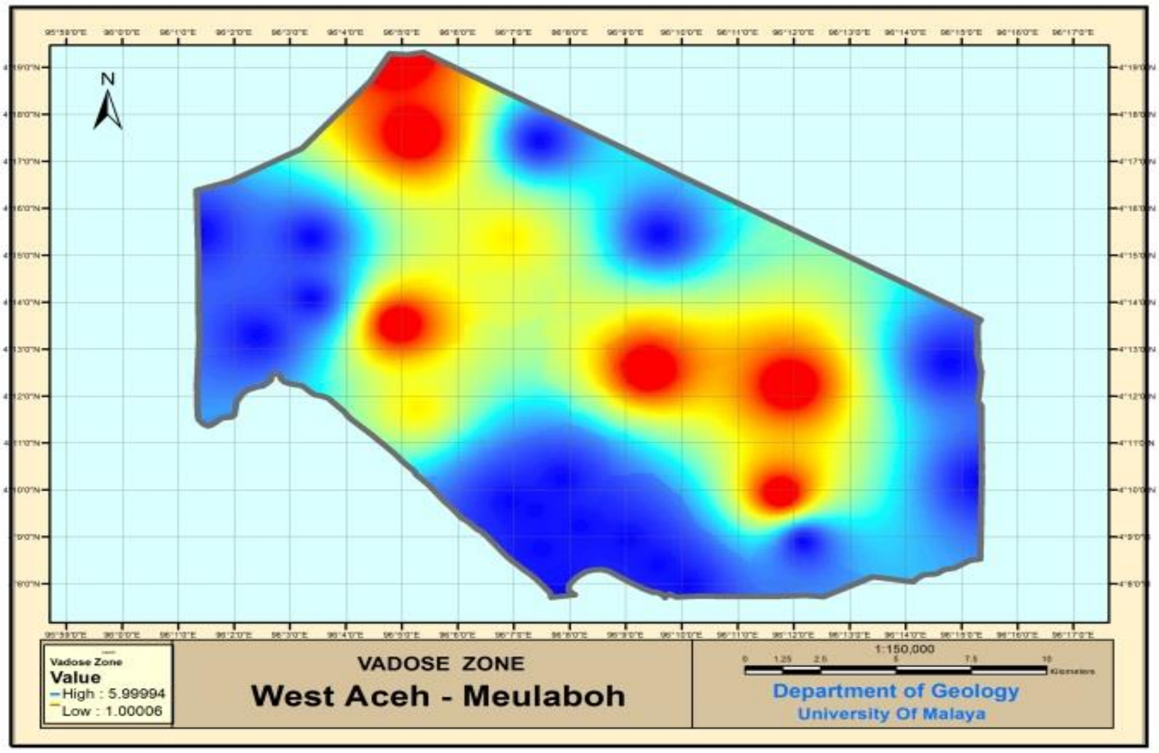


Figure 4.12 Vadose Zone Using Modification Piscopo (2001)

4.1.7 Conductivity

The hydraulic conductivity (C) refers to aquifer ability in transmit water and therefore, it controls the velocity and fate of the contaminants (Al-Zabet, 2002). The value of hydraulic conductivity is controlled by the properties of the aquifer. The groundwater velocity will increase, as to hydraulic conductivity increases, so the pollutants will also move faster, thus increasing vulnerability (Dixon, 2005).

Hydraulic conductivity value is directly proportional to transmissivity (T). Based on the pumping test data, transmissivity value has been calculated through numerical modelling (Singh and Gupta method, 1991). In model modification by Rosen (1994) and Widyastuti (2004), it reveals a range of conductivity value of 0- 0.86 with 18.52% of the total area (76.82 km^2) , 0.86 - 2.59 with 37.04 % of the total area (153.65 km^2) and 2.59 - 6.05 with 7.41% of the total area (30.73 km^2) as noted in Table 4.12.The hydraulic conductivity parameter is distributed using IDW method (Inverse Distance Weight) in ArcGIS 10 (Figure 4.13).

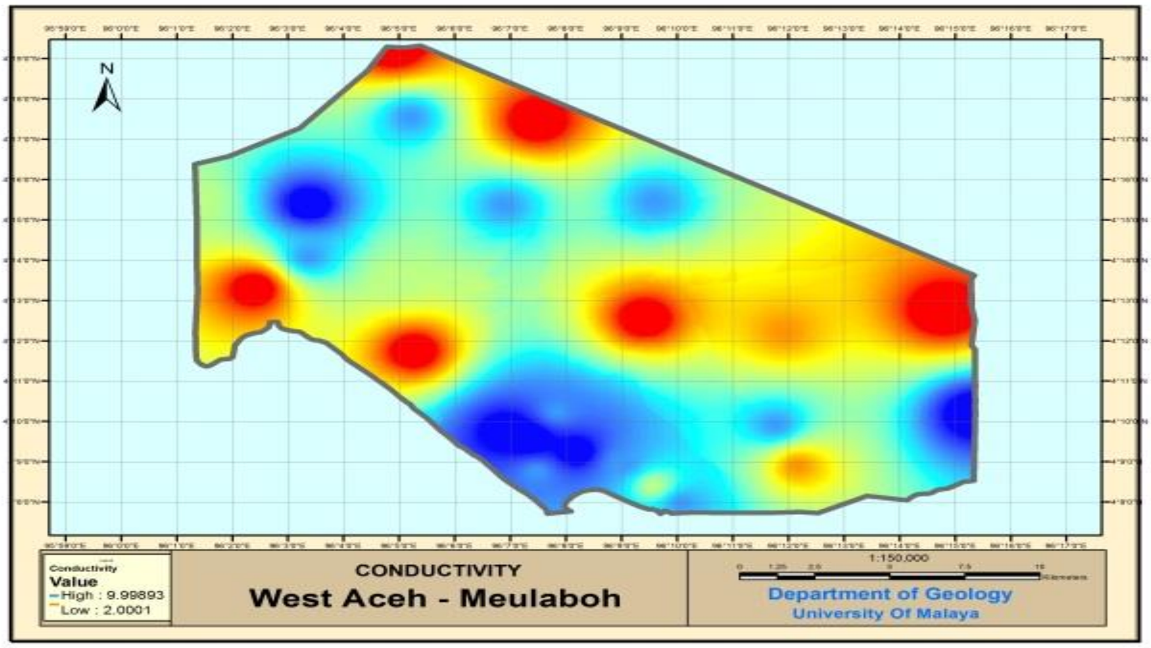


Figure 4.13 Conductivity Using Modification Rosen (1994) and Widyastuti (2004)

Table 4.12 Index Vadose Zone Using Modification Rosen (1994) and Widyastuti (2004)

No	Conductivity	W x R	Percent of Distribution (%)	Area (km^2)
1	0 - 0.86	3 x 1	18.52	76.82
2	0.86 - 2.59	3 x 2	37.04	153.65
3	2.59 - 6.05	3 x 4	7.41	30.73
4	6.05 - 8.64	3 x 6	11.11	46.09
5	8.64 - 17.18	3 x 8	22.22	92.19
6	> 17.18	3 x 10	3.70	15.36

4.1.8 DRASTIC Index

To obtain DRASTIC index value for groundwater vulnerability, application of ArcGIS is used to get more reliable and faster result. It requires three main steps namely: spatial data-base building, spatial data analysis, and data integration. The DRASTIC index is generated by bringing all the reclassified model parameters and assigning appropriate rate and weight into the "*Raster Calculator and Math*" function of Spatial Analysis tool for integration. The final map (Figure4.14 and Table 4.15) has been categorized into three classes using equal interval, low vulnerability zones, moderate vulnerability zones and high vulnerability zones. The result of this study using DRASTIC index by Rosen (1994) and Widyastuti (2004) showed that from the total 414.88 km^2 , about 37.09 km^2 (8.94%) is in the low vulnerability zone, 172.60 km^2 (41.60%) in the moderate vulnerability zone and 205.19 km^2 (49.46%) in the high vulnerability zones as noted in Table 4.13.

In the modification of Piscopo (2001), two classes from moderate to high risk zone from groundwater pollution are in point of view. The result of this study using DRASTIC Index by Piscopo (2001) showed the total of 414.88 km^2 which has high vulnerability and moderately vulnerability. The total of high vulnerability in West Aceh (study area) is 52.09% of total area or 216.11 km^2 and the total of moderately high vulnerability is 47.91 % of total area or 198.77 km^2 (as stated in Table4.14). This means that more than half of the study area is at high risk in terms of pollution potential because it is situated around the coastal area in West Aceh which has alluvial aquifer with topography < 2% and also due to the relatively high recharge potential and shallow water table.

In general, the West Aceh especially in the surrounding coastal area where the physical factors like shallow depth to water table (minimum depth to water table 0.33 meters and maximum 2.56 meters), topography < 2 % , aquifer material contains sandstone and gravel, and high recharge from rainfall from 3500 mm/years to 4000 mm/years has high potential vulnerability.

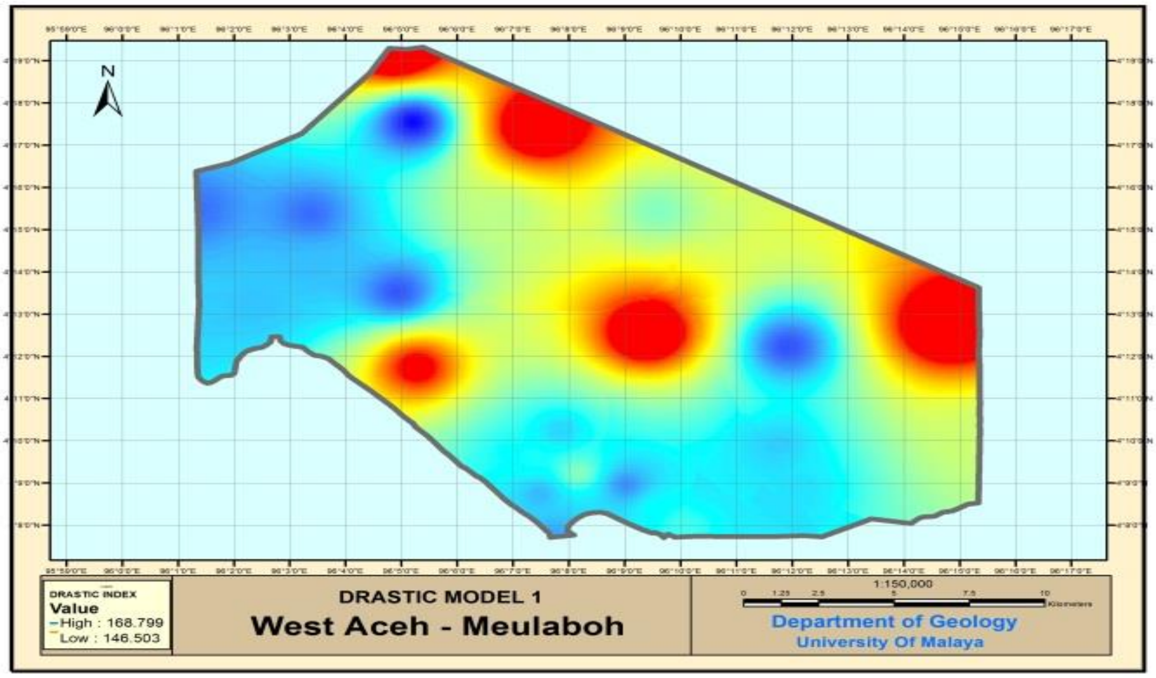


Figure 4.14.Vulnerability Index Using Rosen (1994) and Widyastuti (2004)

Table 4.13 Area under vulnerability to groundwater pollution in West Aceh using modification Rosen (1994) and Widyastuti (2004)

No	DRASTIC Index Value	Vulnerability Zone	Percent of Distribution (%)	Area (km^2)
1	146.50 - 153.93	Low	8.94	37.09
2	153.93 - 161.36	Moderate	41.60	172.60
3	161.36 - 168.79	High	49.46	205.19

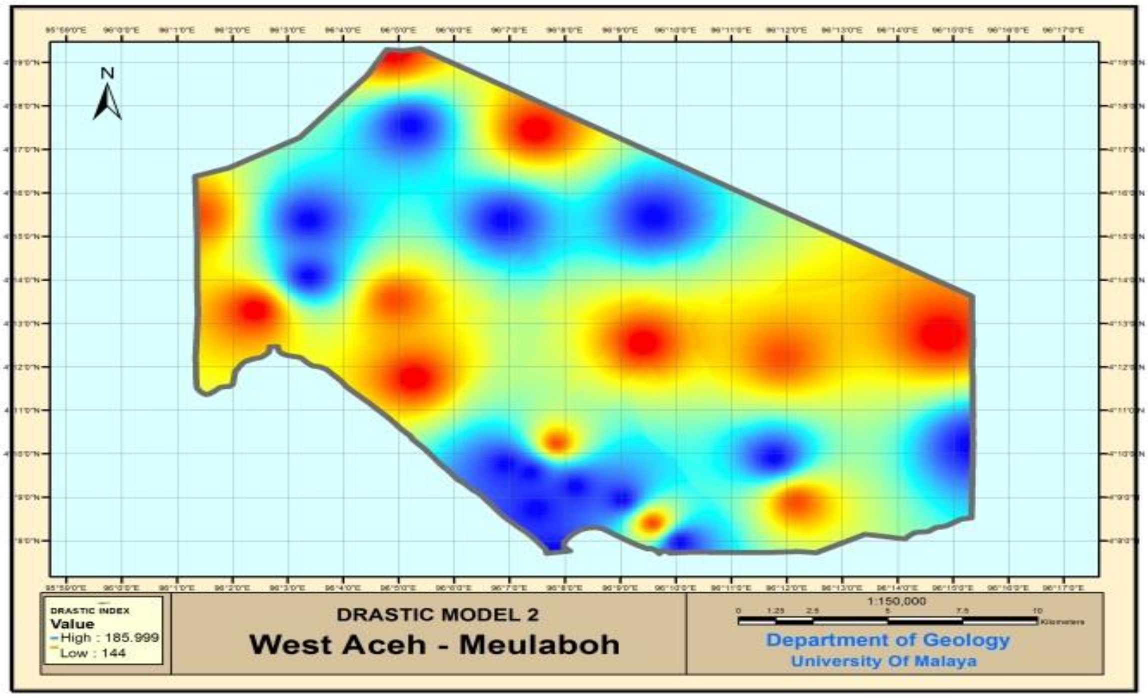


Figure 4.15.Vulnerability Index Using Piscopo (2001)

Table 4.14 Area under vulnerability to groundwater pollution in West Aceh using modification Piscopo (2001)

No	DRASTIC Index Value	Vulnerability Zone	Percent of Distribution (%)	Area (km^2)
1	144.00 - 164.99	Moderately High	47.91	198.77
2	164.99 - 185.99	High	52.09	216.11

4.1.9 Analysis Statistic

In order to examine correlation between seven parameters of the DRASTIC model for modification by Rosen (1994) and Widyastuti (2004) and Piscopo (2001), Pearson correlation coefficient and determination coefficients were used to derive the results. For the Pearson correlation coefficient and determination coefficients test in modification by Rosen (1994) and Widyastuti (2004), 7 tests were conducted such as in test aquifer versus conductivity, test soil media versus depth to water table, test soil media versus vadose zone and test vadose zone versus depth to water table as noted in

Table 4.15.Since these correlations were not found significant or less than 40% of confidence, this means that parameters are less related to each other.

According to modification by Piscopo (2001), correlations of four parameters are found to be significant at or more than 90% level of confidence even though these correlations may result due to chance. It means that parameters are largely independent and there is very little risk of maladjustment in the final index (Table 4.16).

Table 4.17 and Table 4.18 indicated statistical analysis that was performed by removing one or more data layers. In Table 21, the vulnerability index shown seems to be sensitive to the removal impact of vadose zone, conductivity hydraulic, Soil Media, Aquifer and Depth to Water (for modification by Rosen (1994) and Widyastuti (2004)). Furthermore, Table22 showed the vulnerability index which seems to be sensitive to the removal Impact of Vadose Zone and Soil Media (Piscopo, 2001).

Table 4.15 Summary of rank-order correlation between seven parameters using modification Rosen (1994) and Widyastuti (2004)

Pearson Correlation	Index	Rr1	Ar 1	Sr 1	Tr1	Ir1	Cr1	Dr1
Index	1		0.766	0.481		0.816	0.828	0.299
Rr		1						
Ar	0.766		1	0.378		0.36	0.782	-0.151
Sr	0.481		0.378	1		0.333	0.268	0.4
Tr					1			
Ir	0.816		0.36	0.333		1	0.398	0.447
Cr	0.828		0.782	0.268		0.398	1	0.024
Dr	0.299		-0.151	0.4		0.447	0.024	1

Table 4.16 Summary of rank-order correlation between six parameters using modification Piscopo (2001)

Pearson Correlation	Index	Dr2	Rr2	Ar2	Sr2	Tr2	Ir2
Index	1		0.998	0.998	0.931		0.998
Dr		1					
Rr	0.998		1	1	0.904		1
Ar	0.998		1	1	0.904		1
Sr	0.931		0.904	0.904	1		0.904
Tr						1	
Ir	0.998		1	1	0.904		1

Table 4.17 Statistic of map removal sensitivity analysis for Modification Rosen (1994) and Widyastuti (2004)

Test	Variables Remove	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	Ir	.918	.843	.814	9.491
2	Cr	.968	.938	.927	5.964
3	Sr	.998	.995	.994	1.642
4	Ar	.993	.986	.983	2.875
5	Dr	.999	.998	.998	1.043

Table 4.18 Statistic of map removal sensitivity analysis for Modification Piscopo (2001)

Test	Variables Remove	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	Sr	.998	.995	.995	1.438
2	Ir	.931	.867	.862	7.558

4.2 Graphical User Interface AHP-DRASTIC

The Methodology to implement AHP involved intensive computing effort as the number of criteria and sub-criteria increases. In this context, it was decided to develop a Graphical User Interface (GUI) using Delphi 7.0 for implementing the AHP methodology. The GUI facilities consist of 5 group box (DRASTIC Model, Process, Graphic, Analysis Statistic ad AHP). The GUI gave the output of ratings and weights in the form of a Notepad (text file). The calculation performed with regard to determination of rating and weights that are produced as a document file. The number of iteration used, threshold value, the final eigenvector regarding rating and weight, Consistency Index (CI) and Consistency Ratio are all shown in this document file (Figure 4.16).

The opening menu of the GUI, which lets the user create a new file or open an existing file, can be seen in Figure 27. While creating a new file, the user is prompted to enter the number of criteria and sub-criteria and their names are shown in Figure26. A screen resolution of 800 x 1024 is adopted while developing the GUI in order to create a maximum of 7 criteria or sub-criteria in a single GUI form (Figure 4.17).

The size of the PCM (Pair-Wise Comparison Matrix) for each criteria and sub-criteria is decided based on the number of element and PCM element windows are displayed for the user to decide the relative importance. The satay scale of relative importance is displayed as a combo box by having numbers from 1 to 9 along with their intended meaning. While entering the values in the PCM matrix, the user has to input an element of PCM and this element is provided with satay scale value which was filled up automatically as the PCM is reciprocal in nature. The same procedure is repeated for all the upper diagonal elements and the lower diagonal elements which are also automatically filled up as the PCM and found to be reciprocal in nature. The detail regarding input of PCM elements shown as below (Figure 4.18 - Figure 4.20).

The results were obtained by using the “calculate” button, which also guides the user to another display window, where the result of criteria and sub-criteria are displayed in text form (notepad). The eigenvalue are obtained by iteration, till the consistency ratio became less than 10%. The value of ratings for one of the sub-criteria (example: range of depth to water table) along with CI and CR, and the same for weight of criteria (all model parameters). The “Reset” button prompts the user to clear all calculations and start for a new calculation again. The “Record” button prompts the user to save the result as a text file, and also allows the user to save the details of all calculations including the numbers of iterations, CI and CR values.

In this software, it has "Analysis Statistic" for calculation determination, correlations and standard of error to estimate. On the other hand, this programme reveals information about all DRASTIC models, both modified by Rosen (1994) and Widyastuti (2004) and modified by Piscopo (2001).Figure 4.21 has given the information about DRASTIC-AHP programme.

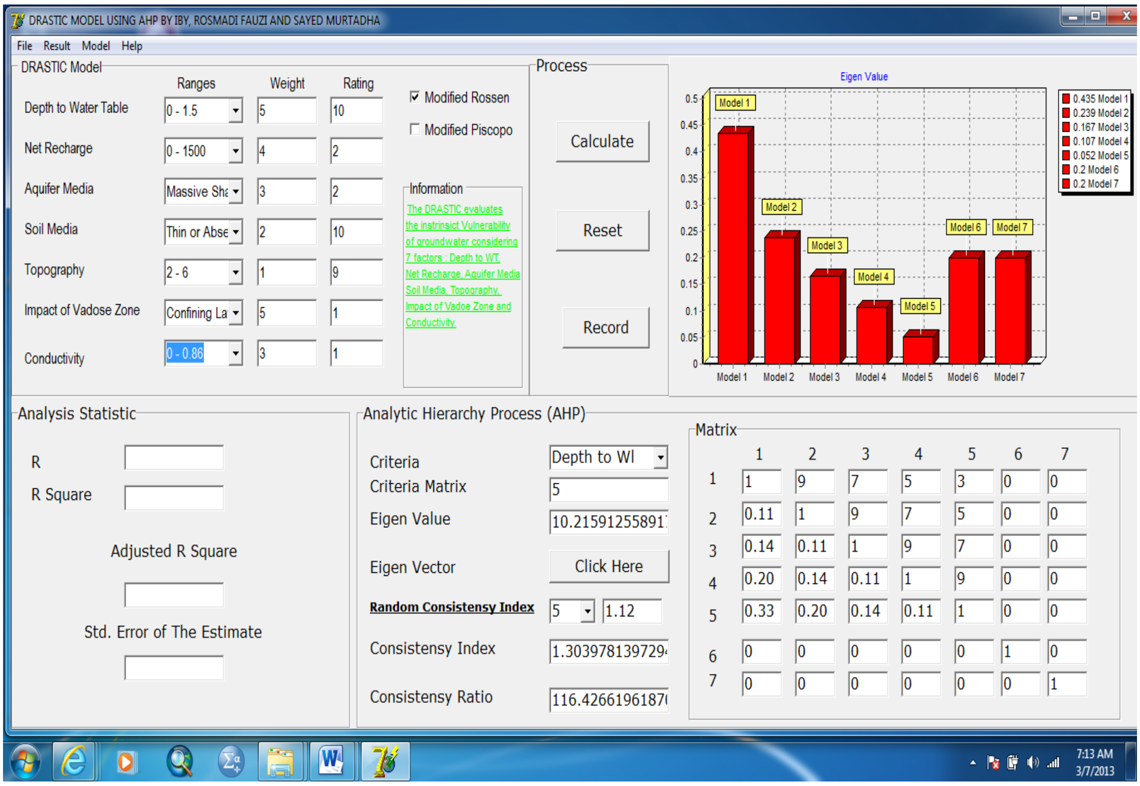


Figure 4.16 GUI DRASTIC-AHP

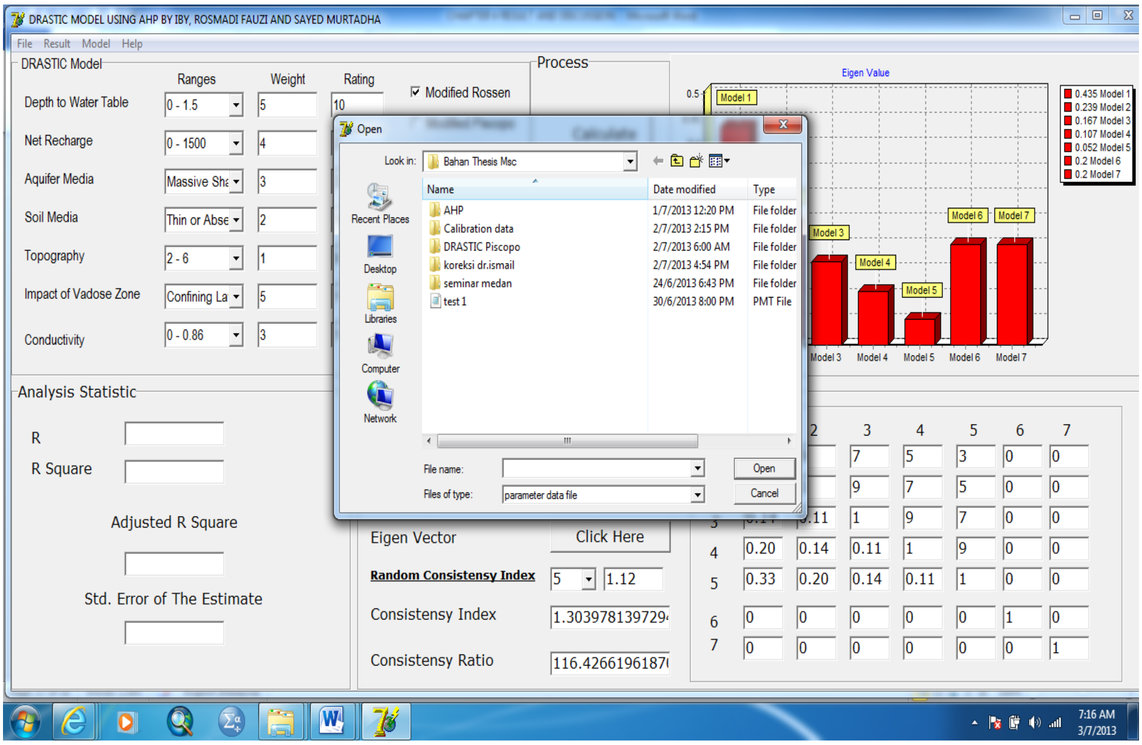


Figure 4.17 Input Data Using File Open

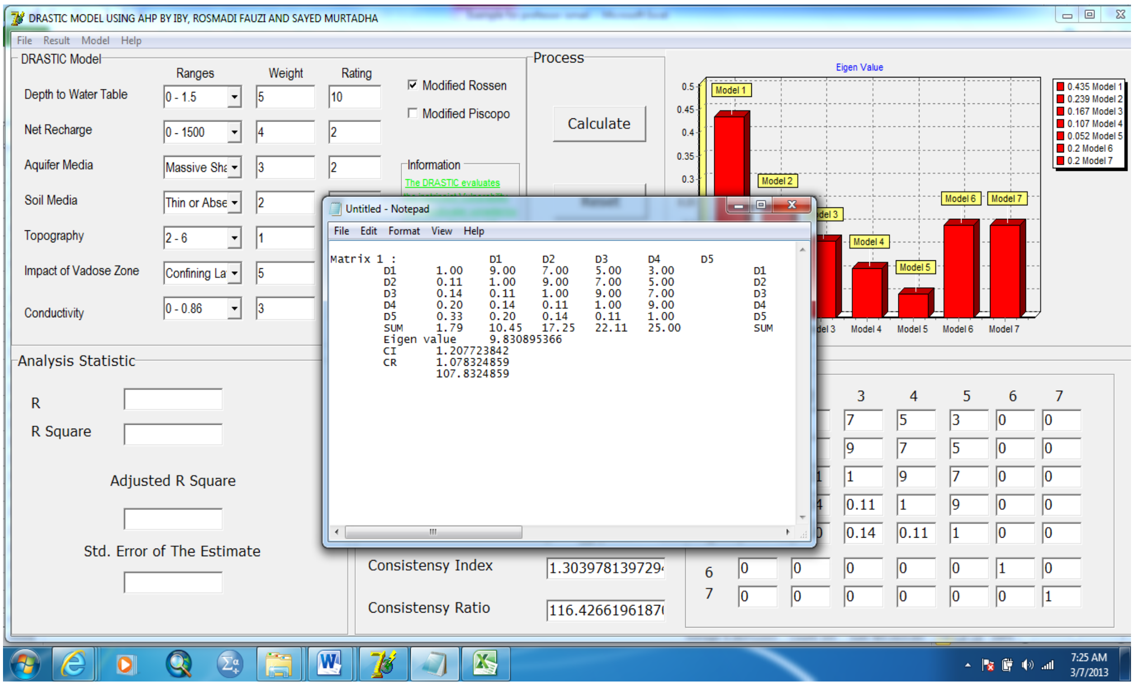


Figure 4.18 Output Data Using Text File (Notepad)

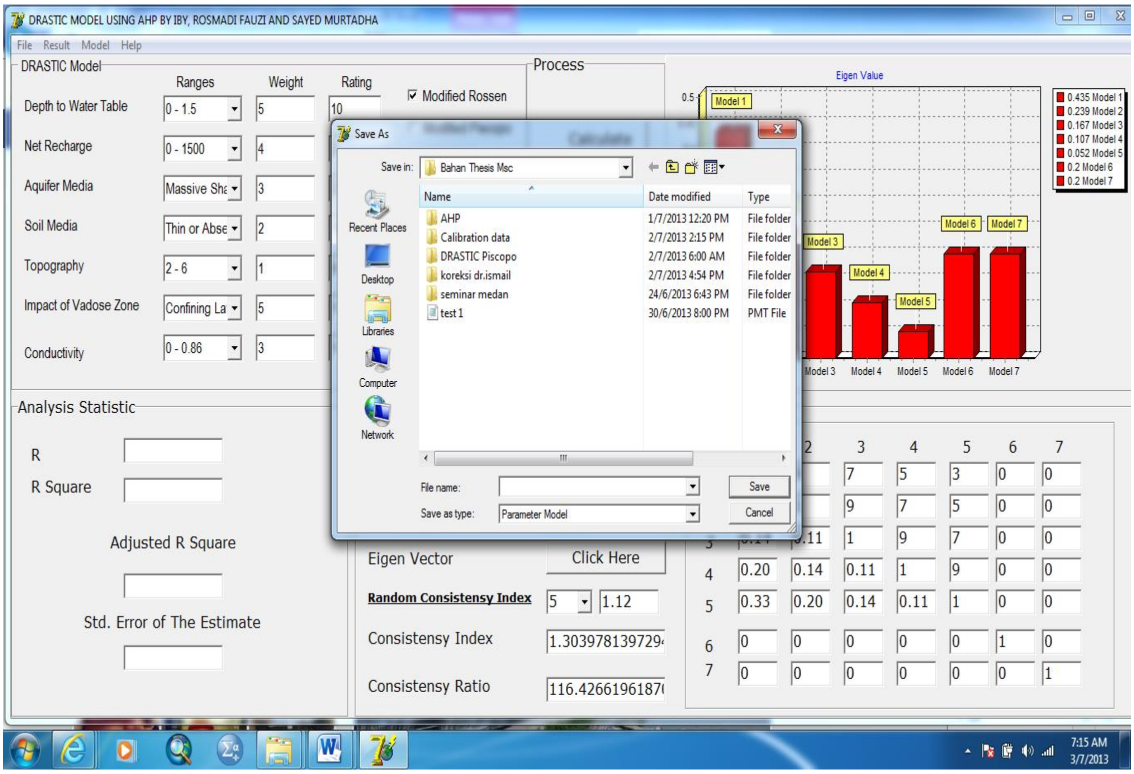


Figure 4.19 Save As Data In GUI

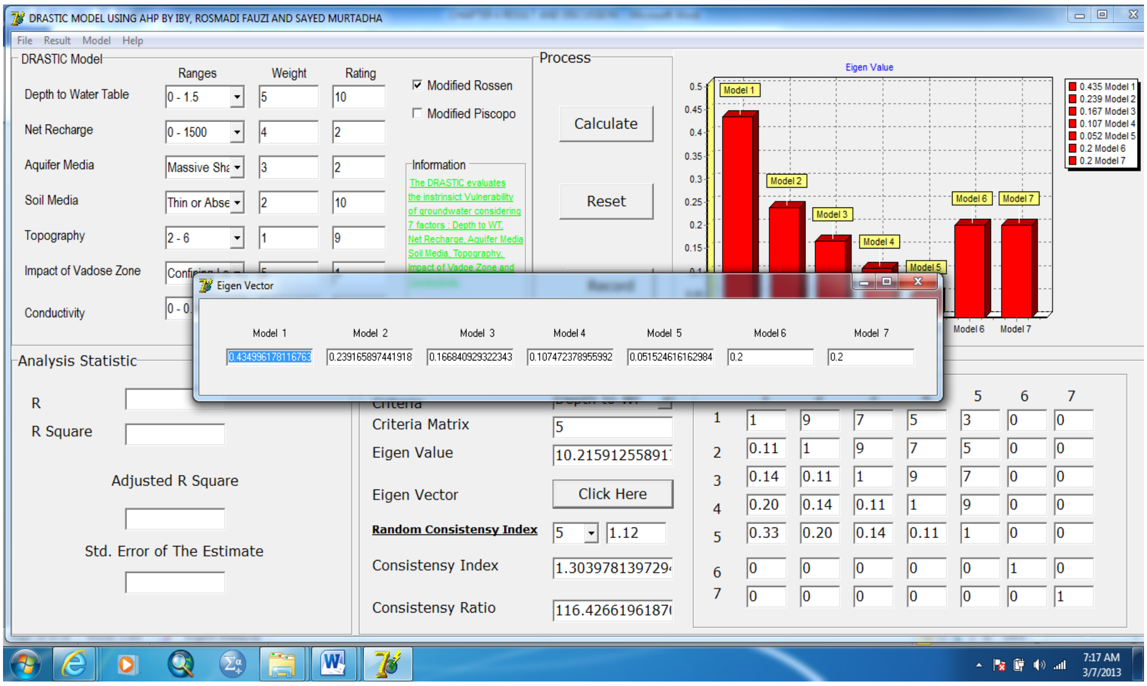


Figure 4.20 Components AHP in GUI

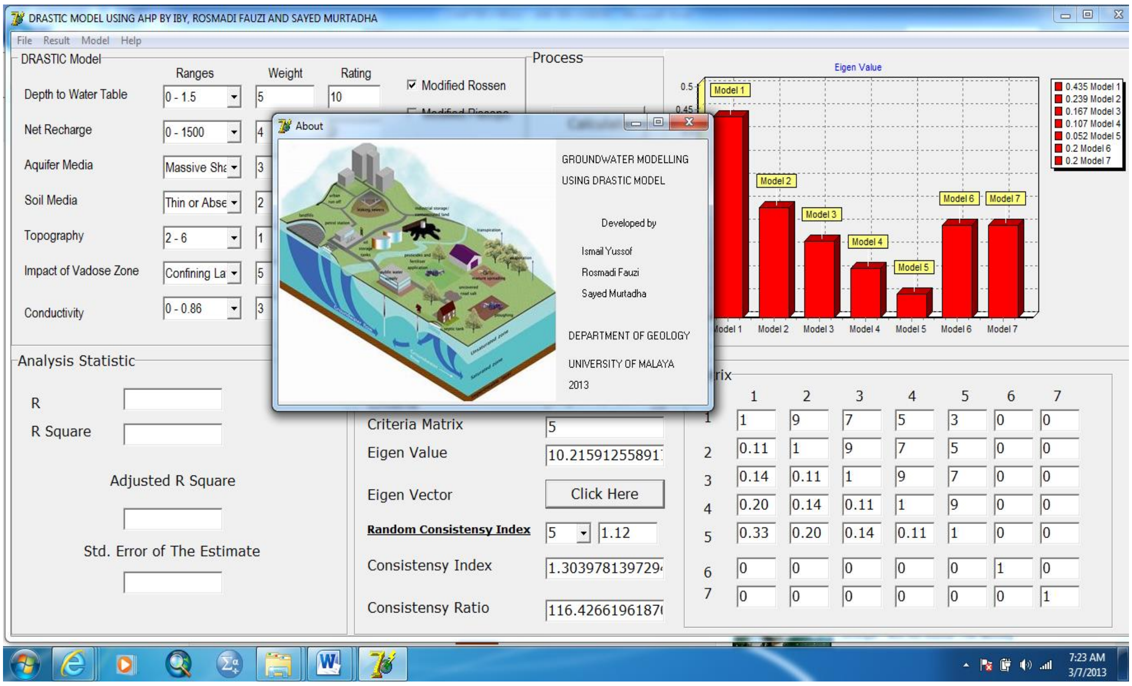


Figure 4.21. Copy Right in GUI

4.3 DRASTIC Index Modified by DRASTIC-AHP

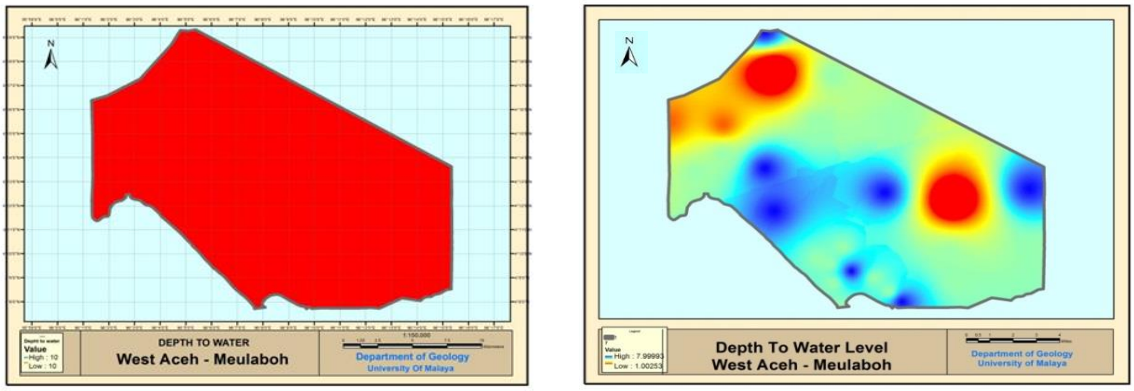
According to results obtained from DRASTIC index for modification by Rosen (1994) and Piscopo (2001), it is found that the correlation parameters are not significant or less than 40% of confidence level for modification Rosen (1994) and Widyastuti (2004) but as for modification by Piscopo (2001), the correlations between four parameters are significant at or more than 90% level of confidence. This means modification by Piscopo (2001) is found better than modification by Rosen (1994) and Widyastuti (2004).

Therefore, the modification by Piscopo cannot provide a detailed description for parameter depth to water table and topography although both parameters are found to be important indicators for the quality status of groundwater. Depth to water table is an important feature as it determines the depth of material through which a contaminant must travel before reaching the water table (Piscopo, 2001). Furthermore, topography is also an important parameter because topography helps to control pollutant run off or retention on the surface. Slopes that provided a greater opportunity for contaminants to infiltrate will be associated with higher groundwater pollution potential (Freeze and Cherry, 1979).

We need to modify both of them using DRASTIC-AHP software to get a better description result. For modification depth to water table and topography, they were calculated using GUI as explained above. Before modification, depth to water table in this study has weight and rating value as shown in Table 2. The depth to water table parameter is shallow and has a range of 0.33 – 2.56 m. Based on modification by Piscopo (2001), the DRASTIC index fits only in one range with rating of 10 (weight < 5%) as shown in Figure 4.22a.

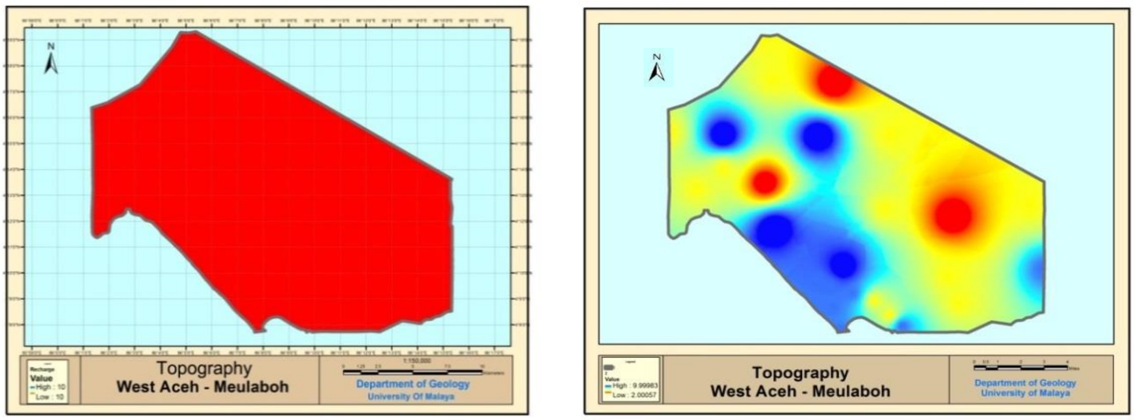
Modifications by DRASTIC-AHP, the ranges of depth to water table parameter were divided into 5 as shown in Table 4.19. After the modification depth to water table parameter using GUI, best result was derived in four (4) of iteration with CR value 0.068 as noted in Table 4.20. The ratings of modification parameter derived as above were transferred to ArcGIS 10 in order to calculate groundwater vulnerability index (Figure 4.22b).

For topography parameter, we found similar problems whereby the topography range is found only in one range with value of 10 (weight < 2%) as shown in Figure 4.23a. After modifying the ranges of topography using DRASTIC-AHP, result was obtained as shown in Figure 4.23b. Sub criteria for model topography and calculation priority vector are noted in Table 4.21and Table 4.22. All in all, the map of groundwater vulnerability index modification reveals different interpretation for groundwater vulnerability in West Aceh as shown in Figure 4.24a (before) and Figure 4.24b (after).



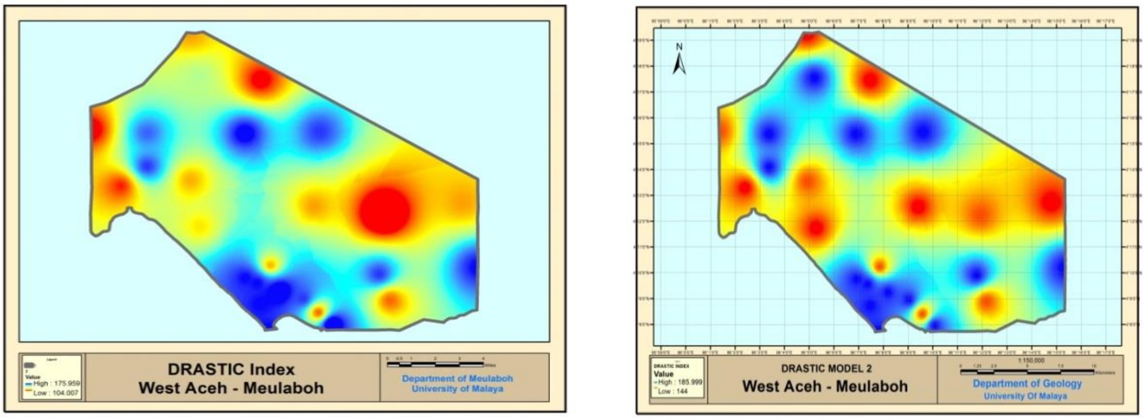
(a) (b)

Figure 4.22 Before and After Modified Parameter Depth to Water table



(a) (b)

Figure 4.23 Before and After Modified Parameter Topography



(a) (b)

Figure 4.24 Before and After Modified DRASTIC Index

Table 4.19 Sub Criteria for Model Depth to Water Table

Depth 1	Depth 2	Depth 3	Depth 4	Depth 5
0 - 0.3	0 - 0.6	0 - 0.9	0 - 1.2	0 - 1.5
0.3 - 0.6	0.6 - 1.2	0.9 - 1.8	1.2 - 2.4	1.5 - 3.0
0.6 - 1.2	1.2 - 2.4	1.8 - 3.6	2.4 - 4.8	3.0 - 6.0
1.2 - 2.4	2.4 - 4.8	3.6 - 7.2	4.8 - 9.6	6.0 - 12.0
> 2.4	> 4.8	> 7.2	> 9.6	> 12

Table 4.20 Priority Vector and CR Value for Depth to Water Table

	Depth 1	Depth 2	Depth3	Depth 4	Depth 5	SUM	Percent
Depth 1	0.45045	0.606061	0.347826	0.355556	0.333333	0.418645	41.86452
Depth 2	0.148649	0.20202	0.347826	0.355556	0.238095	0.258429	25.84291
Depth 3	0.225225	0.10101	0.173913	0.177778	0.190476	0.17368	17.36805
Depth 4	0.112613	0.050505	0.086957	0.088889	0.190476	0.105888	10.58879
Depth 5	0.063063	0.040404	0.043478	0.022222	0.047619	0.043357	4.335733
SUM	1	1	1	1	1	1	100
Eigen value	5.309022						
CI	0.077255						
CR	0.068978						
	6.897802	< 10					

Table 4.21 Sub Criteria for Topography

Topo 1	Topo 2	Topo 3
< 0.5	< 1	< 1.5
0.5 - 0.75	1 - 1.25	1.5 - 1.75
0.75 - 1.5	1.25 - 1.75	1.75 - 2.5
1.5 - 10	1.75 - 20	2.5 - 30
> 10	> 20	> 30

Table 4.22 Priority Vector and CR Value for Topography

	T1	T2	T3	SUM	Percent
T1	0.8	0.823529	0.625	0.74951	74.95098
T2	0.088	0.117647	0.25	0.151882	15.18824
T3	0.112	0.058824	0.125	0.098608	9.860784
SUM	1	1	1	1	100
Eigen value	3.01675				
CI	0.008375				
CR	0.01444				
	1.443966	< 10			

4.4 Comparing between DRASTIC Index and Water Quality Data

4.4.1 DRASTIC Index and Nitrates (NO_3)

To check the reliability of DRASTIC index map in the field condition, groundwater samples have been collected for the analysis of NO3 (Nitrate) which is considered as one of the pollutants. Nitrate (NO3) is a naturally occurring form of nitrogen found in soil and is essential to all life. The formation of nitrates is an integral part of the nitrogen cycle in our environment. In moderate amounts, nitrate is a harmless constituent of food and water but if people or animals consume water that contains high in nitrate, it can cause methemoglobinemia, an illness found especially in infants when the nitrate content exceeded to 10 mg/l of water (Indonesian Drinking Water Standards, 2002).

In this study area, all results of laboratory analysis showed nitrate value less than 10 mg/liter except on sample MBO 21 which was found in District Meurebo where the content of nitrate is at 11.51 mg/l as noted in Table 4.23. People living in this area use wells as source of drinking water whereby initiated the need to monitor level of nitrates in their well water. Drinking water that contains high in nitrates can interrupt the ability of red blood cells to transport oxygen in human body. Infants who consume water high in nitrates have the possibility turn into “bluish” and appear facing difficulty breathing since their bodies receiving insufficient oxygen. Similar to dissolved oxygen, temperature, and pH, the amount of nitrates in water is determined by both natural processes and human intervention. The body of water may be naturally high in nitrates or contains elevated nitrate levels as a result of carelessness by human activities (Young, 2005).

Comparison between DRASTIC Index mapping and nitrate concentration in this area is shown in Figure 4.25. The result showed that some areas contain high vulnerability with low nitrate concentration and otherwise some areas have moderate vulnerability with high nitrate concentration. Some presentations of results occurred as stated by Anthony J. Tesoriero, Emily L. Inkpen and Frank D. Voss (1998), that both urban and agricultural sources of nitrate were suggested by the positive and significant relations between elevated nitrate concentrations and percent of urban and agricultural land surrounding a well. So, this means that nitrate concentration is not only influenced by DRASTIC parameters but also from the after effect by human activity, land uses and animal or plant activity.

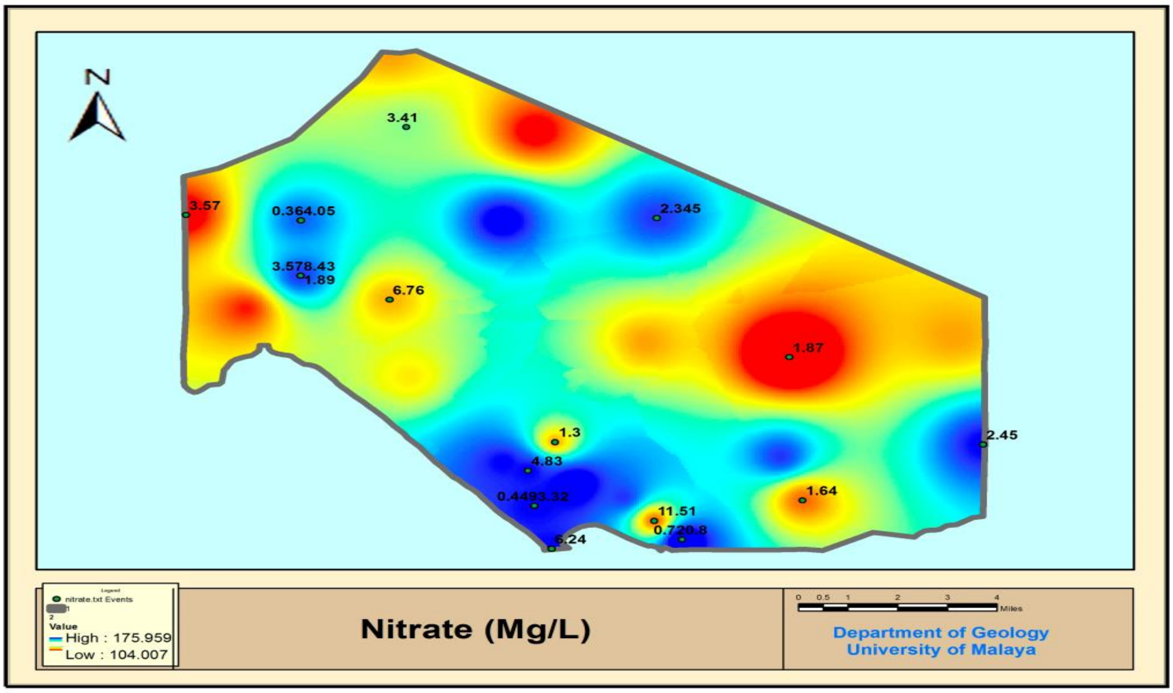


Figure 4.25 DRASTIC-AHP Specific Vulnerability Index Map for Nitrate.

Table 4.23 Water Quality Test in Study Area

Well	Coordinate X	Coordinate Y	Nitrate (mg/L)	Phosphate (mg/L)	Magnesium (mg/L)	Sulphate (mg/L)
MBO 1	173187.00	471075.00	0.36	**0.048**	72.38	5.48
MBO 2	189639.00	475816.40	0.449	0.012	57.3	5.23
MBO 3	185540.20	457379.20	0.72	0.014	116.5	10.76
MBO 4	185540.00	457379.00	0.8	0.021	129.37	2.9
MBO 5	176607.00	475076.00	1	0.005	68.41	7.19
MBO 6	181430.40	461564.20	1.3	0.015	**146.4**	2.9
MBO 7	189441.00	459061.90	1.64	0.024	63.82	4.49
MBO 8	189006.20	465206.70	1.87	0.025	75.22	61.55
MBO 9	194201.66	465586.76	1.89	0.024	76.53	2.9
MBO 10	184717.90	471176.50	2.345	0.021	34.65	24.13
MBO 11	195285.10	461459.60	2.45	0.011	64.32	12.47
MBO 12	180757.00	458818.50	3.32	0.011	98.04	**123.6**
MBO 13	176607.20	475076.00	3.4	0.01	73.9	5.97
MBO 14	173178.00	468696.00	3.57	0.011	37.71	6.7
MBO 15	169470.00	471304.00	3.57	0.017	27.21	17.38
MBO 16	173187.40	471074.60	4.05	0.031	22.34	11.74
MBO 17	180547.00	460334.00	4.83	0.045	47.79	5.48
MBO 18	181307.10	456983.70	6.24	0.023	35.37	24.38
MBO 19	176063.00	467666.00	6.76	0.01	63.22	2.9
MBO 20	173178.30	468696.00	8.43	0.013	57.01	4.99
MBO 21	184637.40	458184.80	**11.51**	0.019	47.2	6.95
MBO 22	180573.00	464040.95	0.98	0.025	39.79	11.35
MBO 23	181283.62	464504.28	1.14	0.029	31.78	34.65
MBO 24	181994.24	464967.61	4.05	0.006	23.77	3.60
MBO 25	171954.53	472736.80	4.39	0.012	91.94	8.78
MBO 26	191716.60	450531.10	7.23	0.003	83.93	4.91
MBO 27	195012.62	444578.58	8.33	0.041	98.77	16.80

Source: Data from analysis water quality in study area

4.4.2 DRASTIC Index and Phosphate

A phosphate is an inorganic chemical, a kind of salt of phosphoric acid. In organic chemistry, a phosphate, or organophosphate, is an ester of phosphoric acid. Organic phosphates are important in biochemistry and biogeochemistry or ecology. Inorganic phosphates are mined to obtain phosphorus for the major use in agriculture and industry (Doerfliger, 1999). In this study, the maximum value for phosphate concentration is 0.048 mg/liter and the minimum is 0.003 mg/liter. Both of them are below public health standards for safe drinking water required and that means maximum contaminant level should not exceed the concentrations of phosphate at 2 ppm.

Comparisons between DRASTIC Index mapping and phosphate concentration in this area are shown in Figure 4.26. All areas are at similar interpretation, but in some parts, it reveals high concentration of phosphate and moderate vulnerability because such areas are under agricultural activity, farming and so on. This condition is relevant as stated by Sansfica Young (2005) that the results clearly showed the influence of fertilization which had affected the nitrate and phosphate concentrations in water. Wells situated within the paddy fields clearly showed an increase in nitrate, which can be directly related to excess fertilizer application. However, wells that are not exposed to cultivation confer a very low amount of nutrients.

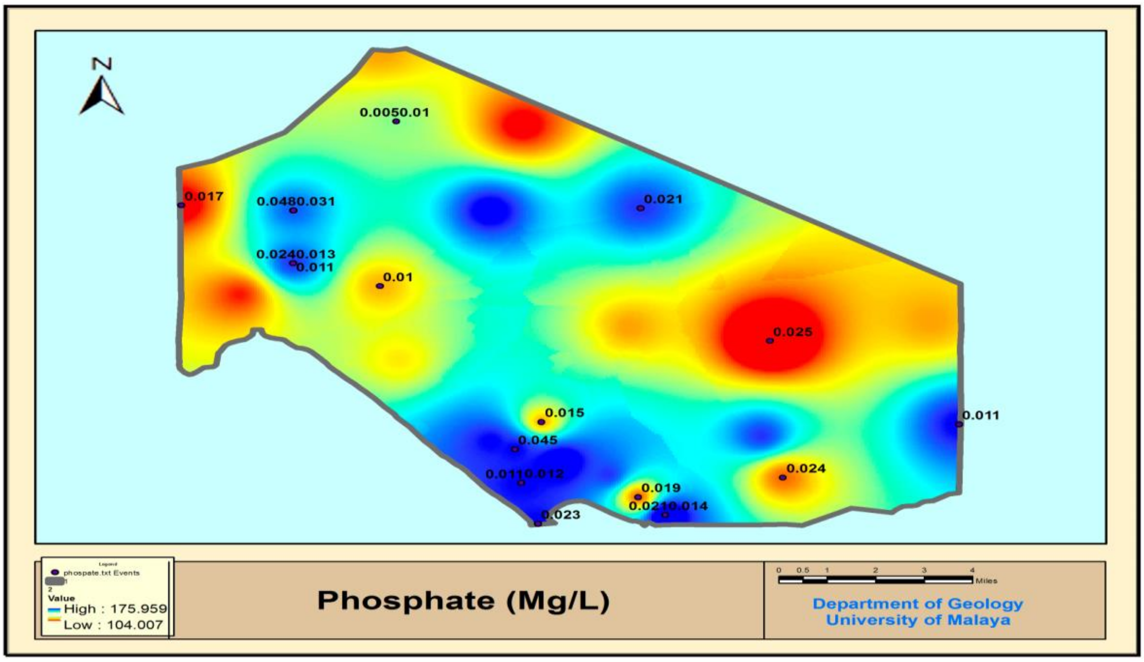


Figure 4.26 DRASTIC-AHP Specific Vulnerability Index Map for Phosphate

4.4.3 DRASTIC Index and Magnesium (Mg)

Magnesium is the eighth most abundant natural element which made up to 2.5 percent of the Earth's crust and is commonly found in minerals such as magnesite, dolomite, olivine, serpentine, talc, and asbestos. It is present in all natural waters and is a major contributor to water hardness. Ferromagnesian mineral igneous rocks and magnesium carbonates in sedimentary rocks are generally considered to be the principal sources of magnesium in natural waters (XinXin, 2011).

In this study area, relatively high content of magnesium is found in AlueKumunengat146.40 mg/liter and 129.37 mg/liter. Other dug wells have the contents of magnesium in a range of 20 – 100 mg/liter. Comparison between magnesium and DRASTIC index indicated that they are positively correlated. Figure 4.27 showed map of comparison between magnesium and DRASTIC Index.

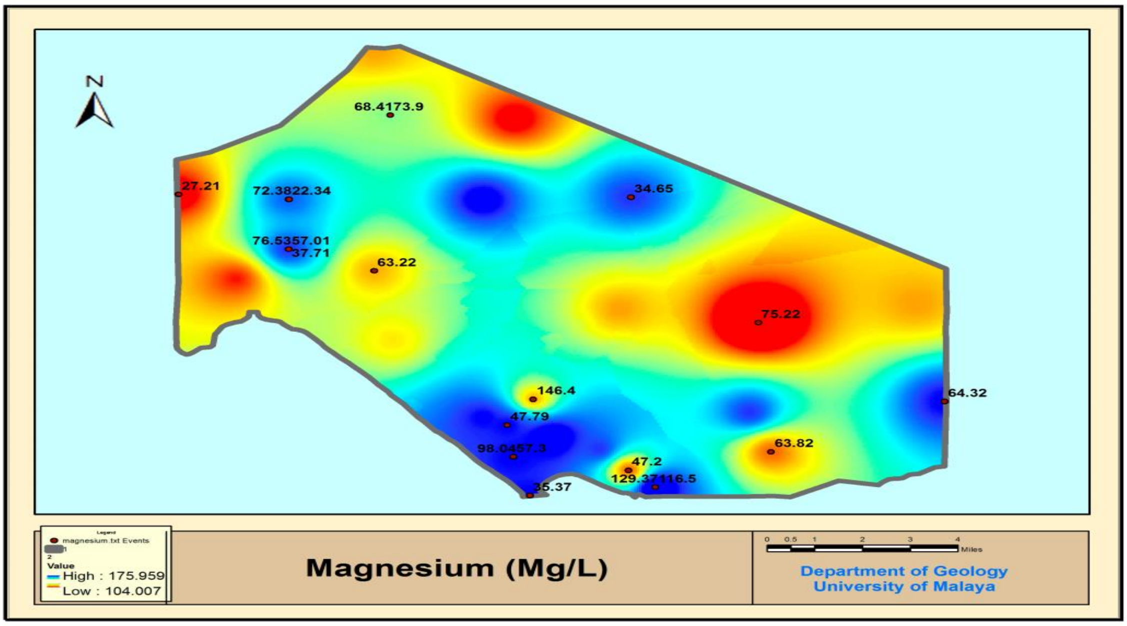


Figure 4.27 DRASTIC-AHP Specific Vulnerability Index Map for Magnesium

4.4.4 DRASTIC Index and Sulfate (SO4)

Sulfate is a substance that occurs naturally in drinking water. Health concerns regarding sulfate in drinking water had risen because of reports concerning diarrhoea may be associated with the ingestion of water containing high levels of sulfate. Particular concerns are grouped within general population that may be living at greater risk from the laxative effects of sulfate when they experience an abrupt change from drinking water content with low sulphate concentrations to drinking water content with high sulphate concentrations (Widyastuti, 2004).

Sulfate in drinking water currently has a secondary maximum contaminant level (SMCL) of 250 milligrams per liter (mg/l), based on aesthetic effects (i.e., taste and odour). This regulation is not a federally enforceable standard, but is provided as a guideline for States and public water systems. In this study area, the maximum value of sulfate is 123.6 mg/liter and in other dug wells, the contents of sulphate found in a range of 2 – 62 mg/liter. Comparison between sulfate and Index DRASTIC has indicated that they appear to be positively correlated (Figure 4.28).

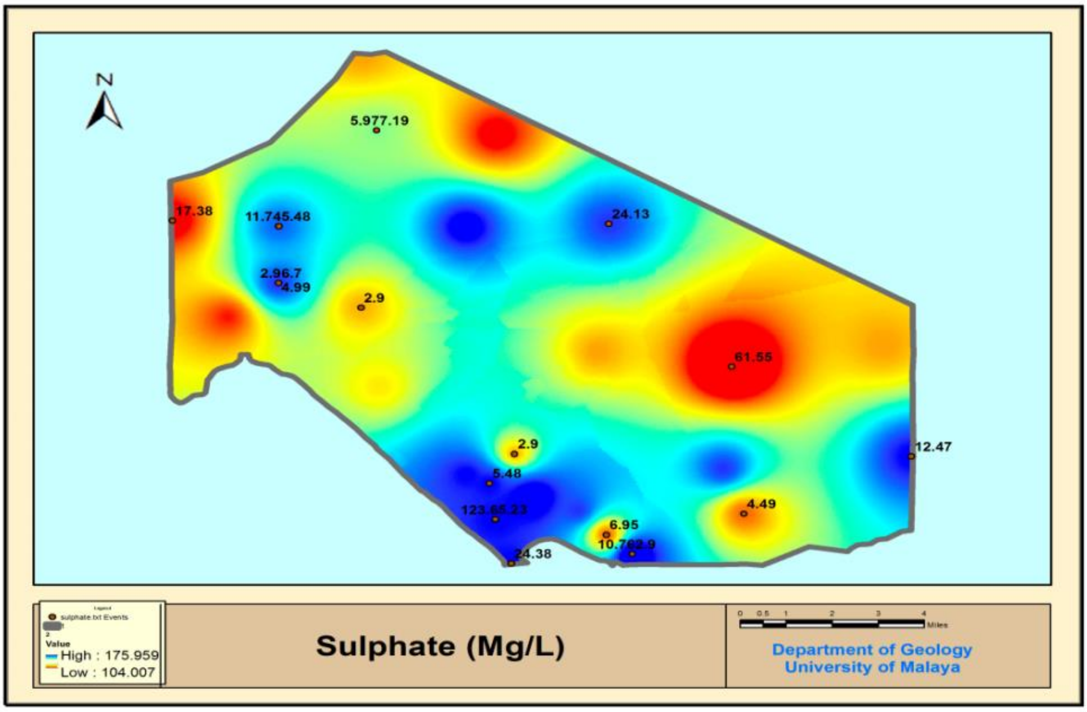


Figure 4.28 DRASTIC-AHP Specific Vulnerability Index Map for Sulfate

5.0 CONCLUSION AND RECOMMENDATION

This chapter deals with the major conclusion drawn from the basis of groundwater vulnerability modelling using DRASTIC method and modification of DRASTIC parameters using AHP in the study area. Recommendation was made based on these findings.

5.1 Conclusion

Based on the result of discussion, researchers can take the conclusion as follows:

1. This study demonstrates that the effectiveness of vulnerability maps can be improved by modification DRASTIC model using numerical method (AHP) Especially for depth to water table parameter and topography parameter. Before modification, depth to water table parameter have 5 classes : 10 (< 5 m), 8 (5 – 10 m), 6 (10 – 15 m), 4 (15-20 m), 1 (> 20 m) and topography also have 5 classes : 10 (< 2 %), 8 (2-10 %), 5 (10-20%), 2 (20-33%), 1 (> 33 %). After Modification, depth to water table parameter displayed rating of 10 (0 – 0.3 m), 8 (0.3– 0.6 m), 6 (0.6-1.2 m), 4 (1.2 – 2.4 m), 1 (> 2.4 m) and topography parameter revealed rating of 10 (< 0.5 %), 8 (0.5-0.75 %), 5 (0.75-1.5%), 2 (1.5-10%), 1 (> 10 %). In this modification, it has same value rating but difference range value.
2. Groundwater vulnerability index modification by Piscopo (2001) is proved to be much better than modification by Rosen (1994) and Widyastuti (2004). As an addition, the modification by Piscopo (2001) has good correlations with more than 90% level of confidence but as for modification by Rosen (1994) and Widyastuti (2004), it significantly indicates less than 40% level of confidence.
3. Groundwater vulnerability index in West Aceh (Meulaboh) have 3 level ranges, 104 – 127.99 (moderate), 127.99 - 151.97 (high moderate) and 151.97 - 175.95

(high) where 22.22% of the study area is moderate, whereas 29.63% is high moderate and 48.15% of the study area is at high vulnerability . Overall, groundwater for this study area has a high vulnerability to contamination.

4. The comparison of groundwater vulnerability index and water quality parameters gives good correlation with concentration of nitrate, magnesium, phosphate, sulphate in groundwater vulnerability. For all water quality parameters, a relevant connection was found with another theory like Anthony J. Tesoriero, Emily L. Inkpen and Frank D. Voss (1998) for nitrate concentration, Sansfica Young (2005) for phosphate concentration , Xin Xin (2011) for Magnesium concentration, and Widyastuti (2004) for sulphate concentrations.
5. This groundwater vulnerability map can be used in the future for groundwater assessment and before any industrial setup in the area mentioned. This map could be very much helpful for keeping groundwater free from pollution. Moreover, groundwater vulnerability map is a support material to make long-term planning for water resource management and also functions as a support tool in overcoming problems of groundwater quality.
6. The combination of DRASTIC by using AHP with Delphi7 meant to be very helpful to facilitate in getting estimation value which is closer to the actual situation in the research area. And programmes developed using Pascal programming language which is mainly based on data contained in the study area.

5.2 Recommendation

The following are recommendations to improve DRASTIC method for estimating groundwater vulnerability:

1. For recharge parameter in modification of Rosen (1994) and Widyastuti (2004), this has been prepared by applying annual rainfall (Table 3.4). Based on the theory, the recharge calculation has been marked with soil moisture technique where the surplus water from the soil zone is calculated using daily rainfall data, evapotranspiration, and soil moisture holding capacity of the soil (Freeze and Cherry, 1979).
2. In the future, the modification of DRASTIC method can be used not only for statistical analysis but also by other models like: ANN (Artificial Neural Network), GA (Genetic Algorithm) and Fuzzy Logic.
3. To solve the problem for groundwater vulnerability at the West Aceh, integrated water resource management (IWRM) can be used to bring groundwater protection within the fold of community growth and land use planning. In this way, groundwater vulnerability assessment could be consulted during official community plan review and other land use planning processes.

REFERENCES

Aller, L., Bennett, T., Lehr, J. H., Petty, R.J., & Hackett G. (1987). DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings. *NWWA/EPA Series*, EPA-600/2-87-035.

Al-Adamat, R.A.N., Foster, I.D.L., & Baban, S.M.J. (2003). Groundwater Vulnerability and Rsik Mapping for the Basaltic Aquifer of Azraq Basin of Jordan Using GIS, Remote Sensing and DRASTIC. *Journal of Applied Geography*, 23, 303-324.

Allied Queensland Coalfields Ltd.(1985). Meulaboh Coal Prospect Aceh, Sumatra-AQC Report No. 64: 23 pp., *prepared by P.A. Rayment*, Brisbane.

Al-Kuisi, M., & Abdel-Fattah, A. (2009). Groundwater Vulnerability to Selenium in Semi-Arid Environments: Amman Zarqa Basin, Jordan. *Journal of Environmental Geochemistry and Health*.

Almasri, M. (2007). Assessment of Intrinsic Vulnerability to Contamination for Gaza Coastal Aquifer, Palestine. *Journal of Environmental Management*, 88,4.

Andreo, B., Ravbar, N. & Vias, J.M. (2009). Source Vulnerability Mapping in Carbonate (Karst) Aquifers by Extension of the COP Method: Application to Pilot Sites. *Hydrogeology Journal*, 17, 1431-2174.

Al-Zabet,T. (2002). Evaluation of Aquifer Vulnerability to Contamination Potential Using the DRASTIC method', *Journal of Environmental Geology*, 43, 203–208.

Anthony, J.T., Inkpen, E.L. & Voss, F.D. (1998). Assessing Groundwater Vulnerability Using Logistic Regression. Proceedings for the Source Water Assessment and Protection 98 Conference Dallas, USA, 157–165.

Al-Kuisi, M., El-Naqa, A., & Hammouri, N. (2006). Vulnerability Mapping of Shallow Groundwater Aquifer Using SINTACS Model in the Jordan Valley Area, Jordan. *Journal of Environmental Geology*, 50, 651-667.

Assaf, H., & Saadeh, M. (2008). Geostatistical Assessment of Groundwater Nitrate Contamination with Reflection on DRASTIC Vulnerability Assessment: the Case of the Upper Litani Basin, Lebanon. *Journal of Water Resources Management*, 23, 775-796.

Aceh Barat, Badan Pusat Statistik Kabupaten.(2011). Kabupaten Aceh Barat Dalam Angka 2009. BPS Aceh Barat, Aceh.

Aceh, Department of Mines and Energy. (2012). Hydrogeological Databook. Provinsi Aceh, Indonesia

Bauman, P. (2006). Progress Report Regarding Groundwater Program in Response to the December 26 Earthquake and Tsunami in Aceh Province, Indonesia.

Bennett, J.D., Bridge, D.McC., Cameron, N.R., Djunuddin, A., Ghazali, S.A., Jeffery, D.H., Keats, W., Rock, N.M.S., Thompson, S.J. & Whandoyo, R. (1981). The Geology of the Calang Quadrangle.- Geological Research and Development Centre, Bandung.

Bukowski, P., Bromek, T. & Augustyniak, I. (2006). Using the DRASTIC System to Assess the Vulnerability of Groundwater to Pollution in Mined Areas of the Upper Silesian Coal Basin. *Journal of Mine Water and the Environment*, 25, 15–22.

Babiker, I.S., Mohamed M.A.A., Hiyama, T., & Kato,K. (2005). A GIS-Based DRASTIC Model for Assessing Aquifer Vulnerability in Kakamigahara Heights, Gifu Prefecture - Central Japan. *Journal of Science of the Total Environment*, 345, 127-140.

Cameron, N.R., Bennett, J.D., Bridge, D. McC., Clarke, M.C.G., Djunuddin, A., Ghazali, S.A., Harashap, H., Jeffery, D.H., Keats, W., Ngabito, H., Rocks, N.M.S. & Thompson, S.J. (1983). The Geology of Takengon Quadrangle, Sumatra. Geological Research and Development Centre, Bandung.

Chitsazm, M., & Akhtari, Y. (2008). A GIS-Based DRASTIC Model for Assessing Aquifer Vulnerability in Kherran Plain, Khuzestan, Iran. *Journal of Water Resources Management*, 10.1007/S11269-008-9319-8.

CGWB, (1998). Detailed Guidelines for Implementing the Ground Water Estimation Methodology 1997. Central Ground Water Board, Ministry of Water Resources, Government of India.

Civita, M.(1994). Le carte Della Vulnerabilita` Degli Acquiferi All'inquinamento, Teoria & Practica (Aquifer vulnerability maps to pollution), Pitarora Ed., Bologna, Italy (in Italian).

Civita, M. and De-Regibus, C. (1995). Sperimentazione di Alcune Metodologie Per la Valutazione Della Vulnerabilita` Degli Aquiferi, Quaderni di Geologia Applicata, Pitagora Ed, Bologna, Italy (in Italian).

Cusimano, G., De-Maio, M., Gatto, L., Hauser, S., & Pisciotta, A. (2004). Application of SINTACS Method to the Aquifers of Piana di Palermo, Sicily, Italy. *Journal of Geofísica Internacional*, 43, 661-670.

Cucchi, F.,Forti, P., & Zini, L., (2004). The Vulnerability of Complex Karst Hydrostructures: Problems and Perspectives. *Journal of Geofisica International*, 43, 533-540.

Corniello, A., Ducci, D., & Monti, G.M. (2004). Aquifer Pollution Vulnerability in the Sorrento Peninsula,Southern Italy, Evaluated by SINTACS Method. *Journal of Geofísica Internacional*, 43, 575-581.

Dixon, B. (2005). Groundwater Vulnerability Mapping: A GIS And Fuzzy Rule Based Integrated Tool. *Journal of Applied Geography*, 25, 237-347.

Doerfliger, N., Jeannin, P.Y & Zwahlen, F. (1999). Water Vulnerability Assessment in Kars environments: A New Method of Defining Protection Areas Using A Multi-attribute Approach and GIS Tools (EPIK method).

Debernardi, L., De-Luca, D.A., & Lasahna, M. (2007). Correlation Between Nitrate Concentration in Groundwater and Parameters Affecting Aquifer Intrinsic Vulnerability. *Journal of Environmental Geology*, 55, 539-558.

Ettazarini, S. (2006). Groundwater Pollution Risk Mapping for the Eocene Aquifer of the Oum-ErRabia Basin, Morocco. *Journal of Environmental Geology*, 51, 341-347.

Foster, S.D.D. (1987). Fundamental Concepts in Aquifer Vulnerability, Pollution Risk and Protection Strategy. TNO Committee on Hydrological Research, Vulnerability of soil and groundwater to pollutants, Proceedings and Information, The Hague, 38, 69–86.

Freeze, R.A & Cherry, J.A. (1979). Groundwater. Prentice-Hall,Inc., Englewood Cliffs, N.J.

Ferreira, J.P.L. & Oliveira, M.M. (2004). Groundwater Vulnerability Assessment in Portugal. *Journal of Geofisica Internacional*, 43, 541-550.

Gogu, R. & Dassargues, A. (2000). Current Trends and Future Challenges in Groundwater Vulnerability Assessment Using Overlay and Index Methods. *Journal of Environmental Geology*, 39, 549-559.

Gogu, R., & Dassargues, A. (2000). Sensitivity Analysis for the EPIK Method of Vulnerability Assessment in a Small Karstic Aquifer, Southern Belgium. *Journal of Hydrogeology*, 8, 337-345.

Gogu, R., Hallet, V. & Dassargues, A. (2003). Comparison of Aquifer Vulnerability Assessment Techniques: Application to the Neblon River Basin (Belgium). *Journal of Environmental Geology*, 44, 881-892.

Gogu., Radu., Constantin., Dassargues., Alain. (2001). Intrinsic Vulnerability Maps of A Karstic Aquifer as Obtained by Five Different Assessment Techniques: comparison and comments. Proceedings of the 7th Conf. on Limestone Hydrology and Fissured Media Sciences et Techniques de l' Environment.

GeoExpert AG & Terratec Geophysical Services. (2005). Geophysical Survey for Ground Water Prospection – Reflection Seismic and Geoelectrical Resistivity Profiling in Meulaboh, Aceh Barat. Funded by CARITAS Switzerland in collaboration with CRS, GeoExpert AG, Schwerzenbach / Switzerland, Terratec, Heitersheim (Germany).

Goldscheider, N., (2005). Karst Groundwater Vulnerability Mapping: Application of a New Method in The Swabian Alb, Germany. *Hydrogeology Journal*, 13, 555-564.

Goldscheider, N., Klute, M., Strum, S., & Hoetzel, H. (2000). The PI Method - A GIS Based Approach to Mapping Groundwater Vulnerability with Special Consideration of Karst Aquifers. *Zeitschrift für Angewandte Geologie*, 46, 157-166.

Hölting, B., Härtle. Th., Hohberger. K. H., Nachtigall,K. H., Villinger. E., Weinzierl. W., & Wrobel, J.-P. (1995). Konzept Zur Ermittlung Der Schutzfunktion Der Grundwasserüberdeckung. Journal of Geologisches Jahrbuch, C63, 5-20.

Hamza, M.H., Added, A., Rodriguez, R., Abdeljaoued, S., & Ben Mammou, A. (2007). A GIS-Based DRASTIC Vulnerability and Net Recharge Re Assessment in an Aquifer of a Semi-Arid Region (Meltine-Ras Jebel-Raf Raf Aquifer, North Tunisia). *Journal of Environmental Managements*, 84, 12-19.

Indonesian Drinking Water Standards. (2002). Ministry of Health, Jakarta.

Ibe, K.M., Nwankwor, G.I., & Onyekura, S.O. (2001). Assessment of Groundwater Vulnerability and Its Application to the Development of Protection Strategy for the Water Supply Aquifer in Owerri, South-eastern Nigeria. *Journal of Environmental Monitoring and Assessment*, 67, 323-360.

IWACO., B.V. (1993). Kabupaten Aceh Barat: Planning for Water Supply Development and Raw Water Sources Allocation.- 105 pp. + app. Ministry of Public Works, Directorate General of Human Settlements, Directorate of Water Supply, Banda Aceh.

Jamrah,A., Al-Futaisi, A., Rajmohan, N. & Al-Yaroubi, S. (2007). Assessment of Groundwater Vulnerability in the Coastal Region of Oman Using DRASTIC Index Method in GIS Environment. *Journal of Environmental Monitor Assessment*, 147, 125–138.

Kistemann, T., Hundhausen, J., Herbst, Susanne., Claben, Thomas., & Farber, H. (2008). Assessment of A Groundwater Contamination with Vinyl Chloride (VC) and Precursor Volatile Organic Compounds (VOC) by Use of a Geographical Information system (GIS). *Int. J. Hyg. Environ.Health*, 211, 308– 317.

Kim, Y., & Hamm, S. (1999). Assessment of the Potential for Groundwater Contamination Using the DRASTIC/EGIS Technique, Cheongju Area, South Korea. *Journal of Hydrogeology*, 7, 227-235.

Kachi, S., Kherici, N., & Kachi, N. (2007). Vulnerability and Pollution Risks in the Alluvial Aquifer of Tebessa-Morsott. *American Journal of Environmental Sciences*. 3, 218-223.

Lee, S. (2003). Evaluation of Waste Disposal Site Using DRASTIC System in Southern Korea. *Journal of Environmental Geology*, 44, 654-664.

Maruo,Y.(2009). Application of Geographic Information System (GIS) for Groundwater Resource Management. Practical Experience From Groundwater Development and Water Supply Training Centre .UNECA.

Margane., A.(1999). Mapping of Groundwater Vulnerability and Hazards to Groundwater in Developing Countries, Hydrogeology and Land Use Management, 29. Congress of IAH, Bratislava, Sep 1999.

Magiera, P. (2000). Methoden zur Abschätzung der Verschmutzungsempfindlichkeit des Grundwassers, Grundwasser . Zeitschrift der Fachsektion Hydrogeologie.

Magiera, P. (2002). GIS-Gestützte Bewertung der Verschmutzungsempfindlichkeit der Grundwassers, Geologischical Annual Report (Arbeitshefte Wasser in German), Sonderhefte, C, SC 3.-165 S. Hannover.

Mahlknecht, J., and Medina-Mejia, M., Garfias-Solis, J., & Cano-Aguilera, I. (2006). Intrinsic Aquifer Vulnerability Assessment: Validation by Environmental Tracers in San Miguel de Allende, Mexico. Journal of Environmental Geology, 51, 477-491.

Mendoza, J. A. & Barmen, G. (2006). Assessment of Groundwater Vulnerability in the Rio Artiguas Basin, Nicaragua. Journal of Environmental Geology, 50, 569-580.

Merkin, B. G. (1979). Group Choice, John Wiley & Sons, NY.

Nas, B., & Berktay, A. (2006). Groundwater Contamination by Nitrates in The City of Konya-Turkey. *Journal of Environmental Management*, 79, 30–37.

National Research Council. (1993). Groundwater Vulnerability Contamination Potential Under Conditions of Uncertainly. Committee for Assessing Groundwater Vulnerability, National Academy Press, Washington.D.C.

Napolitano, P. (1995). GIS for Aquifer Vulnerability Assessment in the Piana Campana, Southern Italy, Using the DRASTIC and SINTACS Methods. M.Sc. Thesis, ITC, Enschede, The Netherlands, unpublished.

Panagopoulus, G.P., Antonakos, A.K., & Lambrakis N.J. (2006). Optimizing Of The DRASTIC Method For Groundwater Vulnerability Assessment Via The Use Of Simple Statistical Methods And GIS. *Hydrogeology Journal* ,14, 894-911.

Pathak, D., Hiratsuka, A., Awata, I., & Chen, L. (2008). Groundwater Vulnerability Assessment in Shallow Aquifer of Kathmandu Valley Using GIS-Based DRASTIC Model. *Journal of Environmental Geology*, 75, 1569-1578.

Piscopo,G. (2001). Groundwater Vulnerability Map Explanatory Notes. NSW Department of Land and Water Conservation, Australia.

Ploethner,D. (1983). Meulaboh Area, North Sumatra. Instructions, Suggestions, Reports Elaborated During Phase II of the Project (1981–1982), Vol. 3: 24–40, German Hydro-geological Advisory Group CTA 40, BGR and Directorate of Environmental Geology (DEG), Bandung.

Prinz, D., 2005. Water and Development, International Summer School, University of Karlsruhe, Karlsruhe.

PT Bintang Purna Manggala & Sembawang Resources PT Ltd. (1985). Proposed Development and Construction of the Meulaboh Coal Mine in the Aceh Province. 15 pp, Jakarta.

PT Petrosea International Indonesia. (1989). Meulaboh Coal Project, Report on Area under Application for Exploitation.12 pp, Jakarta.

Ranjeet Kumar Prasad., V. S. Singh., S. K. G. Krishnamacharyulu., & Pallavi Banerjee .(2010). Application of Drastic Model and GIS : For Assessing Vulnerability in Hard Rock Granitic Aquifer. Journal of Environ Monit Assess. DOI 10.1007/s10661-010-1572-7.

Rahman, A., (2008). A GIS Based DRASTIC Model for Assessing Groundwater Vulnerability in Shallow Aquifer in Aligarh, India. Journal of Applied Geography 28(1): 32-53.

Rao, M. N., & Yang, Z. (2009). Groundwater Impacts Due to Conservation Reserve Program in Texas Country, Oklahoma. Journal of Applied Geography, 1-12.

Rio Tinto & IAGI. (2005). Laporan: Pembuatan 10 Sumor Bor Air Tanah untuk Kebutuhan Air Bersih di Barak Pengungsi sekitar Kabupaten Aceh Barat Pasca Gempa dan Tsunami di Namggroe Aceh Darussalam – Sumatera Utara- 6 pp., Meulaboh, Jakarta.

Rosen, L. (1994). A Study of The DRASTIC Methodology With Emphasis On Swedish Conditions. *Journal of Ground Water*, 32-2.

Saaty, T. L. (1980). The Analytic Hierarchy Process. McGraw-Hill Book Co., New York.

Saaty, T. L. (1986). Axiomatic Foundation of the Analytic Hierarchy Process. *Journal of Management Science*, 32, 841-855.

Saaty, T. L. (1990). An Exposition of the AHP in Reply to the Paper "Remarks on the Analytic Hierarchy Process". *Journal of Management Science*, Vol. 36, No. 3, 259-268.

Saaty, T. L. (1991). How to Make a Decision: The Analytic Hierarchy Process. *European Journal of Operations Research*, Vol. 48, 9-26.

Saaty, T. L. (1994). How to Make a Decision: The Analytic Hierarchy Process, Interfaces, 24, 19-43.

Saaty, T. L. (1991b). Rank and the Controversy About the Axioms of Utility Theory - A Comparison of AHP and MAUT, Proceedings of the 2nd International Symposium of The Analytic Hierarchy Process, Pittsburgh, PA, 87-111.

Saaty, T. L. (1994b). Fundamentals of Decision Making, RWS Publications. Pittsburgh, PA.

Saaty, T. L. (1996). Decision Making with Dependence and Feedback, RWS Publications, Pittsburgh, PA, 1996.

Setiadi, H. (2004): Hydrogeological Map of Indonesia, scale 1:1,000,000, Sheet I Medan. Directorate of Geological and Mining Area Environment, Bandung.

Siemon, B., Ploethner, D. & Pielawa, J. (2006). Interpretation of Electromagnetic Data – Helicopter-Borne Geophysical Investigation in the Province Nanggroe Aceh Darussalam, Northern Sumatra, Indonesia, BGR Report, Vol. B 2: 32 pp, Hannover.

Soetrisno, S. & Sudadi, P. (1986): Hydrogeological Map of Indonesia, scale 1:250,000, sheet 0420 Lhokruet (Sumatra). Directorate of Environmental Geology, Bandung.

Secunda, S., Collin, M.L., Melloul, A.J. (1998). Groundwater Vulnerability Assessment Using a Composite Model Combining DRASTIC with Extensive Agricultural Land Use in Israelis Sharon Region. *Journal of Environmental Managements,* 54, 39-57.

Stigter, T.Y., Ribeiro, L., Carvalho-Dill, A.M.M.(2006). Evaluation of an Intrinsic and a Specific Vulnerability Assessment Method in Comparison with Groundwater Salinization and Nitrate Contamination Levels in Two Agricultural Regions in the South of Portugal. *Hydrogeology Journal*, 14, 79-99.

Tesoriero, A.J., Inkpen, E.L. & Voss, F.D., (1998), Assessing Groundwater Vulnerability Using Logistic Regression: in: Proceedings of the Conference on Source Water Assessment and Protection 98, Dallas, TX, p. 157 - 165.

Tezcan., Levent., & Ekmekci., M. (2004). Surface Cover Infiltration Index : A Suggested Method to Assess Infiltration Capacity for Intrinsic Vulnerability in Karstic Areas in Absence of Quantitative Data. *International Journal of Speleology*, 33: 35-48.

Thirumalaivasan, D., Karmegam, M., & Venugopal, K. (2003). AHP-DRASTIC: Software For Specific Aquifer Vulnerability Assessment Using DRASTIC Model And GIS. *Journal of Modelling and Software,* 18, 645-656.

Topographic Map of Indonesia, scale 1:50,000, series 50 – 0, edition I. (1978). Published by JANTOP TNI AD, Jakarta.

Tóth, J. (1963). A Theoretical Analysis of Groundwater Flow in Small Drainage Basins. *Journal of Geophysical Research,* 68, 4795 4812.

Uhan, J., Pezdic, J., & Civita, M. (2008). Assessing Groundwater Vulnerability by SINTACS Method in the Lower Savinja Valley, Slovenia. *RMZ–Materials and Geoenvironment*, 55, 363-376.

USAID,. (2005). Banda Aceh to Meulaboh Rehabilitation and Recontruction Road Project (Term of Reference). Banda Aceh, Indonesia.

Vander Post, C., and McFarlane, M. (2007). Groundwater Investigation in Semi-Arid Developing Countries, Using Simple GIS tools to Facilitate Interdisciplinary Decision

Making Under Poorly Mapped Conditions: The Boteti area of the Kalahari region in Botswana. *International Journal of Applied Earth Observation and Geoinformation* , 9 , 343–359.

Vias, J., Andreo, B., Perles, M.J., Carrasco, F., Vadillo, I., & Jimenez, P. (2006). Proposed Method for Groundwater Vulnerability Mapping in Carbonate (Karstic) Aquifers: the COP Method Application in Two Pilot Sites in Southern Spain. *Hydrogeology Journal* ,14, 912-925.

Vias, J., Andreo, M., Perles, M., Carrasco F. (2005). A Comparative Study of Four Schemes for Groundwater Vulnerability Mapping in A Diffuse Flow Carbonate Aquifer Under Mediterranean Climatic Conditions. *Journal of Environmental Geology*, 47, 586–595.

Wang, Y., Merkel, B.J., Li, Y., Ye, H., Fu, S. & Ihm, D. (2007). Vulnerability of Groundwater in Quaternary Aquifers to Organic Contaminants: A Case Study in Wuhan City, China. *Journal of Environmental Geology*. Vol. 53, pp.479–484, doi: 10.1007/s00254-007-0669-y.

Wen, X., Wu, J. & Si, J. (2008) . A GIS-based DRASTIC model for assessing shallow groundwater vulnerability in the Zhangye Basin, northwestern China. *Journal of Environmental Geology,* Vol. 57, No. 6, pp.1435–1442, doi: 10.1007/s00254-008-1421-y.

World Health Organization. (1996). Guidelines for drinking-water quality.- 2nd edition, Volume 1: Recommendations, 188 pp.

World Health Organization. (2004). Guidelines for drinking-water quality.- 3rd edition, Volume 1: Recommen¬dations, 515 pp.

Whyte, LL. (1969). Hierarchical Structures. American Elsevier, New York.

Widyastuti., M. (2004). Prediction of Groundwater Vulnerability to Contamination, Study in Ngemplak, Ngaglik and Sleman Districts of Sleman regency, Yogyakarta Special Province.Indonesia. *Indonesian Journal of Geography,* 36, 73 – 121.

Xin, Xin. (2011). Water Resource and Environmental Protection (ISWREP). International Symposium on 2011, V 1, Shaanxi Province, China.

Young S. M., Pitawala A., Gunatilake Jagath. (2005). Vulnerability of the Water Contamination in An Agricultural Area: A Case Study From Dambulla. *Peradeniya University Research Sessions*, page 145.